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Introduction

This thesis explores the issue of Critical Raw Materials, which have become increasingly important for contemporary economies and for the technological transformations associated with the green and digital transitions. These materials constitute an essential material base for a wide range of modern technologies, including renewable energy systems, electric mobility, semiconductors, advanced electronics, and other strategic manufacturing activities. The growing political, economic, and geopolitical interest in this issue, however, does not derive only from their physical properties or from their use in modern technologies. It also reflects the way in which access to these materials has become connected to industrial competitiveness, technological sovereignty, supply-chain resilience, and the broader debate on the European Union's Open Strategic Autonomy.

Despite the growing political and media attention devoted to Critical Raw Materials, many dynamics related to their production, supply, and access to natural resources for extraction remain insufficiently investigated. The debate often focuses on the vulnerability of supply chains, the concentration of global production, and the need to reduce external dependence. Yet these issues are difficult to understand without first clarifying what is being measured, which stage of the supply chain is being considered, and which capabilities are required to transform a geological resource into an input available for industrial production. When we refer to the issue of Critical Raw Materials, we are therefore referring not only to trade dependence or physical scarcity, but also to questions of concepts, data, production capabilities, and territorial conditions.

The role of this thesis is therefore mainly descriptive and exploratory. Its objective is not to provide a definitive solution to the European raw materials challenge, but to clarify a complex

topic in which terminology, information, and data are often incomplete, fragmented, or not fully harmonised. This is particularly relevant because several concepts used in this field — such as critical materials, strategic materials, mineral resources, reserves, extraction, processing, refining, and mining technologies — refer to different dimensions of the problem and cannot be treated as interchangeable. A clearer understanding of these distinctions is necessary before assessing the feasibility and implications of European strategies.

The starting point of the thesis is the concept of Critical Raw Materials and their role in the material base of modern technologies. From there, the analysis moves progressively towards the European policy framework and, in particular, towards the way in which the EU has connected raw materials policy to Open Strategic Autonomy. The Critical Raw Materials Act represents a more recent and operational step in this direction. Within this framework, the policy focus increasingly shifts from the broader category of Critical Raw Materials to the more specific notion of Strategic Raw Materials, which are considered particularly relevant for selected strategic sectors and technologies. This evolution is important because it changes the way in which the problem is framed: from a general concern about supply risk and economic importance to a more targeted concern about the materials needed to sustain specific industrial and technological trajectories.

The European position is examined in relation to other major global players, such as China, the United States, Canada, and Australia. Compared with these countries, Europe appears to face a disadvantage that is not only related to its natural resource endowment, but also to its relatively late operational response to the problem of securing supply chains connected to these materials. While other countries have developed strategies around critical minerals and raw materials in relation to their industrial, geopolitical, and resource positions, the EU has only more recently moved towards a more explicit and coordinated strategy. This does not imply that the EU response is irrelevant; rather, it raises the question of how realistic and effective this response can be, given Europe's geological constraints, industrial structure, regulatory framework, and technological capabilities.

The thesis is organised around three main analytical dimensions. First, it examines EU policies on Critical Raw Materials, with particular attention to Open Strategic Autonomy and the Critical

Raw Materials Act. This part of the work clarifies how the EU has framed the issue of raw materials, how the policy discourse has evolved, and why the concept of strategic materials has become increasingly relevant within the European agenda.

Second, the thesis investigates the resources held by the EU and their geographical distribution, with particular attention to the local and regional level. This territorial focus is important because the EU approach to raw materials is largely top-down, whereas the actual feasibility of extraction and related projects depends on specific places and on the social, environmental, and institutional conditions that characterise them. Resource-endowed territories are not simply passive locations where European targets can be implemented. They are places in which mining projects may generate environmental pressures, conflicts over land use, and different degrees of social acceptance or opposition.

Third, the thesis examines capabilities, with particular reference to mining technologies. The availability of mineral resources does not automatically translate into productive capacity, and the expansion of mining activities does not necessarily imply the development of technological capabilities. This thesis investigates the relationship between mining specialisation and mining innovation in European regions, paying attention to the role of extraction activities, mining-related services, specialised suppliers, engineering firms, equipment producers, and other actors involved in the development of technological solutions for different stages of the mining supply chain.

Overall, this thesis aims to contribute to a clearer understanding of the Critical Raw Materials issue in Europe by connecting policy, resources, geography, and capabilities. Its contribution lies in organising and clarifying a field in which the lack of harmonised data, the ambiguity of terminology, and the fragmentation of information often make it difficult to assess the real scope of the problem. By adopting a descriptive and geographically sensitive perspective, the thesis seeks to show that the European raw materials challenge cannot be understood only through aggregate targets or general policy objectives. It must also be examined through the territorial distribution of resources, the structure of supply chains, and the technological capabilities required to transform mineral endowments into productive inputs for modern industry.

Chapter 1

Critical Raw Materials: EU's Challenges and the Open Strategic Autonomy

Introduction. This chapter develops a critical analytical assessment of the European Union's strategies for addressing its dependence on Critical Raw Materials (CRMs) and strengthening the resilience of CRM supply chains. Particular attention is paid to the main objectives and provisions of the Critical Raw Materials Act (CRMA), which forms part of the EU's Open Strategic Autonomy (OSA) agenda and seeks to expand domestic extraction, processing, and recycling, strengthen industrial competitiveness, and reduce external dependencies. The chapter pursues three related objectives: (1) to examine the importance of CRMs and the factors underlying European and global concerns about their supply; (2) to analyse the broader policy and theoretical context in which the EU has developed its CRM strategy; and (3) to critically assess the measures already adopted and those planned for the short to medium term. Its original contribution lies in bringing these elements together within a common analytical framework. First, the chapter identifies three constitutive dimensions of OSA—the revival of industrial policy, sovereignty and security, and geo-dirigisme—and relates them to recurring tensions concerning efficiency, the distribution of gains, and innovation. Second, it reconstructs the evolution of EU criticality assessments and shows that the classification of materials as critical or strategic reflects not only supply risk and economic importance, but also methodological choices and policy priorities. Third, it classifies the Strategic Projects approved under the CRMA by activity,

material, and location, using this evidence to assess the consistency between the Act's objectives and its operational instruments. The analysis indicates that implementation currently places greater emphasis on expanding supply capacity and facilitating investment than on substitution, innovation-capability creation, and the diversification of international partnerships. Section 1.1 examines the role of CRMs in contemporary technological paradigm shifts. Section 1.2 discusses OSA and technological sovereignty as the broader framework within which the EU's CRM strategy has developed. Section 1.3 examines the evolution of the EU policy framework, the methodology used to identify CRMs and SRMs, and the measures introduced through the CRMA. Section 1.4 discusses the chapter's main findings and implications.

1.1 The Rare Metal Age

Abrahm (2015) labels the contemporary period as the "Rare Metal Age". The term reflects the growing usage of hard metals in the production of everyday goods, which increasingly depend on complex material combinations. At the same time, technological advancements have fostered new markets for metals that were previously little used, in response to evolving societal needs (Gunn, 2014). Unlike base metals, many rare metals and other mineral raw materials are typically utilised in production processes in tiny amounts; yet, due to their irreplaceable chemical, electrical, and mechanical properties, they find extensive technological applications in a large variety of advanced products (Gunn, 2014; Abrahm, 2015; Bobba et al., 2020; Carrara et al., 2023; Li et al., 2024). For instance, gallium is used in semiconductors, and thin-film solar cells; magnesium is valued for its light weight and strength in aerospace and automotive alloys; some rare earth elements (REEs) are critical for permanent magnets, wind turbines, electric vehicles, and advanced electronics; cobalt is a key component in lithium-ion batteries, crucial for electric vehicles and portable devices; and Platinum Group Metals (PGMs), including iridium, platinum, and rhodium, are known for their high resistance to corrosion and are widely used in automotive catalysts, chemical processes, hydrogen technologies, and medical devices[1].

Governments have become increasingly aware of the importance of such natural resources, and

[1] https://scrreen.eu/crms-2023/

certain mineral commodities have gradually been recognised as critical resources and, more specifically, as Critical Raw Materials (CRMs). The concept of raw material criticality is not static; rather, it varies depending on the factors considered relevant when assessing whether a raw material is critical (Glöser et al., 2015; Mayer & Gleich, 2015; Schrijvers et al., 2020; Zhang et al., 2023; Valverde-Carbonell et al., 2024). Since the late 2000s, most criticality assessment models have focused on two main dimensions: (1) supply risk; and (2) the impact of supply disruption (Gunn, 2014). Consequently, whether a material is classified as critical for a particular country depends on both the indicators used to measure these dimensions and the values assigned to those indicators. Labelling a raw material as critical involves a selection process that places a commodity on an official list; these lists can differ across countries and over time due to differences in technical definitions and criticality assessment procedures[2] In the specific case of the EU, CRMs are defined as *"... non-energy, non-agricultural raw materials that are considered to be critical due to their high economic importance and their exposure to high supply risk..."* (Regulation (EU) 2024/125, Pag 1). Accordingly, the EU criticality assessment is based on two core parameters: (1) the risk of supply chain disruption; (2) the economic importance of a given raw material for the EU economy (European Commission, 2010, 2017)[3].

The EU has the longest history of public lists of CRMs (Zhang et al., 2023), but it is not alone in relying on an official classification of critical materials. Canada[4] and UK[5] have both an own official list of Critical Minerals; the US publishes a federal List of CRMs in the Federal Register[6]; Australia maintains two official government classifications: the Critical Minerals List and the Strategic Materials List[7]; and China, Japan, and South Korea also rely on one or more official lists of CRMs or Critical Minerals (Zhang et al., 2023). Divergences across

[2]A comprehensive and insightful review of the methodologies adopted worldwide for assessing material criticality is provided by Schrijvers et al. (2020).

[3]See Section 1.3.1 for a detailed discussion of the EU's criticality assessment methodology.

[4]https://www.canada.ca/en/campaign/critical-minerals-in-canada/critical-minerals-an-opportunity-for-canada.html

[5]https://www.gov.uk/government/publications/uk-critical-minerals-strategy/critical-minerals-technical-annex

[6]https://www.federalregister.gov/documents/2025/11/07/2025-19813/final-2025-list-of-critical-minerals

[7]https://www.industry.gov.au/publications/australias-critical-minerals-list-and-strategic-materials-list?

national and regional lists remain a relevant and often overlooked aspect. While this may be less problematic for analyses focused on a single country, at the global level the concept of CRMs becomes more ambiguous in the absence of a harmonised international list, as differences in terminology, assessment criteria, and policy priorities complicate cross-country comparisons. As Zhang et al. (2023) point out, even the lack of uniform terminology across jurisdictions is not merely a semantic issue. A telling example can be found in the EU definition of CRMs discussed above, which explicitly defines them as non-energy, non-agricultural raw materials, and therefore it excludes energy raw materials from the scope of the EU list[8]. Uranium is the case in point: despite its strategic importance for nuclear energy production, it is not considered a CRM by the EU, whereas it is included in Canada's official Critical Minerals List, and has been recently included in the U.S. federal List of Critical Minerals since 2025. This divergence is due to the fact that Canada and the United States adopt broader and somewhat different notions of criticality than the EU. Canada's approach to critical resources is more explicitly linked to national resource endowments[9], industrial development, clean technology supply chains, and energy security . The U.S. definition is also broader and more security-oriented: the 2025 U.S. critical minerals methodology assesses how mineral supply disruptions could affect the U.S. economy and national security[10].

What emerges from the discussion so far, is that whether a material is considered critical may vary across countries not only because economies differ in their degree of exposure to supply disruptions of specific commodities, but also because different countries and jurisdictions adopt different conceptual and methodological approaches to defining what counts as a critical raw material. Nevertheless, a broad consensus has emerged in both policy and academic debates

[8]Note that the EU does not provide an official definition of non-energy raw materials within its documents related to this strategy. Its meaning can be deduced from the Strategic Implementation Plan for the European Innovation Partnership on Raw Materials (2013), which is part of the European Innovation Partnership (EIP) on Raw Materials (https://single-market-economy.ec.europa.eu/sectors/raw-materials/eip/strategic-implementation-plan-sip_en#documents), and Hamor et al. (2021). These sources consider as non-energy raw materials: 1) industrial minerals (those with chemical and physical applications, such as phosphate rock, potash, magnesite, asbestos, silica sand, diatomite, perlite, zircon, peat, gemstones, etc.), 2) construction minerals, 3) metallic minerals (ferrous and non-ferrous metals, as well as precious metals). Fossil fuels, such as lignite, coal, anthracite, oil, and gas, oil shale, and certain minerals such as uranium and thorium ores, are considered energy minerals.t

[9]https://www.canada.ca/content/dam/nrcan-rncan/site/critical-minerals/Critical-minerals-strategyDec09.pdf

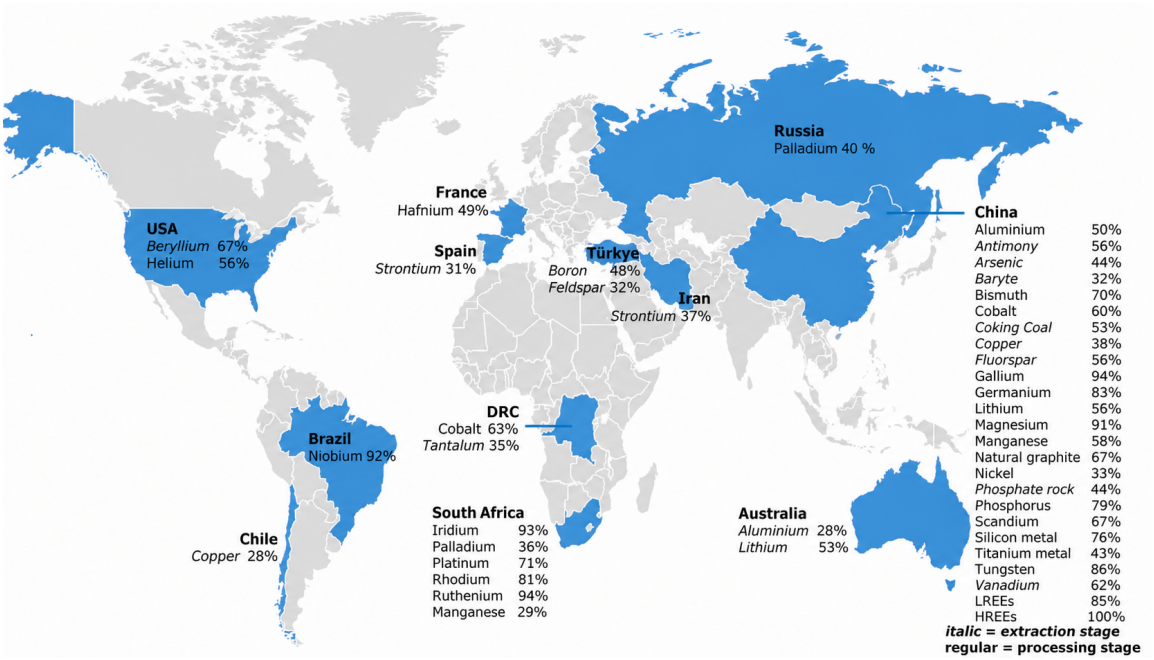
[10]https://www.usgs.gov/programs/mineral-resources-program/science/about-2025-list-critical-minerals

regarding the increasing reliance of contemporary economies on CRMs, alongside the structural fragility of their supply chains driven by geopolitical risks, concentrated mineral deposits, low recycling rates, and social and environmental impacts (Radetzki et al., 2008; Achzet & Helbig, 2013; Girtan et al., 2021; European Commission, 2023a; Draghi, 2024). A key source of vulnerability is the high concentration of CRM extraction and production in a small number of countries, often characterised by low institutional stability, which increases exposure to external shocks, including geopolitical tensions. Such a concentration of CRM supply generates two major risks (Draghi, 2024): 1) price volatility, making it harder for investors to commit to long-term projects; 2) use of CRMs as a retaliation tool on global markets. As reported by the European Commission (2023a), China dominates the global supply of several key raw materials, accounting for 94% of gallium, 91% of magnesium, approximately 90% of REEs, and 60% of cobalt. The Democratic Republic of Congo (DRC) accounts for 63% of the world's cobalt extraction, highlighting a substantial reliance on a single country for this critical resource. Additionally, South Africa plays a leading role in the production of PGMs, supplying 93% of globally produced iridium, 71% of platinum, and 81% of rhodium. Figure 1.1 shows the leading supplier countries for CRMs worldwide.

As scholarly research and institutional reports point out, CRMs are fundamental prerequisites for achieving major goals such as the green and digital transitions (e.g., Bobba et al., 2020; Carrara et al., 2023; Li et al., 2024). Attaining decarbonisation goals and meeting the Paris Agreement targets depends significantly on the availability of critical mineral resources, whose demand – not only of notorious CRMs such as lithium, cobalt, or REEs, but also of base metals rather more widespread and available on the planet such as aluminum, copper, or nickel – is expected to increase dramatically, particularly driven by the renewable energy industry. According to the International Energy Agency (IEA), the demand for lithium is forecast to grow eightfold by 2040, whereas the demand for nickel, cobalt, and REEs is expected to double by the same year (IEA, 2024). Bobba et al. (2020) scenarios estimate that, for renewable energy and e-mobility applications alone, the EU demand could increase by up to around 60 times current consumption levels for lithium, roughly 14 times for graphite, about 12 times for dysprosium, and up to 15 times for cobalt, by 2050. A similar pattern applies to aluminium, copper, and nickel: according to the World Bank (2020), the global demand from the renewable energy sector is projected

to increase by 322%, 213%, and 76%, respectively. In general, mineral resource extraction is expected to increase by more than 60% by 2060 compared to 2020 levels, driven by rising demand for infrastructure, clean energy technologies, and industrial materials (Bruyninckx et al., 2024). The current situation raises significant concerns not only for the present, but even more so for the years to come, particularly as primary raw material production does not appear to be responding quickly enough to demand signals. Increasing primary production is inherently challenging, not only due to the geographical concentration of mineral resources, but also because of the long lead times required to develop new mining projects and the need for specialized capabilities along the entire value chain. These capabilities are required not only for extraction, but also for downstream processing and refining, which are essential to transform mineral commodities into usable material inputs for industrial production.

Figure 1.1: Countries accounting for largest share of global supply of CRMs.



Source: European Commission (2023a).

The expansion of CRM extraction and production is also associated with significant environmental and social externalities, further constraining supply responses. Expanding primary production

is likely to entail significant environmental and social impacts, and recycling and substitution technologies—while promising—are not yet mature enough to supply a substantial share of domestic needs (Ali et al., 2019). According to Bruyninckx et al. (2024), biomass growth and harvesting, mineral and fossil resource extraction, and the processing of materials, fuels, and food together account for more than 55% of global greenhouse gas (GHG) emissions. In particular, the extraction of biomass, minerals, and fossil resources accounted for 35% of this share in 2022, while the processing stage of metals and non-metallic minerals contributed 18%. Mining may also have other devastating effects, such as groundwater pollution, especially in developing countries, and is responsible for 1% of global biodiversity loss (Bruyninckx et al., 2024). Moreover, many CRMs are also referred to as "conflict minerals", as their extraction is often linked to armed conflicts, human rights violations, and environmental degradation. Africa is particularly susceptible to conflicts driven by mineral resources, as highlighted by Berman et al. (2017). The extraction and trade of minerals foster the fighting capacity of armed groups, leading to the escalation of violence. This effect is especially pronounced when rising mineral prices intensify competition for control over resource-rich areas. A well-known case is the cobalt industry in the DRC. The cobalt industry in the DRC is largely dominated by Chinese multinational corporations that frequently rely on artisanal and small-scale mining operations, which often lack proper safety measures, exposing workers to toxic substances and life-threatening conditions (Church & Crawford, 2018). The lack of regulation has led to severe pollution of water sources, affecting both ecosystems and local communities, resulting in significant health risks and long-term environmental degradation. Finally, where political, social, and regulatory systems do not permit open violations of human rights, mining activities are often met with strong opposition from local actors who can significantly slow down or even interrupt extraction, processing, and refining activities (Church & Crawford, 2018).

1.1.1 Critical Raw Materials in Modern Technological Paradigm Shift

The need to ensure secure access to CRMs has led governments to develop strategic programs and policies aimed at strengthening supply chains and reducing dependence on foreign sources, including the EU's "Critical Raw Materials Act" (discussed in Section 1.3.2), the US "Critical

Materials Strategy", Canada's "Critical Minerals Strategy", and Australia's "Critical Minerals Strategy 2023–2030. CRMs are connected to all industries across all stages of the supply chain (European Commission, 2020a, 2023a), making them strategically important for the development of modern technologies, particularly for the transition from mechanical to digital technologies, and for green technologies, including wind turbines, electric vehicle batteries, and energy-efficient lighting (Kiggins, 2015).

However, terms such as CRMs and, as discussed later, "Strategic Raw Materials" - when referring to materials considered important for selected strategic sectors - are not recent. They were already formalised in the "U.S. Strategic and Critical Materials Stock Piling Act of 1939" (U.S. Congress, 1939); however, the meaning attached to these categories differed substantially from their present-day usage. During the era of the World Wars, the notion of "strategic and critical materials" referred primarily to the need to secure the availability of essential commodities for national defence, military preparedness, and industrial mobilisation (Bradfish, 1987; Burnett et al., 2022; Zhang et al., 2023). By contrast, the modern use of terms, particularly in the EU policy framework, is embedded in a much broader agenda that includes not only security concerns, but also industrial competitiveness, technological sovereignty, supply chain resilience, and the green and digital transitions (see Sections 1.2 and 1.3).

In recent years, different contributions have provided evidence that recent technological trajectories are CRM-intensive, highlighting that CRMs (and rare and conflict minerals more broadly) are key inputs for frontier technologies and underpin modern industrial capabilities. Li et al. (2024) conduct an empirical analysis of the relationship between 13 key rare metals and frontier technological innovation by performing text mining on 5,146,615 USPTO granted patents from 1976 to 2015. They find that more than 10% of patents rely on at least one of the materials considered. This work helps to clarify the role of some mineral raw materials within frontier technological innovations and the ongoing technological paradigm shifts.

In an exploratory analysis, Diemer et al. (2025) move the focus of the debate to critical and conflict materials (CCMs) from an economic geography perspective, performing a text analysis of USPTO data. They find evidence of a significant increase in innovation activity related to CCMs between 1975 and 2015, and a particularly strong association between ICT and the six

CCMs considered. Li & Iammarino (2026); focus on the renewable energy sector (wind and solar energy in particular) to assess the impact of domestic CRM supply on industrial competitiveness and technological innovation. Their study examines data from 128 countries between 2007 and 2016 considering a selection of rare and base metals identified as relevant to the RE sector by Moss et al. (2011). The results show that domestic CRM production positively influences both industrial competitiveness, measured through the revealed comparative advantage (RCA) indicator, and technological competitiveness, assessed via the revealed technological advantage (RTA) indicator.

De Cunzo et al. (2025) build upon the insights of the three previous studies, proposing an exploratory analysis of how green innovation activities map onto the demand for CRMs. Using text mining techniques to analyse patent descriptions from the Worldwide Patent Statistical Database (PATSTAT), they find that mature green technologies are the most CRM-intensive. Moreover, countries with a narrower green-tech specialisation, which focus their green technology patenting activity on a few key domains—such as lithium-ion batteries or semiconductors and microchips—are the most dependent on CRMs, as their technological advancements and industrial competitiveness are directly tied to the stable supply of these materials (including Japan, South Korea, Russia, and Taiwan).

The concepts of technological paradigm and technological regime are particularly well-suited to explain the significant relevance and role of CRMs in modern technologies, and to identifying the challenges related to these commodities on the path towards the green and digital transition. Schumpeter (1934) defines production activity as a combination of materials and forces to produce other things, or the same things in a new way. In the recombination process, new materials can be seen as both a product of innovation and a driver of technological advancement. The dynamic process by which innovation patterns may come to form is jointly determined at each time by the current operating characteristics of firms, which determine their input and output levels, exogenous market supply and demand conditions, and the current policy framework (Nelson & Winter, 1982).

The concept of technological regimes dates back to the works of Nelson & Winter (1977, 1982) and was further developed by different authors (among others, Malerba & Orsenigo, 1993,

1996; Breschi et al., 2000). Technological regimes are shaped by natural trajectories, which are specific to a particular technology and emerge from the inherent characteristics of a given technology or industry (Nelson & Winter, 1977). Moreover, Breschi et al. (2000) broadly define a technological regime as the combination of four fundamental factors: technological opportunities, appropriability of innovations, cumulativeness of technological advances, and properties of the knowledge base. Therefore, a change in the technological regime also implies a fundamental transformation in the economic landscape and in the market structure.

On the other hand, Dosi (1982, 1988) highlights how technological change is path-dependent emphasizing the concept of technological paradigm as a model and a pattern of solution of selected technological problems based on selected principles derived from natural sciences and on selected material technologies[11]. A shift in the technological paradigm represents a fundamental change in these underlying principles and practices to solve technological problems. Therefore, technological trajectories are the directions of progress within a paradigm, and the patterns of solution to selected technological problems follow these trajectories.

Innovation often drives shifts in the mix of materials used, even if the prices of competing materials remain relatively stable (Tilton, 1991), as new technologies often require specific materials to be developed and implemented. If these materials are not available in adequate quantities, material scarcity may not only slow down production but also limit the capacity to produce and implement new technologies at the necessary scale (Cameron & Metcalfe, 1987). Thus, the interplay between technological paradigms, path dependency, and material constraints suggests that securing a stable CRM supply is not just a production concern but a fundamental requirement for sustaining innovation and industrial transformation. Progress toward sustainability heavily relies on renewable energy technologies, electric vehicle batteries, and advanced semiconductors (Bobba et al., 2020; Carrara et al., 2023), and supply interruptions of some of these materials can create bottlenecks, slowing down technological progress and the adoption of new technologies, ultimately affecting the achievement of ambitious goals, such as the Green Deal.

[11]This definition is in analogy with Kuhn (1962)

1.2 EU's Open Strategic Autonomy (OSA)

OSA emerges in a context of increasing global connectivity, multidimensional interdependence, and aggressive global competition. Although originally focused on matters of security and defence, OSA has since expanded to encompass a wide range of policies, including geopolitics and economics, technology, the environment, social and governance issues (Cagnin et al., 2021).

Providing a clear and concise definition of OSA is not easy. This complexity stems from the inherently intricate nature of "open autonomy" itself, and the fact that the EU includes a broad range of different initiatives related to this strategy. COVID-19, and subsequently the Russian-Ukrainian war, highlighted the EU's dependence on third countries for essential inputs and showed how geopolitical instability can disrupt European supply chains, posing risks to the EU's long-term security and competitiveness. In 2020, the European Commission announced for the first time its willingness to adopt a model of open strategic autonomy in one of its communications (European Commission, 2020a), addressing the vulnerabilities exposed by the COVID-19 pandemic, such as the disruption of supply chains and economic dependence on some foreign countries, and stressing the importance of open and fair trade to strengthen the EU's economic security. The document also points to the need to reform global economic governance and developing mutually beneficial bilateral relations, while protecting against unfair and abusive practices to avoid future crises.

The concept of OSA is a reworking of the pre-existing concept: "strategic autonomy", reshaped around the adjective "open". The EU's strategic autonomy was mentioned for the first time in 2013 by the European Commission in the COM(2013) 542 final: "Towards a more competitive and efficient defence and security sector", although this concept also dates back to "European Strategic Autonomy" and the first defence cooperation programmes among Western European countries, only to lose relevance after the Cold War (Mariotti, 2024a). This document heavily focuses on military defence and industrial sectors, framing autonomy largely in terms of the competitiveness of EU-produced arms and systems used by Member States' armed forces. It also calls for more intensive support for internal and external security in areas such as the protection of external borders, maritime surveillance, and civil protection. The term "strategic autonomy"

gained renewed prominence in 2016 after the Brexit referendum, with the EU's release of "A Global Strategy for the European Union's Foreign and Security Policy" (European Union External Action Service, 2016), also fostered by growing international uncertainty, particularly in response to Donald Trump's first presidency (Cesnakas & Juozaitis, 2023). Along with security and defence, the scope of OSA underwent an initial expansion, beginning to also consider topics such as strategic communication and reliable energy production. Some years later, with COM (2021) 66 final (European Commission, 2021a), the EU introduced "Open Strategic Autonomy" as a policy choice and a mindset for decision-makers, enabling them to respond to today's global challenges. In this sense, we can consider OSA a broader policy framework within which the EU's approach to Critical Raw Materials can be understood. The objective is not simply to reduce external dependence, but to increase the EU's capacity to act in a global environment where trade, technology, security, and industrial competitiveness are increasingly intertwined

1.2.1 The Technological Sovereignty

In the current EU's approach to OSA, security policy regulation and strategic partnership are central components. This also involves ensuring reliable access to critical resources and maintaining the resilience of supply chains essential to the EU's economic interests. The 2020 Action Plan on CRMs (European Commission, 2020b) and the most recent CRMA (European Commission, 2023b) are considered part of OSA. The role of OSA in addressing dependence on raw and processed materials is also highlighted in the 2021 update of the "Industrial Strategy for Europe" (European Commission, 2021b). Promoting economic competitiveness by diversifying the sources of CRMs is also one of the priorities of the EU Economic Security Strategy (European Commission, 2023c), which is also framed within the OSA agenda. However, CRMs ore only one of the areas OSA addresses. Trippl et al. (2024) identify four key themes at the centre of the OSA debate: (1) the military and defence sector, reflecting the origins of Strategic Autonomy in 2013; (2) the energy transition within the Green Deal; (3) microchip manufacturing; and (4) the de-risking of CRM supply. These priorities are closely linked to the concept of "technological sovereignty", which emerges as the cornerstone of the evolution of strategic security towards the notion of OSA. The notion of technological sovereignty itself is another concept that is

difficult to define with precision, as it encompasses a broad spectrum of dimensions, ranging from control over what the EU considers strategic technologies, to infrastructures and resilience against external dependencies. Its meaning varies depending on the geopolitical, economic, and sectoral context in which it is applied, making it a continuously evolving and debated notion. Edler et al. (2023), refer to the concept of technological sovereignty as:

"...the ability of a state or a federation of states to provide the technologies it deems critical for its welfare, competitiveness, and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency..." (Edler et al., 2023; page 1).

This definition suggests that technological sovereignty goes beyond the mere concept of technological self-sufficiency. As March & Schieferdecker (2023) argue, Edler's definition—widely cited in numerous subsequent works such as Crespi et al. (2021), Schmitz & Seidl (2023) and Trippl et al. (2024)—emphasizes that technological sovereignty should primarily be seen as a capability. Specifically, it refers to the ability to autonomously generate technological and scientific knowledge or to leverage technological capabilities developed externally through the establishment of reliable partnerships. However, Couture & Toupin (2019) note that, as with the definition of OSA, the concept of technological sovereignty has evolved over time in response to contemporary challenges, and the term is increasingly used to describe different forms of independence, control, and autonomy[12].

According to Crespi et al. (2021), achieving an adequate level of technological sovereignty is a precondition for a country's strategic autonomy, as it fosters the creation of new opportunities to compete on the frontier of technological development. When supported by adequate infrastructure, institutional conditions, and capacity for innovation and production, technological sovereignty contributes to economic sovereignty, which in turn supports the broader goal of strategic autonomy. Moreover, beyond the unexpected events of recent years, such as COVID-19 and the Russian-Ukrainian war, the debate on the EU's lack of technological sovereignty is driven in particular by intensifying competition between the U.S. and China for technological and industrial leadership. Europe has several structural dependencies on these two players, especially

[12]Kelly et al. (2020) further observe that the overlap between OSA and technological sovereignty is so strong that the two terms are often used interchangeably. The overlap between the two terms contributes to confusion in the debate, making it difficult to clearly define the scope of objectives.

in the areas of digital platforms and telecommunications infrastructure. From a country's point of view, there is often an effort to achieve technological competitiveness in as many sectors as possible; however, the pursuit of technological sovereignty takes place in selected fields that are considered important according to very specific criteria. The identification of these strategic fields is not straightforward, and in the EU, where the notion of sovereignty is shaped by the pursuit of shared objectives, strategic fields have been identified as those strictly interlinked with the EU's priorities for a sustainable, digital, and healthy society[13](Crespi et al., 2021).

Technological sovereignty, and indirectly strategic autonomy, seem to provide the framework in which renewed interest in industrial policies finds its place in Europe. According to Schmitz & Seidl (2023), technological sovereignty and the emerging trend of "geo-dirigisme" are two of the key drivers of the EU's new industrial policies. The term "geo-dirigisme" refers to a growing tendency for a state to actively steer the economy by prioritising strategic sectors and technologies that matter for international competition and security, in order to reduce vulnerabilities and critical dependencies, and this require a strategic balance of being "as open as possible, as autonomous as necessary" (Schmitz & Seidl, 2023). Industrial policies have gained attraction due to the growing perception that market forces alone are insufficient to ensure technological capabilities as well as economic competitiveness in a world where the decline of multilateralism and rising geopolitical tensions between economic blocs are two of the major challenges (Trippl et al., 2024). The EU has a long history of industrial policy, and the idea of technological sovereignty is similar to past efforts in the 1980s and 1990s to build strong "European industrial champions". However, while a few of these initiatives succeeded, many failed, especially in highly advanced fields like digital technology (Trippl et al., 2024).

Although the EU's definitions of technological sovereignty and OSA, as well as its political orientations, carefully seek to keep the distance from a return to protectionism, the renewed interest in industrial policy and the revival of the concept of strategic autonomy raise critical questions and concerns that cannot be overlooked. In particular, these concerns stem from significant territorial and regional differences within the Union, along with the multiple and

[13]This statement by Crespi et al. is consistent with the previously mentioned classification of key areas at the core of the OSA framework proposed by Trippl et al. (2024), as well as with European Commission (2020b, 2021b, 2023c) and the European Innovation Council (EIC, 2021).

often ambiguous interpretations these concepts may assume when operationalized as policy tools. The risk is that, in the absence of a clear, inclusive, and territorially sensitive framework, such strategies may inadvertently reinforce existing asymmetries, benefiting primarily the most advanced regions and actors.

In summary, the EU's current geopolitical landscape is influenced by emerging global trends that pose potential threats to domestic and external policy objectives and trade diversification. Global uncertainty and growing unilateralism driven by geopolitical tensions have resulted in increased protectionism, and the world is now facing the risk of policy-driven geoeconomic fragmentation. At the same time, accelerating climate change, along with strategic dependencies on third countries for CRM supply, threatens economic security and the EU's transition to a sustainable and resilient economy (European Commission, 2021a; IMF, 2023). In this context, OSA has been proposed as the EU's response to these challenges, balancing trade protection and opportunity (European Commission, 2021a). The following section offers a summary of the main orientations that the literature has developed in relation to these issues.

1.2.2 Tensions and Challenges of Open Strategic Autonomy

Mariotti (2024a) reviews the main positions in the literature on OSA and identifies three prevailing perspectives. The first is "the good" view, which welcomes the return of industrial policy. From this perspective, a deep restructuring and transformation of European industry is needed, particularly in response to changes in the global environment (Van den Abeele, 2021; Della Posta, 2023; Li, 2023; Mirò, 2023; Schmitz & Seidl, 2023; Janger, 2024). However, according to Criscuolo & Lalanne (2024), industrial strategies are undergoing significant changes in the goals they pursue, increasingly incorporating "non-traditional" objectives, including challenges such as the green transition, inclusive growth, strategic autonomy, and supply chain resilience.

Consistently with OSA principles, many of these new policy orientations explicitly refer to emerging challenges—especially the sustainability challenge—to justify the renewed emphasis on industrial policy. Mazzucato (2016) argues that the market-failure approach is limited when

transformative change requires policies that dynamically create and shape new markets. Markets are blind to the direction of change; left on their own, they do not steer innovation toward social goals such as sustainability. Industrial policy must go beyond fixing market failures; it should guide innovation toward social and environmental goals by creating and shaping markets in strategic, transformative sectors and green and digital technologies, where systemic change is essential and markets alone may fall short. A similar view is expressed by Pianta et al. (2020), who argue that the EU needs a new industrial policy capable of steering innovation and production toward common goals such as sustainability and cohesion. The authors also highlight the excessive emphasis on "horizontal" measures implemented without clear sectoral targeting, including regional and cohesion policy, which they consider to be failing to support innovation in strategic areas. The second view is "the bad" view, which expresses concern that moving away from traditional multilateralism may lead to what has been called the "autonomy trap". From this perspective, efforts to achieve autonomy could increase vulnerabilities and reduce the EU's economic and industrial influence (Bargués, 2021; Mariotti, 2024b; Olsthoorn, 2024). Finally, Mariotti also identifies a third, more critical view: "the ugly". Some authors consider the idea of OSA, as developed by the EU, to be fundamentally inconsistent. According to this view, the EU itself has not been able to clearly explain how openness will actually safeguard autonomy. The concept is seen as an "ugly oxymoron", open to multiple opportunistic interpretations, and flexible enough to justify very different policy choices depending on the moment. This perspective is reflected in the works of Lavery et al. (2022), Broeders et al. (2023), Kübek & Mancini (2023), and Soete & Burgelman (2023).

In this section, our intention is not to reiterate a review of existing perspectives in the literature on OSA; rather, we focus more narrowly on the specific challenges the EU will face in trying to achieve OSA, and on the consequences that its actions may have, without forgetting the often-overlooked sub-national level. From what discussed so far, the OSA concept is characterized by three main recurring features: (1) the revival of industrial policies, (2) sovereignty and a security-driven approach, and (3) geo-dirigisme. The debate in the literature seems to follow these three key points in order to discuss the pros and cons of what OSA can offer. Moreover, we also identify three thematic axes on which scholarly criticism has focused regarding the possible effects of OSA and related strategies: (1) isolation and its impact on efficiency and

productivity, (2) unbalanced distribution of gains, and (3) barriers to innovation. What emerges from the review of the documents analysed so far concerning the OSA, is that the three previous cited core aspect of the OSA are deeply interlinked, both among themselves and with the three thematic axes of the literature criticism. Reflections on the OSA's implications thus require an integrated perspective with OSA aims, that considers the mutual reinforcement and trade-offs among efficiency, equity, and innovation.

Since the 1970s, industrial policies have declined, largely due to failures, waste of public resources, vested interests, and anti-competitive effects (Mariotti, 2024a; Trippl et al., 2024). The effectiveness of industrial policies crucially depends on governments' ability to identify the right targets. Achieving effective industrial strategies today requires greater attention than in the past to policy design, rigorous evaluation practices, and international coordination. In particular, promoting green technologies and strengthening countries' supply chains through isolated, uncoordinated interventions, often involving protectionist or distortionary measures, risks undermining the global benefits of climate action. Such approaches can lead to a zero-sum game, with winners and losers, and result in inefficient public spending. This perspective aligns closely with Mariotti (2024b), who points out that after decades of hypergrowth, globalization has been slowing down since the 2008 global financial crisis, a dynamic also characterized by firm-to-firm competition increasingly intertwined with competition between respective nation-states. Governments are now acting as strategists, shaping national policies with the goal of becoming relative winners, even at the expense of overall absolute gains, with the consequence of fostering inequalities. States are thus engaged in a non-cooperative game, where national security takes precedence over efficiency. To pursue these strategies, governments are increasingly using tools such as FDI restrictions (which rose from 6% in 2000 to 28% in 2022), particularly through FDI screening and reverse screening mechanisms (to monitor outbound investments as well), the political use of antitrust and sectoral regulation, and a renewed emphasis on mission-oriented industrial policies (Mariotti, 2024b). Lavery et al. (2022) argue that the EU is undergoing a geoeconomic transformation driven by systemic competition with powers like China and the United States. The shift involves an increasing reliance on some already cited defensive instruments (such as FDI screening, industrial policy, and strategic subsidies), often inspired by more state-centric models like that of China. However, this approach may erode the EU's

competitive advantage within an open economy, as the Union is not structurally equipped to pursue "muscular" policies on par with those of the US or China.

According to Evenett et al. (2024), based on policy measures recorded up to 2023, if one of the major economies (the US, China, and Europe) introduces a subsidy for a specific product, there is a 74% chance that another will respond with a similar subsidy within a year. Furthermore, over 71% of industrial policy interventions are trade-distorting and risk generating retaliatory dynamics and reducing global market openness, with the US, China, and the EU as the major players. Soete & Burgelman (2023) point out that the EU risks losing ground if it focuses too much on "technological sovereignty" without anchoring it in international innovation networks, and this may lead to new forms of closure. The line between the EU's concept of OSA and excessive isolationism appears to be quite blurred. This raise concerns that the concept could be misused for unilateral, protectionist approaches. As noted by Lavery et al. (2022), the strategic shift in the EU's economic policy is further complicated by the conceptual ambiguity of terms such as "strategic autonomy".

The lack of clarity creates room for diverging national interpretations and, in some cases, enables the adoption of protectionist measures under the guise of strategic interests. Rather than fostering resilience through openness and cooperation, such ambiguity risks legitimizing policies that prioritize domestic control over international engagement under the banner of security or technological resilience (Lavery et al., 2022; Broeders et al., 2023). Moreover, this assertive language may clash with the EU's traditional role as a normative power, which is based on openness, free trade, and the protection of fundamental rights.

Some scholars even warn about the risk of "strategic cacophony," where different national views on what strategic autonomy means could lead to political fragmentation within the EU (Broeders et al., 2023). This kind of scenario must receive the utmost consideration from European countries. Since 1995, increased openness has boosted EU income, and trade has played a vital role in the EU's green recovery from the economic slowdown caused by COVID-19 (Carrara et al., 2020; European Commission, 2020a, 2021a, 2021b; and others). The European Commission itself is the first to emphasize that cross-border cooperation is essential for technological progress, post-COVID recovery, and achieving long-term goals such as decarbonization and digitalization

(European Commission, 2021a). Fragmentation and nationalistic approaches may undermine the EU's technological strength in frontier sectors such as AI and biotechnology, which increasingly depend on international flows. Regions or nations that exit international networks risk becoming peripheral in technological trajectories (Binz & Truffer, 2017; Cagnin et al., 2021; Carrara et al., 2023). Environmental and emerging technologies also depend on transnational ecosystems, and if EU defensive and strategic policies lead to overly autarkic approaches, the Union risks moving toward a form of "strategic decoupling" from multilateral networks, excluding itself from essential flows (Hamor et al., 2021; Helwig & Sinkkonen, 2022; Kübek & Mancini, 2023).

In addition to what has been discussed so far, the literature has paid such limited attention to the potential effects of policy interventions designed to promote technological sovereignty and strategic autonomy at the regional and sub-national level. According to Trippl et al. (2024), these policies could have a significant impact on regional development and place-based innovation. The authors point out that OSA goals and measures have first and foremost a national or supranational purpose. European regions differ in their industrial capabilities, natural resources, and contextual conditions, which can affect their ability to benefit from OSA policy, resulting in uneven regional impacts. In particular, the impacts of strategic industrial interventions are likely to be felt most strongly at the regional level, with some regions affected more than others, leading to differentiated regional effects from these policy measures. The authors also note that while some measures might create opportunities for economic development and innovation, others could introduce challenges related to technology access, talent mobility, and competition for resources. Protective measures may pose serious risks for regions highly dependent on global technology flows and foreign talent, such as urban innovation hubs and science-intensive areas. These regions could experience economic disruption, weakened R&D systems, and reduced access to critical global networks. Industrial promotion measures aimed at boosting industrial capacity could support regions with existing manufacturing strengths and help others diversify their economies. However, without careful targeting, they may reinforce the position of already strong regions and leave behind those with weaker institutional or economic structures. Finally, regions with strong research and innovation systems—such as science hubs and university-driven urban areas—are more likely to benefit from protection measures, thanks to their capacity to attract international collaborations and investments. Less advanced regions could also benefit from

these measures, particularly if protection measures encourage the wider diffusion of knowledge or support cross-border collaboration. However, these outcomes are not guaranteed, and barriers such as limited institutional capacity, a lack of skilled labour, or poor connectivity to global networks risk excluding them from these opportunities, reinforcing existing innovation divides.

From an integrated analysis, it is quite clear that access to resources and strategic security are seen by the EU as two sides of the same coin. Strategies defined to reduce dependence on CRMs and to diversify sources of primary raw materials from third countries are not challenges in themselves but essential elements in achieving the overall long-term objectives set by initiatives such as the European Green Deal and the new EU Industrial Strategy. However, the EU's approach to CRMs has varied significantly over time; the following sections trace the various steps up to the most recent updates on CRMs.

1.3 CRMs in the EU

The critical dependence of the EU on certain raw materials was known to European institutions even before the last decade. The "EU Raw Materials Initiative" (European Commission, 2008) can be defined as the starting point of the EU's concrete action regarding raw materials. The initiative is a strategic and comprehensive approach designed to ensure a sustainable and secure supply of raw materials to the European market. Additionally, the document underlines the importance of periodically defining and updating the list of materials considered as "critical", with revisions every three years.

As we anticipated, the category of CRMs is not a static classification, and materials included in this list may change depending on the revision process periodically carried out by the EU. When this process takes place, a very broad range of (candidate) raw materials is considered during the assessment phase, regardless of whether or not they were previously deemed critical. Since 2010, the European Commission has commissioned periodic reports by ad hoc working groups aimed at identifying CRMs. The distinction between critical and non-critical materials was first made in the report "Critical Raw Materials for the EU" (European Commission, 2010), which set out the first EU criteria to assess material criticality. According to the document, the global scarcity of a given material has not been directly considered a significant factor in assessing criticality, which instead depends on two main indicators: (a) an aggregate index of economic importance and supply risk; (b) an environmental risk indicator[14]. Stemming from this report, the first official list of CRMs was published in 2011 based on a study of 62 potential material candidates and includes 14 CRMs[15].

The methodology established in 2010 for addressing criticality was also used for the first revision of the list in 2014, which included 20 elements. In 2017, the European Commission significantly

[14] Section 1.3.1 explores in detail the evolution of EU assessing methodologies.

[15] Note that for the sake of brevity, the EU tends to make public a version of the lists in which certain elements are aggregated into broader mineralogical groups. For example, REEs have been subdivided, starting with the second list of CRMs (2014), into LREEs (light rare earth elements) and HREE (heavy rare earth elements), which involve 5 and 10 elements respectively (see Table 1). Similarly, PGMs category includes 5 elements. During the EU's triennial criticality assessment, these materials are evaluated individually, but they are treated as grouped entities in almost all other official EU communications. To ensure appropriate clarity, when referring to elements from an official list of CRMs, we refer to the most widely used list where REEs and PGMs are considered as aggregated groups, unless we explicitly state that we are referring to individual elements.

revised the methodology for establishing the EU list of CRMs (European Commission, 2017). The updated approach introduces two distinct parameters to assess a material's criticality: (a) economic importance and (b) supply risk (see Section 1.3.1). This new quantitative framework was first applied to the third CRM list and continues to serve as the EU's official model for assessing raw material criticality as of 2025. The number of elements present in the list has increased over time. Every three years, the criticality of selected raw materials is reassessed. Recent disruptions in global supply chains due to trade wars, the COVID-19 pandemic, and geopolitical conflicts, combined with political instability in (highly) concentrated deposits worldwide, have made access to certain materials increasingly difficult, and part of these supply disruption dynamics is captured by the criticality assessment model (European Commission, 2017; Bobba et al., 2020; Carrara et al., 2023). Moreover, the list of candidate materials is an element that can significantly influence the number of elements present on the list. The assessment of critical materials is conducted using quantitative indicators applied to a list of materials, and the final decision is ultimately made by an ad hoc working group based on expert advice[16]. The most significant change came with the fifth list, which introduced a new category: Strategic Raw Materials (SRMs), including 27 individual materials. This category is further discussed in Section 1.3.2, as the introduction of the SRM category represents both a major policy shift and a controversial novelty. Indeed, since the fifth list, this distinction makes it more appropriate to refer to a list of Strategic and Critical Raw Materials (SCRMs), rather than CRMs alone. Table 1.1 and Table 1.2 show the evolution of the SCRM lists up to 2023[17].

[16]For instance, between the first and the second list the number of candidate materials increased from 41 to 54 candidates because new abiotic (inorganic resources that originate from geological processes) materials have been added, and biotic (derived from living or once-living organisms.) materials are assessed for the first time compared to previous studies (European Commission, 2014).

[17]The REEs are counted as a single aggregate in the first CRMs list. From the second list onwards, they have been considered as two distinct material groups: LREE and HREE. These two categories together comprise approximately 17 elements, 7 for LREEs: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium; and 10 for HREEs: gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, yttrium

Table 1.1: All EU lists of SCRMs

Material	**First list (2011)** *- 14 CRMs (33 individual elements) - 62 screened*	**Second list (2014)** *- 20 CRMs (37 individual elements) - 71 screened*	**Third list (2017)** *- 27 CRMs (44 individual elements) - 78 screened*	**Fourth list (2020)** *- 30 CRMs (47 individual elements) - 83 screened*	**Fifth list (2023)** *- 34 SCRMs (51 individual elements) - 87 screened*
Antimony	✓	✓	✓	✓	✓
Arsenic	X	X	X	X	✓
Baryte	X	X	✓	✓	✓
Aluminium/Bauxite	X	X	X	✓	✓
Beryllium	✓	✓	✓	✓	✓
Bismuth	X	X	✓	✓	✓
Boron/Borate	X	✓	✓	✓	✓
Chromium	X	✓	X	X	X
Cobalt	✓	✓	✓	✓	✓
Coking Coal	X	✓	✓**	✓	✓
Copper	X	X	X	X	✓*
Feldspar	X	X	X	X	✓
Fluorspar	✓	✓	✓	✓	✓
Gallium	✓	✓	✓	✓	✓
Germanium	✓	✓	✓	✓	✓
Hafnium	X	X	✓	✓	✓
Helium	X	X	✓	X	✓
HREE	included in REE	✓	✓	✓	✓
Lithium	X	X	X	✓	✓
LREE	included in REE	✓	✓	✓	✓
Magnesite	X	✓	X	X	X
Magnesium	✓	✓	✓	✓	✓
Manganese	X	X	X	X	✓
Natural Graphite	✓	✓	✓	✓	✓
Natural Rubber	X	X	✓	✓	X
Indium	✓	✓	✓	✓	X
Nickel	X	X	X	X	✓*
Niobium	✓	✓	✓	✓	✓
PGMs	✓	✓	✓	✓	✓
Phosphate Rocks	X	✓	✓	✓	✓
Phosphorus	X	X	✓	✓	✓

Continued on next page

Table 1.1 continued

Material	**First list (2011)** *- 14 CRMs (33 individual elements) - 62 screened*	**Second list (2014)** *- 20 CRMs (37 individual elements) - 71 screened*	**Third list (2017)** *- 27 CRMs (44 individual elements) - 78 screened*	**Fourth list (2020)** *- 30 CRMs (47 individual elements) - 83 screened*	**Fifth list (2023)** *- 34 CRMs & SRMs (51 individual elements) - 87 screened*
REE	✓	–	–	–	–
Scandium (former REE)	included in REEs	X	✓	✓	✓
Silicon metal	X	✓	✓	✓	✓
Strontium	X	X	X	✓	✓
Tantalum	✓	X	✓	✓	✓
Titanium metal	X	X	X	✓	✓
Tungsten	✓	✓	✓	✓	✓
Vanadium	X	X	✓	✓	✓

Source: European Commission (2010, 2014, 2017, 2020c, 2023a).

Note: SRMs in italics. * Non-critical but strategic materials. ** Coking coal was just below the criticality thresholds in the 2017 assessment. However, it was included in the third list of CRMs due to its borderline position. The screened materials refer to the number of individual materials examined.

Table 1.2: Focus on PGMs, LREEs and HREEs mineral groups in all EU lists of SCRMs

Material	**First list (2011)** *- 14 CRMs (33 individual elements) - 62 screened*	**Second list (2014)** *- 20 CRMs (37 individual elements) - 71 screened*	**Third list (2017)** *- 27 CRMs (44 individual elements) - 78 screened*	**Fourth list (2020)** *- 30 CRMs (47 individual elements) - 83 screened*	**Fifth list (2023)** *- 34 SCRMs (51 individual elements) - 87 screened*
PGM					
Palladium	✓	✓	✓	✓	✓
Iridium	✓	✓	✓	✓	✓
Rhodium	✓	✓	✓	✓	✓
Ruthenium	✓	✓	✓	✓	✓
Osmium	✓	✓	X	X	X
LREE					
Lanthanum	✓	✓	✓	✓	✓
Cerium	✓	✓	✓	✓	✓
Praseodymium	✓	✓	✓	✓	✓
Neodymium	✓	✓	✓	✓	✓
Samarium	✓	✓	✓	✓	✓
HREE					
Europium	✓	✓	✓	✓	✓
Gadolinium	✓	✓	✓	✓	✓
Terbium	✓	✓	✓	✓	✓
Dysprosium	✓	✓	✓	✓	✓
Erbium	✓	✓	✓	✓	✓
Yttrium	✓	✓	✓	✓	✓
Holmium	✓	✓	✓	✓	✓
Thulium	✓	✓	✓	✓	✓
Ytterbium	✓	✓	✓	✓	✓
Lutetium	✓	✓	✓	✓	✓

Source: European Commission (2010, 2014, 2017, 2020c, 2023a).

Note: SRMs in italics. * Non-critical but strategic materials.

1.3.1 Assessing Criticality of Raw Materials

As explained in the previous section, the EU has changed its quantitative approach to assessing the criticality of raw materials over time. In the first assessment model (European Commission, 2010), the criticality assessment depended on two main indicators: (a) an aggregate index of economic importance and supply risk; and (b) an indicator of environmental risk. Economic importance was computed as the weighted sum of the value added of individual mega-sectors[18] using the specific raw material as an input, divided by EU GDP. The estimator of supply risk for a specific raw material is based on several parameters assessing the extent to which the material can be recycled, its substitutability rate, and the level of concentration of worldwide production. The latter is measured with a Herfindahl-Hirschman Index (HHI) and weighted by the stability/instability level of a country, computed using the Worldwide Governance Indicators (WGI) provided by the World Bank. Environmental risk is assessed using Life Cycle Assessment (LCA) data (including, for instance, the environmental impacts of extraction, processing, transport, and end-of-life recovery/recycling, etc.).

After the 2017 revision of the model (European Commission, 2017), the EU assessment approach no longer includes a specific indicator to account for environmental risk. The two main parameters used to determine the criticality of a raw material are now limited to economic importance and supply risk; unlike in the original 2010 methodology, these two indicators are no longer combined into a single aggregate index. However, environmental implications are not completely excluded from the analysis, as the model still includes the substitution index and the end-of-life recycling rate parameter. The economic importance (EI) is based on EU manufacturing sectors at the NACE Rev. 2 (2-digit level). EI aims at providing insights in terms of end-use application of the raw material:

$$EI = \sum_{s} (A_s \times Q_s)\, SI_{EI} \tag{1.1}$$

where s denotes sectors, A is the share of end use of a specific raw material in a NACE Rev. 2

[18] Conceptually, mega-sectors are defined in order to aggregate sectors belonging to the same value chain, and they derive from a reclassification and aggregation of the European NACE code.

sector, Q is the sector's VA, and SI_{EI} is the substitution index related to the EI. In addition to moving away from mega-sectors, this new approach features a sophisticated substitution index (SI) that considers a cost-performance parameter, the criticality of the substitute material, and whether the proposed substitute is derived as a by-product or co-product.

$$SI_{EI} = \sum_{i} \sum_{a} SCP_{i,a} \cdot SubShare_{i,a} \cdot Share_{a} \tag{1.2}$$

where i denotes an individual substitute material, a denotes an individual application of the candidate material, SCP is the substitute cost-performance parameter, $SubShare$ is the sub-share of each substitute within each application, and $Share$ is the share of the raw materials in an end-use application. The supply risk (SR) indicator reported below reflects the risk of a disruption to the EU supply chain of the raw material. In the 2017 version of the supply risk indicator, HHI_{WGI} refers to both the global supplier concentration (GS) and the concentration of EU-28[19] supplier countries, and is adjusted by a restriction term of trading partners and exports (t).

$$SR = \left[\left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EUsourcing} \left(1 - \frac{IR}{2}\right) \right] \cdot \left(1 - EoL_{RIR}\right) SI_{SR} \tag{1.3}$$

The risk-concentration indicator is multiplied by the Import Reliance term (IR) of the candidate material, given by the ratio between net imports (imports minus exports) and the "apparent consumption" (imports + exports + domestic production). Compared to the previous approach, the new assessment also considers averages over the previous 5 years[20] for both SI and EI indicators. All candidate raw materials that exceed the threshold score of 2.8 in the EI indicator, and 1.0 in the SR indicator, are included in the list of CRMs.

1.3.2 The strategic approach and the Critical Raw Materials Act

Following the European Parliament's Resolution 2019/2712(RSP) on implementing the Paris Agreement (2015), initiatives proposed by the Green Deal (2019), and the 2022 Versailles

[19] Note that, starting from the 4th official list of CRMs (2020), the countries considered in the criticality assessment are those of the EU-27 due Brexit.

[20] In 2010 critical assessments (European Commission, 2010), only the latest available year was used.

Declaration, concerns over access to strategic resources have gained significant prominence. Special emphasis was placed on the circular economy and green technologies; the growing effects of climate change have further increased the EU's concerns about global changes in technological sovereignty and the risks of supply chain disruption (European Commission, 2018; European Commission, 2022; Trippl et al., 2024). As a result, the "Critical Raw Materials Act" (CRMA) is one of the flagship EU legislative initiatives under the Green Deal Industrial Plan and part of OSA. With the CRMA, the European Commission proposes a set of actions to ensure the EU's access to a secure and sustainable supply of CRMs, consistently with existing programmes and policy schemes such as the Net Zero Industry Act and REPowerEU. The plan's main ambitions include ensuring and reinforcing CRM supply chains, investing in research and innovation, and protecting the environment by improving the circularity and sustainability of CRMs.

With the CRMA, the strategic importance of input material demand in strategic sectors has become more relevant, almost central to EU action. The CRMA defines SRMs as vital raw materials of high strategic importance for so-called "strategic technologies" underpinning strategic domains such as the green and digital transitions, as well as defence and aerospace applications. However, these technologies are not directly mentioned in the document, and it seems evident that the European Commission intends to retain wide discretion in selecting these materials. While the EU has progressively refined its methodology for classifying CRMs over time, SRMs were introduced directly in the CRMA with the following provision:

"*In order to ensure that the measures set out in this Regulation focus on the most relevant raw materials, a list of strategic raw materials and a list of critical raw materials should be established. . . The list of strategic raw materials should contain raw materials that are of high strategic importance for the functioning of the internal market, taking into account their use in strategic technologies underpinning the green and digital transitions or for defence or aerospace applications, that are characterised by a potentially significant gap between global supply and projected demand, and for which an increase in production is relatively difficult, for instance due to long lead-times for new projects increasing supply capacity. . . In order to ensure that efforts to increase the Union capacities along the value chain, reinforce the Union's capacity to monitor and mitigate supply risks and increase diversification of supply are focused on the raw*

materials for which they are most needed, certain relevant measures should apply only to the list of strategic raw materials. . . " (Regulation (EU) 2024/1252, Article 6)

By interpreting Recital 6 of the CRMA, it can be inferred that the European Commission considers SRMs to be the raw materials most needed to achieve the general goals of the CRMA. This rationale underpins the decision to establish independence thresholds for domestic consumption by 2030 exclusively based on this category. With the CRMA, SRMs were included in the fifth list of CRMs (2023). Two of them (copper and nickel) are included in the list even though they do not meet the CRM thresholds, but they are considered SRMs by the European Commission. The full identification of SRMs appears fundamentally political, as the designation of certain technologies as strategic has been driven primarily by policy considerations. Additionally, the Commission has considerable flexibility in determining and applying the assessment metrics used to select SRMs, particularly when evaluating the requirements of strategic technologies and forecasting global demand (Zhang et al., 2023; Tröster et al., 2024). The document states that the identification of strategic technologies is based on previous foresight studies (such as Bobba et al., 2020; Carrara et al., 2023), which apply a multi-stage approach to identify different materials in various parts of the supply chains relevant to the green and digital transition and the EU's economic and technological security. In this regard, however, the European Commission merely states that:

"The strategic technologies referred to in the first subparagraph shall include, but are not limited to, batteries for energy storage and e-mobility, equipment related to hydrogen production and utilisation, equipment related to renewable energy generation, traction motors, heat pumps, data transmission and storage, mobile electronic devices, equipment related to additive manufacturing, robotics, drones, rocket launchers, satellites and advanced chips" (Regulation (EU) 2024/1252, Article 24)

The policy-oriented language used in the previous passage and throughout the whole document further hinders a clear understanding of the rationale behind the selection of these materials, especially when terms such as "sectors" and "technologies" are used. The assessment methodology to classify SRMs is included in the Annex I of the Regulation (EU) 2024/1252, but it mainly consists of general guidelines stating that the strategic importance of a raw material is determined:

"...based on the relevance of a raw material for the green and digital transition as well as defence and space applications, taking into account: (a) the amount of strategic technologies using a raw material as an input; (b) the amount of a raw material needed for manufacturing relevant strategic technologies; (c) the expected global demand for relevant strategic technologies."

The introduction of the SRMs is not the only innovation brought by the CRMA. The document sets clear benchmarks for developing domestic capacities across the strategic raw material supply chain and aims to diversify the EU supply by 2030. With the adoption of the CRMA (March 2024), the EU set the following objectives for the consumption of each SRM by 2030:

- At least 10% of the EU's annual consumption must come from EU extraction;
- At least 40% of the EU's annual consumption must come from processing in the EU;
- At least 25% of the EU's annual consumption must come from EU recycling (15% in the previous version of the document);
- No more than 65% of the EU's annual consumption of each SRM, unprocessed and at any stage of processing, may come from a single third country.

In operational terms, the main novelty introduced by the CRMA is the instrument of the "Strategic Projects" (SPs), designed to attract investments within the EU, through which the independence targets listed above are supposedly achieved. To be recognized as a Strategic Project, an initiative must focus on extraction, processing, recycling, or substitution of at least one SRM and meet specific criteria, including technical feasibility, sustainable implementation, and the capacity to benefit the broader EU community[21]. The discussion on SPs is further developed in Section 1.3.2.1.

The rest of the operational strategy primarily draws on coordination provisions among the Member States, and on applicable principles and guidelines. References to the CRMA's international policy are limited to broad statements of intent and vague references to strategic partnerships. Support for extraction and processing SPs in non-EU countries can be seen as an attempt to establish cooperative relations with companies and communities in resource-rich countries, but the absence of specific strategies for CRM-based international relations and the lack of

[21] https://ec.europa.eu/docsroom/documents/59594

projects led by EU companies limits the potential for building direct long-term ties with extra-EU territories. Moreover, SPs stem from private initiatives, not including international agreements between EU public institutions and host countries' governments. This is not surprising from a global trade perspective, considering that current trade policies can offer very low incentives to diversify imports, as the EU already applies low tariffs on CRMs (Rietveld et al., 2022).

Although the document repeatedly refers to the need to enhance international partnerships, in practice, the new developments in this area are limited. Many of these initiatives are in fact simple non-binding Memorandum of Understanding (MoU)[22] rather than formal trade or partnership. Among the most structured CRM arrangements those embedded in the following should be noted: the EU–Mercosur framework, signed in January 2026; the EU–Indonesia CEPA, for which negotiations were finalised in September 2025; and the updated EU–Mexico Global Agreement, for which negotiations were concluded in January 2025. The 2021 EU-Canada Strategic Partnership on Raw Materials can also be mentioned: it does not constitute a fully-fledged trade agreement, but rather a structured cooperation framework established within the framework of the Comprehensive Economic and Trade Agreement (CETA) between Canada and the EU, signed in 2016. Yet, the rest of the international strategy consists in promoting bilateral agreements and encouraging provisions on critical raw materials in existing agreements, through the use of the Global Gateway[23] (an initiative in place since 2021) to support projects along the raw materials value chain and improve connectivity.

To find additional references to the EU's stance on international policy and CRMs, other sources outside the CRMA must be considered. One of the main intentions, even though not explicitly stated in the CRMA, is the attempt to establish a "Critical Raw Materials Club" to collaborate with "like-minded countries" (European Commission, 2023d). The definition of "like-minded" is not provided in the EU documents, and it is unclear whether it refers to the intention of other parties to strengthen CRM global supply chains, or rather to specific political, economic, and social characteristics. However, the concept of a CRM Club has been taken up in more concrete

[22]The list of MoUs can be found here https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/raw-materials-diplomacy_en

[23]The Global Gateway is the EU's strategy to mobilize up to €300 billion by 2027 for sustainable infrastructure projects in partner countries; see the European Commission page on Global Gateway.

form through the creation of the Minerals Security Partnership (MSP[24]), a policy dialogue group and a multilateral cooperation platform. In this context, the 30 like-minded countries[25] are broadly understood as countries aligned with the objective of promoting secure, resilient, and sustainable critical mineral supply chains. This approach may prove risky, strengthening polarizations rather than widening and upgrading international partnerships and multilateral cooperation. Moreover, these cooperative relationships could be undermined by some of these countries' ties with China, that has built over time solid economic relationships with strategic partners through international policy instrument like the Belt and Road Initiative (BRI) (Liu et al., 2018; Wang et al., 2023; Li et al., 2024) in which several members of the MSP also participate. The EU has fallen behind in this area, and many of its international partnerships have been often characterized by a complex technocratic tendency and, at times, a paternalistic attitude. This is particularly evident in relations to African countries, where the EU is sometimes perceived as an actor imposing its own model or priorities without adequately involving local counterparts[26] For instance, the Namibian government has implemented a ban on the export of unprocessed critical minerals, including lithium, cobalt, manganese, graphite, and REEs, just eight months after a MoU tightening in November 2022 with the EU. Namibia's decision aligns with a broader trend among resource-rich African nations, such as Zimbabwe, which have implemented similar bans to retain more value from their natural resources[27], as well as other countries like Nigeria and Ghana in banning unprocessed mineral ores exports[28]. The EU's strategic approach, entirely based on bilateral negotiations and aimed at safeguarding what it defines as "strategic" interests, risks clashing with the interests of resource-rich countries which, in the absence of serious proposal of alternative models of mutually beneficial collaboration and economic development, are inclined to adopt protectionist policies to safeguard their own interests

[24] See https://policy.trade.ec.europa.eu/help-exporters-and-importers/accessing-markets/raw-materials/minerals-security-partnership-forum_en.

[25] Argentina, Australia, Canada, DRC, Dominican Republic, Ecuador, Estonia, EU, Finland, France, Germany, Greenland, India, Italy, Japan, Kazakhstan, Mexico, Namibia, Norway, Peru, Philippines, Republic of Korea, Serbia, Sweden, Türkiye, Ukraine, UK, US, Uzbekistan, and Zambia.

[26] See https://www.gisreportsonline.com/r/eu-africa-strategy/.

[27] See https://www.reuters.com/markets/commodities/namibia-bans-export-unprocessed-critical-minerals-2023-06-08/.

[28] See https://www.globalpolicywatch.com/2024/05/african-raw-material-export-bans-protectionism-or-self-determination/.

1.3.2.1 Strategic Projects Under the CRMA

By the 22 August 2024 deadline, the EC received 170 applications for SPs: 77 for extraction, 58 for processing, 30 for recycling and 5 for substitution. The latter category is the only one dedicated to research and development of new technologies, as it includes initiatives aimed at developing alternatives to SRMs, either through research of substitute materials or by leveraging technological innovation to reduce or eliminate dependence on SRMs. Geographically, 121 applications originated from within the European Union, while 49 were submitted by entities outside the EU[29]. In March 2025, the EU published the list of approved projects located within the EU, amounting to a total of 47 (23 of them with extraction purposes, 23 processing, 10 for recycling and only 2 for substitution[30]. These projects are located across 13 EU Member States: Belgium, France, Italy, Germany, Spain, Estonia, Czechia, Greece, Sweden, Finland, Portugal, Poland, Romania, and cover 14 of the 17 SRMs listed in the CRMA considering REEs and PGMs as aggregate (no projects were submitted for bismuth and silicon metal). Cobalt, nickel, and, especially, lithium are the most targeted materials; 4/10 recycling projects are based in Italy, which is the only country among the 13 mentioned that has not submitted any projects beyond recycling. These selected projects will be able to benefit from coordinated support by the European Commission, Member States and financial institutions to become operational, notably regarding access to finance and support to connect with relevant stakeholders. They will also benefit from streamlined permits processes, to ensure predictability for project promoters. In fact, in line with the CRMA, the permit-granting process for SPs must not exceed 27 months for mining extraction, and 15 months for all the other kinds of projects.

On 4 June 2025, also the list of Strategic Projects located outside the EU was published, adding 13 additional projects located outside the EU and covering 9 Strategic Raw Materials: boron, cobalt, copper, graphite, lithium, manganese, nickel, REE, and tungsten. Projects located outside the EU are not eligible for accelerated permitting procedures, as these measures can only be applied within the EU's jurisdiction. All other benefits remain applicable, as does the requirement that

[29] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/strategic-projects-under-crma_en

[30] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/strategic-projects-under-crma/selected-projects_en. Note that a single project may fall under more than one category.

the project must deliver tangible benefits both to the host countries and to the EU. Taken together, the 60 initiatives have an expected overall capital investment of €28 billion (€22.5 billion[31] for EU projects and €5.5 billion for non-EU projects[32]). Table 1.3 summarises information on SPs. We also provide more detailed information on these projects in Tables A1.1, A1.2, and A1.3 of Appendix 1. Looking at Table 1.3, it appears evident that the expected benefits of projects are asymmetric in various fields selected by EU. The low number of submitted SPs concerning substitution is an illustrative consequence of the fact that the CRMA does not seem to be primarily focused on creating competencies. The substitution project category is the only one dedicated to research and development of new technologies, as it includes initiatives aimed at developing alternatives to SRMs, either through research of substitute materials or by leveraging technological innovation to reduce or eliminate dependence on SRMs. The CRMA grants fast-track permits, but substitution projects are more research-driven and do not benefit from the same streamlined approval process.

As pointed out by Findeisen and Wernert (2023), the CRMA document also reveals a structural weakness in EU funding mechanisms, particularly regarding the lack of a dedicated fund for CRMs, unlike the US CHIPS Act for semiconductors, which provides targeted financial support. Instead of establishing a new, centralized funding instrument, the CRMA merely references a range of fragmented, pre-existing funds, such as InvestEU, the European Regional Development Fund, and the Innovation Fund. SPs are the most operational component of the CRMA, and they are intended to be the main instrument for achieving the 2030 targets. They attract investments in the mining and metallurgical sector, as only projects related to extraction and processing have received a significant number of applications. Moreover, many of these projects were started before the call, and sometimes even before the CRMA (e.g., Aguablanca project: https://denariusmetals.com/project/spain/alto-minerals/aguablanca-project-overview/). Thus, there are few reasons to consider SPs a driver for radically new projects, especially considering the short deadlines with which the calls were announced and the lack of access to dedicated funds.

[31] https://ec.europa.eu/commission/presscorner/detail/en/ip_25_864.

[32] https://www.spglobal.com/commodity-insights/en/news-research/latest-news/metals/060425-eu-identifies-13-new-strategic-critical-mineral-projects-located-outside-bloc.

For non-EU projects, the issue is even more complex: these may benefit from having an EU-based sponsor and from EU-backed credit guarantees, which in effect means that the EU is supporting projects led by extra-EU multinational enterprises in third (and sometimes, developing) countries. This may also pose a risk, as even though SPs are subject to evaluations by an EU ad hoc committee, there are no sanctioning mechanisms in place to address moral hazard on the part of project owners if the projects later turn out to be non-compliant with environmental and social standards (European Commission 2023b). Greater concerns in this regard arise in the mining sector, due to its significant local and social impacts in developing countries. No EU company has proposed extraction projects abroad, so they are focusing on the EU's own resource endowment exclusively (the tables in Appendix 1 contain extended information on all of these projects).

Table 1.3: Strategic Projects under the CRMA (2025)

EU Strategic Projects				
	Extraction	**Processing**	**Recycling**	**Substitution**
No. of projects	23	23	10	2
EU countries involved	France, Spain, Portugal, Czechia, Finland, Greece, Sweden, Romania, Germany	France, Czechia, Estonia, Germany, Belgium, Finland, Spain, Portugal, Greece, Sweden, Poland	Italy, Spain, France, Sweden, Poland, Finland	Germany, Belgium
Non-EU countries involved	–	Namibia (main location: France)	–	–
SRMs	REE, tungsten, lithium, magnesium, manganese, nickel, aluminium, cobalt, PGM, copper, graphite	Aluminium, gallium, cobalt, PGM, nickel, copper, germanium, graphite, lithium, manganese, tungsten, REE	Copper, cobalt, nickel, PGM, lithium, manganese, REE	Graphite, germanium
Extra-EU Strategic Projects				
	Extraction	**Processing**	**Recycling**	**Substitution**
No. of projects	10	3	0	0
Non-EU countries involved	Ukraine, Greenland, Norway, Canada, Serbia, Madagascar, Kazakhstan, Malawi, UK, South Africa	New Caledonia, Greenland, Norway, Zambia, Brazil	–	–
SRMs	Graphite, nickel, lithium, copper, REE, tungsten, manganese	Nickel, graphite, cobalt	–	–

Source: European Commission, selected strategic projects under the CRMA.
Note: A single project may fall under more than one category.

1.4 Discussion

In the previous sections, we have examined the pivotal role of CRMs in modern technological paradigm shifts, along with the significant risks faced by the EU due to the concentration of CRM extraction and processing in a limited number of countries. While the CRMA introduces some novelties, such as strategic benchmarks for domestic supply, streamlined permitting for SPs, and clearer governance mechanisms, these initiatives risk remaining constrained by the lack of a dedicated EU-wide funding instrument, an over-reliance on fragmented financial sources, and a limited prioritization of innovation developments. This highlights an imbalance in the current policy mix, which favours industrial deployment over knowledge creation and technological diversification.

Taken together, the chapter shows that the EU's critical-raw-materials challenge cannot be reduced to physical scarcity or import dependence. Technological change enters this framework primarily as a contextual driver: the green and digital transitions increase demand for particular mineral inputs and expose the economic consequences of concentrated and vulnerable supply chains. However, whether a material becomes "critical" or "strategic" also depends on how these vulnerabilities are measured and politically interpreted. Criticality is assessed through economic importance and supply risk, whereas the designation of SRMs reflects the policy prioritisation of selected technologies, industries, and security objectives. Material dependence is thereby transformed into an economic-security concern and incorporated into the broader frameworks of OSA and technological sovereignty. The CRMA translates this strategic prioritisation into supply-side intervention through production benchmarks, SPs, investment coordination, and accelerated permitting for extraction, processing, recycling, and substitution. Nevertheless, the composition of these instruments reveals an important distinction between expanding productive capacity and developing the capabilities needed to de-risk CRM supply.

More broadly, trying to achieve the net-zero economy and digital transitions through uncoordinated and place-blind policy instruments risks undermining the global and local benefits of climate action and digitalization. Macro-level industrial policy approaches can lead to zero-sum games, fostering inequalities across different geographical scales. Too much emphasis on technological

sovereignty, without anchoring it in international and interregional innovation networks, may lead to new forms of both closure and marginalization (Soete & Burgelman, 2023; Mariotti, 2024a, 2024b; Trippl et al., 2024). The European Commission has traditionally been a front runner in stressing cross-border cooperation as essential for technological progress, post-crisis recovery, and long-term goals such as decarbonization and digitalization (European Commission, 2021a). Fragmentation and nationalistic approaches may undermine the EU's technological strength in frontier industries such as AI and biotechnology, which largely depend on international flows. Regions or nations that exit such networks risk becoming peripheral in technological trajectories (Binz & Truffer, 2017; Cagnin et al., 2021; Carrara et al., 2023; Boschma et al., 2026). Emerging green technologies are especially dependent on transnational ecosystems and, if the EU's defensive and strategic policies set in motion autarkic approaches, the Union risks moving towards a treacherous "strategic decoupling" path (Hamor et al., 2021; Helwig & Sinkkonen, 2022; Kübek & Mancini, 2023).

Furthermore, although the CRMA sets ambitious targets for domestic extraction, processing, and recycling, only a subset of Member States currently possesses the necessary institutional and technological capacity, or the natural resource endowment, to benefit from this framework. With very few exceptions (e.g., Trippl et al., 2024), the debate has paid scant attention to the potential subnational and regional effects of such macro-policy schemes intended to promote technological sovereignty and strategic autonomy. OSA goals and measures have eminently supranational purposes, while at the same time strengthening a governance framework centred on national Member States. As emphasized by longstanding economic geography research (e.g., Iammarino et al., 2019), EU regions differ widely in their industrial and innovation structures and capabilities, natural resource endowments, and institutional settings, determining their ability to benefit, or not, from OSA policies.

The impacts of strategic industrial interventions are likely to be felt most strongly at the local level, with some regions able to grasp the opportunities for growth and innovation, and others failing to do so because of structural challenges related to lack of capabilities, restricted technology access, institutional weakness, and competition for resources. Protective measures towards the rest of the world may pose serious risks even for regions highly dependent on GVCs, global innovation

networks, and foreign talent, such as urban innovation hubs and science-intensive areas (Trippl et al., 2024). With the ongoing dismantlement of EU Cohesion Policy and place-based sectoral approaches, and the rupture of the direct link between the Commission and the "Europe of regions", it is not only the periphery that will bear the costs, potentially reinforcing populism and anti-EU movements (Rodríguez-Pose & Bartalucci, 2024), but also those mid-size cities and regions with strong capabilities that can be diversified to facilitate the dual technological transitions.

Finally, the ambiguity surrounding key concepts such as "strategic technologies" and the criteria for SRM identification leaves ample room for discretionary interpretation. This vagueness may hinder policy predictability and transparency. To fully realize the transformative potential of the CRMA, the EU will need to adopt a more coherent and territorially balanced approach that strengthens R&D capacity and fosters technological sovereignty through international collaboration rather than isolation.

Chapter 2

CRMs in the EU strategy: identification of criticality

Introduction. Chapter 1 explores the content of the CRMA and the EU's mid-term goals to ensure a secure supply of SCRMs and mitigate the risk of supply chain disruptions. The feasibility of achieving the independence targets set by the CRMA may depend on several and, sometimes, interconnected factors that can impose serious limitations. Many of these are rooted in the mining and extractive stage, where access to deposits, ore quality, sustainability, and the diversification of foreign suppliers, shape the EU's actual capacity to expand and secure raw material supply. Strengthening CRM supply chains requires a flexible, multi-level, and territorially sensitive approach, accounting for the spatial distribution of natural resources, existing and potential mining and metallurgical activities, infrastructure endowments, permitting and regulatory capacity, environmental constraints, social acceptance, and the geopolitical exposure of external supply routes. This is crucial because decisions over where and how mineral extractive and related industrial activities take place are not determined solely by the geological characteristics and the natural endowment of SCRMs, although these are undoubtedly key factors. Rather, such decisions involve an intricate balancing of interests between the EU's strategic objectives, environmental and social safeguards, corporate priorities, the interests of local governments, and the claims of different stakeholder groups, including communities concerned with public health, environmental protection, land use, and the preservation of public parks or

protected areas. However, when considered in light of these issues, the strategic orientation of the CRMA appears to move almost in the opposite direction, privileging instead a more top-down approach, centred on industrial and regulatory provisions designed to facilitate business initiatives and attract new investments in industries involved in the extraction, processing, and refining of primary mineral materials. In this chapter we investigate the implications and potential impacts of the CRMA, evaluating the feasibility of the principles introduced by the OSA and their capacity to create robust and secure supply chains and promote balanced and fair territorial development in Europe and beyond. To do this, we integrate dispersed and non-harmonised data from multiple sources, addressing major gaps in the availability and reliability of information on the EU's natural mineral endowment and CRM scorecard indicators, to construct a regional dataset on European CRM and SRM endowments. The dataset combines geological information on mineral deposits with quantitative resource estimates and project-level information concerning operational status and ownership, harmonised at the NUTS-2 level. Material-specific indicators are used to make heterogeneous mineral endowments comparable and to assess their geographical concentration across European regions. By bringing these components together, the chapter connects the material- and supply-chain-stage-specific assessment of the CRMA targets with the regional distribution of the mineral resources and mining projects on which their implementation depends. This integrated perspective makes it possible to distinguish between the existence of a geological endowment, the presence of resources associated with a mining project, and the effective or potential capacity to bring those resources into production. It also allows us to examine how the feasibility of the CRMA objectives varies across materials, stages of the supply chain, and regional contexts. Moreover, we consider that CRMA's top-down approach risks overlooking regional capabilities, geological constraints, and social responses from the communities involve. For this reason, particular attention will be given to the regional level and to the European regions when assessing how CRMA-related objectives interact with territorial specificities and the uneven distribution of mineral natural resources. After that, we revisit the content of the CRMA in light of the empirical evidence provided, with particular emphasis on the mining and extractive phase, where the natural resource endowment affects the current supply and raises questions about the long-term ability to meet growing demand of SCRMs. In Section 2.1 we adopt a discursive approach to describe and assess instruments and provisions

implemented under the CRMA to achieve its goals, with the aim to gain a clearer understanding of the strategic direction the EU intends to pursue. We also provide a representation, as clear and accessible as possible, of the current stage of progress towards the independence target established by the Act. In Section 2.2 we clarify the mineral-resource framework and explore the most up-to-date mineral resource databases currently available, to compare the European mineral resource endowment of SRMs with that of the rest of the world, in order to inform the discussion on the operational part of the CRMA and the realistic prospects of achieving its 2030 targets. In Section 2.3 we then map the regional distribution of CRM and SRMs mineral resources across European territories to highlight further potential geographic disparities and their economic, social, and policy implications. Section 2.4 concludes.

2.1 CRMs in the EU Strategy: Assessing the Targets

To appraise mechanisms and novelties introduced by the CRMA, it's now crucial to clarify that the four targets set by the CRMA discussed in Chapter 1 are non-binding. This means they are not embedded within a legally binding regulation that would not only define the targets but also impose clear obligations and enforcement mechanisms, including sanctions for non-compliance[33]. To fully understand what the CRMA objectives entail, it is also necessary to clarify the structure of SCRM supply chains, as well as those of most mineral commodities in general. SCRMs are usually extracted and processed by mining companies, refined by metallurgical plants and refineries, often located elsewhere, and subsequently used as production inputs by the manufacturing industry. According to the terminology most used in the mining and metallurgical industry, the more upstream stages of the supply chain are those carried out by the mining sector and consist of extraction and processing. In the extraction stage, material is removed from the ground, while the processing stage refers to ore separation and concentration, typically carried out in smelters and concentrators operated by mining companies and classified under NACE Rev. 2, Section B (Mining and quarrying). The more downstream stages instead begin with processed ore

[33]A clear example of legally binding targets is the European Climate Law (Regulation (EU) 2021/1119). This law sets a mandatory goal to reduce greenhouse gas emissions by at least 55% by 2030 and to reach climate neutrality by 2050. Unlike the CRMA, which only sets voluntary targets, this regulation makes it legally compulsory for EU countries to act, with their progress monitored and enforced at the EU level.

and culminate in the production of tradable metals. These activities fall under the manufacturing sector, specifically NACE Rev. 2, Division 24 (C24): Manufacture of basic metals. After this stage, tradable minerals are available on the market and are used by manufacturing firms as material inputs.[34] Hence, mining industry output do not usually constitute finished commodities but rather raw ores and concentrates that must then undergo several stages of processing and refining: this concept is reiterated by several authors (among them Nassar et al., 2015; Hofmann, 2018; Warrian, 2020; Li et al., 2024).

In the SCREEN project[35] factsheets, information on the different production stages for each SCRM is contained including details on primary materials obtained through extraction, smelter processing, refined material forms, end-use applications, collection, and recycling processes. These factsheets are useful not only for understanding the technical pathway through which minerals are extracted and transformed into refined materials, but also for fully appreciating the differences across materials in terms of processing complexity, supply-chain structure, downstream uses, and circular-economy potential. For instance, cobalt in mining is predominantly obtained as a by-product from copper and nickel, with 56% of the global primary cobalt supply coming from copper mines and 37% from nickel mines. Only 7% of the global cobalt supply comes from mining operations where cobalt is the primary product, such as the Bou Azzer mine in Morocco and the Lubumbashi project in the DRC (SCREEN, 2023a). The economic feasibility of cobalt mining production as a by-product depends on ore grade, and specific derived compounds such as cobalt hydroxide, mixed sulphide. Therefore, in addition to common on-site separation techniques such as crushing and flotation, which are used to prepare the ore for processing and separate valuable metals from gangue (waste material), further pyrometallurgical and hydrometallurgical techniques are required, and these also vary depending on the ore type: nickel-cobalt oxide (laterite ores) or nickel-cobalt sulphide ores (SCREEN, 2023a)[36]. Considering lithium instead -

[34]Note that this represents the most common supply-chain for metal elements. However, some CRMs/SRMs are not metals, and may therefore not enter metallurgical transformation stages. Examples include natural graphite, borates, phosphate rock, fluorspar, feldspar etc. For some of these materials, refining may instead be carried out by other manufacturing activities, including chemical manufacturing or NACE Rev. 2 Division 23 (C23): Manufacture of other non-metallic mineral products.

[35]The SCREEN project operates within the Horizon 2020 Programme and compiles factsheets for each specific raw material, relying on data from multiple sources, including the British Geological Survey (BGS), the United States Geological Survey (USGS), World Mining Data (WMD), and the UN COMTRADE and PRODCOM (Eurostat) databases (https://scrreen.eu/crms-2023/).

[36]Note that, across all these stages, cobalt is still considered unrefined: it has undergone mineral processing, but

a raw material often used together with cobalt in applications such as lithium-ion batteries for electric vehicles and rechargeable batteries - it becomes clear that extraction and processing requirements differ substantially compared with cobalt. Lithium is generally not a by-product and is mainly extracted from brines or hard-rock sources, such as spodumene, lepidolite, and clays. In the processing stage, these different extraction routes involve different time and energy costs, which depend strongly on the type of deposit exploited. Brine processing is slower but relatively energy-efficient, as it relies on natural evaporation over a period of 12–24 months, whereas hard-rock processing is more energy-intensive, requiring high-temperature roasting and chemical leaching (SCREEN, 2023b).

As already discussed in Chapter 1, the CRMA establishes four thresholds for each SRM[37] - 10%, 40%, 25%, and 65% - corresponding respectively to extraction, processing, recycling, and external supply independence targets. All four independence targets are based on the domestic consumption of SRMs, but the underlying consumption dimension requires further clarification starting from the different stages of the supply chain discussed above, which include extraction, processing, and refining. Particularly, in the CRMA the European Commission adopts a different classification in which the mining stages of extraction and mining processing described above are grouped together under the label "extraction", while more downstream stages are included under the lable "processing". In this chapter, we use the terms extraction and processing according to the terminology adopted by the EU, where the extraction stage refers to the production of unrefined primary materials (e.g. ores, concentrates, raw mineral forms), whilst the processing stage implies the transformation of such raw materials into refined or semi-refined materials (e.g., cobalt sulphate for batteries, cobalt powder, aluminium sheets, copper cathodes)[38].

Under this point of view, the content of the first target, which requires that by 2030 at least

not yet metallurgical transformation.

[37]Regulation (EU) 2024/1252. Article 5, Recital 1 recites that "The Commission and Member States shall strengthen the different stages of the strategic raw materials value chain through the measures provided for. . . ". This point is often overlooked in official communications about these targets but, as the Strategic Projects factsheets confirm (European Commission, selected strategic projects under the CRMA), it is now clear that targets 1–2–3 (extraction, processing, and recycling), although not spelled out as explicitly as target 4, must be met for each specific SRM rather than in aggregate.

[38]Note that this terminology is adopted here only to ensure consistency with the CRMA independence targets. It is not used in Chapter 3, where the analysis of mining technologies relies instead on a more technical distinction between the stages of the mining supply chain.

10% of the EU's consumption of SRMs must originate from domestic extraction, needs to be better clarified since, differently from the other 3 targets, it can't be based on the consumption of produced refined materials. More specifically, the extraction target refers to the consumption of ore and raw materials from mining (hence, unrefined materials), whereas the processing and recycling targets refer to the consumption of refined materials.[39] Target 4 on supply independence represents an even more distinct case. Although it is the clearest and most ambitious of all the targets, Regulation (EU) 2024/1252 explicitly states that the maximum threshold of 65% import reliance on a single country applies to both the extraction and the processing stages. As a result, this target must be assessed both upstream, on the consumption of unrefined materials, and downstream, on the consumption of refined materials.

2.1.1 Baseline Assessment of the EU's Independence Targets

Assessing the feasibility of the EU's independence targets is challenging due to the limited amount of granular information available. Although the CRMA sets very specific quantitative targets, as of May 2026 no official evaluation of progress towards these targets has yet been published. By collecting and systematising the scattered and fragmented data contained in various EU documents, it is possible to identify the 2023 baseline against which the objectives were defined. We report our own elaboration in Table 2.1 to assess the EU's position with respect to the CRMA targets for each SRM. Data on Table 2.1 are manually gathered and harmonized from the information available in 2023 factsheets by the SCRREEN Project, the 2023 Final Report on CRMs (European Commission, 2023a) and the Raw Materials Information System (RMIS)[40]

It is important to emphasize that none of these sources constitutes a proper database. Rather,

[39] This is why the End-of-Life Recycling Input Rate (EoL-RIR), currently the most used EU indicator to account for CRM recycling, measures the share of material input supplied by secondary raw materials recovered from end-of-life products.

[40] RMIS (https://rmis.jrc.ec.europa.eu/) was set up in the Circular Economy Action Plan (2015) and is led and maintained by JRC. It provides knowledge on raw materials and associated value chains in the context of sustainability, including supply risks and circularity.

they are textual files from which we extracted the information. Starting with targets 1 and 2, Extraction and Processing, we rely on the indicator Input Reliance (IR). This indicator is directly provided by the EU and calculated according to the official methodology of the Commission (2017). It is defined as the ratio of net imports (imports - exports) to apparent consumption[41] (domestic production + imports – exports) for each SRM[42] and can range from 0 to 100, but it cannot take negative values when exports exceed imports. The IR indicators are computed on the basis of different consumption measures, according to whether Extraction or Processing is being considered: the consumption of unrefined SRMs for Extraction, and the consumption of refined SRMs for Processing, since they refer to two different stages of the SRM supply chain. Target attainment for these first two objectives is derived from the inverse of this measure (1–IR) which, in economic terms, captures the share of domestic consumption satisfied without recourse to net imports.

[41]The European Commission constructs apparent consumption using data from PRODCOM, Eurostat, and World Mining Data (WMD), based on averages for the 2019–2023 period.

[42]Note that an IR value of 0 does not imply the absence of imports for a given SRM. Rather, it indicates that net imports are zero or that the EU is a net exporter.

Table 2.1: CRMA target assessment: 2016–2020 averages

Strategic Raw Material	Extraction (Threshold ≥ 10% of domestic consumption)	Processing (Threshold ≥ 40% of domestic consumption)	Recycling: (Threshold ≥ 25% of domestic consumption)	External supply independence (Threshold ≤ **65%** of domestic consumption)	
	Target attainment *(1-IR)*	**Target attainment** *(1-IR)*	**Target attainment** *(EoL-RIR)*	**Main source country for the EU** *(Extraction)*	**Main source country for the EU** *(Processing)*
Bauxite/Aluminium	12%	42%	32%	Guinea (61%)	Russia (19%)
Bismuth	0%	29%	0%	-	China (51%)
Boron/Borate	0%	28%	1%	Turkey (99%)	Turkey (47%)
Cobalt	19%	99%	22%	Russia (25%)	Finland (62%)
Copper	52%	83%	55%	Poland (20%)	Germany (18%)
Gallium	0%	2%	0%	-	China (71%)
Germanium	0%	58%	2%	-	China (45%)
Lithium	19%	0%	0%	-	Chile (79%)
Magnesium	0%	0%	13%	**No imports or production**	China (97%)
Manganese	3%	34%	9%	South Africa (42%)	Norway (32%)
Natural Graphite	1%	-	3%	China (41%)	-
Nickel	69%	25%	16%	Canada (59%)	Russia (38%)
Silicon metal	-	40%	0%	-	Norway (33%)
Titanium	0%	82%	19%	Norway (23%)	Germany (35%)
Tungsten	79%	20%	42%	Austria (35%)	China (32%)
PGMs*	*** 0%**	***4%**	-	-	-
Platinum	-	-	11%	-	UK (51%)
Palladium	-	-	10%	-	USA (31%)
Iridium+Ruthenium	-	-	-	-	South Africa (31%)
Rhodium	-	-	24%	-	South Africa (37%)
REEs	**0%**	**0%**	-	-	-
Cerium	0%	0%	1%	**No imports or production**	Russia (85%)
Praseodymium	0%	0%	10%	**No imports or production**	China (85%)
Neodymium	0%	0%	1%	**No imports or production**	China (85%)
Samarium	0%	0%	1%	**No imports or production**	China (85%)
Gadolinium	0%	0%	1%	**No imports or production**	China (100%)
Terbium	0%	0%	0%	**No imports or production**	China (100%)
Dysprosium	0%	0%	0%	**No imports or production**	China (65%)

Source: own elaboration on European Commission (2023), SCREEN, RMIS data.
Note: (*) Data are only available in aggregate form and not for individual materials. 1-IR is the inverse of the Import Reliance (IR) index and captures the share of domestic consumption met without relying on imports. The EoL-RIR is the End-of-Life Recycling Input Rate, which measures the share of total material input into the economy that comes from end-of-life recycling.

For Recycling, the target attainment is instead calculated using the EoL-RIR provided in the already cited EU official documents. This indicator provides a suitable proxy for assessing the CRMA recycling target. In this case, the consumption used to calculate the indicator is the consumption of refined SRMs. The main supplier for target 4 is also provided in the official documents consulted and as previously discussed, must refer to the supply of both unrefined and refined materials.

However, despite our considerable efforts, Table 2.1 remains incomplete. In some cases, an attainment level of 0% for the extraction target may reflect either a negative trade balance (exports-imports) when IR = 100, or the absence of extraction. In other cases, however, such as for the REEs, combining multiple sources allows us to be more precise and state that no materials were extracted during the five-year period considered. Looking at Table 2.1, six SRMs were above the 10% threshold for extraction (aluminium, cobalt, copper, lithium, nickel, tungsten); 7 met the 40% threshold for processing (aluminium, cobalt, copper, germanium, silicon metal, titanium), while only 3 SRMs met the 25% threshold for recycling (aluminium, copper, tungsten). Given that the CRMA targets were set in 2023, they represent the most up-to-date figures available from the EC at the time the targets were established. Nevertheless, consumption data were available only up to 2020, so the averages were based on the 2016–2020 period. Low recycling rates may stem both from technical, chemical, and engineering challenges in reprocessing certain materials, and from the difficulty of retrieving end-of-life products in which these materials are embedded. For instance, the high EoL-RIR values of some materials, such as tungsten and cobalt, can largely be attributed to high end-of-life collection rates. Tungsten is mainly used in machine tools typically managed by industrial actors and therefore collected efficiently at the point of end-of-life. Similarly, cobalt is primarily used in batteries, which benefit from targeted waste legislation that ensures high collection rates (Blengini et al., 2019). For other materials, such as PGMs, current performance remains well below the technical potential that could be achieved. PGMs are highly suitable for recycling, and up to 95% of their content can be recovered from industrial and automotive catalysts. However, the recycling input rate for platinum and palladium was only around 10% over the 2016–2020 period (European Commission, 2023a). This mainly depends on the fact that a large amount of PGMs is embedded in long-lived products, or to sub-optimal collection of waste containing these specific materials (Blengini et al., 2019).

For target 4, on the processing side, 16 materials were below the maximum threshold of 65% dependence on a single supplier required by the target. The label "No import or production" in the fourth column indicates that there was neither domestic mine production nor imports of unrefined SRMs. Therefore, no main source country can be identified for that specific SRM. This may look rather intricate but follows logically from the structure of the mineral commodity supply chain. In principle, mine production of unrefined commodities constitutes the input demand of metallurgical firms for materials to be refined. For some materials, the IR is 100%, but we also find that the EU share of global refined production for a specific SRM is 0%. This means that, according to the data consulted, there was neither mining nor metallurgical production in the EU, nor any imports of unrefined materials; therefore, in this case, the EU was fully dependent on imports of finished commodities already refined abroad. From this perspective, target 4 about import independence from a single supplier is certainly more achievable for processing than for extraction.

Much of our work consisted in keeping the sources up to date, which still present some gaps and are continuously being updated. In this regard, new factsheets for some of the SRMs included in Table 2.1 were released at the end of 2025, although only for the IR indicator and no recycling data were available. Table 2.2 compares the previously reported values with the updated ones. The indicators are again calculated as five-year averages for the 2019–2023 period.Comparison is possible only for those materials comparable with 2016–2020 data: a comparison can be carried out for 11 SRMs. The new figures reported in Table 2.2 therefore provide a more accurate picture of the situation in 2023, when the CRMA was adopted. For some materials, the update reveals substantial changes, pointing to a situation that is worse than that suggested by the earlier data. This is the case, for example, for aluminium, copper, boron, and nickel extraction. For others, such as tungsten and nickel processing, a slight improvement can be observed compared to the 2016–2020 period. An increase can also be noted in the share of some materials, such as refined cobalt aluminium and copper, supplied by EU or European countries such as Norway. At the same time, there is less reliance on Russia and a greater dependence on China in the case of refined tungsten and gallium.

Table 2.2: CRMA target assessment: averages 2016–2020 compared to 2019–2023 for selected SRMs

Strategic Raw Material	SCREEN 2023: 2016-2020				SCREEN 2025: 2019-2023			
	Extraction Target attainment *(1-IR)*	Processing Target attainment *(1-IR)*	Main source country for the EU *(Extraction)*	Main source country for the EU *(Processing)*	Extraction Target attainment *(1-IR)*	Processing Target attainment *(1-IR)*	Main source country for the EU *(Extraction)*	Main source country for the EU *(Processing)*
Bauxite/Aluminium	12%	42%	Guinea (61%)	Russia (19%)	10%	23%	Guinea (64%)	Norway 16%
Boron/Borate	0%	28%	Turkey (99%)	Turkey (47%)	0%	0%	Turkey (99%)	Turkey (68%)
Cobalt	19%	99%	Russia (25%)	Finland (62%)	15%	100%	Russia (22%)	Finland (72%)
Copper	52%	83%	Poland (20%)	Germany (18%)	49%	85%	Poland (20%)	Germany (20%)
Gallium	0%	2%	-	China (71%)	-	0%	-	China (87%)
Lithium	19%	0%	-	Chile (79%)	100%	0%	Portugal (100%)	Chile (63%)
Manganese	3%	34%	South Africa (42%)	Norway (32%)	5%	22%	Gabon (46%)	Norway (21%)
Natural Graphite	1%	-	China (41%)	-	-	0%	-	China (25%)
Nickel	69%	25%	Canada (59%)	Russia (38%)	59%	28%	Finland (42%)	Russia (28%)
Silicon metal	-	40%	-	Norway (33%)	-	35%	-	Norway (38%)
Tungsten	79%	20%	Austria (35%)	China (32%)	100%	44%	Austria (41%)	China (34%)

Source: own elaboration on SCREEN projects 2023 and 2025 factsheets.

2.2 CRMs in the EU Strategy: the Resources and the Regions

In Section 2.1, as well as throughout much of Chapter 1, the analysis has mainly been conducted within a policy and regulatory framework, with particular attention to the assessment of strategic objectives and institutional targets. Part of the discussion developed in the previous section highlights that one of the main concerns of the EU strategy implemented with the CRMA were highlighted, especially when different stages and mineral situations are examined through a more specific and granular lens. In this section, the focus shifts to the extraction of SRMs and, in particular, to the extent to which the EU endowment and distribution of such natural resources add further complexity to the assessment of the European strategy. Mineral natural resources are unevenly distributed across the Earth's crust. The location of deposits results from geological processes that have occurred over millions of years and cannot be easily modified through policy interventions. Our concerns regarding the uneven geographical distribution of mineral resources, in light of the provisions of the CRMA, include the risk of excessive pressure on certain regions, particularly those rich in rare and highly concentrated raw materials. This could result in environmental degradation, social conflicts, and obstacles to obtaining the Social License to Operate (SLO)[43], increasing the risk that local communities' perceptions and social opposition may delay or block projects aimed at building resilient supply chains and achieving OSA objectives. In this section, we report a descriptive analysis of the EU's natural mineral resource endowment, seeking to highlight both potential strengths and weaknesses of the EU in relation to its known SCRMs resources.

According to Barca et al. (2012), a policy that appears spatially neutral nevertheless produces territorial effects because it is implemented in places with different characteristics. Consequently, the same incentive, investment, or public intervention can produce very different outcomes across regions. Institutions and the territorial context determine whether and how economic activity becomes locally embedded. The authors therefore criticise top-down, predominantly sectoral policies based only on infrastructure, subsidies, and the attraction of large investments when these are implemented without considering the regional context. This framework is closely

[43]The (SLO) refers to the ongoing acceptance/approval of a company's standard business practices by stakeholders and local communities

connected to our discussion of the top-down approach underpinning OSA, with the important distinction that, in our case, the location of mineral resources concretely delimits the regions in which intervention can take place. Within those regions, institutions, productive capabilities, skills, infrastructure, and social acceptance determine whether a project can be implemented and whether it contributes to regional development or instead produces negative effects borne by only a subset of regions. From a place-based perspective, the CRMA cannot be regarded as spatially neutral merely because its objectives are defined at the EU level. Its supply-side instruments necessarily interact with a territorially fixed and unevenly distributed mineral-resource base, as well as with substantial differences in regional institutions, productive capabilities, infrastructure, and social conditions. Consequently, the capacity of SPs to contribute to regional development cannot be inferred solely from their investment value or expected contribution to EU supply targets, but depends on how they are embedded in the economic and institutional structures of the host regions.

Moreover, the implications for regional development are shaped by a mismatch between the scale at which the benefits of the CRMA are pursued and the scale at which many of its costs are likely to emerge. A broader EU-based supply of SRMs may strengthen supply-chain resilience and improve access to essential inputs for industries located throughout the Union. On the other hand, the associated social and environmental costs risk remaining predominantly concentrated in the mining regions where extraction projects are located (Söderholm & Svahn, 2015). From a Pigouvian perspective, these impacts constitute negative externalities when they are borne by host communities but are not fully incorporated into project costs and investment decisions. When the territorial incidence of the benefits and costs of collective intervention does not coincide with the scale of decision-making, decision-makers do not face the intervention's full marginal benefits and costs, potentially producing an inefficient level of intervention (Pigou, 1920; Olson, 1969).

These considerations also connect the analysis to contemporary debates in Economic Geography. European regions follow different development trajectories and possess heterogeneous productive, institutional, and innovation capacities, which calls for place-sensitive rather than uniform policy intervention (Iammarino et al., 2019). Regional diversification generally builds on capabilities related to existing industrial and knowledge bases, while natural resources constitute only one

component of the regional asset base (Boschma, 2017; Trippl et al., 2020). Organisationally thin and peripheral regions are particularly exposed to remaining trapped in path extension, as their limited organisational capacity constrains path renewal and creation (Isaksen, 2015). External investment may provide some of the resources needed to overcome these constraints, but its regional effects depend on the linkages established with the host economy. In this respect, Ascani and Iammarino (2018) show that foreign manufacturing firms can contribute to regional structural change by generating demand for local service providers, although such linkages do not necessarily produce technological or industrial upgrading. CRMA-supported investments may therefore reinforce an existing extractive path when they remain weakly embedded in the regional economy or, where complementary productive, technological, organisational, and institutional capabilities are available, contribute to path renewal, diversification, or creation.

2.2.1 The Mineral Resource Framework: Resources, Reserves, Deposits, and Mines

To have a tool as coherent as possible with the analytical and policy framework of the European Commission, all the geological and mining technical definitions provided in this section are aligned with the Infrastructure for Spatial Information in the European Community (INSPIRE) Directive (2007/2/EC)[44], the most updated INSPIRE technical definitions, and the INSPIRE Registry. Two concepts are crucial and well established in the mining literature: mineral "resources" and "reserves". These notions are particularly important for the analysis developed in the following pages, as they clarify the extent to which the geological presence of a mineral can be translated into economically viable, technically feasible, and institutionally recognised extractive potential. The term mineral resource is referred by the INSPIRE Registry as a "*naturally occurring concentration/accumulation of organic or inorganic material of intrinsic economic interest in or on the Earth's crust such as energy fuels, metal ores, industrial minerals and construction minerals, but excluding water, in such form and quality that there are reasonable prospects for eventual economic extraction*". In short, a mineral resource is defined as a mass of naturally occurring mineral materials (mineral occurrences) with a potential economic viability.

[44] https://inspire.ec.europa.eu/registry.

A mineral reserve instead, represents the portion of a mineral resource that has been evaluated as both economically and technically feasible for extraction under current socio-economic conditions (US Bureau of Mines & USGS, 1980). Thus, although both measures are usually expressed in the same absolute units (typically, metric tonnes[45]), while resources refer to a concentration of material of economic interest and are quantified on the basis of geological criteria and methodologies, reserves quantify the portion of those resources that is economically extractable.

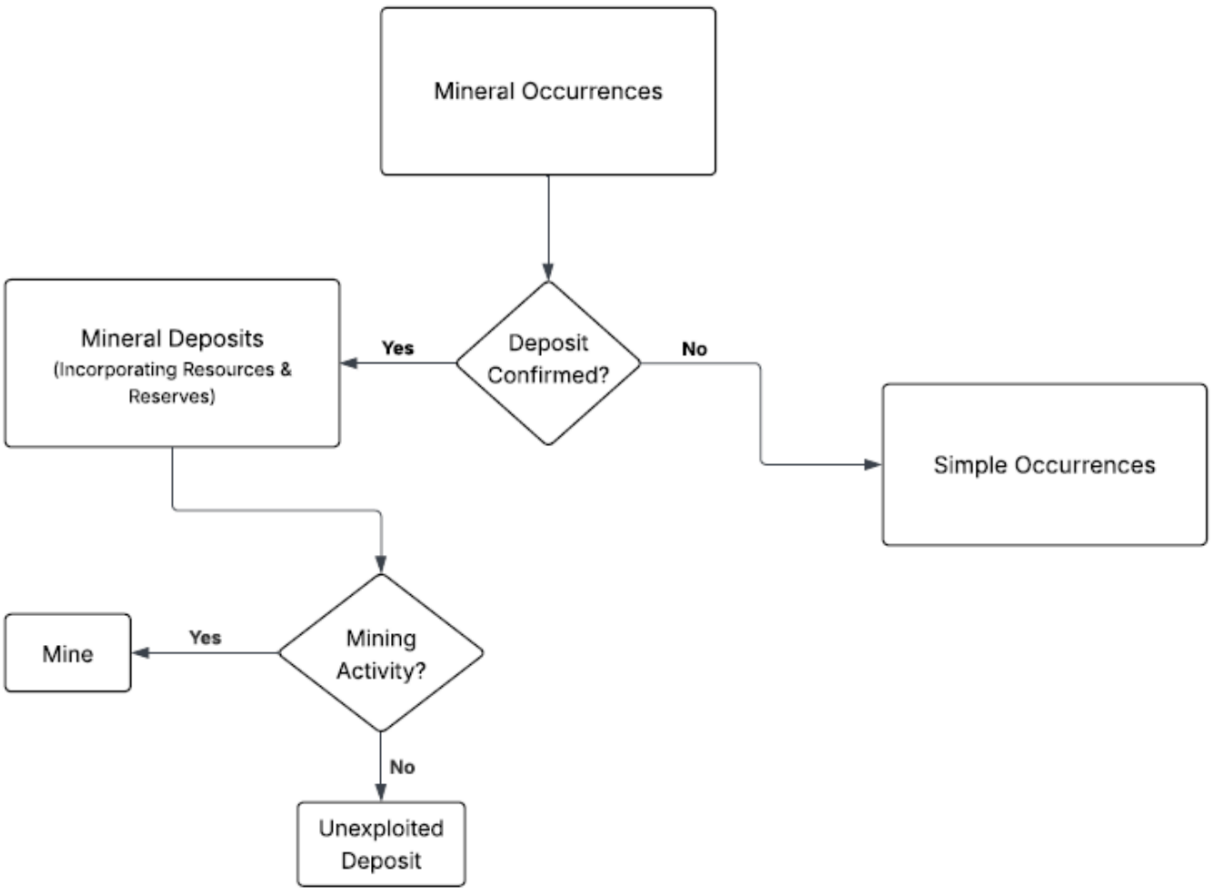
Another concept that will prove useful in the analysis is that of a "mineral deposit", defined by the INSPIRE Registry as "a mass of naturally occurring mineral material, e.g. metal ores or non-metallic minerals, usually of economic value, without regard to mode of origin". The complexity arising from the geological terminology used is only apparent. When a stakeholder, whether a public actor or a private firm, carries out a geological survey in a specific area, the presence or absence of a given mineral in that area may be established. This finding is technically referred to as a "mineral occurrence" and may consist either of a few traces of the mineral or of an actual concentration of resources of that material. In the latter case, in the presence of mineral resources, we have a mineral deposit. At this point, we can elaborate these three concepts — resources, reserves, and deposit — by stating that: mineral resources refer to the content of mineral deposits and consist in a concentration of minerals that has been identified and measured with reasonable certainty but is not yet proven to be economically viable for extraction. This specific information on viability is instead provided by the notion of estimated reserves, which represent the portion of a mineral resource that has been evaluated as both economically and technically feasible for extraction under current socio-economic conditions. Hence, the presence some resources in a mineral deposit does not necessarily mean that such a material is exploitable in the short term. This is particularly evident in Europe in the case of REEs for which there are some interesting geological concentrations in Europe but, to the best of our knowledge, there are no significant operating mines extracting REEs from the soil of the Union (although several projects are emerging, particularly in Sweden and Norway[46]). Finally, a further concept that is relevant to this analysis is the notion of "mine". According to the INSPIRE Registry a mine is

[45] Reporting units may vary across commodities; for instance, precious metals may be reported in troy ounces, diamonds in carats, and other materials in compound- or product-specific unit.

[46] https://www.bbc.com/news/world-europe-64253708,https://www.reuters.com/markets/commodities/companies-forging-rare-earths-industry-eu-2024-06-27/

simply referred as an excavation for the extraction of mineral resources from mineral deposits. A mine therefore exploits mineral properties where reserves are located, acquired or licensed from one or more mining companies for the development of their own projects. Figure 2.1 summarises the mineral resource framework.

Figure 2.1: Mineral resource framework



Key Concepts:

- *Mineral Occurrences*: presence of minerals or rocks in an area under examination
- *Mineral Deposits*: a mineral occurrence of sufficient size that it might, under favorable circumstances, be considered to have economic potential
- *Mineral Resources*: concentration of minerals identified and measured with reasonable certainty
- *Mineral Reserves*: part of mineral resources evaluated as both economically and technically feasible for extraction under current socio-economic conditions
- *Simple Occurrences*: occurrences that are not deposits
- *Unexploited Deposit*: mineral deposit not exploited for extraction purposes
- *Mine*: mineral deposit exploited (or previously exploited) for extraction purposes

2.2.2 Data

The availability of large-scale geolocated data on mineral resources and mining production is a well-known problem, and the EU is no exception. Partial territorial and mineral coverage, difficulties in retrieving from metadata detailed information on the techniques used for data collection, and issues of temporal consistency are widespread. On the basis of the framework reported in Figure 2.1, the analysis relies on two main databases. The first is the proprietary "Metals & Mines Database" provided by S&P Global. We use this dataset both to obtain a quantitative representation of resources in mineral deposits and to map SRM mines. These data have already been used to locate mines and mineral resources by several authors across different disciplines, including Owen et al. (2023), Bastianin et al. (2025), and Mavisakalyan and Minasyan (2025). In fact, S&P Global provides a wide range of information on both mining projects – including their activity status, mining properties, production from mining activities, nationality and financial information of project owners – and resources and reserves in with global coverage. Unfortunately, reserves cannot be included in our analysis, despite being a highly useful measure, because the data associated with this dimension are characterized by low reliability and limited consistency across S&P Global and other available data sources[47]. The identification and geolocation of mines is carried out by geolocating “mining properties”, defined by S&P Global as “an area that has been legally acquired or claimed for the extraction of mineral resources” and identified through latitude and longitude coordinates. Through S&P Global data, we can also retrieve information on the mining projects to which these properties belong, thereby highlighting, for example, whether an active extraction project is still in place for a given mine. We consider 17 SRMs: nickel, bauxite, bismuth, cobalt, copper, graphite, lithium, magnesium, manganese, titanium, tungsten, REEs, and PGMs treated as single elements: platinum, palladium, rhodium, ruthenium, and iridium. Due to data granularity, however, REEs are considered as the lanthanide group + scandium and yttrium. Unfortunately, although data on production are included in S&P Global, the high number of missing values among mining projects classified as active or at an advanced stage of development led us to exclude these variables from the analysis

[47] In S&P Global, reserve values are missing in the vast majority of cases, even when active production of the same material is recorded within the database or in other data sources. This suggests that the absence of reserve values should be interpreted primarily as missing data rather than as evidence of the absence of reserves.

as well.

The second database is the European Geological Data Infrastructure (EGDI[48]), which harmonizes data from multiple sources collected by official national providers, such as the Italian Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), the British Geological Survey (BGS), the French Bureau de Recherches Géologiques et Minières (BRGM), etc. EGDI has three strengths: 1) it is the only one providing, with a sufficient level of accuracy, information about a wide range of raw materials including almost all the SCRMs included in the EU 2023 list; 2) it is an official EU database which follows specific notions, structures, and definitions adopted by the European Commission, and is therefore fully aligned with its programs and objectives (among which, the CRMA); 3) it is a dataset based on mineral deposits rather than on mining properties, which means it geolocates resources in both exploited and non-exploited deposits. Unfortunately, the weaknesses of EGDI are multiple and significant and it only allows us to geolocate the resources of CRMs and SRMs within Europe, but not to quantify them (see Section 2.3). It also suffers from lack of metadata, missing values concerning the date when a specific dimension was either updated or recorded, and the source from which it was taken. We use this data source to build a dataset that considers almost all CRMs and SRMs (only excluding helium and silicon metal), as well as resources embedded in unexploited deposits, providing an overview more on the long term and on the overall geological potential. Although EGDI provides some information on mines, many important countries are missing, as coverage is limited to only 20 EU Member States together with Norway and Switzerland. Moreover, in EGDI the attribution of a mine is technically based on the spatial overlap between the coordinate points of mineral occurrences and the "Mines" layer of the database. This makes the resulting representations unreliable, as spatial overlap of centroids may associate a deposit with an operating mine even when the mine extracts a different commodity. For instance, a deposit of magnesium or a REE may be linked to a nickel mine, leading the data to suggest active extraction of that material even when no such extraction exists in the EU.

[48]EGDI is a geological database assembled by the EuroGeoSurveys (EGS), a not-for profit organization providing European Institutions with experts and services

2.2.2.1 Limitations in the Availability of Georeferenced Mineral Resource Data

During the exploration of information sources, other databases were identified as potentially suitable for a resource analysis, but they resulted to be incompatible with EGDI, S&P Global or INSPIRE technical guidelines. One of them is the Mineral Resource Data System (MRDS) provided by the United States Geological Survey (USGS[49]), which offers data at the global level for a wide set of different materials. The information is based on deposits, as in EGDI, which allows identification of resources in both exploited and non-exploited deposits. However, when compared with European deposit-level data, it becomes immediately clear that, for the purposes of this analysis, the USGS database is significantly less informative than EGDI and S&P Global, both in terms of the number of materials included in the database and the number of observations recorded for the same materials.

An attempt was made to harmonize EGDI and USGS data by normalizing the reported names of mineral deposits — removing spaces, numbers, and capital letters — and by retaining only deposits associated with one the 17 SRMs included in the European list. However, only 2.1% of the EGDI observations could be matched with those reported in the USGS dataset. In addition, quantitative information on mineral resources at the deposit level appears to be highly fragmented in the USGS data, as is also the case in EGDI, especially when compared with the more systematic coverage provided by S&P Global. This must not be interpreted as a total inadequacy of USGS data in providing reliable geological information for Europe. Such poor matching performance is mainly due to the fact that the match could only be performed on the basis of standardized deposit names, since relying on the overlap of simple geographic coordinates indicating deposit locations is not a reliable strategy. The coordinates of deposits are reported as centroids of mineral areas, while both the geometries of these areas and the method used to calculate the centroids are not provided in EGDI. This often leads to mismatches, since the spatial matching of latitude and longitude coordinates is highly sensitive: even small differences in decimal coordinates can place georeferenced observations several kilometres apart. Since merging these two different databases was not feasible, we decided to rely solely on EGDI considering the number of the observations,

[49]USGS was created by an act of the US Congress in 1879, as a science arm of the Department of the Interior. The USGS brings an array of earth, water, biological, and mapping data and expertise to bear in support of decision-making on environmental, resource, and public safety issues

the number of commodities considered and giving priority to data provided by national data providers. Additionally, the temporal dimension of the data must be considered. EGDI provides information updated to 2021, whereas USGS data is based on 2014, when mineral resources in Europe did had not received the same level of attention as they do today.

Another potentially useful source is Mindat[50], an open-access mineralogical database that provides extensive information on minerals, rocks, meteorites, and the localities in which they occur. However, although Mindat contains a large amount of highly detailed geological and mineralogical information, its structure is better suited to technical geological or mineralogical investigations than to our natural-resource framework focused on mineral endowments. Moreover, it does not represent an official EU source, its information is not always directly comparable or easily validated for policy-oriented analysis, and it does not systematically provide quantitative data on mineral resources or reserves at the deposit level.

To understand the origin of the problem of obtaining quantitative and georeferenced information on mineral natural endowments, it is useful to consider that the importance of mineral deposits is often assessed on the basis of the previously discussed resources and reserves. Mineral resource estimation procedures rely on geological methods such as mineral exploration, geochemical analysis, and geological modelling, which are not activities that require a stakeholder (most often private actors, but in some cases also public institutions) interested in a specific geological area and willing to invest resources to carry out the estimations. For reserves, the problem becomes even more complex because they are determined by adding site-specific data to the model, including factors such as market prices, extraction costs, regulatory conditions, etc (US Geological Survey, 1980). Since the size of deposits and the evaluation of their concentration of valuable material rely on these measures, geological mapping as a whole is affected by this issue. In practice, building a quantitative and georeferenced picture of mineral reserves becomes, most of the time, a micro-level data collection exercise carried out by specialized data providers, where the relevant units are individual mines and the firm's holding ownership, or exploitation rights over them. Data concerns have also a significant impact on the calculation of the criticality of various commodities on the EU list of CRMs. Regarding the supply risk indicator in the 2017

[50] https://www.mindat.org/

critical assessment methodology (see Chapter 1), the European Commission itself states:

"... By default, the extraction stage of raw materials is used for the calculation of the supply risk, unless the processing stage is proved to be the most critical point in the supply chain or data for the extraction stage are unavailable or of insufficient quality..." (European Commission, 2017, p. 11)

Operating within such a framework without a solid informational basis for each stage of the supply chain may undermine the internal consistency of the approach, particularly because CRMA objectives encompass a broad category of materials with highly heterogeneous extraction, processing, use, and recycling pathways. This lack of accurate data can already be considered a flaw in the diversification strategies for CRMs if it relies on approximate calculations and, at the same time, the assessment of the feasibility of the strategy and the progress of its objectives may also prove to be particularly challenging. Data reliance problems are also evident when examining the data sources used by the European Commission in the already cited RMIS. In the latest update of the RMIS Resources & Reserves Module[51] all data sources are listed for each raw material included in the system, which are used to estimate European and global resources and reserves. For some SCRMs included in the RMIS, such as aluminium, estimates have been computed by the JRC using data primarily collected by S&P Global, along with additional sources like Minerals4EU for Greece and Romania. For other materials, such as antimony, the JRC's European and global estimates of reserves and resources rely on a modelled estimation by S&P Global, rather than official reported amounts, thereby estimating natural resource endowment through projections. For materials such as Arsenic, the JRC states that no global data on resources and reserves are available. An even further different case is baryte, for which no information about global resources is available, and the data used for reserves come from the USGS but not comprehensively due to a partial country coverage.

[51]This document provides metadata and information on the data sources used in the RMIS project (https://rmis.jrc.ec.europa.eu/uploads/rmp/info-dashboard.pdf).

2.2.3 The European SRM Endowment

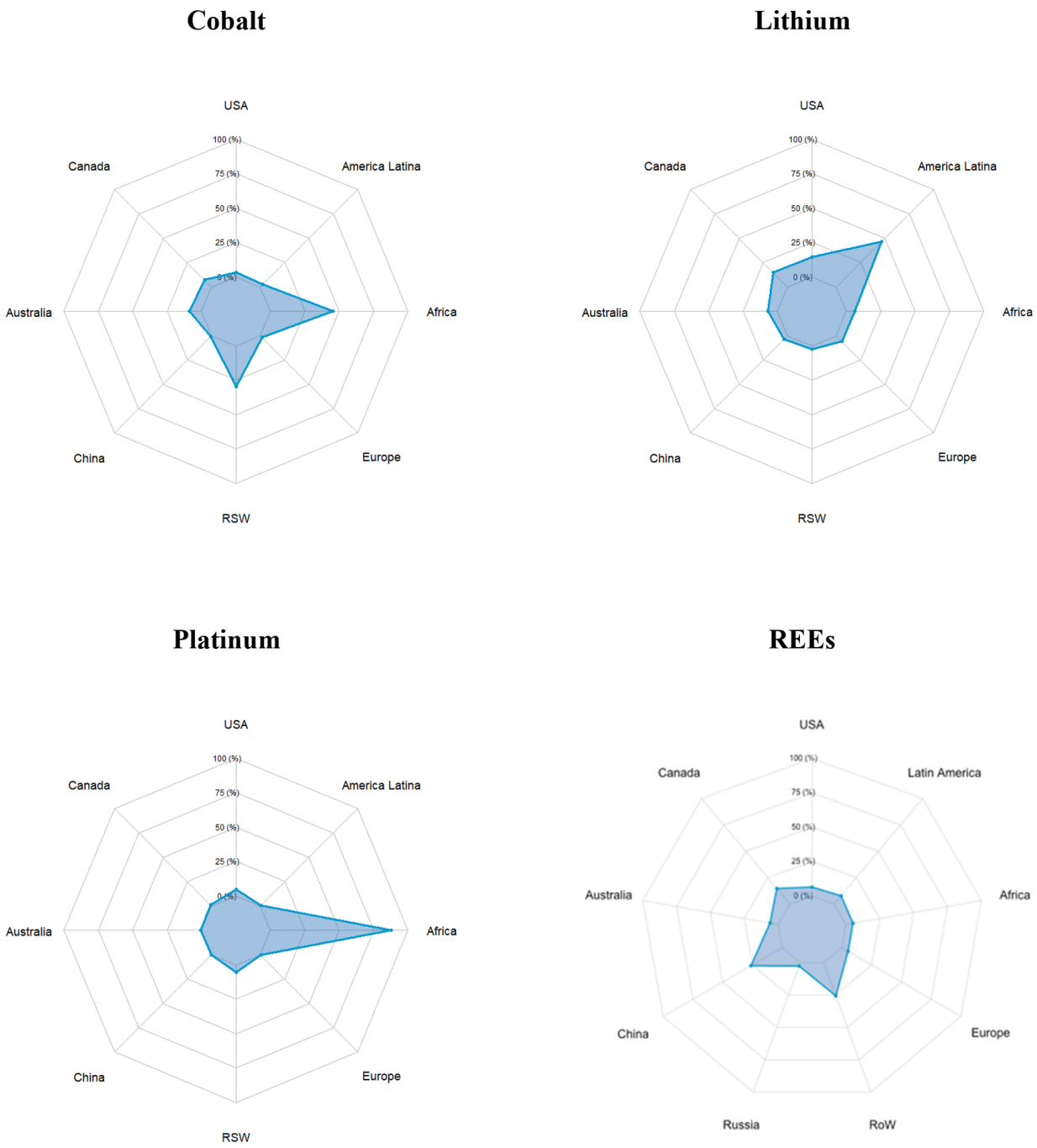
One of the main tasks in assessing the EU's natural endowment of critical mineral resources is to develop a consistent method for comparing resources across geographies in order to identify relative advantages. Figure 2.2 is an example of the kind of representation S&P Global allows to do, in this case considering 4 SRMs (lithium, cobalt, REEs and platinum)[52] for a set of world macroregions including Europe, US, Canada, China, Latin America, Africa and Russia and Rest of the World (RoW).

In the radars, the amount of resources is computed as the sum of mineral resources (in tonnes[53]). For each SRMs contained in mining properties of all mining projects in that region of the world. The feasibility of extracting mineral resources through mining activities clearly depends not only on the amount of economically recoverable resources, but also on geological characteristics, regulatory constraints, social and political resistance, and associated risks. For example, it is highly unlikely that a titanium mine would be opened in a UNESCO World Heritage natural park or in the middle of an urban area, even if the deposit were one of the largest in the world. From Figure 2.2, the distribution of mineral resources does not appear favourable to Europe for the SRMs considered. Though, considering each material individually is useful for obtaining a general representation of the distribution of resources worldwide, but it is not an easy way to evaluate the global natural endowment of CRMs and SRMs. Absolute values of resources of different commodities cannot be summed together, since each occurs in different concentrations within mineral deposits. For example, a deposit containing 1 million tonnes of REE oxide resources has a completely different economic and strategic relevance compared to a deposit with 1 million tonnes of aluminium resources. To address the problems of incomparable absolute values and heterogeneous resource distributions, and to enable international comparisons of resource endowments, we compute z-scores for each SRM in every country. The amount of resources in a given country is thus expressed in terms of standard deviations from the mean resource level for that specific material.

[52] In Appendix 2 we include radars for all 17 SRMs in Figure A2.1, and regions of the world composition in Table A2.1

[53] Note that for PGMs, which are treated as precious metals, the unit of measure is ounce (oz).

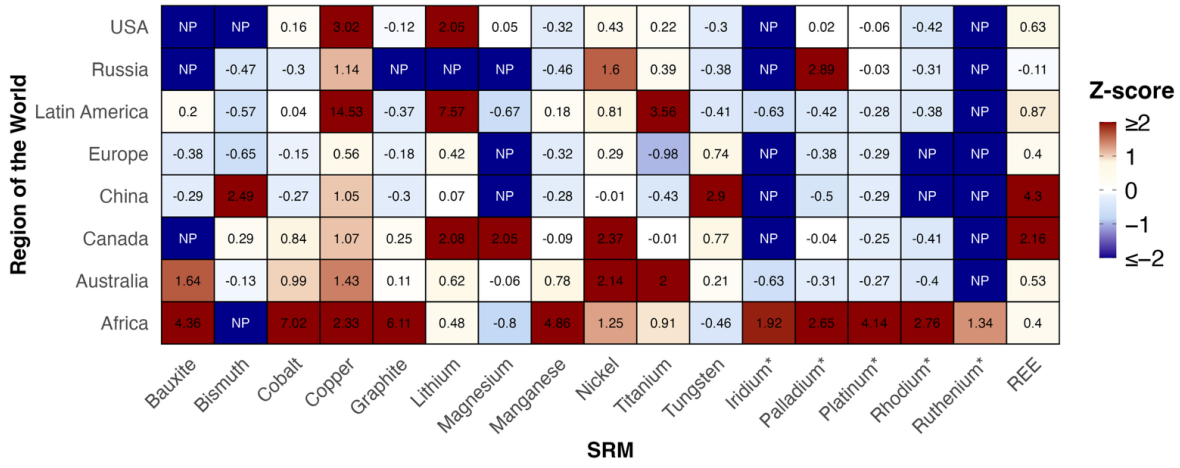
Figure 2.2: Share of global resources for some selected SRMs



Source: own elaborations on S&P Global data (2025).
Note: shares are computed on global endowment of resources (t), across mining properties in mining projects.

In Figure 2.3, z-scores are calculated separately for countries and world regions using the worldwide country-level distribution of resources for each SRM as the reference. At the country level, the indicator expresses the amount of resources in standard-deviation units from the global country mean for the corresponding material. For world regions, the country-level resource quantities are first summed, and a separate z-score is then calculated for the resulting regional total using the same global mean and standard deviation. Regional z-scores are therefore not obtained by summing or averaging country-level z-scores.

Figure 2.3: Resources of SRMs in mining properties across world regions (z-score)



Source: own elaborations based on S&P Global data (2025).
Note: Country-level mineral-resource quantities are aggregated by world region before standardisation. A separate z-score is then calculated for each regional total using the worldwide country-level mean and standard deviation for the corresponding SRM as the reference. NA values indicate cases where resources for a given SRM are equal to zero. (*) PGM.

Values toward red indicate a greater mineral-resource endowment relative to the worldwide country-level benchmark. A value of 0 corresponds to the global country mean for the material considered, while positive and negative values indicate resource endowments above and below that benchmark, respectively. Standardisation gives the reference distribution a mean of 0 and a standard deviation of 1, but does not imply that the underlying resource distribution is normally distributed. When the number of resources is 0, meaning the complete absence of that specific SRM in the world region, we denote it as NP (Not Present). The heatmap highlights the highly uneven global distribution of SRMs. Africa shows strong comparative advantages in several

CRMs, including bauxite, cobalt, graphite, manganese, PGMs, and REEs. Latin America stands out with a particularly high concentration of copper and significant resources of lithium and graphite. Australia holds advantages in bauxite, nickel, copper, and palladium, while China is prominent in bismuth, nickel, and especially REEs. Russia shows relative strength in nickel and palladium, whereas the United States has notable advantages in copper and titanium. Canada presents a more balanced profile, with strengths in lithium, manganese, and PGMs. In contrast, Europe generally appears below the global average, with only limited relative advantages.

2.3 SRM Resources in the European Regions

In this section, we attempt to map and analyse the natural endowment of mineral resources across European regions. By identifying where critical resources are concentrated, it is possible to highlight regions with untapped potential and classify critical commodities for which, based on current knowledge, diversifying domestic supply may be unfeasible in the short and medium term due to the insufficiency or absence of natural endowment, or to excessive costs and risks. As mentioned in Section 2.2.2, the analytical effort developed in this section is divided into two parts. First, Section 2.3.1 uses S&P Global to provide an overview of mining projects and mining properties reporting resources of SRMs, and to quantify the resources contained in the deposits associated with these properties. Second, Section 2.3.2 relies on EGDI to provide an official-data representation of SRM resources, including deposits that are not captured among the mining properties recorded in S&P Global. In addition, EGDI is used to map deposits related to the broader 2023 list of SCRMs.

2.3.1 SRM Resources in Mining Properties

We use S&P Global for quantitative representation of SRM resources in mining projects at the NUTS-2 level. A total of 210 projects was identified, from which we consider the mineral resources contained within the deposits under the ownership or license of a project. We classify deposits by size – small, medium/small, medium/large, and large – based on the quartiles of each

material's global resource distribution[54]. We report the number of deposits classified by size for each SRM in Table 2.3.

Table 2.3: Mineral resources of SRMs in European mining properties by size

Strategic Raw Material	Large	Medium-large	Medium-small	Small	Total Projects	No. of Regions (NUTS 2) with resources
Aluminium/Bauxite	0	0	1	0	1	1
Bismuth	0	0	0	1	1	1
Cobalt	1	5	12	18	36	9
Copper	24	22	31	54	131	45
Graphite	2	0	2	2	6	3
Lithium	2	4	4	8	18	11
Magnesium	0	0	0	0	0	0
Manganese	0	2	2	1	5	4
Nickel	7	5	11	18	41	11
Titanium	0	1	0	2	3	2
Tungsten	4	3	8	8	23	13
Iridium	0	0	0	0	0	0
Palladium	1	1	2	4	8	4
Platinum	0	2	2	3	7	3
Rhodium*	0	0	0	0	0	0
Ruthenium*	0	0	0	0	0	0
REE	2	3	2	2	9	6

Source: own elaboration on S&P Global data (2025).

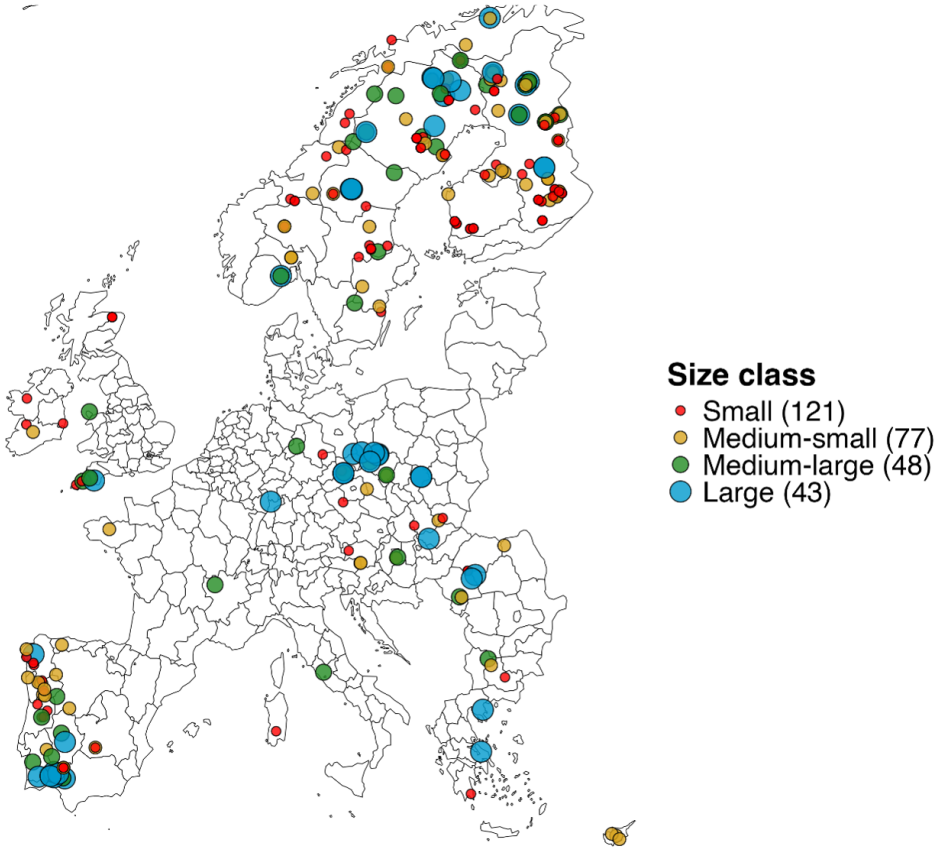
Figure 2.4 maps the distribution of resources for the SRMs listed in Table 2.3 across European regions (27 EU members + Switzerland, Norway and UK)[55]. The EU's criticality assessment model for CRMs, together with the CRMA top-down approach, fails to adequately account for the geographical distribution of resources and the potential socio-economic and environmental implications of the regional concentration of CRM resources. The figure reveals a strong concentration of SRM resources in projects located mainly in two areas: the Nordic countries and south-western Europe (Portugal and Spain). A notable cluster of deposits classified as "large" containing substantial resource volumes is also evident in parts of Central and Eastern

[54]Note: resources of different SRMs may be contained within the deposits of individual projects; therefore, the count of deposits for each material does not match the total number of projects.

[55]The integration of resources from these countries is strongly aligned with the EU CRMA framework (with the UK as a EU Member State until 2020)

Europe. Yet, aggregating all SRMs can yield an overly optimistic picture that obscures the actual concentration of specific resources within regions. As previously stressed, these materials must be analysed individually rather than as a single bundle, because they are extracted and processed at different concentrations, and refined and used for distinct production purposes.

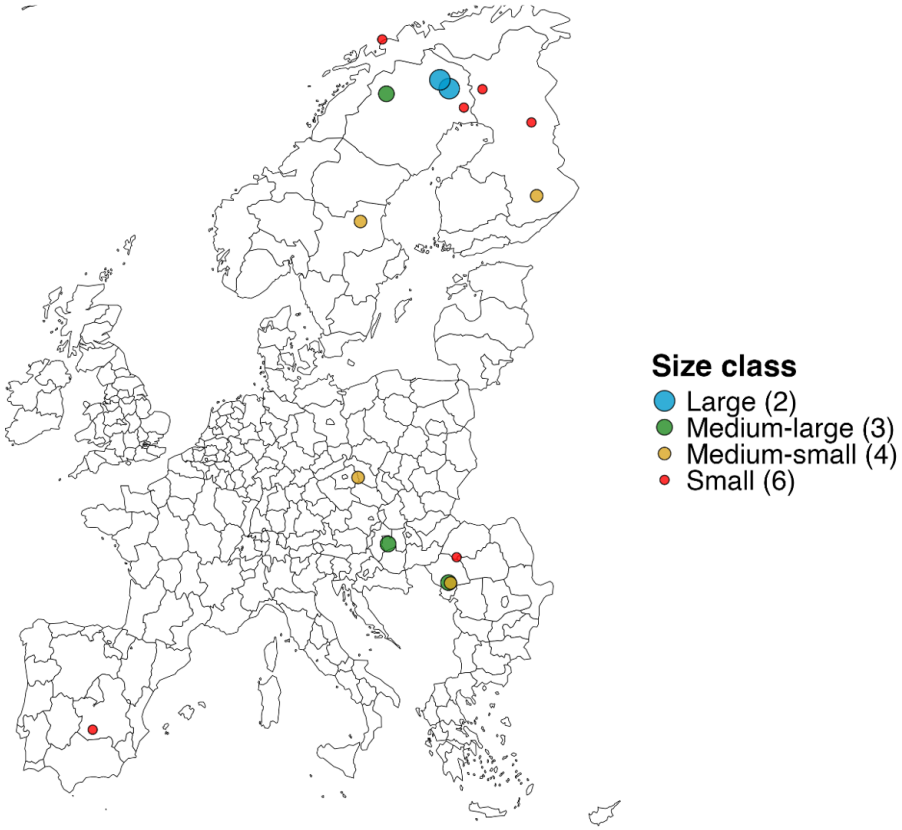
Figure 2.4: Resources of SRMs in European regions mining properties by size (NUTS 2)



Source: own elaboration based on S&P Global (2025) data.
Note: 17 SRMs included. Countries: 30 (27 EU members + Switzerland, Norway and UK). Size classes are computed based on the mineral resources (t) embedded in mining properties, by quartiles of the world distribution for each SRM.

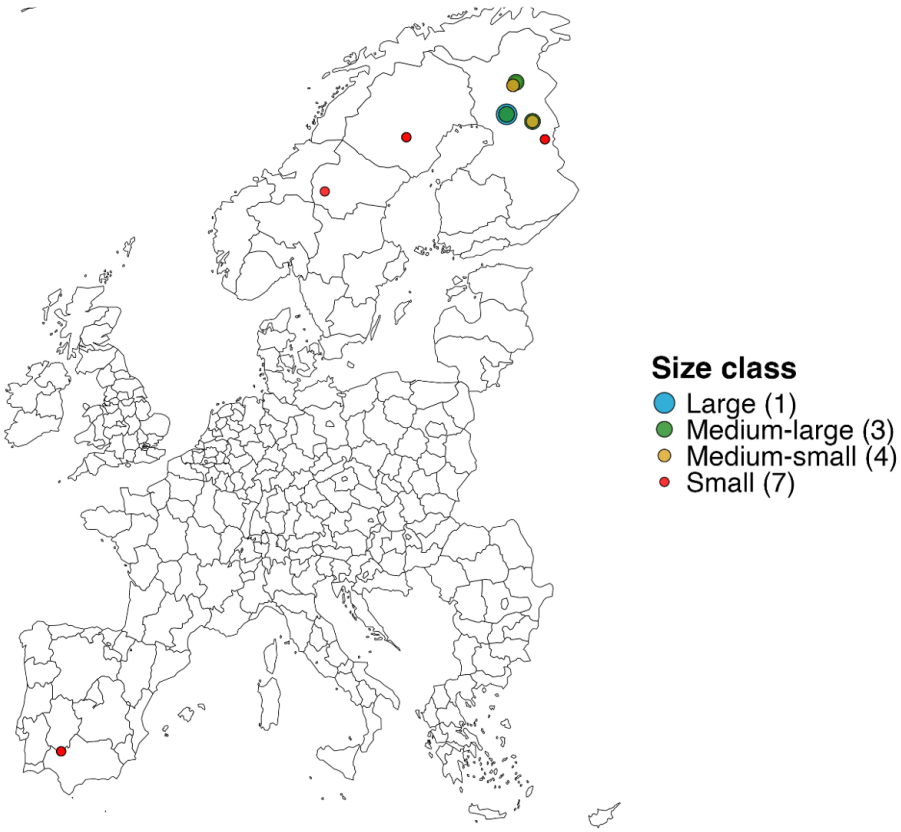
Figures 2.5, 2.6, and 2.7 report the subset of materials included in this data that, at the baseline period (2016–2020), did not meet the 10% domestic-extraction threshold set by CRMA (see Table 2.1), underlining an even more limited number of regions in which resources of such materials are embedded.

Figure 2.5: Resources of bismuth, magnesium, manganese, titanium in European regions mining properties, by size (NUTS 2)



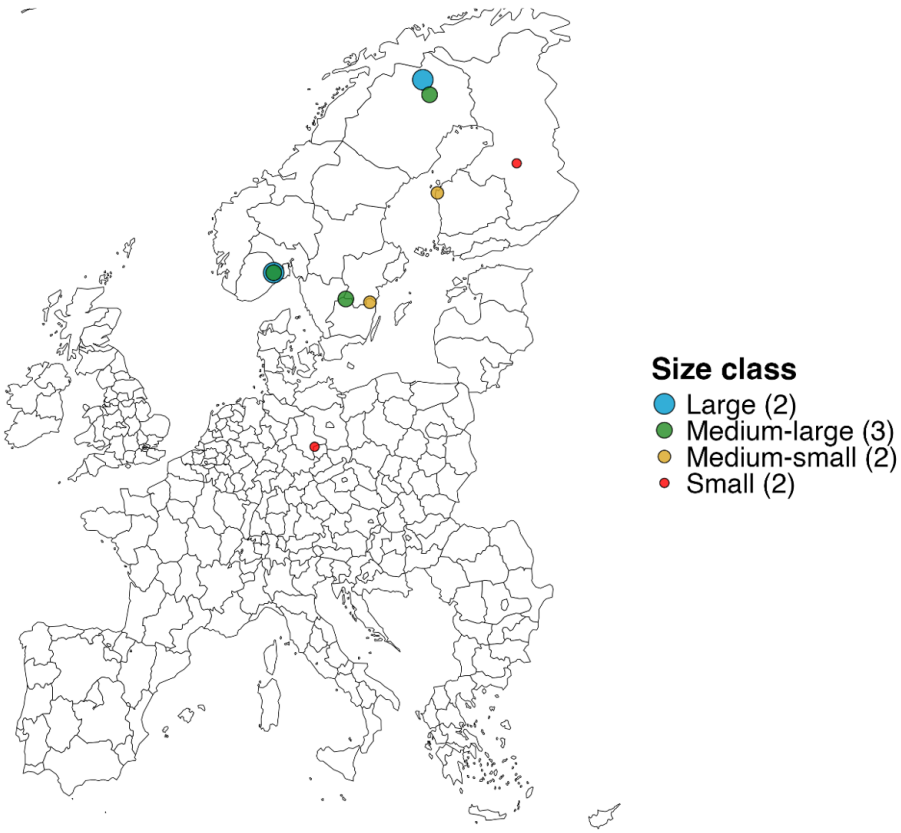
Source: own elaboration based on S&P Global (2025) data.
Note: Countries: 30 (27 EU members + Switzerland, Norway and UK). Size classes are computed based on the mineral resources embedded in mining properties, by quartiles of the world distribution for each SRM.

Figure 2.6: Resources of PGM in European regions mining properties, by size (NUTS 2)



Source: own elaboration based on S&P Global (2025) data.
Note: Countries: 30 (27 EU members + Switzerland, Norway and UK). Size classes are computed based on the mineral resources embedded in mining properties, by quartiles of the world distribution for each SRM.

Figure 2.7: Resources of PGM in European regions mining properties, by size (NUTS 2)



Source: own elaboration based on S&P Global (2025) data.
Note: Countries: 30 (27 EU members + Switzerland, Norway and UK). Size classes are computed based on the mineral resources embedded in mining properties, by quartiles of the world distribution for each SRM.

Mineral resources in mining properties may be exploited at very different paces, but rarely very quickly. The more advanced a licensed project is toward the production stage, the sooner these resources are likely to be brought into use. In Figure 2.8, we reproduce the map shown in Figure 2.4 but report the operational status of the SRM mining projects, using the macro-classification provided by S&P Global, which summarizes the possible stages of activity of a project into Closed Project, Early Development, Late Development, and Mine Stage; the latter is the only one actually in an operational extraction phase, either intermittent or continuous. Late and Early Development stages are gathered into a single category, Under Development, with the exclusion of projects for which no quantified resources are available. Table 2.4, we report the number of the mining projects by status for each SRM. It should be noted that the recording of project status

in S&P Global often refers to dates even earlier than the past decade. A manual check on each individual project was performed, drawing on information from producer websites and local government agencies, and updated project status whenever it was dated prior to 2023[56]. Out of a total of 210 mining projects containing at least one of the considered SRM resources, 36 (17%) are classified as Closed, 134 (63%) are Under Development, and 40 (19%) are in the Mine Stage.

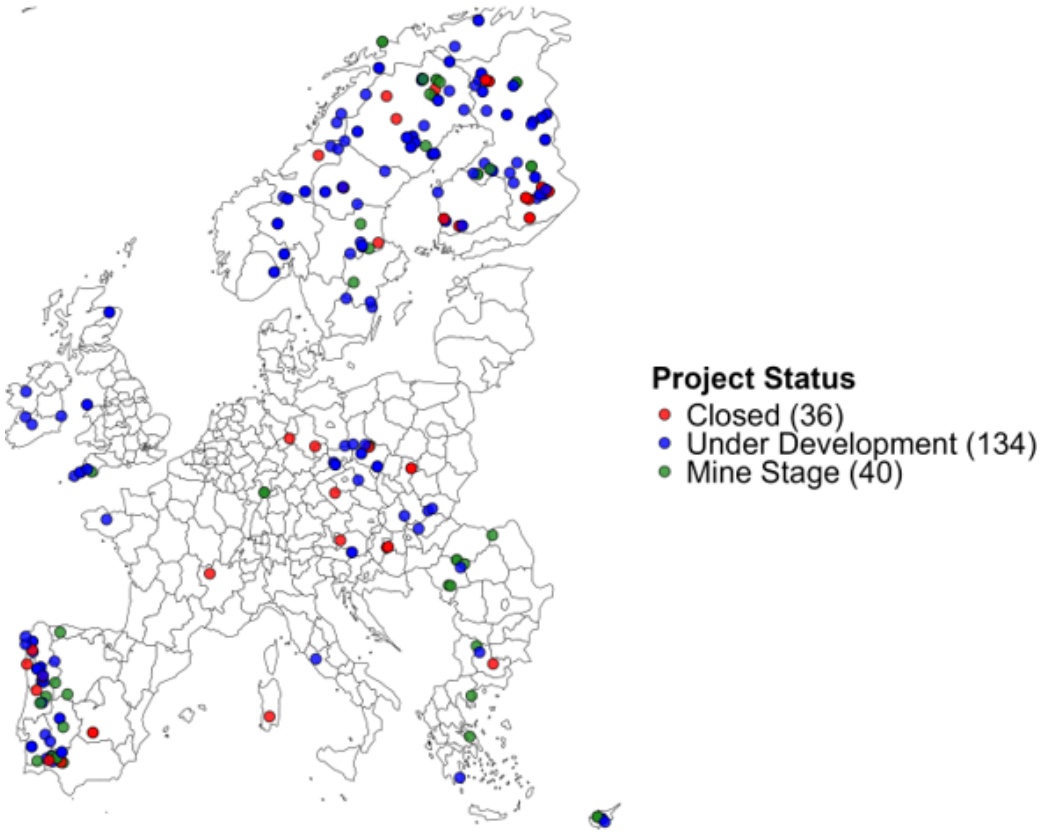
Table 2.4: Number of European mining projects including SRMs, by status

Strategic Raw Material	No. Closed Project	No. Mine Stage Projects	No. Under Development Projects	Total Projects	No. of Regions (NUTS 2) with projects
Aluminium/Bauxite	1	0	0	1	1
Bismuth	0	1	0	1	1
Cobalt	8	3	25	36	9
Copper	25	22	84	131	45
Graphite	0	3	3	6	3
Lithium	1	3	14	18	11
Magnesium	0	0	0	0	0
Manganese	2	2	1	5	4
Nickel	10	4	27	41	11
Titanium	1	0	2	3	2
Tungsten	4	5	14	23	13
Iridium*	0	0	0	0	0
Palladium*	0	1	7	8	4
Platinum*	0	1	6	7	3
Rhodium*	0	0	0	0	0
Ruthenium*	0	0	0	0	0
REE	1	2	6	9	6

Source: own elaboration on S&P Global data (2025).

[56]The update was carried out following a logic aimed at avoiding inconsistencies with S&P Global's classification approach. Projects originally in the Under Development or Mine Stage categories, where the license had expired without renewal and no new ongoing feasibility studies, were reclassified as Closed. Projects in Under Development that had begun extraction activities for at least one year were reclassified as Mine Stage. Finally, projects previously classified as Mine Stage but subsequently closed, and later acquired under license or feasibility studies by another operator, were reclassified as Under Development.

Figure 2.8: Mining projects including SRMs in European Regions (NUTS 2), by status

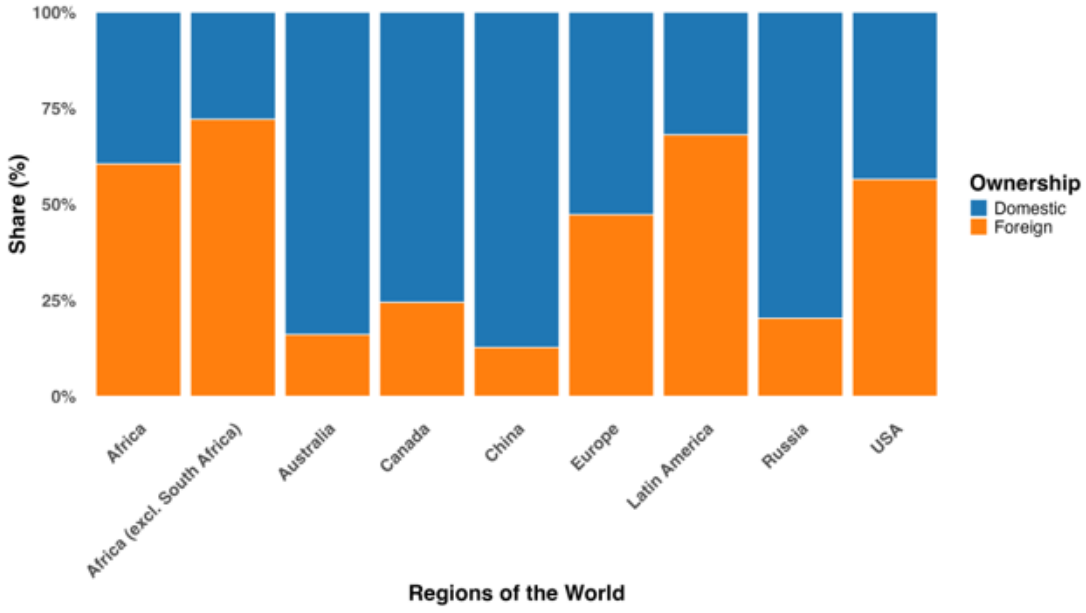


Source: own elaboration based on S&P Global (2025) data.
Note: 17 SRMs included. Countries: 30 (27 EU members + Switzerland, Norway and UK). Size classes are computed based on the mineral resources (t) embedded in mining properties, by quartiles of the world distribution for each SRM.

Overall, Figure 2.8 highlights that while many projects are still under development, 80% of them are active or potential mining sites, with strong geographic concentrations in the Nordic regions and those of the Iberic Peninsula. Active mine stage projects are again primarily located in regions in Finland, Sweden, Portugal, and Spain, with a markedly lower presence in Greek and Romanian regions. In this representation, it is important to note that the presence of resources of a given SRM within the mining properties of a project does not necessarily mean that the material is being extracted, but only that the licensed area contains such resources. This is the case, for instance, of REEs, which, although present in certain quantities, are not yet being extracted in the territories considered as of August 2025.

The ownership structure of the projects previously analysed raises further concerns about the potential lack of skills and expertise at the EU level, a topic addressed in Chapter 3. In Figure 2.9 we use still use S&P Global data on the Global Ultimate Owner (GUO) of SRM project owners to conduct a worldwide comparison of project ownership involving SRM resources.

Figure 2.9: Share of foreign MNEs in SRMs mining projects ownership



Source: own elaboration based on S&P Global (2025).
Note: 17 SRMs included. Europe: 27 EU members + Switzerland, Norway and UK. Ownership is considered on the base of the Global Ultimate Owner.

2.3.2 The Overall Geological Endowment of CRMs and SRMs

This section can be considered analogous to a subsoil analysis and therefore does not take into consideration the presence or intensity of extractive activities in a given area. Table 2.5, based on EGDI, reports information for each CRM and SRM concerning its regional concentration in European regions. As explained in Section 2.2.2, EGDI allows us to obtain a broader territorial overview covering almost all SCRMs included in the fifth list, although this comes at the cost of losing the quantitative information on resources and reserves available for georeferenced deposits.

Table 2.5: Distribution of CRMs and SRMs in European Deposits

CRM/SRM	2023 criticality assessment results		Mineral Deposits	
	Supply Risk (SR)	*Economic Importance (EI)*	*Total observations*	*No. of regions with resources*
Aluminium/Bauxite	1.20	5.80	160	34
Antimony	1.80	5.40	259	33
Arsenic	1.90	2.90	321	33
Baryte	1.30	3.50	846	54
Beryllium	1.80	5.40	47	17
Bismuth	1.90	5.70	124	12
BlackCoal	1.00	3.10	360	15
Boron/Borate	3.60	3.90	1	1
Cobalt	2.80	6.80	366	28
*Copper**	0.10	4.00	3893	82
Feldspar	1.50	3.20	779	47
Fluorspar	1.10	3.80	653	32
Gallium	3.90	3.70	0	0
Germanium	1.80	3.60	15	8
Hafnium	1.50	4.30	2	1
Helium	1.20	2.90	0	0
Lithium	1.90	3.90	47	13
Magnesium	4.10	7.40	133	33
Manganese	1.20	6.90	1245	50
Natural Graphite	1.80	3.40	213	26
*Nickel**	0.50	5.70	227	32
Niobium	4.40	6.50	49	14
Phosphate Rock	1.00	6.40	233	26
Phosphorous	3.30	4.70	89	9
PGM	2.70	7.10	34	7
HREE	5.09	4.18	20	6
LREE	3.74	5.94	43	5
Strontium	2.60	6.50	25	6
Tantalum	1.30	4.80	57	11
Titanium Metal	1.60	6.30	84	21
Tungsten	1.20	8.70	825	33
Vanadium	2.30	3.90	66	16

Source: own elaboration based on EGDI (2021) and European Commission (2023b) data.
Note: SRMs in italics. Countries considered for each category are reported in Table 1. All raw materials of the 5th list are included, except silicon metal. No. of regions: 297.

Table 2.5, all the materials of the 2023 EU official CRMs lists are included except for silicon metals due to data availability. As anticipated, the use of EGDI database resource requires intensive work in data extraction, integration, cleaning, and geolocalisation. EGDI data are prepared and collected through the project Mineral4EU, EURare, ProSUM, RESEERVE, MINTELL4EU and other EU projects. EGDI not only includes mining deposits but also all other forms of mineral occurrences in general (see Figure 2.1). In line with the approach taken in the previous section, and in order to avoid an unnecessary overrepresentation of exploitable resources, simple occurrences are not considered of economic interest[57].Table 2.5 we address this problem, we propose a more

[57]To distinguish deposits from other simple occurrences, we use the "occurrenceType" indicator provided in

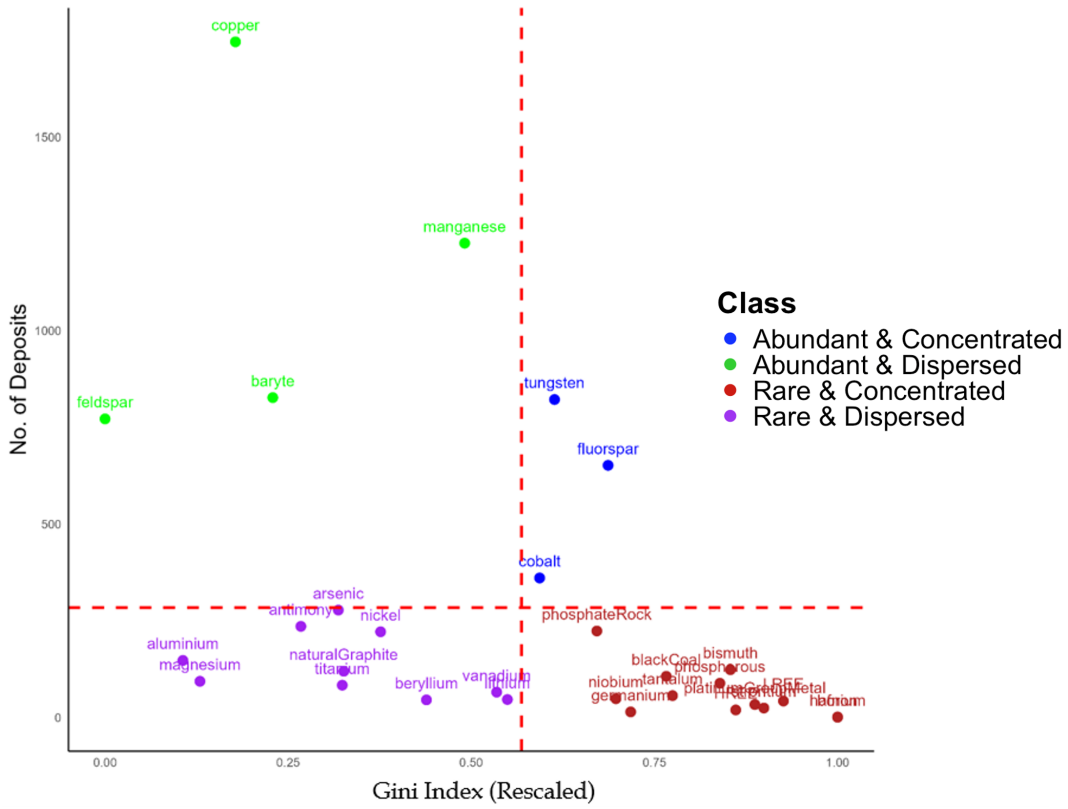
granular, commodity-specific approach that aims for a more realistic representation. The first two columns of Table 2.5 display the values each of these commodities received in the 2023 criticality assessment (European Commission, 2023a). It is important to note that, according to the methodology used by the EU to classify raw materials as critical, these materials must have at least a value of 1 in the Supply Risk Indicator (SR) and a value of 2.8 in the Economic Importance Indicator (EI) (full details in Chapter 1). Based on these two indicators, SCRMs can be considered more or less critical. Due to the lack of quantitative data, what is considered in Table 2.5 can only be seen as a sort of "best-case scenario," as it is impossible to evaluate whether the commodities in these deposits could actually be exploited.

As also shown in Section 2.3.1, for some materials the natural endowment is concentrated in just a handful of regions. A striking example is the case of REEs deposits, both light and heavy (LREEs and HREEs), which are concentrated in 5-6 NUTS 2 regions out of 297, or in the case of PGM. Some other commodities, such as copper or feldspar, are more evenly distributed across regions, with deposits present in over 80 regions. Anyway, the information provided by the number of deposits per region does not offer much understanding of the pressure that some mineral resources can generate at the local and regional levels. Many deposits of certain CRMs (e.g., Niobium in Spain or HREE in Sweden) are geographically clustered, suggesting they may belong to a single, larger mineralized area or mining district. This concentration may increase the risk of over-reliance on a restricted geographical area for extraction, which could have significant implications for the objectives aimed at improving domestic value chains. We compute a Gini Index as a measure of the diversity of concentration of each kind of materials in the European regions. Since the presence of many zero observations may mechanically increase the measured level of spatial concentration, we normalise the index relative to its sample-specific maximum, obtaining a measure ranging from 0 to 1 for ease of interpretation. In this context, a Gini value approaching 0 indicates a distribution of the commodity closer to the minimum, meaning a more equal spread across 297 European regions covering EU27 + Switzerland + Norway + UK. Conversely, a Gini value approaching 1 indicates a distribution closer to the maximum, suggesting a strong concentration of the resource in a few regions. The Gini index allows for

the EGDI database, selecting observations classified as "Deposit". For France and Poland, however, this operation is more complex. The technical details concerning these two countries are therefore discussed separately in the Supplementary Notes section of Appendix 2.

the classification of mterials based on their concentration in NUTS 2 regions. In Figure 2.10, the scatterplot with four quadrants shows the number of deposits and their concentration by NUTS 2 regional units, highlighting four categories of CRMs. We consider SCRMs with a number of deposits above the mean line as Abundant and those below the mean line as Rare. Commodities with a normalized Gini index above the mean are classified as Concentrated, while those below the mean are classified as Dispersed. Combining these two dimensions, we derive the four categories shown in Figure 2.10: Abundant & Dispersed, Abundant & Concentrated, Rare & Dispersed, and Rare & Concentrated. Class assignments are reported in Table 2.6.

Figure 2.10: CRM and SRM deposits by abundance and concentration across European regions (NUTS 2)



Source: own elaboration based on EGDI (2021) data.
Note: Classes in Table 2.6. All raw materials of the 5th list are considered, except silicon metal. Countries: 25 (23 EU members + Switzerland, Norway), NUTS 2 = 297 regions. Mean of the no. of deposits = 350.5, normalized Gini index mean = 0.53.

Table 2.6: Classification of CRMs based on the number of deposits and concentration

SCRM	No. of Deposits	Gini Index	Gini Index (rescaled)	Category
Aluminium/Bauxite	148	0.95	0.11	Rare & Dispersed
Antimony	236	0.96	0.27	Rare & Dispersed
Arsenic	278	0.96	0.32	Rare & Dispersed
Baryte	827	0.96	0.23	Abundant & Dispersed
Beryllium	46	0.97	0.44	Rare & Dispersed
Bismuth	124	0.99	0.85	Rare & Concentrated
Black coal	107	0.98	0.77	Rare & Concentrated
Boron	1	1.00	1.00	Rare & Concentrated
Cobalt	361	0.98	0.59	Abundant & Concentrated
Copper	3668	0.95	0.18	Abundant & Dispersed
Feldspar	772	0.95	0.00	Abundant & Dispersed
Fluorspar	652	0.98	0.69	Abundant & Concentrated
Germanium	15	0.98	0.72	Rare & Concentrated
Hafnium	2	1.00	1.00	Rare & Concentrated
HREE	20	0.99	0.86	Rare & Concentrated
Lithium	47	0.97	0.55	Rare & Dispersed
LREE	43	0.99	0.93	Rare & Concentrated
Magnesium	94	0.95	0.13	Rare & Dispersed
Manganese	1226	0.97	0.49	Abundant & Dispersed
Natural graphite	120	0.96	0.33	Rare & Dispersed
Nickel	222	0.96	0.38	Rare & Dispersed
Niobium	49	0.98	0.70	Rare & Concentrated
Phosphate rock	224	0.98	0.67	Rare & Concentrated
Phosphorous	89	0.99	0.84	Rare & Concentrated
PGM	34	0.99	0.89	Rare & Concentrated
Strontium	25	0.99	0.90	Rare & Concentrated
Tantalum	57	0.99	0.77	Rare & Concentrated
Titanium	84	0.96	0.32	Rare & Dispersed
Tungsten	822	0.98	0.61	Abundant & Concentrated
Vanadium	66	0.97	0.53	Rare & Dispersed

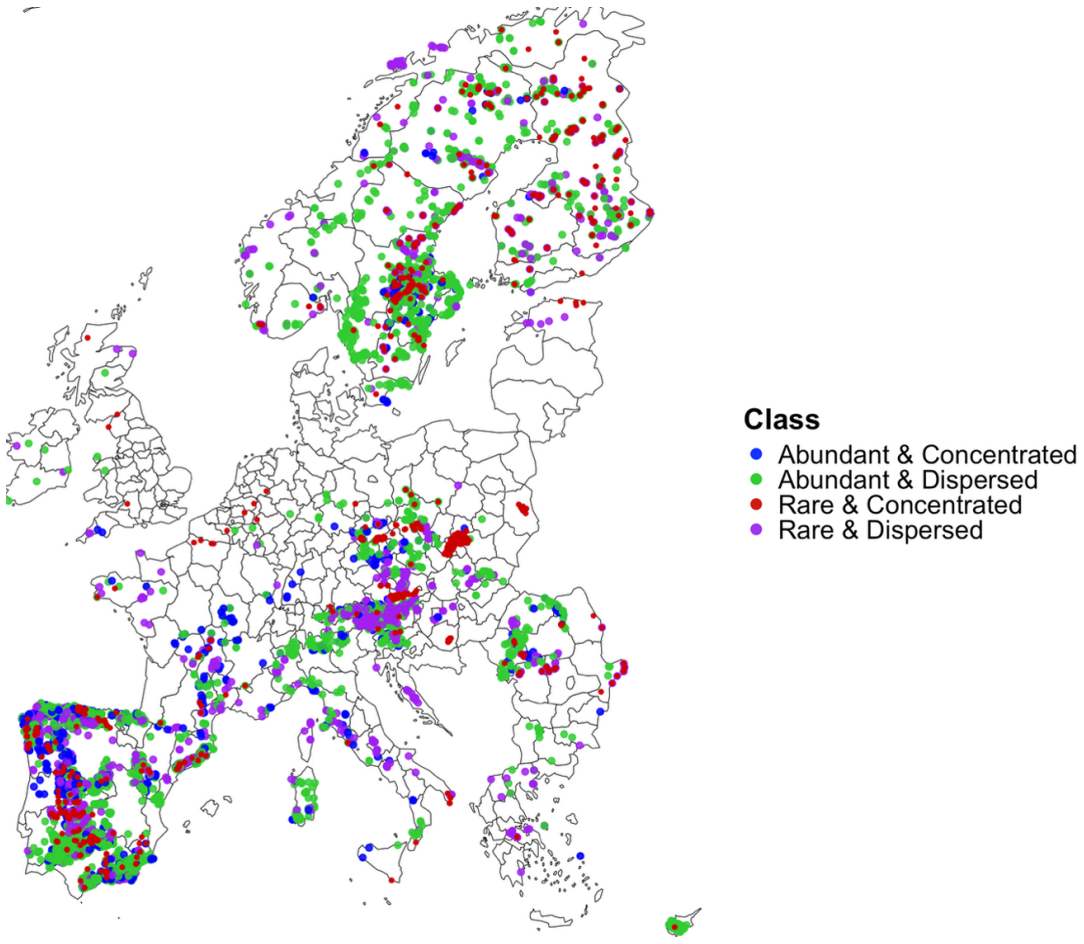
Source: own elaboration based on EGDI data (2021).
Note: Classes are assigned as follows. Commodities with a number of deposits above the mean value of 350.5 are classified as Abundant, while those below the mean are classified as Rare. Commodities with a normalized Gini index above the mean value of 0.53 are classified as Concentrated, while those below the mean are classified as Dispersed. No. of regions: 297. SRMs in italics. Gallium and Helium are excluded because there are no deposits of these elements in the regions considered.

The logic behind these distinctions is that the number of deposits does not directly provide the idea of the geographical concentration of a raw material. For instance, lithium and niobium have a similar and low number of deposits, which are concentrated in roughly the same number of NUTS 2 regions. Despite that, niobium deposits exhibit a significantly higher concentration than lithium and are primarily located in the south-western regions of Spain, while lithium deposits, according to EGDI, are more evenly distributed across Portugal (which is also the largest producer, according to RMIS and S&P Global production data), Finland, the Czech Republic, and Spain. Moreover, vanadium and REEs have a similar number of deposits, but the latter are present in significantly fewer regions and exhibit some of the highest concentration values. The high

concentration of critical commodities in specific areas could increase the potential vulnerability of certain regions to social and environmental shocks.

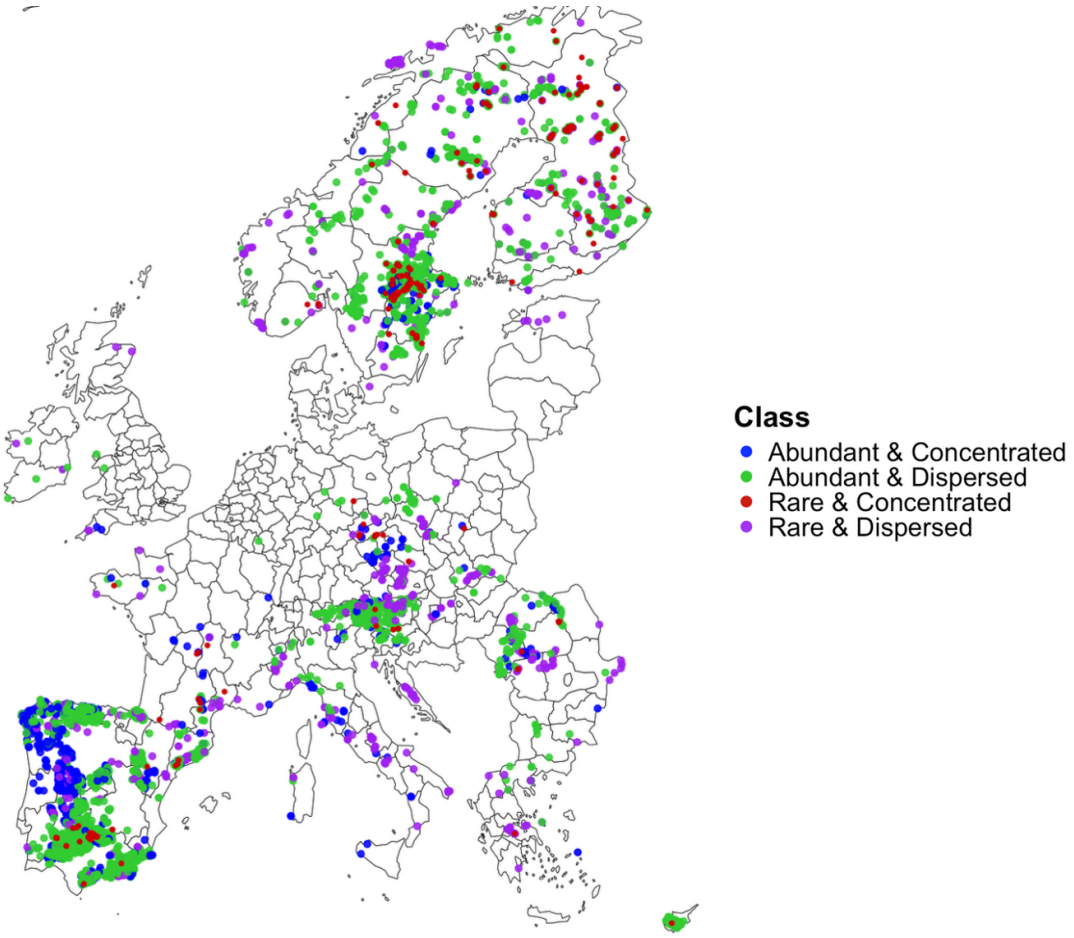
Finaly, In Figures 2.11 and 2.12, we map deposits of CRMs and SMRs, respectively, maintaining the classification into categories from Figure 2.10. "Rare & Concentrated" commodity class (in red) represent those raw materials characterized by a low number of deposits and a strong concentration in a few areas. The scattered distribution is particularly evident in Norra Mellansverige and Östra Mellansverige in Sweden, due to the presence of REE, as well as in Extremadura, Spain, which exhibits the highest concentration of strontium. Materials classify as "Abundant & Concentrated" display a scattered distribution pattern, with notable examples such as cobalt, which shows high concentrations in Eastern Finland and Sweden, and tungsten in Western Spain, both located near deposits of rarer CRMs. In Figure 2.12, we observe a distribution pattern similar to that of Figure 2.11. However, since SRMs constitute a subset of CRMs, the areas of extractive interest appear more restricted.

Figure 2.11: Maps of deposits of SCRMs (NUTS 2)



Source: own elaboration based on EGDI (2021) data.
Note: Commodity classes in Table 2.6. All raw materials of the 5th list are considered, except silicon metal. Countries: 25 (23 EU members + Switzerland, Norway), NUTS 2 = 297 regions.

Figure 2.12: Maps of deposits of CRMs (NUTS 2)



Source: own elaboration based on EGDI (2021) data.
Note: Commodity classes in Table 2.6. All SRMs are considered, except for silicon metal. Countries: 25 (23 EU members + Switzerland, Norway), NUTS 2 = 297 regions.

2.4 Discussion

2.4 Discussion The CRMA represents a bold attempt to secure a stable supply of critical and strategic raw materials. However, our analysis suggests that the strategy outlined in the CRMA is not without significant limitations, which could prevent it from achieving its ambitious independence targets. The CRMA prioritizes increasing domestic supply, but the reality is that many critical mineral resources are geographically concentrated in a few regions within Europe. For most materials, the EU also suffers from comparative disadvantages in resource endowment, which makes it advisable adopting dedicated supply programs and strategies with specific targets for them. Moreover, the uneven distribution of SRMs but also CRMs if they will be incorporated into operational strategies, may create bottlenecks that the CRMA does not fully address. The local dimension and the functioning of the mining sector have been excessively overlooked, and it is unclear whether and where the distribution and concentration of natural resources for various CRMs and SRMs meet the capacities needed for their extraction and processing. Moreover, we should also consider that even if the EU achieves its domestic extraction targets, it will still be heavily dependent on imports for most of its supply. The uncertainty surrounding mineral reserves and the availability of accurate geological data may only foster these issues making more difficult to predict whether specific regions can truly support large-scale mining operations. In areas where extraction and processing are heavily concentrated, local communities might see these activities as unfairly impacting their environment and economy, leading to resistance and opposition. This could result in environmental degradation, social conflicts, and obstacles to obtaining Social License to Operate. Without a governance that integrates the top-down approach with bottom-up actions and involvement of the regions and communities concerned, the concentration of strategic projects around MNEs, combined with the clustering of SMRs in a few regions, could foster social tensions that may hinder the exploitation of the scarce natural resources available in Europe. In areas where extraction and processing are heavily concentrated, local communities may see these activities as unfairly impacting their environment and economy, leading to resistance and opposition. Without gaining Social License to Operate, many SPs could face delays or even fail. If these structural issues remain unaddressed, the CRMA may lead to an inefficient exploitation of resources, failing to achieve its ambitious goals.

Chapter 3

The Geography of Mining: Mining Specialisation and Innovation in the European Regions

Introduction. Chapters 1 and 2 in this thesis provide an extensive analysis of the European strategy for CRMs, with a particular focus on the most recent provisions introduced by the CRMA, under the umbrella of the OSA. Although the CRMA introduces non-binding yet very precise targets, the statistics presented in Chapter 2 confirm that the EU has a structurally limited natural endowment of SCRMs compared to its major competitors. This may come alongside an even more worrying competitive disadvantage. Since the 1970s, with deindustrialisation and decarbonisation, Europe has lost a substantial part of its mining capabilities, following the closure of numerous mines. At the same time, the EU seems to have progressively lost interest in revitalising an industry that, over time, has undergone significant technological and productive transformations elsewhere in the world. Supply challenges are further amplified in the EU context, where stringent environmental standards, permitting procedures, and regulatory frameworks affect the feasibility and competitiveness of extracting mineral raw materials, among which SCRMs. With recent initiatives such as the CRMA, the EU has shown a regained interest in the sector. At the same time, the EU is neither a strong global competitive player in mining, nor one of the leading innovators in the industry. Advances in mining technologies, and their

geography, remain largely understudied at the European level, preventing a clear understanding of how the EU can support the competitiveness of the industry to expand and diversify the supply of SCRMs. This topic deserves much greater attention, especially given the potential of mining innovation not only to partly offset natural resource scarcity, but also to make mining activities more sustainable and thus more consistent with the EU's long-run energy and environmental objectives.

3.1 Overview and Motivation

The mining industry is complex and specific in its operational and managerial functioning, requiring certain conditions to work effectively. Modern mining is organized around projects, and a mine may be defined as a project itself (McKnight and Warrian, 2023). Mining projects are generally long-term and exposed to various types of uncertainty and risk. In particular, exploration activity to discover new mineral deposits is a critical and highly capital-intensive task. Developing a mine on potentially mineral-unprofitable land represents one of the most significant risks, and complex technical feasibility analyses are required to assess whether starting a mining project in a specific location can generate positive net cash flows (Kurkkio et al., 2014). Even the granting of extraction permits is conditional upon exploratory studies that must confirm the economic viability and sustainability of the project according to local regulations. Moreover, mining firms are generally subject to the payment of royalties, as well as additional environmental taxes and charges that vary depending on the specific local regulatory system[58]. After all these steps, mining projects still often require long pre-production periods before operating at full capacity, which implies that mining firms often face large-scale expenditures and that returns are realised in the long term.

For all these reasons, mining firms have long been considered capital-intensive firms operating

[58]Note: The EU does not have harmonised mining standards that regulate uniformly across Member States the administrative and legal functioning of mining permits and concessions (licensing procedures, allocation of responsibilities and liabilities, administrative steps, and fiscal/fee regimes). The EU regulatory framework is thus approximately inferred by combining general EU legislation (Directive 2011/92/EU and Directive 2006/21/EC, the most important) with national and regional legislations that specify the granting conditions, royalties, and procedures associated with mining permits, such as, for example, Spain's Mining Law (Ley 22/1973), Finland's Mining Act (Act 621/2011), or Italy's Legislative Decree No. 152/2006, Piedmont (Italy) Regional Law No. 23/2016.

in enclaves, with weak or limited forward and backward productive linkages or inter-industry technology flows, and with most innovation related to cost-cutting processes (Tilton, 2000, 2001; Bartos, 2007; Valacchi et al., 2023). As discussed in Section 3.2 below, this view has been partly reconsidered over time, following renewed interest in the sector, improved data availability, and growing environmental and social concerns. Mining firms are still not considered major technological innovators. Nevertheless, more recent contributions suggest that, despite their limited propensity to develop technologies internally, they adopt a wide range of technologies in production across different stages of the supply chain and, in this context, establish important links and networks with various entities, such as specialized external suppliers, engineering firms, and external consultants (Pietrobelli et al., 2018; Daly et al., 2019; Warrian, 2020; Daly et al., 2022; Calzada Olvera & Iizuka, 2024). 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 (Bartos, 2007; Humphreys, 2020; Daly et al., 2022).

As highlighted throughout this thesis, the acceleration of technological change has led to a sharp increase in demand for several mineral inputs, making them essential in advanced manufacturing supply chains (Abraham, 2015; European Commission, 2023a; Li et al., 2024; Diemer et al., 2025; Li & Iammarino, 2026), and this trend is expected to intensify dramatically by 2050[59]. 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-based supply chain (Bobba et al., 2020; Carrara et al., 2023; European Commission, 2023a; European Commission, 2023b; IEA, 2024). In this context, technological progress in mining plays a crucial role. Innovation in extraction methods, automation, digital monitoring

[59]For instance, Bobba et al. (2020) scenarios estimate that, for renewable energy and e-mobility applications alone, the EU demand could increase by up to around 60 times current consumption levels for lithium, roughly 14 times for graphite, about 12 times for dysprosium, and up to 15 times for cobalt, by 2050. A similar pattern applies to aluminium, copper, and nickel: according to the World Bank (2020), the global demand for these base metals from the renewable energy sector is projected to increase by 322%, 213%, and 76%, respectively.

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.

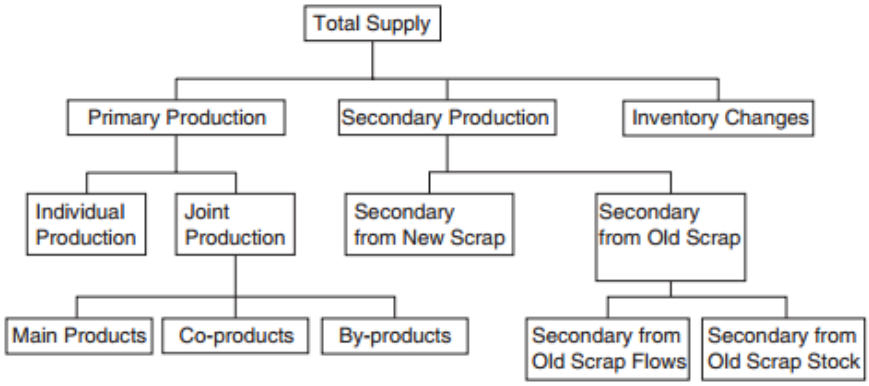
The EU's renewed interest in the mining sector is strongly—if not almost exclusively—driven by the issue of SCRMs. However, especially for SRMs, the key production constraint often lies not in the existence of a natural resource base, but in the ability to extract and process raw materials under viable regulations and at competitive costs, even where the natural resource endowment is relatively strong. First, it is necessary to clarify that even though these materials are highly valued, their demand in absolute terms is often far from sufficient to justify the investment required for a dedicated mine. The economic problem of mining production tends not to be examined from the supply side very often. Some mineral inputs (especially CRMs) are used in manufacturing in very small quantities. These are often metals that, because of their technical and chemical-mechanical properties, currently have few viable substitutes, which makes their demand highly price-inelastic (Tilton & Guzman, 2016), reflecting both the lack of substitutes and the fact that their use in absolute terms as input in manufacturing is extremely limited yet essential[60]. This low substitutability originates in downstream manufacturing demand, where these metals often serve as non-replicable and non-substitutable inputs. Because manufacturers require them as essential inputs, this gives rise to derived demand along the upstream segments of the value chain, affecting refined materials, metallurgical products, and ultimately concentrates and ores produced by the mining sector.

Absolute quantities demanded for SCRMs vary substantially, ranging from base metals such as aluminum and copper, to REEs and PGMs which, unlike the former, are unlikely to be produced as primary commodities[61]. To understand this point, it is useful to take a closer look at the supply side of mineral economics, which Tilton & Guzman (2016) explain with great clarity. Figure 3.1 reports the authors' schematic representation of the sources of supply for mineral commodities.

[60]For instance, on average, a doubling or tripling of the price of lead or platinum, raises the cost of producing automobiles by less than 1 percent (Tilton & Guzman, 2016)

[61]According to RMIS, global primary production of unrefined HREEs amounted to around 32,000 tonnes in 2021, while LREE production reached around 248 000 tonnes, whereas Platinum production was about 183 tonnes in 2022. By comparison, global copper mine production amounted to about 22.2 million tonnes in 2021, while bauxite production (primary aluminum) reached about 396.8 million tonnes in the same year.

Figure 3.1: Sources of supply for mineral commodities



Source: Tilton & Guzman (2016).

The authors distinguish the total supply[62] into primary and secondary production. Primary production consists of extraction of minerals from the earth and processing and refining (i.e. final metallurgic transformation of the commodity into input for other manufacturing industries). Secondary production involves the collection and recycling of materials that have already been used at least once in manufacturing production processes. Primary production can be further divided, as regards the mining stages, into main products, co-products, and by-products[63]. As shown in Figure 3.1, individual products, main products, co-products, by-products, and secondary production output from new and old scrap are all potential contributors to a mineral product's total supply.

By definition, a main product (commodity) is essential to the mine's economic viability, such that its price by itself drives the quantity of ore the mine chooses to extract. If the prices of two or more jointly produced commodities influence that extraction decision, those commodities are co-products. A by-product, in contrast, contributes so little to the mine's overall profitability that changes in its price do not affect the mine's ore output. As a result, by-products can

[62]The authors refer to total supply, as the market supply that encompasses supply from all sellers and it is formed adding horizontally all their individual supply curves.

[63]By-product minerals are commodities recovered during the extraction and processing of a main commodity (or co-products), and their supply depends primarily on that of the associated product. They are produced because they are physically contained in the same ore or process stream and are recovered only when extraction and processing of the main commodity take place. For instance, Cobalt is commonly produced as a by-product of copper or nickel mining, indium is mainly produced as a by-product of zinc (Nassar et al., 2015).

only be obtained in association with either a main product or a set of co-products. Moreover, when joint production occurs, main products, co-products, and by-products may be recovered, creating a connection between primary production and secondary production. Following a basic microeconomic reasoning, advances in technology that reduce mining and processing costs can clearly affect mineral supply, but in the case of by-products the implications are more nuanced. By-product supply is constrained by the output of the associated main product (or co-products). For example, the amount of molybdenum that can be recovered as a by-product of copper mining cannot be greater than the molybdenum physically contained in the copper ore that is extracted (by-product constraint). The by-product constraint shifts in response to changes in the demand and supply of the main product, so a change in the price of the main commodity leads to a movement along its supply curve, but also a shift in the by-product constraint. In this case the by-product constraint moves outward potentially increasing the by-product's availability if its price covers the additional recovery and processing costs, even if nothing changes in the by-product's production recovery technology. At the same time, more advanced processing techniques can both relax the by-product constraint—by allowing a greater share of the by-product to be recovered from a given amount of ore—and improve economic viability by lowering unit recovery and processing costs. This can make it profitable to produce additional by-product units and, in some cases, even turn the mining of a specific commodity into a feasible operation when it was not previously profitable. In other words, technological progress can effectively "create" new reserves: under certain conditions, it makes a geological mineral resource more profitable to extract and process. In doing so, it can partly offset the tendency for a deposit to become more difficult (and more expensive) to exploit as extraction proceeds, and it can delay the need to explore and develop new mining areas—bringing potential economic and environmental advantages. This applies both to base metals and to by-products—including many critical materials such as PGM and REEs, but it is especially true for the latter which can also benefit indirectly from an expansion in the supply of the main commodities. Beyond this, some technologies can directly reduce environmental impacts both at the extraction and processing stages, improve worker safety through automation and remote operation, and enable more effective identification and targeting of new resource rich areas. Innovation in mining may therefore be viewed as a way to align strategic geopolitical targets with development and environmental goals.

However, over the last decades, the EU's response to new 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 an industry that has undergone major technological and productive transformations elsewhere in the world. Some countries have long relied on active policy intervention to support the production of SCRMs. China represents the most prominent example, having deployed a wide range of industrial policy instruments, investing considerably in technological innovation, but in several cases involving unfair practices with significant negative social and environmental impacts[64]. Different forms of industrial policy have also been adopted by the US, Canada, and Australia to support domestic CRM industries and strengthen supply-chain resilience. The US support has been strengthened through measures such as the Inflation Reduction Act, the Defense Production Act, and the Bipartisan Infrastructure Law. Canada has promoted CRM extraction and production through its Canadian Critical Minerals Strategy, while Australia has relied on initiatives such as the Critical Minerals Strategy and the Critical Minerals Facility.

With recent initiatives such as the CRMA, also the EU has shown a regained interest in the industry (see Chapter 1). Although industrial policy is a central component of the EU's OSA, so far it takes mainly the form of coordinating incentives designed to attract business investment. The territorial implications of this approach have been largely disregarded in the literature and deserve closer attention CRMA policies, which are largely project-based, may affect the geography of mining production, especially in geologically endowed areas where mining firms tend to concentrate production facilities. As Anzolin & Pietrobelli (2025) suggests, industrial policy in mining should not target mining as a single, undifferentiated industry. Rather, it should focus on specific tasks and segments of the mining value chain where technological, organizational, and skills upgrading is feasible, and where stronger linkages with the rest of the economy can be built. Otherwise, the risk of an "enclave" outcome is higher, with extractive activities that

[64]China, has historically supported domestic production of REEs and other minerals through relatively lenient environmental rules (Mancheri, 2015; Tilton & Guzman, 2016; Humphreys, 2020; https://www.reuters.com/world/china/how-china-tightened-its-grip-over-its-rare-earth-sector-2025-07-07/). China has also extended this strategy internationally, using outward investment, ownership of mining assets and downstream processing projects to consolidate its position across SCRM supply chains. OECD (2025) identifies this as one of the mechanisms behind China's dominance in the extraction and processing of several CRMs: Chinese investors dominated downstream processing investments in the DRC and Indonesia, while Zimbabwe's restrictions on primary lithium exports were accompanied by announcements of increased Chinese investment in downstream processing.

may expand but remain weakly integrated in the local economic system. This typically translates into limited local value added, greater dependence on geology and commodity-price cycles, and incentives that are less effective at generating skills and promoting innovation flows and networks. As a result, a policy-driven increase in mining projects may expand production capacity without necessarily strengthening the local technological base and competitiveness, while intensifying social and environmental pressures without a compensating payoff.

3.1.1 Mining Specialisation and Regional Innovation: Conceptual Framework

The geography of mining technologies and the factors driving technological development remain largely understudied at the European level, as does the extent to which mining innovation is embedded in the industry. This limits a clear understanding of how the EU's industrial-policy approach to CRM centred on incentives, SPs, and supply-side capacity expansion can foster innovation in mining and enhance its potential to expand and diversify the supply of SCRMs. Addressing this gaps require going beyond the location of mineral resources or the emergence of new mining projects (explored in Chapter 2), and instead requires accounting for the sector-specific territorial components that may support technological development.

The territorial dimension is particularly important because mining firms tend to locate where mineral resources are found and may therefore cluster spatially. Indeed, mining firms can be considered resource-dependent industries in the sense of Porter (2003), and resource-dependent firms tend to locate close to the source of their inputs (Loesch, 1954; Fuchs, 1962). The key point in the analysis does not investigate whether extractive firms locate close to natural resources; we assume this as starting point. A substantial body of literature draws on agglomeration theory to explain why economic and innovative activities tend to concentrate in particular places. Particularly, Marshall (1890) identifies three factors favoring geographic concentration of industries: 1) the pooling of demands for specialized labor; 2) the development of specialised intermediate goods industries; and 3) knowledge spillovers among the firms in an industry. Later, authors such as Arrow (1962) argued that technological progress should not be treated merely as an exogenous variable that increases over time. Knowledge is acquired through experience: by

engaging in productive activities, firms and workers encounter new problems, discover solutions, and gradually become more efficient. Economic growth theorists in the 1980s and 1990s focused attention on the role of knowledge capital in aggregate growth. Romer (1986) and Romer (1990) incorporated the role of knowledge into endogenous growth models, in which knowledge accumulation became a central mechanism for explaining long-run economic growth.

The contributions of Marshall, Arrow, and Romer were brought together by Glaeser et al. (1992), who introduced the concept of Marshall–Arrow–Romer (MAR) externalities. MAR externalities refer to knowledge spillovers among geographically concentrated firms operating within the same industry. Marshall emphasized the advantages generated by industrial localization, Arrow formalized the accumulation of knowledge through learning by doing, and Romer showed how knowledge spillovers can generate increasing returns and sustain endogenous economic growth. The MAR hypothesis predicts that industries grow faster in cities where firms from the same sector are highly concentrated, since geographical proximity facilitates within-industry knowledge spillovers[65]. As Jaffe et al. (1993) point out, one of the main challenges in testing for the geographical localisation of knowledge spillovers is distinguishing genuine spillover effects from correlations driven by pre-existing spatial concentrations. Indeed, as discussed above, other agglomeration mechanisms may also account for the geographical concentration of technologically related activities. This distinction is central to Audretsch and Feldman (1996), who provide some of the earliest evidence that the co-location of production activities alone cannot explain innovation clustering and that proximity to knowledge inputs also matters. They find that innovation is more spatially concentrated in industries where industrial R&D, skilled labour, and university research play a greater role, even after controlling for both the geographical concentration of production and industry dependence on natural resources, measured as the share of inputs purchased from mining and agriculture.

Following the previous literature, the spatial concentration of related activities can generate local external economies through specialised labour markets, supplier linkages, and knowledge spillovers. In the MAR view of localisation economies, industry concentration may support

[65]This theory contrasts with Jacobs (1969), who argues that the most important knowledge spillovers occur across different industries. From this perspective, a diversified urban economy increases the range of ideas, skills, suppliers, customers, and productive activities that can be brought together in novel ways

innovation by facilitating intra-industry learning and reducing communication and transaction costs among actors engaged in similar activities (Glaeser et al., 1992; Audretsch & Feldman, 1996). However, based on the literature reviewed in Section 3.2, and on the evidence provided in this work, the concentration of mining extraction activities does not appear to translate into stronger local innovation in mining technologies. The concentration of mining firms is primarily determined by the presence of natural resource endowments, rather than by competitive advantages built through local capabilities, specialized suppliers, knowledge spillovers, or innovation networks. By contrast, technological development in mining is frequently carried out by specialised suppliers, engineering firms, equipment producers, and mining-related service providers, rather than by extraction firms themselves. As a result, regions specialised in mining extraction may generate operational needs and demand for technological solutions, but this does not necessarily translate into local patenting activity if the relevant innovation capabilities are located elsewhere.

This interpretation is consistent with the geography of innovation literature in light of the distinction between where extractive activities take place and where mining technologies are developed. Innovation does not necessarily occur where production takes place; rather it tends to emerge where knowledge inputs and innovative capabilities are locally available, such as industry R&D, university research, skilled labour, and specialised technological expertise (Audretsch and Feldman, 1996). Moreover, localisation economies based on narrow industry specialisation may be fragile and losing their productivity-enhancing effects over time when they remain isolated (Glaeser et al., 1992; Porter, 2003; Delgado et al., 2014). If the same industry is embedded in a strong cluster of related activities, specialization can foster innovation by generating complementarities across firms, supplier linkages, shared skills, and knowledge spillovers (Glaeser et al., 1992; Porter, 2003; Frenken & Boschma, 2007; Delgado et al., 2014). In such contexts, proximity among firms, suppliers, and specialised workers can facilitate technological spillovers and foster operational problem-solving, cumulative learning, and the adaptation of technological solutions to production needs (Jaffe et al., 1993; Audretsch & Feldman, 1996; Porter, 2003; Delgado et al., 2014).

This discussion also establishes an important connection with the innovation-systems approach.

Spatial proximity may facilitate knowledge exchange, but innovation also depends on the broader configuration of actors, institutions, and relationships through which knowledge is produced, diffused, and used. Lundvall (1992) conceptualises a national innovation system (NIS) as the set of actors, institutions, and relationships involved in these processes. These components shape the competences available in an economy, the incentives to invest in innovation, and the direction and intensity of learning. The definition of an NIS therefore encompasses different factors that influence the development, diffusion, and use of innovations, including not only R&D but also education, training, finance, demand, public policy, the productive structure, norms, and relationships among actors (Edquist, 1997). Extending this perspective to the subnational level, Cooke (1997) argues that important differences in learning processes, institutional capacity, and innovative performance may exist across regions within the same country. A regional innovation system therefore consists not simply of firms located in the same territory, but of the organisations, institutions, and relationships that support the production, diffusion, and application of knowledge. As discussed below, regional specialisation in extractive mining and mining services is only weakly correlated, suggesting that the two activities tend to be concentrated in different regions and may therefore be embedded in different RIS and associated with different innovative outputs.

The empirical relationships examined in this chapter may arise through several complementary and potentially interacting mechanisms. First, historical industrial specialisation may generate path-dependent stocks of skills, organisational routines, supplier capabilities, and inter-firm relationships. However, these cumulative processes need not develop in the same way across extractive and service activities. A long-standing concentration of extraction may primarily reflect the continued exploitation of local deposits, whereas regions hosting specialised service providers may accumulate engineering expertise and technological capabilities through repeated interaction with different mining clients

Second, regional innovation capacity may determine whether operational needs are transformed into patentable technologies. R&D, human capital, university research, absorptive capacity, and relationships between firms and knowledge organisations can facilitate the development, adaptation, and diffusion of new technologies. Institutional conditions may also influence these processes by shaping incentives, access to finance, public support, collaboration, and the

effectiveness of intermediary organisations.

These mechanisms provide a possible explanation for the empirical distinction between extractive and mining-service specialisation. Extractive firms may generate operational problems and demand for technological solutions, while specialised service providers translate these needs into engineering and technological outputs. Since service providers may operate across multiple regions, the same mechanism may also generate interregional relationships in patenting activity. However, the empirical analysis does not directly observe historical capability accumulation, supplier–client relationships, or institutional quality, and therefore cannot distinguish their respective contributions. These channels should consequently be interpreted as theoretically grounded explanations consistent with the results, rather than as separately identified causal mechanisms.

In this chapter, we aim to provide further insight into the regional dynamics of mining innovation by analysing the relationship between mining specialisation in European regions and the development of mining technologies. We rely on the WIPO mining patent classification to identify inventions connected to the mining supply chain, and we use PATSTAT (2024) to replicate their methodology and construct a mining patent dataset. Combining PATSTAT with the WIPO methodology, it is also possible to group these identified mining technologies into nine different classes: Exploration, Blasting, Mining Operations, Transport, Automation, Environmental, Processing, Metallurgy, and Refining[66], and to map them across European regions. Considering different classes 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 CRMs, 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.

[66]Note, as said in Chapter 2, metallurgy and refining are the manufacturing stages of the production process that transforms commodity into inputs. The output of operations in extraction and processing is generally assigned to the mining industry, as codified in the NACE classification (NACE Rev. 2, Section B: Mining and quarrying). In the extraction stage, the material is extracted from the ground; the processing stage refers to ore separation and concentration, typically carried out in smelters and concentrators operated by mining companies. On the other hand, refining activities—i.e., those that start from processed ore and culminate in the production of tradable metal products/inputs—fall under the manufacturing industry, NACE Rev. 2, Division 24 (C24): Manufacture of basic metals. However, here we refer to technologies, which do not correspond to industry classifications: thus, we include all those technologies important for the SCRM supply chain, referring generically to them as "mining technologies".

Our empirical analysis tests three related hypotheses. First, it examines whether specialisation in extraction activities and/or specialisation in mining services affects the regional development of mining technologies. Mining patenting is expected to be positively associated with specialisation in mining services, but not systematically with specialisation in extractive activities. This differential relationship is expected because mining-service specialisation more directly reflects the presence of specialised technological capabilities, whereas extractive specialisation primarily reflects the location of mining production under geological constraints.

Second, it investigates whether these relationships vary across different types of mining technologies associated with different stages of the mining supply chain. Mining technologies are heterogeneous in terms of their knowledge bases, applications, and position along the mining value chain. Exploration and Mining Operations technologies are more directly connected to the technical and site-specific requirements of extractive activities, whereas other classes draw on broader engineering, digital, environmental, and manufacturing capabilities. Consequently, the relative importance of extractive and mining-service specialisation may differ across technology classes.

Third, it examines whether mining specialisation generates spatial spillover effects across neighbouring regions. This is particularly relevant for specialised service providers, which are less directly tied to the location of mineral deposits than extraction firms and may serve mining operations beyond their own region.

The results provide no evidence that greater specialisation in mining extraction activities increases mining patenting per capita. By contrast, we find a strong positive effect of specialisation in mining services on mining technological development across European regions, and across the different classes of mining technologies identified by WIPO. The heterogeneity analysis across technology classes does not reveal any differentiated effect of mining extraction specialisation. This variable is never positive and statistically significant, even for technologies more directly related to upstream extraction processes. Conversely, specialisation in mining services is positive and statistically significant for almost all technology classes, suggesting that mining technological development is more closely linked to service-based capabilities than to extraction activities per se. Finally, the spatial results show that this relationship is not purely local. The indirect effects

of LQs are positive, sizeable, and statistically significant across all specifications that include spatial lags of the explanatory variables, while no comparable evidence emerges for mining extraction specialisation.

The chapter proceeds as follows. Section 3.2 presents a literature review on the mining industry and mining technologies. Section 3.3 introduces the theoretical framework. Section 3.4 is dedicated to the data analysis. Section 3.5 reports the econometric results. Section 3.6 concludes.

3.2 Literature review

The mining industry has frequently been portrayed as a slow innovator and as an enclave activity where, even when relationships with suppliers exist, they are often of foreign origin, with limited local spillover effects (Dietsche, 2014). However, as argued by Pietrobelli et al. (2018), this pessimistic view has recently been challenged, and different contributions (analysed throughout this Section) suggest that the mining industry can create new opportunities for innovative linkages between leading companies and their suppliers, promote economic diversification, and generate knowledge-intensive jobs if supported by institutions and policy intervention. Even today, a widespread pessimistic perception of the sector as conservative and resistant to change persists.

Reviewing the literature on innovation in mining is not straightforward. The industry has changed substantially over the last century, as have the analytical and theoretical approaches used to study it. Much of the pre-Tilton work (1950s–1970s) refers to studies that were never digitalised, and for a long period—from Hotelling's seminal contribution in 1931 through to almost the late 1960s—discussions on mining productivity were primarily approached through an engineering lens. More recently, some empirical studies applying robust quantitative methodologies have emerged, but they are still limited. This gap is not confined to the European context (where contributions are almost entirely absent) but represents a broader limitation in the economic literature, where, despite several important studies, a general understanding of the innovation mechanisms specific to the industry has yet to emerge.

3.2.1 Traditional Approaches to Mining Productivity Determinants

As highlighted by Tilton (2000), according to the traditional approach, resource endowment was the overriding determinant of competitiveness in mining, while all other factors play only a secondary role. From this perspective, new technologies have only a limited impact. Production processes changed very little over time, which means that mines, companies, and countries have few opportunities to use new technologies to gain a cost advantage. The beginnings of this traditional view can be traced as far back as Hotelling (1931). In Hotelling's framework, the exploitation of exhaustible resources is characterized by rising marginal costs as the resource is depleted and becomes less accessible. However, Hotelling does not address key features of mining, such as ore grade, variations in mineral quality, or the role of extraction technology. In fact, his primary objective was not to explain the behaviour of the mining industry, but rather to derive a general rule for the optimal exploitation of exhaustible resources over time. Hotelling's contribution later inspired a range of reinterpretations and applications to extractive and mining activities. These extensions generally preserved a geological-determinist view, emphasizing resource endowment as the primary driver of performance and competitiveness in the sector. Peele (1941) provides one of the earliest systematic discussions of rising extraction costs in mining. Although not formulated as an economic theory, Peele shows that costs tend to increase as the ore body becomes deeper, more difficult to access, or lower in grade, because more rock must be handled and additional support, hoisting, ventilation, and processing efforts are required. Furthermore, according to Cummins & Given (1973), in the first edition of the SME Mining Engineering Handbook, geology is considered the primary determinant of mining productivity and costs. Geological conditions—such as rock mechanics, deposit geometry, and degree of fracturing—influence the choice of mining methods and directly affect operational efficiency; geological characteristics are presented as the foundational constraints that shape both the feasibility and the cost structure of mining operations. Although the role of technological advancement has never been dismissed, it is generally considered only in relation to the geological challenges that need to be overcome. In Barnett & Morse (1963), technological innovation operates primarily as a compensatory force against geological constraints on resource extraction, but only partially. This perspective is very similar to Hartman (1987), another

technical–engineering contribution. Hartman identifies geological characteristics of the deposit (such as depth, thickness, and geometry), the extraction and processing technologies employed, the efficiency of transport and ventilation systems, the organization of work, sequencing, and mine layout, as well as operating conditions and safety, as key determinants of mining productivity. However, these determinants only gradually evolve and remain largely constrained by the nature of the deposit itself, which limits the potential impact of innovation. According to Hartman (1987, 1992), innovation is therefore portrayed as gradual and mainly directed toward cost efficiency, operational optimisation, and improved safety, rather than as a transformative force.

3.2.2 From reserves to institutions and technology

Another milestone in the approach to studying the role of innovation and technological advancement in resource extraction comes from Hartwick (1977), Hartwick and Olewiler (1986), and Hartwick (1990). With Hartwick, geology is no longer an absolute constraint. According to what is now known as the Hartwick Rule, if the rents generated by exhaustible resources are properly reinvested in reproducible capital, the economy can, in principle, maintain constant consumption over time, even as the physical stock of resources diminishes. Although Hartwick's work, like Hotelling's, does not speak directly about the mining industry and is mostly a theoretical contribution on optimal depletion, his approach opens the door to a reinterpretation of how capital accumulation and technological progress can help compensate for declining natural resource endowments. A clear break from the traditional view of non-renewable resource stocks comes with Adelman (1990, 1993). Unlike the physical resource in the ground, "reserves" are not a fixed geological quantity. Instead, they are the outcome of several economic and technological factors. In Adelman's view, reserves depend on investment, prices, technology, and the industrial organization of the extractive sector.

These forces continuously change which part of the deposit is economically recoverable, meaning that the "quality" of a deposit is not only a geological fact, but also the result of economic conditions and technical progress. This perspective is very well connected with the point of view of McKelvey (1972), who stresses the need to identify the economically recoverable portion of mineral resources so that policy and economic decisions can be based on correct estimates

of the potential mineral endowment. The distinction between resources and reserves, already introduced in Chapter 2, does not originate with Adelman, but is now included in a dynamic economic construct redefining the concept of scarcity and changes in the supply of non-renewable resources. The idea of an economically relevant stock of resources was already clearly and formally defined by mining agencies, in particular by the U.S. Bureau of Mines & USGS (1980). Yet, also Hotelling (1931), in his model, assumes a well-known and defined stock of natural resources; therefore, even the earliest models of optimal resource exploitation needed to work with clearly identified stocks to extract. The existence of factors that determine which portion of resources is economically exploitable means that the economic potential of the deposit is not only a geological fact, but also the outcome of economic conditions and technical progress, as well as price expectations and discounting (Miller & Upton, 1985a, 1985b). So, natural endowment is not only geologically determined, but also the result of the economic system capacity.

The emergence of modern mineral economics can perhaps be traced to Tilton's works in the 1990s, which are often characterized by a more empirical approach to the study of mining industries. In his contributions, we find confirmation that reserves tend to increase over time even when the underlying resource stock remains unchanged, and that the extraction costs of many minerals do not necessarily rise in line with geological depletion. Up to that point, the focus of the literature had been less on the mining industry itself and more on the optimal depletion of exhaustible resources, a field shaped by contributions coming from different extractive activities, but dominated by oil and gas studies (see, for instance, Miller & Upton, 1985a, 1985b). The most significant break with the traditional perspective comes from Tilton & Landsberg's (1997, 1999) work on the U.S. copper industry. Before this, Tilton had already examined the copper market, the decline of the U.S. mining industry (Hutchison & Tilton, 1987; Tilton, 1989; Radetzki & Tilton, 1992), and how comparative advantage in mining depends on institutions and technology (Tilton, 1992). Tilton & Landsberg (1997, 1999) provide some of the first comprehensive empirical evidence on how technological progress in mining compensates for declining ore grades and falling prices. In 1970, the US was the world's largest producer of copper, and mines and milling plants employed 37,000 people. However, from 1975 onward, the US copper mining industry fell into a deep recession that persisted for over a decade due to strong global competition (Chile, Australia, Canada) and energy shocks that increased operating costs. Many

companies, including Amoco Minerals, Arco/Anaconda, Cities Service, and Louisiana Land and Exploration, left the industry, and employment in copper mining decreased by 70%. However, in 1995, the world share of U.S. copper production rose again to its 1975 level (though still below its 1970 level). How did the U.S. copper industry manage to re-establish its global competitiveness? Curiously, the recovery of U.S. mining firms was not the result of the discovery of new profitable deposits, but was driven by a sharp increase in productivity, which allowed existing operations to remain competitive despite declining ore grades and price fluctuations. What happened is that the U.S. copper industry restored its competitiveness by radically boosting its productivity in the 1980s without a significant increase in copper resource endowment in that period. According to the authors, this jump in productivity was largely the result of innovative activity and new technology. One particularly important development was the increasing use of solvent extraction-electrowinning (SX-EW) technology, as well as other technologies able to recover, extract or process other materials as co- and by-products, along with copper. This view is also confirmed by Porter & Thomas (1988), who estimate that the new mine plans significantly reduced the amount of waste that had to be removed for each ton of ore mined at the Morenci and Bingham mines. Moreover, according to the authors, the concentration of U.S. commodity production in a smaller number of large mines produced savings from economies of scale. In order to stay competitive, mining firms were required to operate more efficiently, and finding and developing high-quality deposits was just one possible way to lower costs and increase productivity (Tilton & Landsberg, 1997, 1999; Tilton, 2000, 2001).

3.2.3 Innovation in the Mining Value Chain: Contemporary Empirical Works

As already extensively discussed above and in Chapter 2, the production of mineral commodities takes place across different stages, ranging from the discovery of the mineral deposit to the extraction of the mineral ore and its separation from waste—activities carried out by the mining sector—and to the refining of ores into marketable products, which is mostly performed by the metallurgical sector. These materials are then used by other manufacturing firms as material inputs in their production processes. Daly et al. (2019) were the first to synthesize a

comprehensive categorization of the technologies required across the entire supply chain. The strength of this approach lies in the fact that it is accompanied by a methodology for classifying patents based on keywords and IPC/CPC codes (see Section 3.3.1 for details). In recent years, several contributions have relied on this methodology to carry out empirical analyses. What emerges from the recent empirical literature mainly consists of evidence that firms' innovative behaviour is affected by commodity price fluctuations, and that technological advancement in the extraction and production of mineral commodities is largely driven by firms not directly involved in extractive activities, but specialised in mining equipment and services, known as Mining Equipment, Technology and Services (METS). Valacchi et al. (2023)[67] use the same classification and database to analyse the evolution of technological innovation in the mining industry, focusing on how innovation responds to changes in commodity prices. They rely on a multisource firm-level patent database covering mining companies and METS firms from 1970 to 2015, across 127 countries. They find empirical evidence that patent intensity is affected by changes in commodity prices, especially over long cycles, with METS firms driving this phenomenon and reacting more strongly to price cycles. The analysis also shows that, in less specialized countries, mining sectors are more sensitive to changes in prices, probably because METS firms are less tied to the production processes of mining companies and tend to establish themselves in more diversified economies. Countries more exposed to mining on the basis of mineral rents as a percentage of GDP produce more technological innovation, but they are less reactive than less exposed economies and show statistical evidence only of reacting to long cycles. Calzada Olvera & Iizuka (2024) analyse how commodity price fluctuations and firm profits are related to innovation patterns in mining sectors and whether mineral price decline increases linkages between mining firms and other suppliers. Using standard input-output data covering 66 developed and developing economies over the period 1970–2015, the authors find evidence that when the price of mineral commodities rises, innovation, measured by R&D and patents for mining exploration, increases; when prices decline, mining firms' linkages with suppliers for innovation rise as a way for mining firms to improve efficiency and maintain profit margins. This suggests that mining firms tend to pursue expansionary strategies when commodity prices are higher, increasing exploration efforts to secure new deposits and extend future production

[67] Note that they are the same authors of Daly et al. (2019).

capacity. In contrast, when prices fall, mining firms face stronger pressure to defend profitability: they respond by intensifying cost-saving measures and relying more on external suppliers. This latter dynamic resumes the Tilton's (2014) idea that, when prices are high, mining firms have more resources to experiment and invest, but they also tend to focus on expansion and higher volumes, even at the risk of reducing efficiency improvements. Fernandez (2021), utilizing the framework established by Daly et al. (2019), carries out an empirical analysis based on WIPO mining patent families filed by firms between 1970 and 2018. The empirical findings show that important drivers of mining patent families are mineral prices, production, and overall patenting performance. The impact of price cyclicality on mining activity and innovation, as should be clear by now, is a widely felt concern and certainly one of the most empirically studied issues in the field. Price volatility directly affects the value of the project and can cause permanent or temporary interruptions of production activity, but this also depends on exposure to geological factors, macroeconomic trade dynamics, and changes in tax rules (Costa Lima & Suslick, 2006; Valacchi et al., 2023). Furthermore, it should be noted that many mining companies operate primarily as price-takers, as the prices of most commodities are determined externally by the London Metal Exchange (LME)[68] (Filippou & King, 2011; Daly et al., 2019; McKnight & Warrian, 2023).

Other contributions, instead, look for the determinants of mining innovation in the sustainability push. Yamashita & Fujii (2022) explore the key driving factors for innovation in the mining, mineral processing, and metals processing sectors concerning climate change mitigation technology (CCMT), using the WIPO patent database covering the period from 2001 to 2016. General results indicate that the Paris Agreement has contributed to a general increase in the prioritization of CCMT around the world. In any case, the analysis identifies three main trends: (1) in the U.S., Europe, Latin America, and Australia, the increase in CCMT patents has primarily been facilitated by the increase in R&D priority for mining technologies; (2) in Japan and South Africa, the rise in CCMT patents has been mainly driven by a general shift in CCMT priority despite

[68]This is true for the most commonly traded commodities, but it does not apply to many SCRMs. The LME covers a broad set of contract for a list of metals: this list can be grouped as follows: 1) non-ferrous metals: including aluminium, aluminium alloy, NASAAC, copper, zinc, lead, nickel, tin, and aluminium premiums; 2) ferrous metals: including steel scrap, steel rebar, steel HRC, and steel billet; 3) EV and battery metals: including cobalt, Cobalt Fastmarkets MB, lithium hydroxide CIF Fastmarkets MB, and Molybdenum Platts. However, contracts for these commodities are not all equivalent in nature: some products are physically deliverable, while others are cash-settled futures or contracts linked to external price assessments.

a general reduction in the overall scale of R&D activities; (3) in China and other countries, the increase in CCMT patents mainly depends on a general increase in R&D activities in the period. Endl et al. (2021), in one of the few works focused on Europe, provide a comprehensive analysis of innovation trends in the European mining industry, examining their potential to contribute to the United Nations Sustainable Development Goals (SDGs). The study highlights the dual nature of mining innovations, which can simultaneously foster economic growth and address environmental and social concerns, while also pointing out potential trade-offs and synergies between different SDGs. The authors emphasize the importance of a holistic approach to sustainability, considering both direct and indirect impacts of technological advancements in mining. A particularly interesting strand of the literature—often much more discursive and based on qualitative methods—links innovation in the mining industry to its industrial structure, to the changes it has undergone and is still undergoing, and to the actors actively involved in the development of mining technologies. The fragmented nature of the mining innovation system is considered by Warrian (2020), who posits that, over time, the mining sector has evolved from being driven by internal R&D within vertically integrated corporations to a more distributed innovation ecosystem. This transition from a vertically integrated corporate structure to a more networked innovation system led to a redistribution of R&D activities across various entities, such as specialized engineering firms and external consultants. The shift from a vertical supply chain to a more decentralized system is also discussed in Warrian and Mulhern (2009), with a focus on Canadian clusters involving not only mining and METS firms, but also automotive steel, automotive parts, and aerospace. This point is consistent with Calzada Olvera & Iizuka (2024) for which R&D activities in mining are often limited by economic conditions, structural challenges, and a preference for supplier-driven technological solutions. The industry's dependence on external suppliers for technological solutions diminishes the motivation for companies to invest in their own R&D. This situation is exacerbated by the fact that many innovations within the industry are tailored to specific contexts and therefore not widely transferable, which further discourages significant R&D investment. Long-term uncertain returns on R&D investments can also be a source of discouragement. In any case, the decline in corporate R&D budgets may lead to global technological collaboration[69] (GTC), with a shift from basic research to more

[69]GTC between firms must be referred to the phenomenon of techno-globalism and is defined by Archibugi & Michie (1995) as a practice between firms *"... sharing know-how with competitors from different countries, along*

applied and experimental research. Upstill & Hall (2007) share this view in a descriptive study on the Australian mining industry, highlighting how the decline in corporate R&D budgets from 1998 to 2005 fostered global collaboration, greater adoption of ICT, and changes in innovation strategies. Alessandri (2023) analyses technological change in the mining industry between 1970 and 2015 by utilizing patent citation networks, with data sourced from the WIPO mining dataset and the PATSTAT dataset for patent citations; the study follows Daly et al. (2019) in classifying sub-technological fields. The findings reveal that innovation patterns in the mining sector are predominantly driven by patenting activities within a narrow range of technological fields. However, the study highlights the emergence of a noticeable shift from exploration technologies to those focused on the environmental aspects of mining. Additionally, the research confirms that a small number of applicant firms are responsible for most inventive activities, reflecting a highly concentrated and oligopolistic structure in the industry. The study also identifies several technological clusters within mining that can be mapped onto different tasks along the mining value chain (upstream, downstream, and mining-related services), reinforcing the need to analyse mining innovation in a disaggregated way.

3.3 Empirical Framework and Econometric Approach

As discussed in Section 3.1, we investigate the relationship between mining specialisation and the development of mining technologies. Using the Autumn 2024 PATSTAT release, we successfully geolocated 12,266 patent families[70], restricting the sample to families that include at least one granted patent[71]. We prefer counting patent families rather than a simple patent count in order to avoid double-counting patent applications filed at different patent offices but referring to the same invention. All patent families in this analysis are geolocated across NUTS 2 using applicants[72]' locations. For this purpose, we rely on PATSTAT (2024), which provides a specific

with a parallel process of international collaboration between governments and academic institutions".

[70] A patent family is a group of patent applications relating to the same invention, linked through one or more common priority filings (e.g., filings in multiple countries that stem from the same original priority application).

[71] When the patent is unassigned, and therefore not granted, rights to the invention are not still granted to a legal entity.

[72] In PATSTAT, applicants are the legal entities or individuals listed as the filers (assignees) of a patent application at the time of filing. They should be distinguished from inventors, who are the persons credited with creating the invention.

identifier, (*docdb_family_id*), that groups all patent applications corresponding to the same invention under a unique code. The choice to geolocate patent families by applicant reflects both the analytical focus of the chapter and data-quality considerations. The applicant is the legal entity to which the patent application and its associated rights are assigned. Applicant location therefore identifies the organisational location to which the invention is legally attributed, which is particularly relevant to an analysis of the relationship between regional industrial specialisation and firm-level patenting. By contrast, inventor locations refer to the recorded addresses of the individuals involved in the invention and may distribute the same patent family across several regions when inventions are developed by geographically dispersed teams, even in different countries in which the underlying R&D project was financed and organisationally managed. [73]. To assign information on applicants at the family level, we use the earliest application method, identifying, for each patent family, the first granted patent application and then using the applicant information and the earliest filing year[74] reported in that application to assign the family's geographical location and date. We date patents using the earliest filing year rather than the publication year as this measure is preferred because the application date places the invention closer to the time when the underlying R&D and inventive activity occurred (Jaffe et al., 1993; Hall et al., 2001)[75]

Our analysis covers 247 European regions between 2000-2021, including the EU-27 plus Norway and Switzerland, while overseas regions are excluded. The United Kingdom is excluded due to data availability issues, namely missing observations in Eurostat series after 2018. The OpenStreetMap API was used to geolocate applicants when the NUTS indicator provided by PATSTAT was missing. This additional geocoding was performed using the available address information, namely postal codes, city names, and ISO2 country codes. The identification of mining technologies is carried out following the methodology proposed by WIPO and Daly et

[73]Note that even the applicant-based geolocation does not fully eliminate the geographical attribution problem. The applicant's recorded address may correspond to a corporate headquarters or registered office rather than to the establishment or research facility in which the invention was developed

[74]By earliest filing year, in PATSTAT we mean the year of the first filing associated with the invention, i.e., the earliest available filing date (often corresponding to the priority filing or, more generally, the earliest application filing within the patent family).

[75]Since this study does not rely on patent citations—which are typically observed closer to the publication/grant stage (Jaffe et al., 1993)—using the publication year would mechanically shift observed patent outcomes several years forward and would therefore require lagging the explanatory variables by multiple years.

al. (2019), which also allows mining patents to be divided into nine subclasses: Automation, Blasting, Environmental, Exploration, Metallurgy, Mining Operations, Processing, Refining, and Transport. The methodology we use provides not only a higher level of granularity, but also a more accurate identification of patents related to the mining value chain. In fact, within the International Patent Classification (IPC) and Cooperative Patent Classification (CPC) systems, the E21 classification code — Earth or rock drilling; mining — already exists and could be used for a similar purpose. However, this would miss patents that are relevant to the mining value chain but are classified under other IPC codes. The methodology proposed by the authors is more refined, as it also captures relevant patents through keyword-based criteria, even when they are not explicitly assigned an E21 classification code.

Daly et al. (2019) selection methodology relies on a two-stage rule-based selection procedure combining patent classification codes and textual information. First, patents are screened using a selected set of IPC and CPC codes. This first filter acts as a primary selection criterion: it is necessary for a patent to enter the candidate set, but it is not sufficient for final assignment. The final assignment is made only when a second condition is also satisfied. Specifically, among the patents retained by the initial IPC/CPC screening, a patent is assigned to the target category if either 1) it is classified under the IPC/CPC code E21, or 2) its title or abstract contains at least one keyword from the predefined dictionary[76]. For instance, for the Automation category, the search strategy combines a set of relevant IPC/CPC codes — G01C, G01S, G05B, G05D, G05G, G06F, G06N 7/, G06T, and H04L — with either at least one E21 IPC/CPC code, or the presence of at least one of the following keywords — mining, mine, mineral, ore, or coal — in the title or abstract.

In this classification, only mining for minerals and coal are included, whereas quarrying and oil & gas extraction are excluded. Daly et al. (2019) also includes a set of exclusion rules to remove false positives, such as patents referring to “data mining” rather than mining technologies, and keywords are specified in multiple languages to improve coverage. However, the database may still contain oil & gas–related patents, as they may refer to techniques that can also be applied to mineral extraction and processing. Unlike the original methodology, and as already

[76]For the complete keyword and ICP/CPC list and the underlying classification logic, we directly refer the reader to Daly et al. (2019)

mentioned, our search is restricted to granted patents. Moreover, Daly et al. (2019) resolve overlaps across categories by assigning each patent to a single principal category based on a discretional defined hierarchy of mining technologies. Values are ordered from lower to higher according to the authors' hierarchy of relevance and lower values are treated as having higher priority. Therefore, when a patent is matched to multiple mining categories (for example, both Blasting and Environmental), the category with the lowest *mining_category_id* is retained as the principal category. However, the paper does not provide a fully explicit set of criteria for the ordering of this hierarchy. In our case, we chose not to remove the overlap to preserve the content of each patent informational content of each patent (the extent of overlap across mining classes is reported in Table A3.2 in Appendix 3).

As dependent variable, we consider the number of patent families fractioned by NUTS2 regions, per 100,000 inhabitants, in order to make patenting activity comparable across regions of different sizes. The variable is expressed per 100,000 inhabitants to improve readability. Moreover, we also apply a three-year moving average transformation in order to smooth annual volatility in regional patenting activity and reduce the prevalence of zero observations, which represents a major issue in our data, as shown in Section 3.4. This transformation also better reflects the underlying innovation dynamics, since the effect of regional specialisation on patenting is unlikely to be instantaneous. Therefore, the dependent variable takes the following form:

$$P_{r,t} = \frac{1}{3}\sum_{k=1}^{3}\left(\frac{F_{r,t-k}}{Pop_{r,t-k}} \times 100{,}000\right) \tag{3.1}$$

where F denotes the number of patent families assigned to NUTS 2 region r in year $t-k$, and Pop denotes regional NUTS 2 population.

We use a relative index to measure the mining sector specialisation by constructing an employment-based sectoral specialization index—i.e., a location quotient (LQ)— a Balassa-type revealed comparative advantage index based on employment shares, following numerous examples in the literature, including Isard (1960), Marrocu et al. (2013), Delgado et al. (2014), and Paci & Usai (1999). To compute the LQ, we use Eurostat Structural Business Statistics (SBS) data, except for

Switzerland for which we use the Swiss Federal Statistical Office portal. However, our work is not limited to considering workers employed in the NACE Rev. 2 macro-sector "B - Mining and Quarrying". Rather, we extend the analysis by broadening the specialization measure along the mining value chain by considering both specialisation in the extraction sector and specialisation in mining-related services. These latter firms are particularly important for innovation in mining because they are among the main specialised suppliers to mining companies and may also be among the main developers of mining technologies.

Our first step is constructing an indicator that excludes workers employed in firms not directly involved in the extraction or processing of minerals. Indeed, according to NACE Rev. 2, which is the classification used in SBS, the one-digit sector B can be decomposed into two-digit divisions, and we obtain the following subcategories: B05-Mining of coal and lignite; B06-Extraction of crude petroleum and natural gas; B07-Mining of metal ores; and B08-Other mining and quarrying; B09-Mining support service activities. Following other contributions, such as Daly et al. (2019) and Valacchi et al. (2023), we do not draw a sharp distinction between mining activities and quarrying activities. Unlike Chapters 1 and 2, this section does not focus exclusively on SCRMs, and the distinction between mining and quarrying is mainly based on the type of material extracted. In any case, separating the two types of firms within the same macro-sector would be extremely complex, given the way in which NACE Rev. 2 aggregates two-digit sectors under the code B08. Sector B06 — Extraction of crude petroleum and natural gas, instead, is entirely excluded from this analysis because it is not directly related to the extraction or processing of minerals. Moreover, oil and gas extraction activities follow different industrial, regulatory, and geopolitical dynamics and their inclusion would blur the focus of the analysis on the mining value chain for mineral resources. Sector B09-Mining support service activities, is also excluded from this specific specialization indicator. However, unlike oil and gas, it is not removed from the analysis. On the contrary, it plays a central role in our empirical framework, as detailed below.

In a second step, we use the two-digit code B09 to construct an ad hoc specialization indicator for support service activities provided to mining firms. As discussed in Section 3.2, METS play a key role as major innovators and technology suppliers for mining firms. According to the

classification proposed by Valacchi et al. (2023) [77], a large share of the activities included in B09 can be associated with firms that may be classified as METS. The level of detail provided by Eurostat data does not allow us to construct the full METS class as defined by the authors. Therefore, the distinction remains a dichotomy between specialization in extractive activities and specialization in mining support services. Hence, in our analysis, we use two indicators as our main regressors: 1) LQe (Equation 3.2), where E is the number of workers, r denotes a European NUTS 2 region, and j denotes the extractive sector we filtered including workers of companies operating in B05, B07 and B08; 2) LQs, which follows the same formula, but where j^* identifies only sector B09, capturing mining support services (Equation 3.3).

$$LQe_r = \frac{E_{r,j}/E_r}{E_j/E} \tag{3.2}$$

$$LQs_r = \frac{E_{r,j^*}/E_r}{E_{j^*}/E} \tag{3.3}$$

3.3.1 Econometric Model

We rely on a Knowledge Production Function (KPF) framework (Equation 3.4) augmented with mining specialisation terms:

$$P_{r,t} = \beta_0 + \beta_1 LQe_{r,t-3} + \beta_2 LQs_{r,t-3} + \beta_3 \text{R\&D}_{r,t-3} + \beta_4 H_{r,t-3} + \phi \text{Controls}_{r,t-3} + \mu_r + \lambda_t + \varepsilon_{r,t} \tag{3.4}$$

P is the dependent variable, as defined in Equation 3.1. All explanatory variables are lagged by three years to ensure that specialisation precedes the patenting outcome. Since P is expressed as a three-year moving average, the observations for the first three years of the sample are necessarily

[77] Valacchi et al. (2023) classify METS firms as those companies operating in sectors: 2892, 2822 and the whole 09. More specifically, sector 2892 corresponds to "Manufacture of machinery for mining, quarrying and construction", and sector 2822 to "Manufacture of lifting and handling equipment". However, Eurostat data do not provide a sufficient level of sectoral detail to include workers employed in these manufacturing activities.

lost, as the construction of the moving average requires information from previous years. [78]

LQe and LQs are our main independent variable as expressed in Equations 3.2 and 3.3: for ease of interpretation, both indicators are standardised on a 0–1 scale. *R&D* is the KPF input factor and is measured as R&D expenditure as a percentage of GDP, sourced from Eurostat. *H* is the human capital, proxied as the share of tertiary graduates in the 25–64 population. These two terms capture the region's technological absorptive capacity.

We also include general controls, such as population density and GDP per capita, sourced from ARDECO, as well as the specialisation index for NACE Rev. 2 C24, which captures the manufacture of basic metals (*Metals*). We include this last variable to account for the possibility that mining patenting may also be based on regional capabilities located downstream from mining extraction and processing, rather than only on extraction itself or on mining service. We finally also include a set of regional and year fixed effects across different specifications. Since Eurostat R&D data are not complete for all years, missing values were imputed using a standard Kalman interpolation. This choice is in line with the broader data construction strategy adopted in this chapter to identify workers attributable to mining services within the broader mining sector as reported in Eurostat SBS data. The full methodology used to construct these variables is described in the Supplementary Notes of Appendix 3.

As discussed above, the WIPO methodology allows us not only to identify mining patents, but also to classify them into different technological subclasses. Each class can therefore be used as a separate dependent variable. Accordingly, the model in Equation 3.4 can be estimated both on the total number of identified mining patent families and separately for patent families belonging to each mining technology class. This allows us to perform a heterogeneity analysis and assess whether the relationship between mining specialisation and patenting activity differs across mining class.

[78] Note that the use of overlapping three-year moving averages mechanically induces serial correlation because adjacent observations share some of the same underlying patent outcomes. Under the maintained assumptions of conditional exogeneity and correct model specification, however, this overlap does not by itself bias the estimated coefficients. Its main econometric implication concerns the covariance structure of the error term and, consequently, statistical inference. To account for this dependence, standard errors are clustered at the NUTS-2 level in all our specifications, allowing for heteroskedasticity and arbitrary serial correlation within regions over time, including the correlation mechanically generated by the overlapping moving-average windows.

One of the main data-related issue concerns the large number of NUTS2 × Year observations equal to zero, reflecting regions with no patenting activity. Therefore, a log-linear OLS is not ideal in this context as $\ln(0)$ is undefined and ad-hoc fixes such as estimating a generally $\ln(y + c)$ are problematic because the choice of c is arbitrary and can materially affect the results, especially when a large share of observations lies close to zero (Hausman et al., 1984; Santos Silva & Tenreyro, 2006). Although we avoid this type of specification, the issue of excess zeros in the dependent variable remains as OLS does not impose a non-negativity constraint on the fitted values. Hence, the linear predictor $y_{it} = X_{it}\beta$ can easily become negative, even though patent per capita are bounded below by zero (Wooldridge, 2010). We address this problem testing robustness of the FE model results using a Pseudo-Poisson Maximum Likelihood (PPML) estimator with high-dimensional fixed effects, implemented in Stata with the package *ppmlhdfe* which allows to absorb rich sets of region and time effects. PPML accommodates zero outcomes naturally and it can be applied to non-negative dependent variables even when they are not integer-valued (especially useful for per-capita measures). Furthermore, unlike the standard Poisson model, PPML consistency does not rely on equidispersion, so overdispersion is not problematic as long as the conditional mean is correctly specified. Inference can be also conducted using robust, clustered standard errors (see Correia, 2017; and Correia et al., 2020; for a complete review of the methodology and the Stata package).

LQ mining indicators may be endogenous in a patent-based regression for several reasons. First, reverse causality is plausible: regions that experience an increase in patenting may subsequently attract specialised firms, skilled workers, and suppliers, which in turn increases measured mining specialisation. Second, omitted local factors may jointly affect both specialisation and patenting, including unobserved differences in institutional quality, local innovation systems, infrastructure, and historical agglomeration advantages. To address this potential endogeneity, we also implement a Two-Stage Least Squares (2SLS) framework based on instrumental variables. Since our main specialization variables are two, the instrumentation strategy becomes more complex. We therefore construct an instrument that captures the regional geological resource endowments. The indicator combines the physical availability of mineral resources, measured in mega tonnes (Mt), with commodity-specific prices expressed in millions of dollars. More specifically, using the S&P Global data described in Chapter 2, we observe the quantity of

resources available for 36 material categories in each region[79]. Since these geological quantities are heterogeneous across commodities and not directly comparable, we weight each material by its corresponding commodity price, using USGS commodity price data updated to 2021. Note that the purpose of using prices is not to estimate the rent or economic value of a mining area. Rather, prices are used as weights to transform heterogeneous geological endowments into a single comparable index across territorial units. The resulting Endowment indicator can be interpreted as a measure of the relative region's geological endowment over time. All explanatory variables, controls and instrumental variables are summarised in Table 3.1.

Table 3.1: Explicative variables, instrument and controls, general statistics

Variable	Obs	Mean	Std. dev.	Min	Max	Source
LQe	5,434	0.033	0.08	0	1	Eurostat
LQs	5,434	0.004	0.02	0	1	Eurostat
R&D	5,434	25.70	9.00	0	57.78	Eurostat
H	5,434	25.82	9.99	5.2	60.6	ARDECO
GDP per capita	5,434	2787.47	16167.34	2601	101293	ARDECO
Pop. Density	5,434	360.01	1038.787	3.07	10986.97	ARDECO
Metal	5,151	0.081	0.101	0	1	Eurostat
Endowment	5,434	0.007	0.109	0	3.459	S&P Global + USGS

The construction of the Endowment indicator is particularly useful for two reasons. First, it allows us to obtain a time-varying instrument. The S&P Global data provide resource quantities by material, but these quantities are observed as a cross-section. Commodity prices, instead, vary over time. By interacting fixed geological quantities with annual commodity prices, the instrument varies across both regions and years. Second, using mineral-specific prices allows us to weight mineral production by its economic value rather than by physical quantities alone. This is

[79]The 36 aggregate categories represent a larger number of individual material components. REEs comprise 17 elements (the lanthanide group plus scandium and yttrium), while PGMs comprise five elements in the data (platinum, palladium, rhodium, ruthenium, and iridium). Once these two groups are disaggregated, the indicator therefore covers 56 individual material components. Under the 2023 EU classification adopted in this thesis, 20 of the 36 aggregate categories correspond to CRMs; after disaggregating REEs and PGMs, these account for 40 of the 56 individual components. Note that the list of materials considered here is far from being fully comprehensive of the entire geological endowment. It is limited to the raw materials for which data on both resources and prices are available. The list includes resources of the following materials: aluminium, antimony, bauxite, beryllium, chromium, cobalt, copper, gallium, germanium, graphite, heavy sands, ilmenite, indium, iron ore, lead, lithium, magnesium metal, manganese, molybdenum, nickel, phosphate rocks, potash, rhenium, selenium, tantalum, tellurium, tin, titanium metal, tungsten, vanadium, zinc, zirconium, REEs, PGMs, gold, and silver.

important because equal tonnages of different minerals can correspond to very different economic magnitudes (we have anticipated this concept in Chapter 2, absolute quantities expressed in tonnes are not directly comparable across different minerals).

A similar instrument exploiting mineral resources is not new in the literature (see Li & Iammarino, 2026), as the geological formation of these resources can be considered plausibly exogenous. In our case, the instrument is likely to be relevant because mining specialization may naturally follow the presence of rich geological endowments. Regions with larger mineral endowments are more likely to develop extractive activities and mining-related capabilities. At the same time, the exclusion restriction is also plausible to be satisfied, since the endowment indicator should not directly affect patenting activity except through its effect on mining specialization.

In other words, geological resource endowments are expected to shape the regional specialization structure, but they are unlikely to influence the development of mining technologies directly once regional controls and fixed effects are included. This supports the relevance condition, since the Endowment indicator is expected to be strongly associated with mining specialisation. At the same time, the exclusion restriction is also plausible: geological endowments should affect the patenting activity in mining technologies, only indirectly through their impact on the endogenous regressor.

However, this instrument cannot be used alone for two reasons. First, the model includes two potentially endogenous mining specialization variables. With two endogenous regressors, at least two instruments are required for the model to be identified; a single instrument would leave the system under identified. Second, the endowment-based instrument may be less relevant for mining service specialization. As discussed in Section 3.2, METS (and therefore also mining services) firms do not necessarily locate where mineral resources are geologically available. Their location may instead depend on broader industrial capabilities, knowledge networks, supplier–client relationships, and technological specialization. For this reason, natural resource endowments are expected to be a stronger predictor of extractive specialization than of mining service specialization. We address this issue by using three instruments in total. The first is the endowment-based instrument discussed above. The other two are internal instruments based on lagged values of the endogenous explanatory variables, an approach commonly adopted when

credible external instruments are not available. Since lagged regressors may still be problematic if they are correlated with unobserved confounders, as discussed by Bellemare et al. (2017), we reduce this risk by relying on sufficiently distant lags of the location quotients. Specifically, we instrument the three-year lagged values of LQe and LQs with their six-year lags. The 2SLS specification is therefore estimated through the following first-stage and second-stage equations:

First stage for LQe

$$\begin{aligned} LQe_{r,t-3} = \pi_0 + \pi_1 LQe_{r,t-6} + \pi_2 LQs_{r,t-6} + \pi_3 Endowment_{r,t-3} \\ + \pi_4 RD_{r,t-3} + \pi_5 H_{r,t-3} + \theta Controls_{r,t-3} + \mu_r + \lambda_t + \varphi_{r,t} \end{aligned} \tag{3.5}$$

First stage for LQs

$$\begin{aligned} LQs_{r,t-3} = \rho_0 + \rho_1 LQe_{r,t-6} + \rho_2 LQs_{r,t-6} + \rho_3 Endowment_{r,t-3} \\ + \rho_4 RD_{r,t-3} + \rho_5 H_{r,t-3} + \theta Controls_{r,t-3} + \mu_r + \lambda_t + v_{r,t} \end{aligned} \tag{3.6}$$

Second Stage:

$$P_{r,t} = \beta_0 + \beta_1 LQe_{r,t-3} + \beta_2 LQs_{r,t-3} + \beta_3 RD_{r,t-3} + \beta_4 H_{r,t-3} + \phi Controls_{r,t-3} + \mu_r + \lambda_t + \varepsilon_{r,t} \tag{3.7}$$

Part of the literature consulted in Section 2 may arise concerns regarding the exclusion restriction. Such literature documenting a positive relationship between commodity-price cycles and mining-related patenting (Valacchi et al., 2023; Calzada Olvera & Iizuka, 2024). This evidence, however, is primarily based on global or multi-country analyses using global or aggregate commodity-price indicators. It establishes that mining patenting co-moves with global market cycles, but does not directly identify a causal effect of commodity prices on patenting within the same mineral-endowed region, independently of regional mining specialisation. Indeed, commodity

prices are equilibrium signals of global demand and supply conditions. The observed association between prices and patenting may therefore partly capture changes in global mineral demand, expected profitability, and the broader mining cycle rather than an autonomous price effect. This distinction is relevant to the present identification strategy. Global commodity prices are external to the decisions of individual European regions, while year fixed effects absorb the component of global demand and commodity-price movements that is common across regions. Regional fixed effects also absorb persistent differences in pre-existing innovation capacity, and other time-invariant regional characteristics. The remaining identifying variation therefore arises from the interaction between commodity-specific global price movements and differences in regional mineral endowments. Finally, patent families are geolocated according to the applicant's address. Consequently, an increase in global mineral demand or commodity prices cannot mechanically generate additional patenting in a mineral-endowed region if no patent applicant is located there. If the organisations responding to global mining conditions are located elsewhere, their patents are attributed to the regions in which those applicants are based rather than to the regions containing the relevant mineral resources.

3.3.2 Spatial Econometric Analysis

We then introduce a spatial econometric framework to explicitly account for interregional knowledge spillovers. This is particularly relevant in the case of mining-related services, which are less tied to the physical location of mineral deposits than extraction activities. Unlike extraction firms, they do not necessarily follow resource-based location patterns but rather act as specialised providers for firms whose location is constrained by natural resource endowments, so their activity may connect regions where mining demand originates with regions where specialised technological and service capabilities are located.

Consistently with baseline Equation 3.4, all the spatial specifications reported in Tables 3.6 and 3.7 include both regional and year fixed effects. Regional fixed effects control for time-invariant regional heterogeneity, while year fixed effects account for common macroeconomic, technological, and institutional shocks affecting all regions.

We follow a stepwise spatial econometric strategy, moving from the baseline fixed-effects panel specification towards progressively richer spatial lag models. As a first step, we estimate a spatial error model (SEM) to account for residual spatial dependence in the residuals. In the mining context, unobserved spatial dependence may be particularly important, as they may also include similar regulatory frameworks in neighboring regions, common mining policy orientations, comparable permitting regimes. Differences and similarity in dimensions are difficult to account for in the European context, since as said above there is no fully harmonised EU-wide mining standards, and mining regulation is often fragmented across countries, with responsibilities distributed across different national and regional levels of government.

We then extend the analysis by introducing spatial lags of the key explanatory variables, leading to a Spatial Lag of X model (SLX). Unlike the spatial error model, which accounts for residual spatial dependence arising from unobserved regional conditions, the SLX model is designed to capture substantive spillover mechanisms. In this setting, the spatially lagged explanatory variable measures whether the mining specialisation of spatially close regions affects local mining technological development.

We then estimate a Spatial Durbin Error Model (SDEM), which combines spatially lagged LQe e LQs explanatory variables with a spatially autocorrelated error structure. As a final robustness specification, we estimate a General Nesting Spatial (GNS) model, which additionally includes a spatial lag of the dependent variable and therefore jointly models spatial dependence in the outcome, the explanatory variables, and the error term. Formally, the SDEM can be written as:

$$\begin{aligned} P_{r,t} = {} & \beta_0 + \beta_1 LQe_{r,t-3} + \beta_2 LQs_{r,t-3} + \beta_3 \mathrm{R\&D}_{r,t-3} + \beta_4 H_{r,t-3} \\ & + \phi Controls_{r,t-3} + \theta_1 WLQe_{r,t-3} + \theta_2 WLQs_{r,t-3} + \mu_r + \tau_t + \varepsilon_{r,t} \end{aligned} \tag{3.8}$$

Where:

$$\varepsilon_{r,t} = \lambda W \varepsilon_{r,t} + u_{r,t} \tag{3.9}$$

Here, W is the spatial weights matrix, specified either as a contiguity matrix or as an inverse-distance matrix censored at 350 km, and τ_t denotes year fixed effects.

We do not consider a spatial autoregressive model. We use spatial lags of the explanatory variables because our interest lies in local spillover effects generated by neighbouring regions' observable mining comparative advantages. A spatial lag of $P_{r,t}$ would imply a global spatial dependence process, in which mining technological improvement in one region depends on the same outcome in nearby regions and feedback effects propagate throughout other regions. This is not the phenomenon under investigation in our analysis. Moreover, including a spatial lag of the dependent variable would mean to consider a simultaneous spatial autoregressive specification in which outcomes are mutually interdependent across regions, making the estimated spatial parameter harder to interpret.

3.4 Data Analysis

Patent statistics are widely recognized as a good proxy for innovation output, and an appropriate indicator for capturing technological change (Scherer, 1965; Pavitt, 1985; Griliches, 1990)[80]. To map the distribution of mining patent families across European regions, we rely on the WIPO methodology proposed by Daly et al. (2019) to identify and use their classification of nine mining technological fields spanning across the value chain (in technological terms): Exploration, Blasting, Mining (Operational), Transport, Automation, Environmental, Processing, Metallurgy, and Refining. The precise definition of each class is reported in Table A3.1 in Appendix 3. Table 3.2 shows the patent count for all the 9 categories:

[80]Nevertheless, the use of patent measures as a proxy for innovation is subject to several well-known and non-negligible limitations. Patents capture only a subset of innovative activity, since not all inventions satisfy patentability requirements and firms may choose alternative protection strategies. In addition, the propensity to patenting varies substantially across firms, industries, and technological fields, making patent counts only imperfectly comparable across economic activities and territories. Patent-based measures may also underrepresent process and organizational innovations, while individual patents differ considerably in their technological significance and economic value (Scherer, 1965; Jaffe, 1986).

Table 3.2: Mining patent families by classes in Europe (2000–2021)

Class	No. of patent families	% on TOT
Automation	821	4.0
Blasting	168	0.8
Environmental	1111	5.4
Exploration	8815	42.8
Metallurgy	1739	8.5
Mining_Operational	5710	27.8
Processing	646	3.1
Refining	361	1.8
Transport	1205	5.9
TOT	12266	–

Source: our elaboration on PATSTAT (Autumn 2024) data, based on Daly et al. (2019) methodology.
Note: mining patents referring to patent families are granted. Europe: EU-27 + Switzerland and Norway. Classes may overlap.

On a total of 12,266 patent families identified, more than 42% are classified in the Exploration class, while almost 28% fall within Mining Operations. These are the two most relevant upstream classes and closely tied to the physical location of mineral resources. Mining Operations refers to the extraction phase itself, while Exploration captures the search for and assessment of geological sites that may potentially be exploited for extraction activities. By contrast, Processing and Refining are strongly underrepresented, as are the classes defined by Alessandri (2023) as mining-related services (Transport, Automation, and Environmental technologies). Alessandri (2023) himself shows that countries may display different patterns of technological specialisation, as measured by the Relative Specialisation Index (RSI). From this perspective, Europe appears to differ from other major players such as China and Australia, where technological specialisation is more strongly oriented towards Refining, Metallurgy, and mining-related services.

Since both Blasting and Refining account for a very small number of observations, these two classes are no longer considered separately in the rest of the analysis. Refining is merged with Metallurgy, as the two classes overlap in more than 41% of observations (Table A3.2 in Appendix 3) and both refer to downstream stages of metal production, as discussed in Section 3.1. By contrast, all Blasting patents also appear in at least one other technology class, and 99.1% overlap with either Exploration or Mining Operations. We therefore drop the Blasting label from the

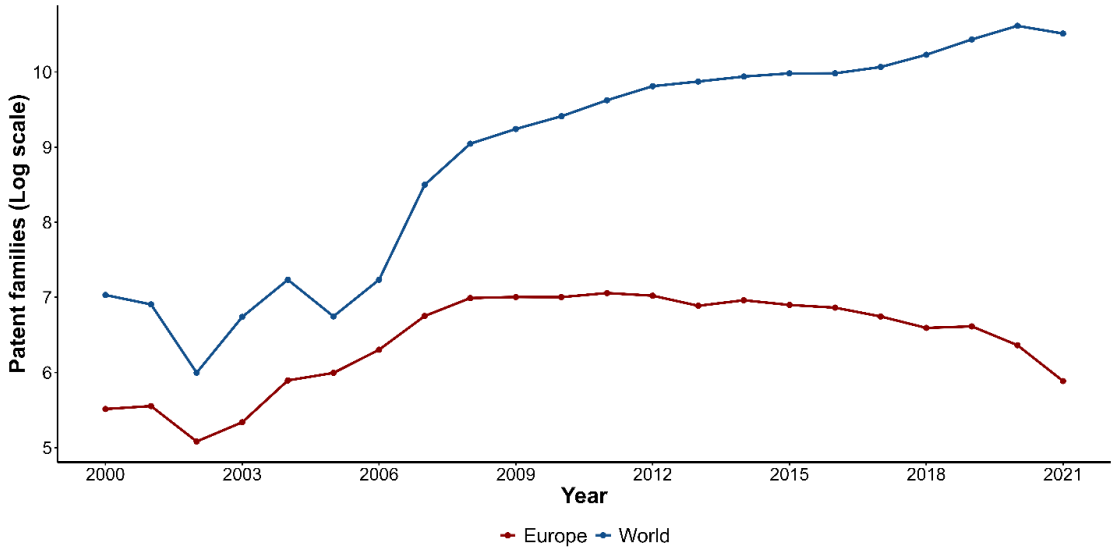
analysis, as it refers to technologies related to very upstream stages of mining activity that are already captured by these two broader classes.

Figure 3.2 illustrates the number of global and European mining patent families developed over the period 2000–2021, considering all technology classes together (in ln scale). It shows a clear upward trend in global mining patenting activity starting in the early 2000s.

Over time, Europe diverges from the global trend, and this divergence is already visible at the beginning of the millennium, when global mining innovation intensifies while Europe's relative position starts to weaken. This representation is consistent with Daly et al. (2019), who show China, Japan, the U.S., the Russian Federation, and Germany were the largest contributors, in absolute terms in 1995, accounting for roughly 90% of all mining technologies. However, the distribution within this group changed substantially over time and China recorded by far the strongest increase, gaining global market share over time. According to Daly et al., (2019, 2022), China's share of mining patents (by top country of origin) rises from around 10% in the early 2000s to more than 70% after the first decade of the new millennium.

We know that, from around 2004 onward, global demand for base metals experienced a major shock, driven primarily by China's rapid economic growth (World Bank, 2006; Tilton, 2014). It is also important to note that, since roughly the early 2000s, mining firm-level productivity has declined substantially–both in terms of labour productivity and multifactor productivity–largely because of falling ore grades and the depletion of the most productive mineral deposits (Tilton, 2014; Humphreys, 2020).

Figure 3.2: Mining patenting trend in Europe and Worldwide, 2000–2021

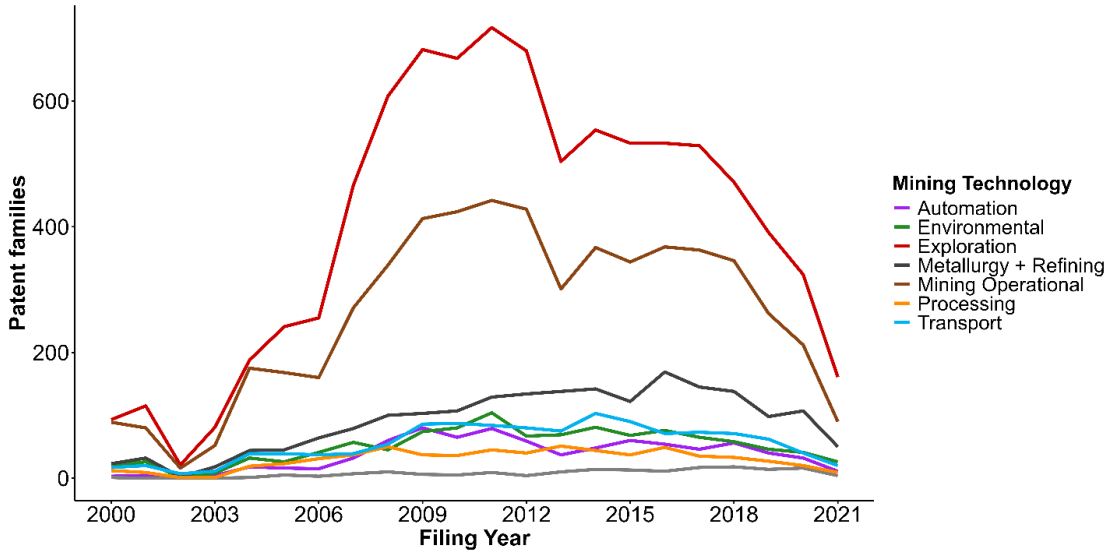


Source: our elaboration on PATSTAT (Autumn 2024) data.
Note: mining patents referring to patent families are granted and geolocated by applicant. Europe: EU-27 + Switzerland and Norway.

Against this backdrop, the sharp increase in mining patenting in the early 2000s can be interpreted as a response to rising technological pressure within the sector. On the one hand, the expansion of mineral demand from emerging economies increased the need for new extraction, exploration, and processing solutions. On the other hand, worsening geological conditions, declining ore grades, and the maturation of existing deposits made it increasingly difficult to sustain productivity on the basis of established technologies. In this context, higher patenting activity may reflect the growing need for innovation to compensate for these constraints and maintain the economic viability of mining operations. Figure 3.3 decomposes European mining patent families by technology class and shows their evolution over time. The figure confirms that Exploration + Mining Operational technologies dominate the overall pattern, both displaying a strong increase during the 2000s and reaching their highest levels around the early 2010s. The timing of this decline coincides with the slowdown in Chinese demand for minerals and metals around 2012–2013 after the rapid expansion recorded during the 2000s (Humphreys, 2020), and it also occurs alongside a broader contraction in global exploration expenditure, which began to fall in 2012 and had declined by approximately 50% by 2017 (Daly et al., 2022). Interestingly, this

shock seems to have affected mainly the more upstream mining classes. By contrast, Processing, Metallurgy + Refining, and Transport continued to grow for a longer period, suggesting that downstream and complementary mining technologies may have followed a more persistent innovation trajectory. After 2015, trends gradually decline across almost all mining classes. This turning point may be related to the broader reorientation of mining innovation following the Paris Agreement and the increasing policy emphasis on climate transition. The decline becomes particularly pronounced toward 2020–2021, although this last drop should be interpreted with caution, as it may reflect disruptions in patenting process activity associated with the COVID-19 pandemic.

Figure 3.3: European mining patenting trends by technology class, 2000–2021



Source: our elaboration on PATSTAT (Autumn 2024) data.
Note: mining patents referring to patent families are granted and geolocated by applicant. Europe: EU-27 + Switzerland and Norway.

3.4.1 Regional Data Analysis

In this section, we explore the spatial distribution of mining technologies and the specialisation of European regions in the mining sector and related services. Starting from a more aggregated perspective and therefore considering all mining classes reported in Table 3.2, several interesting patterns emerge. First, mining patent families per capita appear to be strongly concentrated

in a limited number of areas, while many other regions record little or no patenting activity. Figure 3.4 shows the number of mining patent families per 100,000 inhabitants geolocated across NUTS-2 regions through applicants for three periods: 1) the whole 2000–2021; 2) 2002–2007, the first six years after the strong worldwide increase in mining patenting, and 3) 2016–2021, the last six years of our sample. We observe a concentration of mining patenting activities in Nordic countries, particularly in the Norwegian regions of Vestlandet and Oslo og Viken, the Swedish regions of Norra Mellansverige and Östra Mellansverige, and the Finnish regions of Länsi-Suomi and Helsinki-Uusimaa. The rest of the distribution is instead concentrated in Central European regions, with very low but positive patenting levels in parts of Eastern and Southern Europe, such as Warszawski stołeczny and Podlaskie (Poland), Algarve and Norte (Portugal), Comunidad de Madrid and Principado de Asturias (Spain), and Attiki and Kriti (Greece). The representation suggests a lower propensity for mining patenting in some countries and areas that are nevertheless well known for their historical and current mining activity, such as Portugal–currently the only EU country extracting lithium from mines–, Spain, which extracts (among other materials) SRMs such as tungsten, and Poland, which is active, among other things, in the extraction of copper, silver and nickel.

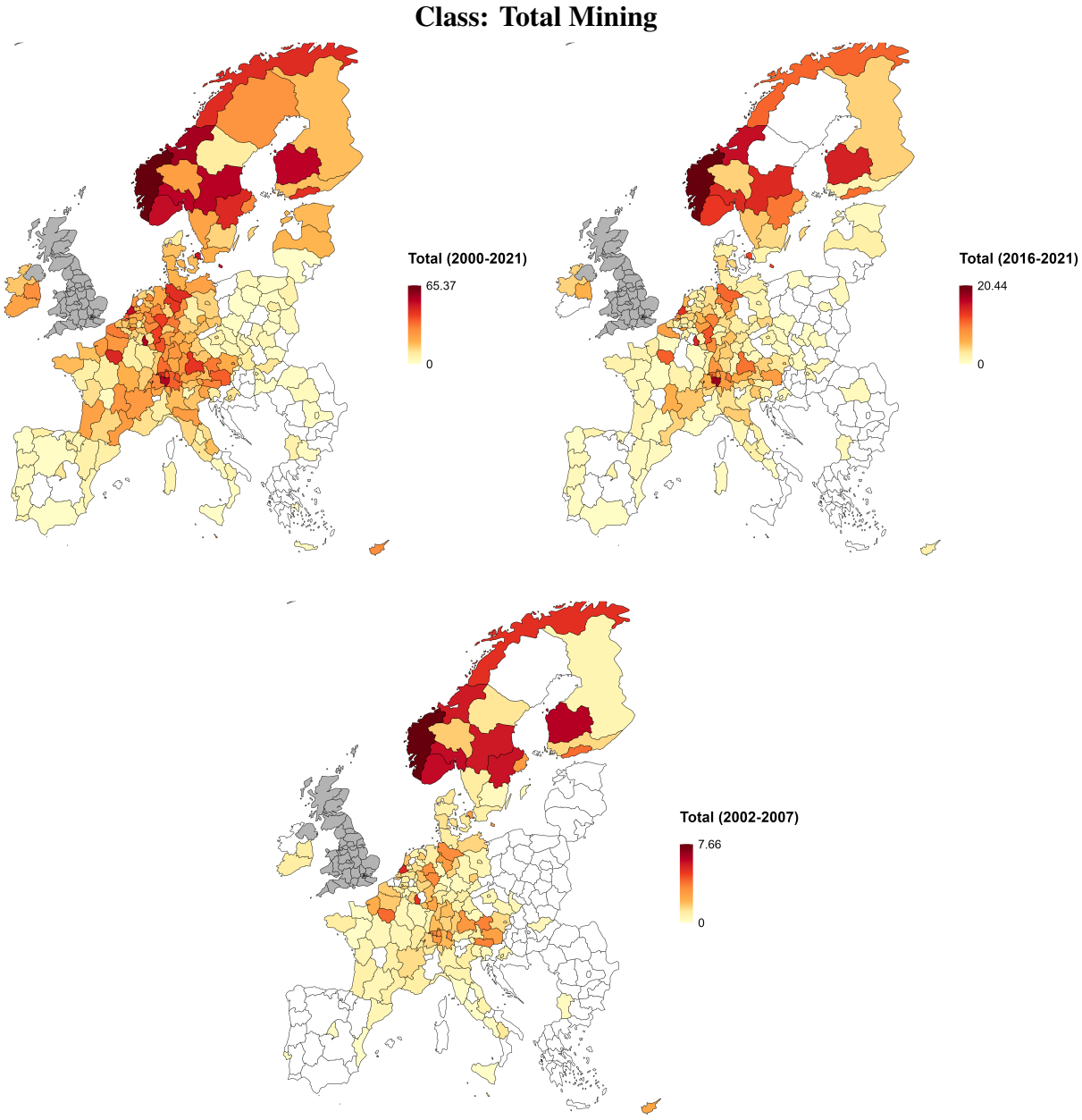
A further interesting perspective can be obtained by focusing on the two sub-periods 2002–2007 and 2016–2021. The figure shows that, in the first period, patenting activity was concentrated in a relatively limited number of European regions, while in the later period a larger set of regions started to develop mining technologies. However, this broader spatial diffusion did not eliminate the strong concentration of the propensity to patent, which remains primarily located in Northern and Central Europe. In particular, many regions located at the eastern and western edges of the map had not yet developed any mining patents by 2007.

Extending the analysis to other mining classes identified, Figure 3.5 shows that, for some of these classes such as Environmental and Processing technologies (measured as averages over the whole period 2000–2021), the spatial distribution is highly skewed, with a large number of zeros and only a limited number of regions recording patenting activity (in Appendix 3, Table A3.3, we report the number of zero observations across NUTS-2 region-year pairs, both for the yearly values and for the three-year moving averages transformation). The maps show

that the overall spatial pattern remains broadly similar: central European and Nordic regions appear more active in patenting, while regions located further to the east and west are more likely to record no patenting activity throughout the whole period (we map all the remining mining classes in Figure A3.1, in Appendix 3).

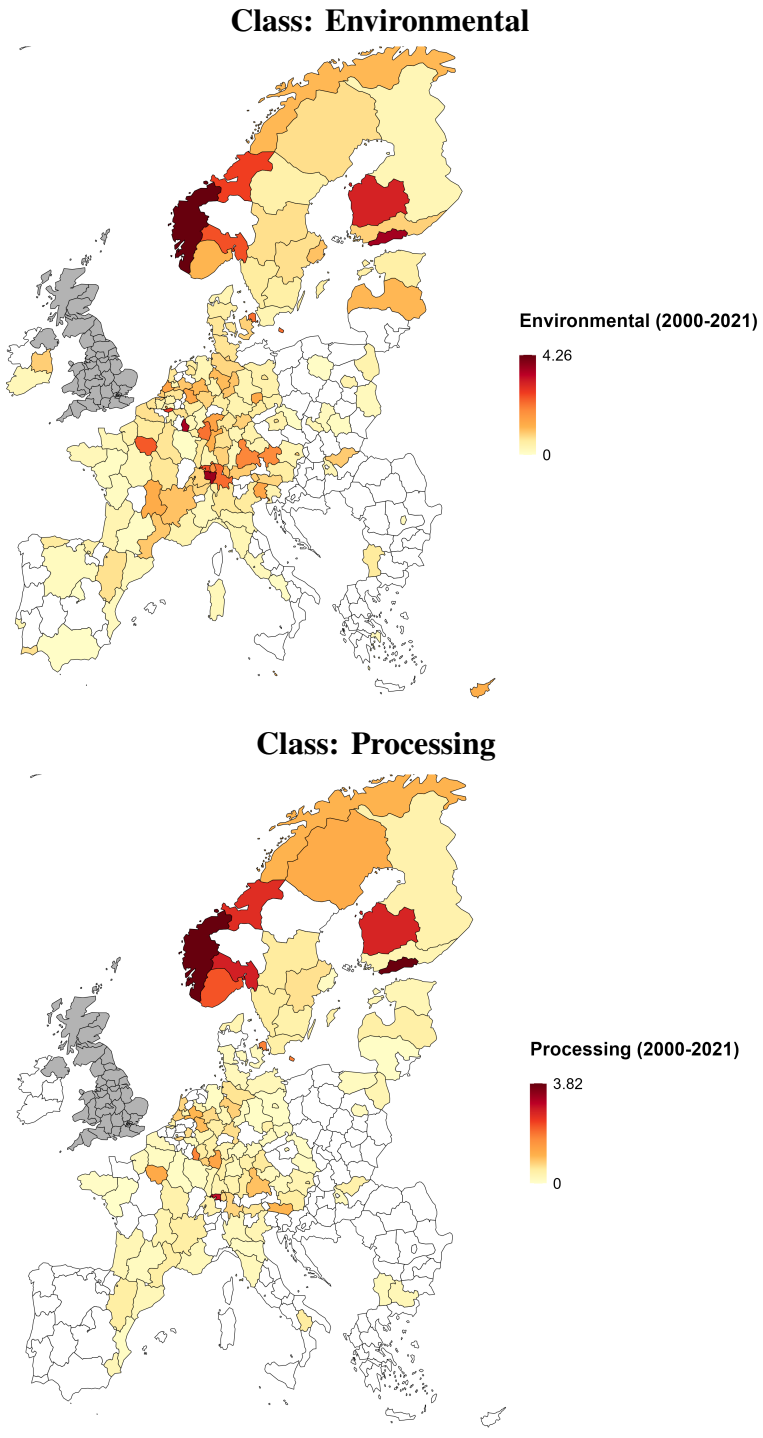
From Figures 3.4 and 3.5, a clear spatial pattern seems to emerge: regions with higher levels of mining patenting tend to be close to other high-patenting regions, while regions with lower levels of patenting are often surrounded by similarly low-patenting regions. To justify the spatial econometric approach adopted in Section 3.5.1, we first test for spatial dependence in the residuals of the baseline specification. Moran's I test based on a contiguity matrix rejects the null hypothesis of independently distributed errors, with a chi-square statistic of 16.41 and a p-value of 0.001. Since there is not a straightforward Moran's I test for residual spatial dependence in the panel setting, we compute Moran's I on the residuals of a cross-sectional specification. The test is based on a block-diagonal contiguity matrix, where regional links are defined within each year and cross-year spatial links are set to zero. We also perform Pesaran's CD test on the residuals of the fixed-effects baseline model in Equation 3.4. The test evaluates the null hypothesis of cross-sectional independence by examining whether residuals are correlated across regions. Rejection of the null indicates that unmodelled interregional dependence remains in the baseline specification, supporting the use of spatial panel models. In our case, the CD statistic is 72.639, with a p-value of 0.000, strongly rejecting cross-sectional independence. We use these two tests to provide complementary diagnostics. Moran's I provides information on whether residual dependence follows the structure imposed by the chosen spatial weights matrix, while Pesaran's CD test assesses whether more general cross-sectional dependence remains across regions in the panel. Both null hypotheses of independence are rejected, providing solid support for the use of spatial econometric models.

Figure 3.4: Patent families per 100,000 inhabitants across European regions, averages for 2000–2021; 2002–2007 and 2016–2021



Source: our elaboration on PATSTAT (Autumn 2024) data, based on Daly et al. (2019) methodology.
Note: mining patents referring to patent families are granted and geolocated by applicant. Europe: EU-27 + Switzerland and Norway.

Figure 3.5: Patent families per 100,000 inhabitants across European regions, averages for 2000–2021, Classes Environmental and Processing



Source: our elaboration on PATSTAT (Autumn 2024) data, based on Daly et al. (2019) methodology.
Note: mining patents referring to patent families are granted and geolocated by applicant. Europe: EU-27 + Switzerland and Norway.

3.4.2 Mining Specialisation

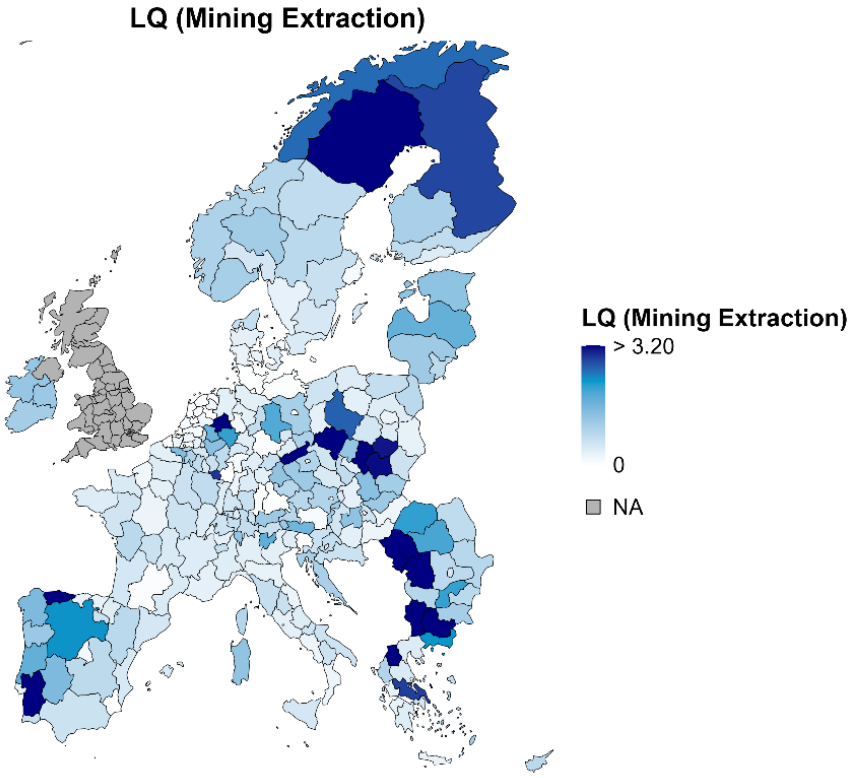
As discussed in Section 3.3, mining extraction and mining services specialisation are the main explanatory variables in this analysis. Their construction follows the procedure described in Section 3.3 and in Equation 3.2. Since these data are not perfectly harmonized and, before 2008, are reported using the NACE Rev. 1 classification of economic sectors rather than NACE Rev. 2, the construction of these indicators required additional processing steps, which are discussed in the Supplementary Notes of Appendix 3.

LQe and *LQs* indeces, as expected, shows a highly uneven spatial pattern: a small number of regions are strongly specialised, while the majority display very low LQ values. When these indicators are not standardised on a 0–1 scale, they can take very large values. In the most extreme cases, over the full period considered, 2000–2021, the mining extraction specialisation index reaches an average value close to 29 in Śląskie, Poland. For mining services specialisation, the Norwegian region of Vestlandet records an even higher average value, close to 59.5. Overall, the distribution is strongly right-skewed, with a mean of 1.06 and a median of 0.050 for *LQe*, e 1.508 and a median ≈ 0 for *LQs*.

Figures 3.6 and 3.7 report the average values of the mining extraction specialisation index *LQe* and the mining services specialisation index *LQs* over the period 2000–2021. Focusing first on *LQe*, the highest values are concentrated in a limited number of areas, particularly in the Nordic countries, with very high levels in Pohjois- ja Itä-Suomi (Finland) and Nord-Norge (Norway); within Norway, Innlandet also records above-average specialisation. High levels of extraction specialisation are also visible in parts of Eastern and South-Eastern Europe, including Śląskie and Dolnośląskie (Poland), Sud-Vest Oltenia and Vest (Romania), Yuzhen tsentralen and Yugozapaden (Bulgaria), and Dytiki Makedonia and Sterea Elláda (Greece). High values are also observed in Alentejo and Centro (Portugal), and Principado de Asturias and Castilla y León (Spain). By contrast, much of Western and Central Europe displays relatively low levels *LQe* specialisation. For *LQs*, Figure 3.7 shows that mining services specialisation is also highly uneven across European regions and the map shows, some regions, in white, do not appear to host these types of firms at all, as indicated by the absence of mining services specialisation in

those areas.

Figure 3.6: Mining extraction specialisation (*LQe*) across European regions (2000–2021)

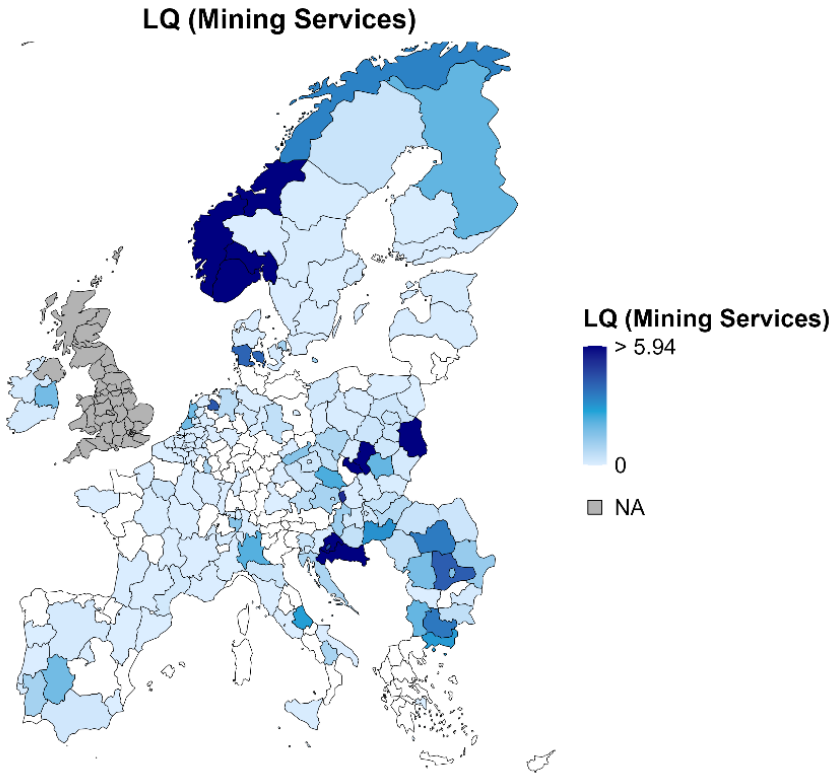


Source: our elaboration on Eurostat data.
Note: Europe: EU-27 + Switzerland and Norway.

Throughout Sections 3.2 and 3.3, we have repeatedly emphasised that mining firms tend to locate close to mineral resources, whereas METS firms, and therefore mining-related services, are not necessarily subject to the same location constraints. We can provide descriptive evidence on this point by examining the correlation between natural resource endowment and the two specialisation indicators, *LQe* and *LQs*. Figure 3.8 shows the spatial distribution of the Endowment indicator used as an instrument in the IV approach (see Equation 3.7). As explained in Section 3.3 this indicator is constructed as a price-weighted measure of regional mineral resource availability by multiplying mineral prices, expressed in million USD, by the quantity of geological resources available in each region, expressed in Mt using USGS and S&P data. The correlation is computed

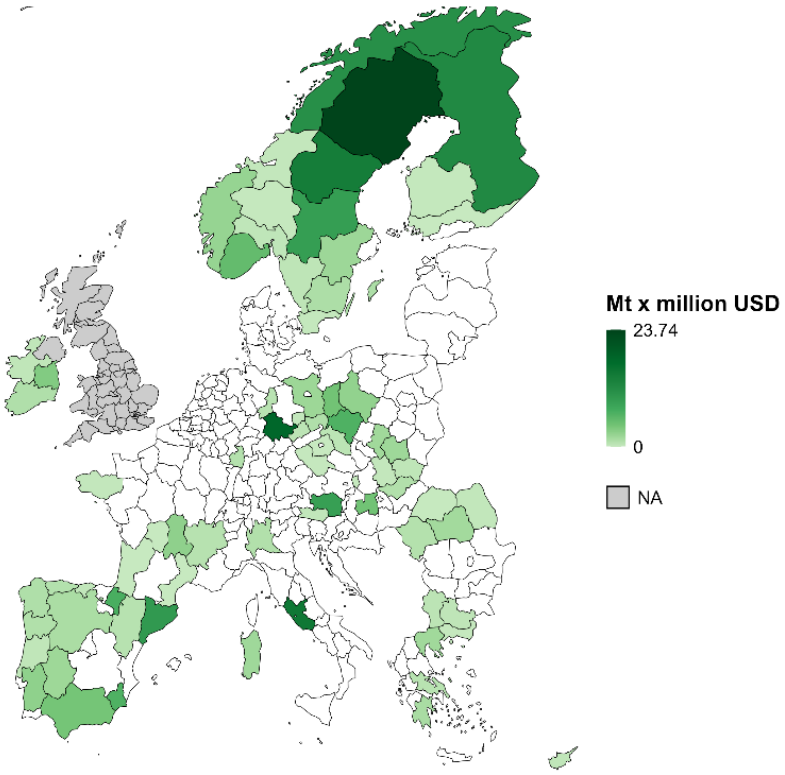
using the Pearson correlation coefficient. The results show a positive correlation between natural resource endowment and mining extraction specialisation *LQe*, with a Pearson correlation coefficient of 0.207. By contrast, the correlation with mining services specialisation *LQs* is close to zero, at -0.003. The results suggest that geological endowment may contribute to explaining the location of extraction firms, but not the spatial distribution of mining services, supporting the hypothesis discussed in different sections of this thesis that mining-related service activities are less tied to the location of natural resources.

Figure 3.7: Mining services specialisation *LQs* across European regions (2000–2021)



Source: our elaboration on Eurostat data.
Note: Europe: EU-27 + Switzerland and Norway.

Figure 3.8: Regional mineral endowment of European regions (2000–2021)



Source: our elaboration on S&P Global and USGS.
Note: Europe: EU-27 + Switzerland and Norway. Materials included: 36 aggregate categories, corresponding to 56 individual material components once REEs (17 elements) and PGMs (five elements) are disaggregated; 40 of these components correspond to CRMs under the 2023 EU classification. Categories: aluminum, antimony, bauxite, beryllium, chromium, cobalt, copper, gallium, germanium, graphite, heavy sands, ilmenite, indium, iron ore, lead, lithium, magnesium metal, manganese, molybdenum, nickel, phosphate rocks, potash, rhenium, selenium, tantalum, tellurium, tin, titanium metal, tungsten, vanadium, zinc, zirconium, REE, PGM, gold, and silver.

3.5 Econometric Results

Table 3.3 reports the estimation results for the baseline model in Equation 3.4. In this table, we focus on the total number of mining patent families identified, without applying any subdivision into subclasses reported in Table 3.2. Columns 1 and 2 estimate the model using pooled OLS with different sets of controls. Column 1 reports the KPF augmented with location quotients. The coefficient of specialization in mining extraction is positive but only weakly significant. By contrast, lagged specialization in services displays a large and statistically significant effect: a one-point increase in the standardized *LQs* index is associated, on average, with an increase of

around 3.9 patents families per 100,000 inhabitants.

Table 3.3: Impact on mining extraction and service specialization on mining technologies (2000–2021)

VARIABLES	(1) Pooled OLS	(2) Pooled OLS	(3) FE	(4) FE	(5) 2SLS	(6) PPML	(7) PPML	(8) PPML
L3.LQe	0.592*	0.519	1.019*	1.057*	-1.503	−3.442*	-0.238	0.781
	(0.347)	(0.344)	(0.616)	(0.627)	(2.055)	(1.986)	(1.418)	(1.472)
L3.LQs	3.891**	3.934**	3.732**	3.746**	3.237**	5.492***	1.402**	0.729**
	(1.651)	(1.666)	(1.507)	(1.523)	(1.347)	(0.683)	(0.485)	(0.304)
L3.H	0.192	0.004	0.008	0.181	0.638	2.581***	2.734**	1.743
	(0.150)	(0.081)	(0.178)	(0.355)	(0.427)	(0.836)	(1.087)	(1.316)
L3.R&D	0.019***	0.013***	0.018***	0.019***	0.015*	0.031***	0.037**	0.032
	(0.006)	(0.004)	(0.007)	(0.007)	(0.008)	(0.011)	(0.016)	(0.024)
L3.ln(GDP per capita)	–	0.039*	0.072*	-0.001	-0.020	1.837***	1.545**	-0.366
	–	(0.023)	(0.043)	(0.037)	(0.032)	(0.203)	(0.671)	(0.402)
L3.ln(Pop. Density)	–	-0.003	0.374***	0.206*	-0.001	−0.350***	-0.324	–
	–	(0.013)	(0.112)	(0.117)	(0.136)	(0.110)	(0.796)	–
L3.Metals	–	0.254	–	–	–	–	–	–
	–	(0.228)	–	–	–	–	–	–
Nordic_dummy	–	0.298**	–	–	–	–	–	–
	–	(0.102)	–	–	–	–	–	–
Constant	-1.107	−0.414*	−2.581**	-1.107	0.117	−20.721**	−17.234*	2.170
	(0.901)	(0.249)	(0.863)	(0.901)	(0.909)	(2.060)	(8.608)	(4.338)
Observations	4,693	4,448	4,693	4,693	3,952	4,693	3,819	3,819
NUTS FE	No	No	Yes	Yes	Yes	No	Yes	Yes
Year FE	No	No	No	Yes	Yes	No	No	Yes
R^2 within	0.223	0.259	0.232	0.276	0.082	–	–	–
R^2 between	0.410	0.504	0.0127	0.0469	0.281	–	–	–
Pseudo R^2	–	–	–	–	–	0.285	0.400	0.425

Note: Robust and clustered standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages.

In Column 2, we include additional controls regional GDP per capita and population density to better account for regional heterogeneity beyond those introduced in Column 1. We also add the standardized location quotient, ranging from 0 to 1, for NACE Rev. 2 sector C24, Manufacture of basic metals (*Metals*). This index is calculated on employment using Eurostat data and follows a methodology analogous to that used for *LQs* and *LQe*[81]. However, in this specification we do not find evidence supporting this hypothesis in this specification. We finally include a dummy variable (*Nordic_dummy*) to account for the overrepresentation of mining patents in the Nordic countries observed. We note that, although the coefficient of this last additional control is positive

[81] Unfortunately, employment data for this sector are not available for Switzerland and, as a result, Swiss regions are not included in this specification

and statistically significant, the magnitude of the coefficients for *LQe* and *LQs* does not change substantially compared with Column 1. In particular, *LQs* remains strongly significant at the 5% level. Since *Metals* reduces the number of observations, and the Nordic dummy is incompatible with the inclusion of regional fixed effects, we do not include these two controls in the following specifications.

In Columns 3 and 4, we progressively introduce a full set of fixed effects. Column 3 adds NUTS-2 regional fixed effects to control for time-invariant regional characteristics, while Column 4 further includes year fixed effects to account for common shocks and time-specific trends affecting all regions. In both cases, the coefficient of *LQs* appears robust, maintaining statistical significance and a similar magnitude across specifications. By contrast, the coefficient of *LQe* is only significant at the 10% level and appears less robust across the different specifications reported in the table.

Column 5 reports the estimates of the 2SLS model in Equation 3.7, where the main explanatory variables, namely *LQe* and *LQs*, are instrumented using their sixth lags (we report the results of the first-stage regressions in Table A3.5 in Appendix 3). The results confirm that regional specialization in mining services remains strongly robust in the instrumental-variable specification. Conversely, the coefficient of *LQe* loses statistical significance and changes sign, suggesting that the relationship between extraction specialization and patenting activity is less stable and more sensitive to the empirical specification. Following Aresu et al. (2023), we also assess the robustness of the instruments by repeating the IV analysis with 5- and 7-year lags of the endogenous variables in Table A3.4. The first-stage F-statistics are above the conventional threshold of 10 for both endogenous regressors: $F = 91.95$, Prob $> F = 0.000$ for extractive specialization, *LQe*, in Equation 3.5, and $F = 11.50$, Prob $> F = 0.000$ for mining service specialization, *LQs*, in Equation 3.6. Since the model is overidentified, with three instruments for two endogenous regressors, we also perform a Hansen J test of overidentifying restrictions to assess instrument validity. The test does not reject the null hypothesis that the excluded instruments are valid, with a Hansen J statistic of 0.005 and a Chi-sq(1) P-value = 0.946, providing no statistical evidence against their exogeneity.

In Columns 6–8 we use the PPML estimator to assess the robustness of the results with a

methodology better suited to handling zero outcomes in the dependent variable[82]. Column 6 reports the specification without fixed effects, while Column 7 introduces regional fixed effects. In PPML with fixed effects, groups with no positive outcomes and that provide no usable information (e.g., isolated cells/singletons, or only zeros groups) may be dropped by the estimator[83] as the likelihood is maximized by the fixed effect alone. This is not an anomaly, but a standard feature of the model estimated with *ppmlhdfe* (Correia et al., 2020).

In Column we 8 include both regional and year fixed effects, but this specification is particularly demaning. Unlike linear estimators, fixed-effects PPML cannot use regions in which the dependent variable is always zero to identify the coefficients. These regions provide no within-region information on the relationship between the explanatory variables and positive patenting outcomes and are therefore automatically excluded from the estimation. In our case, 46 such regions are excluded, leaving 3,819 observations. Within this sample, a diagnostic regression of the three-year lag of log population density on regional fixed effects yields an R^2 of 0.9991 (see Table A3.6 in Appendix 3), indicating that regional fixed effects account for approximately 99.91% of its observed variation. Population density therefore provides very limited additional within-region variation. When year fixed effects are also introduced, including population density prevents the PPML estimation algorithm from converging to a stable solution. Population density is consequently excluded from Column 8, while year fixed effects are retained to control for common shocks and temporal trends. Across the PPML specifications, the coefficient of *LQs* remains positive and statistically significant, confirming the robustness of the role of mining service specialization, although its magnitude declines after regional and year fixed effects are introduced. By contrast, the coefficient of *LQe* remains unstable and is not statistically significant in the most saturated specification. Human capital and R&D intensity are positive across all three PPML specifications, but their statistical significance weakens once both regional and year fixed

[82]Note that under the Poisson distribution, y can only take non-negative values ($y \geq 0$).

[83]An OLS/FE model does not face the non-existence of a finite MLE, which can arise in non-linear models such as PPML. As long as there is variation and no perfect collinearity, the FE-OLS solution exists and zeros in the dependent variable are not special and enter the regression like any other value. By contrast, PPML with fixed effects is estimated by maximum likelihood with conditional mean $\exp(FE + x\beta)$. With very sparse outcomes and many fixed effects, some observations or fixed-effect groups can become redundant or problematic: in some cases (separation) a finite MLE does not exist, and in others (singletons) certain cells/groups are effectively isolated and provide no within-group information to identify β. For numerical stability, *ppmlhdfe* therefore drops such observations by construction.

effects are included.

In Tables 3.4 and 3.5, we extend the analysis reported in Table 3.3 by performing a heterogeneity analysis across all mining technology classes. Table 3.4 reports the results obtained using a FE model with regional and year fixed effects, while Table 3.5 reports the corresponding PPML estimates with regional fixed effects. Overall, the results reveal the same underlying pattern, but in a more granular and systematic way. Starting from Table 3.4, the effect of extractive specialization, *LQe*, on patenting across mining technology subclasses is positive and statistically significant only for Mining Operations, the category most directly related to extractive activities. By contrast, mining service specialization, *LQs*, is positive and statistically significant across most technological subclasses, with the exception of Processing and Environmental technologies. As shown in Table A3.3, these two categories are also those most affected by the excess-zero problem in the dependent variable. However, even in Table 3.5, where we repeat the estimates using a PPML model with regional effects, we do not find robust evidence of a positive and statistically significant for these two subclasses.

In Table 3.5, we repeat the estimates using a PPML model with regional effects. Year fixed effects are not included in these class-specific specifications because the convergence problems discussed above, including those arising when independent variable is combined with regional and year fixed effects, become more pronounced when patent classes are considered separately. Patent classes differ substantially in the number and geographical distribution of patent families and, consequently, in the number of regions providing informative observations. For each class, regions in which patenting is always zero provide no within-region information and are excluded by the fixed-effects PPML estimator. Adding year fixed effects would further increase the dimensionality of the models and create convergence difficulties, as the estimator would have to account simultaneously for regional and time-specific effects in the presence of a large and class-specific number of zero outcomes. We therefore retain regional fixed effects only to obtain consistently convergent and comparable estimates across patent classes [84].

[84]Note that the PPML estimates are sensitive to the inclusion of population density even in specifications estimated without the high-dimensional fixed effects absorbed by *ppmlhdfe*. This sensitivity therefore does not result solely from the overlap between population density and regional fixed effects, but also from the nonlinear structure of PPML. Because PPML specifies the conditional mean exponentially, adding population density changes the predicted outcome for every observation and, consequently, each region's contribution to the maximisation of the log-pseudolikelihood. This is particularly relevant for regions with higher predicted levels of patenting. Once

In Table 3.5, *LQs* remains positive and statistically significant for all the other subclasses, while the coefficient estimates for *LQe* once again appear highly unstable and not robust across specifications. Compared with the previous baseline results in Table 3.4, the KPF inputs (human capital and R&D) are positive and strongly significant in almost all specifications, with the exception, again, of Processing and Environmental technologies. These exceptions risk to be related to the very sparse distribution of patenting activity in these subclasses, which limits within-region variation and makes the estimates more sensitive to the choice of estimator and specification. At the same time, we cannot exclude the possibility that these results also reflect some degree of model misspecification, as Processing and Environmental technologies may follow innovation dynamics that are not fully captured by the regional controls included in the model.

Table 3.4: Impact on mining extraction and service specialization and on mining technologies (2000–2021). FE estimates by class

VARIABLES	(1) Automation	(2) Environmental	(3) Exploration	(4) Metallurgy	(5) Mining Operational	(6) Processing	(7) Transport
L3.LQe	0.072	0.025	0.944	0.119	0.376*	0.007	0.134
	(0.051)	(0.038)	(0.602)	(0.087)	(0.209)	(0.050)	(0.085)
L3.LQs	0.318***	0.110	3.361**	0.455**	1.308***	0.030	0.535***
	(0.076)	(0.124)	(1.640)	(0.194)	(0.401)	(0.203)	(0.164)
L3.H	0.025	-0.000	0.084	0.107	0.028	-0.003	-0.028
	(0.026)	(0.026)	(0.300)	(0.125)	(0.153)	(0.019)	(0.039)
L3.R&D	0.001*	0.002**	0.015**	0.005*	0.008***	0.002*	0.001
	(0.001)	(0.001)	(0.007)	(0.003)	(0.003)	(0.001)	(0.001)
L3.ln(GDP per capita)	-0.007	0.001	0.012	-0.002	-0.017	-0.003	-0.007
	(0.005)	(0.004)	(0.033)	(0.008)	(0.016)	(0.004)	(0.005)
L3.ln(Pop. Density)	-0.008	0.035**	0.171*	0.045*	0.072	0.006	0.003
	(0.014)	(0.014)	(0.098)	(0.025)	(0.057)	(0.013)	(0.015)
Constant	0.094	−0.185*	-1.045	-0.235	-0.218	-0.007	0.061
	(0.116)	(0.099)	(0.773)	(0.193)	(0.412)	(0.088)	(0.104)
Observations	4,693	4,693	4,693	4,693	4,693	4,693	4,693
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2 within	0.110	0.0859	0.255	0.105	0.206	0.0405	0.132
R^2 between	0.116	0.0349	0.0333	0.0289	0.0303	0.0741	0.0563

Note: Robust and clustered standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages.

population density is included, the maximisation procedure may attribute to it part of the variation previously captured by the LQ coefficients, thereby changing both their magnitude and precision. In a linear model, by contrast, population density enters additively and has only a weak partial correlation with the LQs; its inclusion therefore produces a much smaller change in their estimated coefficients.

Table 3.5: Impact on mining extraction and service specialization and on mining technologies (2000–2021). PPML estimates by class

VARIABLES	(1) Automation	(2) Environmental	(3) Exploration	(4) Metallurgy	(5) Mining Operational	(6) Processing	(7) Transport
L3.LQe	-3.362	-4.143	-0.180	-2.969	-0.249	-2.274	-0.229
	(4.462)	(4.110)	(1.757)	(3.271)	(1.771)	(4.166)	(3.074)
L3.LQs	4.645**	-0.165	1.600***	2.635***	1.221**	-1.204	3.168***
	(2.213)	(0.901)	(0.580)	(0.934)	(0.506)	(2.315)	(0.899)
L3.H	6.371***	0.929	3.248**	5.022**	2.537**	0.215	4.762***
	(2.365)	(1.349)	(1.509)	(2.242)	(1.121)	(3.145)	(1.807)
L3.R&D	0.046	0.035	0.049**	0.089**	0.029**	0.045	0.032
	(0.036)	(0.022)	(0.023)	(0.043)	(0.014)	(0.035)	(0.028)
L3.ln(GDP per capita)	2.118	1.631***	1.467	1.071	1.666**	2.394*	1.882
	(1.423)	(0.629)	(0.912)	(1.260)	(0.685)	(1.403)	(1.202)
L3.ln(Pop. Density)	−5.177**	2.283	-1.133	-1.404	-0.015	0.591	-3.418
	(2.327)	(1.496)	(0.853)	(2.650)	(0.910)	(2.891)	(2.162)
Constant	-4.279	−32.789***	-13.331	-9.901	−20.539**	-32.175	-8.715
	(19.124)	(10.914)	(10.854)	(17.029)	(8.865)	(21.504)	(10.564)
Observations	2,014	2,831	3,401	2,774	3,534	2,166	2,584
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No	No	No
Pseudo R^2	0.209	0.165	0.423	0.249	0.296	0.224	0.231

Note: Robust and clustered standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages.

3.5.1 Spatial Econometric Results

In this section, we report the spatial econometric estimates for total mining patent families identified. All specifications include regional and year fixed effects. Note that the implementation of spatial econometric models in Stata does not allow the use of heteroskedasticity-robust standard errors in these specifications. In Table 3.6 we first test our hypothesis using a contiguity-based spatial weights matrix, which identifies neighbouring regions on the basis of shared borders. This specification captures short-distance spatial interactions and is particularly suitable for testing whether mining specialisation in extraction and mining services in immediately adjacent regions affect local mining patenting. In Table 3.6 we progressively move from a spatial error model (SEM), which controls for residual spatial dependence, to SLX specifications including spatial lags of the explanatory variables, and Spatial Durbin Error Models (SDEM), which combine spatially lagged explanatory variables with a spatially autocorrelated error term. The table reports direct, indirect, and total impacts computed using the *estat impact* post-estimation command in

Stata.[85]

As a robustness exercise, the final column of Tables 3.6 and 3.7 reports a General Nesting Spatial (GNS) specification. The GNS model simultaneously includes a spatial lag of the dependent variable, spatial lags of the two mining-specialisation variables, and a spatially autocorrelated error term. It therefore allows for three distinct forms of spatial dependence: interdependence in regional patenting outcomes, spillovers associated with mining specialisation, and residual dependence generated by omitted spatially correlated factors. By encompassing these channels within the same specification, the GNS model provides a more general benchmark against which the results from the more restrictive SEM, SLX, and SDEM specifications can be evaluated. The persistence of the estimated impacts of mining-service specialisation in this model indicates that the main findings are not driven exclusively by a single representation of spatial dependence.

The results show a clear and robust pattern. Mining-service specialisation has a positive and statistically significant effect on mining patenting across all specifications, both through direct and indirect effects. By contrast, we find no statistically significant evidence that extraction specialisation is associated with greater mining patenting in any of the spatial specifications. This pattern is robust to the progressive inclusion of controls. Columns 3 and 5 add regional controls such as GDP per capita and population density. Columns 4 and 6 further test an extended knowledge production function by spatially lagging human capital and R&D showing a positive and significant indirect effect of R&D, suggesting that neighboring regions' innovative capacity also contributes to the development of mining technologies. Column 7 adds the spatial lag of the dependent variable while retaining spatially lagged explanatory variables and spatial error dependence; the positive direct, indirect, and total impacts of mining-service specialisation remain statistically significant. The spatial error coefficient is positive and highly significant in the SEM, SDE, and GNS models, confirming the presence of residual spatial dependence.

[85]For a given explanatory variable, the matrix of partial effects is $(I - \rho W)^{-1}(\beta I + \theta W)$. The direct impact is the average of its diagonal elements, whereas the indirect impact is the average sum of its off-diagonal elements; the total impact is their sum. These impacts therefore incorporate the spatial feedback generated by $\rho W y$ and cannot be inferred directly from the estimated coefficients β and θ.

Table 3.6: Impact of mining extraction and service specialisation on mining technologies, 2000–2021. Spatial regression approach

VARIABLES	(1) SEM	(2) SLX	(3) SLX	(4) SLX	(5) SDE	(6) SDE	(7) GNS
Spatial lag of Y (ρ)							−0.212**
							(0.106)
Spatial error (λ)	0.270***				0.248***	0.251***	0.428***
	(0.028)				(0.028)	(0.028)	(0.084)
Direct							
L3.LQe	0.185	0.137	0.165	0.141	0.171	0.139	0.120
	(0.137)	(0.137)	(0.137)	(0.137)	(0.135)	(0.135)	(0.135)
L3.LQs	2.179***	2.075***	2.055***	2.039***	2.063***	2.040***	2.022***
	(0.116)	(0.114)	(0.113)	(0.113)	(0.111)	(0.111)	(0.111)
L3.H	0.108	0.192*	0.059	0.155	0.095	0.169	0.179
	(0.111)	(0.102)	(0.107)	(0.118)	(0.113)	(0.118)	(0.120)
L3.R&D	0.021***	0.021***	0.019***	0.016***	0.018***	0.016***	0.016***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
L3.ln(GDP per capita)			0.023	0.023	0.035	0.033	0.034
			(0.027)	(0.027)	(0.030)	(0.030)	(0.032)
L3.ln(Pop. Density)			0.290***	0.261***	0.301***	0.273***	0.281***
			(0.069)	(0.069)	(0.072)	(0.073)	(0.076)
Indirect							
L3.LQe		-0.202	-0.149	-0.186	-0.375	-0.434	−0.491*
		(0.280)	(0.280)	(0.280)	(0.301)	(0.301)	(0.279)
L3.LQs		3.067***	3.005***	3.010***	3.044***	3.031***	2.745***
		(0.237)	(0.237)	(0.237)	(0.249)	(0.249)	(0.262)
L3.H				-0.127		-0.121	-0.100
				(0.111)		(0.119)	(0.117)
L3.R&D				0.009***		0.011***	0.011***
				(0.002)		(0.003)	(0.003)
L3.ln(GDP per capita)							-0.005
							(0.005)
L3.ln(Pop. Density)							−0.038*
							(0.020)
Total							
L3.LQe	0.185	-0.066	0.016	-0.045	-0.204	-0.295	-0.371
	(0.137)	(0.294)	(0.295)	(0.294)	(0.334)	(0.335)	(0.315)
L3.LQs	2.179***	5.142***	5.059***	5.049***	5.107***	5.070***	4.767***
	(0.116)	(0.236)	(0.237)	(0.237)	(0.264)	(0.265)	(0.280)
L3.H	0.108	0.192*	0.059	0.028	0.095	0.047	0.079
	(0.111)	(0.102)	(0.107)	(0.124)	(0.113)	(0.141)	(0.134)
L3.R&D	0.021***	0.021***	0.019***	0.026***	0.018***	0.027***	0.028***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
L3.ln(GDP per capita)			0.023	0.023	0.035	0.033	0.029
			(0.027)	(0.027)	(0.030)	(0.030)	(0.027)
L3.ln(Pop. Density)			0.290***	0.261***	0.301***	0.273***	0.243***
			(0.069)	(0.069)	(0.072)	(0.073)	(0.067)
Observations	4,693	4,693	4,693	4,693	4,693	4,693	4,693
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial error	Yes	No	No	No	Yes	Yes	Yes
Pseudo R^2	0.349	0.399	0.043	0.060	0.041	0.059	0.056
Log likelihood	2231	2269	2279	2287	2317	2326	2327
AIC	-4413	-4489	-4503	-4515	-4578	-4592	-4593
BIC	-4258	-4327	-4329	-4328	-4397	-4398	-4393
Wald spatial terms	92.9***	168.0***	161.0***	177.5***	226.0***	244.0***	274.3***

Note: standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages. All specifications include regional and year fixed effects. Spatial weights are measured using a contiguity matrix, normalised by the maximum eigenvalue.

In Table 3.7, we estimate the same spatial specifications using an inverse-distance spatial weights matrix. This alternative matrix assigns larger weights to geographically closer regions and progressively decreasing weights to more distant regions. The rationale is that knowledge spillovers may not be limited to strictly contiguous regions, as spillovers may also occur between regions that are geographically close even when they are not directly adjacent. We censor the matrix at 350 km to restrict spillovers to a plausible local range and to avoid assigning positive spatial links to distant region pairs. Across all specifications, *LQs* retains positive and statistically significant direct, indirect, and total impacts. Neither the direct nor the indirect impacts of *LQe* are statistically significant, confirming that the spatial results are specifically associated with mining-service specialisation.

Table 3.7: Impact of mining extraction and service specialisation on mining technologies, 2000–2021. Spatial regression approach

VARIABLES	(1) SEM	(2) SLX	(3) SLX	(4) SLX	(5) SDE	(6) SDE	(7) GNS
Spatial lag of Y (ρ)							0.179
							(0.118)
Spatial error (λ)	0.240**				0.347***	0.346***	0.238*
	(0.103)				(0.099)	(0.101)	(0.131)
Direct							
L3.LQe	0.166	0.169	0.203	0.217	0.206	0.220	0.222
	(0.138)	(0.138)	(0.137)	(0.138)	(0.137)	(0.138)	(0.138)
L3.LQs	2.422***	2.389***	2.359***	2.366***	2.353***	2.360***	2.398***
	(0.112)	(0.112)	(0.112)	(0.112)	(0.112)	(0.112)	(0.115)
L3.H	0.059	0.135	-0.020	-0.052	-0.059	-0.062	-0.059
	(0.106)	(0.104)	(0.109)	(0.116)	(0.111)	(0.117)	(0.116)
L3.R&D	0.023***	0.023***	0.021***	0.020***	0.020***	0.020***	0.020***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
L3.ln(GDP per capita)			0.039	0.038	0.053*	0.052*	0.052*
			(0.028)	(0.028)	(0.029)	(0.029)	(0.029)
L3.ln(Pop. Density)			0.341***	0.341***	0.354***	0.351***	0.353***
			(0.070)	(0.070)	(0.071)	(0.071)	(0.071)
Indirect							
L3.LQe		0.021	0.161	0.100	0.184	0.168	0.232
		(0.379)	(0.380)	(0.411)	(0.364)	(0.382)	(0.427)
L3.LQs		4.005***	3.893***	4.055***	4.481***	4.611***	4.893***
		(0.785)	(0.783)	(0.798)	(0.831)	(0.844)	(0.930)
L3.H				0.142		0.064	0.044
				(0.144)		(0.158)	(0.165)
L3.R&D				-0.002		0.000	0.000
				(0.003)		(0.003)	(0.004)
L3.ln(GDP per capita)							0.003
							(0.003)
L3.ln(Pop. Density)							0.019
							(0.014)
Total							
L3.LQe	0.166	0.190	0.364	0.317	0.390	0.388	0.454
	(0.138)	(0.398)	(0.399)	(0.432)	(0.393)	(0.410)	(0.458)
L3.LQs	2.422***	6.394***	6.252***	6.421***	6.834***	6.971***	7.291***
	(0.112)	(0.784)	(0.783)	(0.799)	(0.833)	(0.847)	(0.945)
L3.H	0.059	0.135	-0.020	0.090	-0.059	0.002	-0.015
	(0.106)	(0.104)	(0.109)	(0.151)	(0.111)	(0.167)	(0.176)
L3.R&D	0.023***	0.023***	0.021***	0.019***	0.020***	0.020***	0.020***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)	(0.004)
L3.ln(GDP per capita)			0.039	0.038	0.053*	0.052*	0.055*
			(0.028)	(0.028)	(0.029)	(0.029)	(0.030)
L3.ln(Pop. Density)			0.341***	0.341***	0.354***	0.351***	0.372***
			(0.070)	(0.070)	(0.071)	(0.071)	(0.076)
Observations	4,693	4,693	4,693	4,693	4,693	4,693	4,693
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spatial error	Yes	No	No	No	Yes	Yes	Yes
Pseudo R^2	0.355	0.352	0.022	0.020	0.021	0.020	0.015
Log likelihood	2189	2200	2212	2212	2217	2218	2219
AIC	-4331	-4350	-4370	-4367	-4379	-4375	-4375
BIC	-4176	-4188	-4195	-4180	-4198	-4182	-4175
Wald spatial terms	5.5**	26.0***	24.8***	26.1***	34.9***	35.8***	37.3***

Note: standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages. All specifications include regional and year fixed effects. Spatial weights are measured using an inverse-distance matrix, censored at 350 km and normalised by the maximum eigenvalue.

3.6 Concluding Remarks

This chapter analysed the regional dynamics of mining innovation in Europe by examining whether mining specialisation contributes to the development of mining technologies. The analysis provides three main findings:

First, the geography of mining technologies is not simply explained by the geography of extraction. Regions more specialised in mining extraction do not systematically display higher levels of mining patenting. This result is robust across the baseline fixed-effects specifications, the instrumental-variable estimates, the PPML robustness checks, and the heterogeneity analysis across technology classes. Even for technologies more directly related to upstream extraction processes, extraction specialisation does not show a stable positive effect.

Second, mining services play a much more central role. Specialisation in mining-related services has a positive and statistically significant effect on mining patenting across the main specifications and across most mining technology classes. This result is consistent with the view that technological development in mining is often driven by specialised suppliers, engineering firms, equipment producers, and service providers rather than by extraction firms alone. Mining services appear to capture a set of capabilities that are closer to the actual production of mining technologies: technical knowledge, engineering expertise, problem-solving capacity, and the ability to respond to operational needs emerging along the mining value chain.

Third, the spatial econometric results provide evidence of spillover effects related to mining-service specialisation under both the contiguity-based and inverse-distance matrices. Its direct, indirect, and total impacts remain positive and statistically significant, whereas no similarly robust evidence is found for extraction specialisation, whose direct and indirect impacts remain statistically insignificant.

The interpretation of the coefficients requires a distinction between conditional association and causal inference. In the baseline model, β_1 and β_2 can be interpreted causally only under the conditional-exogeneity assumption that, after accounting for the observed controls and regional and year fixed effects, no unobserved factor remains that is correlated with both regional mining

specialisation and patenting. Regional fixed effects absorb time-invariant characteristics, such as persistent geographical, institutional, and historical industrial differences, while year fixed effects account for shocks common to all regions. Lagging the explanatory variables also establishes temporal precedence. The 2SLS strategy is intended to address some of these endogeneity concerns, but its causal interpretation remains conditional on instrument relevance and, especially, on the exclusion restriction. The key identifying assumptions underlying all these estimators are not directly verifiable from the observed data, as they often require all relevant confounders to be either observed or absorbed by the included controls and fixed effects. The exogeneity assumption is therefore less credible than in research designs that exploit temporal variation and an explicit control group. This limits the extent to which the estimated coefficients can be interpreted as definitive causal effects. Nevertheless, the analysis is strengthened by a solid, theoretically grounded, and in-depth explanatory interpretation of the results. The theoretical and institutional framework developed throughout the chapter connects the estimated patterns to the distinct roles played by extractive firms and specialised mining-service providers within the mining innovation system.

From a policy perspective, these findings are important for understanding how industrial policy can promote mining innovation in Europe and avoid a purely extractive strategy that expands production capacity without strengthening the broader technological base of the sector. These findings point to the need for differentiated, place-based strategies under the CRMA/OSA: strengthening innovation in mining-intensive regions through targeted support for operational technologies and skill formation, while simultaneously building processing and technology-supplier capacities in regions (Dessì et al., 2026). In doing so, policy can better align strategic supply-chain objectives for SCRMs with environmental goals, reducing the risk that an expansion of mining activity translates into enclave-type outcomes with limited local upgrading.

These findings should be interpreted in light of several limitations. First, the analysis focuses on the development of patented mining technologies. Patents capture only some forms of technological activity and may not adequately reflect innovation. This limitation is particularly relevant in mining, where firms are highly capital-intensive and innovation may involve organisational and operational know-how, incremental improvements in production practices and adaptations to

site-specific geological conditions. Moreover, mining firms typically operate under geographically exclusive exploration or extraction permits, which already provide a degree of protection from direct competition within a given deposit or concession area. As a result, they may face weaker incentives to use patents as a mechanism for appropriating returns from innovation.

Second, because of both conceptual complexity and data limitations, the analysis cannot fully account for the role of institutions. The legal and regulatory framework governing mining is fragmented and often operates across multiple levels of governance, making regulatory conditions difficult to measure consistently across European regions. Mining associations, industry networks, and other intermediary organisations are also difficult to identify and geographically locate with the data available to us. In addition, the analysis is unable to capture the role of the Social Licence to Operate, relationships with local communities, and forms of social acceptance or contestation that may influence both mining activity and the direction of technological development. We consider these institutional and social dimensions the most important omitted factors.

Third, the indicator of mining-services specialisation, (LQs), does not encompass the full range of mining equipment, technology, and services firms. It captures workers employed in activities classified as mining services, but it does not fully identify specialised suppliers located in other manufacturing and service sectors. In particular, producers of mining machinery, equipment and instruments may be classified outside the mining-services categories used in the analysis.

Finally, the absence of sufficiently detailed regional and sector-specific data on mining production, firm output, investment, and R&D expenditure limits the set of controls that can be included in the empirical analysis. It is therefore not possible to distinguish fully between the effects of regional specialisation and those associated with differences in the scale of production, intensity of technological investment, firm size, or internal R&D capabilities. Although the empirical strategy addresses several sources of unobserved heterogeneity and potential endogeneity, these data constraints prevent a complete identification of all the mechanisms underlying the observed relationships.

Future research should extend the analysis to incorporating some these factors more explicitly, even if this requires restricting the analysis to a smaller number of regions in order to examine

institutional conditions in greater depth. A more geographically focused approach could allow for a better assessment of the legal, regulatory, organisational, and social factors that may shape the development and adoption of mining technologies. Firm-level analysis may also allow to investigate more closely the relationships between mining firms and the different types of service and equipment providers. This would help clarify the structure of both interregional and cross-border innovation networks linking mining firms, METS companies, universities and other relevant actors. Future research may also address the heterogeneity of the technologies required for the extraction and processing of different minerals and under different geological and production conditions. The technological needs of mining operations vary substantially according to the characteristics of the deposit, the extraction method, the mineral being produced, and the stage of the value chain considered. Finally, another important direction concerns policy evaluation. Future studies could assess the effects of specific regulatory changes, public funding programmes, industrial strategies, and recent European initiatives on the development and adoption of mining technologies. Where possible, the use of quasi-experimental methods could help identify whether these policies effectively strengthen regional technological capabilities, promote local upgrading, and support the emergence of more integrated mining value chains.

Conclusions

One of the main conclusion emerging from this thesis is that the issue of CRMs cannot be understood as a simple problem of physical scarcity, trade dependence, or industrial delay. Rather, it is a complex question in which geology, economics, geography, industrial policy, technological innovation, environmental regulation, and social conflict are deeply intertwined. For this reason, relying on a single disciplinary perspective risks producing only a partial understanding of the phenomenon. SCRMs are not merely resources located underground, nor are they simply productive inputs for green and digital technologies. They represent the point of intersection between natural constraints, productive capabilities, technological knowledge, firm strategies, geopolitical interests, and highly differentiated territorial conditions.

A first element highlighted by this thesis concerns the role of terminology. The categories used in the public debate and in European strategies — Critical Raw Materials, Strategic Raw Materials, resources, reserves, deposits, extraction, processing, refining — are not neutral. On the contrary, they can significantly influence how the problem is measured, interpreted, and addressed. Ambiguous or non-harmonised definitions may distort comparisons across countries, materials, and stages of production. They may also lead to excessive simplifications in public policy. The risk is to treat as equivalent phenomena that belong to different stages of the supply chain: the geological presence of a mineral, the technical and economic possibility of extracting it, the capacity to transform it into mining output, the subsequent metallurgical production, and finally its use as a material input in manufacturing sectors. This distinction is crucial. The presence of a resource underground does not automatically imply the possibility of transforming it into an input available for European industry. Between geological endowment and manufacturing use, there are intermediate stages that may take place in different locations, be controlled by different firms,

and require different technological capabilities. Extraction is necessarily tied to the location of mineral deposits. Processing is usually linked to the proximity of mines for logistical, technical, and efficiency reasons, but this proximity depends largely on the specific case. Refining and metallurgy, by contrast, may be located elsewhere, even in other very distant countries, and may depend on industrial, energy, and technological capabilities that do not necessarily coincide with those of mining regions. For this reason, speaking generically of the "production" of raw materials risks obscuring the differences between mine output, metallurgical output, and the productive inputs actually available to manufacturing.

This complexity is further aggravated by the quality and fragmentation of available data. The problem does not concern only data on Europe's natural resource endowment, which is to some extent a global issue, especially with regard to mineral resources and economically extractable reserves. It also concerns the lack of fully harmonised and granular data at the European level on mining activities, the different stages of processing and refining, and the connection between these stages and the manufacturing sectors that use these materials. Building a coherent empirical picture often requires the manual integration of heterogeneous sources, textual documents, indicators that are not always comparable, and databases with incomplete coverage. This limits the ability to assess precisely how realistic European policy targets are, where they can be pursued, and which territories are expected to bear their costs.

The CRMA certainly represents an important step, because it makes the role of mining in the European strategy more explicit and places critical raw materials within the broader agenda of OSA. In this sense, it is as if a veil of opacity surrounding the mining dimension of Europe's technological transition has only recently begun to be lifted. However, the fact that mining has returned to the centre of policy attention does not mean that the European strategy is already able to address its full implications. The targets on extraction, processing, recycling, and supply diversification define a clear political direction, but they remain constrained by geological, technological, social, and territorial conditions.

A central risk is to interpret the European strategy as a policy for expanding mining supply without sufficiently examining the capabilities that make such expansion possible, sustainable, and territorially embedded. If strategic projects are concentrated in a limited number of resource-

endowed territories, but are not accompanied by local capabilities, technical skills, specialised suppliers, adequate infrastructure, and processes of community involvement, their effects may remain limited. They may increase extraction or metallurgical capacity without producing a real strengthening of the European technological base. In that case, the risk is to reproduce enclave forms of development, in which extractive activities generate localised environmental and social pressures but limited upgrading effects for the regional economic system. From this perspective, the social dimension remains one of the most uncertain components of the European strategy. The opening or expansion of mining projects does not depend only on the presence of deposits and the availability of capital. It also depends on the social acceptability of extraction activities, the perceived environmental costs, the relationship between firms, local institutions and communities, and the ability to secure a SLO. Where communities perceive projects as top-down impositions or as forms of territorial exploitation, social resistance may delay or prevent investment. The social question, therefore, should not be considered an external obstacle to industrial policy, but an internal condition of the economic and institutional feasibility of mining projects.

Technological innovation plays a decisive role because it can alter the relationship between natural resources, extraction costs, and productive possibilities. Innovation does not only affect the quantity of material that can be extracted. It also affects the economic convenience of extracting a specific material that is present in a given form, quantity, and quality within a known mineral deposit. More advanced technologies can improve the recovery of by-products, reduce processing costs, increase productivity, mitigate environmental impacts, improve worker safety, and make resources economically exploitable that were previously not viable. In this sense, innovation can shift the boundary between what is geologically present and what is economically producible.

However, the results of this thesis suggest that innovation in mining does not necessarily emerge where extraction takes place. Regional specialisation in extraction activities does not appear to translate automatically into greater development of mining technologies. Rather, the evidence points to a stronger association between mining innovation and mining-related services, specialised suppliers, engineering firms, equipment producers, and other actors involved in the development of technological solutions for different stages of the mining supply chain. At the same time, the local development of mining technologies should not be underestimated,

especially considering that some technologies may not be easily scalable when they depend on the geological characteristics of the deposit, the quality of the ore, the regulatory context, environmental conditions, and locally available capabilities. For this reason, investments aimed only at expanding the mining industry risk being insufficient to develop the capabilities required by OSA.

Appendix 1

Supplementary Tables

Table A1.1: Strategic Projects under CRMA (2025): Extraction

Name	Promoter	Country	SRM	GUO	GUO Country
Extra-EU					
Balakhivka Graphite Deposit	Pobuzhzhya's Development LLC	Ukraine	Graphite	BGV Group Management (Gennadii Butkevych)	Ukraine
Greenland Graphite a/s and Norgraph a/s	GreenRoc Strategic Materials Plc	Greenland and Norway	Graphite	GreenRoc Strategic Materials Plc	United Kingdom
Integrated Dumont Nickel Project	Magneto Investments Limited Partnership	Canada	Nickel, Cobalt	Waterton Global Resource Management	Canada
Jadar	Rio Tinto (Rio Sava Exploration doo)	Serbia	Lithium, Boron	Rio Tinto Group	United Kingdom/Australia
Maniry Graphite Mine Project	Evion Group NL	Madagascar	Graphite	Evion Group NL	Australia
Nussir	Nussir ASA	Norway	Copper	Blue Moon Metals Inc.	Canada
Sarytogan Graphite Project	Sarytogan Graphite Limited	Kazakhstan	Graphite	Sarytogan Graphite Limited (ASX-listed)	Australia
Songwe Hill Rare Earths	Mkango Resources Ltd.	Malawi	REEs	Mkango Resources Ltd.	Canada
Tungsten West	Tungsten West PLC	United Kingdom	Tungsten	Tungsten West PLC	United Kingdom
Zandkopsdrift	Frontier Rare Earths Limited	South Africa	REEs, Manganese	Frontier Rare Earths Limited	South Africa
EU					

Continued on next page

Table A1.1 continued

Name	Promoter	Country	SRM	GUO	GUO Country
Ageli	Eramet	France	Lithium	Eramet S.A.	France
Aguablanca Project	Rio Narcea Recursos S.A.	Spain	Cobalt, PGMs, Nickel, Copper	Spain	Canada
Barroso Lithium Project	Savannah Lithium Unipessoal, Lda	Portugal	Lithium	United Kingdom	United Kingdom
Chvaletice Manganese Project	Euro Manganese Inc.	Czechia	Manganese	Euro Manganese Inc.	Canada
Cinovec lithium project	Geomet s.r.o.	Czechia	Lithium	Geomet s.r.o.	Czechia
Emili	Imerys Ceramics France	France	Lithium	Imerys Ceramics France	France
Keliber Lithium Project	Keliber Technology Oy	Finland	Lithium	Keliber Oy	Finland
Kolmisoppi	Terrafame Ltd	Finland	Nickel, Cobalt	Terrafame Ltd	Finland
La Parrilla Mine (P6 Metals)	Iberian Resources Spain	Spain	Tungsten	Iberian Resources Spain	Spain
Las Navas	Lithium Iberia, S.L.	Spain	Lithium	Lithium Iberia, S.L.	Spain
Metlen BAUX-EU, GALLANT, LEADER	Metlen Energy and Metals and European Bauxites	Greece	Bauxite, Gallium	Metlen Energy and Metals	U.S.A.
Mina Doade Project	Recursos Minerales de Galicia, S.A.	Spain	Lithium	Recursos Minerales de Galicia, S.A.	Spain
Mining project El Moto	Abenojar Tungsten S.L.	Spain	Tungsten	Abenojar Tungsten S.L.	Spain
Neves Corvo - 3rd Silo, Lombador, Semblana	Somincor	Portugal	Copper	Somincor - Empresa de Desenvolvimento Mineiro	Portugal
Polymetallic primary sulphite project PMR project	Cobre las Cruces S.A.U.	Spain	Copper	Cobre las Cruces S.A.U.	Spain
ReeMAP Project: Malmberget, Lulea Industrial Park, Per Geijer	LKAB (Luossavaara-Kirunavaara AB)	Sweden	REEs	LKAB	Sweden
Romano Mine	Lusorecursos Portugal Lithium S.A.	Portugal	Lithium	Lusorecursos Portugal Lithium S.A.	Portugal

Continued on next page

Table A1.1 continued

Name	Promoter	Country	SRM	GUO	GUO Country
Rovina	Euro Sun Mining Inc.	Romania	Copper	Euro Sun Mining Inc.	Canada
Sakatti Project	Anglo American Services (UK) Ltd.	Finland	Cobalt, PGMs, Copper, Nickel	Anglo American plc	United Kingdom
Salrom Baia de Fier	Societatea Nationala a Sarii S.A.	Romania	Graphite	Societatea Nationala a Sarii S.A.	Romania
Talga Natural Graphite One	Talga AB	Sweden	Graphite	Talga AB	Sweden
Verde Magnesium	Verde Magnesium SRL	Romania	Magnesium	Verde Magnesium SRL	Romania
Zero Carbon Lithium	Vulcan Energie Ressourcen GmbH	Germany	Lithium	Vulcan Energie Ressourcen GmbH	Germany

Source: Own elaboration on European Commission, selected strategic projects under the CRMA, and ORBIS (2025).
Note: Information on the Global Ultimate Owner (GUO) was manually checked using ORBIS and refers to the sponsor of the project. Tot: 10 (Extra-EU) + 23 (EU).

Table A1.2: Strategic Projects under CRMA (2025): Processing

Name	Promoter	Country	SRM	GUO	GUO Country
Extra-EU					
CaledoNi	Societe Le Nickel	New Caledonia	Nickel	Eramet	France
Norgraph a/s and Greenland Graphite a/s	GreenRoc Strategic Materials Plc	Greenland/Norway	Graphite	GreenRoc Strategic Materials Plc	United Kingdom
Kobaloni Energy Zambia Ltd	Kobaloni Energy Zambia Limited	Zambia	Cobalt	Kobaloni Energy Zambia Limited	Zambia
SMP Nickel and Cobalt Refinery Restart	Jervois Brasil Metalurgia Ltda.	Brazil	Nickel, Cobalt	Jervois Global Limited	Australia
EU					
Ageli	Eramet	France	Lithium	Eramet	France
BAM4EVER (Phase I&II)	Tokai COBEX Savoie	France	Graphite	Tokai Carbon Co. Ltd	Japan
CAREMAG	Caremag SAS	France	REEs, Boron	Caremag	France
Chvaletice Manganese Project	Euro Manganese Inc.	Czechia	Manganese	Euro Manganese Inc.	Canada
Cinovec Lithium Project	Geomet s.r.o.	Czechia	Lithium	Czechia Rep.	Czechia
CO_2 Graphite	UP Catalyst OU	Estonia	Graphite	UP Catalyst OU	Estonia
EMILI	Imerys Ceramics / Lithium France	France	Lithium	Groupe Bruxelles Lambert SA	Belgium
European Initiative for Graphite Prod.	NGC Battery Materials GmbH	France, Germany, Namibia	Graphite	Northern Graphite Corporation	Canada
GePETO	Umicore	Belgium	Germanium	Umicore	Belgium
GALLICAM	Sibanye-Stillwater Sandouville Refinery	France	Nickel, Cobalt, Lithium, Graphite, Manganese, Copper	Sibanye-Stillwater Limited	South Africa
Hycamite TCD Technologies	Hycamite TCD Technologies Ltd	Finland	Graphite	Hycamite TCD Technologies	Finland

Continued on next page

Table A1.2 continued

Name	Promoter	Country	SRM	GUO	GUO Country
Jervois Finland Cobalt Refinery Exp.	Jervois Finland Oy	Finland	Cobalt	Jervois Global Limited	Australia
Keliber Lithium	Keliber Technology Oy	Finland	Lithium	Sibanye-Stillwater Limited	South Africa
Lift One	Lifthium Energy S.A.	Portugal	Lithium	Jose de Mello Capital, S.A.	Portugal
Lithium Hydroxide Converter Guben	Rock Tech Guben GmbH	Germany	Lithium	Rock Tech Lithium Inc.	Canada
Metlen BAUX-EU, GALLANT, LEADER	Metlen Energy and Metals and European Bauxites	Greece	Bauxite, Gallium	Metlen Energy and Metals	U.S.A.
Neves Corvo - 3rd Silo, Lombador, Semblana	Somincor	Portugal	Copper	Somincor - Empresa de Desenvolvimento Mineiro	Portugal
P6 Metals	Iberian Resources Spain	Spain	Tungsten	Iberian Resources Spain	Spain
Polymetallic Primary Sulphide Project	Cobre Las Cruces S.A.U.	Spain	Copper	First Quantum Minerals Ltd	Canada
Pulawy Rare Earths Separation Plant	Mkango Resources Ltd.	Poland	REEs	Mkango Resources Ltd.	Canada
ReeMAP Project (Malmberget / Per Geijer)	LKAB	Sweden	REEs	Regeringskansliet	Sweden
Sakatti	Anglo American Services (UK) Ltd	Finland	Cobalt, Nickel, Copper, PGMs	Anglo American plc	United Kingdom
Viridian Lithium	Viridian Lithium	France	Lithium	Viridian Lithium	France

Source: Own elaboration on European Commission, selected strategic projects under the CRMA, and ORBIS (2025).
Note: Information on the Global Ultimate Owner (GUO) was manually checked using ORBIS and refers to the sponsor of the project. Tot: 4 (Extra-EU) + 23 (EU).

Table A1.3: Strategic Projects under CRMA (2025): Recycling + Substitution

Name	Type	Promoter	Country	SRM	GUO	GUO Country
Extra-EU						
-	-	-	-	-	-	-
EU						
ProHiPerSi	Substitution	PCC Thorion GmbH	Germany	Graphite	PCC SE	Germany
ReGAIN	Substitution	Umicore	Belgium	Germanium	ProHiPerSi	Belgium
Alpha Project	Recycling	Solvay Chimica Italia Spa	Italy	PGMs	Solvay SA	Belgium
CirCular	Recycling	Atlantic Copper SLU	Spain	Copper, PGM, Nickel	Freeport-McMoRan Inc.	USA
Hydrometallurgy	Recycling	Orano Batteries	France	Lithium, Cobalt, Nickel, Manganese, Graphite	France (Gov.)	France
LIFE-22-ENV-IT-INSPIREE	Recycling	Itelyum Regeneration SpA	Italy	REEs	Verde Holdings S.C.A.	Luxembourg
MagFactory	Recycling	MagREEsource	France	REEs	MagREEsource	USA
NorthCYCLE	Recycling	Northvolt Revolt AB	Sweden	Manganese, Lithium, Graphite, Nickel, Cobalt	Northvolt Revolt AB	Sweden
POLVOLT	Recycling	Elemental Strategic Metals Sp. z o.o.	Poland	Nickel, Copper, Cobalt, Lithium, PGMs, Manganese	Elemental Holding	Luxembourg
Portovesme CRM Hub	Recycling	Portovesme srl	Italy	Lithium, Nickel, Cobalt, Copper	Glencore plc	United Kingdom
Project Fortum Hydromet	Recycling	Fortum Battery Recycling Oy	Finland	Lithium, Copper, Nickel, Cobalt	Valtioneuvoston Kanslia	Finland
RECOVER-IT	Recycling	Circular Materials s.r.l.	Italy	Copper, Nickel, PGMs	Circular Materials s.r.l.	Italy

Source: Own elaboration on European Commission, selected strategic projects under the CRMA, and ORBIS (2025).
Note: Information on the Global Ultimate Owner (GUO) was manually checked using ORBIS and refers to the sponsor of the project. Tot: 0 (Extra-EU) + 12 (EU).

Appendix 2

Supplementary Tables

Table A2.1: Countries considered in regions of the world for Figure 2.2

Region of the World	Countries
Europe	Italy, France, Germany, Spain, Poland, Ireland, Finland, Sweden, Norway, Portugal, Romania, Austria, Belgium, Greece, Czechia, Hungary, Slovakia, Netherlands, Slovenia, Luxembourg, Croatia, Bulgaria, Denmark, Estonia, Latvia, Lithuania, Cyprus, Malta, United Kingdom
Africa	Egypt, Mozambique, Namibia, Zambia, Mauritania, South Africa, Dem. Rep. Congo, Botswana, Nigeria, Niger, Algeria, Côte d'Ivoire, Somalia, Zimbabwe, Sudan, Ethiopia, Ghana, Kenya, Morocco, Eritrea, Cameroon, Mali, Guinea, Madagascar, Sierra Leone, Angola, Chad, Burkina Faso, Senegal, Liberia, Tanzania, Central African Rep., South Sudan, Burundi, Rwanda, Djibouti, Eswatini, Equatorial Guinea, Guinea-Bissau, Mauritius, Libya, Western Sahara
Latin America	Mexico, Brazil, Argentina, Colombia, Chile, Peru, Venezuela, Bolivia, Paraguay, Ecuador, Uruguay
Canada	Canada
USA	USA
China	China
Russia	Russia

Supplementary Figures

Figure A2.1: Share of global resources for all SRMs considered



Source: own elaborations on S&P Global data (2025).
Note: shares are computed on global endowment of resources (t), across mining properties in mining projects. The figure reports the SRMs listed in Table 2.3, excluding Aluminium/Bauxite, Copper, REE, Lithium, and Cobalt.

Figure A2.1 continued



Source: own elaborations on S&P Global data (2025).
Note: shares are computed on global endowment of resources (t), across mining properties in mining projects.

Figure A2.1 continued



Source: own elaborations on S&P Global data (2025).
Note: shares are computed on global endowment of resources (t), across mining properties in mining projects.

Supplementary Notes

In EGDI we use the "occurrencetype" indicator to distinguish deposits from other kinds of occurrences, but this classification process requires additional effort as the indicator does not work for France and Poland as each occurrence is simply classified as "field"[86]. However, for France, large part of the information is recovered using another indicator the "*importance*" indicator. This indicator reflects the size of the commodity within the deposits and is intended to distinguish between small, medium, large, and very large deposits[87]. According to the INSPIRE Registry, such EU ranking is based on a statistical study of a large set of deposits worldwide, and the classification is based on the potential endowment (resources). The *importance* indicator has plenty of missing values, and for some countries (e.g., Italy and Hungary), coverage is completely absent, but fortunately it works relatively well for France. Therefore, we classified the observations as deposits when the *importance* indicator takes at least the category of "small deposit" for France. For Poland, this approach was not feasible due to the near-complete absence of the variable, but a good level of coverage was available for reserve estimates. The estimate of mineral resources, as we already seen with S&P Global data, represents a quantitative assessment of the material present underground in the deposit. This measure in EGDI is unusable due to the numerous missing values and partial information, but fortunately it works quite well at least for Poland. Therefore, we classified an occurrence as a deposit if, for a given commodity, its estimated resources were greater than or equal to the minimum value observed in at least one deposit of the same commodity classified as a "small deposit" by the previous cited *importance* indicator within the entire dataset. We excluded values of 0 or 1 ton[88], which were assumed as data entry errors.

[86] A field indicates a studied area for geological purposes, and this could include both deposits and simply occurrences as well (INSPIRE).

[87] Several commodities may be of interest inside a deposit. A deposit may be a medium-sized deposit for one commodity (this commodity is the main one) and a different-sized deposit for some other commodities (https://inspire.ec.europa.eu/codelist/ImportanceValue/mediumSizedDeposit).

[88] Resources equal to 0 and 1 are present in many observations, sometimes even when the deposit is considered large or medium according to the importance indicator. For this reason, we treat these values as data entry errors.

Appendix 3

Supplementary Tables

Table A3.1: Mining technological classes and definitions

Blasting	Fuses	Fuses (relating to mining)
	Blasting	Explosive or thermic compositions; detonating or priming devices; fuses; pyrophoric compositions; generation of gas for blasting or propulsion (chemical part); Blasting cartridges; Blasting methods (all relating to mining) Cutting or destroying pipes, packers, plugs, or wire lines, located in boreholes or wells by explosives or by thermal or chemical means; Fishing for or freeing objects in boreholes or wells combined with cutting or destroying means
Environmental	Reclamation of mining areas	Reclamation of surface-mined areas
	Treatment of waste water from metallurgical processes	Treatment of waste water from quarries or from mining activities
	Treatment of waste water	Treatment of waste water relating to mines/mining
	Biological treatment of soil	Reclamation of contaminated soil (from mines/mining) microbiologically or by using enzymes
	Soil treatment	Reclamation of contaminated soil (from mines/mining)
	Waste Disposal	Disposal of solid waste (from mines/mining)
	Protection against radiation	Protection against x-radiation, gamma radiation, corpuscular radiation or particle bombardment; treating radioactively contaminated material relating to mines/mining
	Environmental	Technologies for mitigation of climate change relating to mines/mining
	Technologies related to mineral processing	Technologies or applications for mitigation or adaptation against climate change relating to the processing of minerals
	Technologies related to metal processing	Technologies or applications for mitigation or adaptation against climate change related to metal processing
Processing	Crushing/grinding mineral	Crushing, pulverizing, or disintegrating minerals/ore; milling and mills
	Crushing/grinding	Crushing, pulverizing, or disintegrating in general; milling and mills relating to mines/mining
	Flotation	Flotation and differential sedimentation of minerals/ore
	Separation	Physical & chemical processes and apparatus for separating and mixing, including: Separating minerals/ore using liquids or using pneumatic tables or jigs; Separation of suspended solid particles from liquids by sedimentation; Filters; Filtering minerals/ores; Separating mineral particles from liquids; Separation devices for treating liquids from earth drilling, mining; Separating minerals from solids by sieving, screening, or sifting or by using gas currents; other separating by dry methods applicable to bulk material; Magnetic or electrostatic separation of solid materials from solids or fluids
	Processing	Centrifuges; Apparatus using free vortex flow, e.g. cyclones; Drying solid materials or objects by removing liquid therefrom
	Bio-processing	Microorganisms; enzymes and combinatorial chemistry (for bio-leaching of minerals)
Refining	Ferrous	Metallurgy of iron: Manufacture of iron or steel; Refining of pig-iron; Cast iron; Treating molten ferrous alloys, e.g. Steel
	Non-ferrous	Production or refining of metals; pretreatment of raw materials; Obtaining metal compounds from mixtures, e.g. ores, which are intermediate compounds in a metallurgical process for obtaining a free metal
	Inorganic chemistry	Compounds of alkali metals, rare-earth metals and other metals

Table A3.1 continued

Metallurgy	Metallurgy	Metallurgy of iron: Processing of pig-iron; Alloys; Changing the physical structure of non-ferrous metals or non-ferrous alloys
	Pyrometallurgy	Details or accessories of furnaces, kilns, ovens, or retorts, in so far as they are of kinds occurring in more than one kind of furnace
	Casting/powder metallurgy	Casting; powder metallurgy: Foundry moulding; Casting of metals; Making and working metallic powder; manufacture of articles from metallic powder.
	Furnaces	Furnaces, kilns, ovens, or retorts in general; open sintering or like apparatus
	Coating	Metallurgy: Coating metallic material
	Electrometallurgy	Metallurgy of iron: Modifying the physical structure of ferrous metals; general devices for heat treatment of ferrous or non-ferrous metals or alloys; making metal malleable by decarburisation, tempering, or other treatments Metallurgy: Electrolytic or electrophoretic processes
Exploration	Exploration	Electric digital data processing, relating to minerals/ore Measuring length, thickness or similar linear dimensions; measuring angles; measuring areas; measuring irregularities of surfaces or contours; Measuring distances, levels or bearings; surveying; navigation; gyroscopic instruments; photogrammetry or videogrammetry; Measurement of mechanical vibrations or ultrasonic, sonic or infrasonic waves; Radio direction-finding; radio navigation; determining distance or velocity by use of radio waves; Image data processing or generation, in general; Transmission systems in which the medium consists of the earth or a large mass of water thereon all relating to mines/mining Details of seismic processing or analysis relating to minerals/ore/mining/mines Geophysics; gravitational measurements; detecting masses or objects; tags relating to ore/mining/mines
	Surveying and testing - automatic control	Automatic control; Surveying or testing of boreholes and wells
	Surveying and testing	Surveying of boreholes and wells; Testing the nature of borehole walls; Formation testing; Methods or apparatus for obtaining samples of soil or well fluids, specially adapted to earth drilling or wells
	Core extraction	Apparatus for obtaining or removing undisturbed cores, e.g. Core barrels, core extractors; Containers for collecting or depositing substances in boreholes or wells, e.g. Bailers for collecting mud or sand; Drill bits with means for collecting substances, e.g. Valve drill bits
	Methods or apparatus for drilling	Earth or Rock Drilling: Methods or apparatus for drilling; Rotary drilling; Drives for drilling, used in the borehole; Drives for drilling with combined rotary and percussive action; Special methods or apparatus for drilling
	Drilling tools	Earth or Rock Drilling: Drilling tools; Accessories for drilling tools
	Drilling	Earth or Rock Drilling: Well equipment or well maintenance; Drilling rods or pipes; Flexible drill strings; Kellies; Drill collars; Sucker rods; Casings; Tubings; Handling rods, casings, tubes or the like outside the borehole; Methods or apparatus for flushing boreholes, e.g. By use of exhaust air from motor; Apparatus for displacing, setting, locking, releasing or removing tools, packers or the like in boreholes or wells; Vibration generating arrangements for boreholes or wells, e.g. For stimulating production; Fishing for or freeing objects in boreholes or wells; Heating, cooling, or insulating arrangements for boreholes or wells, e.g. For use in permafrost zones; Methods or apparatus for cleaning boreholes or wells; Obtaining a slurry of minerals from wells, e.g. By using nozzles Grinding; polishing (drilling and drill bits)
	Drilling - oil & gas	Earth or Rock Drilling: Cutting or destroying pipes, packers, plugs, or wire lines, located in boreholes or wells, e.g. Cutting of damaged pipes, of windows; Sealing or packing boreholes or wells; Valve arrangements for boreholes or wells; Tubing catchers, automatically arresting the fall of oil-well tubing; Other equipment or details for drilling; Obtaining fluids from wells
	Assays	Investigating or analyzing minerals/ore by determining their chemical or physical properties

Table A3.1 continued

Mining	Ground control support	Ground control support and working-face supports in mines Devices affording protection against falling rocks; Means for anchoring structural elements or bulkheads; Caps for supporting mine roofs; Provisional protective covers for working space in mines; Anchoring-bolts for roof, floor, or shaft-lining protection; Mine roof supports
	Excavation	Dredging; soil-shifting (for accessing mine sites) Mining or quarrying: Cutting; slitting; dislodging; Machines which completely free the mineral from the seam; Other methods or devices for dislodging with or without loading; Devices for testing in situ the hardness or other properties of minerals; Mining picks
	Safety/rescue	Protective garments relating to mines/mining, such as headwear, gloves, respirators Life-saving; fire-fighting relating to mines/mining; Methods or apparatus for preventing or extinguishing fires for boreholes or wells; Devices preventing sparking of machines or apparatus in mines; Flameproof or explosion-proof arrangements Mine safety devices; Rescue devices; Special adaptations of signaling or alarm devices for mines; Mine rescue devices or other safety devices, e.g. Safety chambers or escape ways Devices for allowing seemingly-dead persons to escape or draw attention; Breathing apparatus for accidentally buried person Safety devices structurally associated with lighting devices: Closed-circuit television systems, i.e. Systems in which the signal is not broadcast
	Shafts	Mine shafts; Lining mine shafts; Sinking mine shafts; Raising mine shafts; Mine shaft equipment, e.g. Timbering within the shaft
	Tunnels	Mine tunnels; Galleries; Large underground chambers; Linings therefor; Drainage of mine tunnels
	Ventilation	Heating, cooling, ventilating relating to mines/mining
	Subsea	Vessels or like floating structures adapted for mining purposes; Equipment for dwelling or working under water; Means for searching for underwater objects; Equipment or details for drilling specially adapted for underwater drilling; Obtaining minerals from underwater
	Mining (original)	*The marks in this category were marks that were originally included in the definition of the mining industry/ mining related activities* Methods of mining or quarrying; Open-pit mining; Layouts therefor; Methods of hydraulic mining; Transport specially adapted to underground conditions; Methods or devices for placing filling-up materials in underground workings; Mine drainage; Methods or devices for use in mines or tunnels; Non-electric hand-lamps for miners Manufacture or reconditioning of tapered poles, e.g. Mine props; Improving or preserving soil or rock, e.g. Preserving permafrost soil; Dredging; soil-shifting for making embankments; for back-filling; Mine lighting; Data processing systems or methods, specially adapted mining; Telephone sets specially adapted for use in mines; Electric heating; electric lighting relating to mines/mining
	Extraterrestrial	Apparatus for, or methods of, winning materials from extraterrestrial sources
	Mining (E21)	Earth or rock drilling; Mining (i.e. all patents with an E21 mark)
	Mining (mining)	All patents with mining in the title or abstract
	Mining (mine)	All patents with mine in the title or abstract
	Mining (Ore)	All patents with ore in the title or abstract
	Mining (Ore*)	All patents with a specific ore in the title or abstract (as listed in Appendix D).
	Mining (Mineral)	All patents with mineral in the title or abstract
	Mining (Coal)	All patents with coal in the title or abstract

Table A3.1 continued

Mining	Mining (additional)	*These additional marks in this category were marks that were identified as relevant through observing relevant patents based on keyword and firms searches.* Generating or transmitting mechanical vibrations in general; Cleaning; prevention of fouling; Layered products relating to mines/mining Performing operations; transporting in general; Land vehicles for travelling otherwise than on rails; Aviation relating to mines/mining Microstructural technology; Nanotechnology relating to mines/mining Construction and Building relating to mines/mining Machines or engines in general; engine plants in general; steam engines; Positive-displacement machines for liquids; pumps; Rotary-piston, or oscillating-piston, positive-displacement machines for liquids; Pumping of fluid by direct contact of another fluid or by using inertia of fluid to be pumped; Fluid-pressure actuators; hydraulics or pneumatics in general relating to mines/mining Liquid handling; Storing or distributing gases or liquids; Refrigerators; cold rooms; ice-boxes; cooling or freezing apparatus; Heat-exchange apparatus relating to mines/mining Recognition of data; presentation of data; record carriers; handling record carriers; Counting of objects; Computer systems based on specific computational models; Data processing systems or methods; Registering or indicating the working of machines relating to mines/mining Basic electric elements; Electric communication techniques relating to mines/mining
Transport	Rail	Railway systems; Locomotives; motor railcars; railway vehicles; Couplings specially adapted for railway vehicles; Brakes or other retarding apparatus peculiar to rail vehicles; Shifting or shunting of rail vehicles; Guiding railway traffic; ensuring the safety of railway traffic Mine cars
	Rail infrastructure	Construction of railways; machines for making railways; Switches; Crossings
	Conveying	Transport or storage devices e.g. conveyors for loading or tipping
	Hoisting	Hoisting; lifting; hauling; Control systems of elevators in general specially adapted for mining hoists; Lifts in hoistways of mines; Hoistway equipment for mines; Mining-hoist operation; Winding towers for mines
	Hauling	Vehicles adapted for load transportation or to transport, to carry, or to comprise special loads or objects; Machines, apparatus, methods for packing/unpacking
	Vehicles	Wheels; Axles; Tyres; Vehicles for use on both rail and road; Air-treating devices for vehicles; Propulsion of electrically-propelled vehicles; Power supply lines, or devices along rails, for electrically-propelled vehicles; Motor vehicles; trailers Checking devices for registering or indicating the working of vehicles Trucks or other devices for transporting machines for slitting or completely freeing the mineral from the seam
	Infrastructure	Construction of roads; Construction of, or surfaces for, roads; Additional construction work, such as equipping roads or the construction of platforms, helicopter landing stages, signs, snow fences, or the like; Traffic control systems
	Containers	Conveying; packing; storing Rigid or semi-rigid containers of polygonal cross-section, formed by folding-up portions connected to a central panel from all sides to form a container body, with extensions of sides permanently secured to adjacent sides, with sides permanently secured together by adhesive strips, or with sides held in place solely by rigidity of material Large containers

Table A3.1 continued

	Control	Control of position, course, altitude, or attitude of land, water, air, or space vehicles, e.g. Automatic pilot; Control of linear speed; Control of angular speed; Control of acceleration or deceleration, e.g. Of a prime mover Systems for controlling or regulating non-electric variables specifically for mining vehicles
	Shipping	Ships or other waterborne vessels; related equipment
Automation	Automation	Measuring distances, levels or bearings; surveying; navigation; gyroscopic instruments; photogrammetry or videogrammetry; Radio direction-finding; radio navigation; determining distance or velocity by use of radio waves; locating or presence-detecting by use of the reflection or reradiation of radio waves; analogous arrangements using other waves; Control or regulating systems in general; functional elements of such systems; monitoring or testing arrangements for such systems or elements; Systems for controlling or regulating non-electric variables; Control devices or systems insofar as characterized by mechanical features only; Electric digital data processing Computer systems based on specific mathematical models; Image data processing or generation, in general; Transmission of digital information, e.g. telegraphic communication relating to mines/mining

Source: Daly et al. (2019).

Table A3.2: Overlap matrix between mining patent categories (%), in Europe

	Exploration	Mining (Oper.)	Metallurgy	Automation	Environmental	Processing	Blasting	Transport	Refining
Exploration	–	44.77	8.84	9.65	2.56	1.00	13.83	4.44	0.08
Mining (Oper.)	44.65	–	11.76	7.10	5.38	2.77	13.05	13.79	0.22
Metallurgy	43.98	58.69	–	7.59	5.40	3.63	0.75	19.15	2.05
Automation	89.43	65.99	14.14	–	3.18	0.89	1.91	20.00	0.00
Environmental	30.00	63.23	12.74	4.03	–	21.29	0.81	16.13	5.81
Processing	16.74	46.33	12.16	1.61	30.28	–	1.15	7.57	2.98
Blasting	91.70	86.78	1.00	1.37	0.46	0.46	–	1.09	0.00
Transport	26.22	81.66	22.73	12.74	8.12	2.68	0.97	–	0.41
Refining	8.22	21.92	41.10	0.00	49.32	17.81	0.00	6.85	–

Source: our elaboration on PATSTAT (Autumn 2024) data, based on Daly et al. (2019) methodology.
Note: mining patents (by applicant) are granted and counted by family ID. Europe: EU-27 Switzerland and Norway.

Table A3.3: Zero counts in the dependent variables: patents per capita vs. moving-average transformation

	Original			Moving Averages (3 years)		
Class	**Obs**	**No. of zeros**	**% zeros**	**Obs**	**No. of zeros**	**% zeros**
TOT	5434	4077	75%	4693	2538	54%
Automation	5434	5093	94%	4693	3983	85%
Environmental	5434	5080	94%	4693	3858	82%
Exploration	5434	4100	76%	4693	2558	55%
Mining (Operational)	5434	3968	73%	4693	2469	53%
Processing	5434	5196	96%	4693	4113	88%
Refining/Metallurgy	5434	4815	89%	4693	3486	74%
Transport	5434	4898	90%	4693	3574	76%

Table A3.4: Impact on mining extraction and service specialization and on mining technologies (2000–2021). 2SLS robustness test

VARIABLES	(1) 2SLS	(2) 2SLS	(3) 2SLS
Endogenous Variables			
L3.LQe	-1.503	0.034	-1.702
	(2.055)	(0.138)	(1.389)
L3.LQs	3.237**	3.392***	2.282***
	(1.347)	(1.043)	(0.792)
Exogenous Variables			
L3.H	0.638	0.443	0.617*
	(0.427)	(0.373)	(0.359)
L3.R&D	0.015*	0.015*	0.013*
	(0.008)	(0.007)	(0.008)
L3.ln(GDP per capita)	-0.020	-0.007	-0.017
	(0.032)	(0.031)	(0.038)
L3.ln(Pop. Density)	-0.001	0.127	-0.087
	(0.136)	(0.112)	(0.132)
Constant	0.117	-0.670	0.538
	(0.909)	(0.834)	(0.860)
Observations	3,952	4,199	3,705
NUTS FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Instruments (Z)	L3.Endowment, L6.LQe, L6.LQs	L3.Endowment, L5.LQe, L5.LQs	L3.Endowment, L7.LQe, L7.LQs
R^2 within	0.082	0.209	0.041
R^2 between	0.281	0.127	0.239
Hansen J Test: 0.005 and a Chi-sq(1) P-value = 0.946			

Note: Robust and clustered standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages).

Table A3.5: Impact on mining extraction and service specialization on mining technologies (2000–2021). First Stages robustness check

	(1)	(2)
VARIABLES	**LQe**	**LQs**
L6.LQe	0.371	0.364**
	(0.234)	(0.182)
L6.LQs	0.225*	0.557***
	(0.128)	(0.120)
L3.Endowment	0.034***	-0.015**
	(0.010)	(0.007)
L3.H	0.062**	-0.058**
	(0.026)	(0.026)
L3.R&D	0.000	-0.000
	(0.000)	(0.000)
L3.ln(GDP per capita)	-0.005	0.004
	(0.009)	(0.005)
L3.ln(Pop. Density)	-0.025	0.017
	(0.021)	(0.015)
Constant	0.176	-0.117
	(0.170)	(0.113)
Observations	3,952	3,952
Region FE	Yes	Yes
Year FE	Yes	Yes
First-stage F-test	91.93	11.50
Prob > *F*	0.000	0.000

Note: Robust and clustered standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Dependent variables are 3-year moving averages).

Table A3.6: Population density and regional fixed effects

	(1)
	Lagged log population density
Regional fixed effects	Yes
Number of regions	201
Observations	3,819
$F(200, 3618)$	20,246.83
Prob > F	0.0000
R^2	0.9991
Adjusted R^2	0.9991
Root MSE	0.03668

Notes: The table reports a diagnostic OLS regression of the three-year lag of log population density on a complete set of regional fixed effects. The regression is estimated using the same 3,819 observations retained in the PPML specification reported in Column 7 of Table 3.3. The coefficients of the regional indicators are not reported.

Supplementary Figures

Figure A3.1: Patent families per 100,000 inhabitants across European regions, averages for 2000–2021. All classes

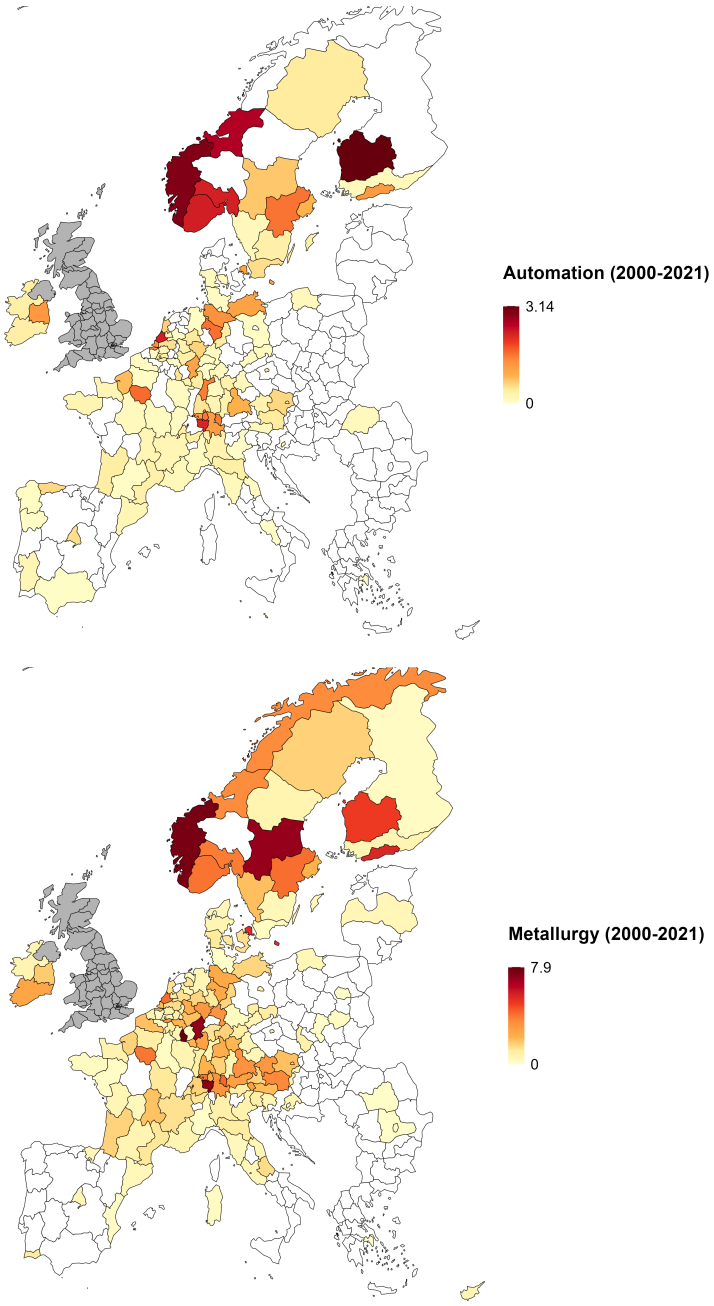
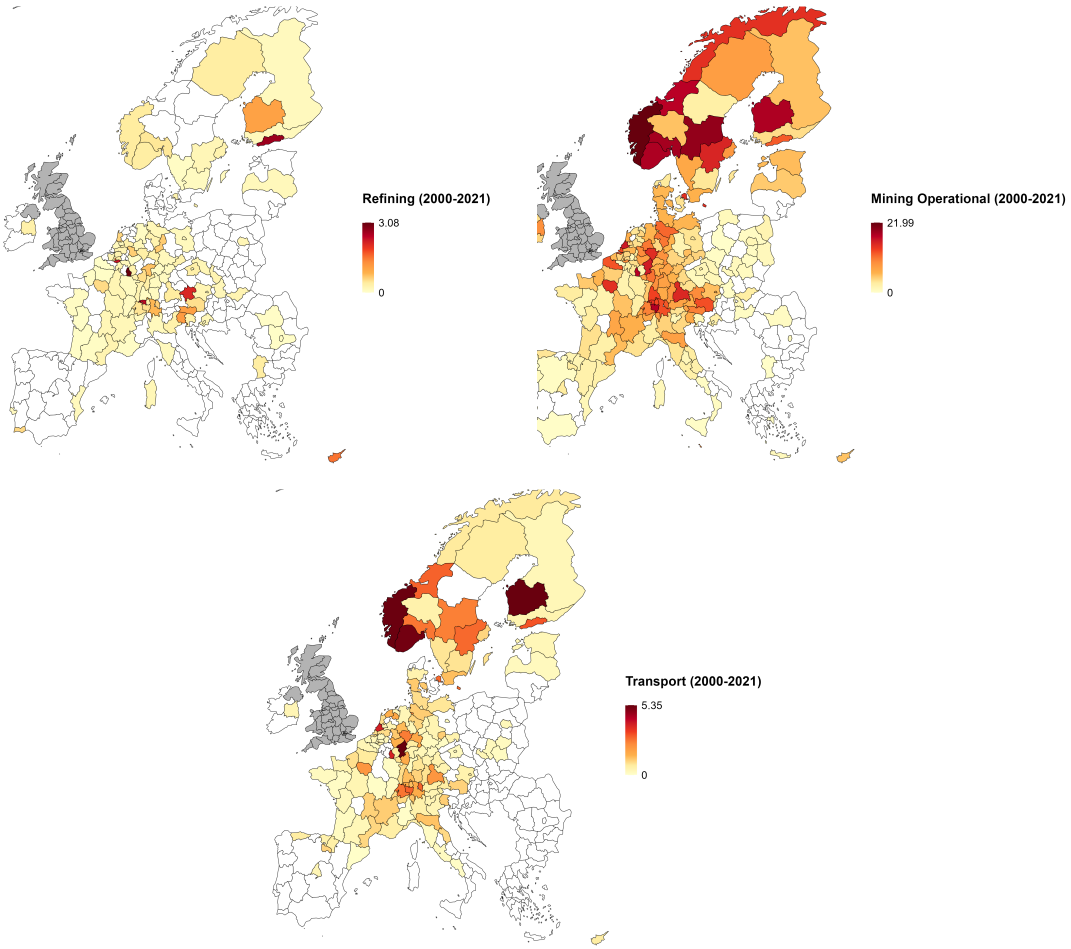


Figure A3.1 continued



Source: our elaboration on PATSTAT (Autumn 2024) data, based on Daly et al. (2019) methodology.
Note: mining patents referring to patent families are granted and geolocated by applicant. Europe: EU-27 + Switzerland and Norway.

Supplementary Notes

To obtain a complete panel of mining employment values used to calculate *LQs* and *LQe*, the following procedure was applied.

Period 2008–2021

We use only Eurostat SBS data. For the years 2008–2021, Eurostat uses the NACE Rev. 2 sectoral classification. Therefore, the macro-sector B – Mining and quarrying is disaggregated at the two-digit level into the following subsectors: B05 – Mining of coal and lignite; B06 – Extraction of crude petroleum and natural gas; B07 – Mining of metal ores; B08 – Other mining and quarrying; and B09 – Mining support service activities. The one-digit employment values for sector B, which displayed 17.9% missing values across the full set of NUTS-2 regions (247) × years (2000–2021) considered, were filled using the more complete official ARDECO data. Since ARDECO does not report sector B separately, but only the broader sectoral aggregate B–E, employment in sectors C, D, and E was separated using SBS data and subtracted from the ARDECO B–E aggregate in order to obtain a clean measure of employment in sector B[89]. All missing values in one-digit sector B employment were covered through this procedure.

After that, for observations in which B09 is available in absolute values, the observed value is directly used in the count of workers employed in mining support service activities. In the other cases, we derive this information. SBS data identify workers according to the firm's primary sector of activity. As a result, the two-digit subsectors belonging to one digit sector B are mutually exclusive, and their sum corresponds to total employment in B. Where information on B09 is missing, and the ratio between the sum of all two-digit subsector workers and total B employment is lower than 1, the indicator is computed residually as the difference between total employment in macro-sector B and B06. This methodology leaves only 15.9% of B09 employment values missing in the NUTS-2 × year count for the period considered.

The calculation of *LQe* is less complex. Employment values for extraction-only activities are

[89]Note that, since the sector B employment values are not entirely sourced from Eurostat SBS data, the employment shares of the different two-digit subsectors may not always sum exactly to one.

computed either as the sum of the relevant extractive subsectors or, equivalently, by exclusion, by subtracting both the reconstructed B09 employment component and B06 workers from total sector B employment.

Period 2000–2007

For the years prior to 2008, SBS data still rely on the NACE Rev. 1 classification, in which mining support service activities are not explicitly identified as a separate category. Workers employed in these activities are therefore embedded within the various extractive subsectors. To reconstruct a consistent measure of mining support service employment for the pre-2008 period, Orbis data from Bureau van Dijk are used. Specifically, the number of workers belonging to firms whose primary NACE Rev. 2 code is B09 is identified in Orbis, together with the number of workers belonging to firms whose primary NACE Rev. 2 code falls within one-digit sector B. These values are obtained by summing workers across all firms classified in the respective sectors. A ratio is then computed between employment in B09 and total employment in macro-sector B, thereby obtaining a correction coefficient – or discount factor – that estimates the share of workers attributable to mining support services. This coefficient, derived from Orbis data, is applied year by year and region by region to the number of workers reported in the original SBS data under the one-digit NACE Rev. 1 sector C – Mining and quarrying, which is then relabeled as sector B for consistency with NACE Rev. 2.

Again, employment values for extraction-only activities were obtained by exclusion, by subtracting reconstructed B09 employment and crude petroleum and natural gas extraction workers, or by summing the remaining extractive subsectors.

Finally, since the missing-value replacement procedure reconstructs all missing values for mining service workers in the pre-2008 period, while some missing values remain in the post-2008 period, the reconstructed time series is interpolated using a standard Kalman filter to fill the remaining gaps.

Cross-validation results

The use of the discount factor is preferred to absolute Orbis values because Orbis does not fully

cover the universe of firms: its coverage varies across countries, industries, years, and variables, and the sample is skewed toward larger, older, and more productive firms (Bajgar et al., 2020). Although we can reasonably assume that most extractive and mining service firms fall within this better-covered segment, Orbis employment data still contains missing values for some firms.

Therefore, Orbis is used to estimate the relative sectoral composition of mining support services, rather than as a direct source of absolute employment levels. To assess the performance of the imputation method, we implemented a holdout cross-validation exercise for the post-2008 period only, since observed B09 data are available only from 2008 onwards under NACE Rev. 2. Starting from the set of observations with observed employment values, we randomly masked 20% of them and treated these observations as missing. The imputation procedure was then applied using only the remaining observed values, and the imputed values were compared with the true observed values in the masked test set. Based on this validation framework, we computed the same error metrics for both sets of mining service employment values: those reconstructed using the previously explained discount factor-based methodology (A), and those obtained using Orbis data only (B).

$$\text{RMSE} = \sqrt{\frac{1}{|T|}\sum_{r,t}\left(\widehat{w}_{r,t} - w_{r,t}\right)^2} \tag{A(1.1)}$$

$$\text{MAE} = \frac{1}{|T|}\sum_{r,t}\left|\widehat{w}_{r,t} - w_{r,t}\right| \tag{A(1.2)}$$

where RME is the root mean squared error, expressed in the same unit as employment and giving greater weight to large errors; MAE is the mean absolute error, measuring the average absolute difference between imputed and observed values. In the notation, r denotes the NUTS-2 region, t denotes the year.

Cross-validation results for B09 employment reconstruction

Methodology	RMSE	MAE
(A): the discount-factor approach	960	160
(B): Orbis absolute values only	4397	893

Source: own elaboration on ORBIS and Eurostat data.

Note: The period considered is 2008–2021. Summary statistics refer to original SBS B09 employment data across NUTS-2 × year observations: mean = 333 workers; standard deviation = 1,751.

Taken together, the MAE and RMSE indicate that methodology (A) generally produces small average prediction errors. Although the RMSE for methodology (A) is larger than the average observed B09 employment level (410 workers), it remains below one standard deviation of the observed distribution (1,751 workers). Since the standard deviation is substantially larger than the mean, observed B09 employment is highly heterogeneous across NUTS-2 × year observations. In this context, the RMSE remains contained compared to the overall dispersion of the data. For this reason, we consider methodology (A) to provide a reliable estimate of B09 employment.

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