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Summary

We map the mining sector in Europe, with a focus on Energy Transition Metals (ETMs), and present an in-depth analysis of the environmental impact and associated monetary costs, at the regional level, of extraction activities. We aim to offer a spatially disaggregated view of the current mining projects and associated environmental costs in terms of CO2 emissions and their monetary value. To do this, we collected global warming potential (GWP) data from Life Cycle Assessment Impact Analysis (LCIA) and linked these to their expected monetary value. By considering the full spectrum of sourced ETMs, we map the environmental, physical, and monetary impact of current mining activities in Europe, and understand what a further increase in exploiting European reserves to reduce dependence from abroad and facilitate the green transition, could imply for European regions.

Keywords: Critical raw materials, Europe, Life Cycle Assessment Impact Analysis, mining, regional

JEL Classification: L72, O52, Q32, Q51, R11

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March 3rd, 2025

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1. Introduction

The clean energy transition needed to mitigate the effects of the climate crisis is associated with increased mining activity, at least in the short term (Draghi, 2024; Jones, 2023; Lèbre et al., 2024; Sonter et al., 2023). In fact, the transition from fossil fuels to renewables and the electrification of the transport sector require technologies that use a variety of raw materials as key production inputs (Carrara et al., 2023; IEA, 2024a; Li et al., 2024). Several of such raw materials are considered critical or even strategic under the EU's Critical Raw Materials Act (European Commission, 2023a,b).

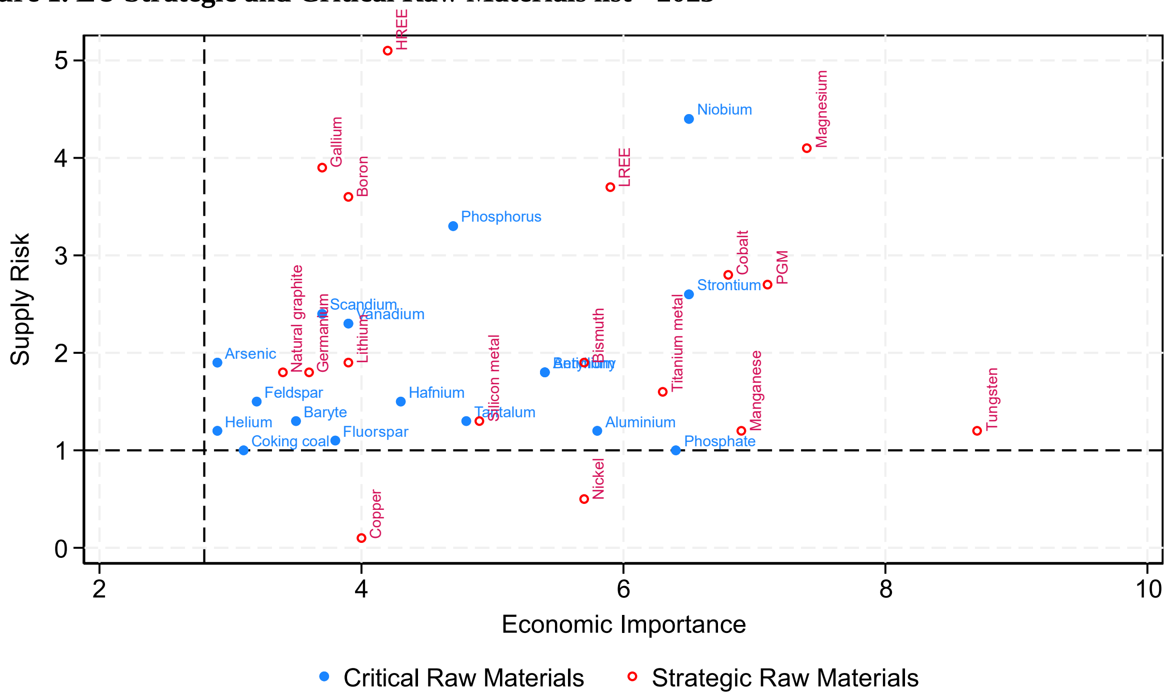
The European Commission regularly compiles and updates a list of critical raw materials (hereafter CRMs) and in its most recent criticality assessment also included a list of strategic raw materials (hereafter SRMs). Materials are critical if they have a high economic importance and a high supply risk, as measured by a number of indicators. SRMs are raw materials that are key inputs for strategic technologies (i.e. clean energy, e-mobility, digital technologies, defense, and aerospace applications). The fifth CRM list, published in 2023, consists of 34 critical raw materials, of which 15 are also strategic. Copper and nickel are not critical but deemed as strategic due to their high importance for the EU economy. Figure 1 shows that the battery metals - namely cobalt, lithium, manganese, natural graphite and nickel - which will be key to e-mobility and the expansion of renewable electricity generation, are both critical and strategic.

Over the period 2021-23, both exploration expenditure and investment in the extraction of selected CRMs have globally increased by around 45% (IEA, 2024a). In the future, recycling and the circular economy may outweigh the importance of raw material extraction (Månberger, 2023), and innovative technologies may reduce our need for Energy Transition Metals-ETMs (e.g. for wind turbines, see Pavel et al., 2017). However, future innovations and trajectories are not easily predictable, and current projections suggest that more mining will be needed. See Figure 2(b), Section 2.

There is a global risk of a supply shortfall; in fact, in the case of a 2°C scenario[1], production of graphite, lithium and cobalt would need to increase by more than 450 per cent by 2050 - from 2018 levels - to meet the demand for energy storage technologies (Hund et al., 2023). The situation in Europe is particularly troublesome: current figures suggest that external dependence is significant, with 75% of critical materials being imported, in some cases from countries presenting a high-risk profile (see, e.g., Nakano, 2021). Expanding the amount of CRM sourced internally would thus entail several benefits for the EU, including reducing supply risk and exposure to highly volatile international markets (IEA, 2024a) and avoid using "conflict minerals", i.e. those resulting from mining activities that fund conflicts in that region directly (Diemer et al., 2022).

[1] The "2°C scenario" (2DS) implies a 50% chance of limiting future global average temperature increases to 2°C by 2100. See IEA (2017).

Figure 1. EU Strategic and Critical Raw Materials list - 2023



Notes: the figure shows the critical (blue dots) and strategic (red circles) raw materials. The dashed lines indicate the level of supply risk and economic importance used to determine the criticality of a material (1 and 2.8, respectively). *Source*: Authors' calculations based on European Commission (2023b).

However, increasing internal mining activities would also entail social and environmental costs. Focusing on the latter, there are several studies aimed at quantifying the environmental costs of mining activities, with different methodologies, including Environmental Impact Assessments (Badakhshan et al. 2023) or Life Cycle Impact Assessment (LCIA), but few focus on the EU as a whole. Additionally, while there is an increasing consensus that the EU must take action to address the challenges posed by the climate crisis with respect to CRMs, to date, there has been no attempt to map mining resources and their associated environmental impact for a wide set of raw materials at a disaggregated spatial level in Europe.

LCIA, according to the definition proposed in ISO 14040/14044, is a standardized tool that evaluates an entire process's potential environmental impact, based on the mix of inputs and outputs over the full life cycle. LCIA methods classify the external impacts associated with the project into standard impact categories, which are then translated into common units of measurement to allow comparison. Applied to mining, LCIA thus provides measures accounting for and quantifying environmental impacts of the whole extraction process.

In this paper, we map the mining sector in Europe using geo-referenced project site data and present an in-depth analysis of the environmental impacts of mining activities at the NUTS-2 regional level. We provide, to the best of our knowledge, the first spatially disaggregated view of current mining projects and their associated environmental costs in terms of CO_2 emissions. Societal costs are measured in terms of global warming potential (GWP), as this is the environmental cost category with the highest value (Arendt et al., 2022; Santero and Hendry, 2016). To do this, we collected data on the GWP of sourced minerals and materials from available LCIAs and linked them to their expected monetary value. A total of 25 materials, including pure metals (e.g., cobalt, lithium, and zinc), minerals (e.g., bauxite and chromite) and compounds (e.g. heavy mineral sands) are included in our study. These materials are key inputs in a wide range of industrial applications and fall into multiple, often overlapping categories. Indeed, many of them are considered both critical and strategic materials for the EU. In addition, 14 of the 25 materials considered fall within the list of ETMs tracked by the International Monetary Fund (IMF). While the IMF tracks only those ETMs whose prices are publicly available[2], several other minerals and metals needed for the energy transition are not yet traded on regulated exchanges (graphite is a case in point). For an overview of ETM pricing systems, see IEA (2024a). In this analysis, therefore, we consider a broader definition of ETMs, which is the same as that used in Owen et al. (2023). Descriptive statistics and demand-supply scenario analyses for some of the materials considered in the study are provided in Section 4.

Mapping extraction of selected materials and minerals along with their environmental impact and related monetary value at the NUTS-2 regional level provides a basis for discussing the consequences of public intervention in the mining sector in Europe. This exercise also allows for an understanding of what a further increase in the exploitation of European reserves, in order to reduce external dependency and facilitate the green transition, could mean for European regions in terms of an important associated social cost category, namely GWP.

The paper is organized as follows: Sections 2 presents descriptive statistics, supply and demand scenarios for the materials considered in the study; Sections 3 and 4 describe methods and data. National and regional level results are discussed in Section 5, where a Monte Carlo analysis allows us to discuss uncertainty issues. Section 6 concludes.

2. The global and European landscape for ETMs

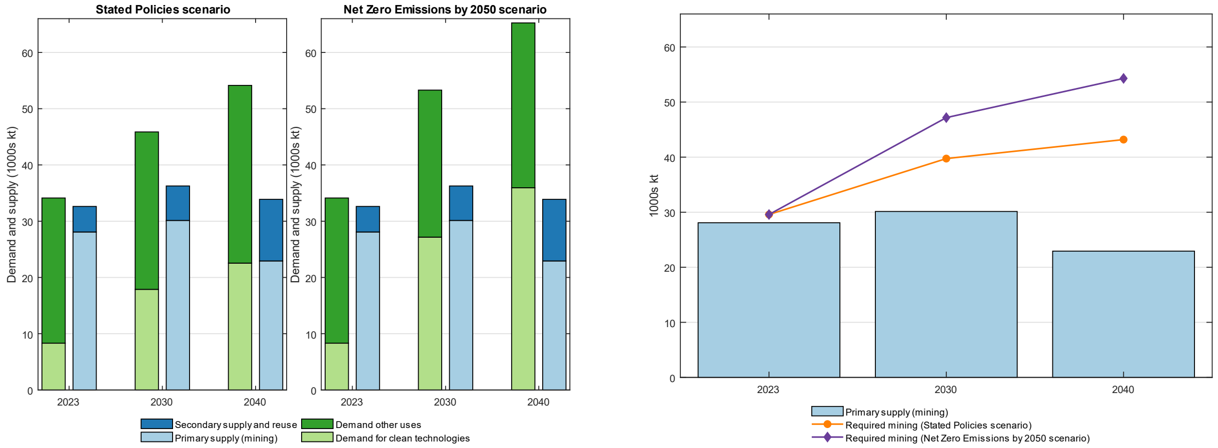
The energy transition is associated with a massive increase in global demand for the minerals and materials used as inputs in the production of the technologies needed to structurally transform entire

[2] The ETM price index, published as part of the IMF's Primary Commodity Price System, includes 7 base metals (aluminum, cobalt, copper, lead, molybdenum, nickel, zinc), 3 precious metals (palladium, platinum, silver) and 6 minor metals (chromium, lithium, manganese, rare earth elements, silicon, vanadium) that are essential for the deployment of clean energy technologies and electric vehicles on the scale required for the energy transition.

sectors of the economy, such as power generation and electric mobility. Demand for these minerals is also being driven by their use in the ICT, defence and aerospace sectors (Carrara et al., 2023).

Figure 2: Global demand, supply and mining scenarios for key critical raw minerals

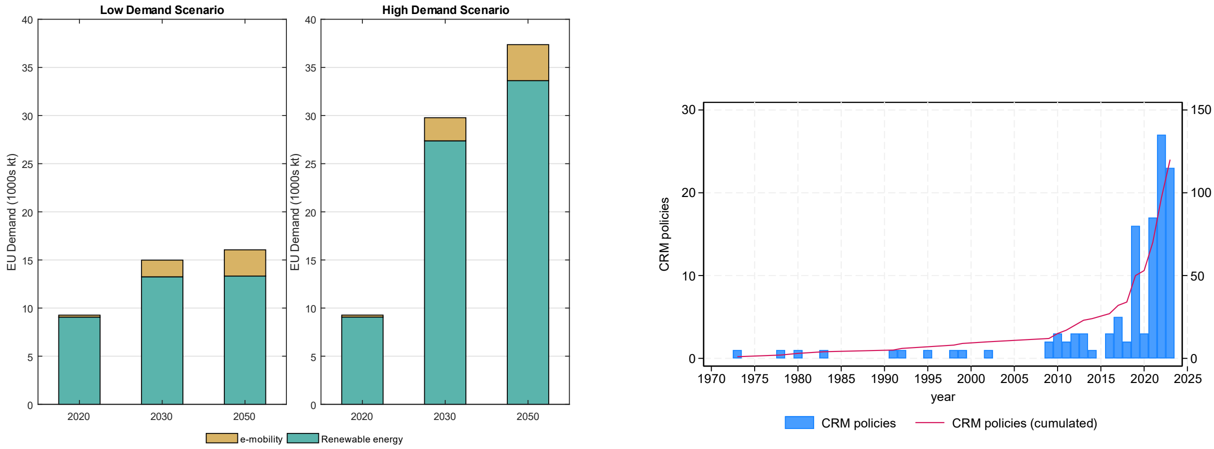
(a) Demand and supply scenarios (b) Primary supply and required mining



Notes: the figure shows the evolution of demand and supply for key critical raw materials under different policy scenarios. The commodities considered are copper, cobalt, lithium, nickel, rare earth magnets (i.e. praseodymium, neodymium, terbium and dysprosium) and graphite. Supply projections are made by the IEA using data for the pipeline of operating and announced mining projects. In Panel (b) "Required mining" is computed as "Total demand" minus "Secondary supply from recycling and reuse". *Source*: Authors' elaboration based on IEA (2024a,b).

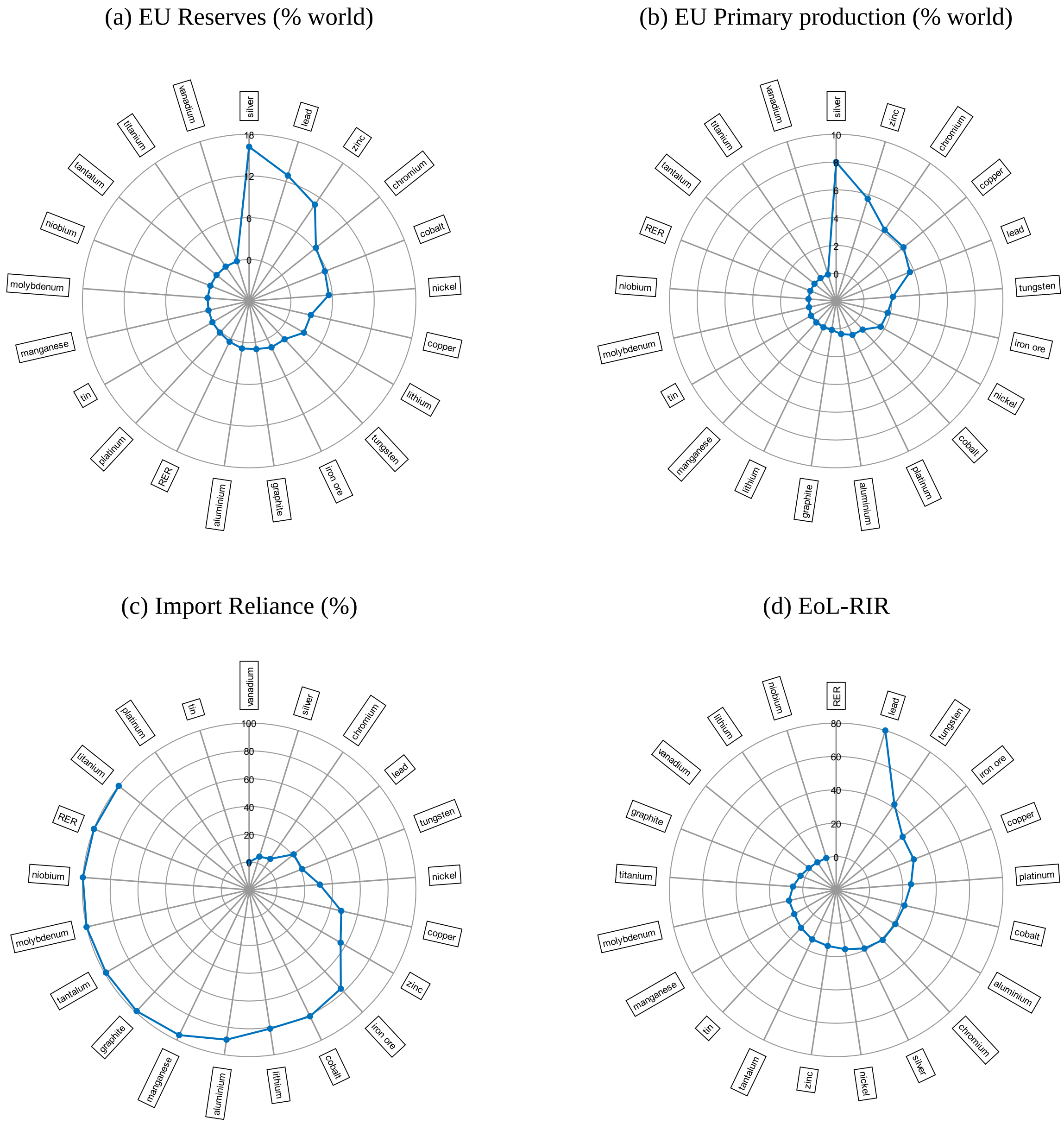
Figure 3: EU demand scenarios and policies for critical raw minerals

(a) EU demand scenarios (b) CRM Policies



Notes: figure in Panel *b* shows the number (and the cumulated number) of CRM policies announced and in force by year. CRM policies include measures related to three main objectives: "Ensuring reliability and resilience of supply", "Promoting exploration, production and innovation", "Promoting sustainable and responsible practices". *Source*: Authors' elaboration based on: https://zenodo.org/records/7736782 (Panel a) and IEA (2024c) for Panel b.

Figure 4: EU reserves, primary production, import reliance and recycling rates



Notes: In Panel (c) "import reliance" is the ratio of net imports to apparent consumption (i.e. production plus imports minus exports). The "End-of-life Recycling Input Rate" (EoL-RIR) in panel (d) measures the share of metal and metal products produced from End-of-Life scrap and other metal-bearing low grade residues. *Source*: Authors' elaboration based on data sourced from the European Commission's Raw Materials Information System (https://rmis.jrc.ec.europa.eu/rmp/).

Figure 2(a) shows that global demand for minerals in 2040 will increase by a factor of 1.3 to 1.5 compared to 2023, depending on the IEA's scenario[3] we consider. Figure 2(a) also indicates that, according to the IEA's current supply projections - based on data for the pipeline of operational and announced mining projects - even considering an increasing contribution from reuse and recycling,

[3] The Stated Policies Scenario represents the energy system based on current policy settings and is associated with a temperature increase of 2.4°C in 2100 (with a 50% probability). In the Net Zero Emissions by 2050 (NZE) scenario, the global energy sector is assumed to evolve to achieve the goal of net zero CO_2 emissions by 2050 and is associated with a temperature increase of 1.5°C above pre-industrial levels in 2100 (with at least a 50% probability). See IEA (2024a).

further mining will be required to keep up with the expected boom in global mineral demand. This is made clear in Figure 2(b) that plots global "mining requirements", defined as the difference between world demand and secondary supply (from recycling and reuse). Depending on the IEA scenario, mining would have to increase by a factor of 1.5 to 1.8 in 2040 compared to 2023 to keep up with rising demand.

Figure 3(a) illustrates demand scenarios for the EU, focusing on the demand for CRMs resulting from the growth of renewable energy and e-mobility. Depending on the scenario considered[4], total mineral demand is projected to increase by a factor of 1.7 or 4 in 2050 compared to 2020. Figure 3(b) clearly shows that although CRM policies have been in place in European countries for several decades, the number of such policies has increased exponentially in recent years, to support the EU's ambitious energy and climate policy goals.

An overview of the current situation in the EU with regard to ETMs mined at the sites in our analysis is given in Figure 4. Focusing on panels *a* and *b*, we see that EU countries have access to scarce reserves of ETMs and produce modest quantities. This is not limited to minor metals, but also extends to aluminium, which has a large number of industrial applications. Looking at Figure 4(c), we can see that the dependence of EU countries on imports of ETMs is in most cases between 80% and 100%. This is accompanied, as can be seen from the Figure 4(d), by extremely low rates of production through recycling and reuse of materials.

In summary, the global and EU future scenarios, as well as the current market conditions for ETMs in Europe, clearly indicate that increased mining is a necessary measure to be considered to support ambitious environmental and energy policy goals and, ultimately, the energy transition (see e.g. Draghi, 2024; Jones, 2023; Lèbre et al., 2024; Sonter et al., 2023).

3. Methods

In measuring, assessing, and comparing the negative environmental impacts of mining activities, we rely on LCIA, specifically focusing on the most commonly used and examined midpoint indicator, which measures the GWP of a process. LCIAs estimate the environmental impacts of a product, service, or technology, by quantifying resource use and emissions throughout the life cycle (for an overview of LCIA methods, see Finnveden et al., 2009). LCIAs provide this information through a

[4] The "High Demand Scenario" (HDS) assumes rapid technology deployment and a combination of market shares and material intensities leading to a sharp increase in material demand. Future technology deployment is thus aligned with energy and climate change targets set by countries/regions (e.g. REPowerEU targets for the EU in 2030). The "Low Demand Scenario" implies a slower technology deployment and thus a more moderate increase in materials demand than in the HDS. See Carrara et al. (2023).

limited set of impact categories, both midpoint and endpoint. Midpoint indicators provide information on single environmental issues, such as climate change emissions, acidification, and eutrophication, while endpoint indicators assess the impact on broader categories such as human health, biodiversity. While the information provided by endpoint indicators is more comprehensive, it is also associated with additional uncertainty about the underlying causal mechanisms with respect to midpoint indicators (Bare et al., 2000). Thus, we have decided to consider GWP, which is one of the most discussed and computed midpoint impacts (Amadei et al. 2021), for which we were thus able to find data from several sources.

In our empirical analysis, we have collected impacts from comparable LCIAs on the different ETMs. First, all studies shared a common system boundary, namely a cradle-to-gate approach, which evaluates impacts considering as system boundaries the initial phases of mining up to the pre-manufacturing of derived products. We have selected multiple papers on the most relevant midpoint impact for the mining industry, which, according to Santero and Hendry (2016), is GWP.

The midpoint indicator (*MPI*) is used to quantify site-specific environmental impacts, based on the amount of the *i*-th material sourced in each location, *j*, at time *t* ($Q_{i,j,t}$)[5]:

$$GWP_{i,j,t} = Q_{i,j,t} \times MPI_i \quad (1)$$

Given that there is a wide range of estimates of MPI_i in the literature for the different ETMs analyzed in this paper, we have chosen, where possible, to collect a range of values and present results focusing, for the most part if not otherwise noted, on the minimum value that emerges from the literature, with the aim of being conservative.

Midpoint impact indicators are expressed in physical units, such as kg of CO_2 equivalent emissions per ton (kgCO_2e/t). A further step is to provide a monetary value to the amounts of CO_2 equivalents, in the case of GWP, associated with the amounts mined and processed. Monetization implies adopting a societal welfare approach and relates the selected LCIA midpoint impacts to monetary values, thus leading to the quantification, in monetary terms, of the selected environmental impacts. Monetary valuation is used to convert measures of physical impacts into monetary units, thus determining a monetary value in cases where markets do not exist or are incomplete or imperfect (Pizzol et al. 2015). In our models, monetary values are also easier to convey to non-specialists, especially when presenting the case for public policies or when analyzing their impact. Monetary values are then used to identify the site-specific monetary value for each category of environmental cost:

[5] Q is defined as the physical amount contained in reserves and resources in each location of the mined material. See note 4 in the Data Section for additional details.

$$\text{€}GWP_{i,j,t} = GWP_{i,j,t} \times MV_{GWP} \quad (2)$$

As a last step, GWP and corresponding monetary values from the various mining sites are aggregated at the regional level, allowing us to compute regions-specific values for the environmental impact, in terms of GWP and the corresponding monetary cost.

We have then explicitly accounted for the uncertainty in the value of the midpoint impact indicators for metals and minerals and their monetary valuation by performing a simple Monte Carlo exercise that treats MPI_i and MV_{GWP} as uniform random variables with support over the minimum and maximum values previously reported in the literature. See Table 1 and Section 5.3.

4. Data

Mining projects. The data on global mining projects are based on Owen et al. (2023) who collect information for projects where multiple ETMs are or will be produced, either as a primary target or as a by-product (e.g. cobalt is often a by-product of copper and nickel) and refer to the year 2021[6]. In addition, more than one ETM may be produced from the same project. Although the initial database includes mining projects at all stages of development, Owen et al. (2023) only retain records for deposits with reserves and resources[7]. This allows us to focus on projects that are at a more advanced stage of development - where investment has been made in defining the deposit or developing the mining infrastructure - and also to exclude projects that have been shut down or for which no information has been disclosed. No information is given on the time frame of extraction nor its relation to quantities, thus excluding the possibility of performing a dynamic analysis. For each mining site, geographic coordinates are available, thus allowing a regional aggregation and analysis.

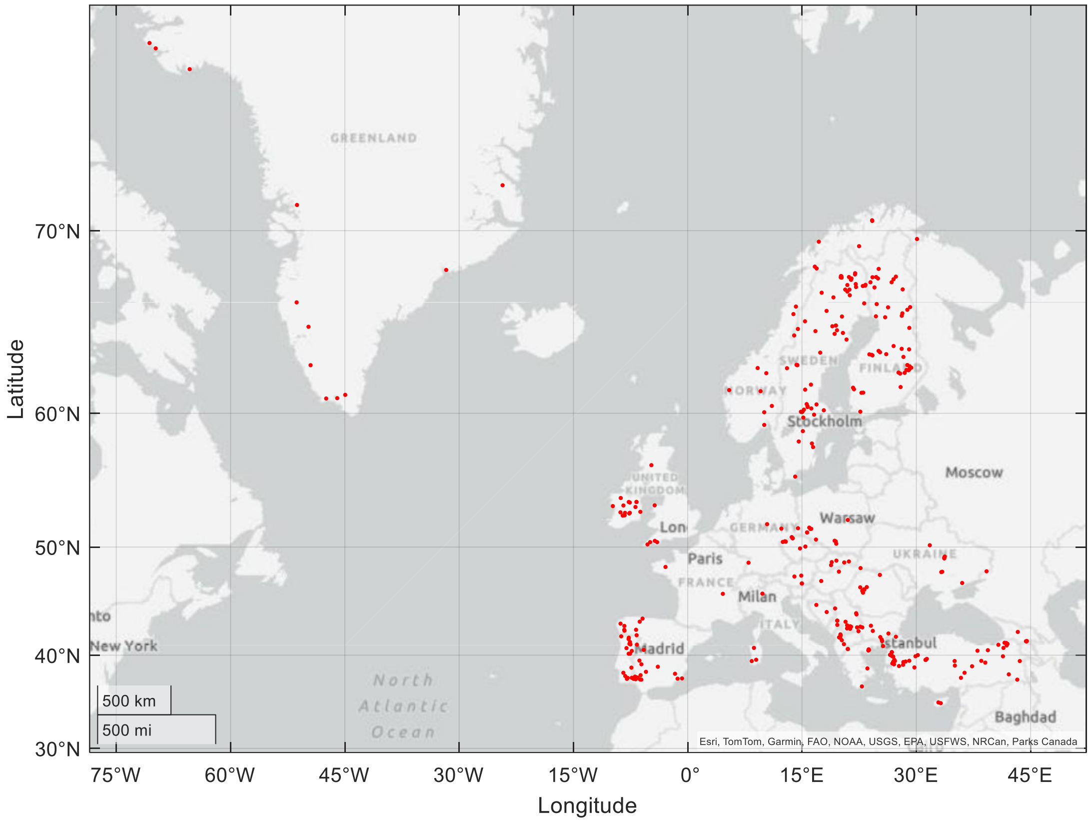
To limit the geographical scope of the analysis to countries that share or have shared common policies, we retain a subset of projects located in European Union (EU-27), EU candidates, former EU, European Free Trade Association (EFTA) countries, and Greenland. This leaves us 352 mining projects, each of which can supply one or more ETMs[8].

[6] Owen et al. (2023) obtained mining project data from the S&P Capital IQ Pro database as of November 2021.

[7] A mineral resource is a concentration of naturally occurring material in such form and quantity that economic extraction of a commodity from the concentration is currently or potentially feasible. The reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices (e.g. grade, quality). Reserves are the estimated part of the reserve base that could be economically extracted or produced at the time of determination (which does not imply that extraction facilities are in place and operating). See: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-appendixes.pdf

[8] This is the number of unique mining projects. A mining project can mine more than one type of material.

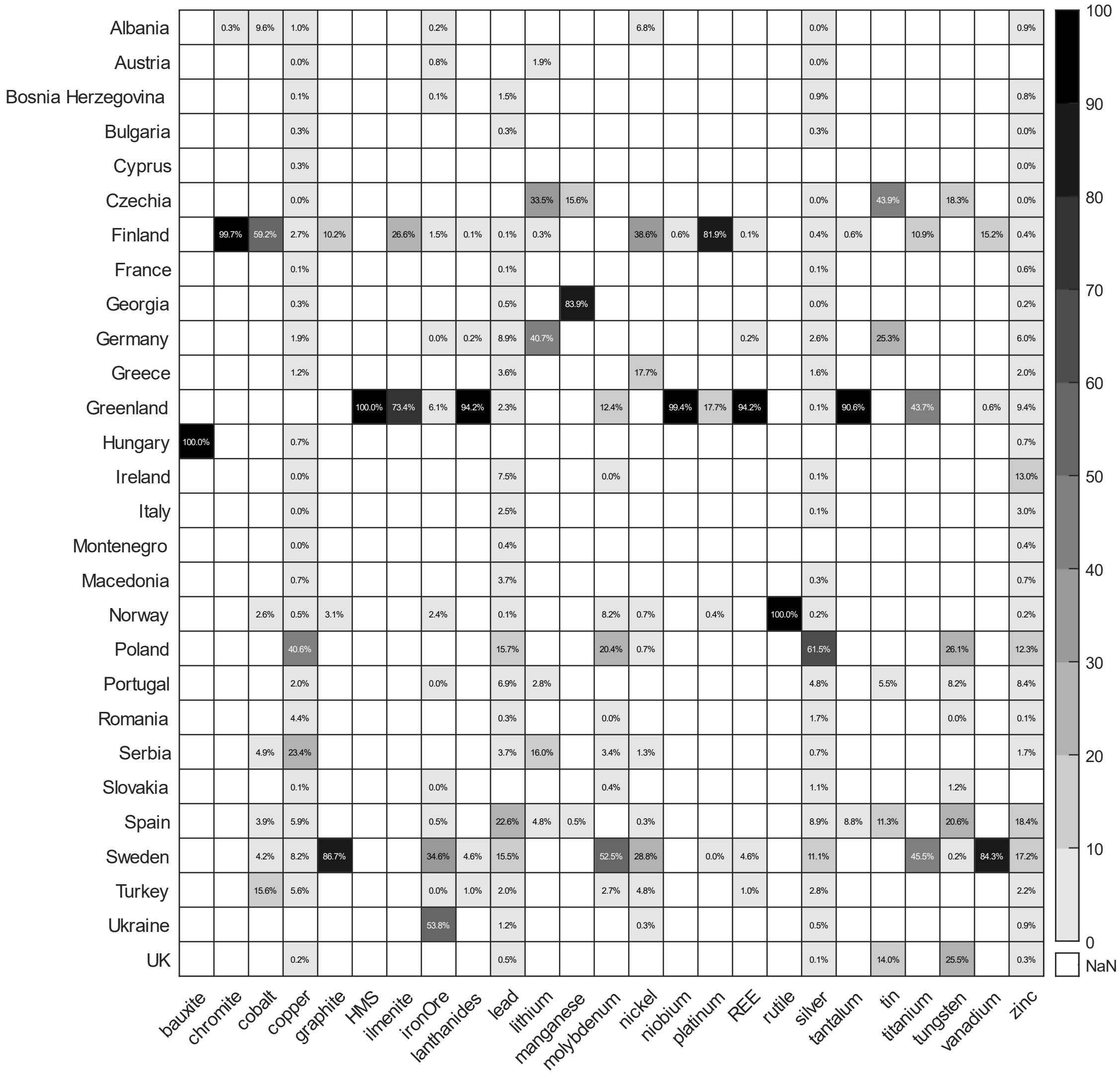
Figure 5: Mining projects in the analysis



Source: Authors' elaboration based on data in Owen et al. (2023).

Figure 5 provides a map of the projects included in our database. We extend the analysis beyond the official EU boundaries to consider the potential of agreements with countries that are likely to become official Member States in the near future, have existing official economic relations with the EU that could be extended to include mining activities for specific CRMs, and countries that can be considered as reliable trade partners. From visual inspection of the map, it is clear that there is significant heterogeneity of project location, with very few, if any, mining project in Central Western Europe. It also clear that there are some clusters of several projects in narrow geographic areas, which can be considered hotspots. Figure 6 provides a more detailed visualization of this, by showing how ETMs are concentrated in the different countries of our sample. A few countries, namely Greenland, Finland, Hungary, Norway, Sweden and Georgia, house the majority of one of few ETMs, other countries provide several ETMs, and several others have very little ETM mining activities at all.

Figure 6: ETM concentration by country



Notes: the figure shows the percentage of ETM by country as a share of total. *Source*: Authors' elaboration based on data in Owen et al. (2023).

Table 1: Midpoint values (kgCO2e/t) and global warming potential damage cost (2019 EUR per kgCO2e/t)

(a) Midpoint values (kgCO2e/t)				
Material	min	avg	max	Source
Aluminium/Bauxite	12.2	43.4	79.0	Rachid et al. (2023); Sáez-Guinoa et al. (2024); Farjana et al. (2019a); Farjana et al. (2018a)
Chromite*	960.0	2400.0	3840.0	Nuss et al. (2014)
Cobalt	8300.0	20807.5	39500.0	Rachid et al. (2023); Nuss et al. (2014); Farjana et al. (2019b)
Copper	2800.0	3886.8	5840.0	Rachid et al. (2023); Nuss et al. (2014); Tao et al. (2022)
Graphite	2140.0	6210.0	9600.0	Sadhukan and Christensen (2021); Engels et al. (2022)
Heavy minerals sands - zircon sands*	128.0	320.0	512.0	Nuss et al. (2014)
Heavy minerals sands - silica sands	36.8	42.8	48.8	Nuss et al. (2014)
Ilmenite	295.4	890.1	1484.7	Sáez-Guinoa et al. (2024); Farjana et al. (2018b); Farjana et al. (2018a)
Iron ore	25.0	33.4	47.2	Rachid et al. (2023); Farjana et al. (2018a)
Lanthanides*	4400.0	11000.0	17600.0	Nuss et al. (2014)
Lead	632.0	1200.7	1670.0	Rachid et al. (2023); Nuss et al. (2014)
Lithium	329.0	10903.8	20400.0	Rachid et al. (2023); Nuss et al. (2014); Jiang et al. (2020)
Manganese	1000.0	3692.5	6030.0	Rachid et al. (2023); Nuss et al. (2014); Westfall et al. (2016)
Molybdenum*	2280.0	5700.0	9120.0	Nuss et al. (2014)
Nickel	801.0	7825.3	13900.0	Rachid et al. (2023); Nuss et al. (2014); Nickel Institute (2023)
Niobium	5090.0	8795.0	12500.0	Nuss et al. (2014); da Silva Lima et al. (2022)
Platinum*	5000000.0	12500000.0	20000000.0	Nuss et al. (2014)
Rare earth elements	22300.0	56233.3	115000.0	Rachid et al. (2023); Zapp et al. (2022)
Rutile	1535.0	4623.7	7712.4	Sáez-Guinoa et al. (2024); da Silva Lima et al. (2022)
Silver*	78400.0	196000.0	313600.0	Nuss et al. (2014)
Tantalum*	104000.0	260000.0	416000.0	Nuss et al. (2014)
Tungsten*	5040.0	12600.0	20160.0	Nuss et al. (2014)
Tin*	6840.0	17100.0	27360.0	Nuss et al. (2014)
Vanadium	12000.0	22550.0	33100.0	Nuss et al. (2014); Neometals (2023)
Zinc	3100.0	4723.3	6120.0	Rachid et al. (2023); Nuss et al. (2014)
(b) Monetary valuation: Damage cost (2019 EUR per kgCO_2e/t)				
Damage cost	0.0295	0.2720	0.6850	Amadei et al. (2021); Bruyn et al. (2010); Schneider-Marin and Lang (2020).

Notes: "*" denotes that in the absence of a range from the literature we computed min and max values as avg×(1±0.6), where 0.6 is based on the ranges for other minerals.

LCIA parameters. Data on the LCIA midpoints described for each material are the results of an in-depth survey of the literature which is detailed in Table 1. For each item we collected a range of values from the literature (i.e. minimum, maximum and average value) and applied appropriate conversion factors where necessary to have all midpoints in the same measurement unit (i.e. $kgCO_2$ equivalent units per ton, kgCO2e/t). Table 1 shows the minimum, average, and maximum LCA midpoint values for each material that is extracted in the mining sites in our data. The highest minimum[9] midpoints, way above the median average, are associated with platinum (5000000 $kgCO_2e/t$), tantalum (104000 $kgCO_2e/t$) and silver (78400 $kgCO_2e/t$).

Following equation (2), in order to provide a monetary estimate of the value of the GWP midpoint impact, a monetary valuation is needed. We follow the literature and consider the "damage cost" valuation approach (Amadei et al. 2021) which associates a monetary value to an environmental impact based on the associated value of the damage derived from the change in natural capital or emission. As done with GWP, we have derived minimum, average and maximum values from the recent literature. See Table 1(b).

5. Results

With the aim of providing a clear picture of mining of ETMs in Europe, with a focus on the associated environmental impacts and related costs from a European perspective, we focus on both a national and regional level analysis. At the country level, we compute the weight of the impacts of ETM mining over the total, by considering how much of total aggregate emissions can be attributed to ETM mining and how their monetary evaluation compares against national GDP. At the regional level we focus instead on two measures of spatial concentration of mining activities for ETMs and the related environmental impacts and costs, to provide evidence of the existence of hotspots, which is relevant from a policy planning perspective.

5.1. Country level analysis

Our estimates of the aggregate emissions of mining ETMs can be compared to the estimated aggregate emissions of CO_2 at the national level for the year 2021 (Source: Edgar database, JRC). Similarly, the monetary value of these emissions, evaluated at the lower, average and upper bound and can be compared to each country's GDP in 2021 (Source: Eurostat, 2021). Table 2 provides the resulting

[9] In what follows we will mainly focus on the minimum value of GWP for each material, in order to present conservative, lower-bound figures.

percentages, ordered in terms of mining environmental monetary costs associated with CO2 emission in percentage of GDP.

Table 2: Incidence of environmental and monetary costs of mining

Country	GWP/GHG	€GWP_min %GDP	€GWP_avg %GDP	€GWP_max %GDP
Albania	26.56	0.37	3.38	8.52
Austria	1.62	0.01	0.07	0.19
Bosnia & Herzegovina	6.08	0.23	2.11	5.32
Bulgaria	1.45	0.03	0.28	0.71
Cyprus	7.22	0.07	0.64	1.61
Czechia	0.01	0.00	0.00	0.00
Finland	190.66	1.00	9.17	23.11
France	0.23	0.00	0.01	0.02
Georgia	176.05	5.01	46.17	116.27
Germany	1.76	0.01	0.09	0.22
Greece	5.31	0.05	0.49	1.24
Hungary	3.29	0.04	0.33	0.83
Ireland	18.92	0.07	0.61	1.55
Italy	1.42	0.01	0.07	0.18
North Macedonia	17.19	0.37	3.42	8.61
Norway	33.68	0.11	1.05	2.65
Poland	27.40	0.48	4.43	11.16
Portugal	32.09	0.21	1.91	4.80
Romania	8.72	0.10	0.96	2.42
Serbia and Montenegro	64.17	1.91	17.58	44.27
Spain	2.75	0.02	0.16	0.40
Sweden	170.42	0.42	3.91	9.84
Turkey	0.76	0.02	0.16	0.40
Ukraine	7.96	0.33	3.05	7.68
United Kingdom	0.29	0.00	0.01	0.03
TOTAL	*11.09*	*0.077*	*0.70*	*1.79*

Source: Authors' elaboration

At an aggregate level, the lower bound, conservative estimates of CO2 equivalent emissions of mining and their corresponding monetary value represent, respectively, 11% of total emissions in 2021 and in a range between less than 1% to 1.79% of aggregate GDP in 2021. Considering cross-country variability, Georgia, Finland and Sweden bear the higher percentage cost and higher emissions. On the other extreme, the monetary and physical impact of mining is lowest in Czechia and France. This ranking reflects both the magnitude of the mining sector in each country, economic size and level of aggregate emissions, along with policies aimed at curbing them.

5.2. Regional level analysis

In this subsection, we first look at the location of mining sites in Europe, highlighting if these are in the EU, EFTA or candidate countries and whether the mined materials are considered critical or strategic. We then provide an analysis of the spatial concentration of the activities in Europe, by presenting two spatial indexes. In Subsection 5.3, we examine the regional environmental impact of site-specific mining activities and the associated monetary valuation. Table 3 lists the materials that can be mined in Europe, distinguishing between EU, EFTA and Candidate countries, highlighting whether these belong to the critical or strategic raw materials group and also indicating if the mining sites are located within a region within the EU-proper.

Table 3: Location and critical nature of mining activities.

Material	n° mining sites	Location	n° EU regions	Critical/Strategic
bauxite	1	EU	1	CRM
chromite	2	EU-EFTA-Candidate	1	
cobalt	23	EU-EFTA-Candidate	4	CRM
copper	104	EU-EFTA-Candidate	35	SCRM
graphite	5	EU-EFTA	3	CRM
ilmenite	1	EU	1	
iron ore	27	EU-EFTA-Candidate	9	
lead	56	EU-EFTA-Candidate	27	
lithium	15	EU-EFTA-Candidate	9	SCRM
manganese	2	EU-EFTA-Candidate	2	SCRM
molybdenum	8	EU-EFTA-Candidate	6	
nickel	31	EU-EFTA-Candidate	7	SCRM
niobium	1	EU	1	CRM
platinum	6	EU-EFTA	2	CRM
rare earth element	4	EU-Candidate	4	CRM
rutile	1	EFTA		
silver	75	EU-EFTA-Candidate	37	
tantalum	3	EU-Candidate	2	CRM
tin	18	EU	9	
titanium	3	EU-Candidate	2	CRM
tungsten	18	EU-Candidate	11	CRM
vanadium	8	EU-Candidate	4	CRM
zinc	76	EU-EFTA	34	

Source: Authors’ elaboration

Table 4: Distribution of relative regional concentration index (LQ) – Source: Authors' elaboration

Country	Region	Material	LQ
Sweden	Ovre Norrland	copper	2.47E-05
Turkey	West Marmara	copper	0.462621
Finland	Etela-Suomi	tantalum	631074.4

Source: Authors' elaboration

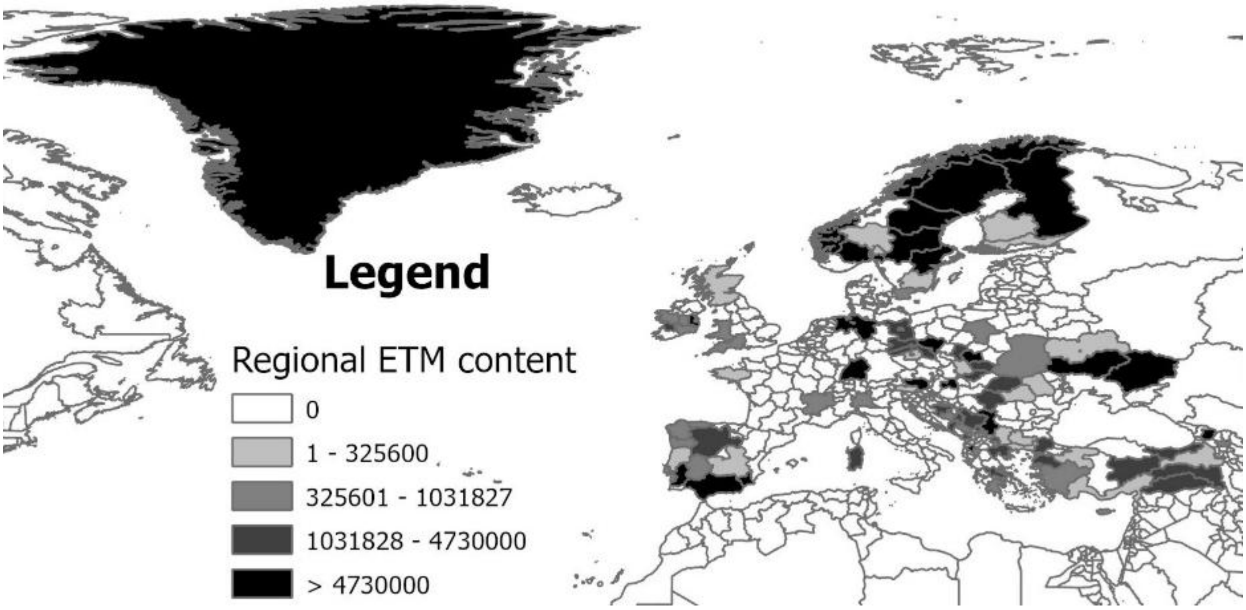
Table 5: Regions with European regional concentration index (ERCI) >0.20 –

Country	Region	Material	ERCI
Hungary	Kozep-Dunantul	bauxite	1
Norway	Vestlandet	rutile	1
Greenland	Greenland	niobium	0.994466
Georgia	Imereti	manganese	0.993974
Greenland	Greenland	tantalum	0.905942
Greenland	Greenland	rare earth elements	0.848474
Finland	Pohjois-ja Ita-Suomi	chromite	0.80614
Germany	Baden-Wurttemberg	lithium	0.5577
Poland	Dolnoslaskie	silver	0.554524
Greenland	Greenland	ilmenite	0.553491
Sweden	Mellersta Norrland	vanadium	0.424736
Finland	Pohjois-ja Ita-Suomi	platinum	0.381175
Sweden	Ovre Norrland	graphite	0.375285
Sweden	Ovre Norrland	graphite	0.373622
Poland	Dolnoslaskie	copper	0.341675
Sweden	Mellersta Norrland	vanadium	0.335433
Poland	Slaskie	tungsten	0.323633
Sweden	Mellersta Norrland	molybdenum	0.315882
Finland	Pohjois-ja Ita-Suomi	nickel	0.277059
Finland	Pohjois-ja Ita-Suomi	ilmenite	0.266254
Finland	Pohjois-ja Ita-Suomi	platinum	0.247441
United Kingdom	South West	tungsten	0.24239
Serbia	Sumadija and West Serbia	lithium	0.241196
Finland	Pohjois-ja Ita-Suomi	cobalt	0.205743
Poland	Slaskie	molybdenum	0.204668

Source: Authors' elaboration

The first index we propose is the regional relative concentration index (LQ), which measures the location quotient of each material with respect to the country average. An LQ of one implies equal specialization of the region and country, while values higher (lower) than one imply the region is more (less) specialized than the country by the value of the LQ. According to Wheeler (2005), the location quotient, computed as a ratio of ratios, allows measuring relative concentrations of sub-areas with respect to the whole area. In our case, we examine how each ETM mining activity is concentrated in each region with respect to how it is concentrated in the respective country.

Figure 7: Map of regional aggregate ETM content (tonnes)



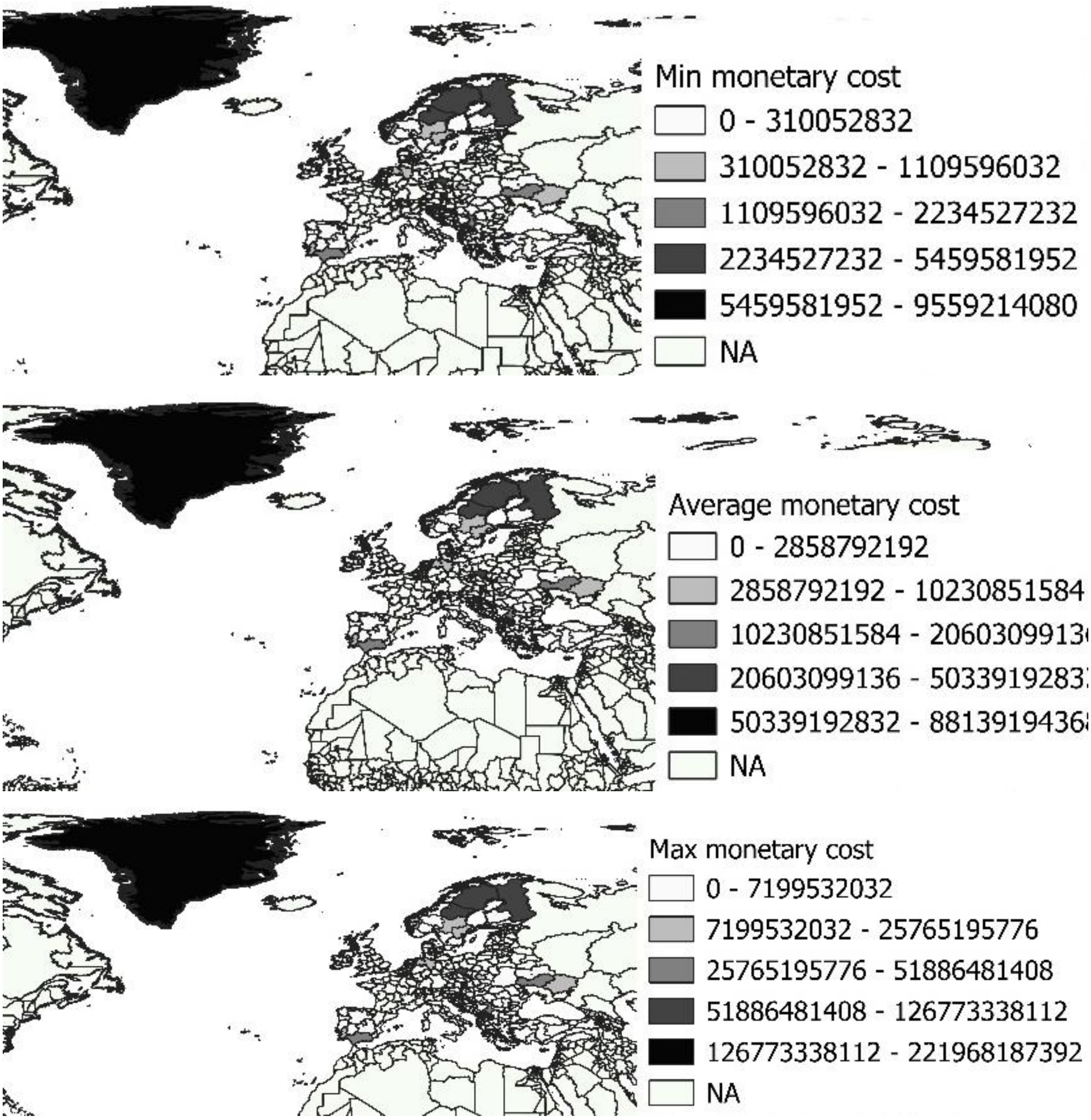
Source: Authors' elaboration

Table 4 shows the distribution of measured LQ, with a median value of 0.45 and a maximum of 624067.3, shown in the Table, and the average value of the index is 0.46. Further inspection of these statistics suggests that ETM mining activity is, as expected, concentrated in few regions, with a higher heterogeneity at the regional level than at the country level. Mining activities depend on the concentration of the materials within the Earth's crust, and typically orebodies are highly spatially concentrated in relatively narrow areas. This finding thus suggests, from a policy perspective, that any decision concerning mining in Europe should be guided by considering the local costs and benefits, along with the aggregate, to assess if further mining activities are to be undertaken.

Region Etela-Suomi of Finland which produces tantalum tops the index, followed by Anatoliki Makedonia, Thraki of Greece which produces silver. Other European regions that present high values of the index are the North region of Ukraine (producing nickel), Scotland (silver), the West region of Ukraine (silver, zinc and lead), Hedmark og Oppland of Norway (cobalt and nickel), and Smaland Med Oarna of Sweden (rare earth elements).

The second measure we propose is the European regional concentration index (ERCI), computed as the regional quantity sourced for each material by region over the material's European total amount. While LQ is unbounded by construction, ERCI is a share, thus ranging between zero and one. ERCI allows us to identify, for each mined material, which regions are hotspots, where a high share of the European production is concentrated. This is especially relevant when examining the local effects of mining in terms of negative environmental impacts. Table 5 shows which regions are characterized by values of ERCI exceeding 0.20.

Figure 8: Map of minimum, average and maximum monetary value (Euro 2021) from mining activities of energy transition materials



Source: Authors' elaboration

Focusing on regions and materials exhibiting values above 0.9, two regions in Hungary and Norway mine all bauxite and rutile respectively, in Europe, according to the information contained in our dataset.[10] Greenland has a high concentration of other materials, including niobium, lanthanides, rare earth elements, and tantalum, while Georgia, Finland, Sweden, and Poland, present concentration indices above 0.5.

[10] See Section 3 where we have remarked on the possible differences between figures from other sources and information in our dataset.

We now present the regional ETM content and monetary quantification of the impact midpoint physical impact (i.e., global warming potential, in kgCO2 equivalent, evaluated in 2021 Euros). Figure 7 visualizes the regional aggregate of all mined materials in Europe, defined as EU, EFTA, candidate and former EU countries; the darker the shade on the map, the higher the aggregate amount of all ETM mined. Broadly, there are 3 clusters in Europe where the source of ETM is the highest.

The first hotspot in Europe is the Nordics (especially Finland, Sweden, and Greenland); the second hotspot is the Eastern European regions (especially Poland, Ukraine, and Serbia); the third hotspot is the Iberian Peninsula. Additional relevant sources of ETM are in Turkey and Georgia, countries that along with Greenland are not in the European Union, but should be considered as potential partners, if feasible, if the EU aims at tapping into the mining potential and reduce external dependency.

Figure 8 visualizes the minimum, average and maximum global warming potential damage cost, evaluated in 2021 Euros, associated with each subnational region with ETM mining activities in Europe.

5.3. Monte Carlo analysis

As shown in Table 1, the LCIA literature presents a wide range of estimates for both midpoint values and the global warming potential damage costs associated with mining. Relying on a single estimate from the literature to assess environmental costs thus overlooks the substantial uncertainty inherent in the underlying parameters. A widely adopted approach to accounting for this uncertainty is to employ Monte Carlo analysis, which systematically incorporates variability in parameter estimates used in the LCIA. See Bastianin et al. (2022) for an example of the use of Monte Carlo methods in the context of social cost-benefit analysis. Our Monte Carlo analysis builds on the estimates obtained from the literature review summarized in Table 1. Specifically, at each iteration of the simulation, we draw both midpoint values and GWP damage costs from uniform distributions, with support defined by the minimum and maximum estimates reported in Table 1. Across 100,000 Monte Carlo simulations, we compute the site-specific GWP and its corresponding monetary value, generating site-specific empirical distributions that can be aggregated at the desired geographical level.

In Table 6 we show the Monte Carlo results aggregated at country level. Starting with the relative standard error (RSE), we observe that it remains low across most countries, indicating a high degree of precision in the Monte Carlo estimates. The highest RSE values, around 0.10–0.13, are observed for countries with relatively small mining-related environmental damages, such as Georgia, Germany, and Norway. In contrast, countries with larger estimated impacts, such as Greenland and Sweden, exhibit lower RSE values.

Focusing on the average environmental damage in gigatonnes of CO_2 equivalent per tonne ($GtCO_2e/t$), Greenland stands out with the highest value (932.82 $GtCO_2e/t$), followed by Sweden (683.35 $GtCO_2e/t$), while most other countries show considerably lower figures. The coefficient of variation (CV), which measures relative dispersion, is relatively low for many countries, particularly Sweden (0.09) and Finland (0.08). The interquartile range, defined by the 25th (q025) and 75th (q075) percentiles, confirms this pattern: for most countries, the interquartile spread is moderate, but for Greenland and Georgia, the range is notably wider, reflecting higher variability in estimated impacts.

A similar pattern emerges for the monetary valuation of environmental damage. The average cost per $GtCO_2e/t$ is highest in Greenland (400.08 EUR) and Sweden (279.68 EUR), while in most other countries, it remains below 100 EUR. The CV values indicate greater relative uncertainty in monetary estimates compared to the $GtCO_2e/t$ values, particularly for Germany (0.54) and Georgia (0.78), suggesting that monetary damage estimates are more sensitive to parameter uncertainty. The interquartile range in monetary values follows the same pattern as in $GtCO_2e/t$, with countries exhibiting higher absolute damages also showing greater variability in estimates.

Figure 9 relies on boxplots to visualize the distribution of environmental damage estimates across Monte Carlo simulations. The central line within each box represents the median, while the lower and upper edges of the box indicate the 25th (q025) and 75th (q075) percentiles, respectively. The whiskers extend to the most extreme data points within 1.5 times the interquartile range (IQR), and any points beyond this range are plotted as outliers, represented by individual markers. Wider boxes and longer whiskers suggest higher variability in estimates, whereas more compact boxes indicate greater stability in results. Note that countries with larger CV in Table 6, tend to exhibit wider interquartile ranges and hence wider boxes.

Overall, the results highlight substantial cross-country differences in the estimated environmental damages of mining, with both absolute values and relative uncertainty varying significantly across the sample.

Results at the NUTS-2 regional level are shown in Figure 10 and Table A1 in the Appendix. Focusing on the left panel of Figure 10, the boxplots illustrate the distribution of estimated environmental damages from mining across various regions. Greenland, which represents a single NUTS-2 region, exhibits the highest environmental impact. Other NUTS-2 regions, such as Övre Norrland (Sweden) and Pohjois- ja Itä-Suomi (Finland), also display high dispersion, with multiple outliers. In contrast, regions like Baden-Württemberg (Germany) and Andalucía (Spain) exhibit more compact distributions, indicating relatively stable estimates across Monte Carlo simulations.

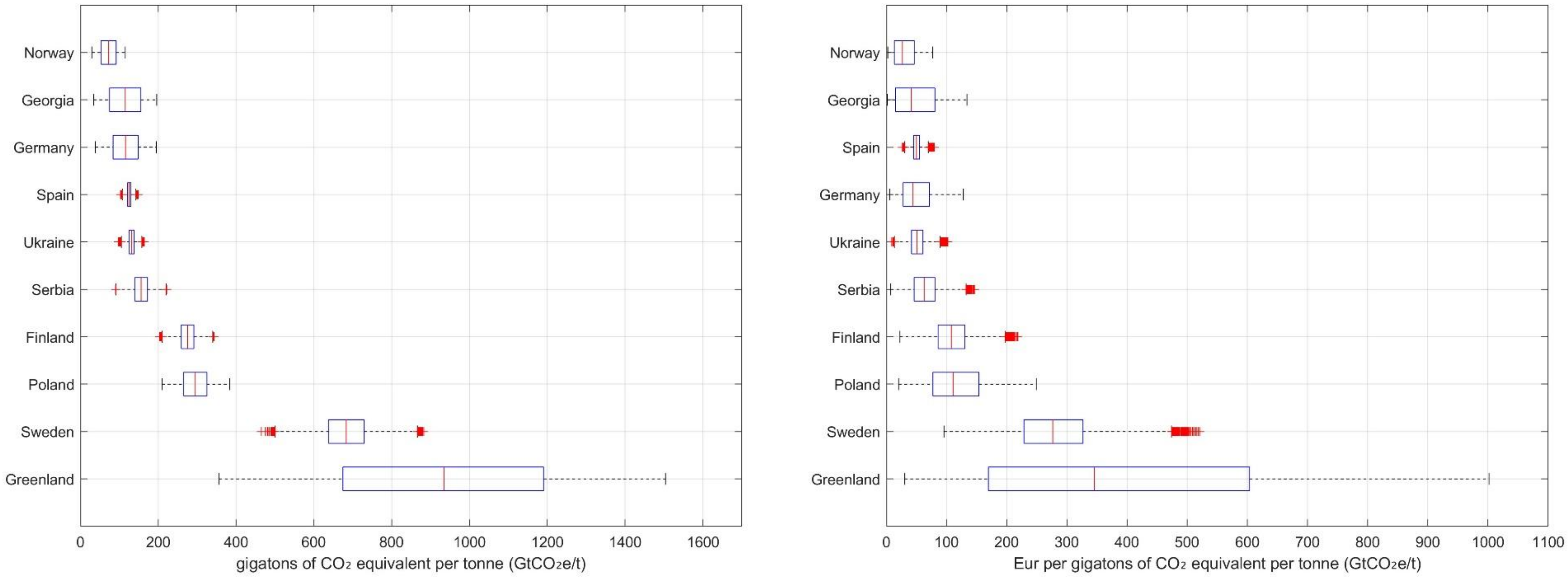
Table 6. Monte Carlo results: environmental damages of mining at country level

Country	Avg.	CV	q025	q075	Avg. (eur)	CV (eur)	q025 (eur)	q075 (eur)	RSE (%)
Greenland	932.82	0.32	674.72	1190.54	400.08	0.64	169.45	603.64	0.10
Sweden	683.35	0.09	637.63	729.32	279.68	0.24	228.56	326.68	0.03
Poland	294.96	0.12	264.84	324.91	116.49	0.40	77.06	153.79	0.04
Finland	275.06	0.08	258.77	291.27	108.65	0.29	85.76	130.26	0.03
Serbia	155.84	0.15	139.62	172.05	63.76	0.38	45.92	80.49	0.05
Ukraine	131.27	0.07	124.68	137.84	51.27	0.26	41.57	60.51	0.02
Spain	125.08	0.05	120.70	129.45	50.00	0.14	45.02	54.82	0.02
Germany	115.81	0.32	83.67	148.00	50.52	0.54	27.62	71.36	0.10
Georgia	114.83	0.41	74.58	155.04	49.87	0.78	14.87	80.39	0.13
Norway	72.18	0.31	52.65	91.66	30.71	0.64	13.13	46.15	0.10
Turkey	53.01	0.09	49.74	56.29	21.59	0.20	18.42	24.56	0.03
Portugal	52.52	0.11	48.08	56.95	21.04	0.36	15.00	26.84	0.03
Ireland	49.52	0.09	46.34	52.73	19.50	0.31	14.91	23.73	0.03
Greece	33.49	0.28	25.41	41.53	14.29	0.51	8.31	19.75	0.09
Romania	23.45	0.14	20.70	26.20	9.25	0.46	5.65	12.68	0.04
Albania	16.24	0.14	14.59	17.89	6.82	0.29	5.38	8.17	0.05
Italy	11.82	0.14	10.43	13.22	4.65	0.49	2.73	6.48	0.04
United Kingdom	9.53	0.11	8.70	10.36	3.78	0.28	2.98	4.55	0.03
North Macedonia	7.39	0.11	6.84	7.94	2.93	0.35	2.19	3.63	0.03
Hungary	6.68	0.13	6.03	7.32	2.66	0.43	1.78	3.47	0.04
Austria	5.30	0.27	4.21	6.40	2.32	0.48	1.47	3.09	0.09
Bosnia & Herzegovina	4.11	0.13	3.66	4.56	1.62	0.45	1.00	2.21	0.04
France	2.66	0.12	2.42	2.90	1.05	0.41	0.71	1.37	0.04
Montenegro	1.84	0.17	1.58	2.10	0.73	0.57	0.36	1.07	0.05
Bulgaria	1.84	0.15	1.61	2.08	0.73	0.49	0.41	1.02	0.05
Cyprus	1.44	0.16	1.25	1.63	0.57	0.51	0.32	0.80	0.05
Czechia	0.04	0.12	0.03	0.04	0.01	0.42	0.01	0.02	0.04

Notes: results based on 100,000 Monte Carlo simulations. The leftmost panel shows the environmental damage of mining, expressed in gigatonnes of CO_2 equivalent per tonne ($GtCO_2e/t$), and the middle panel shows the monetary value of environmental damage, expressed in eur per GtCO2e/t. The right panel shows the relative standard error (RSE), which is the Monte Carlo standard error divided by the mean, expressed as a percentage. CV is the coefficient of variation, q025, q075 are the 0.25 and 0.75 quantiles.

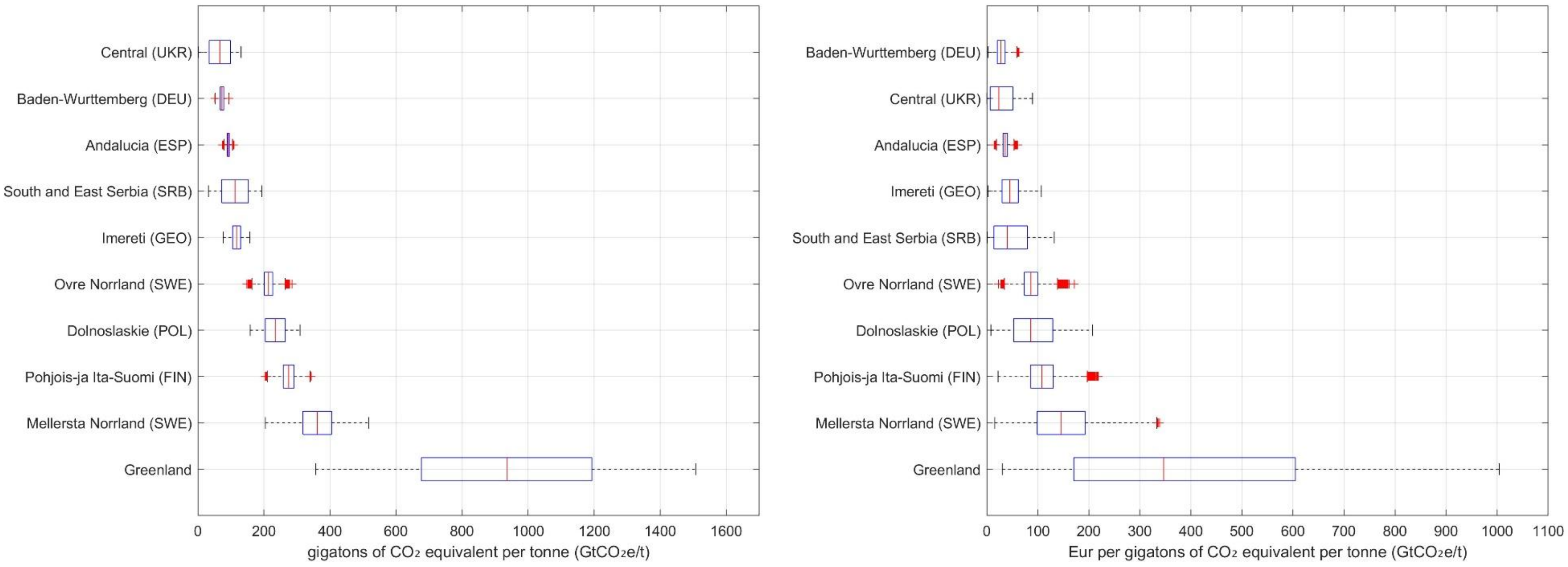
Regional disparities are evident, as some areas within the same country display significantly different environmental cost estimates. For instance, Swedish and Finnish regions show considerable variation, whereas regions in Spain and Germany are more homogeneous. The presence of numerous outliers in several regions highlights the underlying uncertainty in the estimates, emphasizing the importance of incorporating regional-level variability when assessing the environmental footprint of mining activities.

Figure 9: Country level Monte Carlo results



Source: Authors' elaboration

Figure 10: Regional level Monte Carlo results



Source: Authors' elaboration

6. Discussion and Conclusions

Our results suggest that, while limited, there is current and potential availability of ETMs in Europe, but these are highly spatially concentrated. We have identified a set of hotspots where mining resources are concentrated that however differ in terms of their environmental impact and associated costs in monetary terms. ETMs are concentrated in Greenland, Finland, Hungary, Norway, Poland and Georgia, with very few projects in Central Western Europe. Depending on the spatial distribution of ETMs, each of which is characterized by a different impact in terms of CO2eq emissions and costs, some hotspots account for higher or lower proportion of environmental impact and costs. Looking at the regional level, the five regions producing the highest impact in terms of CO2eq are in Sweden, Poland, Finland and Greenland. In aggregate terms, 11% of total CO2eq emissions in 2021 can be attributed to mining for ETMs.

This heterogeneity suggests that any policy intervention regarding mining for CRMs should take the regional dimension into account, by adopting a regional perspective when designing policies in this sector.

Our analysis has also shown that these mining activities are associated with relevant environmental costs, which should be taken into consideration when designing public policies, given the uneven distribution at both the national and regional level. Considering all the countries in our analyses, the monetary value of CO2eq emissions of mining for ETMs ranges from 0.07% to 1.79% of the value of GDP in 2021, with Finland, Sweden and Georgia bearing the highest proportion of costs.

Results of risk analyses suggest that, at the country and especially at the subnational, regional level, there is considerable variation across units of analysis. Both country and regional disparities are present, and the presence of outliers highlights the underlying uncertainty in the estimates, further stressing the relevance of accounting for regional-level heterogeneity at the policy design phase.

Additional research is needed to better understand the local environmental impact of mining activities and their related costs. This information could be then considered when developing policies aimed at increasing mining activity in Europe, by considering the global and local costs and benefits of local sourcing.

References

Amadei, A. M., De Laurentiis, V., & Sala, S. (2021). A review of monetary valuation in life cycle assessment: State of the art and future needs. *Journal of Cleaner Production*, 329, 129668.

Arendt, R., Bach, V., & Finkbeiner, M. (2022). The global environmental costs of mining and processing abiotic raw materials and their geographic distribution. *Journal of Cleaner Production*, 361, 132232.

Badakhshan, N., Shahriar, K., Afraei, S., & Bakhtavar, E. (2023). Determining the environmental costs of mining projects: A comprehensive quantitative assessment. *Resources Policy*, 82, 103561.

Bare, J. C., Hofstetter, P., Pennington, D. W., & De Haes, H. A. U. (2000). Midpoints versus endpoints: The sacrifices and benefits. *The International Journal of Life Cycle Assessment*, 5, 319-326.

Bastianin, A., Del Bo, C. F., Florio, M., & Giffoni, F. (2022). Projecting the socio-economic impact of a big science center: the world's largest particle accelerator at CERN. *Applied Economics*, 55(49), 5768-5789.

Bruyn, S. de, Korteland, M., Markowska, A., Davidson, M., Jong, Femke deBles, M., Sevenster, M., (2010). Annexes - Shadow Prices Handbook, pp. 1–128. https://www.cedelft.eu/en/publications/1032/shadow-prices-handbook-valuation-and-weighting-of-emissions-and-environmental-impacts.

Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, A., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D. and Christou, M. (2023). *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study*, Publications Office of the European Union, doi:10.2760/386650, JRC132889.

da Silva Lima, L., Alvarenga, R. A., de Souza Amaral, T., Nolli, P. D. T. G., & Dewulf, J. (2022). Life cycle assessment of ferroniobium and niobium oxides: Quantifying the reduction of environmental impacts as a result of production process improvements. *Journal of Cleaner Production*, 348, 131327.

Diemer, A., Iammarino, S., Perkins, R., & Gros, A. (2022). Technology, resources and geography in a paradigm shift: the case of critical and conflict materials in ICTs. *Regional Studies*, 1-13.

Draghi, M., (2024). The future of European competitiveness. Part A: A competitiveness strategy for Europe. Available online at: https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

Engels, P., Cerdas, F., Dettmer, T., Frey, C., Hentschel, J., Herrmann, C., & Schueler, M. (2022). Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. *Journal of Cleaner Production*, 336, 130474.

European Commission (2023a). Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending. COM(2023) 160.

European Commission (2023b). Study on the critical raw materials for the EU 2023: final report, Publications Office of the European Union. Available online at: https://data.europa.eu/doi/10.2873/725585

Farjana, S. H., Huda, N., & Mahmud, M. P. (2018a). Life-cycle environmental impact assessment of mineral industries. In IOP Conference Series: Materials Science and Engineering (Vol. 351, No. 1, p. 012016). IOP Publishing.

Farjana, S. H., Huda, N., & Mahmud, M. P. (2019a). Impacts of aluminium production: A cradle-to-gate investigation using life-cycle assessment. *Science of the Total Environment*, 663, 958-970.

Farjana, S. H., Huda, N., & Mahmud, M. P. (2019b). Life cycle assessment of cobalt extraction process. *Journal of Sustainable Mining*, 18(3), 150-161.

Farjana, S. H., Huda, N., Mahmud, M. P., & Lang, C. (2018b). Towards sustainable TiO_2 production: An investigation of environmental impacts of ilmenite and rutile processing routes in Australia. *Journal of Cleaner Production*, 196, 1016-1025.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., ... & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, 91(1), 1-21.

Hund, K. L., Arrobas, D. L. P., Fabregas Masllovet, T. P., Laing, T. J., & Drexhage, J. R. (2023). *Minerals for climate action: The mineral intensity of the clean energy transition*. World Bank Group. https://documents.worldbank.org/curated/en/099052423172525564/P16627806f5aa400508f8c0bdcba0878a3e

IEA (2017), Energy Technology Perspectives 2017, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2017

IEA (2024a), Global Critical Minerals Outlook 2024, IEA, Paris. Available online at: https://www.iea.org/reports/global-critical-minerals-outlook-2024

IEA (2024b), Critical Minerals Data Explorer, IEA, Paris. Available online at: https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer

IEA (2024c), Policies and Measures Database, IEA, Paris. Available online at: https://www.iea.org/policies/about

Jiang, S., Zhang, L., Li, F., Hua, H., Liu, X., Yuan, Z., & Wu, H. (2020). Environmental impacts of lithium production showing the importance of primary data of upstream process in life-cycle assessment. *Journal of Environmental Management*, 262, 110253.

Jones, A. G. (2023). Mining for net zero: The impossible task. *The Leading Edge*, 42(4), 266-276.

Lèbre, É., Sharma, V., & Corzo-Remigio, A. (2024). Extracting minerals for the energy transition: Local data for global decision-making. *Journal of Cleaner Production*, 143563.

Li, G. Y., Ascani, A., & Iammarino, S. (2024). The material basis of modern technologies. A case study on rare metals. *Research Policy*, 53(1), 104914.

Månberger, A. (2023). Critical raw material supply matters and the potential of the circular economy to contribute to security. *Intereconomics*, 58(2), 74-78.

Nakano, J. (2021). The Geopolitics of Critical Minerals Supply Chains. Center for Strategic and International Studies (CSIS).

Neometals. (2023). Vanadium Recovery Project – Feasibility study results and project update. https://www.criticalmetals.eu/reports/179-02642069.pdf

Nickel Institute. (2023). Life cycle data. https://nickelinstitute.org/media/fbmdel4y/lifecycledata-summary-updatejan2023.pdf

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: A scientific synthesis. *PLOS ONE*, 9(7), e101298.

Owen, J. R., Kemp, D., Lechner, A. M., Harris, J., Zhang, R., & Lèbre, É. (2023). Energy transition minerals and their intersection with land-connected peoples. *Nature Sustainability*, 6(2), 203-211.

Pavel, C. C., Lacal-Arántegui, R., Marmier, A., Schüler, D., Tzimas, E., Buchert, M., & Blagoeva, D. (2017). Substitution strategies for reducing the use of rare earths in wind turbines. *Resources Policy*, 52, 349-357.

Pizzol, M., Weidema, B., Brandão, M., & Osset, P. (2015). Monetary valuation in life cycle assessment: A review. *Journal of Cleaner Production*, 86, 170-179.

Rachid, S., Yassine, T. A. H. A., & Benzaazoua, M. (2023). Environmental evaluation of metals and minerals production based on a life cycle assessment approach: A systematic review. *Minerals Engineering*, 198, 108076.

Sáez-Guinoa, J., García-Franco, E., Llera-Sastresa, E., & Romeo, L. M. (2024). The effects of energy consumption of alumina production in the environmental impacts using life cycle assessment. *The International Journal of Life Cycle Assessment*, 29(3), 380-393.

Santero, N., & Hendry, J. (2016). Harmonization of LCA methodologies for the metal and mining industry. *The International Journal of Life Cycle Assessment*, 21, 1543-1553.

Schneider-Marin, P., & Lang, W. (2020). Environmental costs of buildings: monetary valuation of ecological indicators for the building industry. *The International Journal of Life Cycle Assessment*, 25, 1637-1659.

Sonter, L. J., Maron, M., Bull, J. W., Giljum, S., Luckeneder, S., Maus, V., & Watson, J. E. (2023). How to fuel an energy transition with ecologically responsible mining. *Proceedings of the National Academy of Sciences*, 120(35), e2307006120.

Tao, M., Nie, K., Zhao, R., Shi, Y., & Cao, W. (2022). Environmental impact of mining and beneficiation of copper sulphate mine based on life cycle assessment. Environmental Science and Pollution Research, 29(58), 87613-87627.

Westfall, L. A., Davourie, J., Ali, M., & McGough, D. (2016). Cradle-to-gate life cycle assessment of global manganese alloy production. The International Journal of Life Cycle Assessment, 21, 1573-1579.

Wheeler, J. O. (2005). Geography. In K. Kempf-Leonard (Ed.), Encyclopaedia of Social Measurement (pp. 115-123). Elsevier.

Zapp, P., Schreiber, A., Marx, J., & Kuckshinrichs, W. (2022). Environmental impacts of rare earth production. MRS Bulletin, 47(3), 267-275.

APPENDIX

Table A1. Monte Carlo results: environmental damage of mining at NUTS2 regional level

Country	Region	Avg.	CV	q025	q075	Avg. (eur)	CV (eur)	q025 (eur)	q075 (eur)	RSE (%)
GRL	Greenland	935.11	0.32	676.97	1192.98	401.06	0.64	170.37	604.72	0.10
SWE	Mellersta Norrland	361.53	0.17	318.39	404.73	148.44	0.43	98.49	192.70	0.05
FIN	Pohjois-ja Ita-Suomi	274.78	0.08	258.50	291.00	108.53	0.29	85.64	130.15	0.03
POL	Dolnoslaskie	234.01	0.15	204.02	264.00	92.21	0.50	52.52	129.30	0.05
SWE	Ovre Norrland	213.85	0.08	201.21	226.49	86.83	0.22	73.50	99.57	0.03
SRB	South and East Serbia	117.23	0.14	105.14	129.29	46.47	0.46	29.91	61.86	0.04
GEO	Imereti	112.35	0.41	72.12	152.56	48.89	0.79	13.91	79.40	0.13
ESP	Andalucia	92.05	0.05	88.85	95.22	36.26	0.17	31.85	40.49	0.02
UKR	Central	72.94	0.10	67.63	78.27	28.48	0.37	20.68	35.88	0.03
DEU	Baden-Wurttemberg	66.29	0.56	34.13	98.41	30.63	0.87	6.57	51.15	0.18
NOR	Vestlandet	58.79	0.38	39.26	78.33	25.28	0.77	7.63	40.75	0.12
SWE	Ostra Mellansverige	57.41	0.26	44.66	70.17	24.00	0.55	13.14	34.18	0.08
UKR	East	54.27	0.11	49.89	58.65	21.17	0.40	14.68	27.24	0.03
PRT	Alentejo	41.98	0.13	37.62	46.36	16.54	0.44	10.56	22.34	0.04
POL	Malopolskie	39.57	0.17	33.71	45.39	15.60	0.60	7.39	23.23	0.05
SWE	Norra Mellansverige	37.00	0.12	33.69	40.32	14.79	0.38	10.35	19.04	0.04
SRB	Sumadija and West Serbia	32.64	0.49	18.80	46.51	14.84	0.77	4.47	23.74	0.16
DEU	Niedersachsen	24.70	0.16	21.35	28.06	9.73	0.55	5.03	14.12	0.05
IRL	Mid-East	23.09	0.15	20.27	25.93	9.11	0.51	5.18	12.84	0.05
IRL	Mid-West	18.62	0.15	16.21	21.03	7.32	0.53	3.94	10.46	0.05
POL	Slaskie	18.56	0.13	16.86	20.26	7.56	0.34	5.69	9.33	0.04
GRC	Sterea Ellada	18.18	0.51	10.10	26.26	8.25	0.84	1.95	13.65	0.16
ROU	Nord-Vest	16.19	0.20	13.45	18.94	6.40	0.64	2.71	9.78	0.06
DEU	Sachsen	14.91	0.21	12.36	17.46	6.24	0.38	4.40	7.95	0.07
GRC	Kentriki Makedonia	13.43	0.11	12.33	14.55	5.30	0.38	3.77	6.71	0.04
TUR	West Marmara	13.15	0.09	12.33	13.98	5.20	0.29	4.09	6.25	0.03
SWE	Sydsverige	10.27	0.27	7.86	12.68	4.19	0.71	1.51	6.60	0.09
DEU	Brandenburg	9.90	0.17	8.45	11.36	3.91	0.56	1.97	5.72	0.05
ESP	Extremadura	9.35	0.42	5.92	12.77	4.21	0.68	1.74	6.42	0.13

TUR	East Marmara	9.34	0.38	6.29	12.37	4.01	0.75	1.29	6.40	0.12
ITA	Sardegna	9.16	0.18	7.77	10.54	3.60	0.61	1.65	5.40	0.06
NOR	Nord-Norge	8.39	0.12	7.58	9.20	3.31	0.43	2.14	4.43	0.04
ESP	Region de Murcia	8.17	0.12	7.40	8.95	3.22	0.41	2.15	4.24	0.04
TUR	East Black Sea	7.58	0.07	7.18	7.98	2.99	0.25	2.46	3.51	0.02
TUR	Central East Anatolia	7.51	0.20	6.22	8.80	2.98	0.65	1.25	4.57	0.06
GBR	South West	7.43	0.14	6.60	8.25	2.95	0.34	2.17	3.69	0.04
ALB	Shkoder	7.25	0.12	6.63	7.87	2.86	0.40	1.98	3.66	0.04
ESP	Galicia	6.25	0.14	5.62	6.89	2.60	0.36	1.88	3.27	0.05
ROU	Vest	6.06	0.14	5.46	6.67	2.39	0.46	1.55	3.13	0.04
HUN	Eszak-Magyarorszag	6.06	0.14	5.43	6.68	2.39	0.47	1.52	3.18	0.04
ESP	Castilla y Leon	5.77	0.13	5.22	6.32	2.30	0.40	1.55	3.03	0.04
TUR	Aegean	5.57	0.33	4.25	6.90	2.52	0.54	1.41	3.46	0.10
ALB	Korce	5.53	0.37	4.05	7.02	2.51	0.60	1.27	3.57	0.12
MKD	East	4.91	0.12	4.46	5.37	1.95	0.41	1.33	2.54	0.04
TUR	South East Anatolia	4.46	0.19	3.73	5.19	1.77	0.62	0.79	2.66	0.06
PRT	Norte	4.32	0.41	2.89	5.75	1.99	0.64	0.95	2.93	0.13
BIH	Central Bosnia	3.94	0.14	3.49	4.39	1.55	0.47	0.93	2.14	0.04
IRL	Midland	3.79	0.13	3.44	4.14	1.49	0.45	0.98	1.94	0.04
UKR	West	3.71	0.17	3.18	4.24	1.46	0.58	0.72	2.15	0.05
KSV	Mitrovica	3.64	0.15	3.18	4.10	1.44	0.52	0.81	2.04	0.05
AUT	Karnten	3.37	0.42	2.29	4.45	1.56	0.64	0.74	2.29	0.13
PRT	Area Metropolitana de Lisboa	3.31	0.12	3.00	3.62	1.30	0.40	0.87	1.70	0.04
SWE	Smaland med oarna	3.29	0.39	2.18	4.40	1.42	0.78	0.42	2.30	0.12
TUR	Central Anatolia	3.12	0.13	2.79	3.46	1.23	0.45	0.77	1.67	0.04
PRT	Centro	2.91	0.16	2.59	3.23	1.22	0.30	0.95	1.47	0.05
POL	Mazowieckie	2.82	0.18	2.39	3.25	1.11	0.61	0.50	1.67	0.06
ESP	Principado de Asturias	2.67	0.17	2.29	3.06	1.05	0.58	0.51	1.55	0.05
ITA	Lombardia	2.67	0.17	2.26	3.07	1.05	0.60	0.48	1.57	0.06
GEO	Kvemo Kartli	2.48	0.12	2.25	2.71	0.98	0.40	0.67	1.27	0.04
MKD	South East	2.37	0.20	1.95	2.79	0.94	0.67	0.38	1.46	0.06
KSV	Pristina	2.33	0.30	1.75	2.91	1.00	0.54	0.57	1.40	0.09
IRL	South-East	2.27	0.12	2.06	2.47	0.89	0.40	0.61	1.16	0.04
ALB	Elbasan	2.15	0.36	1.50	2.81	0.95	0.61	0.46	1.39	0.11

GBR	Wales	2.10	0.13	1.90	2.29	0.83	0.43	0.55	1.09	0.04
AUT	Steiermark	1.93	0.17	1.64	2.22	0.75	0.64	0.32	1.15	0.06
FRA	Rhone-Alpes	1.91	0.15	1.67	2.15	0.75	0.53	0.42	1.07	0.05
GRC	Peloponnisos	1.84	0.19	1.54	2.14	0.72	0.66	0.30	1.11	0.06
MNE	North	1.84	0.17	1.58	2.10	0.73	0.57	0.36	1.07	0.05
IRL	West	1.76	0.18	1.48	2.03	0.69	0.63	0.30	1.05	0.06
NOR	Oslo og Akershus	1.64	0.38	1.11	2.18	0.70	0.77	0.21	1.13	0.12
BGR	Yugozapaden	1.49	0.18	1.25	1.73	0.59	0.60	0.27	0.88	0.06
TUR	North East Anatolia	1.49	0.10	1.37	1.60	0.58	0.36	0.42	0.74	0.03
CYP	Total	1.44	0.16	1.25	1.63	0.57	0.51	0.32	0.80	0.05
ALB	Lezhe	0.96	0.13	0.87	1.05	0.38	0.43	0.25	0.49	0.04
ESP	Castilla-la Mancha	0.82	0.35	0.57	1.06	0.35	0.67	0.15	0.54	0.11
TUR	Mediterranean	0.78	0.14	0.70	0.86	0.31	0.47	0.19	0.41	0.04
FRA	Bretagne	0.75	0.15	0.65	0.85	0.30	0.53	0.16	0.43	0.05
ROU	Centru	0.68	0.14	0.59	0.76	0.26	0.60	0.12	0.39	0.05
NOR	Sor-Ostlandet	0.66	0.16	0.58	0.74	0.27	0.43	0.18	0.36	0.05
HUN	Kozep-Dunantul	0.62	0.42	0.39	0.85	0.27	0.79	0.08	0.44	0.13
ROU	Nord-Est	0.52	0.13	0.47	0.56	0.20	0.43	0.14	0.27	0.04
NOR	Hedmark og Oppland	0.40	0.33	0.29	0.51	0.17	0.56	0.09	0.25	0.10
BGR	Yuzhen tsentralen	0.35	0.10	0.33	0.38	0.14	0.33	0.11	0.17	0.03
ALB	Diber	0.35	0.05	0.33	0.36	0.13	0.57	0.06	0.19	0.02
UKR	North	0.34	0.52	0.19	0.50	0.16	0.85	0.04	0.26	0.16
FIN	Lansi-Suomi	0.20	0.23	0.17	0.24	0.09	0.40	0.06	0.11	0.07
BIH	Republica Srpska	0.17	0.18	0.14	0.20	0.07	0.65	0.03	0.10	0.06
MKD	North East	0.11	0.12	0.10	0.12	0.04	0.46	0.03	0.05	0.04
FIN	Etela-Suomi	0.07	0.35	0.05	0.09	0.03	0.75	0.01	0.05	0.11
CZE	Stredni Cechy	0.04	0.12	0.03	0.04	0.01	0.42	0.01	0.02	0.04
GRC	Anatoliki Makedonia, Thraki	0.02	0.15	0.02	0.03	0.01	0.64	0.00	0.01	0.05
GBR	Scotland	0.01	0.15	0.01	0.01	0.00	0.63	0.00	0.00	0.05

Notes: results based on 100,000 Monte Carlo simulations. The leftmost panel shows the environmental damage of mining, expressed in gigatonnes of CO_2 equivalent per tonne ($GtCO_2e/t$), and the middle panel shows the monetary value of environmental damage, expressed in eur per GtCO2e/t. The right panel shows the relative standard error (RSE), which is the Monte Carlo standard error divided by the mean, expressed as a percentage. CV is the coefficient of variation, q025, q075 are the 0.25 and 0.75 quantiles.

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