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The geography of mining and its environmental impact in Europe

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ABSTRACT

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 in order to add to the debate of policy interventions, including new mining activities in Europe, to secure the needed materials to fuel the green transition. 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 achievement of Europe's green goals, could imply for European regions, while accounting for the uneven distribution of mining resources, and thus associated costs, across Europe.

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. Fig. 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 Fig. 2(b) in 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

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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).

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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).

However, increasing internal mining activities would also entail social and environmental costs.² Focusing on the latter, there are several studies aimed at quantifying the environmental costs of mining activities, with different methodologies, including input-output models (Benita, Gaytán-Alfaro, 2024), Environmental Impact Assessments (Badakhshan et al., 2023) or Life Cycle Impact Assessment (LCIA), but few focus on the EU as a whole. LCIA, according to the definition proposed in ISO 14040/14044, is a standardized tool that evaluates a 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. 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, comprehensive efforts to map mining resources and their associated environmental impacts across a wide set of raw materials at a disaggregated spatial level remain limited. Some initiatives, such as the European Geological Data Infrastructure (EGDI), have mapped the presence of deposits - either active or potential - but these do

referenced project site data and present an in-depth analysis of the environmental impacts of mining activities, focusing on ore extraction, 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 CO₂ emissions.³ Societal costs are measured in terms of global warming potential (GWP), as this is the environmental impact category with the highest estimated value (Arendt et al., 2022; Santero and Hendry, 2016). As discussed in detail in Section 3, while LCIAs can address multiple impact categories (e.g., acidification, eutrophication), we focus on GWP, which is one of the most commonly discussed categories (Amadei et al., 2021) and for which data are available from several sources.

Therefore, 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,⁴ 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

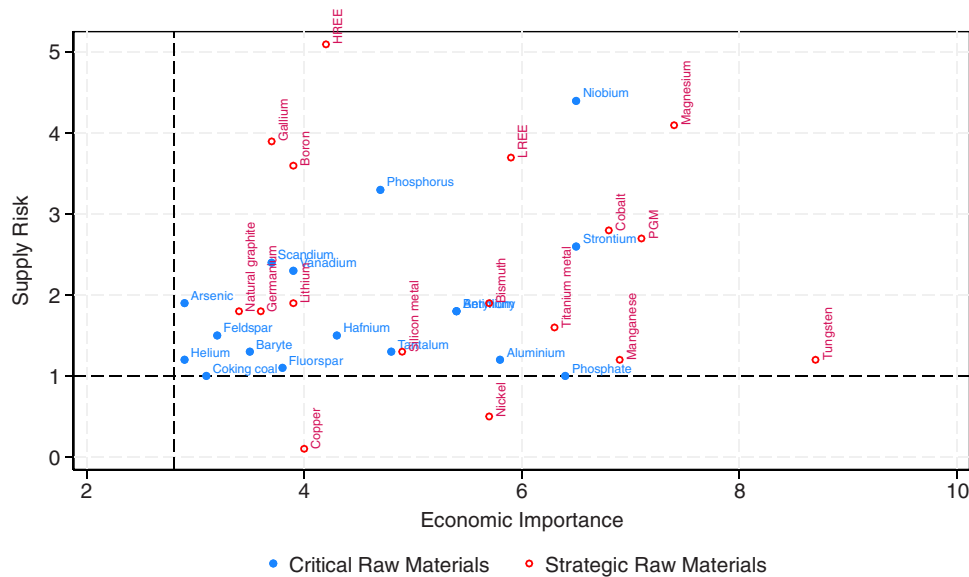


Fig. 1. EU Strategic and Critical Raw Materials list - 2023. *Notes:* the figure shows the critical (blue dots) and strategic (red circles) raw materials. The dashed lines indicate the level of supply risk and economic importance used to determine the criticality of a material (1 and 2.8, respectively).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

not provide integrated assessments of environmental impacts, present a rather fragmented mapping of active, inactive and developing mines, as well as incompleteness of information regarding resource endowments and reserves and, with respect to our data, mostly are available only up to 2019 at the most.

In this paper, we map the mining sector in Europe using geo-

² While we focus on environmental costs, the issue of CRMs also concerns national technological sovereignty, as highlighted by Edler et al. (2023), who frame access to key technologies - and thus to CRMs - as vital for preserving state agency in global innovation systems.

³ Our work should be seen as an initial step in the direction of quantifying environmental costs related to mining for ETMs. Our midpoint impact values and associated monetary values are not site-specific and rely from a variety of sources, which might cause imprecise estimates. However, the Montecarlo simulations aim at partially mitigating these limitations.

⁴ 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.

consider a broader definition of ETMs, which is the same as that used in Owen et al. (2023). Importantly, we note that the set of ETMs we consider does not perfectly overlap with the European Commission's list of CRMs and may also go beyond the scope of current European policies on minerals and materials.

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: Section 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 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).

Fig. 2(a) shows that global demand for materials in 2040 will increase by a factor of 1.3–1.5 compared to 2023, depending on the scenario provided by the International Energy Agency⁵ (IEA) we consider. Fig. 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, further mining will be required to keep up with the expected boom in global demand. This is made clear in Fig. 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 1.5–1.8 in 2040 compared to 2023 to keep up with rising demand.

Fig. 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,⁶ total demand is projected to increase by a factor of 1.7 or 4 in 2050 compared to 2020. Fig. 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 Fig. 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 Fig. 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 Fig. 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).

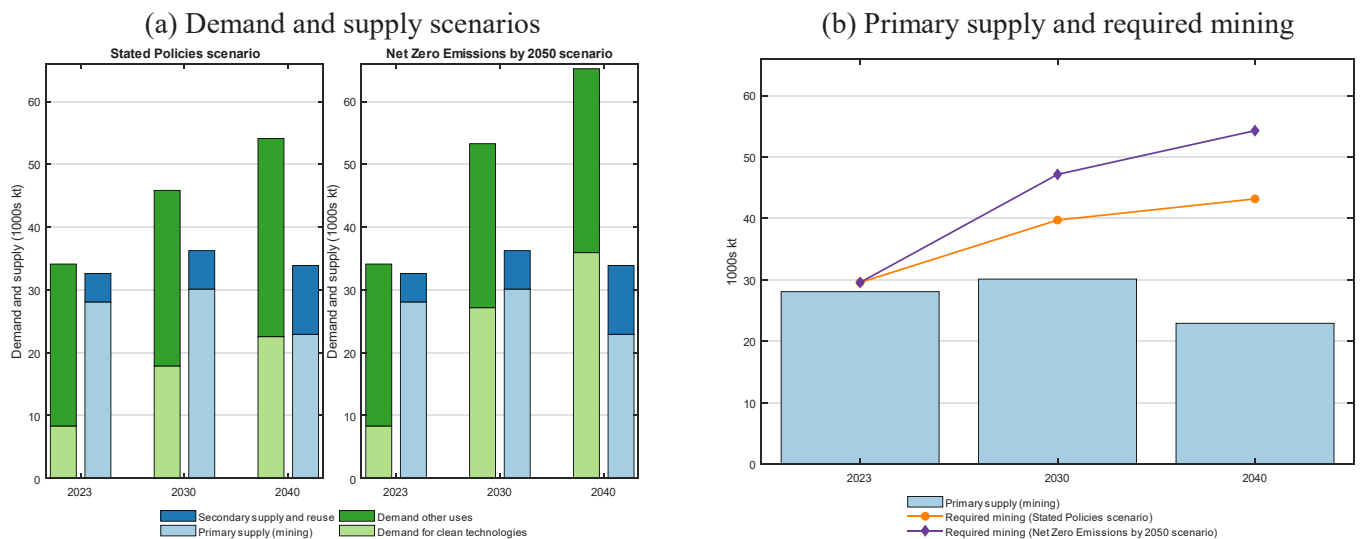


Fig. 2. Global demand, supply and mining scenarios for key critical raw materials. *Notes:* the figure shows the evolution of demand and supply for key critical raw materials under different policy scenarios. The commodities considered are copper, cobalt, lithium, nickel, rare earth magnets (i.e. praseodymium, 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).

⁵ 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 CO₂ 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).

⁶ 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).

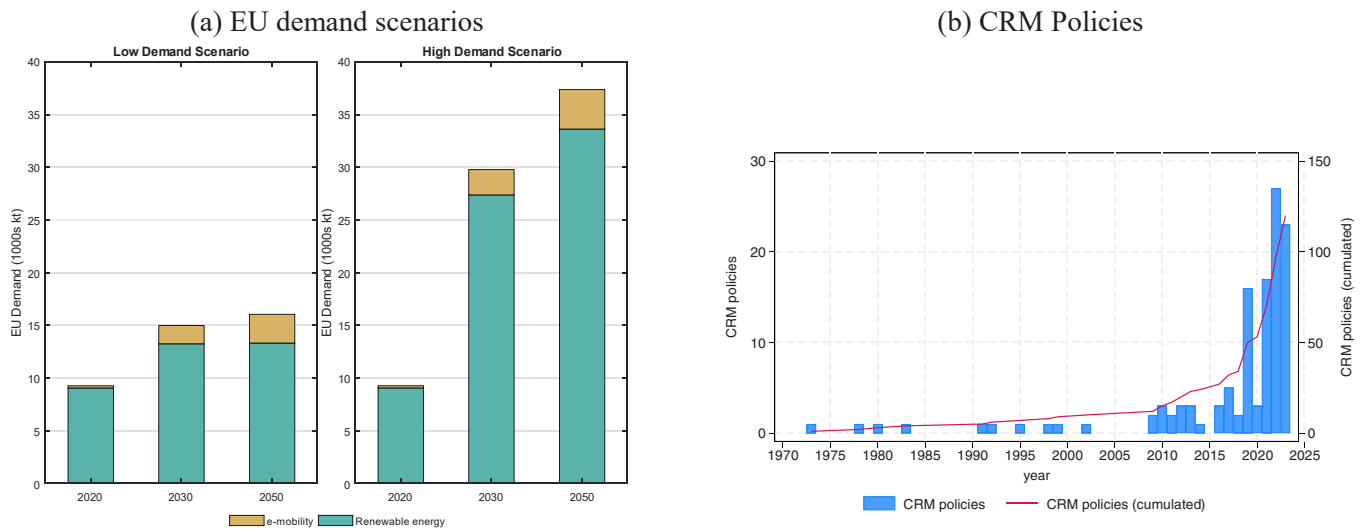


Fig. 3. EU demand scenarios and policies for critical raw materials. *Notes:* figure in Panel b shows the number (and the cumulated number) of CRM policies announced and in force by year. CRM policies include measures related to three main objectives: "Ensuring reliability and resilience of supply", "Promoting exploration, production and innovation", "Promoting sustainable and responsible practices". *Source:* Authors' elaboration based on: <https://zenodo.org/records/7736782> (Panel a) and [IEA \(2024c\)](https://www.iea.org/reports/2024/crm) for Panel b.

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. LCIA estimates 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](#)). LCIA provides this information through a 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 or 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 impact categories ([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 LCIA 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 impact categories for the mining industry,

which, according to [Santero and Hendry \(2016\)](#), is GWP.⁷

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* ($Q_{i,j,t}$):

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

$Q_{i,j,t}$ is defined as the physical amount contained in reserves and resources⁸ in each location of the mined material. 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 indicators are expressed in physical units, such as kg of CO₂ equivalent emissions per ton (kgCO_{2e}/t). A further step is to provide a monetary value to the amounts of CO₂ 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 indicators 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](#)). Monetization thus involves expressing the impacts different activities on social welfare in monetary terms. There are different methodological options, including a willingness to pay, damage cost or abatement cost

⁷ While data on midpoint and monetization values was limited to studies that focused on mining projects that were similar to our sample in terms of geography, technology and time frame, there is still considerable variability in the figures. The Montecarlo exercise aims exactly at explicitly accounting for this uncertainty and quantitatively assess their potential effects on the results.

⁸ 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-appendix.pdf>

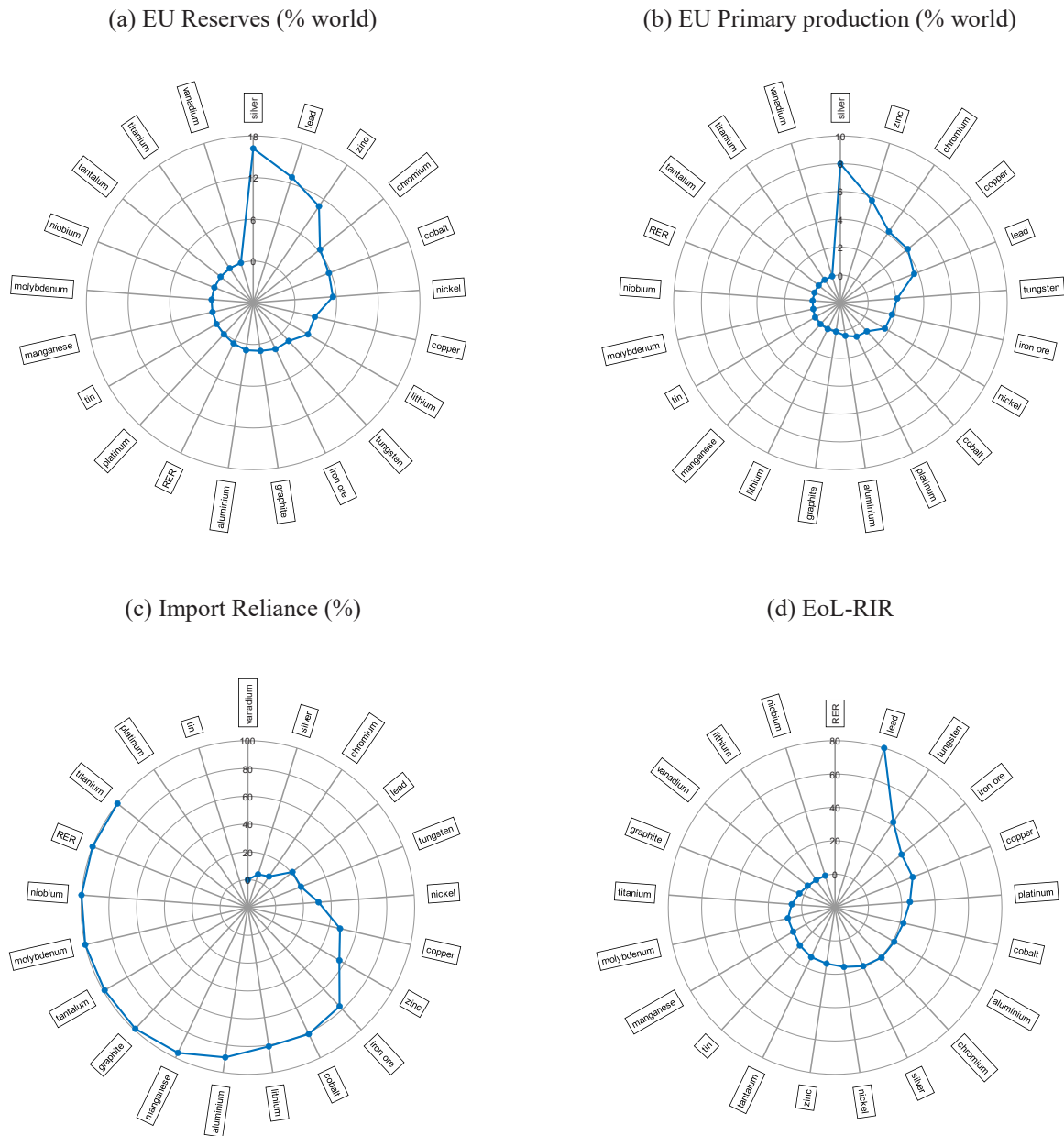


Fig. 4. EU reserves, primary production, import reliance and recycling rates. *Notes:* In Panel (c) “import reliance” is the ratio of net imports to apparent consumption (i.e. production plus imports minus exports). The “End-of-life Recycling Input Rate” (EoL-RIR) in panel (d) measures the share of metal 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/>).

approach. In what follows we use monetization values associated with mining activities derived using the damage cost approach, which focuses on identifying, evaluating and assigning a monetary value to all the costs associated with the analysed activity (Arendt, 2022). 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:

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

As a last step, GWP and corresponding monetary values from the various mining sites j 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 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

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

(a) Midpoint indicators values (kgCO ₂ e/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, Eckelman (2014)	
Cobalt	8300.0	20,807.5	39,500.0	Rachid et al. (2023); Nuss, Eckelman (2014); Farjana et al. (2019b)	
Copper	2800.0	3886.8	5840.0	Rachid et al. (2023); Nuss, Eckelman (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, Eckelman (2014)	
Heavy minerals sands - silica sands	36.8	42.8	48.8	Nuss, Eckelman (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	11,000.0	17,600.0	Nuss, Eckelman (2014)	
Lead	632.0	1200.7	1670.0	Rachid et al. (2023); Nuss, Eckelman (2014)	
Lithium	329.0	10,903.8	20,400.0	Rachid et al. (2023); Nuss, Eckelman (2014); Jiang et al. (2020)	
Manganese	1000.0	3692.5	6030.0	Rachid et al. (2023); Nuss, Eckelman (2014); Westfall et al. (2016)	
Molybdenum*	2280.0	5700.0	9120.0	Nuss, Eckelman (2014)	
Nickel	801.0	7825.3	13,900.0	Rachid et al. (2023); Nuss, Eckelman (2014); Nickel Institute (2023)	
Niobium	5090.0	8795.0	12,500.0	Nuss, Eckelman (2014); da Silva Lima et al., (2022)	
Platinum*	5,000,000.0	12,500,000.0	20,000,000.0	Nuss, Eckelman (2014)	
Rare earth elements	22,300.0	56,233.3	115,000.0	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*	78,400.0	196,000.0	313,600.0	Nuss, Eckelman (2014)	
Tantalum*	104000.0	260000.0	416,000.0	Nuss, Eckelman (2014)	
Tungsten*	5040.0	12,600.0	20,160.0	Nuss, Eckelman (2014)	
Tin*	6840.0	17,100.0	27,360.0	Nuss, Eckelman (2014)	
Vanadium	12,000.0	22,550.0	33,100.0	Nuss, Eckelman (2014); Neometals (2023)	
Zinc	3100.0	4723.3	6120.0	Rachid et al. (2023); Nuss, Eckelman (2014)	
(b) Monetary valuation: Damage cost (2019 EUR per kgCO ₂ e/t)					
Damage cost	0.0295	0.2720	0.6850	Amadei et al. (2021); Bruyn et al. (2010); Schneider-Marín and Lang (2020).	

Notes: "*" denotes that in the absence of a range from the literature we computed min and max values as $\text{avg} \times (1 \pm 0.6)$, where 0.6 is based on the average distance between minimum and maximum for other materials.

refer to the year 2021.⁹ 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. 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.

For each mining site, geographic coordinates are available, thus allowing 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 with 352 mining projects, each of which can supply one or more ETMs.¹⁰ Given the lack of more granular and detailed information on mining sites, it is important to point out the limitations of our analysis and how the results should be interpreted. First, no information is provided on the time frame of extraction nor its relation to quantities, thus excluding the possibility of performing a dynamic analysis. Second, the analysis and simulations effectively assume the complete geological depletion of all European resources and reserves associated with the mining projects considered; therefore, the results should be regarded as estimates of the upper bound of the environmental cost of ore extraction.

Fig. 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

⁹ Owen et al. (2023) obtained mining project data from the S&P Capital IQ Pro database as of November 2021.

¹⁰ This is the number of unique mining projects. A mining project can mine more than one type of material.

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. Fig. 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.

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. kgCO₂ equivalent units per ton, kgCO₂e/t). Table 1 shows the minimum, average, and maximum LCA midpoint indicators values for each material that is extracted in the mining sites in our data. The highest minimum¹¹ midpoints, way above the median average, are associated with platinum (5,000,000 kgCO₂e/t), tantalum (104,000 kgCO₂e/t) and silver (78,400 kgCO₂e/t).

Following Eq. (2), in order to provide a monetary estimate of the value of the GWP 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

¹¹ In what follows we will mainly focus on the minimum value of GWP for each material, in order to present conservative, lower-bound figures.

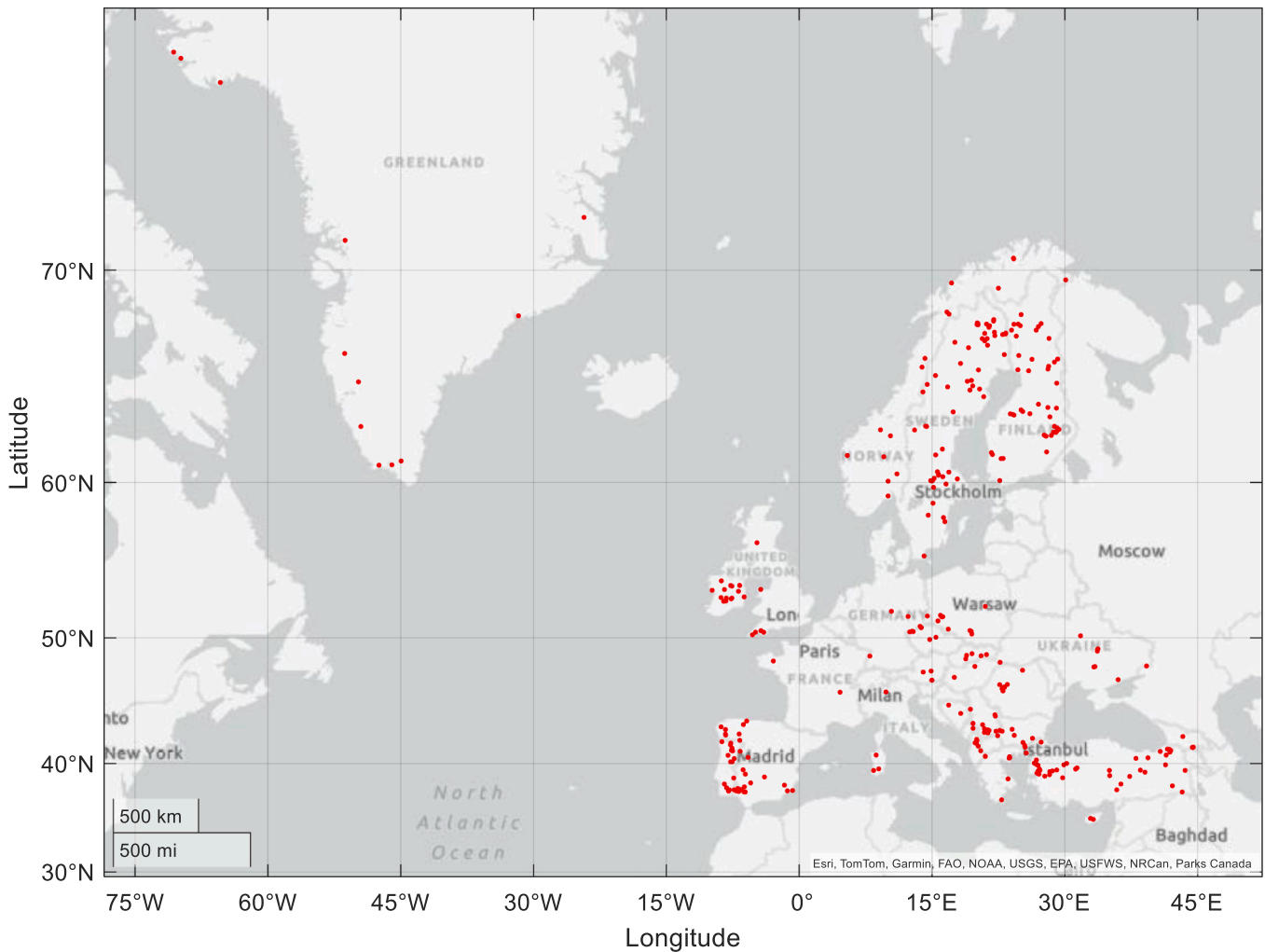


Fig. 5. Mining projects in the analysis. Source: Authors' elaboration based on data in Owen et al. (2023).

change in natural capital or emission, as detailed above. 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 greenhouse gases (GHG) 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 CO₂ 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 percentages,

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

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 1–1.79 % of aggregate GDP in 2021. Considering cross-country variability, Georgia, Finland and Sweden bear the higher percentage cost and higher emissions.¹² 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.

¹² GHG values rely on data from different sources, including climate scenarios, as such potentially suffering from measurement error. They also allow for the inclusion of “negative” values, associated with the effect of actions aimed at removing GHG emissions from the atmosphere, such as, e.g., carbon capture and reforestation. If a country engages in significant public intervention and activities that go in the direction of GHG reduction/removal, the ratio between our GWP and GHG can exceed 100 %. Both these explanations could help interpret the values above 100 in our sample: Georgia, which could be explained by measurement error, and Finland and Sweden, countries that invest heavily in interventions aimed at reducing GHG emissions (<https://ccpi.org/wp-content/uploads/CCPI-2021-Kurzfassung-Deutsch-201211.pdf>)

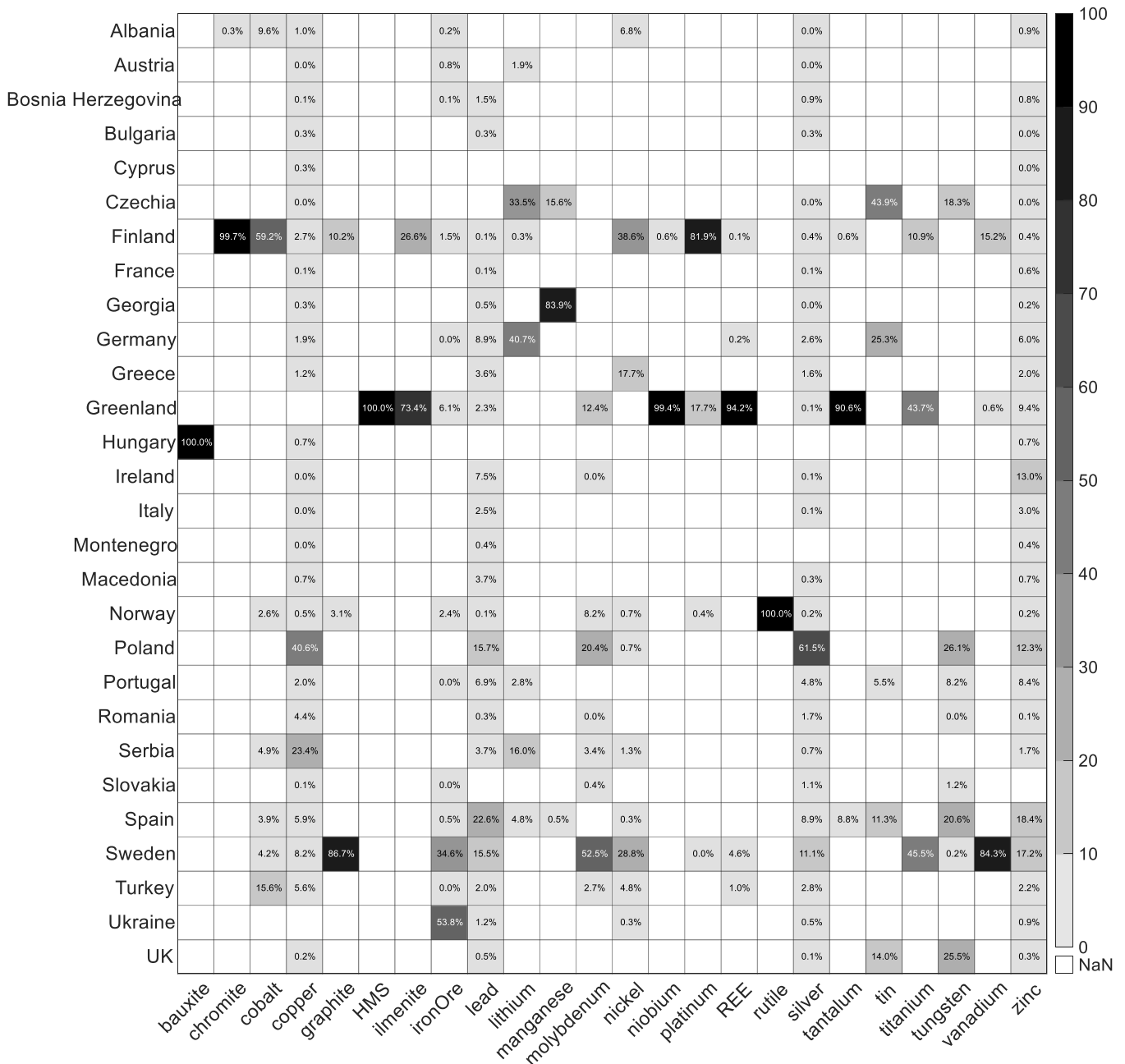


Fig. 6. ETM concentration by country. Notes: the figure shows the percentage of ETM by country as a share of total. Source: Authors' elaboration based on data in Owen et al. (2023).

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. Finally, 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.

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.

Table 4 shows the distribution of measured LQ, with a median value of 0.45 and a maximum of 624,067.3, shown in the Table, and the average value of the index is 0.46. LQs are computed using Europe as a benchmark. This means that min, mean, and max values are calculated with respect to the European average and Table 4 indicates in which region the mining project is located and which material is considered. Thus, for example, the max value reflects the scarcity of tantalum within

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

Notes: We omit Greenland from the table due to lack of GHG data. Source: Authors' elaboration.

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

Europe and the relative (to the European context) concentration in Finland. 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 ore bodies 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 the regional distribution of ERCI for each material considered. A common reading of Tables 4 and 5 reiterates our claim that the spatial clustering in relatively few regions of mining sites is clear.

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.¹³ 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.

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). Fig. 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.

Fig. 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. This figure, once again, visually corroborates our claim that ETM mining in Europe entails uneven monetary costs related to environmental impacts, and suggests that this aspect should be explicitly considered in the public policy formulation phase. The quantification in monetary terms could also be used as an input in the context of ex-ante Cost Benefit Analyses (CBA) of new mining projects (see for example Baffo et al. 2024 and Tartaglia et al. 2025 for examples of evaluation methods and monetary quantification of environmental impacts in other sectors).

¹³ See Section 3 where we have remarked on the possible differences between figures from other sources and information in our dataset.

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

Material	n° mining sites	Min	Country	Region	Mean	Max	Country	Region
bauxite	1	1.100	Hungary	Észak-Magyarország	1.100	1.100	Hungary	Észak-Magyarország
chromite	3	0.192	Finland	Itä-Suomi	32.981	97.943	Albania	Dibër
cobalt	29	0.000	Finland	Itä-Suomi	74.752	1803.380	Norway	Vestlandet
copper	151	0.000	Sweden	Mellersta Norrland	2.664	126.769	Greece	Notio Aigaio
graphite	6	0.031	Sweden	Mellersta Norrland	0.801	1.824	Sweden	Övre Norrland
ilmenite	3	0.249	Greenland	Greenland	0.672	1.000	Finland	Itä-Suomi
iron ore	41	0.003	Sweden	Mellersta Norrland	1.018	18.615	Portugal	Norte
lead	76	0.002	Sweden	Mellersta Norrland	49.577	3504.993	Ukraine	Lviv
lithium	15	0.089	Germany	Dresden	17.712	107.293	Austria	Kärnten
manganese	2	1.021	Georgia	Mtskheta-Mtianeti	146.419	291.817	Spain	Canarias
molybdenum	14	0.002	Sweden	Mellersta Norrland	78.203	935.450	Norway	Agder og Rogaland
nickel	43	0.000	Finland	Itä-Suomi	1779.683	74,958.990	Ukraine	Kyiv
niobium	2	1.000	Finland	Itä-Suomi	1.007	1.015	Greenland	Greenland
platinum	8	0.008	Finland	Itä-Suomi	0.532	1.161	Norway	Agder og Rogaland
rare earth eleme	9	0.012	Greenland	Greenland	447.203	3844.235	Sweden	Sydöstra Sverige
rutile	1	13.346	Norway	Trøndelag	13.346	13.346	Norway	Trøndelag
silver	125	0.000	Turkey	Batu Anadolu	1064.638	125,634.800	Greece	Voreio Aigaio
tantalum	4	1.015	Greenland	Greenland	156,033.700	624,067.300	Finland	Länsi-Suomi
tin	21	0.059	Portugal	Norte	3.728	18.461	Portugal	Centro
tungsten	18	0.042	Sweden	Mellersta Norrland	7.797	30.007	Spain	Ceuta y Melilla
vanadium	9	0.008	Finland	Itä-Suomi	27.564	152.777	Sweden	Småland och öarna
zinc	105	0.001	Ireland	South-West	36.219	3504.993	Ukraine	Lviv

Note: The values in the final column “LQ” represent the minimum, average and maximum values of the index, respectively.

Source: Authors' elaboration

Table 5
Distribution of regional concentration index (ERCI).

Material	n° mining sites	Min	Country	Region	Mean	Max	Country	Region
bauxite	1	1.000	Hungary	Észak-Magyarország	1.000	1.000	Hungary	Észak-Magyarország
chromite	3	0.003	Albania	Dibër	0.333	0.806	Finland	Itä-Suomi
cobalt	29	0.000	Finland	Itä-Suomi	0.034	0.206	Finland	Itä-Suomi
copper	151	0.000	Sweden	Mellersta Norrland	0.007	0.342	Poland	Opolskie
graphite	6	0.025	Sweden	Mellersta Norrland	0.167	0.375	Sweden	Mellersta Norrland
ilmenite	3	0.180	Greenland	Greenland	0.333	0.553	Greenland	Greenland
iron ore	41	0.000	Portugal	Norte	0.024	0.137	Ukraine	Kharkiv
lead	76	0.000	Turkey	Batu Marmara	0.013	0.138	Poland	Małopolskie
lithium	15	0.002	Finland	Itä-Suomi	0.067	0.558	Germany	Stuttgart
manganese	2	0.006	Spain	Canarias	0.500	0.994	Georgia	Imereti
molybdenum	14	0.000	Russian Federation	Nord-Vest	0.071	0.316	Sweden	Norra Mellansverige
nickel	43	0.000	Finland	Itä-Suomi	0.023	0.277	Finland	Itä-Suomi
niobium	2	0.006	Finland	Itä-Suomi	0.500	0.994	Greenland	Greenland
platinum	8	0.000	Sweden	Mellersta Norrland	0.125	0.381	Finland	Itä-Suomi
rare earth elements	9	0.001	Finland	Itä-Suomi	0.111	0.848	Greenland	Greenland
rutile	1	1.000	Norway	Trøndelag	1.000	1.000	Norway	Trøndelag
silver	125	0.000	Turkey	Batu Anadol	0.008	0.555	Poland	Śląskie
tantalum	4	0.006	Finland	Länsi-Suom	0.250	0.906	Greenland	Greenland
tin	21	0.000	Portugal	Norte	0.048	0.159	Germany	Dresden
tungsten	18	0.000	Sweden	Mellersta Norrland	0.056	0.324	Poland	Śląskie
vanadium	9	0.001	Finland	Itä-Suomi	0.111	0.425	Sweden	Norra Mellansverige
zinc	105	0.000	Finland	Itä-Suomi	0.010	0.098	Poland	Małopolskie

Source: Authors' elaboration

5.3. Monte Carlo analysis

As shown in Table 1, the LCIA literature presents a broad range of estimates for both midpoint indicator values and the global warming potential damage costs associated with mining, and relying on a single estimate to assess environmental costs overlooks the significant uncertainty inherent in the underlying parameters. By incorporating uncertainty into the model parameters, our goal is to provide a more transparent picture of how data gaps and variability in the inputs affect the outcomes, rather than presenting a single deterministic result. A commonly used approach to account for this uncertainty and make it transparent to the reader is the use of Monte Carlo analysis, which systematically incorporates variability in the 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 indicators 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 CO₂

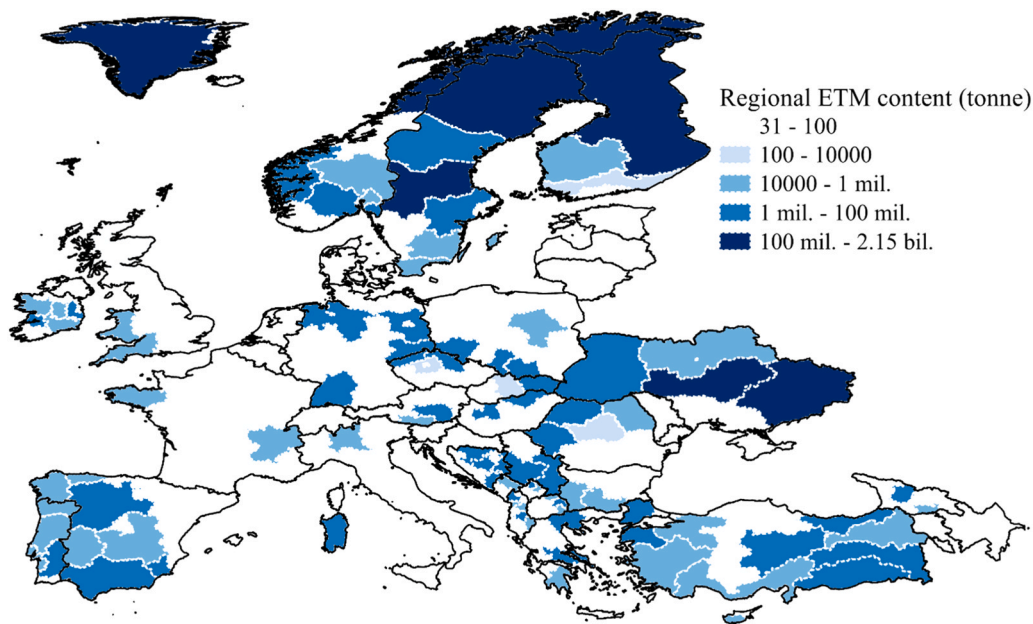


Fig. 7. Map of regional aggregate ETM content (tonnes). Source: Authors' elaboration.

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.

Fig. 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 Fig. 10 and Table A1 in the Appendix. Focusing on the left panel of Fig. 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.

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.

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 CO_{2e} 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 CO_{2e} are in Sweden, Poland, Finland and Greenland. In aggregate terms, 11 % of total CO_{2e} 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 CO_{2e} 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

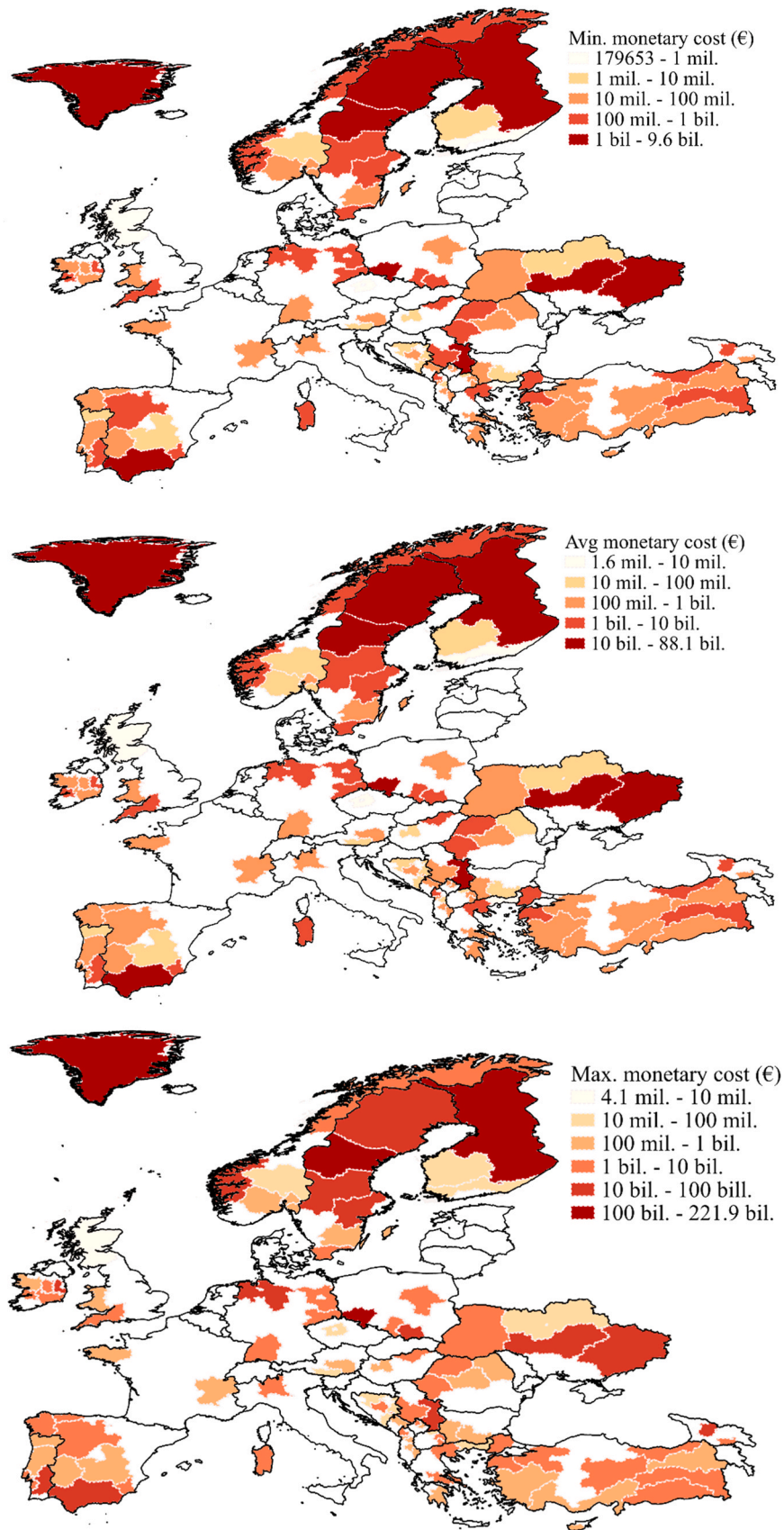


Fig. 8. Map of minimum, average and maximum monetary value (Euro 2021) from mining activities of energy transition materials. *Source:* Authors' elaboration.

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 CO₂ equivalent per tonne (GtCO₂e/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.

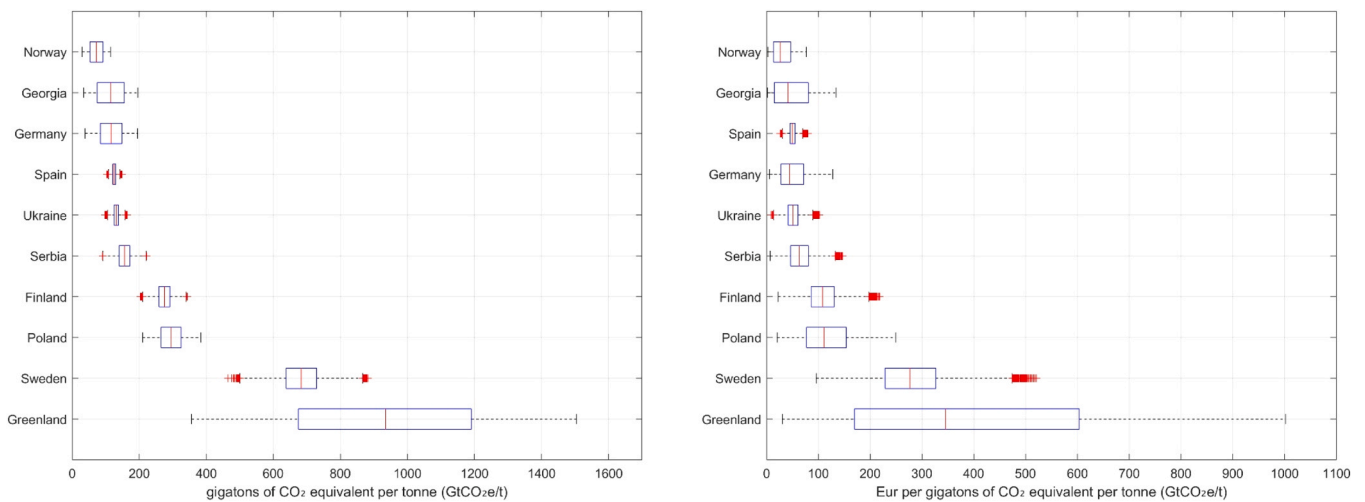


Fig. 9. Country level Monte Carlo results. Source: Authors' elaboration.

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. To this end, European authorities, in the framework of the renewed interest in opening new sites and revamping existing ones¹⁴ should consider requiring promoters to provide standardized data for a better evaluation and monitoring of environmental impacts and to better shape public policies. Promoters should report detailed information on the resources and reserves, the adopted mining methods and technologies used for extraction and processing of

¹⁴ https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/strategic-projects-under-crma/select-d-projects_en (accessed 26/09/2025)

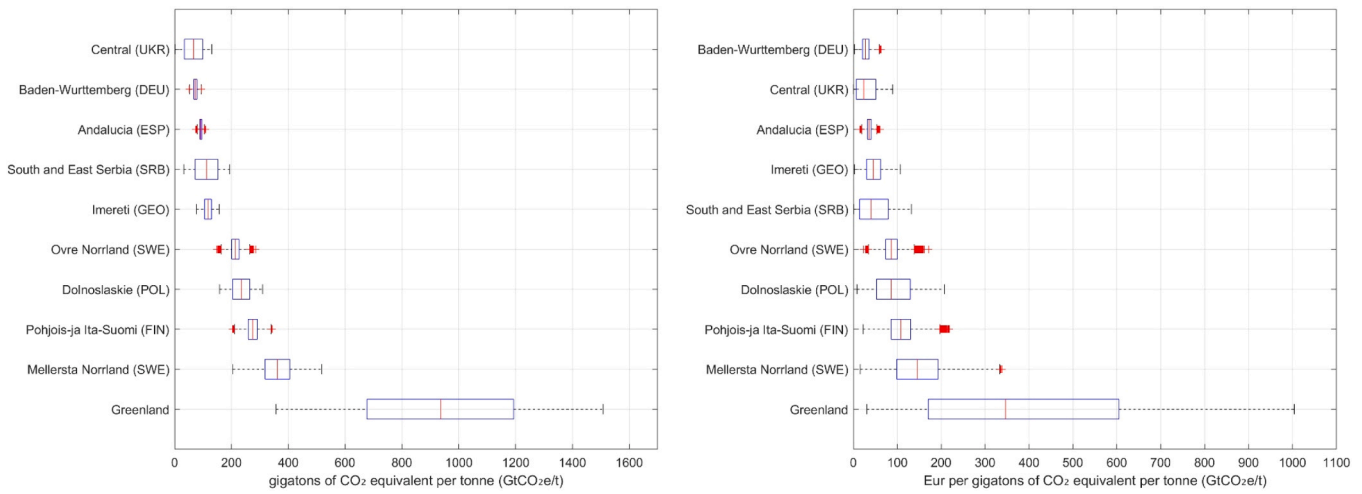


Fig. 10. Regional level Monte Carlo results. Source: Authors' elaboration.

the materials, the environmental standards and mitigating actions, if any, thus allowing decision-makers to assess the potential environmental impact of the sites. This type of consistent data collection would also benefit the development of standards for conducting cost benefit analysis of CRM mining projects, further informing decision makers with solid evidence on social and environmental issues.

CRedit authorship contribution statement

Chiara F. Del Bo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Bastianin:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luqman Shamsudin:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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

(continued on next page)

Table A1 (continued)

Country	Region	Avg.	CV	q025	q075	Avg. (eur)	CV (eur)	q025 (eur)	q075 (eur)	RSE (%)
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	Stereia 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-Magyarország	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	Yuzopapaden	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 CO₂ equivalent per tonne (GtCO₂e/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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