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Climate policy stringency and trade in energy transition minerals: An analysis of response patterns

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ABSTRACT

Climate policies directly affect cleaner energy technology markets, affecting price signals for greener electricity production. In turn, the manufacturing of energy technologies relies heavily on mineral inputs, posing challenges in securing mineral ores and concentrates either from local mines or overseas. This paper contributes to the mineral-energy literature by examining the impact of climate change policies on the net import demand for five essential minerals used in cleaner energy technologies: copper, aluminium, nickel, cobalt, and manganese. We examined country-level panel data from 33 countries from 1992 to 2015 to understand patterns in net imports relative to renewable generation. This metric allows the examination of technological improvements that contribute to more efficient use of imported mineral inputs in renewable energy systems. Results suggest that while both net import volumes and renewable generation have increased over time, net imports per renewable generation have continuously declined on average, suggesting that nations may have efficiently utilized imported resources to generate more than proportionate increases in cleaner energy. Moreover, results from a cross-sectional autoregressive distributed lag model show that the stringency of environmental policies significantly affects net mineral imports per renewable generation, with marked variations across minerals and countries. Notably, with stricter policies, import reliance on cobalt and aluminium per renewable energy increases in the short run and eventually declines in the long run. Import reliance for copper declines per unit of renewable energy in the short run but increases in the long run. These findings emphasize the need for tailored policies to navigate mineral trade dynamics effectively. The research contributes valuable insights to the ongoing discussions surrounding sustainable energy transitions and global mineral trade patterns.

1. Introduction

Climate change policies, driven by the urgent need to address environmental concerns, have been implemented by various countries to promote the adoption of cleaner and more sustainable energy alternatives. These policies often include initiatives to incentivize the use of renewable energy sources and reduce the reliance on fossil fuels (Sims, 2004; Jefferson, 2006; Tian et al., 2021; Omri et al., 2022; Belaïd et al., 2023; Belaïd and Al-Sa, 2024). For example, policies that put a price on carbon emissions (e.g., carbon trading or carbon tax) provide the incentive to replace pollution-generating technologies and reduce carbon footprints; investment and production-based credits offer the financial incentives to invest in renewable energy sources by lowering costs (e.g., tax credit for solar energy systems). Likewise, non-market-based instruments provide limits and standards for maximum allowable emissions or prescribe a carbon-intensity for energy production. Alternatively, governments may provide funding for Research and Development (R&D) for innovative net-zero energy technologies.

As nations continue to implement stricter climate change policies, markets are expected to respond by increasing investments in renewable energy (RE) technologies, which could drive up the demand for materials and inputs needed to produce these technologies. One such type of inputs needed in producing cleaner energy technologies is minerals and metals (Perkins, 2012). For example, copper, aluminum, nickel, cobalt, and manganese are essential components of solar panels, energy storage

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systems, and other renewable energy infrastructure. Accordingly, global demand for minerals such as copper, cobalt, nickel, and lithium is expected to increase with policy-induced investments in renewable energy technologies (IEA, 2023). The economic mechanism through which climate change policies could drive changes in global mineral markets can conceptually be presented as an *induced demand for inputs* or as the responsiveness of input demand (i.e., minerals are the inputs) to changes in policies that incentivize cleaner output production (e.g., RE is the output). That is, stricter climate change policies raise the price of carbon emissions, which creates an incentive for investment in renewable energy technologies and lower emissions (Belaïd, 2022). As more renewable energy technologies are manufactured, the demand for inputs (that is, minerals and metals) used in their production also increases (induced input demand). Yet, there are no empirical studies that provide a quantitative examination of the strength of the impact of climate change policies on mineral input markets.

The context of this paper lies at the intersection of the mineral-energy literature and the growing importance of climate change policies in the global effort to transition towards RE sources. It aims to empirically assess the impact of climate change policies on the net import demand for hard-to-substitute minerals essential to cleaner energy technologies. Over the last few years, there has been significant interest in understanding the relationship between RE generation and its impact on mineral trade dynamics (Hammond and Brady, 2022; Zhu et al., 2022; Chang et al., 2023; Islam et al., 2022b) as well as the implications of mineral input supply gap for energy transition goals (Bonakdarpour and Bailey, 2022). These studies neglect to consider the potential impact of the varying levels of commitment to environmental protection on mineral trade dynamics.

Building upon recent mineral-energy nexus studies (e.g., Chang et al., 2023; Islam et al., 2022b), this research makes a significant contribution by empirically assessing the impact of climate change policies on net import demand for five essential mineral inputs used in green energy technologies: copper, aluminum, nickel, cobalt, and manganese. First, this paper focuses on five main minerals to study how climate change policies affect them. Moreover, our study goes beyond previous research by evaluating environmental policies' short- and long-term effects on mineral net imports for a diverse sample of 33 countries. This broader perspective allows the study to identify potential challenges and trade-offs faced by nations with varying levels of natural resource endowment when transitioning to green energy technologies. Nations endowed with abundant natural resources could be better positioned to extract the required minerals cost-effectively for green energy technologies as climate change policies become more stringent (Fabre et al., 2020). However, they need mineral processing and refining capabilities to convert mineral resources into useable final inputs. On the other hand, countries with limited mineral resources may resort to either increased mineral imports or opt for importing green technologies themselves as governments implement additional environmental protection policies (Islam et al., 2022b). Hence, the main issue addressed here is how changes in climate change policies ultimately translate into higher demand for minerals imported from overseas to be used as inputs in producing RE technologies.

Finally, while previous studies examine mineral import volumes or values (gross or net), this study uses *normalized metrics* of net import volumes per renewable energy to capture potential technological or structural factors that contribute to more efficient use of imported mineral inputs in renewable energy systems. This study provides valuable insights into ongoing discussions surrounding sustainable energy transitions and global mineral trade patterns. The results also provide some insights as nations strive to implement effective climate change mitigation strategies and achieve their energy source diversification targets in an environmentally responsible and economically feasible manner.

The following sections of this paper are organized as follows: Section 2 delves into the conceptual framework and research hypotheses of the study. Section 3 outlines the data and methodology utilized in this study. Section 4 presents results, and finally, Section 5 concludes the paper and provides policy recommendations concerning the interplay between climate policies and mineral net imports.

2. Conceptual framework and hypothesis development

2.1. A summary of lessons from previous mineral-energy nexus studies

A growing number of studies examine the importance of energy transition minerals in the context of supply chain issues, energy security, national security, and achieving climate change goals (Yu et al., 2021; Galos et al., 2021; Jasiński et al., 2018; Robinson et al., 2023). A clean energy transition infrastructure is particularly reliant on key hard-to-replace mineral inputs. For instance, the production of solar cells, wind turbines, and grid storage batteries depends on essential minerals such as copper, aluminum, and nickel. Critical minerals are becoming more and more important as the emphasis on energy decarbonization grows (Srivastava, 2023; Zhu et al., 2020).

There are also a growing number of studies examining mineral trade dynamics and their role in facilitating the clean energy transition, and our study contributes to this line of literature (He, 2018; Hayes and McCullough, 2018). For instance, several studies have examined how the demand for mineral imports has changed in response to a shift to a more sustainable energy system (Shi et al., 2023; Kilinc-Ata et al., 2023; Islam et al., 2022a, 2022b). Table 1 summarizes recent studies on the connection between mineral trade dynamics and clean energy indicators. Overall, these studies point to a marked rise in the need for essential minerals to facilitate energy transition goals. Additionally, existing studies focus on current mineral reserves, their uses, and future extractions related to global energy production systems. For example, as the table indicates, most studies examine the impact of RE generation capacity (e.g., solar and wind) on a nation's demand for mineral imports. There are no empirical studies that comprehensively examine how mineral imports respond to climate change policies, making it crucial to analyze the role that policies play in mineral trade dynamics. Furthermore, existing studies rely on measuring import volume or value without normalization. For example, Kilinc-Ata et al. (2023) and Fikru and Kilinic-Ata (2024) examine the impact of RE on the value of aggregate or individual mineral imports.

2.2. Conceptual framework and hypotheses

Climate change policies could affect mineral trade patterns through various economic channels. Environmental protection policies put an implicit or explicit price on polluting activities such as carbon emissions from power generators or industrial facilities. Such policies provide a price signal for carbon-intensive industries to adopt cleaner production technologies, such as large-scale electricity production from renewable sources (e.g., solar panels and wind turbines). This, in turn, affects the renewable technology market, where green energy technology manufacturing occurs. Production of green energy technologies such as solar panels, wind turbines, and energy storage systems requires significant quantities of mineral inputs, which are often hard to replace in the production process.

Even when climate change policies are instituted directly on energy-generating technologies and power generators based on the polluter principle, they could induce a change in the market for mineral inputs. For example, carbon credits, carbon taxes, and standards (e.g., limit values) on carbon emissions directly affect the power generation market, while green technology producers could benefit from R&D subsidies for innovative and novel technologies. Even if climate policies are not meant or designed to directly affect mineral trade dynamics, the price signals will likely be transmitted as an induced demand spillover effect in the mineral input market.

Fig. 1 presents our conceptual framework for hypothesizing the

Table 1
Empirical studies examining determinants of mineral imports.

Study	Time Period/ Countries	Mineral definition	Determinants of import
Shi et al. (2023)	2002–2019/18 leading mineral resource-endowed countries	Mineral rents	Renewable capacity
Kilinc-Ata et al. (2023)	2000–2021/14 top mineral importing countries	All mineral groups	Renewable capacity
Islam and Sohag (2023)	1996–2020/USA	All mineral groups	Installed wind capacity
Feng et al. (2023)	2001–2020/30 provinces in China	All mineral groups	Renewable capacity
Wang et al. (2023a)	2003–2019/71 economies	Metallic minerals	Renewable capacity
Wang et al. (2023b)	2000–2021/China and ten ASEAN members	396 HS codes of products of natural resources	Mineral resources trade
Islam et al. (2022a)	1996–2019/9 top mineral importing countries	All mineral groups	Wind and solar capacity
Islam et al. (2022b)	1990–2020/29 OECD countries	All mineral groups/copper and nickel	Wind and solar capacity/Renewable-based electricity generation
Irfan et al. (2022)	1980–2020/20 minerals exporting countries	All mineral groups	Renewable capacity
Galos et al. (2021)	2009–2018/Poland	148 minerals	–
Aldakhil et al. (2020)	1995–2018/12 resource-abundant economies	All mineral groups	Renewable capacity
Beylot et al. (2019)	2012–2050/France	Steel, copper, aluminum, and concrete	Carbon emission
Brainard et al. (2018)	2014/US	12 nonfuel minerals	–
Li et al. (2019)	1992–2015/China	28 minerals	Fossil fuels
Stuermer (2017)	1840–2010/12 industrialized countries	Aluminum, copper, lead, tin, and zinc	Manufacturing sector output

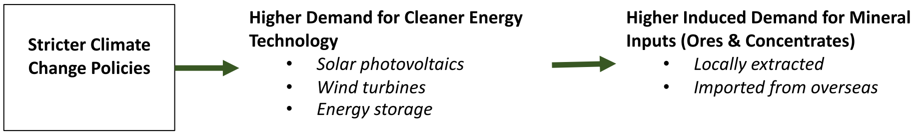

Fig. 1. Conceptual framework.
Source: Created by authors

impact of climate change policies on demand for mineral inputs. As the figure illustrates, climate change policies directly affect the production of cleaner energy technologies that require mineral inputs. Mineral inputs can be sourced either locally (e.g., by developing local mines) or by importing them from overseas. Climate policies often encourage the adoption of RE sources like solar, wind, hydro, and geothermal power. By transitioning from fossil fuels to clean energy sources, nations can reduce GHG emissions and air pollution. This shift towards RE requires significant quantities of mineral inputs, which can either be sourced from domestic mines or from overseas (upstream industry). Once raw material mineral inputs (e.g., ores) are extracted, they need to be processed and refined as per the type of downstream industry needed (e.g., type of battery chemistry used in energy storage systems, type of solar panels, etc.).

We hypothesize that stricter climate policies induce nations to import more of a given mineral on the net. This implies the nation could, on net, depend on imported minerals as pollution gets more expensive due to the stringency of environmental policies.[1] The imported mineral inputs could be refined in the importing nation (if the importer has cost-effective processing capability) and used to produce clean energy technologies. This could suggest that local mineral resources may not be sufficient to enable the energy transition, thus increasing import reliance on the net. A similar argument is that importing nations may rely more on mineral imports than domestic resources to facilitate their energy transition as climate policies become stricter. Accordingly, we test the following hypothesis:

Hypothesis 1. As the stringency of climate policies increases, net import demand for mineral inputs increases, keeping other factors constant.

On the contrary, if the hypothesis is rejected, it could mean that a more stringent climate policy (e.g., a higher carbon tax) correlates with fewer net mineral imports, and this could indicate a shift away from imported inputs to (possibly) locally extracted minerals. For example, due to geopolitical and national security reasons, net importers may reduce their reliance on minerals from overseas and explore more locally. An alternative explanation could be when nations shift to importing clean energy technologies rather than the inputs needed to produce them. Finally, countries with increasing climate policies may not wish to import mineral inputs from overseas, where the environmental regulatory framework may not be as stringent as their own. The alternative hypothesis also suggests that the stringency of climate policies could create an unintended trade barrier where increases in the stringency of policies lead to reductions in mineral import reliance for renewable generation.

Thus, there could be different possible ways of achieving a clean energy transition with stricter climate policies: (1) by importing more mineral inputs that can be used to produce cleaner energy technologies as given by *Hypothesis 1*, or (2) via alternative means such as importing the energy technologies themselves rather than producing them locally using imported minerals or developing local mines for mineral inputs.

We test whether the impact of climate policies on mineral trade patterns is non-linear. This is because mineral trade dynamics may not respond linearly to changes in climate policies (e.g., the impact of policies could level off). Studies show that the impact of policies on increasing environmental quality tends to follow a pattern of diminishing returns, resulting in improvements at a declining rate (Setyari and Ayu, 2021; Ricci, 2007). For example, a stricter policy could encourage more imports as nations look for competitive mineral prices from overseas, but after a threshold level, a nation may start to consider the environmental, social, and governance (ESG) of mining and mineral sources and reduce trading with nations with ESG concerns. Instead, nations may start incentivizing local mining companies to explore new

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[1] We utilize the OECD Environmental Policy Stringency Index in determining the strictness of environmental policies in specific countries. The term "stringency" signifies the extent to which environmental regulations enforce an explicit or implicit cost on behaviour that causes pollution or is in other ways detrimental to the environment (Kruse et al., 2022).

mining sites. Geopolitical and national security goals may also make countries eventually balance the rate of import reliance with increases in clean energy investments.

Hypothesis 2. As the stringency of climate policies increases, net import demand for mineral inputs increases, but at a declining rate, keeping other factors constant.

2.3. Empirical approaches

Since we are interested in minerals used to produce cleaner energy technologies (e.g., solar panels), we construct a variable that indicates mineral import demand for the energy transition by taking the ratio of net mineral import (*NI*) of five specific mineral inputs per kilowatt hour (kWh) of renewable electricity (*RE*) generation. Net import is the difference between import volumes and export volumes such that $NI > 0$ for net imports and $NI < 0$ for net mineral exports. The subscript *j* represents a given mineral type, such as cobalt, copper, aluminum, nickel, and manganese ($j = 1, 2, 3, 4, 5$).

$$Y_{j,t} = \frac{NI_{j,t}}{RE_t} \ . \qquad [1]$$

For net importers of the *j*th mineral, $NI_{j,t} > 0, \ Y_{j,t} > 0$, and vice versa for net exporters of a given mineral in a given year *t*. The variable $Y_{j,t}$ measures net demand for the *j*th mineral used to produce a kilowatt hour of renewable energy. It indicates the mineral import reliance for the energy transition (how dependent a nation is on importing minerals to generate each unit of cleaner energy). When $Y_{j,t}$ increases a nation needs more of the *j*th mineral to be imported for each unit of renewable energy it generates and when $Y_{j,t}$ declines, the nation needs less imports per unit of energy due to a combination of reasons such as technological advancement, which lowers mineral intensity, more reliance on domestic mineral sources, or importing the RE technology rather than producing it locally using minerals.

We undertake this normalization procedure because while net import volume provides a simpler measure of import reliance, import volume per unit of renewable energy can provide additional insights into the *mineral intensity* of renewable energy and provide a metric that accounts for potential *technological progress* (e.g., with improvements in technology manufacturers can produce renewable energy technologies with fewer mineral imports). For example, $Y_{j,t}$ provides additional information on whether a nation's mineral net imports have grown at the same rate as progress in renewable generation.

With stricter climate policies we expect nations to produce more renewable energy using technologies such as solar panels and wind turbines. Thus, stricter climate policies are expected to increase renewable electricity generated (*RE*) and reduce $Y_{j,t}$ for a given *NI*. Since minerals are key inputs in RE technologies, demand for mineral inputs (either or both from local and domestic sources) is expected to increase for a given level of technology. Nations can either import more mineral inputs on net (*NI* increases), use the same units of imported minerals (*NI* stays the same), or reduce their mineral imports (*NI* declines) as more policy induced RE is produced. In the first scenario, some, or all of the decrease in $Y_{j,t}$ could be offset (it declines slowly or stays the same or slightly rise with higher imports) when policy-induced renewable generation increases, and this indicates reliance on imports for mineral inputs. In the second scenario, $Y_{j,t}$ is expected to decline when policy-induced renewable generation increases and this implies that despite increased investments in renewable energy, the nation does not demand additional mineral imports. This could be driven by technological progress that reduces the mineral intensity of renewable production or the switch to locally sourced mineral inputs. In the third scenario, $Y_{j,t}$ is expected to significantly decline as the nation reduces mineral inputs, possibly due to a combination of technological advancement that reduces the mineral intensity of RE technology production (e.g., technology that allows substitution with other inputs), and expansion of domestic mining. It is also possible that offshoring of manufacturing of cleaner technologies is correlated with reductions in mineral import volume per unit of renewable energy.

Equation [2] presents the benchmark model used to test *Hypotheses* 1 and 2. We control for the impact of trade openness (TO) and GDP per capita on mineral trade patterns. For instance, nations with higher volumes of trade may be likely to engage in more mineral trade (e.g., fewer trade barriers), while GDP per capita (2015 values in US dollars) controls living standards, income, and the size of the economy. The empirical analysis is based on the following model where $j = 1, \ldots, 5$ represents five specific minerals.

$$Y_{j,i,t} = f\left(EPS_{i,t}, EPS_{i,t}^2, GDP_{i,t}, TO_{i,t}\right). \qquad [2]$$

We fit data to the benchmark model presented in Equation [2], where data is obtained from 33 countries over several years. Equation [2] proposes that the relationship between climate policies and the net import of energy transition minerals per renewable energy is non-linear. We use appropriate econometric approaches to fit the equation onto panel data. The analysis is based on country-level macro data from 33 countries over multiple years. The choice of the 33 countries is determined by data availability. As a robustness check, the Appendix presents a model where the dependent variable is net import volume instead of a normalized ratio. That is, $NI_{j,i,t} = f\left(EPS_{i,t}, EPS_{i,t}^2, GDP_{i,t}, TO_{i,t}\right)..$

Running regressions based on macro-level panel data could suffer from the possibility of cross-sectional dependency and correlation among countries due to global common shocks that affect countries in similar or different ways. The impact of climate policies on mineral trade patterns is likely to be heterogeneous where countries could have different slope parameters. When cross-sectional dependencies exist, the error term of a panel data regression model becomes cross-sectionally correlated (i.e., the error correlation between two countries is different from zero). There is a growing body of econometric studies that propose empirical strategies for modeling relationships when cross-sectional dependencies exist. Most of these studies propose the cross-sectional autoregressive distributed lag (CS-ARDL) model to account for the cross-sectional dependency and control for lagged effects of the dependent variable. For a detailed discussion of the CS-ARDL model and underlying assumptions, readers are referred to Voumik et al. (2023), Kilinc-Ata and Alshami (2023), and Kilinc-Ata (2022).

Appendix B summarizes the CS-ARDL approach and presents all the pre-estimation tests required before fitting the CS-ARDL model. Pre-estimation tests include cross-sectional dependency test, slope homogeneity test, and cointegration and stationarity tests. Our pre-estimation results indicate the presence of cross-sectional dependency for the sample used in this study. This violates the assumptions of running a fixed effects regression model (e.g., when observations are not independent, fixed effect estimates may be inconsistent and inefficient leading to biased parameter estimates). Thus, we adopt CS-ARDL to fit the benchmark model presented in Equation [2].

One advantage of CS-ARDL is that it allows for the estimation of the short- and long-term impacts of climate change policies on mineral net imports (Kilinc-Ata et al., 2023; Chen et al., 2023). The short-term elasticities of the CS-ARDL model measure the responsiveness of normalized net imports to changes in the independent variables (climate policy stringency) over a short period, where changes in the independent variables are used to proxy for this effect. The long-run elasticities measure the steady-state responsiveness of the dependent variable (net mineral imports per renewable energy) to changes in the independent variables over an extended period. It captures the equilibrium relationship between the variables after accounting for short-term dynamics.

3. Data and variable measurement

3.1. Data source and descriptive statistics

This study investigates the impact of climate policies on mineral trade patterns in a sample of OECD and non-OECD countries. The selection is based on countries where data on the stringency of environmental policies are available. The sample consists of 27 OECD countries and 6 non-OECD countries over the years 1992–2015/2020. The dependent variables measure the kilogram of minerals imported (net) per renewable electricity produced for each country and each year. We first take net imports (import volume minus export volume) and then divide this difference by RE generation (kWh). We use mineral import data for five key energy transition minerals, namely copper, aluminum, cobalt, nickel, and manganese. Consequently, we have five dependent variables. The importance of these five minerals in the production of renewable electricity, as well as the future requirement for minerals on a global scale has been highlighted in the literature (Lennon et al., 2022; Tang et al., 2021; Bella et al., 2021; Farjana et al., 2019; Schipper et al., 2018; Alves Dias et al., 2018). Table 2 presents the definition and measurements of variables used in the analysis.

Import volumes for the five minerals are obtained from the World Integrated Trade Solution (WITS) database which is publicly available. RE generation (kWh) is obtained from the World Development Indicators (WDI) database and *EPS* data is obtained from OECD stats, both of which are publicly available datasets. The *EPS* is an index from 0 (very weak policies) to 6 (strict policies), measuring the extent to which comprehensive climate policies exist. The OECD measures policy comprehensiveness by collecting data on market and non-market-based policies as well as technology support. Although the EPS is not a perfect and complete measure of climate change policies, it has been widely used in empirical studies that examine the economic impact of environmental policies across OECD member countries (Martínez-Zarzoso et al., 2019; Albulescu et al., 2022). Studies also show that the index correlates with country-wide trends in environmental innovation, abatement efforts, and carbon efficiency (Galeotti et al., 2020). Given the challenge of finding other measures of climate change policy, we use the EPS index as a proxy for measuring variation in the stringency of environmental policies across countries and over time (Brunel and Levinson, 2016). More information on the construction of the *EPS* index is discussed in Kruse et al. (2022). The Appendix presents trends in EPS for each country in the sample over the years 1992–2020.

Data on *TO* and *GDP* are obtained from WDI. Harmonized System (HS) product codes for imported ores and concentrates are given in Table 3. Thus, the dependent variables measure the net import demand for mineral ores and concentrates per unit of renewable energy generation. Ores and concentrates undergo certain refining and processing steps before becoming technology-grade inputs.

Descriptive statistics of the variables and their correlations are presented in Tables 4 and 5, respectively. The net import of minerals per RE ranges from negative to positive values, indicating net exporters and net importers, respectively. Data for these variables is available for the years 1992–2015. Aluminum net import per renewable energy exhibits the largest average net imports, while the average value for cobalt net imports is negative, suggesting net exports' dominance over net imports. The *EPS* ranges from zero to 4.8, with an average of 2.

Table 2
Description of variables and units of measurements.

Variables	Definition	Measurement
Dependent Variables		
Co_RE	Cobalt net import per RE	kg/kWh
Cu_RE	Copper net import per RE	kg/kWh
Al_RE	Aluminum net import per RE	kg/kWh
Ni_RE	Nickel net import per RE	kg/kWh
Mn_RE	Manganese net import per RE	kg/kWh
Climate Change Policy		
EPS	Environmental Policy Stringency	Index 0 (no policy) to 6 (strict)
Control Variables		
TO	Trade openness	Percent of GDP
GDP	GDP per capita	Constant 2015 dollars

Table 3
Harmonized System (HS) product codes for imported ores and concentrates.

Product Code	Product Description
260500	Cobalt ores and concentrates
260300	Copper ores and concentrates
260600	Aluminum ores and concentrates
260400	Nickel ores and concentrates
260200	Manganese ores and concentrates

Table 4 shows that the correlations between most of the variables are relatively weak. The exception is the relatively higher positive correlation between manganese net imports and copper net imports (0.9209), which could be because these two ores are sometimes found geologically closer to each other or mined together (e.g., endowed nations export both). The high correlation could also be due to the two ores acting as potential complement inputs (e.g., nations that import one ore also import the other). Table 5 also shows a positive correlation between EPS and GDP (0.5364), where countries with higher living standards are also the ones that are likely to institute stricter climate policies. Although weakly correlated, EPS is positively correlated with cobalt and nickel net imports per kWh and negatively correlated with copper, aluminum, and manganese.

3.2. Net import of energy transition minerals: variation across time and space

In this sub-section, we present time trends and explore geographical patterns in net import volume (kg) and net import volume per unit of renewable energy (kg/kWh) as calculated using Equation [1] for the five minerals. We also present trends in RE. Since RE data is available only for the years 1992–2015, Equation [1] can be calculated for this time frame while net import volumes are available until 2020. Fig. 2 demonstrates that for the average country in the sample, RE generation has continuously increased over the given period.

Fig. 3 presents the time trend for average net import volumes (kg), which indicates an overall increase in net import volumes, although there were some declines in certain years (e.g., 2002, 2010, 2016, etc). Fig. 4 illustrates the time trend in the average net mineral import demand per kWh of renewable energy generation. The figures illustrate that although net import volumes (kg) have generally increased from the 1990s to the 2010s, net imports per unit of renewable energy (kg/kWh) have been continuously declining over the given period.

This is primarily due to increasing renewable generation over time. It could also be due to faster rates of increase in renewable technology investments compared to the growth in demand for minerals imported

Table 4
Descriptive statistics for 33 countries.

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Co_RE	771	−0.0006	0.01	−0.20	0.13
Cu_RE	771	0.6949	9.63	−3.18	190.39
Al_RE	771	1.0723	17.67	−107.28	396.86
Ni_RE	771	0.0021	0.63	−6.76	11.03
Mn_RE	771	0.6216	10.42	−26.02	197.33
EPS	957	2.0052	1.14	0.00	4.89
TO	951	75.3935	40.85	15.64	252.25
GDP	949	28842.21	19935.25	546.44	87123.66

Table 5
Correlation coefficients based on 763 observations.

	Co_RE	Cu_RE	Al_RE	Ni_RE	Mn_RE	EPS	TOP	GDP
Co_RE	1							
Cu_RE	0.0088	1						
Al_RE	0.0190	0.0674	1					
Ni_RE	−0.0845	0.0133	0.0102	1				
Mn_RE	0.0697	0.9209	0.0892	0.0226	1			
EPS	0.0677	−0.0924	−0.0703	0.0281	−0.0789	1		
TO	0.0209	−0.0425	0.1155	−0.0028	−0.0225	0.3667	1	
GDP	0.0543	−0.0613	0.0066	0.012	−0.0324	0.5364	0.2171	1

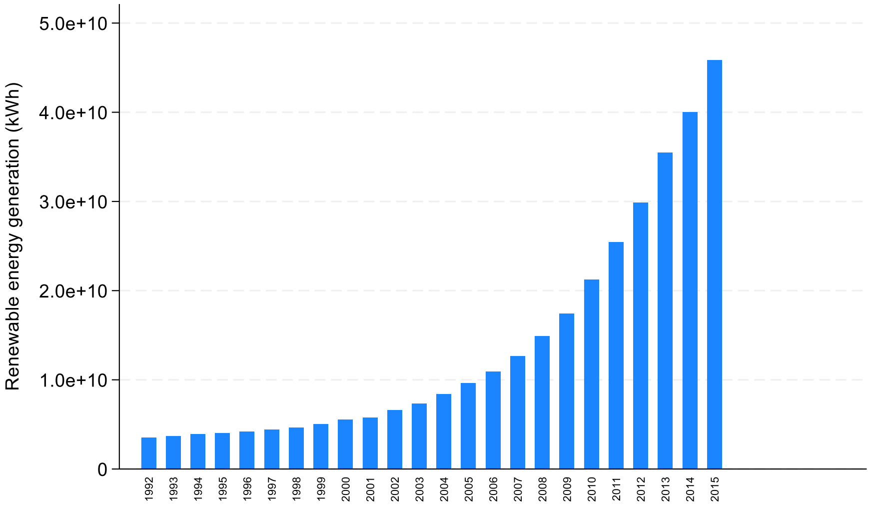

Fig. 2. Average electricity produced from renewable sources (kWh).
Source: Created by authors based on the WDI dataset.

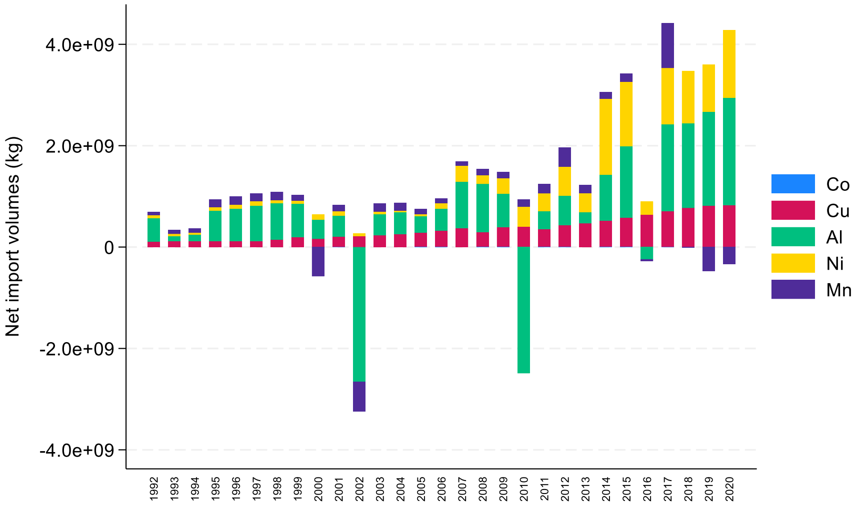

Fig. 3. Average net import volume in kilograms.
Source: Created by authors based on the WITS dataset.

from overseas. This could imply that while overall, more minerals are imported with increases in renewable energy over time, technological innovations could allow a reduction in the mineral intensity of RE technologies and allow each unit of renewable energy to be produced with fewer minerals imported from overseas. It could also be due to nations developing their local mines, alongside importing, to satisfy growing demands for clean energy production.

Fig. 5 shows that OECD countries have, on average, over time, reduced net import per unit of renewable energy whereas most non-OECD countries (e.g., South Africa is a net exporter of manganese and Indonesia is a net exporter of nickel) have been net exporters for most of the given years. Some non-OECD countries like China have remained net

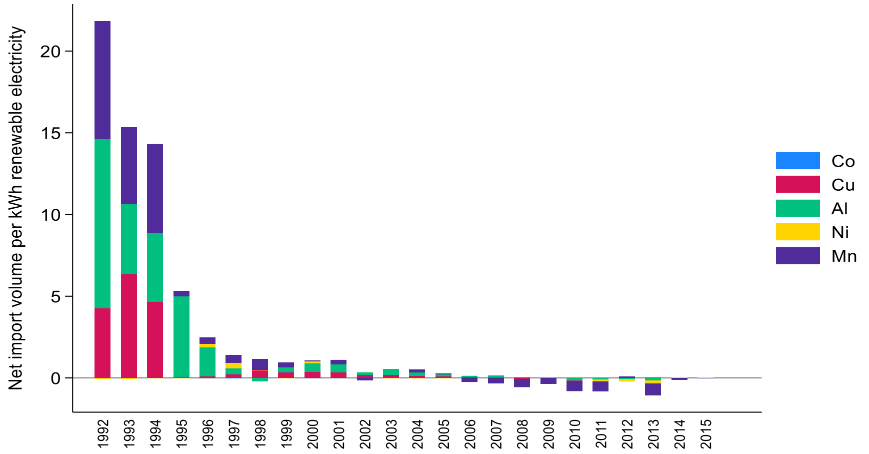

Fig. 4. Average net import volume per kilowatt hour of renewable generation (1992–2015).
Source: Created by authors based on the WITS and WDI datasets.

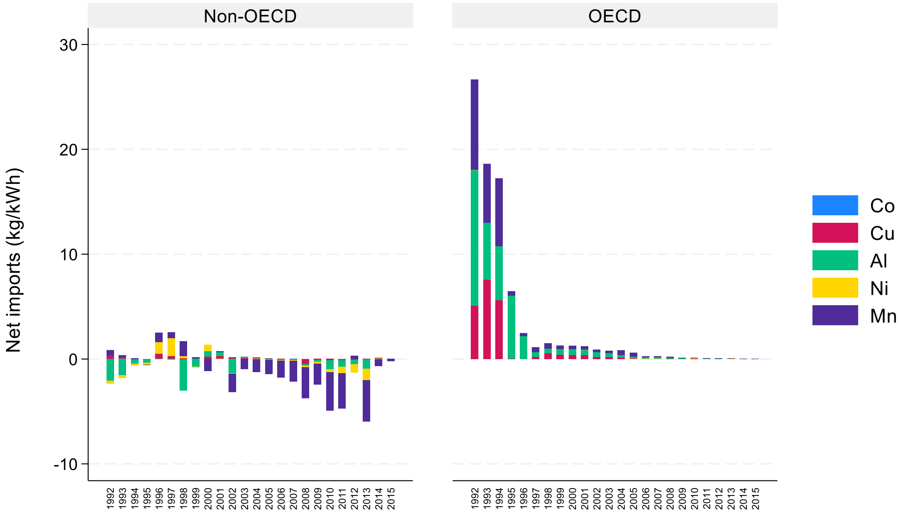

Fig. 5. Mineral trade dynamics for OECD and non-OECD countries in the sample.
Source: Created by authors based on WITS and WDI dataset.

importers for some of the minerals like nickel and aluminum, possibly importing ores and concentrates for further processing or refining. Fig. 6 presents country rankings for the net import of the five minerals (kg/kWh). The figure shows that Korea and Ireland are the top two net importers per unit of renewable energy. While nations like China, Japan, and the US are top importers in total volumes of net imports (kg), they do not necessarily rank higher in mineral imports per kWh. This illustrates that while the normalized values measuring net import per unit of renewable energy (kg/kWh) are generally positively correlated with net import volumes (kg), the patterns across countries reveal different insights (See Appendix for additional analysis and illustrations).

4. Results and discussions

In Section 4.1, we present bivariate correlations between EPS and net imports of the five minerals per unit of renewable energy and study how this correlation varies across countries. In Section 4.2, we present and discuss the regression analysis results to examine the impact of climate policies on the net import of energy transition minerals in the short and long run.

4.1. Relationship between climate policy stringency and mineral net imports

To better visualize the potential non-linear relationship between EPS and mineral net imports, we aggregate the five variables measuring net imports of the five minerals into one. Approximately, 71% of the observations have positive net imports for the sum of five minerals, while 25% have net exports (or negative net imports), and the rest have zero net imports. This shows that the sample of country-year observations is mostly representative of net importers. Fig. 7 presents a quadratic fit and scatter diagram showing the relationship between EPS and mineral net imports per renewable energy (kg/kWh) for each country while Table 6, Panel A presents a summary of the results, which are statistically significant at 5% level (that is, estimates of $\frac{dY_t}{dEPS_t}$ for each country) (See Appendix for additional analysis using net import volumes in kg).

The results suggest that as EPS increases over time, the response is, at best, heterogeneous across the different countries. For instance, countries like the US reduce their import reliance on mineral ores and concentrates (kg/kWh) with the increase in EPS, and this is likely due to insufficient mineral processing capabilities. Thus, the US exports some

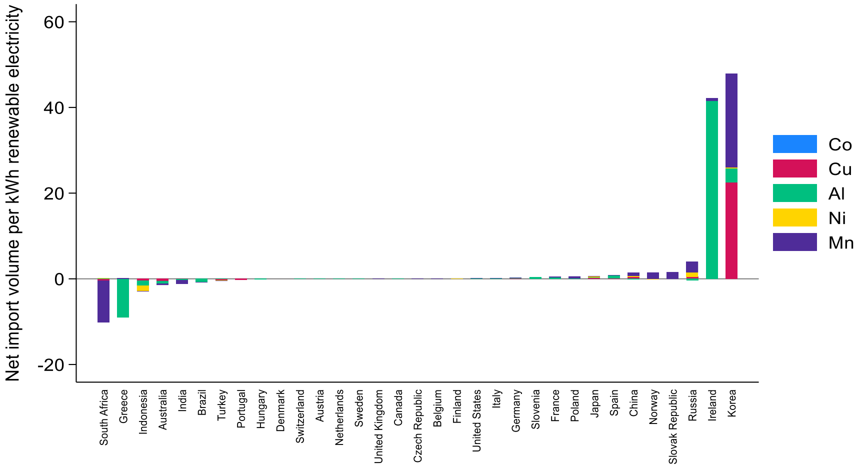

Fig. 6. Net import country rankings based on 1992–2015 averages.
Source: Created by authors based on the WITS and WDI datasets.

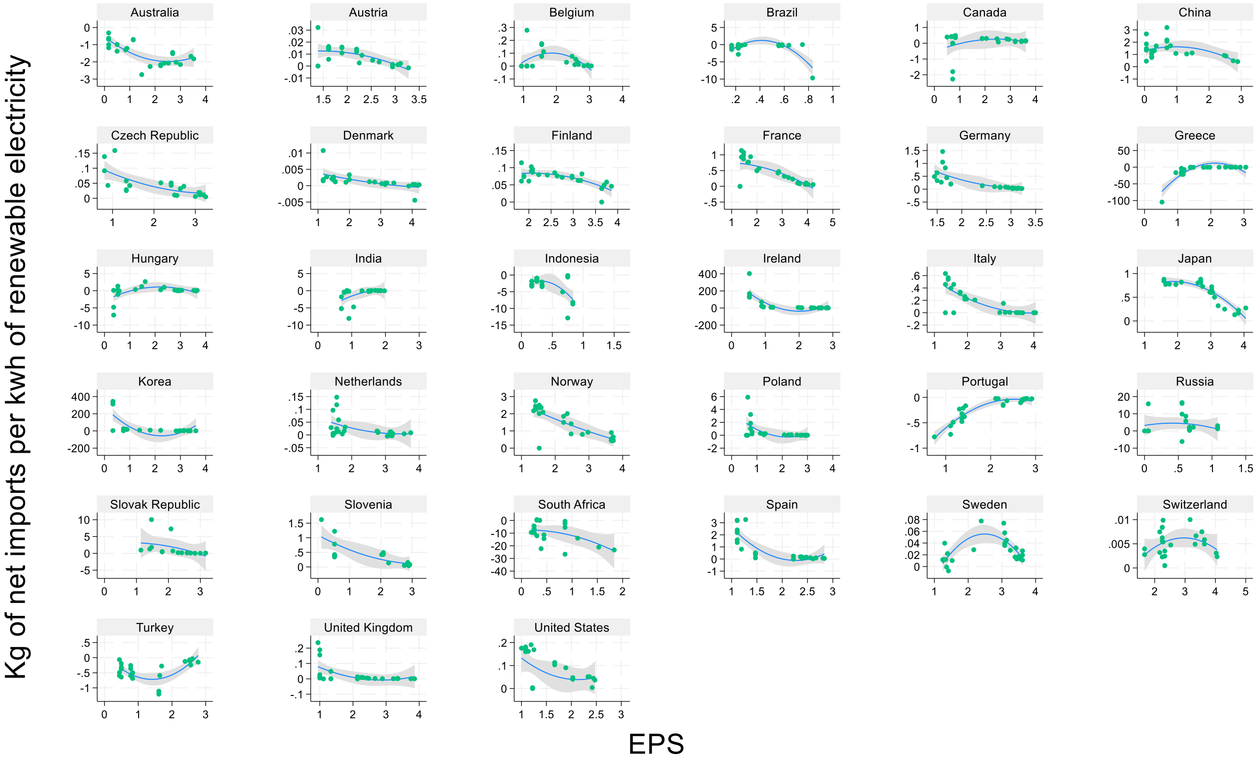

Fig. 7. EPS and net import volume per unit of renewable energy (kg/kWh) for five energy transition minerals (both axes are rescaled).
Source: Created by authors based on OECD stat, WITS, and the WDI datasets.

of these ores and concentrates elsewhere for refining/processing, which are then imported as refined metals for the energy transition. Another possible explanation is the faster growth in renewable investments, which exceeds the growth in mineral imports. Alternatively, countries like China may be investing more in local mineral exploration while also increasing imports, but the proportional increase in local mining may be higher than the relative increase in imports.

When using the normalized net import (kg/kWh), we find that countries such as Sweden, Japan, and Belgium experience an inverted-U relationship between net imports per renewable energy and EPS. This means that these countries rely on more imported minerals for each unit of renewable energy with stricter climate policies, but after a certain threshold level of policy stringency, net imports per kWh would level off as these countries potentially develop alternative resources locally (e.g., exploring local mines, onshore mining, deep sea mining, recycling minerals, etc.), develop technologies to reduce mineral-intensities, or resort to other means such as finding innovative substitute inputs to replace mineral inputs, etc. Another explanation for an eventual

Table 6

Impact of EPS on net import demand per kWh (summary of results).

Panel A: Change in mineral net import demand (all five minerals) per renewable generation (kg/kWh) with respect to changes in EPS over time for each country

Increasing	Increasing at a declining rate	Declining	Declining at a declining rate	Declining at an increasing rate
India	Belgium Greece Hungary Japan Portugal Sweden	Australia China Czech Rep. Slovenia South Africa UK USA	Korea Spain	Indonesia

Panel B: Changing rate of mineral import demand per kWh with respect changes in EPS in the short-run (CS-ARDL results)

Increasing	Increasing at a declining rate	Declining	Declining at a declining rate	Declining at an increasing rate
N/A	Cobalt Aluminum Nickel	N/A	Copper Manganese	N/A

Panel C: Changing rate of mineral import demand per kWh with respect to changes in EPS in the long-run (CS-ARDL results)

Increasing	Increasing at a declining rate	Declining	Declining at a declining rate	Declining at an increasing rate
N/A	Copper	N/A	Aluminum	Cobalt

slowdown of mineral import per kWh with climate policy stringency could be resorting to the import of cleaner energy technologies as climate policies get stricter (e.g., offshoring manufacturing), which reduces the total demand for mineral inputs. For instance, countries with strict EPS could eventually reduce the manufacturing of solar panels and instead import these technologies from overseas, leveling off their increasing demand for imported mineral inputs per kWh of renewable generation. So, initially, such countries may be importing more minerals to produce cleaner technologies locally, but eventually, they may shift to importing technologies rather than mineral imports, or they could shift to other, more innovative solutions to substitute minerals. When using net import volumes (million kilograms), we find that this U-shaped trend remains the same for countries like Belgium, Japan, and Sweden (see Appendix).

Countries such as South Korea experience a U-shaped relationship between net imports per renewable energy and EPS. However, for South Korea, net import volumes (kg) continuously increase, suggesting a more than proportional increase in RE with EPS. Such countries can generate much larger units of cleaner energy with increased units of minerals imported from overseas. Finally, Indonesia experiences a declining rate of net imports per kWh due to the country's export of mineral ores and concentrates with policy-induced improvements in renewable generation, or it could be due to the country's rich mineral reserves.

Overall, the result in this subsection implies that with the stringency of climate change policies, some countries experience increases in net import demand per unit of renewable generation while others experience a decline. The former group of countries is due to the important role of mineral imports in enabling energy transition goals (more imports needed per unit), where mineral imports increase at a faster rate than investments in RE. Demand for mineral imports for this group of countries could eventually level off with technological progress (e.g., mineral substitutes, recycling, etc.). The latter group of countries reduce mineral import demand per renewable energy unit at different rates. The decline in import reliance per unit implies slower growth of import demands relative to the fast pace of energy transition. This could be due to a combination of factors such as domestic mining, technological progress, or importing energy transition technologies rather than producing them locally.

4.2. *Short-run and long-run drivers of mineral net imports*

Table 7 presents short and long-run elasticities for the five minerals based on fitting the CS-ARDL model. In all cases, a change in net imports (kg/kWh) from the previous year, perfectly predicts the current year's net import in the short run. For example, a one percent increase in the growth rate of the normalized net import of a mineral is associated with a one percent increase in the current year's net import. All regressions include *TO* and *GDP* as control variables. Since we are not primarily interested in interpreting the impact of control variables, the full results from the control variables are delegated to the Appendix. Table 7 shows that EPS has a considerable impact on normalized net imports of all minerals in the short term, long term, or both. However, the direction of impact and its strength on mineral net imports per kWh varies across the different ores and concentrates, as well as across short versus long run periods.

In the short run, increases in climate policy require higher volumes of cobalt, aluminum, and nickel net imports per cleaner energy production, where the increase is at a declining rate. This implies that import reliance for these three minerals levels is off or declines. Increases in import reliance on these three minerals are not sustainable in the long run and are even reversed for cobalt and aluminum. In the long run, increases in the stringency of climate policies are correlated with fewer net imports of cobalt and aluminum per kWh. This result suggests that in the short run increasing the stringency of climate policies is correlated with increasing import reliance on cobalt, aluminum, and nickel up to a certain point (Yu et al., 2023). This finding also suggests the short-run role of international trade in driving the energy transition triggered by climate policies. However, in the long run, further improvements in climate policies could act as a trade barrier as nations strive to be self-sufficient in the extraction and processing of energy transition minerals or invest in technologies that minimize the use of imported minerals.

For copper and manganese, we find that as climate policy stringency increases in the short run, net import per kWh reliance declines at a declining rate. In the long run, copper net imports per kWh increase, but changes in manganese net imports with respect to EPS are not statistically significant. This could be due to the option of importing copper *metals* in the short run (unwrought or scarp) instead of copper-containing ores and concentrates. That is, in the short run, nations could import more metals than ores to facilitate their energy transition.

Table 7

Short-run and long-run elasticities for net imports of five minerals (552 observations). All variables are log-transformed.

Dependent Variable ($Y_{i,t}$)	*Co_RE*	*Cu_RE*	*Al_RE*	*Ni_RE*	*Mn_RE*
	Coefficients (Standard Errors)				
Short Run Estimates					
$\Delta Y_{i,t-1}$	1[a] (3.251)	1[a] (3.051)	1[a] (8.271)	1[a] (4.230)	1[a] (3.071)
ΔEPS	0.491[b] (0.231)	−1.911[a] (0.791)	0.411[a] (0.201)	1.73[a] (0.541)	−1.531[a] (0.631)
ΔEPS^2	−1.131[a] (0.461)	0.981[a] (0.351)	−1.431[a] (0.541)	−1.431[a] (0.671)	0.696[a] (0.295)
ΔControls	Yes	Yes	Yes	Yes	Yes
Adjustment Term	−1.74[1a] (0.351)	−1.421[a] (0.651)	−1.601[a] (0.771)	−2.360[a] (1.029)	0.487[a] (0.207)
Long Run Estimates					
EPS	−0.032[a] (0.014)	0.170[b] (0.087)	−0.121[a] (0.059)	−0.127 (0.064)	−0.101 (0.042)
EPS^2	−0.081[a] (0.004)	−0.106[a] (0.050)	0.150[a] (0.055)	0.076[a] (0.030)	0.019[a] (0.005)
Controls	Yes	Yes	Yes	Yes	Yes

[a] indicates 1% statistical significance.

[b] indicates 5% statistical significance.

In the long run, nations may resort to importing ores and concentrates, which are relatively cheaper than refined metals in some cases. This could be possible in the long run as nations develop their mineral processing and refining capabilities (Zhang et al., 2022; Wang et al., 2021).

Overall, the findings in Table 7 demonstrate how EPS increases short-run net import demand for some minerals but not others. In addition, short-run effects may not be sustainable and may even be reversed in the long run. The findings about EPS influencing mineral trade are generally consistent with studies that imply that environmental policies could potentially reduce or create unintended trade barriers for some minerals but not all (Chen et al., 2023; Noubissi et al., 2021; Martínez-Zarzoso et al., 2019; Costantini and Mazzanti, 2012). Table 6, Panels B and C summarize the regression results (see Appendix for additional regressions with net import volumes).

The study's findings have significant policy implications for countries aiming to transition to cleaner energy sources while reducing import reliance on critical minerals. Firstly, the short-term impact of climate policy stringency on increasing cobalt, aluminum, and nickel imports in the short run suggests a need for targeted measures to manage import fluctuations and ensure sustainable supply chains (e.g., trade disruptions could create a bottleneck for energy transition progress). Measures could involve strategic stockpiling, diversification of sourcing, and incentives for domestic production or recycling of these minerals in the short run.

The trends also highlight the importance of enhancing domestic processing and refining capabilities in the short run to refine/process imported ores and concentrates like cobalt and aluminum into technology-grade inputs. Policies should prioritize investments in technology and infrastructure for mineral extraction, processing, and/or recycling, fostering a more resilient supply chain in the energy transition sector. Lastly, the study underscores the evolving role of international trade and trade patterns in affecting energy transition, with implications for trade policies and agreements. Policymakers need to balance the short-term benefits of international trade with long-term goals of achieving mineral self-sufficiency and minimizing environmental impacts associated with mineral extraction and transportation. This could involve integrating sustainability criteria into trade agreements and promoting cooperation for technology transfer and capacity building in mineral processing and recycling.

5. Conclusions and policy implications

Renewable energy (RE) technologies have rapidly gained prominence as a fundamental pillar of climate policies aimed at combating climate change and steering the world toward a cleaner and more sustainable energy system. Notably, solar, wind turbines, and batteries have emerged as crucial elements of green energy solutions, driving the focus toward reducing GHG emissions and reinforcing energy security. Nevertheless, amidst the push for RE adoption, energy transition minerals' indispensable role in manufacturing these technologies is a vital aspect often overlooked.

The transition to RE sources necessitates using minerals such as copper, nickel, and cobalt. These minerals hold a pivotal position in the production of various green energy technologies, encompassing solar panels, wind turbines, and energy storage systems. As climate change policies gain momentum worldwide, incentivizing the widespread adoption of cleaner energy alternatives, the demand for these critical minerals has surged, creating many challenges for policymakers and substantial implications for energy technology markets. Despite the growing importance of climate change policies in facilitating the adoption of RE sources, there remains a significant gap in understanding the implications of these policies on critical mineral trade patterns. This article bridges the gap between the mineral-energy literature and the escalating relevance of climate change policies in the global push toward transitioning to RE sources. The study focused on five key mineral inputs - copper, aluminium, nickel, cobalt, and manganese - which are indispensable in producing cleaner energy technologies.

The findings reveal that environmental policy stringency considerably affected net mineral imports per renewable energy generation, both in the short and long term. In the short term, the stringency of climate policies negatively impacted the net import of magnesium and copper per renewable energy, while positively affecting net import demand for cobalt, aluminium, and nickel per kilowatt hour of renewable electricity. Over the long term, climate policy negatively affected net imports of aluminium and cobalt but positively affected copper. This suggests that environmental policy stringency affects different minerals in a different way.

In summary, the study underscores the intricate interplay between environmental policies, the import of critical minerals, and long-term resource planning to ensure a sustainable global mineral trade framework in the context of RE technologies. While some minerals, such as cobalt and nickel, may experience increased import reliance with more stringent policies, others may not show the same pattern. This indicates the need for tailored policies and actions to address mineral trade dynamics effectively in the context of clean energy transitions.

Policymakers should consider these findings when formulating strategies to strike a balance between environmental sustainability, economic growth, and the responsible trade of essential minerals crucial for RE technologies. By doing so, countries can work toward achieving climate goals while ensuring a sustainable supply of critical minerals for the clean energy transition.

The empirical findings emphasize the need for a holistic approach to sustainable energy planning that acknowledges the interdependence between RE technologies and the availability/accessibility of essential minerals via domestic and/or imported sources. Integrating these considerations into policymaking can foster more informed and effective strategies for a greener, cleaner, and more resilient energy system. Policymakers should prioritize enhancing environmental regulations efficiency, diversifying mineral suppliers, promoting recycling and circular economy initiatives, and strengthening international cooperation to address the increasing demand for critical minerals. Additionally, investment in innovation, addressing social and environmental concerns in mining regions, and supporting energy efficiency measures are crucial in optimizing resource utilization and achieving environmental goals to pursue the energy transition pathway.

Related to this, the 2023 UN Climate Change Conference, know as Conference of the Parties (COP28), highlighted the importance of international trade in securing minerals and materials needed for the energy transition. While it is important for nations to strengthen their domestic capabilities to source critical materials for the energy transition, trade is expected to remain important, and nations need to form a global network for sourcing and policy coordination. The results of this study imply that one approach for an international cooperation on critical materials could come from climate change policies as well as other types of environmental policies to facilitate responsible mining. While more minerals are needed for the clean energy transition, nations must cooperate to create a global standard to ensure that the extraction of minerals is done in a sustainable and equitable manner.

Finally, we would like to acknowledge the limitations of this study in the generalizability of results and data challenges. First, the EPS is an index and is only available for a sub-set of 33 countries. The index is not available for several other mineral-rich countries (e.g., Congo), so the results of this study should be interpreted only in the given context. Second, while EPS is the best available indicator for environmental policy stringency, more studies are needed to generate additional measures to meaningfully compare climate change policies across nations and over time. Third, there could be several other potential variables that could affect mineral trade dynamics, such as the financial development of a country and geopolitical factors which are not captured in this study. In this study, we fit the most parsimonious model with fewer control variables that are expected to affect net imports (i.e., trade openness and GDP per capita) and so future studies can control for other potential explanatory variables and their role in governing mineral trade dynamics.

CRediT authorship contribution statement

Mahelet G. Fikru: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nurcan Kilinc-Ata:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing. **Fateh Belaïd:** Conceptualization, Investigation, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Appendix A. The impact of EPS on net import volume per unit of renewable energy

The results of a linear regression model with robust standard errors are shown in Table 1A. Statistically significant coefficients are marked in bold. All values are log transformed.

$$Y_t = a_0 + a_1 EPS_s + a_2\, EPS_t^2 + e_t$$

Table 1A
A linear regression with robust standard errors for countries

Country	EPS (average)	a_1	a_2	Turning point
Australia	0.137	**−0.004**	0.000	
Austria	0.822	0.000	0.000	
Belgium	0.692	**0.003**	**−0.003**	**1.02**
Brazil	−1.007	−0.126	−0.057	
Canada	0.504	0.003	−0.001	
China	−0.551	**−0.003**	−0.001	
Czech Republic	0.706	**−0.001**	0.000	
Denmark	0.940	0.000	0.000	
Finland	1.024	0.002	**−0.001**	
France	0.965	0.011	−0.010	
Germany	0.888	−0.013	0.003	
Greece	0.578	**4.305**	**−3.547**	**1.21**
Hungary	0.494	**0.018**	**−0.025**	**0.70**
India	0.310	**0.035**	−0.016	
Indonesia	−0.867	**−0.102**	**−0.037**	**−2.72**
Ireland	0.491	**−0.842**	**0.672**	**1.25**
Italy	0.896	−0.006	0.001	
Japan	1.039	**0.021**	**−0.015**	**1.39**
Korea	0.496	**−0.472**	**0.374**	**1.26**
Netherlands	0.843	−0.001	0.000	
Norway	0.905	−0.009	−0.005	
Poland	0.514	−0.018	0.012	
Portugal	0.658	**0.008**	**−0.003**	**2.73**
Russia	−0.933	−0.008	−0.001	
Slovak Republic	0.262	0.051	−0.064	
Slovenia	−1.181	**−0.003**	0.001	
South Africa	−0.708	**−0.119**	−0.053	
Spain	0.617	**−0.075**	**0.048**	**1.56**
Sweden	0.946	**0.002**	**−0.001**	**1.63**
Switzerland	1.037	0.000	0.000	
Turkey	0.192	0.000	0.005	
United Kingdom	0.704	**−0.002**	0.001	
United States	0.515	**−0.003**	0.003	

Appendix B. Econometric tests

For cross-sectional independence in panel data, we apply Pesaran's (2004) CD test. The investigation of cross-sectional dependence in any variable and residual series is possible with this pre-estimation technique. The test computes the CD-test statistics, including the p-value, average correlation coefficient, and absolute correlation coefficient. The statistics from the CD test have been extensively discussed and available from studies such as Pesaran (2021), Wursten (2017), and Pesaran (2015).

Table 1B
CD test (all variables are log-transformed)

Variables	CD-test statistic	Average correlation	Absolute correlation
Co_RE	5.86*	0.157	0.156
Cu_RE	−6.42*	−0.313	0.318
Al_RE	16.26*	0.144	0.370
Ni_RE	4.49*	0.168	0.195
Mn_RE	17.64*	0.157	0.335
EPS	38.51*	0.342	0.659
TO	65.94*	0.591	0.695
GDP	98.73*	0.886	0.886

Null Hypothesis: There is no cross-sectional dependency.
* indicates p-value <0.000.

Table 1B's CD-test results of all mineral net import per kWh indicate statistical significance at a level of 1% or less, indicating that there is cross-sectional dependence among the panel units (countries). Additionally, the average and absolute correlation coefficients are shown in the table.

Table 2B shows data for the slope homogeneity test developed by Pesaran and Yamagata (2008) as well as those by Blomquist and Westerlund (2013) to further account for concerns about homoscedasticity and serial correlation.

Table 2B
Slope homogeneity test (all variables used in the tests are log-transformed)

Dependent variables	Statistics
Co_RE	
$\widetilde{\Delta}$	−3.149*
$\widetilde{\Delta}_{adj}$	−3.539*
Δ_{HAC}	−3.384*
$\Delta_{HAC\ adj}$	−3.803*
Cu_RE	
$\widetilde{\Delta}$	7.771*
$\widetilde{\Delta}_{adj}$	8.734*
Δ_{HAC}	5.672*
$\Delta_{HAC\ adj}$	6.374*
Al_RE	
$\widetilde{\Delta}$	3.315*
$\widetilde{\Delta}_{adj}$	3.726*
Δ_{HAC}	−4.212*
$\Delta_{HAC\ adj}$	−3.238*
Ni_RE	
$\widetilde{\Delta}$	−4.108*
$\widetilde{\Delta}_{adj}$	−4.617*
Δ_{HAC}	−3.802*
$\Delta_{HAC\ adj}$	−4.274*
Mn_RE	
$\widetilde{\Delta}$	3.619*
$\widetilde{\Delta}_{adj}$	3.695*
Δ_{HAC}	3.661*
$\Delta_{HAC\ adj}$	3.867*

* *indicates p-value 0.000.*

Table 2B demonstrates that there is slope heterogeneity as there is evidence for slope variance between cross-section units, and the very low (zero) p-values from the two tests lead us to reject the null hypothesis that slope uniformity exists in panel units for net import per kWh. Then, we run Pesaran's CADF (the second-generation panel unit-root) panel unit root tests (Pesaran, 2007) and Westerlund cointegration test; and the results are given in Table 3B.

Table 3B
Co-integration and stationarity tests (values in this table are p-values)

Variables	CADF (Level)	CADF (Change)	Westerlund Cointegration Test
Co_RE	0.000	0.000	0.000*
Cu_RE	0.000	0.000	0.000*
Al_RE	0.000	0.000	0.000*
Ni_RE	0.000	0.000	0.000*
Mn_RE	0.000	0.000	0.000*
EPS	0.000	0.000	
TO	0.000	0.000	
GDP	0.000	0.000	

Table 3B shows the p-values for each variable and confirms that all variables are stable/stationary in the level and first difference. Levin-Lin-Chu unit root testing requires strong balancing of data (Levin et al., 2002; Im et al., 2003) so we performed the Westerlund cointegration test and the p-values for all regressions are statistically significant at the 1% level or less.

Appendix C. Additional analysis for EPS and net import volumes (kg)

Figure C1 presents the time trend in EPS for each country in the sample over the years 1992–2020. The figure suggests that the countries in the sample have different rates of change in the EPS. While for most countries EPS is increasing over time (e.g., more stringent climate policies), not all countries exhibit the same rate of change in the stringency of their policies. For some countries, the time trend shows a recent stagnation or decline (e.g., Spain, Russia, Korea) in the stringency of policies, while other countries continue to continuously improve the stringency of their climate policies (e.g., Switzerland, France). A change in the stringency of climate change policies could be due to several economic and non-economic factors. For example, when nations make commitments under an international agreement (e.g., the Paris Agreement), they are likely to consider instituting new policies and regulatory frameworks to reduce greenhouse gas emissions. Changes in the political landscape could also trigger a change in the stringency of environmental policies (e.g., discarding prescriptive cleaner technologies or abandoning emission standards). Some countries may institute more moderate climate policies as part of an industrial policy framework to encourage poorly performing sectors and industries. The growing concerns about energy accessibility and affordability may also influence the stringency of climate policies that are likely to cause high-energy prices (Ahmad and Satrovic, 2023; Cameron et al., 2016).

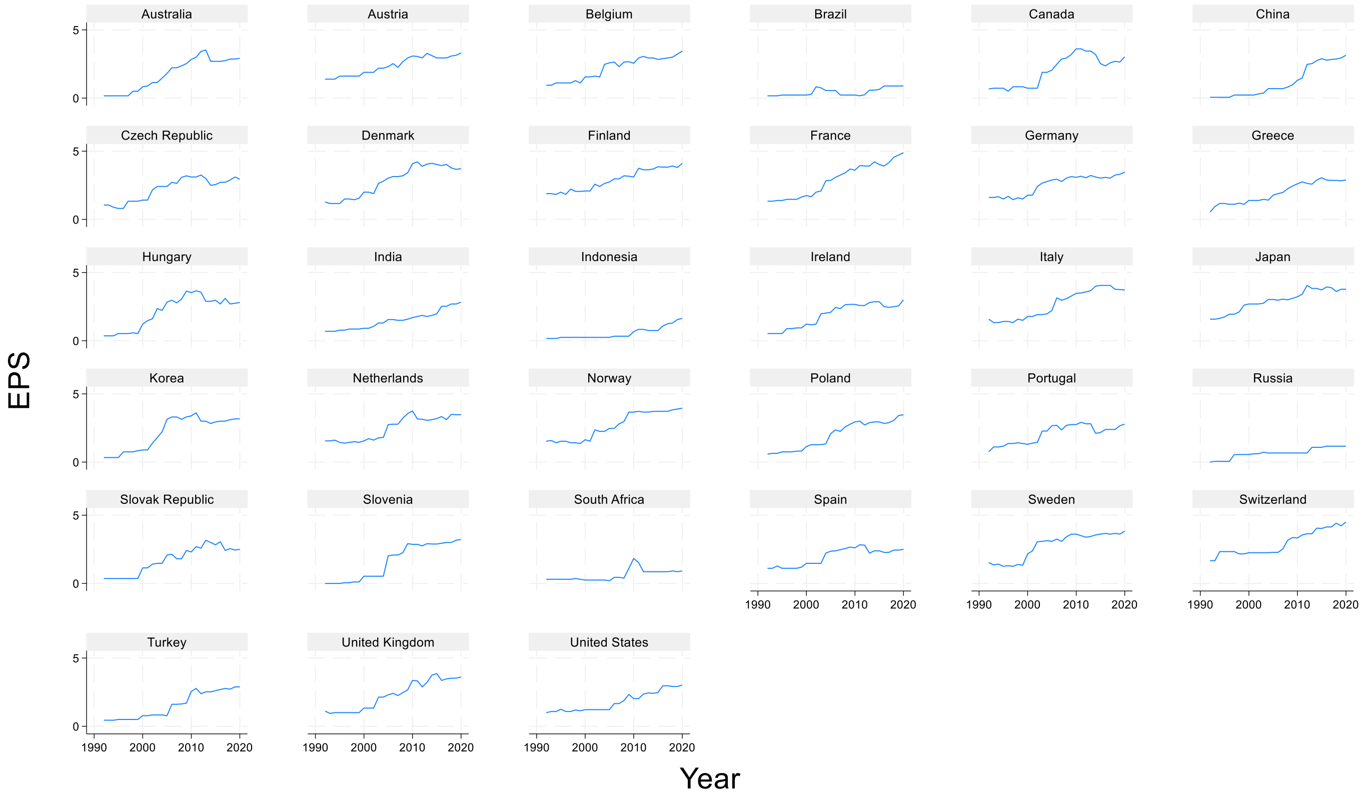

Fig. C1. Stringency of environmental policies over time.
Source: Created by authors based on OECD EPS dataset.

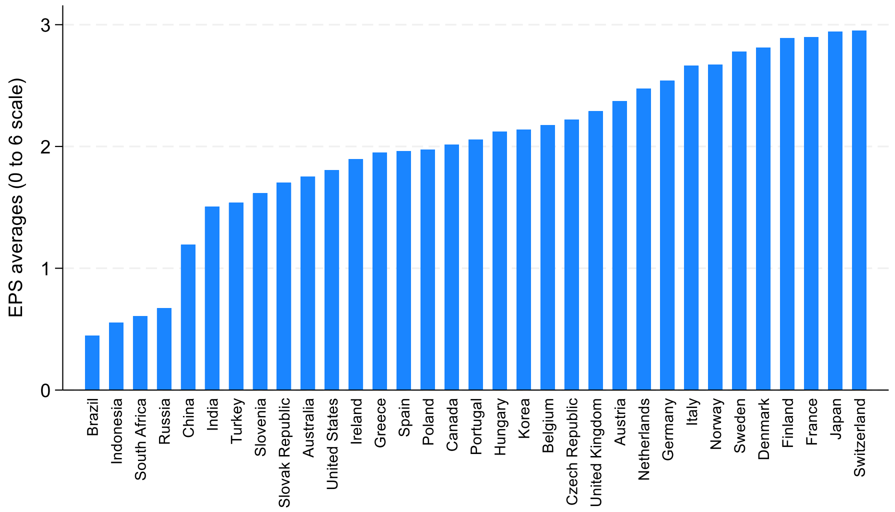

Fig. C2. Country rankings by average EPS from 1992 to 2020.
Source: Created by authors based on OECD's EPS dataset.

Figure C2 presents a ranking of the 33 countries based on their average EPS over the given time period. Countries such as Switzerland, Japan, France, and the Nordic nations (Finland, Denmark, Sweden, and Norway), rank as having the most stringent climate policies, followed by other European countries (Italy, Germany, the Netherlands, Austra, the UK, etc.). The non-OECD countries (Brazil, Indonesia, South Africa, Russia, China, India, and Turkey) are lagging behind the climate policy curve. The ranking of countries presented in Fig. 3 is fairly stable for each year where data is available.

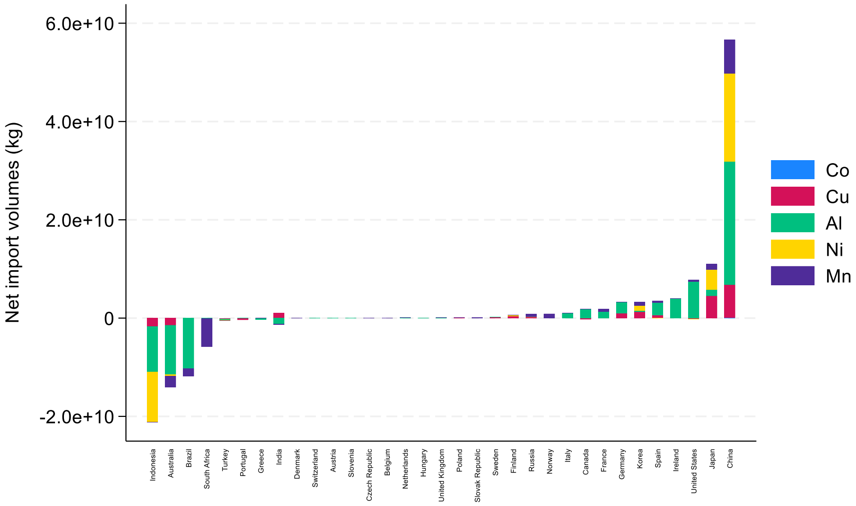

Fig. D2. Average net import volumes measured in kilograms (not normalized).
Source: Created by authors based on WITS and WDI dataset.

Table C1
Descriptive statistics for non-normalized variables.

Variables	Observations	Mean	Standard deviation	Minimum	Maximum
Co Net Import (millions, kg)	957	3.8	27.6	−76.0	349.0
Cu Net Import (millions, kg)	957	352	1890	−2880	22000
Al Net Import (millions, kg)	957	495	9600	−100000	112000
Ni Net Import (millions, kg)	957	376	6060	−64800	71200
Mn Net Import (millions, kg)	957	67	2780	−23300	27600
RE (millions, kWh)	792	13800	33300	0	317000

Table C2
Correlation between normalized and non-normalized net imports.

	Correlation coefficient
Cobalt	0.1938
Copper	0.0242
Aluminum	0.0455
Nickel	0.3973
Manganese	0.0956

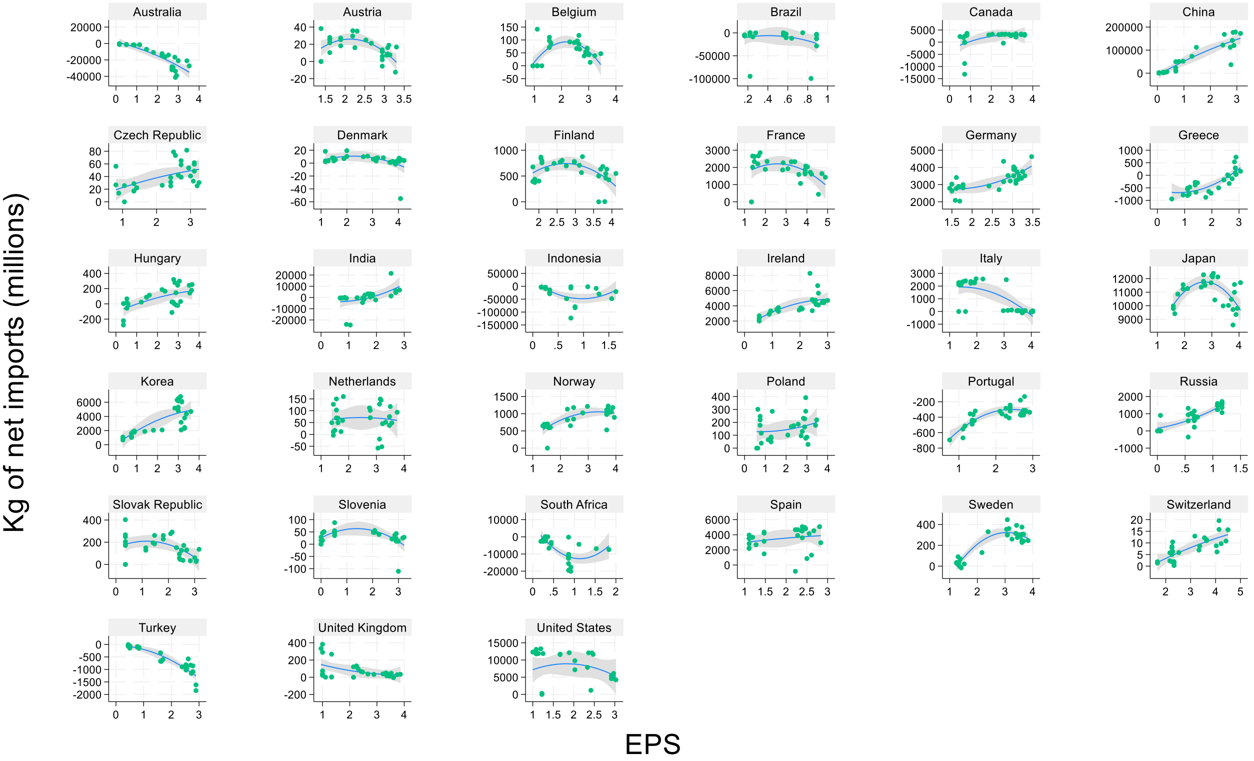

Fig. D1. EPS and net import volume (kg) of five energy transition minerals (both axes are rescaled).
Source: Created by authors based on OECD stat, WITS and WDI dataset.

Table C3
CD test (all variables are in kg of net imports and log-transformed).

Variables	OECD Countries			Non-OECD Countries		
	CD-test statistic	Average correlation	Absolute correlation	CD-test statistic	Average correlation	Absolute correlation
Co	−1.10	−0.011	0.149	0.89	0.042	0.254
Cu	0.88	0.009	0.242	−1.53	−0.073	0.324
Al	4.19*	0.042	0.299	−1.88	−0.090	0.172
Ni	2.25	0.022	0.174	1.27	0.061	0.165
Mn	−0.21	−0.002	0.169	2.75*	0.132	0.261
EPS	−0.16	−0.002	0.449	−1.31	−0.063	0.375
TO	70.99*	0.704	0.722	2.48*	0.119	0.496
GDP	83.38*	0.856	0.856	19.45*	0.933	0.933

* indicates p-value <0.00.

Table C4
Slope homogeneity test (all variables used in the tests are in kg of net imports and then log-transformed)

Dependent variables	OECD Countries	Non-OECD Countries
	Statistics	Statistics
Co		
$\widetilde{\Delta}$	0.795	6.953*
$\widetilde{\Delta}_{adj}$	0.873	7643*
Δ_{HAC}	0.041	12.327*
$\Delta_{HAC\ adj}$	0.045	13.550*
Cu		
$\widetilde{\Delta}$	10.539*	10.825*
$\widetilde{\Delta}_{adj}$	11.585*	11.899*
Δ_{HAC}	9.190*	17.770*
$\Delta_{HAC\ adj}$	10.102*	19.533*
Al		

(*continued on next page*)

Table C4 (*continued*)

Dependent variables	OECD Countries	Non-OECD Countries
	Statistics	Statistics
$\tilde{\Delta}$	4.145*	2.395*
$\widetilde{\Delta_{adj}}$	4.556*	2.633*
Δ_{HAC}	5.018*	2.134*
$\Delta_{HAC\ adj}$	5.516*	2.346*
Ni		
$\tilde{\Delta}$	−0.257	−2.696*
$\widetilde{\Delta_{adj}}$	−0.282	−2.965*
Δ_{HAC}	0.152	−2.742*
$\Delta_{HAC\ adj}$	0.167	−3.014*
Mn		
$\tilde{\Delta}$	−4.131*	2.790*
$\widetilde{\Delta_{adj}}$	−4.541*	2.869*
Δ_{HAC}	−4.347*	2.011*
$\Delta_{HAC\ adj}$	−4.779*	2.012*

* *indicates p-value 0.000.*

Table C5
Co-integration and stationarity tests (values in this table are p-values)

Variables	OECD Countries			Non-OECD Countries		
	CADF (Level)	CADF (Change)	Westerlund Cointegration Test	CADF (Level)	CADF (Change)	Westerlund Cointegration Test
Co	0.000	0.000	0.000*	0.000	0.000	0.045
Cu	0.000	0.000	0.000*	0.918	0.000	0.117
Al	0.003	0.000	0.000*	0.774	0.000	0.019
Ni	0.000	0.000	0.000*	0.000	0.000	0.013
Mn	0.000	0.000	0.000*	0.681	0.000	0.057
EPS	0.150	0.000		0.841	0.000	
TO	0.000	0.000		0.135	0.000	
GDP	0.031	0.000		0.268	0.078	

Table C6
Pedroni test for cointegration (values in this table are p-values)

Variables	OECD Countries			Non-OECD Countries		
	Modified Phillips–Perron t	Phillips–Perron	Augmented Dickey–Fuller t	Modified Phillips–Perron t	Phillips–Perron	Augmented Dickey–Fuller t
Co	0.000	0.000	0.000	0.079	0.000	0.000
Cu	0.000	0.000	0.000	0.450	0.006	0.013
Al	0.000	0.000	0.000	0.141	0.000	0.000
Ni	0.000	0.000	0.000	0.040	0.000	0.000
Mn	0.000	0.000	0.000	0.114	0.000	0.000

Table C7
Short-run and long-run elasticities for net imports (kg) of five minerals for OECD countries

Dependent Variable ($NI_{i,t}$)	*Co*	*Cu*	*Al*	*Ni*	*Mn*
	Coefficients (Standard Errors)				
Short Run Estimates					
$\Delta\ Y_{i,t-1}$	1*** (1.87e)	1*** (1.51e)	1*** (2.64e)	1*** (3.84e)	1*** (9.33e)
ΔEPS	−2.64e (3.20e)	1.14e (1.27e)	3.36e** (1.53e)	8.81e (2.70e)	−2.92e (2.89e)
ΔEPS^2	4.59e 5.15e	−1.45e (1.27e)	−3.76e** (1.79e)	−7.68e (2.91e)	2.26e (2.47e)
ΔControls	Yes	Yes	Yes	Yes	Yes
Adjustment Term	−2.34e (1.87e)	2.31e (1.51e)	8.33e (2.64e)	5.24e (3.84e)	1.19e (9.33e)
Long Run Estimates					
EPS	0.217 (2.225)	−1.797 (2.313)	0.093 (0.086)	−0.047 (0.036)	0.027 (0.022)
EPS^2	−0.419 (2.346)	1.526 (2.006)	−0.101 (0.089)	0.041 (0.031)	−0.021 (0.019)
Controls	Yes	Yes	Yes	Yes	Yes

**p < 0.05 and ***p < 0.01.

For OECD countries, the CS-ARDL estimations using net import (kilogram) show that as EPS increases, the net import volume for aluminum increases at a declining rate in the short run. This suggests that OECD nations could increase the (unnormalized) net import of aluminum with stricter climate policies in the short run.

Table C8
Short-run and long-run elasticities for net imports (kg) of 5 minerals for non-OECD countries

Dependent Variable ($NI_{i,t}$)	*Co*	*Cu*	*Al*	*Ni*	*Mn*
	Coefficients (Standard Errors)				
Short Run Estimates					
$\Delta\ NI_{i,t-1}$	1*** (1.55e)	1*** (3.54e)	1*** (2.37e)	1*** (1.36e)	1*** (5.46e)
ΔEPS	−4.69e (6.44e)	2.23e (4.32e)	−4.63e (4.52e)	−3.01e (3.39e)	1.17e (0.951)
ΔEPS^2	8.87e (1.06e)	−4.05e (5.98e)	6.81e (6.55e)	4.20e (4.39e)	6.34e (7.69e)
Δ*Controls*	Yes	Yes	Yes	Yes	Yes
Adjustment Term	−2.50e (1.54e)	−2.78e (3.54e)	−2.90e (2.37e)	−1.08e (1.36e)	−6.24e (4.57e)
Long Run Estimates					
EPS	4.575 (3.366)	−20.538 (19.101)	6.259 (6.570)	−1.949 (1.557)	−3.829** (1.837)
EPS^2	−6.215 (5.172)	25.142 (23.487)	−7.377 (8.295)	−0.311 (0.639)	6.918** (3.316)
Controls	Yes	Yes	Yes	Yes	Yes

**$p < 0.05$ and ***$p < 0.01$.

The CS-ARDL estimations using net import (kilogram) show that as EPS increases, the net import volume for manganese declines at a declining rate in the long run for non-OECD countries. This suggests that non-OECD nations could reduce the (unnormalized) net import of manganese with stricter climate policies. None of the short-run estimates were significant for non-OECD countries. Comparing CS-ARDL results with and without the normalized dependent variable shows that climate policies affect the normalized mineral net imports more often than the unnormalized net import due to their impact on RE.

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