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ORIGINAL PAPER

Metals at the nexus: renewable vs. nuclear energy systems, metal import requirements, and energy security in the European Union

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Abstract
This study examines the compatibility of the EU's current 2050 clean energy transition plan, aiming to increase the share of renewable power generation to 80%, with mineral and energy security in the EU, acknowledging the interplay between these security aspects when dealing with metal-intensive energy systems. It also explores the potential advantages of an alternative electricity mix that combines the existing renewable generation share with expanded nuclear energy capacity. The results demonstrate that the planned renewable-intensive electricity mix requires substantially higher quantities of metals to increase and sustain electricity production capacity than the alternative nuclear-intensive system. This is not only the case in terms of volume requirements, which is already evident from the existing literature, but also in terms of value and import requirements. Further, our results reveal that the bottleneck risks in the planned renewable-intensive system are primarily associated with insufficient mining of essential metals inside the EU. In contrast, the bottleneck risks in the nuclear-intensive system are primarily associated with lack of processing inside the EU. Based on the assumption that acquiring relevant mineral reserves and mining capabilities may be more challenging than acquiring new processing capacities, this suggests that the planned renewable-intensive system may come with more serious bottleneck risks than an alternative nuclear-intensive system. Overall, this study leads to the conclusion that a nuclear-intensive electricity mix could offer greater metal-related energy security than the planned renewable-intensive system.

Keywords Energy security · Renewable · Nuclear · Metal requirements · Metal imports

Introduction

In 2018, the European Union (EU) presented a long-term proposal to achieve net zero emissions. According to the proposal, the EU aims to achieve more than 80% of its electricity production from renewable energy sources by 2050, with nuclear power contributing around 15% (European Commission 2018). Execution of this plan will not only reduce greenhouse gas (GHG) emissions but can also reduce the EU's reliance on other countries, particularly Russia, for natural gas imports. The urgency to implement this plan increased after the EU experienced a sudden gas shortage and a significant rise in electricity prices in 2022 due to the conflict in Ukraine. However, increasing reliance on renewable power generation may lead to a new energy security risk in terms of metal import dependence (European Council 2022). The International Energy Agency (IEA) highlights the metal-intensive nature of renewable energy technologies (IEA 2022). At the same time, EU production of metals is limited (Boulamanti and Moya 2016). In addition, production of the metals required for clean energy technologies is unevenly distributed across the world, with many being highly geographically concentrated in countries and regions outside of the EU (IEA 2022). For example, China plays a significant role in the processing section of metal production (IEA 2022). In contrast, the amount of metals required for generating electricity per unit of nuclear energy is comparatively small (IEA 2022). Furthermore, concerns surrounding nuclear energy, such as equipment safety and toxic waste disposal, which caused stagnation in EU nuclear energy capacity growth after 1990, have largely been addressed through technological advancements (Zhan et al. 2021). The introduction of the concept of small modular nuclear power

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plants has also prompted some EU countries such as France and Romania to reconsider increasing financial support for nuclear power plants in recent years (Lokhov et al. 2016). Studies suggest that investing in modular nuclear energy is economically feasible as it can, under certain conditions, have the same high rate of return as onshore wind energy projects (Locatelli et al. 2014; Mignacca and Locatelli 2020; Qu and Bang 2023). Overall, these indicate that nuclear energy could represent a viable and advantageous complement and/or alternative to renewable energy in the future EU energy supply.

The scientific literature acknowledges the benefits of renewable energy in combating climate change (Kotzebue and Weissenbacher 2020; Li et al. 2020; Qadir et al. 2021; Yuan et al. 2018). Several scholars draw comparisons between renewable energy and natural gas, highlighting the potential of renewable energy as a partial substitute for natural gas in driving the clean energy transition (Gursan and Gooyert 2021; Najm and Matsumoto 2020). But at the same time, many scholars such as Fatima et al. (2023) and Ashourian et al. (2013) argue that relying solely on renewable energy to achieve and foster energy transformation is unrealistic in many instances, especially for island countries. In addition, several studies confirm that the renewable-intensive energy system gives rise to new worries about access to metals. For example, studies by Valero et al. (2021) and Franks et al. (2023) emphasize that minerals and metals are important in the clean energy transition and Sustainable Development Goals (SDGs), while Månberger and Johansson (2019), He et al. (2020), and Su et al. (2021) point out that there are geopolitical risks in the world's metal production, which makes renewable energy incompatible with energy security. Hache (2018) also warns that expanding the usage of renewable energy will cause new metal interdependencies between countries in the long run. Meanwhile, multiple studies demonstrate that nuclear energy can play a substantial role in reducing emissions and stimulating environmental sustainability, indicating compatibility with the SDGs (Azam et al. 2021; Khan et al. 2022; Lau et al. 2019; Ozcan et al. 2021). At the same time, Lou and Gandy (2019), Zhan et al. (2021), Koyanagi et al. (2020), and Beylot et al. (2019) find that the need for crucial metallic resources, such as silicon and zinc, in the context of nuclear energy technology, does not raise significant concerns, reaffirming that there could be good arguments for developing nuclear energy capacity.

Although many studies have shown that renewable energy has energy security risks due to the high metal requirements, we have failed to identify studies that estimate the extent to which execution of the current EU energy plans will affect EU energy security through metal imports and bottleneck risks. And although many studies point to nuclear energy as possibly advantageous to renewable energy in terms of metal requirements, we have not found any studies that quantify the extent to which this could be true. While it is clear that construction of renewable energy capacity requires more metals compared to construction of nuclear energy capacity, this does not automatically imply higher metal imports or more significant metal-related bottleneck risks. Whether this is the case, and to what extent, depends on the type of metals required by the systems and how these requirements align with the EU's current and potential supply of metals. This entails not only the considerations of metal requirements per megawatt (MW) of new electricity production capacity, as found in IEA (2022), but also the maintenance requirements of energy technologies (the lifetime of the energy technologies), and considerations of the mineral resource and reserve availability, as well as the mining and processing capabilities in the EU. Naturally, the availability and diversity of import sources may also play a role.

Considering the above, this study sets out to investigate the compatibility of the 2050 EU planned energy system, and an alternative nuclear-intensive system, with mineral and energy security in the EU. Specifically, we aim to assess the impact of the current energy plan on future metal requirements, metal value requirements, metal imports, and associated bottleneck risks, considering the metal-intensive nature of renewable energy, EU metal consumption, and EU mineral and metal supply. Additionally, we aim to quantify the potential advantages of nuclear energy as an alternative to renewables, given its lower metal requirements per unit of power generation and its potential to enhance energy security through lower metal import requirements. To achieve our objectives, we construct two future scenarios: a renewable-intensive scenario, aligned with the current EU plans, and a nuclear-intensive scenario. Next, we present and employ a calculation framework that incorporates data from various sources to conduct a comprehensive comparative study of the two scenarios. Overall, we hope to contribute to the existing literature by providing insights of high contemporary relevance to ongoing public debates, as well as policy- and decision-making.

The "Materials and methods" section presents the calculation framework, which encompasses the scenarios, equations, and data sources, including assumptions made. The "Results" section outlines the results, focusing on metal requirements in terms of volume and value, metal imports in terms of quantity and share, and the bottleneck issues associated with renewable- and nuclear-intensive electricity mixes. The "Sensitivity analysis" section conducts a sensitivity analysis, while the "Discussion" section offers discussions and provides possible avenues for future researchers. The "Conclusion" section concludes.

Materials and methods

We compare two future electricity mix scenarios: a renewable-intensive electricity mix and a nuclear-intensive electricity mix. The renewable-intensive scenario aligns with the EU's current 2050 plan, which aims for an 80% share of renewable power generation while reducing the proportions of nuclear and natural gas power generation to 15% and 5%, respectively, by 2050. The nuclear-intensive electricity mix is an alternative constructed for this study. This scenario maintains the proportion of renewable power generation at the 2020 level over the next 30 years and increases the proportion of nuclear power generation, while reducing the proportion of natural gas power generation to 5%.

Figure 1 provides an overview of the calculation framework. The framework uses the 2020 EU electricity mix, and the 2020 EU renewable, natural gas, and nuclear electricity production capacity, as a starting point. Next, the framework estimates the target electricity production for 2050 based on the 2050 targets for the electricity mix and the 30-year average annual growth rate of electricity consumption. The framework then simulates the electricity production capacity for three types of clean energy (renewable energy, nuclear energy, and natural gas) throughout the period 2021 to 2050, assuming linear target-seeking behavior and that alternative energy sources are gradually phased out. It is important to note that while the carbon dioxide emissions from natural gas usage are higher than those from renewable energy sources such as wind and solar, they are significantly lower than the emissions from coal and oil usage. Thus, this paper categorizes natural gas—a relatively clean source—as clean energy.

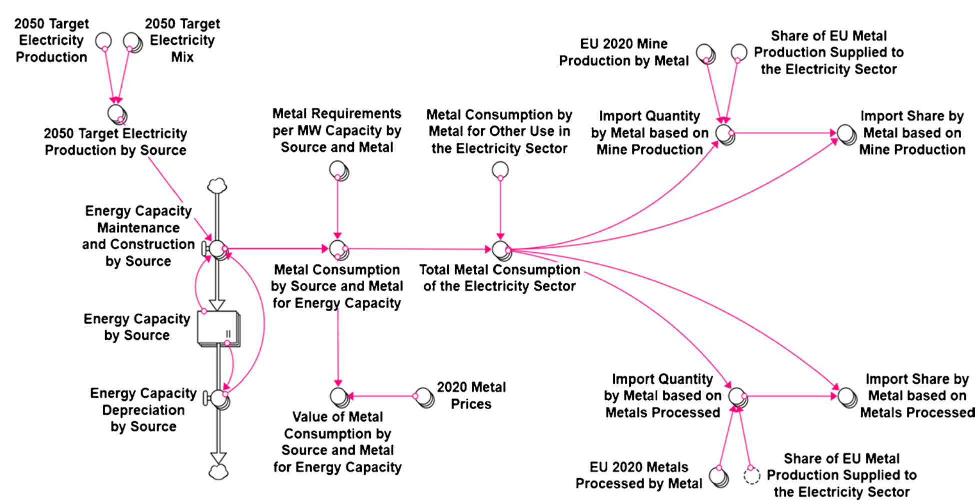
The subsequent calculation process, following the above initial data calculations, can be broken down into three distinct steps. Each of these steps yields one of the three primary results of this study. First, the framework calculates the EU metal requirements to cover for depreciation and construct new capacity (for the electricity production section of the EU electricity sector), considering the average lifetime of the various energy technologies as well as their construction requirements.

Second, the value of the metal requirements for the electricity production section is then determined as the product of the volume requirements and the 2020 unit prices of each metal, assuming for simplicity that these prices remain stable throughout the time horizon.

Third, we calculate the EU metal import requirements. To do so, we address the metal requirements of the entire EU electricity sector, as opposed to only the electricity production section. The reason for this is that the EU metal supply and import data is available for the sector as a whole, and not for the energy production section alone. In relation to this calculation, we assume the EU electricity sector's consumption of metals for purposes other than maintenance and additional production capacity remains unchanged at 2020 levels. The required metal imports, both in terms of quantity and share, are then calculated based on the total metal consumption of the entire EU electricity sector and data on the EU's metal supply for the electricity sector. In addition, two perspectives are considered regarding EU metal supply, i.e., EU metal supply based on mining and EU metal supply based on processing, to further figure out potential bottlenecks. It is assumed that the EU's metal supply for the electricity sector, based on both mining and processing production, will remain constant at 2020 levels for the next 30 years.

In the main analysis, we employ a series of conservative assumptions, as outlined above. For example, we assume the future growth rate of EU's total electricity consumption, future metal prices, future EU metal supply for the electricity sector, and future EU electricity consumption of other sections of the electricity sector beyond electricity capacity maintenance and increase remains constant at 2020 levels. Thus, we will also

Fig. 1 Calculation framework



conduct selected sensitivity analyses where we change some of these assumptions and discuss the implications.

Calculation of metal volume requirements for the EU electricity production section

The EU metal requirements in terms of volume, in the electricity production section of the electricity sector, for maintaining and increasing electricity production capacity, are calculated as follows:

$$Vol_{req_{m,t}} = Vol_{maint m,t} + Vol_{incr m,t} \tag{1}$$

In this notation, $Vol\_req_{m,t}$ is EU's total metal requirements in terms of volume in year t for metal m. $Vol\_maint_{m,t}$ is the volume-based metal requirements in the EU for maintaining existing capacity in year t for metal m. $Vol\_incr_{m,t}$ is the volume-based metal requirements in the EU for increasing capacity from year $t-1$ to year t for metal m. The time period t spans from 2021 to 2050. The index of metal type, i.e., m, encompasses seven kinds of metals: copper, zinc, silicon, manganese, rare earths, chromium, and nickel. These specific metals were chosen based on the 2022 IEA report, which highlights that renewable energy production technologies primarily rely on five key metals: copper, zinc, silicon, manganese, and rare earths, while nuclear technologies primarily depend on three metals, namely, copper, chromium, and nickel. Although metals like lithium and aluminum play significant roles in the electricity sector, their primary applications are in transmission and storage, rather than electricity production. However, considering that this paper primarily focuses on electricity production capacity, our analysis centers on the seven metals most relevant in this context and excludes the remaining.

The metal requirements for maintenance in the EU in terms of volume are calculated as follows:

$$Vol\_maint_{m,t} = \sum_{r=1}^{R=3} (Cap_{r,t} \times d_r \times Unit_{r,m}) \tag{2}$$

In this notation, r denotes the type of clean energy resources, namely, renewable, nuclear, and natural gas. $Cap_{r,t}$ is the power generation capacity in the EU from energy r in year t, which is calculated by Eq. 3. d_r is the annual depreciation rate for energy r, as specified in Table 1. $Unit_{r,m}$ is the metal requirements for metal m per unit of power generation from energy r, as presented in Table 2. It should be noted that the values for renewable energy in Tables 1 and 2 are weighted averages of the five main types of renewable energy. The ratios for each type are as follows: offshore wind 0.25, onshore wind 0.37, solar 0.24, hydro 0.00, and biomass 0.14. These ratios are estimated based on the energy developing expectations outlined in the European Commission (2018).

We assume that future electricity consumption in the EU will follow the same growth rate as observed over the past 30 years, which is 0.00766. Taking 2020 as the baseline year, we calculate the EU's annual electricity generation from each energy resource as follows:

$$\begin{aligned} Cap_{r,t} = & (Cap_{2020} \times (1+\gamma)^{(t-2020)}) \times TF_r \\ & \times (s_{r,2020} + \frac{(s_{r,2050} - s_{r,2020})}{30} \times (t-2020)) \end{aligned} \tag{3}$$

where Cap_{2020} is the total electricity consumption in the EU in 2020, and γ is the EU's annual growth rate of electricity consumption in the future. $s_{r,2020}$ and $s_{r,2050}$ are the power generation shares in the EU from energy r in 2020 and 2050. TF_r is the transition factor for energy r to transfer the unit of capacity from MWh to MW to make it consistent with the unit of $Unit_{r,m}$, which is kg/MW, as shown in Table 3.

The second part of the total EU volume-based metal requirements, i.e., the volume-based metal requirements in the EU for increasing electricity capacity from the previous year to the current year, is calculated as follows:

$$Vol\_incr_{m,t} = \sum_{r=1}^{R=3} ((Cap_{r,t} - Cap_{r,t-1}) \times Unit_{r,m} \times Incr_r) \tag{4}$$

Table 1 Depreciation rate for different energy sources (Data source: Statista (2020))

	Renewable	Nuclear	Natural gas
Lifetime (years)	24	30	28
Depreciation rate	4.24%	3.33%	3.57%

Table 2 Metal requirements per unit of power generation (kg/MW) (Data source: IEA (2022))

	Renewable	Nuclear	Natural gas
Copper	3718	1473	1100
Nickel	208	1297	16
Manganese	482	148	0
Chromium	303	2190	48
Zinc	3392	0	0
Rare earths	51	0.5	0
Silicon	949	0	0

Table 3 Transition factor from MWh to MW (Data source: Statista (2021))

	Renewable	Nuclear	Natural gas
Capacity factor	0.33	0.92	0.55
Transition factor	2859.63	8059.20	4818.00

In this notation, $Incr_r$ is a dummy variable to represent whether the capacity in 2050 is higher than 2020. If the electricity capacity for energy r increases from 2020 to 2050, the value of this variable is equal to 1, or else is 0.

Calculation of metal value requirements for the EU electricity production section

The following equation represents the value-based metal requirements in the EU electricity production section (for maintaining and increasing electricity production capacity).

$$Val\_req_{m,t} = Vol\_req_{m,t} \times P_m \tag{5}$$

In this notation, $Val\_req_{m,t}$ is the value-based metal requirements in the EU for metal m in year t. P_m is the unit price of metal m, as specified in Table 4. It is worth noting that the price of rare earths represents the average price of all the major rare earth elements. This choice is due to the availability of other pertinent data. Despite the variations in prices among different elements, this paper considers it feasible to employ an averaging method.

Table 4 Unit price of metals (Data source: Daily Metal Prices (2022))

Metal	Unit price of metals (euros/tonne)
Copper	7576
Nickel	20,328
Manganese	1894
Chromium	11,452
Zinc	2685
Rare earths	22,270
Silicon	8841

Calculation of metal import requirements for the entire EU electricity sector

The calculation for metal imports, both in terms of quantity and share, for the entire EU electricity sector (including electricity production and other sections such as transmission and storage) is as follows:

$$Import\_q_{m,t} = Vol\_req_{m,t} + Vol\_other_m - S_{m,l} \tag{6}$$

$$Import\_share_{m,t} = \frac{Vol\_req_{m,t} + Vol\_other_m - S_{m,l}}{Vol\_req_{m,t} + Vol\_other_m} \tag{7}$$

where $Import\_q_{m,t}$ and $Import\_share_{m,t}$ are EU's import quantity and share in the electricity sector for metal m in year t. Vol_other_m is the metal consumption for other sections in the whole electricity sector other than the electricity production section in the EU, as shown in Table 5. We assume that the metal consumption in other sections in the future will keep constant at the 2020 level. Thus, the sum $Vol\_req_{m,t} + Vol\_other_m$ is the total metal consumption in the whole electricity sector in the EU. Again, the reason we calculate the metal consumption for the whole electricity sector instead of the electricity production section like the previous equations is because the metal supply data is only available for the whole electricity sector. $S_{m,l}$ is the EU's supply of metal m for the whole electricity sector in 2020, with l represents two links in metal production, namely, metal mining and metal processing. We assume that the metal supply in the EU electricity sector in the future by 2050 will also keep constant at the 2020 level. The data for the metal supply in the EU in terms of mining and processing is from USGS and the World Bank (2022), as shown in Table 5.

Table 5 EU's supply and consumption of different metals in 2020 (thousand tonnes) (Data source: USGS (2022), World Bank (2022))

Metal	EU metal supply based on mining	EU metal supply based on processing	EU metal consumption in the whole electricity sector	EU metal consumption for electricity transmission, storage, and other purposes, excluding consumption for electricity production capacity
Copper	150.77	557.11	2172.49	2047.39
Nickel	7.65	9.36	321.70	311.06
Manganese	112.63	212.56	1462.73	1447.23
Chromium	72.56	0.02	399.18	382.66
Zinc	117.17	368.81	1643.27	1537.57
Rare earths	0.005	0.01	459.83	458.25
Silicon	0.21	0.23	40.68	11.10

Results

This section outlines the comparative results for the two scenarios from three aspects. First, we present the EU's volume-based metal requirements. In relation to this, we focus on three comparisons: the amounts of metals needed to maintain existing electricity production capacity versus increasing the electricity production capacity to the desired levels, the amounts of required metals in the renewable-intensive system versus the nuclear-intensive system, and past versus future volume-based total metal requirements. The historical raw data comes from Eurostat (2022). Second, we showcase the value-based metal requirements in the EU for the currently planned renewable-intensive electricity mix and the alternative nuclear-intensive electricity mix. Finally, we present the estimated import shares and quantities for each metal based on EU mine production and EU processing, respectively. Overall, we expect our findings to add useful insights to the contemporary debate on EU mineral and energy security.

Metal volume requirements for the EU electricity production section

Figure 2 displays the results from the calculation of the volume-based metal requirements in the EU for the electricity production section. The results provide three key insights. First, the EU's total metal requirements for the renewable-intensive electricity mix are significantly greater than those for the nuclear-intensive electricity mix. In 2050, EU's total amount of metals required for the renewable-intensive electricity mix is 624 thousand tonnes, while that for the nuclear-intensive electricity mix is 286 thousand tonnes. This outcome is in line with the information presented in the IEA report, highlighting the higher unit requirements for most metals in renewable energy compared to nuclear energy. However, we also offer further insight from a maintenance perspective, as demonstrated below.

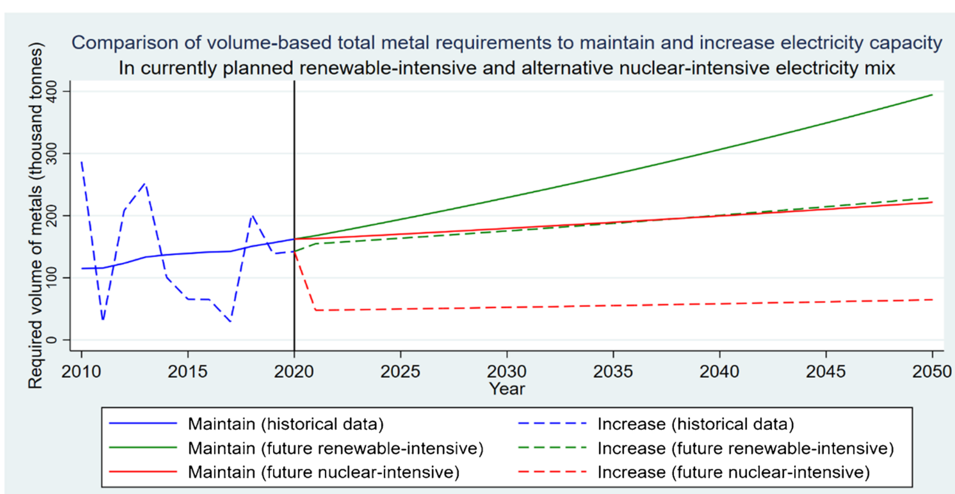
Secondly, the results indicate that over the next 30 years, EU's volume-based metal requirements for both electricity mixes, in order to offset depreciation and maintain existing capacity, are considerably higher than the requirements for annual capacity expansion. For example, the amounts of metals used for maintenance in the renewable-intensive and nuclear-intensive electricity mix in the EU in 2050 are 395 and 222 thousand tonnes, respectively, while those for construction of new capacity are 229 and 65 thousand tonnes, respectively. This is because as the capacity expands, there is a corresponding increase in the amount of capacity that must be replaced each year to ensure the continuous operation of that capacity.

Third, based on the comparison of historical data and future projections, the results show that the annual growth trend of EU's volume-based metal requirements for the planned renewable-intensive electricity system will be slightly steeper in the next 30 years compared to the past 10 years. Meanwhile, the results show that the incorporation of a nuclear-intensive electricity mix could play a vital role in mitigating the future annual growth rate of metal requirements for the EU.

Metal value requirements for the EU electricity production section

The results presented in the previous section focus on the analysis of future metal requirements for EU's two electricity system scenarios in terms of quantity. However, it is crucial to consider that the unit prices of primary metals used in renewable energy tend to be lower than those used in nuclear energy. To illustrate, in 2020, zinc and manganese were priced at 2.7 and 1.9 thousand euros per tonne,

Fig. 2 Comparison of volume-based metal requirements in the EU for electricity production section (to maintain and increase the electricity capacity)



respectively, while chromium and nickel were priced at 11 and 20 thousand euros per tonne. However, rare earths are an exception with a price as high as 22 thousand euros per tonne. Such differences in prices can significantly influence the overall results when evaluating the value aspect of metal requirements for each system. As such, it is crucial to consider the unit prices of metals when assessing the implications in terms of value.

Figure 3 indicates that the value-based metal requirements in the EU for the electricity production section are significantly greater for the renewable-intensive electricity mix compared to the nuclear-intensive electricity mix. For example, the renewable-intensive electricity mix has 42% higher total value-based metal requirements in 2050 compared to the nuclear-intensive electricity mix. This observation highlights that while the unit price of the main metals required for nuclear technologies may be comparatively higher than those for renewable energy technologies, it does not undermine the previous finding that the nuclear-intensive electricity mix surpasses the renewable-intensive electricity mix in terms of metal requirements.

The comparison for different metals in Figs. 4 and 5 provides more detailed insights. First, over the next 30 years, regardless of whether the EU adopts a renewable-intensive or nuclear-intensive electricity mix, there will be an increase in the metal requirements for all seven metals regarding both volume and value. Second, the renewable-intensive electricity mix is estimated to require 57%, 66%, 59%, 65%, and 66% more copper, zinc, manganese, silicon, and rare earths, respectively, than the nuclear-intensive alternative in 2050. Conversely, the nuclear-intensive

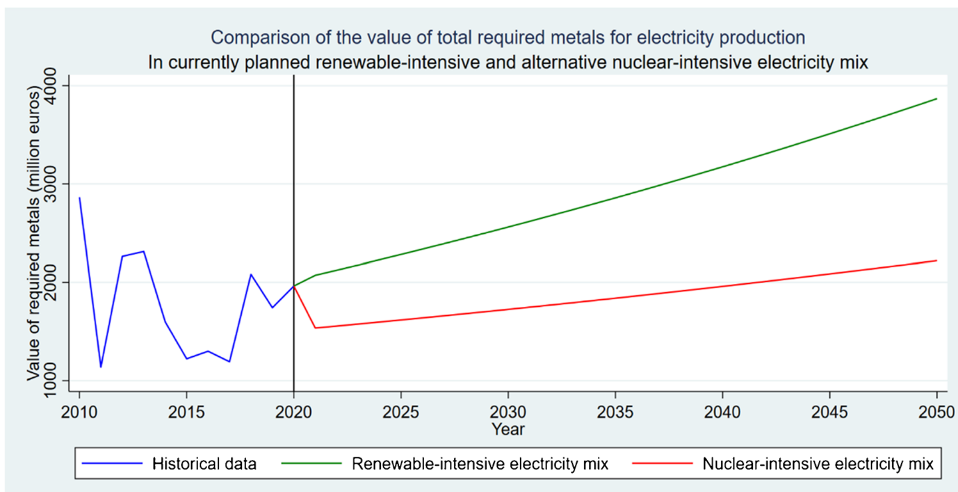


Fig. 3 Comparison of value-based total metal requirements in the EU for electricity production section (to maintain and increase the electricity capacity)

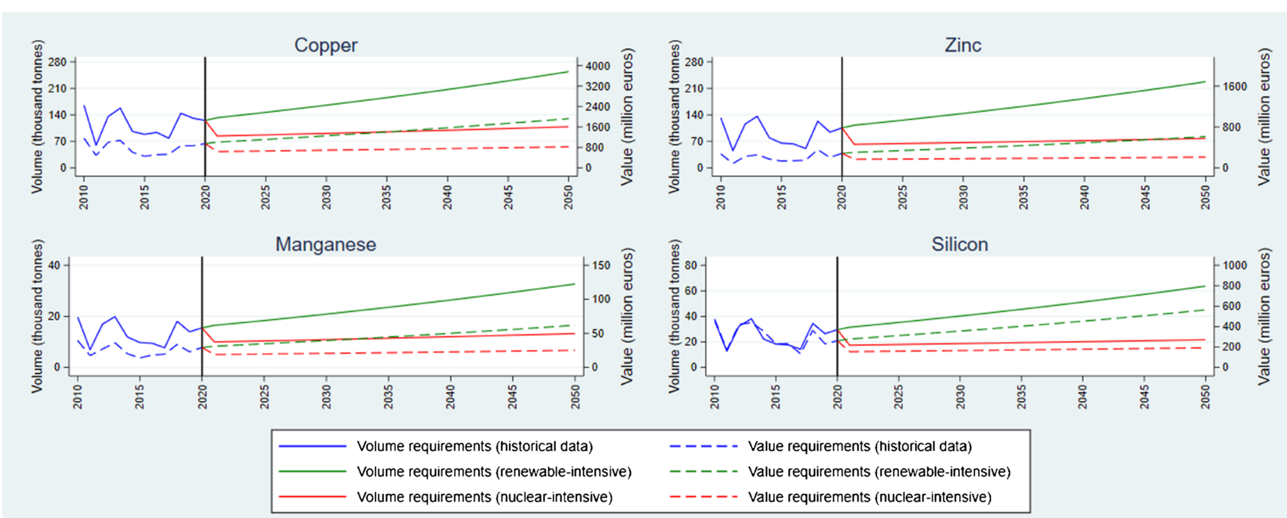


Fig. 4 Total volume-based and value-based metal requirements in the EU for electricity production section (to maintain and increase the electricity capacity) of copper, zinc, manganese, and silicon

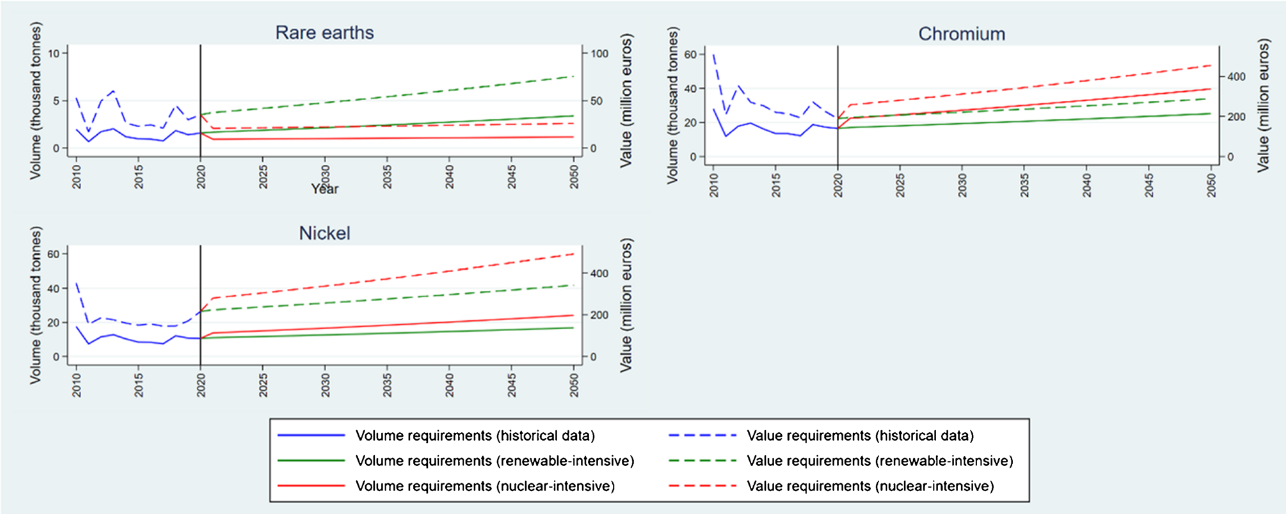


Fig. 5 Total volume-based and value-based metal requirements in the EU for electricity production section (to maintain and increase the electricity capacity) of rare earths, chromium, and nickel

electricity alternative is estimated to require 58% and 43% greater expenditure of chromium and nickel in 2050.

Metal import requirements for the entire EU electricity sector

The previous two sections analyze renewable-intensive and nuclear-intensive electricity mixes in the EU from the perspective of metal requirements, but how much of these metal requirements needs to be imported and how much can rely on EU self-sufficiency is a more important question that can affect energy security issue. If the EU's production of metals primarily required by renewable energy is substantial, while the production of metals primarily needed by nuclear energy is limited, it could potentially overturn the previous findings that indicate the superiority of the nuclear-intensive electricity mix in terms of metal security. This is because despite the renewable-intensive electricity mix has larger metal requirements, its import requirements for metals could be comparatively smaller. Therefore, there is a need to further explore the EU's metal security of the two electricity mixes at the import level. This section will present the different import requirements of the seven primary metals necessary for renewable and nuclear energy technologies under different electricity mixes, considering both the share and quantity. It is important to note again that while the previous sections only consider requirements for electricity production capacity, the results presented in this section encompass metal imports for the entire electricity sector, assuming that metal consumption in other sections, apart from the electricity production section, remains constant at 2020 levels.

In general, the findings presented in Figs. 6, 7, 8, 9, 10, 11, and 12 demonstrate that the total import quantities for the electricity sector in the renewable-intensive electricity mix in the EU are greater than those in the nuclear-intensive electricity mix. To illustrate, EU's total import amounts of all seven metals when considering metal mining and processing production as metal supply in the renewable-intensive electricity mix in 2050 are 6358 thousand tonnes (including 2151 thousand tonnes of copper, 1648 thousand tonnes of zinc, 75 thousand tonnes of silicon, 1367 thousand tonnes of manganese, 462 thousand tonnes of rare earths, 335 thousand tonnes of chromium, and 320 thousand tonnes of nickel) and 5671 thousand tonnes (including 1744 thousand tonnes of copper, 1396 thousand tonnes of zinc, 75 thousand tonnes of silicon, 1267 thousand tonnes of manganese, 462 thousand tonnes of rare earths, 408 thousand tonnes of chromium, and 319 thousand tonnes of nickel), respectively, whereas those in the nuclear-intensive electricity mix are 6020 thousand tonnes (including 2005 thousand tonnes of copper, 1498 thousand tonnes of zinc, 33 thousand tonnes of silicon, 1348 thousand tonnes of manganese, 458 thousand tonnes of rare earths, 350 thousand tonnes of chromium, and 328 thousand tonnes of nickel) and 5333 thousand tonnes (including 1599 thousand tonnes of copper, 1246 thousand tonnes of zinc, 33 thousand tonnes of silicon, 1248 thousand tonnes of manganese, 459 thousand tonnes of rare earths, 422 thousand tonnes of chromium, and 326 thousand tonnes of nickel), respectively. This indicates that the previous result suggesting that the nuclear-intensive electricity mix outperforms the renewable-intensive electricity mix in the EU in terms of metal requirements is still valid after considering metal imports.

Specifically, the quantities of copper, zinc, manganese, silicon, and rare earths that need to be imported for the renewable-intensive electricity mix are considerably higher

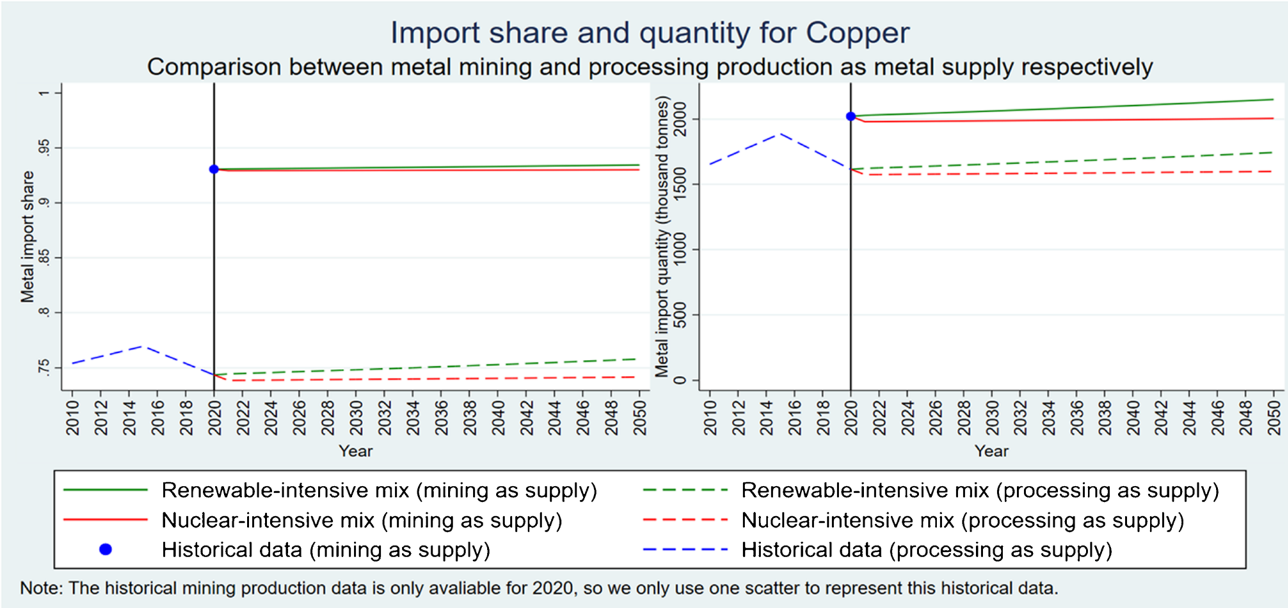


Fig. 6 EU's metal imports in terms of share and quantity for copper in the whole electricity sector

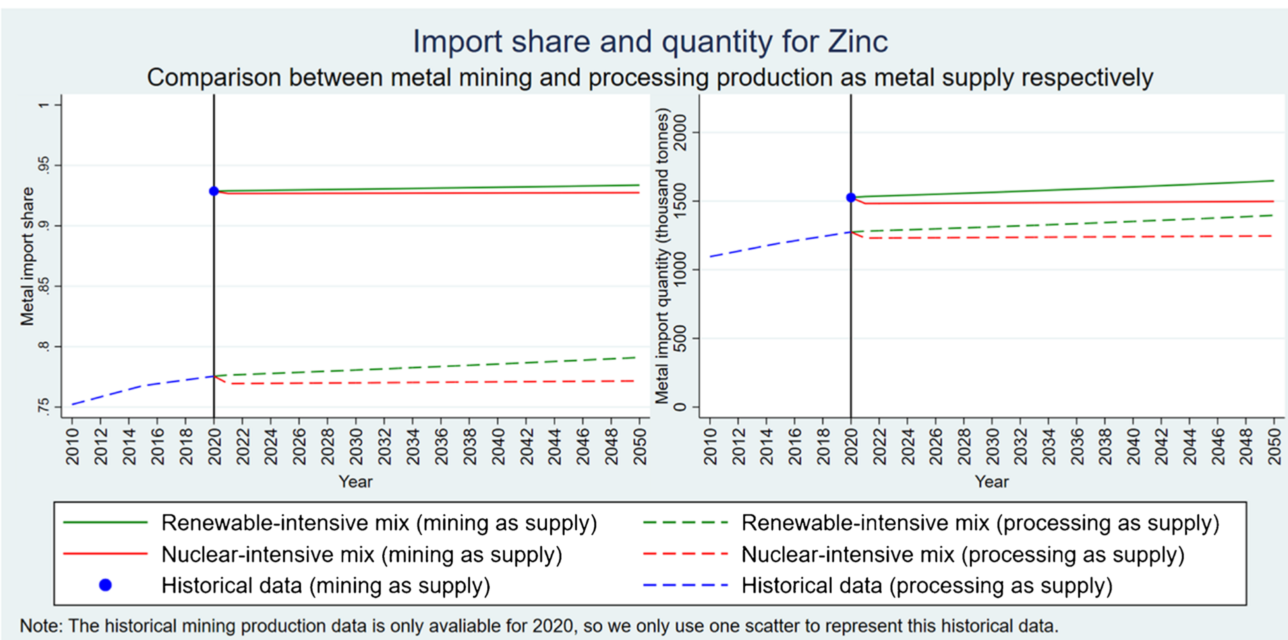


Fig. 7 EU's metal imports in terms of share and quantity for zinc in the whole electricity sector

compared to that required for the nuclear-intensive system. Conversely, the nuclear-intensive electricity mix necessitates higher import amounts of chromium and nickel in comparison to the renewable-intensive electricity mix. We will provide a detailed description of the import characteristics for each metal below.

Three metals, namely, copper, zinc, and manganese, which require more imports in the renewable-intensive electricity mix than in the nuclear-intensive electricity mix, possess similar properties. (Figs. 6, 7 and 8). These three metals share two main attributes. First, the calculation of metal imports in the EU using mining and processing production as metal supply respectively yields significantly divergent results. For example, the import share in the renewable-intensive electricity mix in 2050 based on mining is 19%, 15%, and 7% higher than the import share based

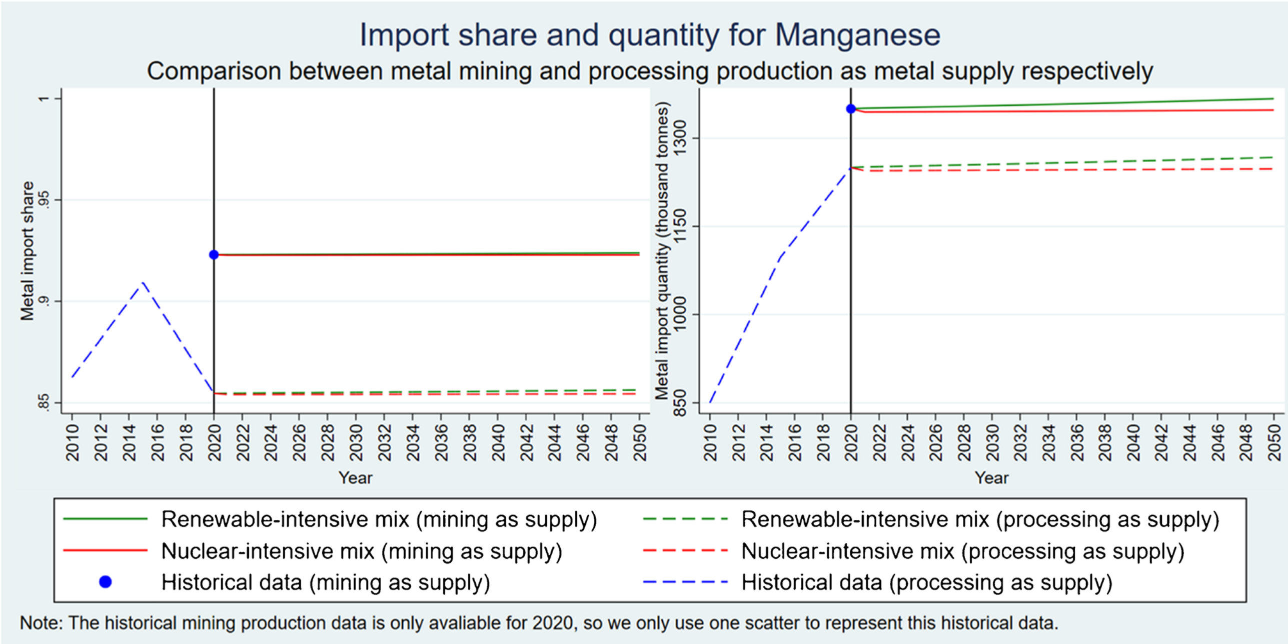


Fig. 8 EU's metal imports in terms of share and quantity for manganese in the whole electricity sector

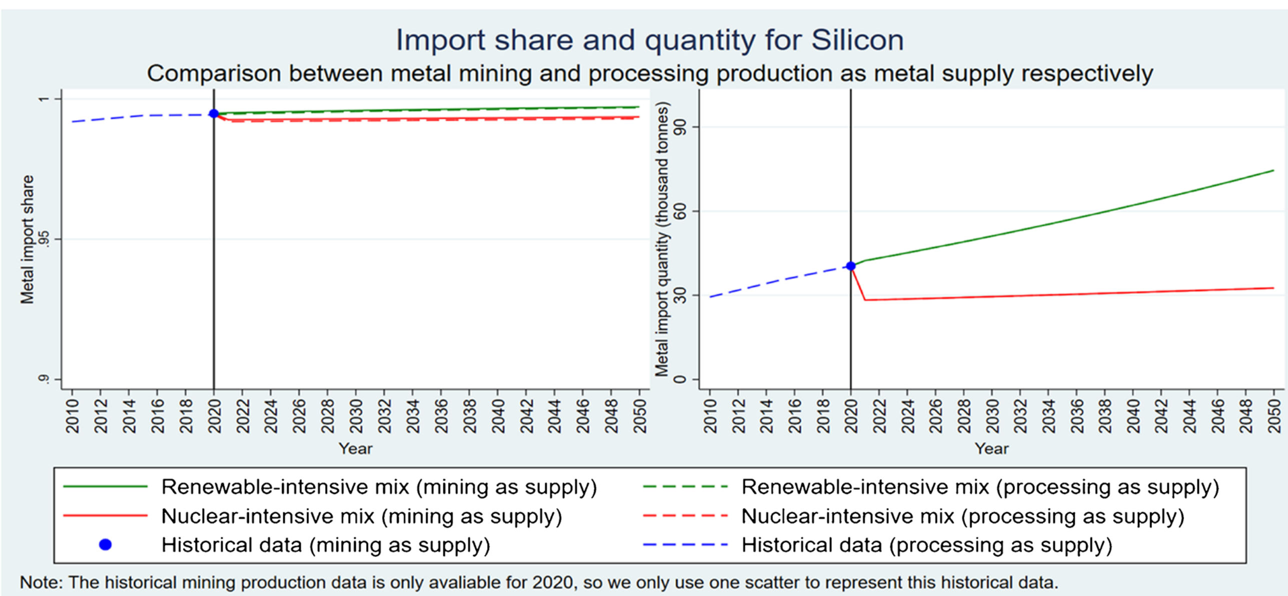


Fig. 9 EU's metal imports in terms of share and quantity for silicon in the whole electricity sector

on processing for copper, zinc, and manganese, respectively. This is because the excavation of these three metals in the EU is small, but there are many processing plants. For example, the EU imported about 400, 252, and 100 thousand tonnes of copper, zinc, and manganese ores in 2020 from other countries for processing and domestic use in electricity production section (USGS 2022). The fact that the external dependence of metal imports with processing production as metal supply is relatively small suggests that the import dependence issue for these three metals crucially lies in the mining phase of metal production rather than the processing phase. Second, despite these three metals having a relatively small import share among all metal types (i.e., about 75%), their import requirements in terms of quantity are the highest

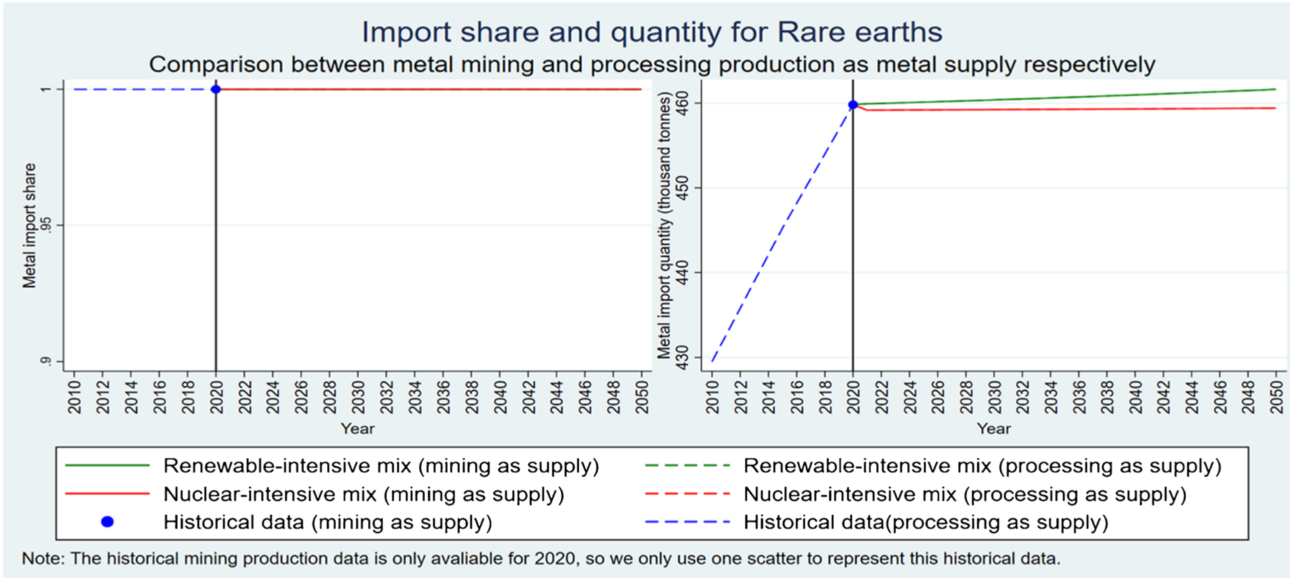


Fig. 10 EU's metal imports in terms of share and quantity for rare earths in the whole electricity sector

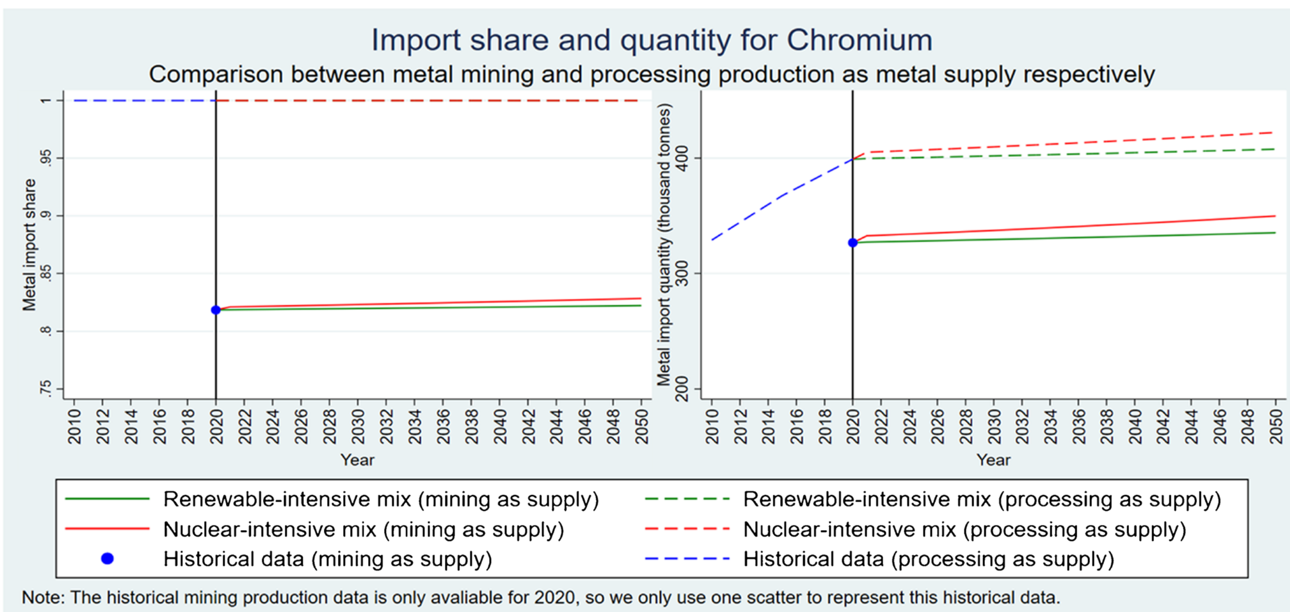


Fig. 11 EU's metal imports in terms of share and quantity for chromium in the whole electricity sector

(i.e., about 1500 thousand tonnes). This indicates that the import security risks associated with these three metals are still comparatively elevated.

The import performance of the other two main metals required by renewable energy, silicon and rare earths, differs significantly from the three metals in three distinct ways (Figs. 9 and 10). First, there is minimal disparity between the mining and processing volumes of these two metals in the EU, resulting in similar metal imports regardless of whether mining or processing production is considered as the metal supply. Second, the production of these two metals in the EU is small, so their demand in the EU heavily relies on imports. Consequently, the import share for these two metals consistently exceeds 99% across various electricity mixes. Third, the unit requirements of these two metals in renewable and nuclear energy technology

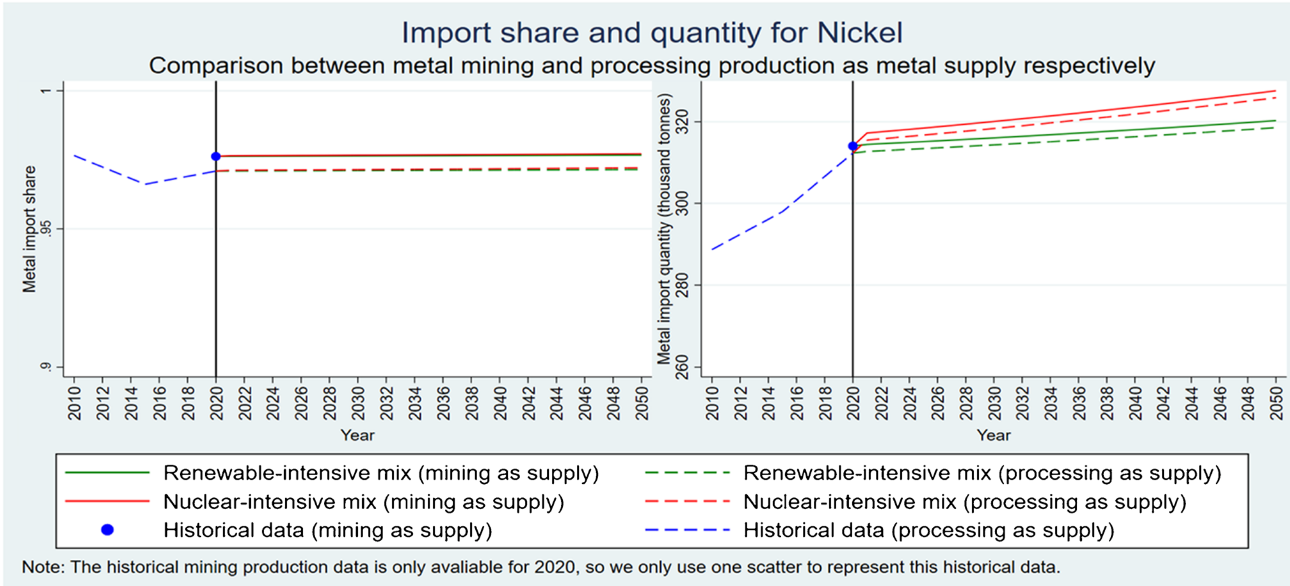


Fig. 12 EU's metal imports in terms of share and quantity for nickel in the whole electricity sector

are relatively low compared to other metals, so the actual amount of imports is small compared to the previous three metals even though their import shares are high. The import quantity required for these two metals remains below 500 thousand tonnes throughout the analysis period. It is worth noting that rare earths hold a unique status, given that its production exhibits the most pronounced geographical concentration among all metals. The fact that China accounts for 60% of rare earths mining and 90% of its processing (IEA 2022) makes its import risk more significant.

Figures 11 and 12 present the import analysis results of two major metals required more in the nuclear-intensive electricity mix, i.e., chromium and nickel. The findings demonstrate that the import requirements, both in terms of share and volume, for these two metals are higher in the nuclear-intensive electricity mix compared to the renewable-intensive electricity mix (e.g., chromium and nickel in nuclear-intensive electricity mix are 3% and 2% higher than those in the renewable-intensive electricity mix in 2050). However, chromium exhibits a feature that distinguishes it from all other metals. That is, the EU has a substantial chromium mining capacity (with 99.6% from Finland (Euromines 2022)), but lacks sufficient processing capabilities. Consequently, the import share of chromium calculated using mining volume as the metal supply stands at approximately 80%, while the import share calculated using processing volume as the metal supply approaches 100%. This suggests that the main root of chromium's import dependence problem lies in the processing stage of metal production. Furthermore, although the import shares of chromium and nickel are not low, the actual import quantities required are small, both around 400 thousand tonnes.

Sensitivity analysis

Sensitivity analysis is important, as our calculations rely on assumptions about the future which are uncertain. In this section, we will concentrate on assessing the influence of different changes in the EU's future electricity consumption and metal supply on the comparative results of renewable- and nuclear-intensive electricity mixes.

First, this study assumes that the change in electricity consumption in the EU over the next 30 years will maintain the average growth rate over the past 30 years (which is 0.00766). However, with technological advancements and increased awareness of environmental protection, future electricity consumption may be decreased. It also has the probability to be increased at a faster pace due to greater economic activities. These varying trends of electricity consumption in the future will inevitably impact the comparison results. To account for this, we conduct sensitivity analysis by alternatively increasing the future annual electricity consumption growth rate to 0.01 and reducing it to 0. Table 6 shows the comparison results of EU's metal quantity requirements, metal value requirements, and metal import requirements of all metals between renewable-intensive electricity mix and nuclear-intensive electricity mix in 2050 under different annual electricity consumption growth rates.

The results indicate that if future electricity consumption grows faster than assumed in this study, the metal security

Table 6 EU's metal requirements and imports with different annual electricity consumption growth rates in 2050

Metal requirements and metal imports	Annual growth rate = 0		Annual growth rate = 0.00766		Annual growth rate = 0.01	
	Renewable-intensive	Nuclear-intensive	Renewable-intensive	Nuclear-intensive	Renewable-intensive	Nuclear-intensive
Volume requirements for the EU electricity production section (thousand tonnes)	442	195	624	286	690	320
Value requirements for the EU electricity production section (million euros)	2751	1517	3868	2220	4280	2481
Metal imports for the entire EU electricity sector (calculated using EU metal supply based on mining) (thousand tonnes)	6177	5929	6358	6020	6425	6055
Metal imports for the entire EU electricity sector (calculated using EU metal supply based on processing) (thousand tonnes)	5490	5242	5671	5333	5737	5367

concerns of the currently planned renewable-intensive electricity mix in the EU will be more significant than anticipated. This is evident from the fact that the gap in metal requirements and imports between the two electricity mixes is higher when the growth rate is 0.01 compared to 0.00766. That is, the concerns raised in the previous section regarding the renewable-intensive mix are underestimated. In contrast, if the future growth rate of electricity consumption slows down relative to the past, the advantages of the nuclear-intensive electricity mix in terms of metal security will not be as prominent as estimated in the previous section. However, the table also confirms that regardless of the varying trends in future electricity consumption, the conclusion from the previous section remains valid: the nuclear-intensive electricity mix consistently outperforms the renewable-intensive electricity mix in terms of energy security. This is because, within a reasonable range of changes in the growth rate of electricity consumption, the requirements for metals and imports of the nuclear-intensive electricity mix are always smaller than those of the renewable-intensive electricity mix.

Second, we assume that future metal prices will remain unchanged at 2020 levels. However, there are some reports, such as the ones from the IEA (2022) and Watari et al. (2021), suggesting that metal prices may rise in the future due to the strong demand expectations resulting from increased efforts by many governments to accelerate energy transitions. Therefore, it would be interesting to analyze the value-based metal requirements of the EU under the assumption of future metal price increases and compare these results with previous findings that assumed unchanged future metal prices.

As depicted in Fig. 13, under the assumption that the prices of various metals will increase at an annual growth rate of 5%, by 2050, the value of metals required for a renewable-intensive electricity mix in the EU will exceed that required for nuclear-intensive electricity mixes by 6785 million euros. This is a significant increase compared to the difference in value-based metal requirements between the two electricity mixes under the assumption of unchanged future metal prices, which stand at 1648 million euros. This suggests that future expectations of metal price increases

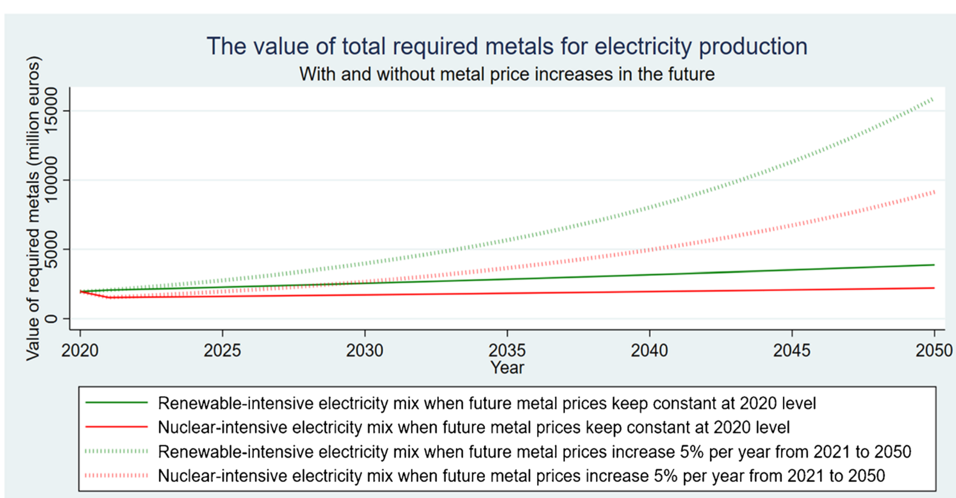


Fig. 13 Value-based metal requirements of total metals in the EU for electricity production (to maintain and increase the electricity capacity), with and without considering the increase of metal prices in the future

will further amplify the advantageous performance of a nuclear-intensive electricity mix in the EU in terms of value-based metal requirements.

Third, this study assumes that future EU metal supply for the electricity sector will remain constant at the 2020 level when analyzing metal imports. However, it is plausible that the EU will strive to enhance energy security by expanding its metal production in the future. We therefore alternatively expand future metal supply (both mining and processing production) to double its 2020 level and compare the outcomes with the results in the previous section. Table 7 is the comparison results of the total imports of all major metals under the assumptions of unchanged and increased future metal mining and processing volumes.

The findings demonstrate that while expanding metal production can reduce EU's import requirements, it does not alter the energy security comparison results between the renewable-intensive electricity mix and the nuclear-intensive electricity mix from the previous section. Because it is found that the metal import requirements of renewable-intensive electricity mix are still significantly higher than those of the nuclear-intensive electricity mix even with increased metal production. It is also interesting to find that expanding metal production has little effect on the gap in import requirements between the two electricity mixes. This is mainly because we have calculated imports assuming constant metal consumption in the electricity sector other than the electricity production section. The amount of metals required for the electricity production section is not significant in the entire electricity sector (Table 5 in the "Calculation of metal import requirements for the entire EU electricity sector" section). Therefore, it is reasonable to expect that the changes in the metal supply in the electricity production section would have an insignificant effect on the import requirements of the whole electricity sector.

Discussion

In this section, we compare the results of the renewable-intensive electricity mix obtained in this study with the findings from previous literature that examine the impact of renewable energy on energy security. Next, we shift the focus to the novel aspects that arise from the comparative analysis between the planned energy system and the alternative nuclear-intensive system. Finally, we point out the limitations of this study and provide avenues for future research.

Renewable metal requirements: our study vs. literature

Concerns in the literature about the energy security implications of renewables focus on two aspects. First, renewable energy generation technologies require large amounts of metals (Hache 2018; He et al. 2020; Månberger and Johansson 2019; Su et al. 2021). Second, there is a geographic concentration of major metals needed for renewable energy technologies across the globe (Franks et al. 2023; Valero et al. 2021). The findings of this study regarding the renewable-intensive electricity mix align with the existing literature. Taking the EU with limited metal production as an example, this study substantiates that the large-scale expansion of renewable energy utilization in the future will lead to an accelerated rise from 305 thousand tonnes (including 162 thousand tonnes for maintaining the existing electricity production capacity and 143 thousand tonnes for increasing the production capacity) in 2020 to 624 thousand tonnes (including 395 thousand tonnes for maintaining the existing electricity production capacity and 229 thousand tonnes for increasing the production capacity) in 2050 in volume-based metal requirements (see Fig. 2).

This study also provides a novel aspect by considering the depreciation of facilities. It reveals that as the existing renewable energy capacity expands, the future renewable-intensive electric mix in the EU will require high quantities of metal to keep the existing capacity compared to what would be required for increasing electricity production. This indicates that building additional renewable capacity will not only mean a short-term high need for metals, but also a long-term one for maintenance. The policy implication derived from this finding is that when the proportion of renewable energy power generation in the EU has already reached a significant level (37%), pursuing further expansion to an exceedingly high level (such as the currently planned 80%) may not be a favorable option considering the associated metal requirements.

Table 7 Metal imports for the whole electricity sector in the EU in 2050 excluding and including EU metal supply increase (thousand tonnes)

Metal imports for the entire EU electricity sector	EU metal supply based on mining will remain constant at 2020 level until 2050	EU metal supply based on mining will double the 2020 level by 2050	EU metal supply based on processing will remain constant at 2020 level until 2050	EU metal supply based on processing will double the 2020 level by 2050
Renewable-intensive	6358	5897	5671	4523
Nuclear-intensive	6020	5559	5333	4185

Renewable vs. nuclear metal requirements: comparative insights

There is no comparative study of renewable and nuclear energy regarding metal value requirements, metal imports, and bottlenecks in the literature, making it one of the main contributions of this study. Under the assumption of maintaining the existing power generation share of renewable energy and increasing the share of nuclear power generation, this study provides a nuclear-intensive electricity mix as an alternative to a renewable-intensive electricity mix and makes a comparison between the two. The comparative results provide three main insights and some policy implications for the EU.

First, this study considers the possibility that the low unit price of most metals required for renewable energy may lead to lower value-based metal requirements in the renewable-intensive electricity mix, thereby mitigating concerns over metal security associated with renewable energy expansion. However, the findings of this study contradict this assumption, as they demonstrate that the renewable-intensive electricity mix exhibits 42% higher value-based metal requirements compared to the nuclear-intensive electricity mix (see Fig. 3). Although the unit prices of different metals do not invalid the superiority of the nuclear-intensive electricity mix in terms of metal volume requirements, they do narrow the gap between two electricity mixes since the renewable-intensive electricity mix has 54% higher volume-based metal requirements compared to the nuclear-intensive electricity mix (see Fig. 2). Overall, in terms of requirement-based metal security considerations, the nuclear-intensive electricity mix outperforms the renewable-intensive electricity mix.

Secondly, in order to account for the possibility that the availability of different metals within the EU may impact the previous requirement-based comparative findings and potentially favor the renewable-intensive electricity mix over the nuclear-intensive electricity mix in terms of metal imports, we delve deeper into the analysis of metal import quantities and shares in the EU. The results indicate that the renewable-intensive electricity mix requires a greater total import quantity of all seven major metals for clean energy technologies compared to the nuclear-intensive electricity mix. Five metals (copper, zinc, manganese, silicon, and rare earths) have a higher share and volume of import in the renewable-intensive electricity mix than in the nuclear-intensive electricity mix. Only two metals, chromium and nickel, have greater import requirements in the nuclear-intensive electricity mix. Although the import share of copper, zinc, and manganese is relatively low, the actual required import quantity is substantial. In contrast, despite chromium and nickel having larger import shares, their import requirements are considerably lower than those of copper, zinc, and manganese.

Additionally, the supply security of metals mainly required by the two energy mixes also shows obvious differences. Metal producers essential for renewable energy are more concentrated, and their geopolitical relationship with the EU is relatively unstable. The global production distribution of copper and zinc is relatively dispersed, with the top three producing countries accounting for about 50% of total production in 2021 (Statista 2022a, b; Government of Canada 2022). However, the production volumes of silicon, manganese, and rare earths show strong geographical concentration. In 2022, China produces 82% of silicon (Statista 2023a, b). In 2021, South Africa produces 40% of manganese (Statista 2022a, b), and China mines and processes 60% and 82% of rare earths in 2019, respectively (IEA 2022). Thus, three out of the five metals primarily needed for renewable energy exhibit geographical concentration, with China playing a significant role. Given China's active implementation of its metal export restriction policy recently (Blakemore 2023), the EU's future metal imports from China warrant attention. Conversely, the metals mainly required for nuclear energy have a more global distribution. South Africa, Turkey, and Kazakhstan together account for 70% of the world's chromium production in 2022 (Statista 2023a, b), while Indonesia and the Philippines together contribute to 50% of global nickel production in 2019 (IEA 2022). For the EU, these countries can be considered as relatively secure and stable sources of supply, eliciting minimal concern. In summary, from a metal supply security perspective, the potential supply risks faced by a nuclear-intensive electricity mix are relatively smaller than a renewable-intensive electricity mix.

Third, the bottleneck problem of the renewable-intensive electricity mix in the EU is more significant than that of the nuclear-intensive electricity mix. The bottleneck problem of metals mainly required by renewable energy is related to the mining production, while the bottleneck problem of metals mainly required by nuclear energy technology lies in processing. Expanding the processing capacity is easier than increasing the mining volume. Expanding the processing capacity only involves building more processing plants. But increasing mining means more deposits need to be excavated, which not only needs more advanced technology but may cause hidden dangers such as destroying biodiversity. Therefore, from the perspective of the difficulty of solving the bottleneck problems, the potential of the nuclear-intensive electric mix outweighs that of the renewable-intensive electricity mix.

The takeaway from these contrasting perspectives of metal value requirements, metal imports, and bottlenecks is that the nuclear-intensive electricity mix performs better overall on metal safety than the renewable-intensive electricity mix in the EU. The renewable-intensive electricity mix currently planned by the EU is to continue to increase renewable energy capacity while phasing out existing nuclear power generation capacity. These two opposing processes result in wasted metal inputs. However, although the nuclear-intensive electricity mix in this study focuses primarily on nuclear energy, it is to increase the nuclear energy capacity without eliminating the existing renewable energy capacity but maintaining it at the current high level. Hence, the low metal requirements and imports associated with the nuclear-intensive electricity mix can be attributed not only to the lower unit demand for metals in nuclear energy but also to the reduction in metal consumption resulting from the decision to retain existing capacity rather than phasing it out. Essentially, the nuclear-intensive electricity mix can be seen as relying on both nuclear and renewable energy, while the currently planned renewable-intensive electricity mix relies solely on renewable energy. Therefore, the policy implication for EU governments is that utilizing both nuclear and renewable energy as the foundation for future clean energy transition is a better choice compared to solely replacing natural gas with renewable energy, regarding the consideration of energy security in terms of metals.

Avenues for future research

Through the modeling process, some limitations were imposed, and some aspects were excluded—some of which could represent opportunities for future research. First, the data on renewable energy in this study are the weighted average values obtained by mixing the five major renewable energy sources (offshore wind, onshore wind, solar, hydro, and biomass) according to their respective growth ratios. As explained in the "Calculation of metal volume requirements for the EU electricity production section" section, the ratios are estimated by the EU based on the existing capacity and development potential of various renewable energy types. The estimations are reasonable, but it is also important to note that the proportion of hydro is assumed to be zero in that mixing value. This stems from the fact that hydro power has limited expanding potential, given its already substantial current capacity, and it is not a focal point for future development. Nevertheless, as the only stable form of renewable energy, hydro power will always play a significant role. That is, hydro power capacity is also possible to increase in the future. Therefore, future researchers can utilize the calculation framework presented in this study to further investigate the impact on energy security if the EU pursues wind energy development while concurrently allowing hydro power generation capacity to increase in the future.

Second, this study assumes that metal consumption in the electricity sector except for the electricity production section (including maintaining and increasing electricity production capacity) will remain at the current level in the future. However, as the share of renewable energy in the energy mix grows in the EU, its intermittent nature implies an anticipated expansion in the grid's demand for transmission capacity and energy storage equipment. This suggests that the future may see an increase in metal requirements from sections in the electricity sector other than the electricity production section, particularly for transmission and storage of electricity. Thus, future research could investigate how this could impact the metal and import requirements and its implications for energy security.

Third, the metal supply discussed in this paper only considers new production quantities, including mining and processing, without considering the potential amount of recycling. Many obsolete devices contain metals that can be recycled. As a result, the metal supply in this paper may be somewhat underestimated. Additionally, the recycling potential varies among different metals. For example, according to Reuter et al. (2013), metals such as copper and silicon can be highly recycled (i.e., the potential recycling rates are 95% and 92%, respectively) due to the ease of collecting simple products for recycling, while the potential recycling rates of chromium and rare earths are as low as 37% and 5%, respectively. Despite the potential for recycling, the current global metal recycling rate remains modest at approximately 34%, primarily due to technical challenges in collecting waste materials (Rebecca et al., 2022). Future researchers can thus investigate the influence of the recycling capability of different metals on the comparative results of two electricity mixes in terms of metal security.

Lastly, an intriguing aspect related to this topic is the carbon emissions resulting from metal mining and excavation. While this falls outside the scope of this paper, we posit that it could be a viable direction for future research related to energy transition and metal requirements. Specifically, while renewable and nuclear energy sources emit significantly less carbon during use compared to non-clean energy sources like coal and oil, the production process of metals required for renewable and nuclear infrastructure construction also involves carbon dioxide emissions. Notably, the carbon emissions from the excavation process of some metals with low concentration or located deep underground cannot be overlooked (Ren et al. 2023). This introduces another question worth investigating: while this paper demonstrates that the EU's nuclear-intensive energy mix performs well from a metal safety perspective, does this conclusion still hold true when considering the environmental impact of carbon emissions?

Conclusion

In conclusion, this study presents a calculation framework to evaluate metal volume requirements, metal value requirements, and metal import requirements of electricity systems in the EU. By comparing the currently planned EU energy system with an alternative nuclear-intensive energy system, we aimed to determine which option offers greater energy security.

Our findings demonstrate that the renewable energy plan, due to its metal-intensive nature, will lead to an accelerated increase in the metal volume and metal value requirements in the electricity production section. Additionally, our results suggest that the execution of the current plan will result in a substantial rise in the metal import requirements. The results also show that increasing the share of renewables from 37 to 80% will result in maintenance requirements that exceed the requirements of constructing additional capacity in the future, indicating a significant long-term dependence on metals, which could potentially pose a serious security risk.

The alternative nuclear-intensive mix, comprising 37% renewables and 58% nuclear power by 2050, offers several advantages over the renewable-intensive mix. Firstly, it has lower metal volume requirements, meaning that it requires less metals for construction and maintenance. Additionally, the nuclear-intensive mix also has lower metal value requirements than the planned renewable system, despite the higher unit price of metals used in nuclear energy technology. This indicates that the overall cost of future metal requirements for the nuclear-intensive electricity mix is lower compared to the renewable-intensive mix. Moreover, the nuclear-intensive mix demonstrates lower metal import shares and quantities. This means that it relies less on importing metals from external sources, enhancing energy security and reducing dependence on foreign metal supplies. Furthermore, the nuclear-intensive mix benefits from a more solvable bottleneck problem regarding metal supply. The primary bottleneck for this mix lies in insufficient metal processing capacity, which can be addressed through targeted infrastructure development. On the other hand, the renewable-intensive mix faces a bottleneck due to inadequate metal mining, which presents a more challenging obstacle to overcome. These factors collectively suggest that the future development potential of the nuclear-intensive electricity mix is greater than that of the renewable-intensive mix, offering a more viable and sustainable solution for the EU's energy system.

In summary, these findings indicate that EU governments should consider implementing a nuclear-intensive electricity mix that combines renewable and nuclear energy, instead of relying excessively on renewable energy alone. Such an approach would enable a better balance between clean energy transition and energy security in the future. However, it is essential to note that the conclusions and policy implications of this study solely consider energy security in terms of metals. National energy policies should take into account a more comprehensive range of factors, including public perception, as nuclear energy may face challenges in other aspects. Therefore, the suggestion in this study that a nuclear-intensive electricity mix is preferable can only serve as a reference for EU governments based on energy security regarding metal requirements and imports, rather than a definitive recommendation.

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Declarations

Conflict of interest The authors declare no competing interests.

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