# Energy and Mineral Security in the European Union: Metal Requirements for Renewable and Nuclear Intensive Electricity Mixes

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DISCUSSION PAPER

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# ENERGY AND MINERAL SECURITY IN THE EUROPEAN UNION: METAL REQUIREMENTS FOR RENEWABLE AND NUCLEAR INTENSIVE ELECTRICITY MIXES

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**ABSTRACT**

In 2022, the EU finds itself in the midst of an energy crisis due to the outbreak of the war between Russia and Ukraine and has to accelerate its path to energy independence. Part of the EU's strategy is to double down on the transition to a renewable-intensive energy system. However, this has raised concerns about whether the EU risks swapping one type of energy dependence for another, namely fuel import dependence for metal import dependence. This paper investigates to what extent the EU would rely on metal imports if it is to execute its current energy plan, and whether a nuclear-intensive electricity production system could be a better option. When compared to today's electricity mix, we find that a renewable-intensive electricity mix will increase the overall energy security in the EU – the reduction in fuel import dependence more than compensates for the increase in metal import dependence. However, we also find that a nuclear-intensive electricity mix can increase the overall energy security in the EU even further. When compared to a renewable-intensive electricity mix, a nuclear-intensive mix does not only have lower metal import requirements in terms of volume and value, but also reduces risk of bottleneck problems related to rare earths and silicone. Still, even with a nuclear-intensive energy mix, the EU will still rely on metal imports, and face potential bottleneck risks in terms of chromium.

**KEYWORDS**

Energy policy; Energy security; Mineral security; Renewable energy; Nuclear energy; Ukraine crisis

**JEL CODES**

Q28, Q43, Q47, Q48, Q54, Q56

## INTRODUCTION

The purpose of this study is to investigate future possible electricity mixes in the European union, and their compatibility with energy security, including related mineral and metal security. Although energy and mineral security are both extremely hot topics in 2022, due to ongoing geopolitical events and development, we have failed to find studies that investigate the compatibility between energy security in the EU and the metal import requirements associated with the EU's current energy plan and alternative solutions. This study aims to cover that gap.

In response to climate change, 154 countries signed the United Nations Framework Convention on Climate Change in 1992. The convention stipulates that developed countries, including 13 Western European countries that belong to the European Union, need to take responsibility for the massive emissions of greenhouse gases caused by industrial development (UNFCCC, 1994).

The energy sector has long been the biggest contributor to climate change, accounting for 40% of total $CO_2$ emissions and 73.2 % of total GHG emissions (World Bank, 2014; Ritchie et al., 2020). Therefore, reducing emissions from the energy sector has been considered key to meeting climate and environmental challenges. To achieve this, without significantly reducing economic activity and living standards, it has been, and still is, widely acknowledged that humanity must conduct a clean energy transition (United Nations, 2021).

The $CO_2$-equivalent emissions per unit of energy for coal, oil, natural gas, nuclear and renewables are 900g$CO_2$/kWh, 780g$CO_2$/kWh, 400g$CO_2$/kWh, 4g$CO_2$/kWh, and 13g$CO_2$/kWh, respectively (Steen, 2017). As such, in comparison to coal and oil, natural gas, nuclear, and renewable energy can all be classified as clean energy. All three can contribute to achieving Sustainable Development Goals (SDGs). And they have all been prioritized in the EU's clean energy plans at one point or another.

In the early days of the clean energy transition, the EU saw nuclear energy as a key solution to meet its emission challenges and future energy needs. From 1970 to 1990, the EU increased its nuclear power share in the electricity mix from 1.6% to 30% (IEA, 2019). However, the occurrence of multiple nuclear power plant accidents around the world raised concerns about the safety of nuclear power and the disposal of toxic waste (IAEA, 2016). This made the EU and EU countries reconsider their stance on nuclear energy. For example, Germany's 2011 Nuclear Energy Act announced that Germany would shut down all nuclear power plants by the end of 2022 and achieve complete denuclearization (World Nuclear Association, 2022). Some countries such as Belgium and Spain followed similar suit, while France and Netherlands continue to stay in the nuclear club (Morison et al., 2022). Some countries always try to develop nuclear power generation, but the issues of being over budget and long construction periods drag down the implementation (IAEA, 2011). As a result, nuclear energy capacity in the EU has been in steady decline since around 2004 (Eurostat, 2021). Despite this, nuclear energy still constitutes a significant source of the EU's energy supply.

Since 1990, the EU has increased its reliance on natural gas (IMF, 2022). Natural gas has been preferred due to its mature technology and convenient access channels (Heflich and Saulnier, 2021). With the shift in the EU's attitude towards nuclear energy, natural gas became even more important. Thus, while coal, oil, and nuclear energy consumption were slowing down and declining, natural gas consumption exploded and went through a remarkable growth up until 2010, from which time the consumption of natural gas stabilized, and renewable energy sources started making real significant contributions to the overall energy supply in the EU.

EU has made itself heavily dependent on natural gas, especially from Russia. In 2020, Russia provided 40% of EU natural gas. The average EU countries' dependency index on Russia's gas imports is as high as 80. The EU realized that it was in a serious energy crisis in terms of energy security. Therefore, the EU has accelerated the development of renewable energy since 2010 and regarded it as a reliable long-term clean energy option. Andreas et al. (2017) point out that 75% of EU countries support that if renewable energy can be expanded over a long period, it will not cause adverse economic effects. The EU's plan was to gradually replace natural gas's main role in the clean energy transition with renewable energy over the 30 years after 2020 (European Commission, 2012).

However, the sudden outbreak of the war in Ukraine in 2022 forced the EU to change this original long-term plan and find solutions to make up for the sudden and large drop in the natural gas supply (Guénette et al., 2022). Pretty soon after the invasion started, European support for Ukraine and sanctions on Russia led Russia to restrict gas deliveries to EU countries. According to the IMF (2022), the shutdown of Russian gas transmissions reduced the size of the EU LNG market by more than 30%.

According to Alves (2022), the monthly electricity price in EU countries went through a shock of rapid increases from the first half to the second half of 2022.

Part of Europe's proposed long-term solution to the current energy crisis, without compromising its emission reduction ambitions, is to double down on renewable energy production. For example, REPowerEU is a plan published in May 2022 by the European Commission to help the EU become independent from Russian fossil fuels. This plan proposed to increase the 2030 target for renewables from the current 40% to 45% (REPowerEU, 2022).

However, renewable energy technologies are metal intensive, resulting in another potential energy security issue. Renewable technologies, such as turbines for wind power and photovoltaic panels for solar power, require large amounts of metals. Wind energy technology mainly needs copper and zinc, solar energy technology mainly needs copper and silicon. Electricity transmission networks and storage, and other infrastructure tied to electrification, also requires high quantities of metals. 30% of the world's copper is extracted in Chile (IEA, 2022), 34.8% of the world mine production of zinc is in China (Canada Government, 2022). China is also the world's largest silicon producer in 2021 (Statista, 2022). This raises the question of whether the EU risks swapping dependence on Russian natural gas with an undesirably high dependence on metal imports from other narrow interest spheres such as China. In contrast, nuclear technologies such as safety equipment in nuclear power plants, also need metals such as copper, nickel, and chromium. But it is not as metal-intensive as renewables. According to the IEA (2022), nuclear power generation technologies require a much smaller amount of metal per unit of electricity produced than renewable energy.

Many reports give backing to the EU strategy of developing a renewable-intensive energy system to meet future needs. For example, Rystad Energy (2022) indicates that the cost of photovoltaic power generation can reach one-tenth of natural gas power generation. They estimate that the installed capacity of renewable energy can replace forecast gas-fired generation by 2028 based on the current growth rate of renewable energy capacity. They conclude that renewable is a better option for Europe than natural gas in the far future. However, some studies also pointed out that the renewable-intensive energy system will arise new worries about metal demand. Studies by Calvo and Valero (2022) and Franks et al. (2022) suggest that metals are important for renewables so their sustained adequate supply is crucial for SDGs. Hache (2018) warns that expanding the usage of renewable energy will cause new metal interdependencies among countries.

Although the EU acknowledges such concerns and has stated its commitment to secure access to critical metals (European Council, 2022), it is still not clear whether the EU is able to secure the much-needed metals without relying heavily on imports from narrow interest spheres in an unstable geopolitical environment – especially in the short- to medium-long term. Moreover, it is not clear how serious this issue is, e.g., compared to today's energy situation.

Considering the EU's planned energy trajectory, and the potential security threat at play, this paper aims to determine the extent to which a renewable-intensive energy mix is compatible with achieving energy security in the EU. Furthermore, based on the fact that nuclear energy is relatively less metal-intensive, this paper also attempts to investigate whether a nuclear-intensive electricity mix could prove more compatible with both the SDGs and energy security in the EU than a renewable-intensive electricity mix.

To achieve the objectives, this paper provides an exploratory data analysis and a future-oriented scenario analysis. The exploratory data analysis describes the EU electricity consumption, production, and imports. Moreover, it describes the fuel production and import situation, as well as the metal production and import situation. This lays the necessary foundation for the future-oriented scenario analysis, which investigates future metal and metal import requirements for the electricity production sector in the EU, and potential metal-related bottleneck problems. It should be noticed that we only focus on metal consumption tied to electricity production capacity and leave metal consumption tied to electricity transmission and storage out of the scope in this analysis.

The novelty of the paper lies in the study of the interconnections between EU energy security and metal and metal import requirements. To the best of our knowledge, it is the first to define and forecast different measurements of energy independency after considering metal independency. Overall, the paper provides a deeper understanding of the challenges that the EU is facing in relation to the energy crisis and achieving energy independence without coming in conflict with the SDGs.

## EXPLORATORY DATA ANALYSIS

This section discusses the changes in the past 30 years and the current status of the EU electricity sector. We first analyze the energy structure of the EU's power generation sources, focusing on changes in the proportion of natural gas and renewable energy power generation. We then look at imports of fossil fuels. The purpose of this part is to identify the impact of the heavier use of natural gas on the EU's import dependence. This section ends with an exploration of the supply, consumption and import of metals in the EU electricity sector, in particular renewable energy generation. The aim is to demonstrate that metal imports are indeed an energy security concern in the EU.

### *Electricity consumption, production, and import*

Figure 1 shows the changes in electricity consumption in EU countries from 1990 to 2020. Overall, from 1990 to 2010, electricity consumption in the EU increased year by year. In the period from 2010 to 2020, electricity consumption in the EU has shown a slow downward trend. In 2020, the total electricity consumption of the 27 countries in the EU is about 3000TWh. Among them, the electricity consumption of Germany and France ranks the top two among 27 countries. Germany and France consume 20% and 17% of the EU's overall electricity consumption in 2020, respectively. Both Italy and Spain also consume more than 200TWh of electricity per year. The remaining countries have an average annual electricity consumption of less than 150TWh. In addition, the electricity consumption of almost all countries has been rising year by year before 2010 and gradually decreasing after 2010, which is consistent with the electricity consumption characteristics of the EU.

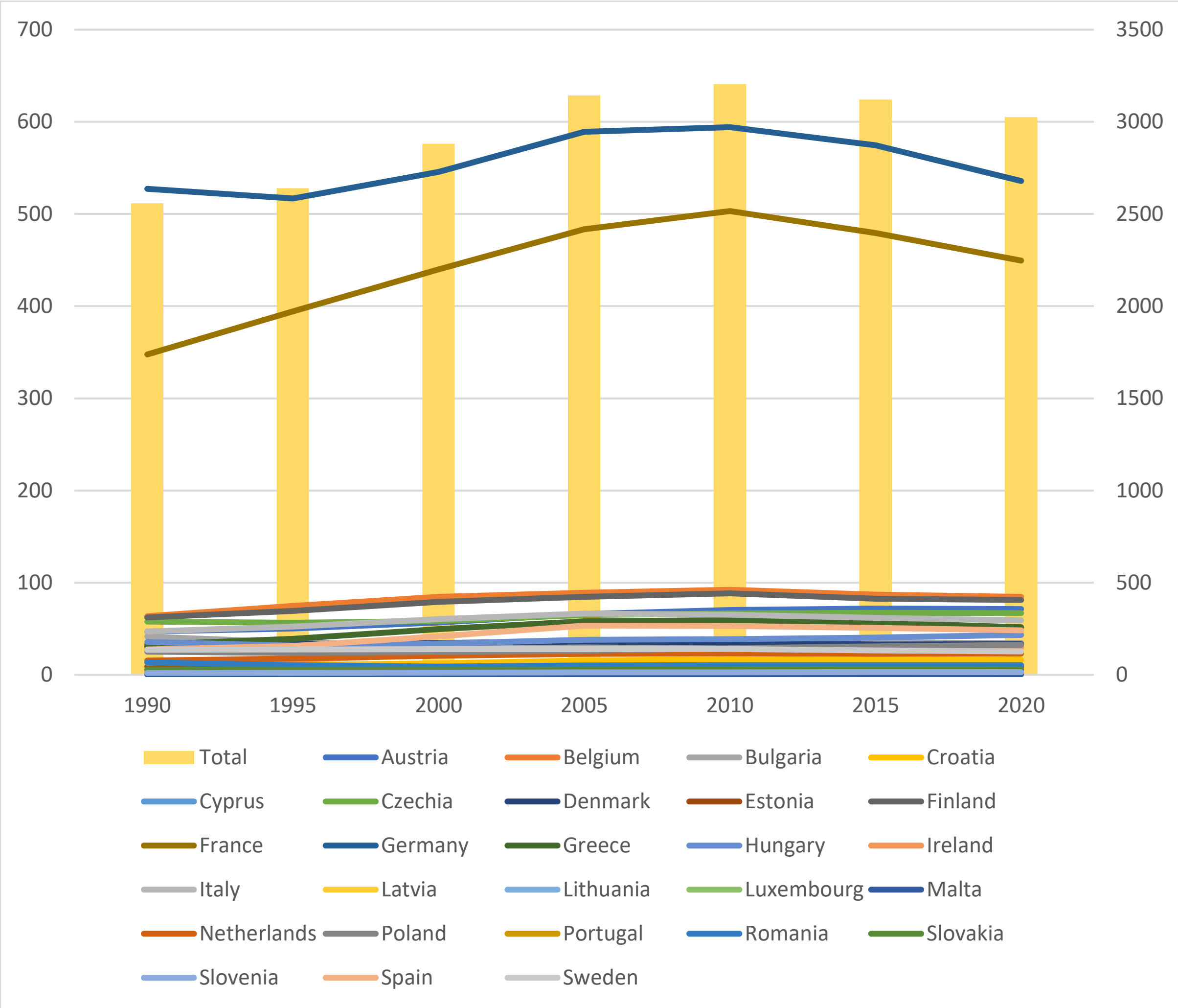

**Fig. 1** Electricity consumption in EU (units: TWh). Data sources: International Energy Agency (2021)

Figure 2 shows that the total electricity production in the EU reflects the development of increasing and then decreasing electricity consumption. From 1990 to 2010, the EU's electricity production increased from 2290.2TWh to 2986.8TWh. From 2010 to 2020, electricity production fell slowly to 2816.5TWh.

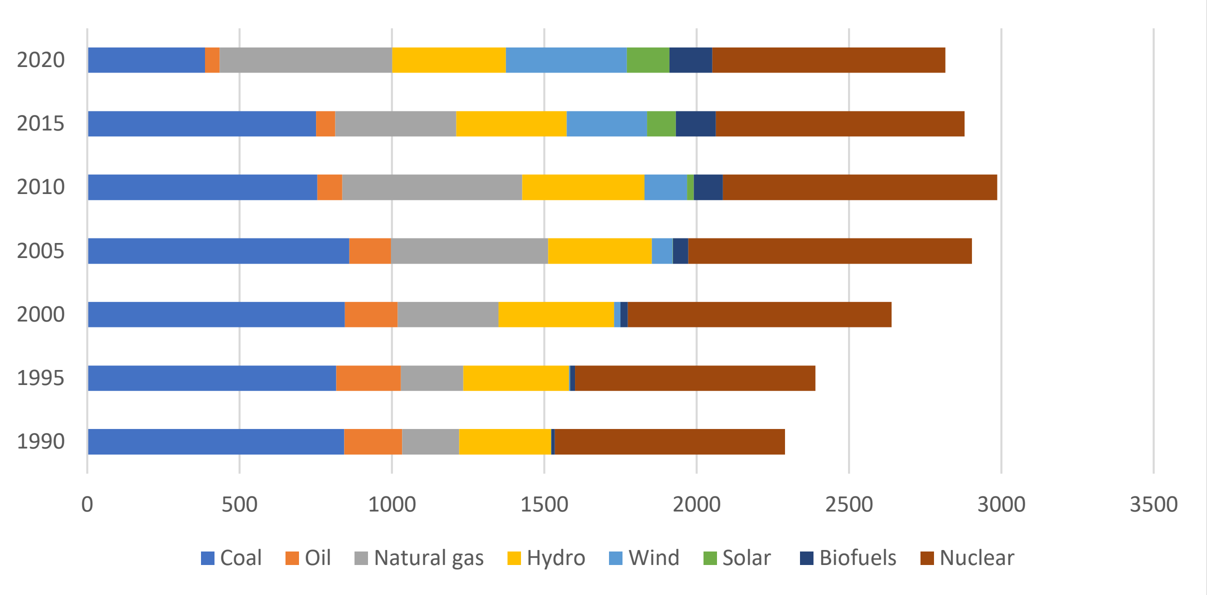


**Fig. 2** Electricity production by sources in EU (units: TWh). Data sources: International Energy Agency (2021)

From the perspective of energy sources, the electricity production based on coal and oil is decreasing year by year. In contrast, electricity generation from natural gas and renewables is on the rise overall. Specifically, the growth rate of natural gas power generation was high before 2010. In the 20 years from 1990 to 2010, electricity generation from natural gas nearly tripled. However, from 2010 to 2015, the proportion of natural gas power generation dropped sharply, which is one of the main reasons for the decline of total power generation in the EU from 2010 to 2015. From 2015 to 2020, electricity production from natural gas rebounded, but coal production fell sharply over the same period. The combination of the two led to a slight reduction in total electricity generation in the EU between 2015 and 2020. And in 2020, the power generation of natural gas exceeds that of coal. Figure 3 shows that the share of renewable energy generation did not change significantly from 1990 to 2005. However, since 2005, renewable energy has developed rapidly, and the proportion of total electricity production has risen from 15.9% to 37.3%. Renewable energy accounts for more power generation than natural gas and nuclear power, making it the largest electricity generation energy source in 2020.

Further analysis of different types of renewable energy shows that hydropower has always accounted for a significant proportion of renewable energy generation. But from 1990 to 2020, the growth of hydropower generation was slow. In 1990, the hydropower generation was 301TWh, but until 2020, the hydropower generation still did not exceed 400TWh. In contrast, wind power has grown rapidly over the past 30 years. In 1990, wind power generation was less than 1TWh. By 2020, wind power generation reached 397TWh, surpassing hydropower generation to become the type of renewable energy that accounts for the largest proportion of power generation. Solar and biomass power generation is also increasing year by year. In 1990, the power generation of the two was 0.015TWh and 11.385TWh respectively. By 2020, both generated around 140TWh. The doubling of the share of renewable energy in power generation from 2005 to 2020 is mainly due to the increase in wind power generation, supplemented by the development of solar and biomass power generation.

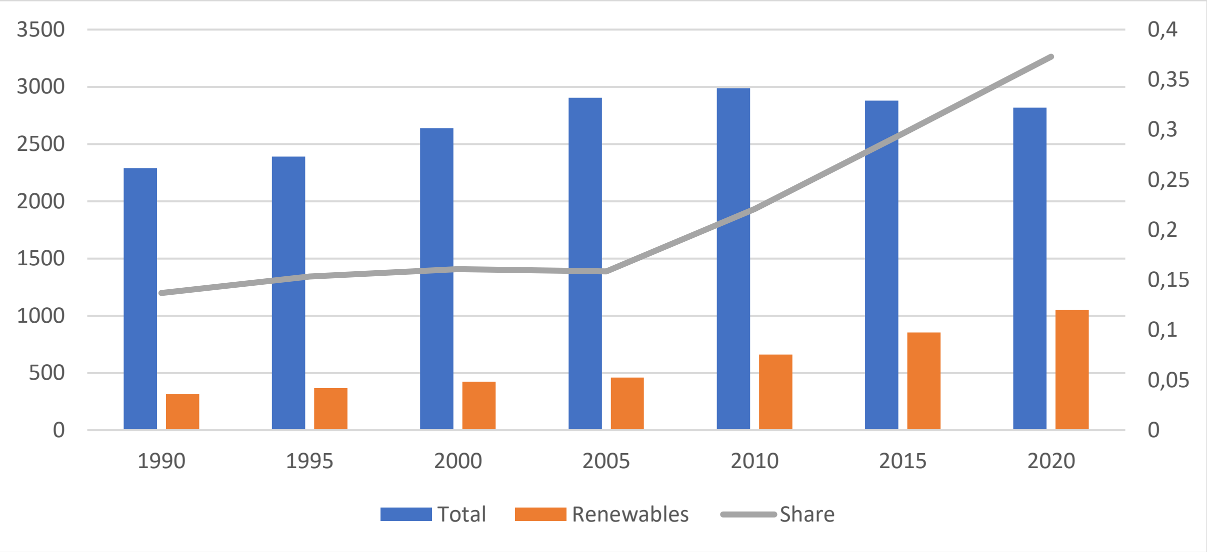


**Fig. 3** Renewable power generation (Units: TWh & %). Data sources: International Energy Agency (2021)

Figure 4 shows the share of nuclear power generation in total power generation in EU countries. Overall, the share of nuclear power generation in the EU showed a slow downward trend from 1990 to 2020. In 1990, nuclear power generation in the EU accounted for 32.8% of total electricity generation, by 2015 this figure had dropped to 26.4%. Combined with Figure 2, from 2015 to 2020, nuclear power generation is also decreasing. Of the 27 countries in the EU, France has the largest share of nuclear power generation, with the percentage remaining stable at 70% to 80%. The share of nuclear power generation in Lithuania was high in 1990 at 79%. But in 2005 there was a notable decline. From 2011 to 2015, the share of nuclear energy development in Lithuania dropped significantly from 74.9% to 30.8%. The share of nuclear power generation in the Czech Republic, Slovakia and Hungary has shown a clear upward trend in the past 25 years. The share of nuclear power generation in most of the remaining countries showed a more or less decrease. But the reduction is not significant.

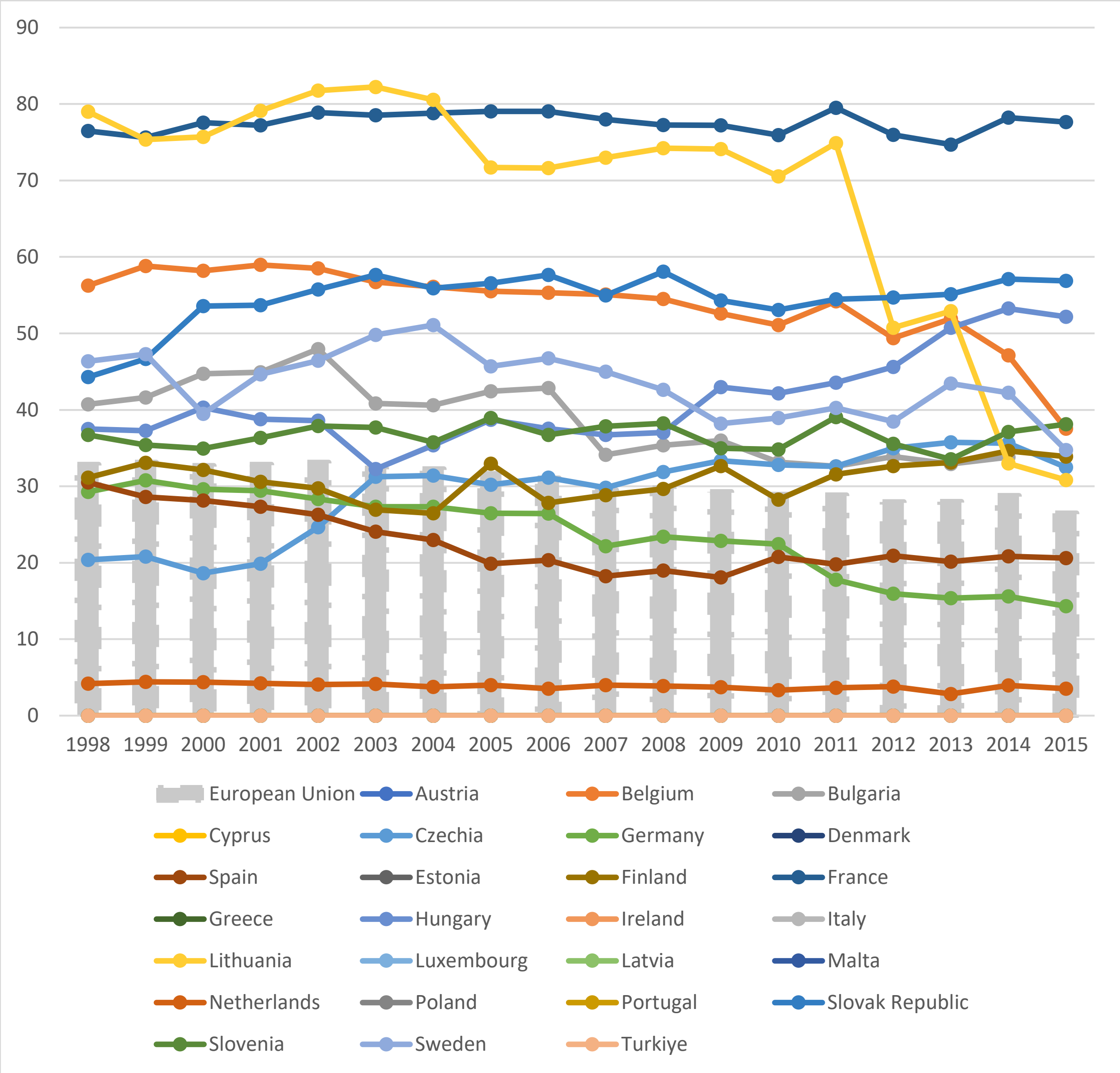


**Fig. 4** Electricity production from nuclear (units: %). Data sources: World Bank Group (2017)

Figure 5 shows that electricity consumption in the EU is consistently somewhat higher than domestic electricity production. This means that the EU imports electricity to make up for the shortfall between its production and consumption. Norway is responsible for the vast majority of direct electricity transmission (European Commission, 2022). However, because the gap between electricity demand and supply is not large, the EU can still basically be regarded as electricity independent when not taking fuel and metal imports into account.

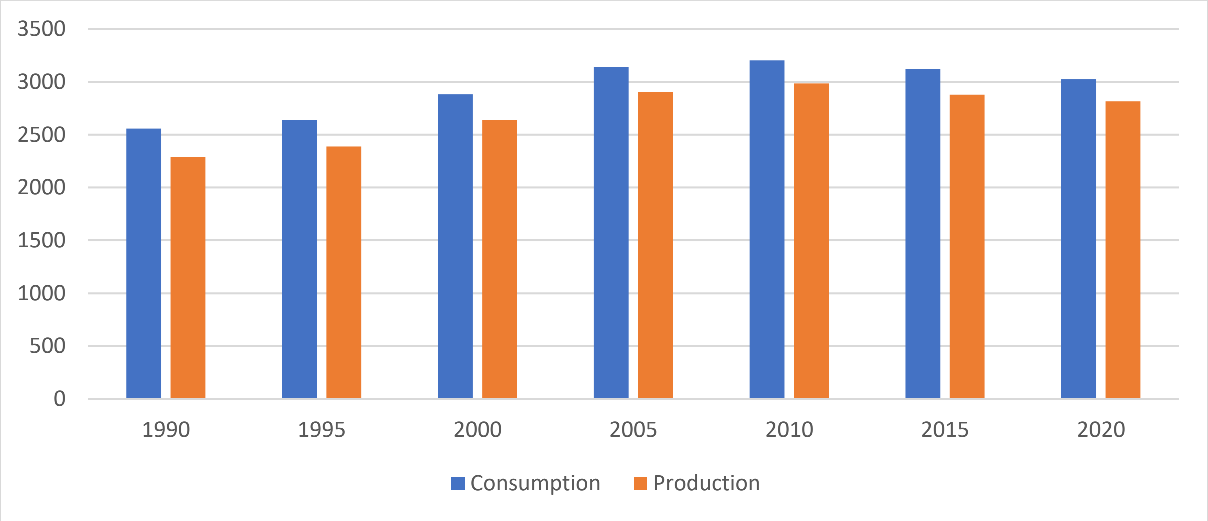


**Fig. 5** Electricity consumption and production in EU (units: TWh). Data sources: International Energy Agency (2021)

***Electricity production and imports of fuels***

Fossil fuel power generation requires inputs in terms of raw materials, such as coal, oil, and natural gas. However, the EU production of these inputs is not sufficient to meet the EU demand, so the consumption of all three fossil fuels rely on imports to some extent. According to Figure 6, from 1990 to 2020, both the EU production and consumption of coal decreased significantly. From 1990 to 2010, the coal import volume of the EU showed a trend of first decreasing and then increasing. Since 2011, the coal import volume has been steadily decreasing year by year. According to Figure 7, the EU's importing dependence index of coal rose from 18.7% in 1990 to 41.6% in 2008. Afterwards, the number in 2009 dropped relatively significantly, because Russia and Ukraine failed to agree a price for Russian gas supply to Ukraine and a tariff for the transit of Russian gas to Europe in January 2009 (Pirani et al., 2009). Then it rose from 36.6% in 2009 to 43.8% in 2018. In 2019 and 2020, EU coal dependence on other countries fell from 43.3% to 35.8%. Overall, in the 30 years from 1990 to 2020, the import dependence on coal has never exceeded 45%.

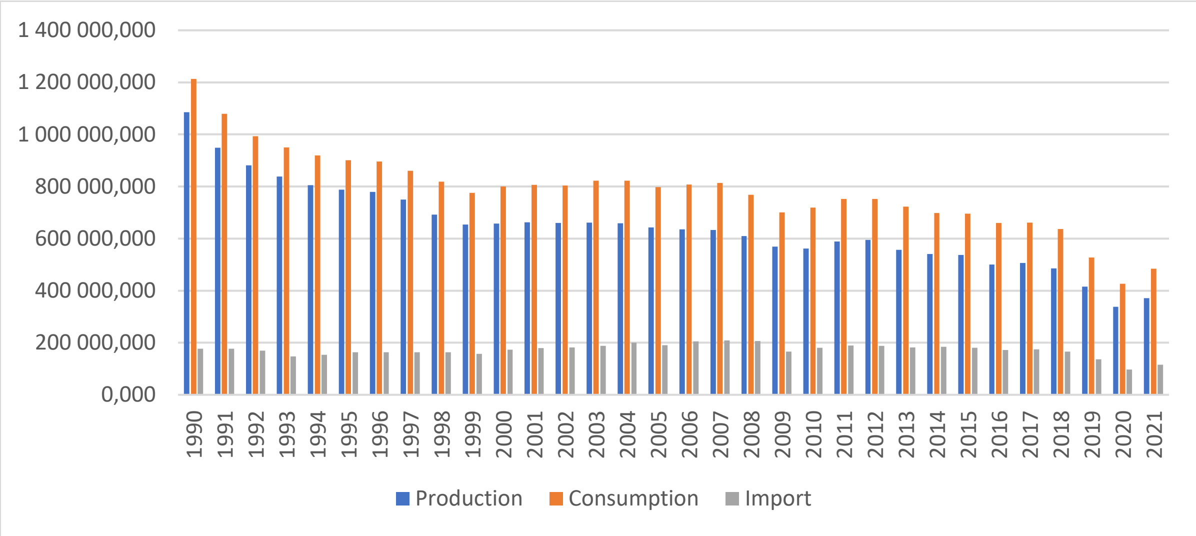


**Fig. 6** Consumption, production, and imports of coal for electricity in EU (units: thousand tons). Data sources: Eurostat (2021)

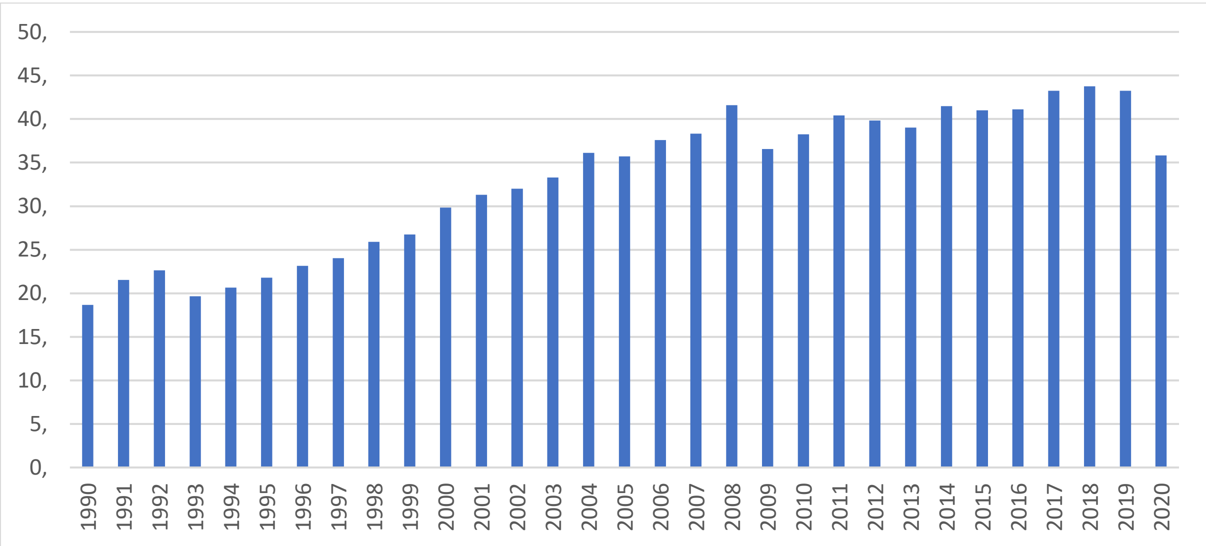


**Fig. 7** Dependency index of coal in EU (units: %). Data sources: Eurostat (2021)

The EU produces less oil than it consumes, resulting in ademand for imports. Figure 8 shows that the EU's oil imports did not change significantly from 1990 to 2020 as a whole, and remained within the range of 700,000 to 830,000 thousand tons. According to the oil external dependence indicator shown in Figure 9, the proportion of oil imports from other countries to consumption in the EU is consistently higher than 88%. From 2002 to 2015 and from 2018 to 2020, there is a clear overall upward trend.

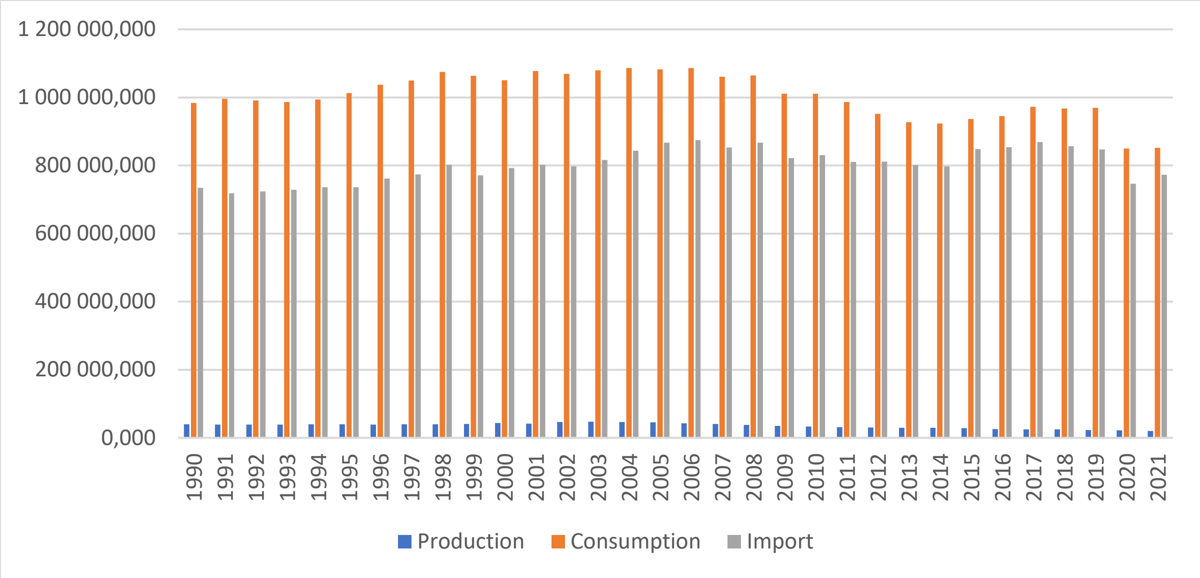


**Fig. 8** Consumption, production, and imports of oil for electricity in EU (units: thousand tons). Data sources: Eurostat (2021)

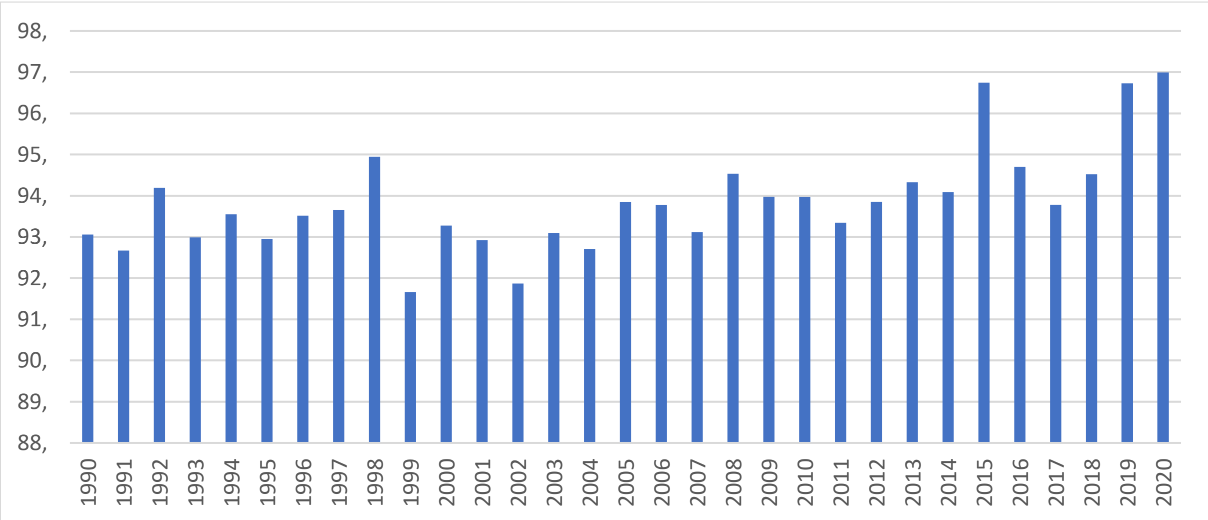


**Fig. 9** Dependency index of oil in EU (units: %). Data sources: Eurostat (2021)

Figure 10 shows that the production of natural gas in the EU decreased year by year from 1990 to 2020. However, natural gas consumption has shown an upward trend in two long periods from 1990 to 2010 and from 2015 to 2020. Moreover, EU natural gas imports increased first and then decreased from 1990 to 2014. From 2015 to 2020, gas consumption in the EU has become increasingly dependent on imports. According to Figure 11, from 1990 to 2020, especially from 2015 to 2020, the EU gas import dependence indicator has become higher.

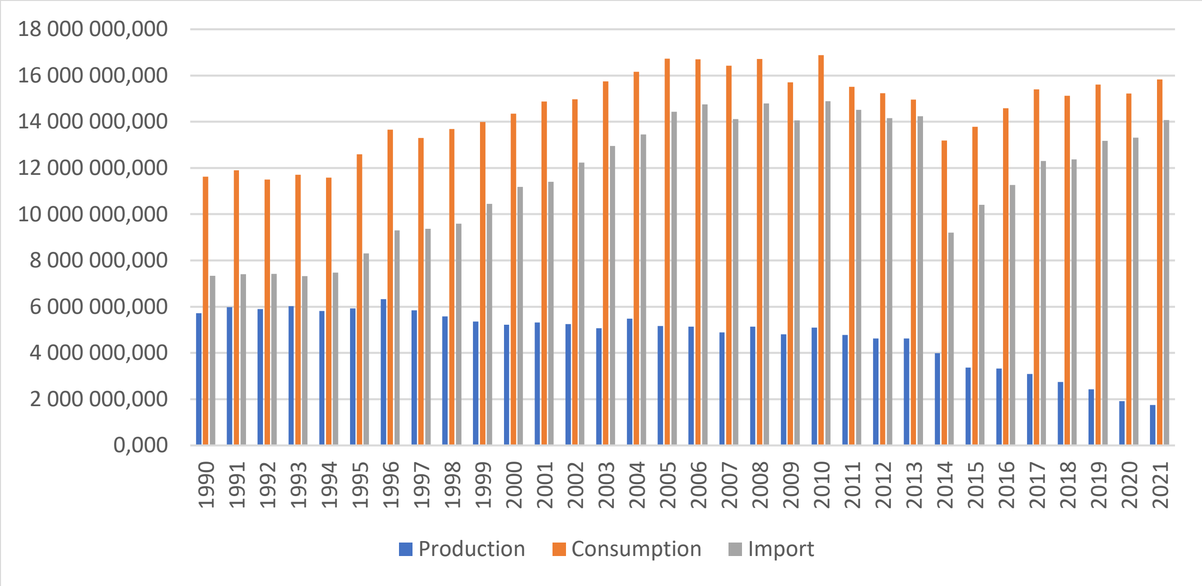


**Fig. 10** Consumption, production, and imports of natural gas for electricity in EU (units: TJ). Data sources: Eurostat (2021)

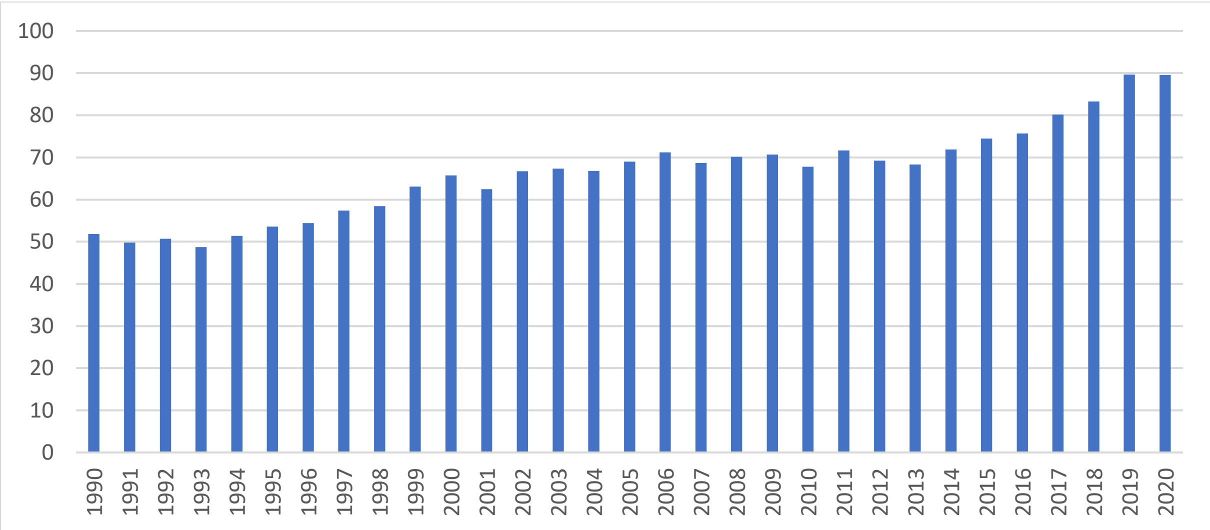


**Fig. 11** Dependency index of natural gas in EU (units: %). Data sources: Eurostat (2021)

From a country perspective, according to Figure 12, in Bulgaria, Czech Republic, Estonia, Latvia, Hungary, Romania, Slovakia, and Finland, the dependence indicator of natural gas imports from Russia is consistently above 80% from 2015 to 2020. In 2018, Poland, Greece, Lithuania, and Slovenia's dependence on Russia's natural gas imports decreased significantly, but Germany, Belgium, Spain, Croatia, and Sweden's natural gas imports from Russia increased significantly. After Russia, the EU's second-largest source of natural gas imports is Norway. Among them, Bulgaria, France, Lithuania, Luxembourg, and the Netherlands are strongly dependent on Norway's natural gas imports. However, according to Figure 13, it can be found that from 2015 to 2020, all the other countries depended on

Norway for natural gas imports not more than 50%, except Bulgaria's natural gas dependence index on Norway was 51.93% and 52.36% in 2017 and 2018, respectively. This shows that the natural gas dependence between the EU and Norway is far less than that of Russia.

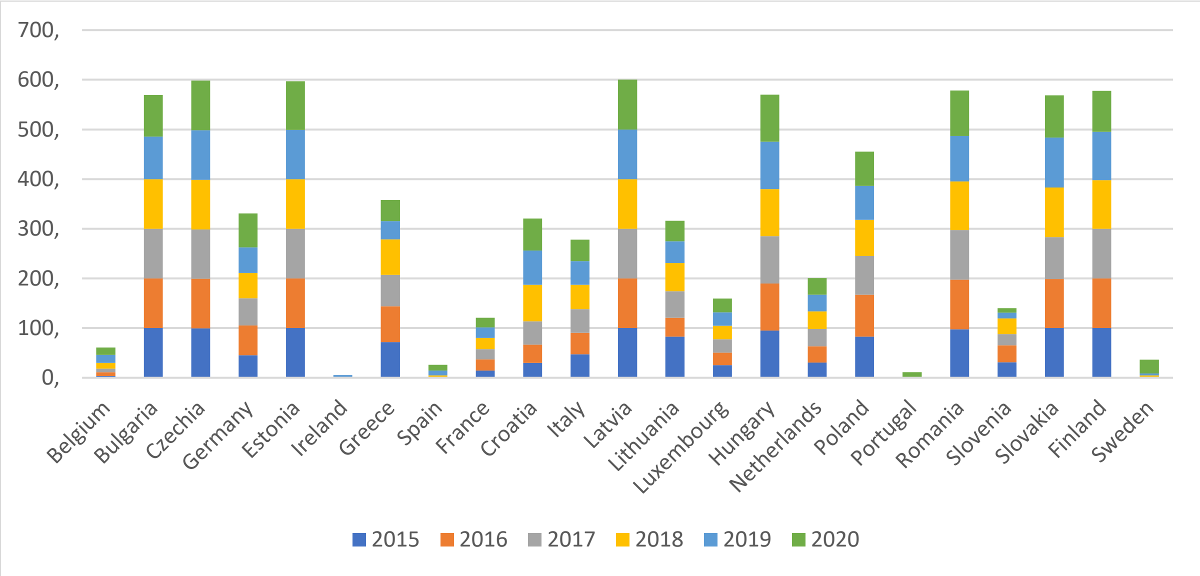


**Fig. 12** EU countries' dependence index on Russia (units: %). Data sources: Eurostat (2021)

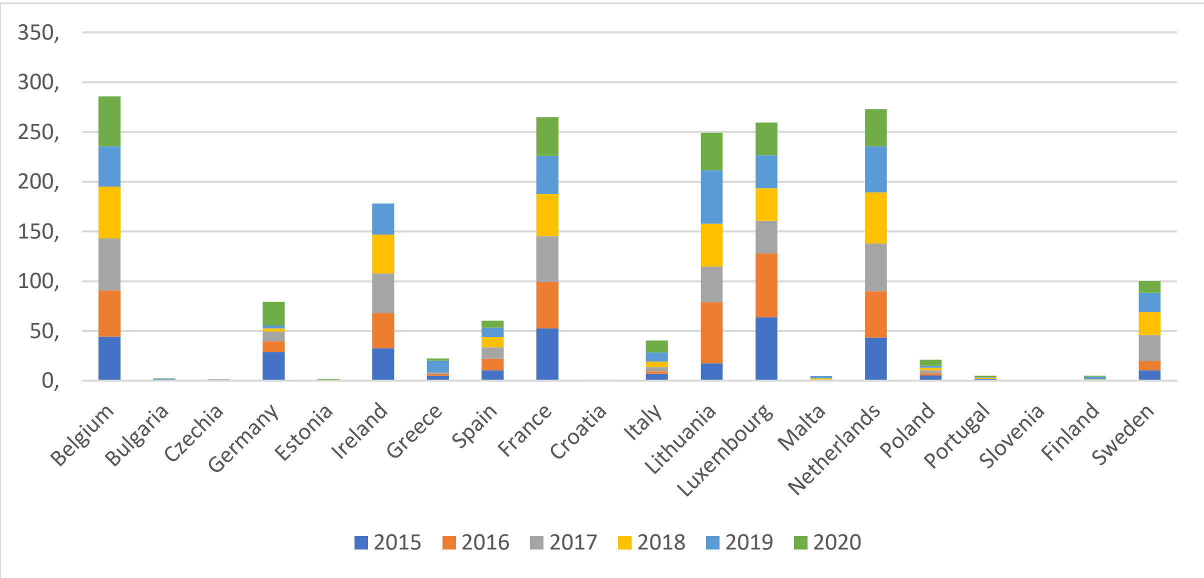


**Fig. 13** EU countries' dependence index on Norway (units: %). Data sources: Eurostat (2021)

In summary, among the fossil fuels required for electricity production in the EU, oil is the most import-dependent, followed by natural gas. More importantly, the proportion of natural gas imports from other countries has been rising. In the EU's natural gas supply sources, Russia accounts for the largest proportion, and more than 80% of the natural gas imports of many countries come from Russia. Thus, there are two main problems with natural gas in the EU: First, it is heavily dependent on imports. Second, the source of natural gas imports is concentrated in Russia. This creates the EU's gas dependence on Russia on dual levels. That is to say, if the EU's clean energy transition target is dominated by natural gas, it causes serious energy security problems.

***Renewable electricity production and imports of metals***

In recent years, although the EU has been trying to shift its energy structure from coal and oil to natural gas, it has also strengthened its emphasis on the development of renewable energy due to concerns of over-reliance on Russia (Cebotari, 2022). But the outbreak of war between Russia and Ukraine, causing European countries to face gas shortages and rising electricity prices, made the EU's need for energy independence more urgent (World Bank, 2022).

To meet the challenges, the European Commission introduced the REPowerEU Plan in May 2022. According to the plan, the EU needs to solve the energy crisis from two aspects. First, import natural gas from other countries as soon as possible. The United States, Qatar, Norway, and Canada are all alternative suppliers. Second, increase investment and support for renewable energy, especially wind and solar power. In June 2022, the European Union released a project named Save Gas for a Safe Winter, which plans to reduce the use of gas in Europe by 15% by March 2023. This is further evidence that the EU believes that natural gas should not continue to be seen as the main direction of the energy transition. In contrast, the development of renewable energy is seen as more in line with the needs of long-term sustainable development and energy security (Siddi, 2017).

Renewable energy does not rely on any fuel imports since the energy infrastructure makes use of wind and light at the site. However, renewable energy technologies are metal-intensive. The amount of metals consumed in the renewable energy sector is shown in Table 1. According to Figure 14, the amount of metal required for renewable energy generation in the EU has two characteristics. First, the demand for copper and zinc is much greater than for other metals. Second, from 2000 to 2020, as the share of electricity generated from renewable sources grows, so does the amount of the six main metals required.

Table 1 Metals demand for renewable electricity sector (units: metric tons). Data sources: USGS (2021)

| Year | Copper | Nickel | Chromium | Zinc | Silicon | Rare earths |
|---|---|---|---|---|---|---|
| 2000 | 727439 | 40765 | 59232 | 663552 | 185677 | 9 899 |
| 2005 | 789835 | 44261 | 64312 | 720469 | 201604 | 10 748 |
| 2010 | 1131371 | 63401 | 92122 | 1032010 | 288780 | 15 396 |
| 2015 | 1462869 | 81977 | 119114 | 1334394 | 373394 | 19 907 |
| 2020 | 1801486 | 100953 | 146686 | 1643272 | 459825 | 24 515 |

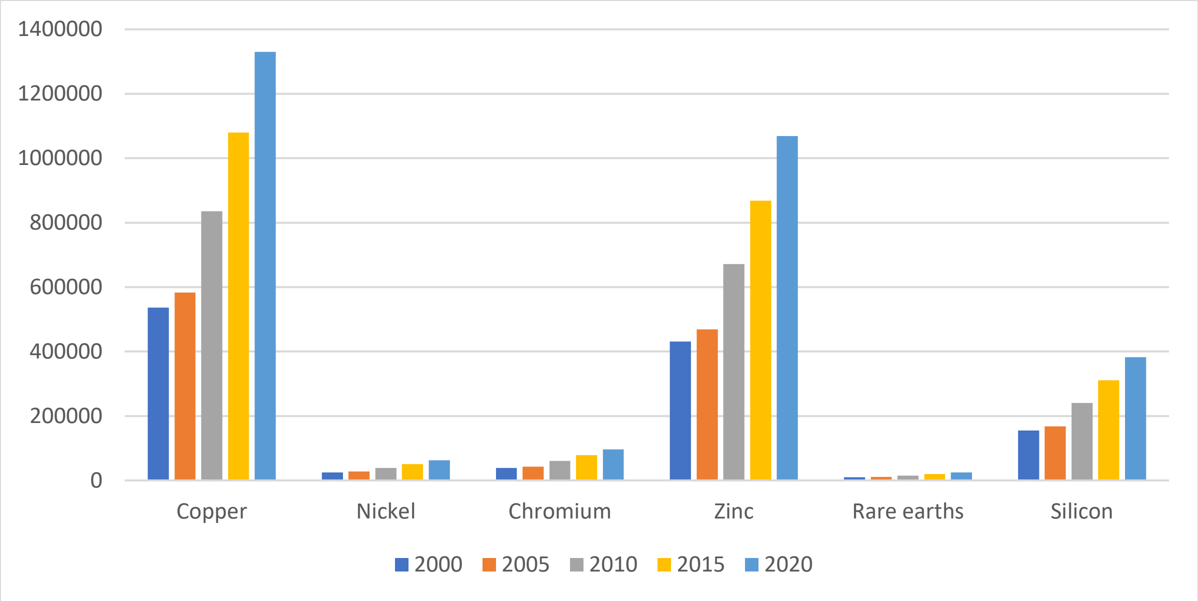


**Fig. 14** Metals demand for renewable generation (units: metric tons). Data sources: USGS (2021)

The supply of metals is divided into two parts, mining, and processing. Table 2 provides an overview of the EU mining production. Table 3 shows the processing capacities of the EU. Rare earths are mined and processed in negligible quantities in the EU, so supplies of rare earth metals are not included in the tables.

Tables 2 and 3 show that the EU mining production of copper and zinc is lower than the EU processing of the very same metals. This means that the EU imports the mined copper and zinc ore for processing. For nickel, there is little difference between mine production and processing capacity in the EU. This shows that nickel is both mined and processed in the EU. Finally, for chromium and silicon, the EU mining volume is much greater than the processing volume, implying that after these two metal ores are mined in the EU, most of them need to be transported outside the EU for processing.

Copper and zinc, which have small mine production and high process production, are the main requirements for renewable generation. This means that the import of metals needed for renewables is dual, including the import of ore for processing and the import of metals after being processed. That is, of the three main metals required for renewable energy, two have dual import requirements, while of the three main metals required for nuclear energy, only one (copper) has dual import requirements.

Table 2 Mine production of metals in EU in 2020 (units: metric tons) Data sources: euromines (2021)

| Metal | Mine production | By countries |
|---|---|---|
| Copper | 753 828 | Poland (57%), Bulgaria (14.3%), Sweden (11%), Portugal (10%) |
| Zinc | 732 289 | Ireland (46%), Sweden (26%) |
| Chromium | 426 817 | Finland (99.6%) |
| Nickel | 63 733 | Finland (60.5%), Greece (27.1%) |
| Silicon | 209 000 | France (51%), Spain (24%), Poland (20%) |

Table 3 Processed metal production in EU (units: metric tons)

| Year | Copper | Nickel | Chromium | Zinc | Silicon |
|---|---|---|---|---|---|
| 2000 | 1 926 232 | 107 363 | 8 | 2 207 499 | 125 |
| 2005 | 2 569 470 | 66 530 | 8 | 2 536 869 | 130 |
| 2010 | 2 697 470 | 57 767 | 8 | 2 255 932 | 112 |
| 2015 | 2 825 336 | 87 022 | 13 | 2 261 551 | 100 |
| 2020 | 2 885 533 | 78 012 | 14 | 2 305 063 | 108 |

Metal ore can only be used after processing, and the processing data is more comprehensive than the mine data. Therefore, we can think of processing volumes as the supply of metal. But we cannot directly compare Table 3 with the demand in Table 1. Because the metal supply in Table 3 is the total supply for all sectors, while the metal demand in Table 1 is only for the electricity sector.

According to USGS statistics, only around 20% of copper, 16% of zinc, 21% of silicon, 12% of nickel, and 17% of chromium are used for the electricity sector. Based on this, we can estimate the EU metal supply for the whole EU electricity sector. The results are found in Table 4.

Table 4 EU metal supply for the electricity sector (units: metric tons)

| Year | Copper | Nickel | Chromium | Zinc | Silicon |
|---|---|---|---|---|---|
| 2000 | 385 246 | 12 884 | 1 | 353 199 | 26 |
| 2005 | 513 894 | 7 984 | 1 | 405 899 | 27 |
| 2010 | 539 494 | 6 932 | 1 | 360 949 | 24 |
| 2015 | 565 067 | 10 444 | 2 | 361 848 | 21 |
| 2020 | 577 107 | 9 361 | 2 | 368 810 | 23 |

Further, according to the IEA report (2022), the amount of copper required for electricity generation from renewable energy accounts for about 75% of the total copper required for electricity generation from all energy sources. Almost all of the zinc and silicon used to generate electricity are used in renewable energy technologies. 25% of nickel and 30% of chromium used in the power generation industry is allocated to renewable energy technologies.

Table 5 EU metal supply for the renewable electricity sector (units: metric tons)

| Year | Copper | Nickel | Chromium | Zinc | Silicon |
|---|---|---|---|---|---|
| 2000 | 288 935 | 3 221 | 0.4 | 353 199 | 26 |
| 2005 | 385 421 | 1 996 | 0.4 | 405 899 | 27 |
| 2010 | 404 621 | 1 733 | 0.4 | 360 949 | 24 |
| 2015 | 423 800 | 2 611 | 0.7 | 361 848 | 21 |
| 2020 | 432 830 | 2 340 | 0.7 | 368 810 | 23 |

Using the data in Table 1 and Table 5, we can estimate the historical imports of copper, chromium, zinc, nickel, rare earths, and silicon for the EU renewable electricity generation. The results are shown in Table 6.

Table 6 EU metal imports for the renewable electricity sector (units: metric tons)

| Year | Copper | Nickel | Chromium | Zinc | Silicon | Rare earths |
|---|---|---|---|---|---|---|
| 2000 | 247 964 | 22 008 | 38 931 | 78 366 | 154 457 | 9 899 |
| 2005 | 197 531 | 25 397 | 42 269 | 62 684 | 167 707 | 10 748 |
| 2010 | 430 407 | 37 505 | 60 548 | 310 256 | 240 242 | 15 396 |
| 2015 | 655 895 | 48 124 | 78 289 | 506 024 | 310 643 | 19 907 |
| 2020 | 896 787 | 60 138 | 96 411 | 699 952 | 382 552 | 24 515 |

Table 6 indicates that the EU relies on large imports of copper and zinc to meet the demands of its renewable electricity sector – and again, this is without considering that the EU also imports copper and zinc ore for processing.

The EU's mine production and processing of silicon are essentially non-existent. As a result, it relies on significant silicon imports. That means, among other things, that solar power generation, which has the highest silicon intensity, relies heavily on imports from other countries.

The EU renewable electricity sector's consumption of nickel, chromium and rare earth metals also relies heavily on imports. In the case of nickel, this is a result of insufficient EU mine production and processing. In the case of chromium, it is due to insufficient EU processing. In the case of rare earth metals, it is a result of non-existent EU mine production and processing.

Table 6 and Figure 15 also show that the import volumes of the six main metals required by renewable generation show a continuously increasing trend from 2000 to 2020. This indicates that the

EU's expansion of the renewable electricity sector contributes to an increasing need for metal imports. Such a strong dependence on metal imports may raise new energy security concerns.

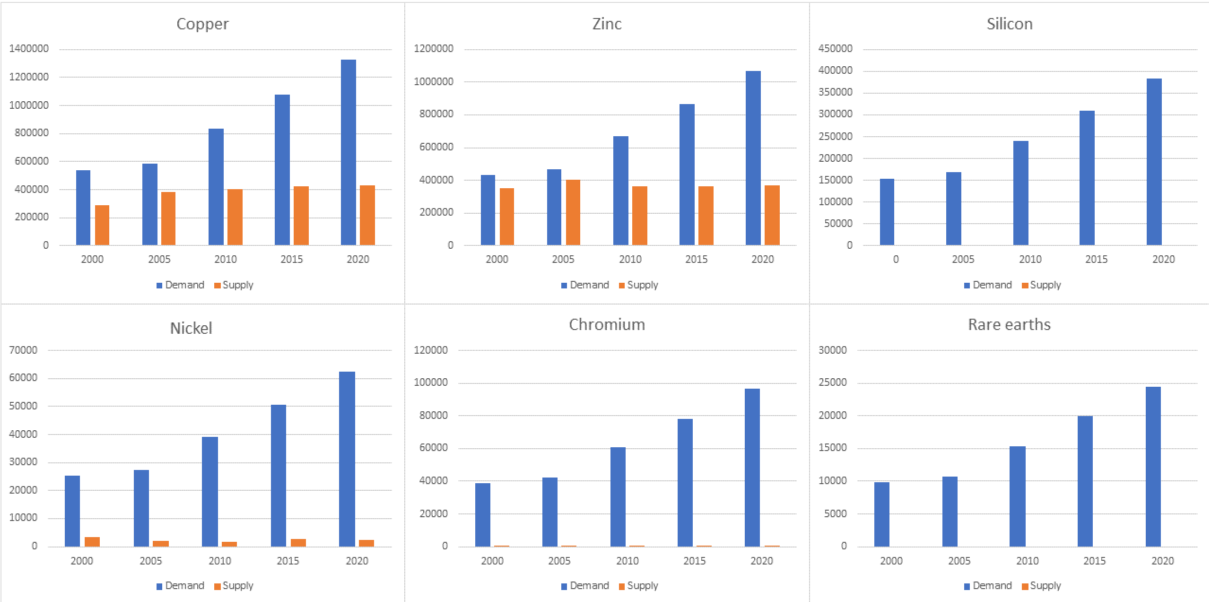


**Fig. 15** Supply and demand for metals (Copper, Zinc, Silicon, Nickel, Chromium, Rare earths) used for renewable generation in the EU (units: metric tons)

## SCENARIO ANALYSIS

The exploratory analysis in the previous section shows that the EU relies heavily on natural gas imports. Moreover, it reveals that the EU renewable electricity sector is heavily dependent on metal imports. The metal import dependency is already increasing, and the EU's renewable energy plan can be expected to accelerate the increase in metal import dependency even further. This raises two questions. First, it raises the question about the extent to which metal import dependency represents a security issue. Second, it raises the question of whether alternative energy mixes, such as a nuclear-intensive energy mix, could be preferable to a renewable energy mix in providing reduced emissions and energy security in the EU.

In this section, we attempt to find a basis to answer the above questions by exploring different potential future energy mixes and their metal and metal import requirements. Regarding additional metal and metal import requirements, we focus on both volumes and the monetary values of those volumes. The reason for considering both perspectives is that the prices of different metals can vary widely, which has the potential to reverse the outcome. For example, if the required import quantity of one metal (such as rare earths) is relatively small compared to other metals, but its unit price is very high. This may lead to the fact that from the perspective of value, the import of this metal requires a higher capital investment than other metals with large demand but a low unit price.

This section also defines three measures representing energy independence. The purpose of this part is to explore how much of the EU's electricity can be produced by itself, how much of the fossil fuels it required needs to be imported, and how much of the metals needed for electricity generation can be supplied locally. These provide more intuitive understandings of the how important the metal independence is to EU energy security. This section ends with a discussion of whether expanding domestic metal production in the EU is a viable way to increase its energy independence.

***The scenarios***

We use the year 2040 as the starting point for our analysis. As shown in Table 7, the electricity consumption of the EU in 2020 is 3026TWh. The electricity production from renewable and nuclear is 1129.8TWh and 822TWh, respectively. The average annual electricity consumption growth rate every 5 years from 1990 to 2020 was 2.96%. Assuming that in the next 20 years, electricity consumption changes according to the current trend, the total electricity consumption of the EU will reach 3399TWh in 2040.

Table 7 Current electricity generation by energy source in EU. Data sources: International Energy Agency (2021)

| Year | 2020 |
|---|---|
| Electricity consumption (TWh) | 3 026 |
| Renewable share in electricity production (%) | 0.37 |
| Nuclear share in electricity production (%) | 0.27 |
| Natural gas share in electricity production (%) | 0.20 |
| Coal share in electricity production (%) | 0.14 |
| Renewable capacity (TWh) | 1 130 |
| Nuclear capacity (TWh) | 822 |
| Natural gas capacity (TWh) | 609 |
| Coal capacity (TWh) | 415 |

Based on the estimated electricity consumption in 2040, we explore eight different electricity supply mixes – ranging from renewable-intensive to nuclear-intensive electricity supply. We first set up scenario 0, in which future energy consumption is satisfied with the current energy mix (37% or renewable, 27% nuclear, 20% of natural gas, and 14% of coal). This scenario is produced as a baseline for comparison – it is not realistic for the future, but provides an interesting baseline nonetheless.

Scenarios 1 to 7 represent different energy mixes for future clean energy transition with the reduction of power generation from fossil fuels. Scenario 1 is defined in line with the current EU Clean Energy Plan target, which is to achieve renewable electricity production that makes out 70% of the electricity supply (Bloomberg NEF, 2016). For simplicity, we assume natural gas, coal power generation, and nuclear make out the remaining 30% of the electricity mix, each with a 10% share. The settings for the other six scenarios are 60% renewable and 20% nuclear, 50% renewable and 30% nuclear, 40% renewable and 40% nuclear, 30% renewable and 50% nuclear, 20% renewable and 60% nuclear, 10% renewable and 70% nuclear, all else equal. The electricity capacity of different energy sources corresponding to each scenario is shown in Table 8.

Table 8 Electricity generation by energy source in 2040 of EU

| | Scenario 0 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 |
|---|---|---|---|---|---|---|---|---|
| Electricity consumption (TWh) | 3 399 | 3 399 | 3 399 | 3 399 | 3 399 | 3 399 | 3 399 | 3 399 |
| Renewable share in electricity production (%) | 37 | 70 | 60 | 50 | 40 | 30 | 20 | 10 |
| Nuclear share in electricity production (%) | 27 | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
| Natural gas share in electricity production (%) | 20 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Coal share in electricity production (%) | 14 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Renewable capacity (TWh) | 1 258 | 2 379 | 2 039 | 1 699 | 1 359 | 1 019 | 679 | 339 |
| Nuclear capacity (TWh) | 918 | 339 | 679 | 1 019 | 1 359 | 1 699 | 2 039 | 2 379 |
| Natural gas capacity (TWh) | 680 | 339 | 339 | 339 | 339 | 339 | 339 | 339 |
| Coal capacity (TWh) | 476 | 339 | 339 | 339 | 339 | 339 | 339 | 339 |

Next, we estimate the increase in renewable energy, nuclear, natural gas, and coal power generation from 2020 to 2040. It should be noted that to convert the data in TWh into MW to facilitate subsequent calculations, the conversion efficiencies of renewable energy, nuclear energy, coal, and natural gas in this paper are set to 0.25, 0.92, 0.33, 0.92 respectively, following NREL (2022). The results are shown in Table 9.

Table 9 Increase of renewable and nuclear power generation in 2040 of EU

| | Scenario 0 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 |
|---|---|---|---|---|---|---|---|---|
| Increase in renewable generation (TWh) | 128 | 1 250 | 910 | 570 | 230 | 0 | 0 | 0 |
| Increase in nuclear generation (TWh) | 96 | 0 | 0 | 197 | 537 | 877 | 1 217 | 1 557 |
| Increase in natural gas generation (TWh) | 71 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Increase in coal generation (TWh) | 61 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Increase in renewable generation (MW) | 58 508 | 570 814 | 415 570 | 260 325 | 10 5081 | 0 | 0 | 0 |
| Increase in nuclear generation (MW) | 11 872 | 0 | 0 | 24 527 | 66 713 | 108 899 | 151 085 | 193 271 |
| Increase in natural gas generation (MW) | 32 582 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Increase in coal generation (MW) | 27 677 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

According to the IEA report, the types and quantities of metals required for unit power generation of different energy sources vary widely, and the specific data are shown in Table 10. We note that the metal requirements for additional renewable electricity capacity are calculated based on an assumption regarding the renewable electricity mix. We assume additional renewable capacity is based on a renewable electricity mix consisting of 61.5% wind, 24% solar, 0% hydro, and 14.5% biofuels. These weights are calculated from the renewable electricity source's share of additional renewable electricity production capacity in the period 2015-2020.

Combining the increase of power generation of different energy in Table 9 and the amounts of various metals required for each new 1MW of power generation of different energy sources in Table 10, we can get the requirements of various metals for power generation and of natural gas and coal in different scenarios in Table 11. The reader should also note that we do not consider the metal requirements for replacing existing capacity, i.e., we do not consider depreciation. The lifespan of a solar panel, for example, is 25 to 30 years, which indicates that it makes sense assuming that the depreciation of power generation capaicity can be ignored and will not distort the conclusion.

Table 10 Metal requirements for different energy (units: kg/MW) Data sources: International Energy Agency (2022)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths |
|---|---|---|---|---|---|---|
| Renewable Mix | 3 718 | 3 392 | 208 | 949 | 303 | 51 |
| Nuclear | 1 473 | 0 | 1 297 | 0 | 2 190 | 0.5 |
| Natural gas | 1 150 | 0 | 721 | 0 | 307 | 0 |
| Coal | 1 100 | 0 | 16 | 0 | 48 | 0 |

***Metal requirements in terms of volume***

From Table 11 and scenario 0, it is found that the amount of metals needed for future additional electricity production is only 662 thousand tons if the EU continues with the current energy mix. Comparing the alternative scenarios, all scenarios, except scenario 5, generates higher metal requirements than the baseline scenario. This is because coal and natural gas still make up a significant portion of electricity generation in the current energy mix, and these two energies do not require much metals. However, if the new clean energy transition is carried out, reducing the proportion of coal and natural gas power generation while increasing the proportion of renewable energy and nuclear power generation, it will lead to a significant increase in the metals required due to the metal intensity of renewable and nuclear energy. This conclusion is consistent with that of an IEA report in 2021, which indicates that if the world wants to achieve global net zero emission by 2050, the metal requeirements will increase  more than four times due to the expanding use of clean energy.

Table 11 EU metal requirements for additional electricity production capacity in different scenarios in 2040 (units: thousand tons)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths | Total metals |
|---|---|---|---|---|---|---|---|
| Scenario 0 | 303 | 198 | 48 | 56 | 54 | 3 | 662 |
| Scenario 1 | 2 123 | 1 936 | 119 | 542 | 173 | 29 | 4 921 |
| Scenario 2 | 1 545 | 1 410 | 87 | 394 | 126 | 21 | 3 583 |
| Scenario 3 | 1 004 | 883 | 86 | 247 | 133 | 13 | 2 366 |
| Scenario 4 | 489 | 356 | 108 | 100 | 178 | 5 | 1 237 |
| Scenario 5 | 160 | 0 | 141 | 0 | 238 | 0 | **540** |
| Scenario 6 | 223 | 0 | 196 | 0 | 331 | 0 | 750 |
| Scenario 7 | 285 | 0 | 251 | 0 | 423 | 0 | 959 |

Further, from Table 11, it is seen that when the proportion of electricity generation from renewable energy is greater than or equal to that of nuclear energy (scenarios 1 to 4), the requirements for copper and zinc for additional electricity production capacity are most significant, at least in terms of volumes. Moreover, it shows that when the share of renewable energy decreases, while the share of nuclear power generation increases, the total metal requirement decreases.

Our results show that scenario 5 produces the lowest metal requirements. This means that when 30% of the EU's electricity generation comes from renewable energy and 50% from nuclear energy, the amounts of metals required for additional electricity production capacity are minimal.

When the proportion of renewable energy further decreases relative to nuclear power generation (scenarios 6 to 7), the requirements of copper demand start to slowly rise. This is because nuclear energy replaces existing renewable energy production capacity. At the same time, the requirements for chromium, which is a key demand metal for nuclear energy, rise sharply. As a result, when the proportion of renewable energy generation decreases from 30% in scenario 5 to 20% and 10%, respectively, in scenarios 6 and 7, the total requirement for metals gradually increases.

Overall, it can be concluded that if the EU wants to reduce its metal consumption as much as possible, an energy structure with 30% renewable energy power generation combined with 50% nuclear power generation is the best option. More interestingly, the total amount of metal required for scenario 5 is even less than the total amount of metal required for scenario 0. This means that if the EU reduces the share of coal and natural gas to 10% each in the future but allocates the remaining power generation to renewable energy and nuclear energy according to a ratio of 3:5, then even if the metal intensity of renewable energy and nuclear energy is greater, this energy mix makes the corresponding total demand for metals smaller than that without reducing the share of coal and natural gas generation. This result is undoubtedly satisfactory.

The values in Table 11 are the total metal requirements for continuing to increase renewable and nuclear power generation. Assuming that these total metal requirements are spread over each year, we can obtain the annual metal requirements for additional electricity production capacity from 2020 to 2040. The results are shown in Table 12. The historical annual metal requirements for new electricity production capacity are shown in Table 13.

Table 12 EU metal requirements per year for additional electricity production capacity from 2020-2040 (units: metric tons)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths | Total metals |
|---|---|---|---|---|---|---|---|
| Scenario 0 | 15 136 | 9 922 | 2 403 | 2 777 | 2 690 | 148 | 33 076 |
| Scenario 1 | 106 126 | 96 805 | 5 947 | 27 088 | 8 641 | 1 444 | 246 052 |
| Scenario 2 | 77 263 | 70 477 | 4 330 | 19 721 | 6 291 | 1 051 | 179 133 |
| Scenario 3 | 50 206 | 44 149 | 4 303 | 12 354 | 6 627 | 659 | 118 298 |
| Scenario 4 | 24 450 | 17 821 | 5 423 | 4 987 | 8 896 | 268 | 61 844 |
| Scenario 5 | 8 020 | 0 | 7 064 | 0 | 11 925 | 3 | 27 012 |
| Scenario 6 | 11 127 | 0 | 9 801 | 0 | 16 544 | 4 | 37 476 |
| Scenario 7 | 14 234 | 0 | 12 538 | 0 | 21 163 | 5 | 47 940 |

Table 13 EU historical metal requirements per year for electricity production (units: metric tons)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths | Total metals |
|---|---|---|---|---|---|---|---|
| 2000-2005 | 14 926 | 23 519 | 1 655 | 485 | 2 033 | 156 | 42 775 |
| 2005-2010 | 27 756 | 36 095 | 2 539 | 7 572 | 3 116 | 239 | 77 317 |
| 2010-2015 | 57 148 | 62 162 | 4 370 | 26 206 | 5 357 | 411 | 155 655 |
| 2015-2020 | 66 530 | 84 192 | 5 922 | 20 184 | 7 265 | 558 | 184 651 |
| 20-year average | 41 590 | 5 1492 | 3 622 | 13 612 | 4443 | 341 | 115 100 |

If we compare the annual metal requirements for the next 20 years with the historical data for the past 20 years from 2000 to 2020 (Table 13), we can find two characteristics. First, in the past 20 years, due to the continuous increase in the proportion of renewable energy power generation, the requirements for various metals have increased year by year. Second, if the EU continues the current energy mix in the future 20 years, the annual requirements for all main metals will be significantly less than the recent historical metal requirements (metals requirements of scenario 0 < metals requirements in 2015-2020). In addition, when the future share of renewable energy generation is more than 50% (scenarios 1-3), the annual metal requirement in the next 20 years will be more than the average in the past 20 years.

***Metal requirements in terms of dollar value***

Scenario 5 reduces the metal volume requirements as much as possible by increasing the proportion of nuclear generation while reducing the power generation share of natural gas. However, it leads to a new concern that this proposal may cause high metal purchase expenditure. The prices for nickel and chromium, which are mainstay requirements for nuclear, are high (22705$/tons and 12456$/tons, respectively)[1]. Meanwhile, the main metals of renewables, zinc, and silicon, have relatively low prices (2920$/tons and 9616$/tons, respectively)[2]. Therefore, even though the metal volumes required for a nuclear-intensive energy system are lower than that of a renewable-intensive system, the overall expenditure could be higher.

To explore how scenario 5 compares to other scenarios in terms of metal value requirements rather than metal volume requirements, we calculate the monetary values for the metals required for additional electricity production capacity in all scenarios. The results are shown in Figure 16 (with prices of copper and rare earths at 7536$/tons and 24222$/tons[3], respectively). The results suggest that scenario 5 (30% of renewable and 50% nuclear) not only generates the lowest metal volume requirements but also the lowest metal value requirements, which amounts to 4.1 billion USD. This indicates that even though the unit prices of mainstay metals for nuclear are high, the total cost of increasing the proportion of nuclear to 50% and keeping 30% for renewable energy will not cause high metal value requirements when compared to the other scenarios.

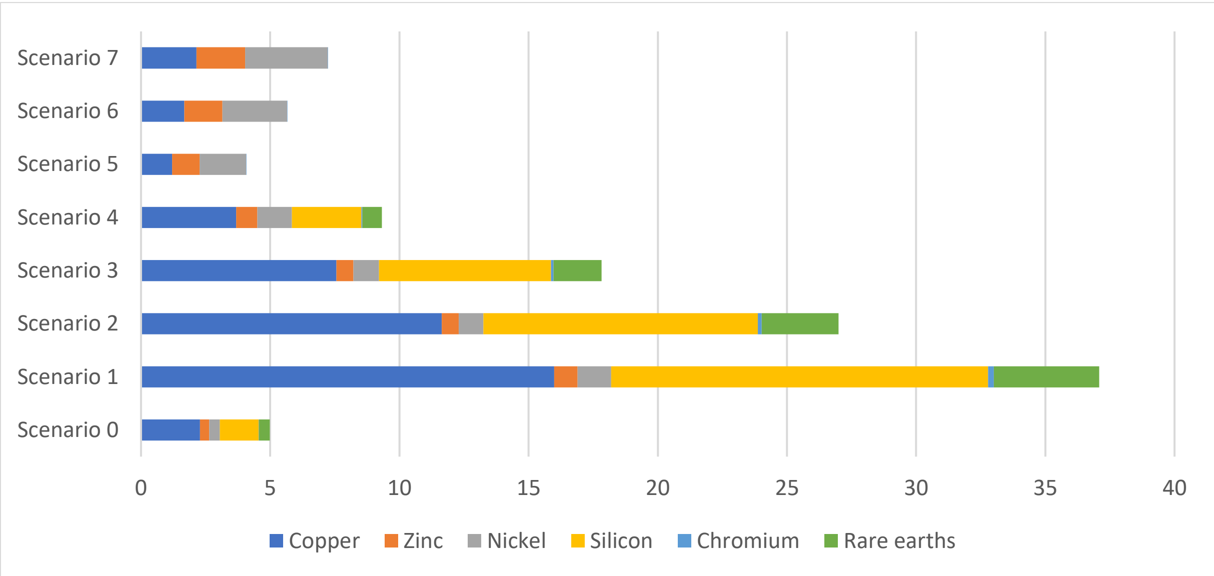


**Fig. 16** Values for required metals for additional electricity production capacity for different scenarios (units: billion USD)

[1] Data sources: KMD Group, metal prices
[2] Data sources: pharmacompass, prices
[4] The price of rare earths is the average price of different commodities of rare earths, including Neodymium, Praseodymium, Gadolinium, Lanthanum, PrNd, Cerium, Samarium, SmEuGd, Yttrium.

Interestingly, the cost of scenario 1, which represents the current EU proposal (renewable energy generation in the EU should reach 70% of the total in the future), is 37 billion USD. This is the metal value requirement planned for the renewable-intensive energy system. In comparison, based on the 2020 data about natural gas consumption (IEA, 2021) and price (World Bank, 2021), the cost of natural gas consumption in the EU is about 185 billion USD, of which 131 billion is spent on Russian import. Therefore, although the EU's current energy mix plan (scenario 1) is not the best option to minimize the metal value requirements, its cost is still much lower than the current situation. That is, the idea that the EU should use renewable energy to replace natural gas, although will cause greater metal requirements, can still be regarded as improving energy security in terms of value.

In addition, the results show that the renewable-intensive energy mix scenarios (scenarios 1-4) need more rare earths, while the nuclear-intensive energy system does not. Rare earths are worthy to be noticed is because it has the strongest geographic concentration. According to the IEA (2022), 60% and 87% of the world's rare earths are extracted and processed in China. This is evidence of a strong dependence on China for rare earth imports. Rare earths are also more expensive than other metals based on a unit price comparison. Combining the two we find that rare earths have the greatest scarcity and import dependence risk of all main metals. So, it can be said that although the amount of rare earth in the demand for renewable energy is small, its importance cannot be underestimated. Thus, nuclear energy that does not require rare earths faces less risk of energy dependency than renewable energy.

***Metal import requirements***

In the previous subsection, we considered metal volume requirements and metal value requirements. In the following, we investigate future potential metal import volume requirements. To do so, we use the EU's current metal demand, metal supply, and metal import situation as a starting point. Then we use the results from the scenario analysis to see how future scenarios will change current metal demand. About this, we make some assumptions regarding the EU electricity sector's metal consumption for other things than additional electricity production capacity – that is, for use in the development of transmission systems, storage, etc. Further, we make some assumptions regarding future EU metal supply. Finally, based on all this, we can investigate future potential metal import requirements.

First, regarding demand, we have information about the total metal consumption of the EU electricity sector. The reader should recall that this includes metal consumption tied to the development of transmission systems, electricity storage, etc. Further, available information lets us calculate the historical average annual metal consumption for additional electricity production capacity in Table 13. Using this information together, we can calculate the electricity sector's metal consumption for other things than additional electricity production capacity. This is done by taking the total metal consumption of the sector and subtracting the consumption tied to additional electricity production capacity. The result from this calculation is shown in Table 14. The results highlight that the metal requirements for electricity production only account for a small proportion of the total metal requirements for the electricity sector.

Table 14 Metal requirements for different divisions in the electricity sector in 2020 (units: metric tons)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths |
|---|---|---|---|---|---|---|
| Metal consumption for electricity sector | 2 172 486 | 1 643 272 | 321 698 | 24 562 | 399 182 | 459 825 |
| Metal requirements for electricity production | 66 530 | 84 192 | 5 922 | 20 184 | 7 265 | 558 |
| Metals consumption for electricity sector excluding electricity production | 2 105 956 | 1 559 080 | 315 776 | 4 379 | 391 917 | 459 268 |

Using the knowledge acquired through Table 14, we can calculate the future metals consumption for the EU electricity sector, including consumption relating to production, transmission, storage, etc. We do this by assuming consumption relating to transmission, storage, etc. remains constant at 2020 levels. The estimated total metal requirements of the electricity sector in the different future scenarios are shown in Table 15.

Table 15 EU metal requirements for the electricity sector in 2040 (units: metric tons)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths |
|---|---|---|---|---|---|---|
| Scenario 0 | 2 121 092 | 1 569 003 | 318 179 | 7 155 | 394 607 | 459 416 |
| Scenario 1 | 2 212 081 | 1 655 885 | 321 723 | 31 467 | 400 558 | 460 712 |
| Scenario 2 | 2 183 219 | 1 629 557 | 320 106 | 24 100 | 398 208 | 460 319 |
| Scenario 3 | 2 156 162 | 1 603 229 | 320 080 | 16 732 | 398 544 | 459 927 |
| Scenario 4 | 2 130 406 | 1 576 901 | 321 199 | 9 365 | 400 813 | 459 535 |
| Scenario 5 | 2 113 976 | 1 559 080 | 322 841 | 4 379 | 403 842 | 459 270 |
| Scenario 6 | 2 117 083 | 1 559 080 | 325 577 | 4 379 | 408 461 | 459 271 |
| Scenario 7 | 2 120 190 | 1 559 080 | 328 314 | 4 379 | 413 080 | 459 272 |

Next, we consider the EU supply and import of metals. Tables 4 and 6 in the exploratory data analysis give information about the current EU supply to the electricity sector and the import of metals for the electricity sector. If we assume that the metal supply in the EU stays constant at today's level in the future, we can estimate the EU metal import requirements for the electricity sector in future scenarios. Further, we can calculate the corresponding import shares. The results from these calculations are shown in Tables 16 and 17, respectively.

Table 16 EU metal import requirements for the electricity sector in 2040 (units: metric tons)

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths |
|---|---|---|---|---|---|---|
| Scenario 0 | 1 543 984 | 1 200 193 | 308 818 | 7 132 | 394 605 | 459 416 |
| Scenario 1 | 1 634 974 | 1 287 075 | 312 362 | 31 444 | 400 556 | 460 712 |
| Scenario 2 | 1 606 111 | 1 260 747 | 310 745 | 24 077 | 398 206 | 460 319 |
| Scenario 3 | 1 579 055 | 1 234 419 | 310 719 | 16 709 | 398 542 | 459 927 |
| Scenario 4 | 1 553 299 | 1 208 091 | 311 838 | 9 342 | 400 811 | 459 535 |
| Scenario 5 | 1 536 869 | 1 190 270 | 313 480 | 4 356 | 403 839 | 459 270 |
| Scenario 6 | 1 539 976 | 1 190 270 | 316 216 | 4 356 | 408 459 | 459 271 |
| Scenario 7 | 1 543 083 | 1 190 270 | 318 953 | 4 356 | 413 078 | 459 272 |

Table 17 EU metal import share for the electricity sector in 2040

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths |
|---|---|---|---|---|---|---|
| Scenario 0 | 0.7279 | 0.7649 | 0.9706 | 0.9968 | 1.0000 | 1.0000 |
| Scenario 1 | 0.7391 | 0.7773 | 0.9709 | 0.9993 | 1.0000 | 1.0000 |
| Scenario 2 | 0.7357 | 0.7737 | 0.9708 | 0.9990 | 1.0000 | 1.0000 |
| Scenario 3 | 0.7323 | 0.7700 | 0.9708 | 0.9986 | 1.0000 | 1.0000 |
| Scenario 4 | 0.7291 | 0.7661 | 0.9709 | 0.9975 | 1.0000 | 1.0000 |
| Scenario 5 | 0.7270 | 0.7634 | 0.9710 | 0.9947 | 1.0000 | 1.0000 |
| Scenario 6 | 0.7274 | 0.7634 | 0.9712 | 0.9947 | 1.0000 | 1.0000 |
| Scenario 7 | 0.7278 | 0.7634 | 0.9715 | 0.9947 | 1.0000 | 1.0000 |

Table 17 gives two important insights. First, the difference in the import share of the electricity sector under different scenarios, especially between scenario 0 (no clean energy transition) and the other scenarios (energy transition), is not large. This is mainly because the biggest difference between different scenarios lies in the metal demand for power production, but the metal requirements for power production account for a small proportion of the total metal requirements in the electricity sector. Second, the requirements for imports of different types of metals is significantly different. Almost all chromium and rare earths needed by the EU's electricity industry are imported. Over 97% of nickel and 99% of silicon needed to be imported. In contrast, the import shares of copper and zinc are relatively lower, but both are above 70%. These prove that the metal requirements in the EU are worthy to be considered because they are strongly dependent on imports.

***Energy security and independency index***

Using the information acquired through the analyses in the previous subsections, we measure energy and metal independence in various future scenarios. In relation to this, we define three measurements. The first measurement focus on how much of the EU electricity consumption can be produced within EU borders, without considering where any of the fuels or metals come from. The second measurement considers how much of the EU electricity consumption can be produced within EU borders with fuels produced within EU borders. The third measurement focus on how much of the electricity sector's metal consumption can be covered by the EU metal supply.

Table 18 shows the mathematical definition of the measurements. It should be noted that the metal production required in the calculation process is calculated on the basis that we keep the assumption introduced in the previous section regarding the future metal supply, namely that it remains constant at today's level.

Table 18 Mathematical definition of three measurements

| Measurement | Mathematical definition |
|---|---|
| 1st measurement (Electricity independence) | $Production\ of\ electricity\ in\ EU / electricity\ consumption\ in\ EU$ |
| 2nd measurement (Electricity independence when also considering fuel imports) | $1st\ measurement * (Min\ [(Natural\ gas\ production\ in\ EU / natural\ gas\ consumption); 1] * natural\ gas\ share + Min\ [(coal\ production\ in\ EU / coal\ consumption); 1)] * coal\ share + renewable\ share + nuclear\ share)$ |
| 3rd measurement (Metal independence) | $Metal\ production\ for\ electricity\ sector / metal\ consumption\ for\ electricity\ sector$ |

In Table 19, we compare the results for scenarios 0, 1, and 5. In this way, we can explore the independency indicator if EU continues its current energy mix (scenario 0), implements its current clean energy transition plan (scenario 1), and implements the optimal energy mix (scenario 5), respectively.

Table 19 Energy Independency index in 2040

| | Scenario 0 | Scenario 1 | Scenario 5 | Units |
|---|---|---|---|---|
| Electricity consumption of EU | 3 399 | 3 399 | 3 399 | TWh |
| Electricity production in EU | 3 250 | 3 250 | 3 250 | TWh |
| **1st measurement** | **0.956** | **0.956** | **0.956** | |
| Electricity production from renewable | 1 203 | 2 275 | 975 | TWh |
| Electricity production from nuclear | 878 | 325 | 1 625 | TWh |
| Electricity production from natural gas | 650 | 325 | 325 | TWh |
| Electricity production from coal | 455 | 325 | 325 | TWh |
| Consumption of natural gas | 2 543 875 | 1 271 937 | 1 271 937 | TJ |
| Consumption of coal | 169 390 | 120 993 | 120 993 | thousand tons |
| Production of natural gas | 1 913 438 | 1 913 438 | 1 913 438 | TJ |
| Production of coal | 338 148 | 338 148 | 338 148 | thousand tons |
| **2nd measurement** | **0.909** | **0.956** | **0.956** | |
| Electricity production from renewable | 549 172 | 1 038 975 | 445 275 | MW |
| Electricity production from nuclear | 108 888 | 40 329 | 201 644 | MW |
| Electricity production from natural gas | 80 666 | 40 333 | 40 333 | MW |
| Electricity production from coal | 157 420 | 112 443 | 112 443 | MW |
| Consumption of copper for renewable | 2 041 822 763 | 3 862 907 930 | 1 655 531 970 | kg |
| Consumption of nickel for renewable | 114 227 847 | 216 106 737 | 92 617 173 | kg |
| Consumption of silicon for renewable | 521 164 551 | 985 986 989 | 422 565 853 | kg |
| Consumption of zinc for renewable | 1 862 792 580 | 3 524 202 178 | 1 510 372 362 | kg |
| Consumption of chromium for renewable | 166 399 219 | 314 809 334 | 134 918 286 | kg |
| Consumption of rare earths for renewable | 28 007 789 | 52 987 710 | 22 709 018 | kg |
| Consumption of metals for renewable | 4 734 414 750 | 8 957 000 879 | 3 838 714 662 | kg |
| Consumption of copper for nuclear | 160 391 931 | 59 404 419 | 297 022 094 | kg |
| Consumption of nickel for nuclear | 141 271 209 | 52 322 670 | 261 613 350 | kg |
| Consumption of chromium for nuclear | 238 464 582 | 88 320 215 | 441 601 077 | kg |
| Consumption of rare earths for nuclear | 54 444 | 20 164 | 100 822 | kg |
| Consumption of metals for nuclear | 540 182 166 | 200 067 469 | 1 000 337 344 | kg |
| Consumption of copper for natural gas | 92 765 598 | 46 382 799 | 46 382 799 | kg |
| Consumption of nickel for natural gas | 58 159 997 | 29 079 998 | 29 079 998 | kg |
| Consumption of chromium for natural gas | 24 764 381 | 12 382 191 | 12 382 191 | kg |
| Consumption of metals for natural gas | 175 689 976 | 87 844 988 | 87 844 988 | kg |
| Consumption of copper for coal | 173 162 450 | 123 687 464 | 123 687 464 | kg |
| Consumption of nickel for coal | 2 518 727 | 1 799 090 | 1 799 090 | kg |
| Consumption of chromium for coal | 7 556 180 | 5 397 271 | 5 397 271 | kg |
| Consumption of metals for coal | 183 237 356 | 130 883 826 | 130 883 826 | kg |
| Consumption of metals for electricity sector | 5 633 524 248 | 9 375 797 161 | 5 057 780 820 | kg |
| Production of metals for electricity sector | 955 303 000 | 955 303 000 | 955 303 000 | kg |
| **3rd measurement** | **0.170** | **0.102** | **0.189** | |

According to the results, 95.6% of electricity is estimated to be produced within EU borders across all scenarios. This means that the energy independency of the EU in terms of electricity capacity is satisfying. If the EU continues its current energy mix, in which the power generation shares of natural gas and coal are 37% and 27%, respectively, the estimated consumption of natural gas and coal are 254 million TJ and 169,390 thousand tons. If the EU wants to reduce the natural gas and coal power generation shares to 10%, respectively by 2040 (scenarios 1 and 5), the required amount of natural gas and coal are estimated at 127 million TJ and 120,993 thousand tons, respectively.

Under the assumption that EU production of coal and natural gas stays constant at the 2020's level, it is estimated that the production of coal in the EU can meet the demand in all scenarios, while the production of natural gas in the EU can cover the demand only in scenarios 1 and 5. That is, under scenario 0, the import of natural gas negatively affects the fuel production independence of the EU in 2040.

Based on the energy mix with 10% of natural gas electricity generation, the second measurement of energy independency after considering the fuel imports is 0.956 for scenarios 1 and 5. This high fraction indicates that energy independence from the perspective of external fuel independence is also at a high level. This is because of the low proportion of fossil fuels in this chosen energy mix. In contrast, if the EU will not decrease the proportion of natural gas and coal in the future, the fuel independency index is 0.909 (scenario 0), which is lower than that of scenarios 1 and 5. This comparison indicates that reducing the power generation from fossil fuels can increase energy independency in terms of fuel imports.

The good performance of the first two measurements does not necessarily mean that the energy independence in the EU is good. As already communicated, the EU relies heavily on metal imports. If this is considered, the energy security discussion becomes more complicated and nuanced.

If the EU continues with its current energy mix, its metal independence is estimated at 0.17 in 2040. This is a small number which means that the EU is importing most of the metals it needs for the electricity sector. However, if we compare the value of the third measurement of scenario 0 with scenario 1, the metal independency under the current energy mix is higher. This is because under the current energy mix, 34% of electricity generation comes from low-metal-intensity fossil fuels, and 27% comes from medium-metal-intensity nuclear energy. The combined share of these two is larger than metal-intensive renewables. In contrast, If the EU increases its renewable generation share to 70%, its metal independency drops to 0.102. This means that the use of renewable to replace fossil fuels while reducing the use of nuclear energy would result in a significant reduction in the EU's metal independence. However, if the EU can use renewable energy and nuclear energy to replace fossil fuels and control the proportion of the two to 30% renewable energy and 50% nuclear energy, its metal independence will rise again to 0.189. It can be found that the metal independence of scenario 5 is even higher than the energy independence of scenario 0. This means that the EU's current plan to reduce the use of natural gas is feasible. But it also proves that the EU should not completely rely on renewable energy to replace natural gas. Let nuclear generation share accounts for a larger proportion is a better choice.

Combining the comparison of the three scenarios, we can draw two conclusions. First, the current energy mix has low fuel independence due to the still significant proportion of fossil fuels. Although the renewable-intensive energy mix currently planned by the EU can improve energy independence from the perspective of fuel imports, on the other hand, it will cause a significant reduction in metal independence. For the EU, scenario 5 is the optimal choice. Because it can not only achieve the goal of reducing the proportion of natural gas power generation and improving fuel independence but also maintain metal independence at a relatively high level as much as possible. Second, through the longitudinal comparison of the three measures in each scenario, it can be found that the energy independence of the EU is satisfactory if only electricity and fuel imports are considered, but once metal imports are also taken into consideration, its energy independence will be greatly reduced. Even if the EU chooses the energy mix of scenario 5 from the perspective of energy security, its energy independency in terms of metal import is still less than 0.2, which means that it will still face a relatively serious problem of strong metal import dependence. This conclusion once again proves that metal requirements make energy security a concern that cannot be ignored. In other words, as long as the EU tries to shift its dependence on natural gas to renewable or nuclear energy in the next 20 years, it will cause the dependence on imports of natural gas from Russia to dependence on imports of metals from other countries such as China. This is more like a dependency transformation, not a solution.

***The metal supply challenge***

Even if the EU can adjust its energy mix and minimize its energy dependence on other countries, metal supply needed to expand renewable energy and nuclear power generation is still the problem it is facing in the clean energy transition because its own metal production and processing volume is too small.

To further address the issue of insufficient metal supply in the EU, there are two possible solutions. The first is to increase the diversity of import source countries. For example, the large quantities of copper needed by the EU can be imported from Chile, Peru, and China, while nickel can be imported from Indonesia, the Philippines, or Russia (IEA, 2022). In addition, from the processing point of view, although metal processing is highly dependent on China, the EU still has other options. For example, Chile and Japan could replace China as options for copper processing, and Indonesia and Japan could be options for nickel processing (IEA, 2022). Taken together, the EU can choose Chile as an alternative for producing and processing copper and Indonesia as an alternative for producing and processing nickel. In this way, the EU can reduce its metal dependence on China to a certain extent to improve energy security.

The second way is to expand the EU's metal production, that is, to increase the capacity of metal mining and processing. The above analysis assumes that the metal supply in the EU keeps constant in the future 20 years. Then, if now we assume that the EU tries to increase the metal supply following the growth rate in the past 30 years (that is, the growth rate of copper, zinc, nickel, silicon, chromium, and rare earths are 0.02, 0.005, 0.02, 0.00, 0.02 and 0.00, respectively), how the metal import share and the third measurement for independency index will change?

The results are in Tables 20 and 21. If we compare Table 20 with Table 17, we can find that the import shares of copper, zinc, and nickel have all decreased significantly, among which copper is the most obvious (from greater than 0.7 to about 0.6). This means that expanding the EU's metal production is indeed a method that can reduce the demand for metal imports to a certain extent and further ensure energy security. According to the results in Table 21, when the EU expands metal production in the future, the value of the third measure of energy independency will increase, which means that the independence of metals will be significantly improved. Both results demonstrate that expanding metals production in the EU can contribute to further energy security.

Table 20 EU metal import share for electricity sector in 2040 with metal production increases

| | Copper | Zinc | Nickel | Silicon | Chromium | Rare earths |
|---|---|---|---|---|---|---|
| Scenario 0 | 0.5957 | 0.7403 | 0.9563 | 0.9968 | 1.0000 | 1.0000 |
| Scenario 1 | 0.6123 | 0.7539 | 0.9568 | 0.9993 | 1.0000 | 1.0000 |
| Scenario 2 | 0.6072 | 0.7499 | 0.9565 | 0.9990 | 1.0000 | 1.0000 |
| Scenario 3 | 0.6023 | 0.7458 | 0.9565 | 0.9986 | 1.0000 | 1.0000 |
| Scenario 4 | 0.5975 | 0.7416 | 0.9567 | 0.9975 | 1.0000 | 1.0000 |
| Scenario 5 | 0.5943 | 0.7386 | 0.9569 | 0.9947 | 1.0000 | 1.0000 |
| Scenario 6 | 0.5949 | 0.7386 | 0.9573 | 0.9947 | 1.0000 | 1.0000 |
| Scenario 7 | 0.5955 | 0.7386 | 0.9576 | 0.9947 | 1.0000 | 1.0000 |

Table 21 Third measurement for independency with and without metal production increases

| | Scenario 0 | Scenario 1 | Scenario 5 |
|---|---|---|---|
| 3rd measurement (without metal production increases) | 0.170 | 0.102 | 0.189 |
| 3rd measurement (with metal production increases) | 0.227 | 0.136 | 0.253 |

However, we cannot ignore the bottleneck risks of silicon, chromium and rare earths. According to the comparison with and without metal production increases, the metal import share of silicon remains above 0.99, while the import of rare earths is always maintained at 1. The expansion of production has little effect on these two metals because their original production is so low relative to demand that it is almost negligible. However, silicon is the most needed metal for solar power generation. Offshore wind technology requires rare earths. Solar energy and wind energy are currently listed by the EU as the most important sources of future renewable energy generation (IEA, 2021). Therefore, the high import share of silicon and rare earth is a hidden danger to energy security in terms of expanding renewable energy use. The solutions to these risks are complicated. Deep sea mining has been pointed to as a possible solution to this problem (U.S. GAO, 2021). Many Europenan countries are already looking into this, such as Norway and Belgium. But other countries such as Spain, Italy and Sweden remain skeptical of this solution because of the harm it could do to biodiversity (European Commission, 2021).

The bottleneck risk for nuclear energy is chromium. Nuclear energy technology requires large amounts of chromium. The mine production of chromium in the EU is high, with Finland being the largest producer, but the EU lacks processing capacity for chromium. This is the reason why increasing production cannot improve the import share of chromium. That is, the bottleneck problem of chromium is more on processing capacity rather than mine production capacity like silicon and rare earths. This means that it could be easier for the EU to deal with the chromium bottleneck risk because it is easier to become self-sufficient if it lacks only processing capacity, compared with lacking the resource foundation. As such, it could solve this risk by building up EU's own processing capacity for chromium.

To sum up, expanding the metal production locally can only partially address the energy security problem caused by the large share of metal imports. For both renewable energy and nuclear energy, there are still complex bottleneck issues that need to be further resolved. But if the two are compared, the bottleneck problem of nuclear energy is relatively easier to solve than that of renewable energy.

## CONCLUSION

To achieve the Sustainable Development Goals, the EU has been reshaping its energy and electricity mix by reducing consumption of fossil fuels and increasing the clean energy capacity. Up to 2005, natural gas was preferred due to its mature technology and easy availability. However, the EU's heavy reliance on imports of natural gas, coupled with its strong concentration in Russia, led to concerns about its future energy security. Thus, since 2005, the EU planned to gradually shift its focus from natural gas to renewable energy. However, in 2022, the outbreak of the Ukraine crisis forced the EU to speed up this original plan to reduce its dependence on natural gas. The EU's current strategyis to pay even more attention to renewable energy – three months after the outbreak of the Ukraine crisis, the EU urgently formulated the REPowerEU plan, saying that the EU's new proposal hopes that its renewable power generation share can reach 70% of total electricity production by 2040.

However, the current strategy has raised new concerns about the future. Renewable energy is metal-intensive. Too much reliance on renewable energy will require high quantities of metals like copper, zinc, and nickel – much more than what the EU is currently able to cover through its production and processing. Moreover, renewable technology also require metals that the EU does not have the capability to mine and process, for example, silicon and rare earths. That is, replacing natural gas with renewable energy may result in a significant increase in the EU's metal import dependence, which will adversely affect the EU's energy security.

Nuclear energy has a relatively low metal intensity compared to renewable energy. Thus, this paper tries to explore that whether nuclear-intensive energy system would be a more appropriate option if renewable energy may cause serious metal security problem. To this end, this paper conduct scenario analysis, attempting to find an electricity mix with a reasonable distribution ratio of renewable energy and nuclear energy, to minimize the amount of required metals. There are a total of 8 scenarios we use to represent the electricity mixes. Scenario 0 represents the electricity mix in 2020, and scenario 1 represents the electricity mix with increasing the proportion of renewable energy to 70% and reducing the proportion of nuclear energy to 10% in accordance with the EU's current energy transition plan. Scenarios 2 to 7 represent different electricity mixes for every 10% reduction from 70% in the renewable share and every 10% increase from 10% in the nuclear share.

Based on the above, we forecast the metal volume requirements for different 2040 scenarios based on the 30-year trends in electricity, energy, and metal production, demand, and imports from 1990 to 2020. The results show that metal requirements are minimized with the electricity mix in scenario 5 consisting of 30% renewables, 50% nuclear, 10% natural gas and 10% coal. In addition, in order to prevent the inconsistency that the result of the value-based metal requireents being different from the volume-based metal requirements that may be caused by the large unit price gap of different metals, this paper also calculates the metal value requirements in 8 scenarios. The results show that the electricity mix with 30% renewable and 50% nuclear will still be the best in terms of metal value requirements.

It should be noted that the above metal requirements are calculated based on the assumption that we do not consider the depreciation of electricity capacity and the metal requirements for electricity sector other than electricity production are constant in the future. So, it is possible that they are underestimated. But such underestimation is valid for each scenario so that it will not distort the conclusion that the scenario 5 is the best for energy security in terms of both metal volume requirements and metal value requirements. In addition, our conclusion saying that the energy mix consists of 30% renewable and 50% of nuclear is good is only based on the perspective of achieving lowest metal requirements, it does not means we think it is the recommended option for EU. Because there are a lot of other things also matter when the EU make the final decision for the future energy mix, such as resources availability, investment potential, development cycle and technical difficulity. But they are out of the scope of this paper's analysis and worthy further studies in the future.

We also calculate three measurements for energy independency. The first measurement represents energy independency in terms of electricity import share, the second measurement shows energy independency when also considering fuel imports, while the third measurement is focus on energy independency in terms of metal independence. In this part of the analysis, we compare scenario 0, which represents the current power mix, scenario 1, which represents the latest clean energy transition plan, and scenario 5, which is proved to be able to minimize metal requirements in our scenario analysis.

It turns out that the results for energy security of the EU are positive in all three scenarios when we only consider electricity independence and fuel independence, while the energy security becomes an issue that worthy to be concerned once the factor of metal dependence is added. Accordig to the results, when metal imports are considered, the EU's energy independence index falls from more than 90% in the first two measurements to less than 20% in the third measurement. If we compare the results of the three scenarios, scenario 5, which represents a nuclear-inetnsive electricity mix, has a higher metal independence than scenario 1, representing a renewable-intensive electricity mix. But the metal independency of scenario 5 is still below 20%. This means that even an electricity mix (30% renewable and 50% nuclear) that minimizes the metal requirements is not be able to help the EU to a significant extent in getting rid of its energy dependence on metal imports.

After proving that the adjustment of the distribution of renewable energy and nuclear energy cannot fundamentally solve the risk of high dependence on foreign metals caused by the clean energy transition plan, this paper attempts to explore whether expanding the EU's local metal production is a way that might help. According to the results of the comparison between the increase and non-increase of metal production in the EU in the next 20 years, the expansion of metal production will have a more obvious effect on reducing the import share of copper, zinc and nickel. But its impact on silicon, chromium and rare earths is not significant. This is a potential bottleneck risk for the development of clean energy in the future. But because the main problem of chromium is that the production is not low but the processing capacity is insufficient, while the main problem of silicon and rare earths is the insufficient local production capacity, we can think that the bottleneck problem of nuclear energy that mainly needs chromium is easier to be solved than the bottleneck problem of renewable energy that mainly needs silicon and rare earths.

In short, this paper concludes that the EU's current new clean energy transition plan suggesting that the renewbale power generation share should achieve 70% by 2040, needs to be reconsidered due to its high metal requirements and metal import dependency. In contrast, a nuclear-intensive electricity mix does not only have greater energy security performance in terms of metal volume and value requirements, but also has relatively less serious bottlenecks risks related with silicon and rare earths. This conclusion is drawn on the basis of only considering energy and metal security without considering other influencing factors for electricity sector, so that it can only be used as a partial reference for the improvement of the EU's future clean energy transition plan.

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