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The vulnerability of shifting towards a greener world

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Original Research Articles

The vulnerability of shifting towards a greener world: The impact of the EU's green transition on material demand

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ABSTRACT

The green transition from fossil fuels to renewables requires acquisition of rare earth minerals and other materials for construction of renewable energy technologies and may lead to new dependencies through imports potentially causing immense pressure on global supply chains. This study investigates the material vulnerability of sectors and countries in the EU. Vulnerability maps are created for the EU's material demands by combining three analyses: input-output analysis, forward linkage analysis and network analysis. The approach reveals the relative importance of individual sectors and their vulnerability given increasing demand. As such, the analyses help to identify which sectors, based on their current implementation of renewable energy sources, could put a country and the EU at risk of not meeting their mitigation targets by 2050. The analysis concludes that Austria, Germany, the Czech Republic, Denmark and Slovakia will experience particularly large material vulnerabilities in several of the materials investigated. Hence, such findings can provide early warnings to sectors and countries about potential implications in their supply chains along with potential mitigation measures such as secondary sourcing, material substitution and material diplomacy.

1. Introduction

The post-carbon transition implies fundamental changes to the global economy followed by a shift in natural resource dependencies. Restructuring away from fossil fuels will bring an associated shift to the acquisition of raw materials which will increasingly depend on international trade. Overall, there is large agreement among researchers that the green transition creates new production and consumption patterns. Hence, metal industries such as copper, nickel, zinc and precious metals are examples of where the United Nations encourages to create sustainable patterns to decouple economic growth from environmental degradation. Moreover, coordination among nations is needed to foster transparency and accountability for sustainable sourcing of materials and incentivize research institutions to explore new resource streams for primary metals as these are still needed if future demands are to be fulfilled.

Europe is an ideal location for exploring the above-outlined implications. The European Union's (EU) ambition of becoming climate-neutral by 2050 depends on the union's ability to adapt and implement new strategies that challenges the results of climate change and environmental degradation. An example of such an initiative is the Green Deal which aims to overcome these challenges by adopting climate, energy, transport and taxation policies fit for reducing greenhouse gas emissions and decoupling economic growth from resource use (European Commission, 2019). This will be challenging as the EU's mining production has steadily decreased over the last few years, thus becoming more dependent on material import (Regueiro and Alonso-Jimenez, 2021). However as the EU has a high-tech mining industry and is self-sufficient in production of some industrial metals there is great potential for creating sustainable production and consumption patterns using the union's vast land area for diversification of renewable energy production, such as hydropower, geothermal and biomass resources, to reduce their dependency on international trade. Furthermore, there are large potentials for electricity generation by solar and wind however, as these resources exhibit intermittency issues, they create an additional dependency on storage technologies. Hence, it is implied that the EU

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will be dependent on international trade (i.e. import of raw materials) to become climate-neutral and meet its sustainability targets.

On the other hand, new dependencies on materials such as copper, nickel and zinc do not only cause immense pressure on global supply chains but also force both industries and countries to explore alternative options. Domestic sourcing of materials would increase the flexibility of supply chains and manufacturing processes, improving companies' control of supply chain management, and reduce costs due to smaller distances between supplier and customer (Harper and Scott, 2022). Moreover, it further reduces the EU's dependency on Russian energy and sourcing of "green-commodities" from countries with poor social and environmental standards. However, domestic sourcing also includes risks such as resource availability, potential environmental destruction through mining, local resistance to mining projects, higher costs due to more stringent environmental regulations or higher labor costs and less efficient suppliers with limited economies of scale (Unleashed, 2019; Braide, 2021; Rion, 2023). The green transition thus not only involves industrial sectors but also establishes linkages between ecological, social, and economic systems.

Supply chain analysis forecasting material demand due to the EU's ambitious climate targets have been convincingly demonstrated multiple times however it has not been presented in consideration with monetary and structural importance. This study investigates the EU's predicted increase in demand for four material groups (i.e., copper, nickel, lead zinc and tin and, precious metals) for the green transition between 2020 and 2050. These materials were defined as critical materials for the energy transition according to the IEA, IRENA and WWF (IEA, 2023; IRENA, 2022; WWF, 2014), stating that these materials are essential resources to the economy and the supply of which may be disrupted if production and consumptions patterns change. Investigating the feasibility of the EU's climate goals is evaluated in terms of vulnerability which is based on monetary and structural importance. 'Vulnerability maps' are thus created to determine which countries and/or sectors (within the EU) are vulnerable to changes in material demand. Increase in demand for the four material groups are investigated based on predicted changes in electricity production by 11 sources (i.e. coal, gas, nuclear, hydro, wind, petroleum and oil derivatives, biomass and waste, solar photovoltaic, solar thermal, tide wave and ocean, and geothermal).

2. Methodology

The methodology is inspired by a paper by Kerschner et al. (2013) where their approach, exploring the economic vulnerability of peak oil, reveals the relative importance of sectors and how vulnerable they are to oil price shocks. In this paper, we apply a similar approach to analyse the vulnerability the EU is currently facing regarding material demand and supply for the construction and use of green energy technologies. The time frame is set between 2020 and 2050 due to released data availability for 2020 and EU's target of becoming carbon-neutral by 2050. An exception was made when considering electricity production from various sources as data from 2020 was heavily influenced by the global pandemic and hence data from 2019 was used to ensure data reliability and for results to display as close to normal human lifestyles as possible. The model uses data extracted from EXIOBASE version 3.8.2 (Zenodo, 2021). The analysis also uses final demand (ΔY) data from Černý et al. (2024) which gradually replaces the production of electricity from non-renewable energy sources with production from renewables until 2050.

2.1. Input-output aanalysis

The Leontief input-output analysis is a sector and country specific economic approach that is used to estimate potential economic effects of material supply and demand. In this analysis, the transactions are expressed in hybrid units by taking the original interindustry transaction matrix (Z-matrix) and replacing monetary units for material and energy rows with physical and energy units respectively (Miller and Blair, 2009).

$$A = Z * X^{-1} \tag{1}$$

Where A contains interindustry coefficients, Z is the transaction matrix, and X is the total output.

$$\Delta D_M = (I - A)^{-1} * \Delta Y \tag{2}$$

Where D_M is the change in material demand between 2020 and 2050, I is the identity matrix, A contains the interindustry coefficients, and Y is the estimated change in electricity produced from various sources between 2020 and 2050.

2.2. Forward linkage analysis

Forward Linkage Analysis (FLA) is used to indicate interconnections between sectors as it considers both direct and indirect contributions of a sector to GDP. Hence, it is used to determine which sectors exhibit monetary importance to EU's economy (Kerschner et al., 2013; Miller and Blair, 2009; McMahon, 2022). This can for example include production of raw materials and components used for manufacturing as well as steps along the distribution chain (McMahon, 2022). The approach is considered supply-driven as the analysis uses the Ghosh inverse matrix which is driven by changes in value added and not changes in final demand.

The same data as acquired for the input-output model is used when performing FLA, however the interindustry matrix is altered into a direct-output coefficient matrix (see Eq. (3)). Next, the generation of the inverse output matrix (i.e. Ghosh inverse matrix) is obtained (see Eq. (4)). Finally, the forward-linkages are calculated by summing each row individually (see Eq. (5)), revealing the total value of intermediate sales per sector per country.

$$B = \frac{Z}{X} \tag{3}$$

Where B is the direct-output coefficients matrix, Z is the transaction matrix, and X is total output.

$$G = (I - B)^{-1} \tag{4}$$

Where G is the Ghosh inverse matrix, I is the identity matrix, and B is the direct-output coefficients matrix.

$$FL_i = \sum_{j=1}^{n} g_{ij} \tag{5}$$

Where FL refers to the forward linkages for sector *i*, and g_{ij} are the flows of the Ghosh inverse matrix of sector *i* to sector *j*.

2.3. Social network analysis

Social Network Analysis (SNA) is a methodological approach originating from sociology. It is commonly used to analyse social relations such as friendships and acquaintanceship but can also be used to identify important actors according to their structural position in an interconnected network (Kerschner et al., 2013). The concept of *outdegree centrality* is a measure reflecting the number of sectors to whom a given sector provides monetary inputs.

The transaction matrix is first dichotomised to create a binary matrix where 1 represents a connection between sectors and 0 represents the absence of a connection. For simplicity, the cut-off value is set at anything greater than 0. This ensures that all relevant connections between sectors are considered. In addition, a binary setup avoids monetary considerations between connections and instead considers all flows equally. The outdegree centrality scores are converted to percentiles for easier interpretation of results, indicating in which percentiles the sectors reside.

$$C_i = \sum_{j=1}^{n} D_{ij} \tag{6}$$

Where C_i refers to the outdegree centrality of sector *i*, and D_{ij} are the dichotomised, binary flows of sector *i* to sector *j*.

3. Results

The subsections below display the findings using the three analyses for copper, nickel, lead, zinc and tin, and precious metals. Figs. 1-4 display bubbles where the size of the bubble reflect the size of demand. The bubbles are also relative to each other within each sector and expressed in percentage. Furthermore, relative structural importance (*C* from SNA), reflecting the number of sectors to whom a given sector provides monetary inputs, is displayed on the x-axis while the y-axis represents relative monetary sector importance (*FL* from FLA), which considers both direct and indirect contributions of a sector to GDP. The figure is also colour-coded to ease sector identification and divided into four quadrants for easier determination of vulnerable sectors. The latter will be discussed in detail below. Sectors which display either decreasing or static material demands are omitted from the figure for improved visualisation and due to the study's focus on increasing material demands. These mostly reside within the electricity produced by coal, solar thermal, tide, wave and ocean, and geothermal sectors but also extend to other sectors. The focus on the following argumentation is on the larger bubbles as these are the main points of interest.

The distinction between the quadrants is decided based on the median of the percentile (from 0 % to 100 %) for monetary importance and the median of the results (ranging from 22 to 48) for structural importance. The bottom-left quadrant (Q1) includes sectors with the least importance in terms of both structural and monetary contributions, however the analysis show no sectors being present in this quadrant. The upper-left quadrant (Q2) should hold sectors with increasing monetary importance; however, no sectors display this increase while simultaneously exhibiting a low structural importance. The bottom-right quadrant (Q3) is home to sectors with increasing structural importance. Given the provided coordinates for the division lines, most sectors reside in this area. This creates a large variety of energy sources located within the quadrant but also indicates high levels of vulnerability towards price increases. However, in terms of the green transition and with regards to the topic of this study and its focus on material demand, structural importance provides vital insights to constructional requirements needed for the EU to reach its climate goals. An example of an industry which fall into Q3 could be aluminium and aluminium products in Slovakia as one of the main industries contributing to the country's overall GDP is metal and metal products. As reflected in Fig. 1, Slovakia currently contains facilities suitable for producing electricity by nuclear power reflecting the country's commitment to nuclear power. However as some of these nuclear reactors currently are under construction, Fig. 1 display a low relative monetary importance which is expected to increase once the reactors are operating (World Nuclear Association, 2021). Finally, the upper-right quadrant (Q4) contains sectors with high levels of both monetary and structural importance. An example of an industry which falls into Q4 is the cattle industry in Austria which has a high structural importance due to its large-scale agricultural production with about 1.9 million cattle and high monetary importance as it accounts for about 21 % of total animal production (Federal Ministry of Austria, 2020). Thus, it is suggested that sectors within this quadrant exhibit the highest vulnerability where the larger bubbles should be the main areas of concern.

3.1. Copper ores

Fig. 1 displays the vulnerability map of copper. Austria exhibits the highest levels of monetary importance such as for electricity produced by hydro. The presence of other bubbles displaying similar monetary importance is noted but, as they have lower material demands, are more difficult to distinguish and interpret. Next follows electricity by nuclear in Czech Republic, oil derivatives in Denmark, and biomass and waste, solar PV, wind and gas in Germany. The results are deemed valid as the Czech Republic currently has 6 nuclear reactors in operation, producing about one-third of its electricity. Moreover, the government is strongly committed to future use and expansion of nuclear power by 2040 using this policy as a part of cutting carbon emissions and align with the EU's emission reduction targets (World Nuclear Association, 2022). When looking at structural importance, high levels are observed in all sectors mentioned above in addition to nuclear in Slovakia. These results are also deemed valid as Slovakia's government has strong commitments to electricity produced by nuclear power, with four operating nuclear reactors and two under construction, in order to become independent from fossil fuels (World Nuclear Association, 2021).

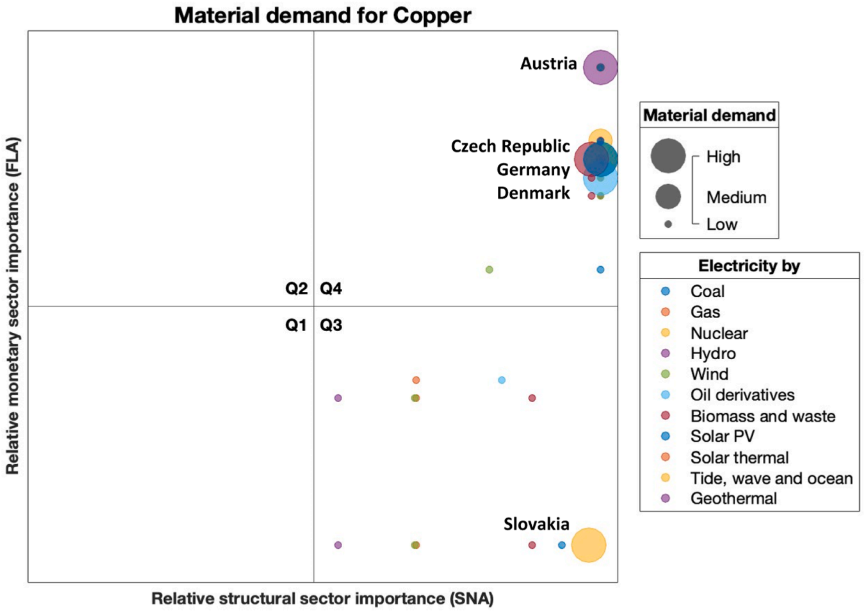

Fig. 1. Sectors importance and vulnerability to increasing demand of copper between 2020 and 2050.

By global production volume of metals, copper extraction ranks third after iron and aluminium. It is widely used in construction and infrastructure sectors and is also a key material in emerging green energy technologies such as wind turbines and solar photovoltaics (Ciacci et al., 2020). Moreover, research performed by several experts suggest that future copper demand might exceed current reserve estimates (Schipper et al., 2018; Elshkaki et al., 2016; Kuipers et al., 2018). Creating a regenerative industrial system replacing primary copper with recycled materials is thus key to reduce dependency on international suppliers and create a sustainable demand-supply balance within the EU while simultaneously reducing energy intensities and lowering other burdens such as potential for resource depletion and landscape impacts. There is however one major challenge with this approach as the EU currently exports most of its copper scrap due to non-functional recycling facilities (Ciacci et al., 2020). A related solution, is to increase the efficient extraction of valuable materials from end-of-life technologies. This is currently extensively debated within the European copper industry (Ciacci et al., 2020). Thus, construction of efficient recycling facilities along with technological advancement and a more thorough focus on creating a circular economy are key components for the EU to lower its vulnerability and dependency on copper import.

3.2. Nickel ores

The vulnerability map of increasing nickel demand is displayed in Fig. 2. The focus is again on bubbles which display high increases in material demand as these exhibit larger vulnerabilities. Austria seems to require materials for electricity by hydro, showing high levels of both

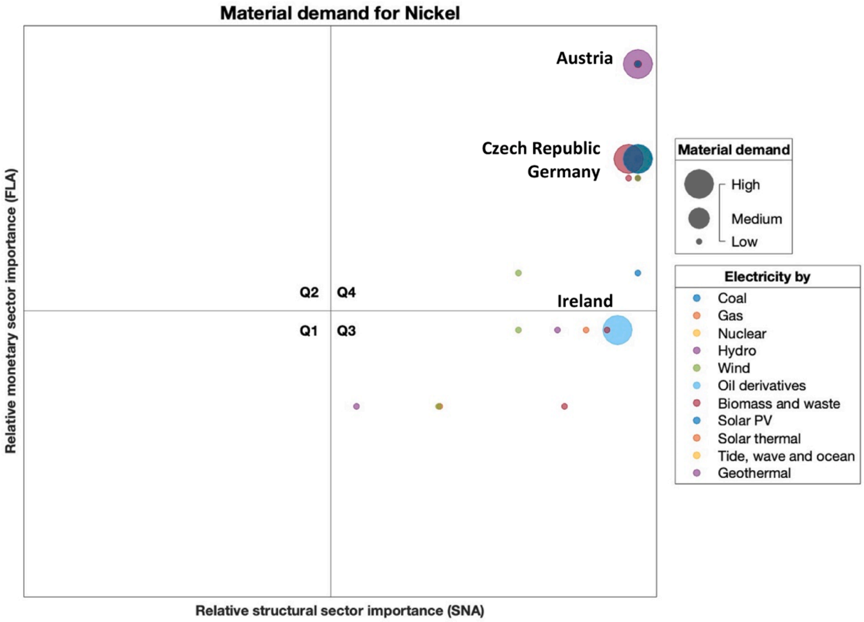

Fig. 2. Sectors importance and vulnerability to increasing demand of nickel between 2020 and 2050.

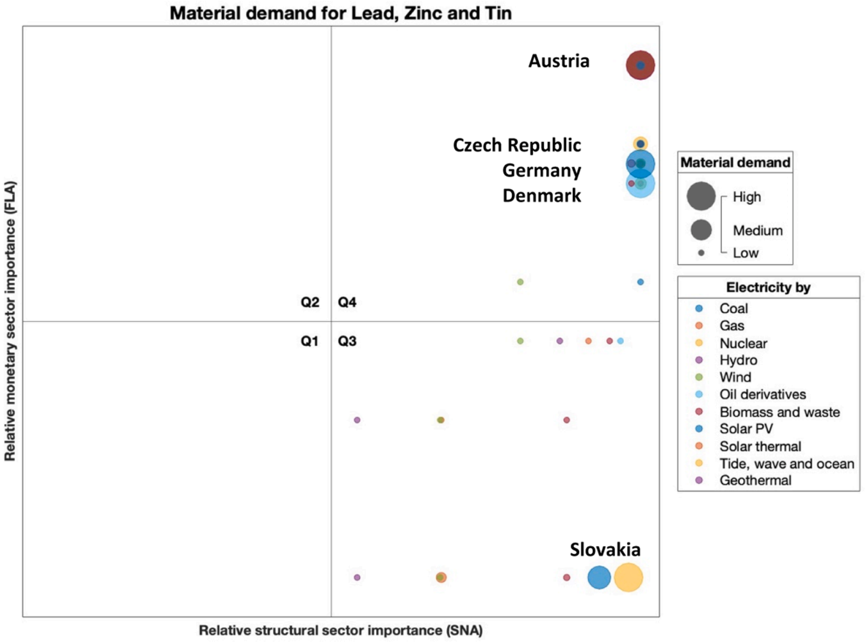

Fig. 3. Sectors importance and vulnerability to increasing demand for lead, zinc and tin between 2020 and 2050.

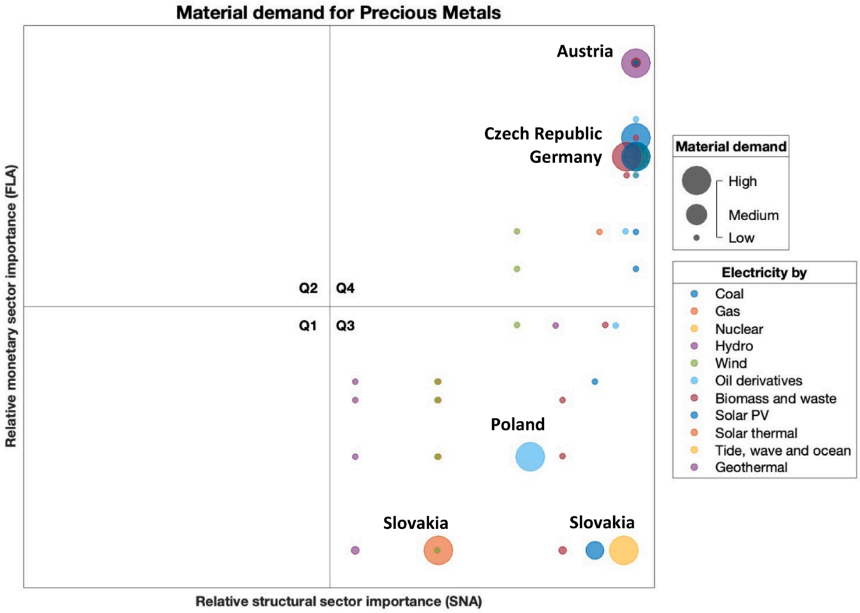

Fig. 4. Sectors importance and vulnerability to increasing demand for precious metals between 2020 and 2050.

monetary and structural importance. Then follows high demands for biomass and waste in Czech Republic alongside solar PV, wind and gas in Germany. Czech Republic currently ranks 13 in electricity generated by biomass and waste (Knoema, 2020). Moreover, the country has high biomass availability from forestry and agriculture along with other biowaste and post-consumer wood, supporting the display of high nickel demand (Panoutsou and Singh, n.d.). Furthermore, evaluating high levels of structural importance also brings attention to oil derivatives in Ireland. This is an interesting observation as Ireland has low energy security due to its high dependency on imports of fossil fuels and natural gas. In 2014, 97 % of all imports were fossil fuels, most of which is used in the transportation industry (e.g., 97 % of energy used in the transport industry came from oil-based products). The country also has large imports of natural gas with a difference of 31 % when compared to the rest of the EU member countries (Sustainable Energy Authority of Ireland, 2016). This has led to an overall reduction in energy security in Ireland with near total dependence on a single energy source.

Nickel is extracted extensively as it has a wide range of applications due to its material properties. However, this has also created concerns in recent years with regards to material availability and the possibility of nickel scarcity. An investigation of future supply and demand of nickel estimated that its demand can increase by up to 350 % by 2050 (Elshkaki et al., 2017), exceeding current nickel reserves. Compared to copper however, nickel can be produced from two types of ores (i.e., sulphides and laterites) and thus nickel reserves will still be available by mid-century although a decline in ore grade is to be expected (Elshkaki et al., 2017; Mudd, 2010). Another concern regarding nickel production is its large water consumption however major current nickel production fields are located in water-rich regions such as Canada, Russia, Australia, the Caribbean and across the western Pacific archipelago (Mudd, 2010; Northey et al., 2017). The nickel industry can thus relatively easy meet its future water requirements but this will create a lot of stress on the surrounding environments. Increasing secondary sourcing of nickel from its current recycling rate at 30 % could thus be a solution, along with research and development on the nickel industry focusing on reducing water requirements in production regions.

3.3. *Lead, zinc and tin ores*

Biomass and waste in Austria scores the highest in terms of vulnerability for material demand of lead, zinc and tin. Nuclear in Czech Republic, solar PV in Germany and oil derivatives in Denmark follow closely. All sectors display high levels of monetary and structural importance. In terms of the latter, nuclear and solar PV in Slovakia are also included. There is additionally a medium material increase of lead, zinc and tin in the electricity produced by gas sector in Slovakia. Comparing Slovakia to other EU member states reveals that the country plans to implement a lower share of renewable energy sources than its fellow members (19.2 % in comparison to 32.0 %) (IEA, 2022). Fig. 3 thus reflects that the difference is to be covered by electricity produced by gas.

Research papers investigating future demand and supply of lead, zinc and tin are sparse, particularly for tin. Lead has high production costs and environmental implications, and thus recycled material has been the main source of acquisition since 2014 (Sverdrup et al., 2019). Zinc production is a highly energy intensive process where significant efforts have been put in to developing alternative technologies however zinc recovery rates are currently too low. As a result, countries with advanced zinc recycling facilities are currently importing post-consumer scrap as a measure to cover domestic demand and reduce energy usage and emissions (Meylan and Reck, 2017). Europe currently has an end-of-life recycling rate of above 50 % but has a maximum potential of about 95 % (International Zinc Association, 2022), and hence the EU should focus on creating a circular economy to potentially become completely independent on international trade of zinc. Lastly, tin is widely used in applications such as batteries and solar panels, creating a global demand for the material. In 2015, tin mining was mostly located in China, Indonesia, Myanmar, Bolivia, Peru and Brazil, accounting for about 92 % of output (Yang et al., 2018). The EU is thus dependent on trade with regards to sourcing of primary tin but technological advancements and construction of recycling facilities can turn today's resources into tomorrow's reserves. Overall, utilising secondary sources will not only address potential shortage of metal supply but also reduce energy usage, protect the environment, reduce carbon emissions and lead to material circularity and potential material independence within the EU.

3.4. *Precious metal ores*

Precious metals are rare and generally have large economic value.

The group consists of iridium, rhenium, ruthenium, rhodium, palladium, osmium, platinum, silver and gold. As the database uses aggregated material sectors without other specifications, it is not known if this group, known as precious metals, contains all of the above-mentioned materials. Regardless, hydro, and biomass and waste in Austria have the highest vulnerabilities, followed by biomass and waste, wind and solar PV in Germany, and coal in Czech Republic. As can be indicated from the above subsections, Austria has a general lack of domestic resources required by the green transition. In 2010, the country only had two operating metal mines, none of which extracted any of the metals listed as precious (AZO mining, 2012). Subsequently, as Germany boarders to Austria, similar metal extractions are found there, supporting Fig. 4's display of increasing demand of precious metals. The increase in demand for precious metals by producing electricity from coal in the Czech Republic is an interesting observation as it does not coincide with simulations by Černý et al. (2024). This difference is due to the year (i.e., 2015) the data was extracted from along with more recent rises in costs of carbon credits, making coal power plants almost financially inviable. Hence, although coal is currently a significant domestic energy resource covering over 50 % of electricity produced (Euracoal, 2022), it is estimated that electricity produced by coal will be largely replaced by the ongoing construction of nuclear reactors (World Nuclear Association, 2022; International Trade Administration, 2023). The commitment towards nuclear power is further supported by Černý et al. (2024) due to the country's limited options in terms of renewable energy. Nuclear power in Slovakia exhibits a high level of structural importance in addition to the specified sectors. Other relatively large bubbles are solar PV and gas in Slovakia, and oil derivatives in Poland.

By concentrating on material demand required for the green transition, platinum attracts the most attention and concern. Most concerning is the uneven distribution. For example, South Africa currently contains 7 out of the world's 10 largest platinum mines (Mining Technology, 2021), holding over 90 % of known reserves (Rasmussen et al., 2019). The material is needed in the future for sustainable and renewable fuels as production of these often require platinum as a catalyst. Research suggest that future platinum supply will not face geological constraints but rather geopolitical risks and price fluctuations (Rasmussen et al., 2019). Long-term mitigation strategies should thus include exploration of new geological deposits, better collection of recycling materials and construction of suitable recycling facilities. Material substitution is also mentioned but discouraged as a suitable solution due to material scarcities of the suitable substitution materials. Increasing recycling rates is especially encouraged as it is not limited to geological distribution. Moreover, one of the world's largest precious metal recycling facilities is located in Belgium (Umicore, 2023), along with smaller recycling facilities present in countries such as Italy, Switzerland and Turkey (Environmental Expert, 2023). Hence the EU should encourage technological advancement, ensure better methods of material collection and support construction of new recycling facilities to ensure that the future demand of platinum is fulfilled without any implications from poor social standards.

4. Discussion and conclusion

The above analysis and results can be used as a tool to check for economic and material implications of the green transition. Moreover, it allows for implementation of proactive measures to counteract possible economic or material crises. The analysis can thus also be applied to the development of adaptive resource management strategies such as construction of recycling facilities and establishment of supply agreements. Overall, there are two possible routes for adaptive policy action. The first implies to add policies which move highly vulnerable sectors from the fourth towards the first quadrant. This reduces both monetary and structural importance but does not change the expected increase in demand. As a result, this move can make electricity production from certain energy sources (i.e., coal, gas, and oil derivatives) inviable, forcing the government to implement other means. This is for example happening in the Czech Republic where the government now has decided to phase out energy produced by coal and replace it with nuclear energy as a result of the EU increasing costs of carbon credits from the European Trading System (World Nuclear Association, 2022; International Trade Administration, 2023). Austria is used as an example as the country displays high levels of vulnerability in all material groups in various electricity producing sectors. These specific findings are consistent with reality as domestic material resources of metals are almost non-existent, resulting in a high dependency on imports (Federal Ministry Republic of Austria, 2022). Furthermore, the Austrian government's most recent energy policy plan aims for the country to become carbon-neutral by 2040. Although they have large capacities for innovation and access to private fundings (IEA, 2020), results from this analysis indicate that the target can be hard to reach. This is also supported by the simulations by Černý et al. (2024), estimating that electricity produced by gas in 2050 will account for about 20 % of the electricity mix. Germany is another country which displays high increases in material demand because of its ambitious climate goals. They initiated the Energiewende in 2010, aiming to electrifying the country by the use of (mostly) renewable energy sources (IEA, 2022). This again corresponds to simulations by Černý et al. (2024) as they estimate complete removal of nuclear power and up to 50 % reduction of electricity produced by coal or petroleum and oil derivatives. Meanwhile, electricity by gas, hydro, wind, biomass and waste, and solar PV are expected to grow by 120 %. Germany currently has multiple active mines and is considered an important mining country in the EU. However, the majority of resources are coal with small quantities of copper, iron and lead (Boemkem and Watson, 2021). The country is thus expected to depend on material import as self-sufficiency is currently not an option. The other policy action involves material substitution. In most cases, a material substitution will inevitably shift the new material sector towards the fourth quadrant, forging similar difficulties as the sector that is being replaced. Another problem which can be encountered is if the material industry producing the substitute material is mature. This can greatly reduce most scale effects and cost saving possibilities as they will have already been realised. It is important to note that these implications do not signify that there are no suitable substitutes but rather indicate that other options might be (more) applicable. Recycling is a viable solution to prevent material insecurity while also reducing environmental footprints and lowering energy requirements. An example presented earlier suggests the support of existing recycling facilities such as the platinum recycling business in Belgium. It is however important to note that while recycling reduces material insecurity and includes environmental considerations, material substitutions might threaten sectors with high levels of vulnerability. For example, aluminium can be used as a replacement for copper if its conductivity property is boosted to make it more economically competitive with copper. This enquires an alteration of the structure of aluminium and introducing some additives which are currently researched by multiple universities worldwide (AZO Materials, 2022). Copper-based alloys is another example which can be used as a substitute material for tin, however without a proper regenerative industrial system, this will increase the demand for copper and correspondingly increase dependency on international suppliers (MatWeb, 2023). Hence, each potential solution needs to be carefully considered before a final decision is made.

What should also be mentioned is the fact that this study only considers the renewable energy industry, excluding material demand for other industries. Industry experts warn that an explosive growth in demand can quickly lead to shortages in raw materials even when recycling is considered (Noyan, 2022). Unconventional measures are therefore required to avoid potential disruptions in supply chains. In addition to increasing mining capacities within the EU, diversifying value chains, construction of recycling facilities, and engagement in material diplomacy to create long-term partnerships are crucial to get access to raw materials. This is due to limited availability of certain materials within the EU (e.g. platinum). Moreover, the EU is considered quite diverse in terms of green energy technology implementation and thus shifting the focus towards recycling of materials can lessen dependency on international trade. Nonetheless, trade will still play a key role in supplying certain materials.

Multiple studies highlight the green transition's and subsequently the EU's dependency on China. China's dominance as an international developer of green technologies and exporter of materials, components and final products implies a potential supply risk for the global market. For example, 19 of 30 raw materials the EU has listed as critical for the transition are located in China (Noyan, 2022). This shows that the future dependency on China and other such exporters can result in supply implications to EU countries due to geographical confinement of geological resources. Hence, these high levels of concentrations can create detrimental instabilities for international markets and trade. Additionally, ongoing global scrutiny of social and environmental implications, such as lack of access to water and sanitation or adequate housing for platinum miners and pollution of water resources in South Africa (Swedwatch, 2013) or geopolitical disturbances (Garcia-Herrero, 2022), further accentuates supply risks, creating the need for diversifying the supply of such materials and further development of efficient recycling techniques and facilities (Dutta et al., 2016). However, international trade will still be a fundamental part of meeting future material demand regardless of domestic sourcing of metals unless energy consumption is reduced significantly.

CRediT authorship contribution statement

Elena Vaagenes Andersen: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Yuli Shan:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision, Project administration. **Benedikt Bruckner:** Software. **Martin Černý:** Data curation. **Kaan Hidiroglu:** Data curation. **Klaus Hubacek:** Methodology, Conceptualization, Investigation, Resources, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

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

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