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Analyzing Germany's current and future critical raw material situation for water electrolysis and offshore wind turbines

Andrea Schreiber *, Petra Zapp, Christina Wulf, Lavinia Reitz

Forschungszentrum Jülich GmbH, Institute of Climate and Energy Systems, Jülich Systems Analysis (ICE-2), Jülich, D-52425, Germany

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ABSTRACT

Renewable energies require various raw materials that will drastically increase global demand in the coming years. The European Commission classifies materials with a high supply risk and a high economic importance as critical if they exceed the thresholds for both criteria. In 2023, the European Commission classified 34 materials as critical for the European Union's economy, 15 of which are also rated as strategic materials. Based on the EC's methodology using various indicators such as the Herfindahl-Hirschman Index, import dependency and the gross value added of individual economic sectors, this study is assessing the use of critical raw materials in water electrolyzes and offshore wind power for Germany. Both technologies are crucial for Germany to become climate neutral by 2045. These two technologies alone contain 12 of the 34 materials critical for the EU. To assess also future criticality, this study considers the targets of the European Commission's Critical Raw Materials Act, published in March 2023. These targets include a diversification of supplier countries, a drastic increase of domestic production of ores, concentrates and refined products as well as an increase in recycling rates.

1. Introduction

The rapid growth of renewable energies requires large quantities of various raw materials, which will drastically increase their global demand in the coming years [1,2]. In this context, the sufficient availability of raw materials is of crucial importance for the German energy transition [3,4]. Increasing globalization, combined with recent demand shocks and repeated supply chain disruptions, is motivating increased activity in the assessment of critical resources and supply chains [5–7].

Several approaches assessing the criticality of raw materials have been developed over the last two decades [5,8–24] which differ in terms of indicators and perspectives. Some criticality assessments (CA) focused on products [12,14,16], technologies [23,24], materials [22], and companies [15]. Other assessments were conducted for different specific countries [9–11], regions [5,18–21] or at the global level [8,17]. Various efforts have also been made to harmonize these methods [25–30].

To provide timely recommendations for action to mitigate or even avoid supply risks, it is necessary to assess future disruption risks along the raw material supply chains. However, today's CAs are usually periodically updated snapshots based on historical data, which tend to "solve yesterday's problem" rather than look ahead [31]. Few studies are dealing with future projects [32–38]. These studies rely on demand scenarios [33,35], extrapolation of historical trends [32,36], proxies [33], estimates of population and material intensity [34], and agent-based demand methods [36–38].

CAs are particularly important for countries like Germany, which have a high degree of industrialization but low domestic raw material extraction and processing, resulting in a high dependency on imports [39]. Therefore, in a first step of this study, the CA of raw materials (EC-CRM) [5] for the European Union (EU) provided by the European Commission (EC) is regionalized Germany.

To prove its feasibility the newly regionalized indicators are applied to 26 raw materials required for water electrolysis and offshore wind energy, which are two key technologies of the German energy transition. According to the Offshore Wind Energy Development and Funding Act [40], the capacity of offshore wind turbines is to increase to at least 40 GW by 2035. In line with the German government's targets, electrolyzer capacity is to be expanded to 10 GW by 2035 [41]. As part of the National Hydrogen Strategy, the Federal Ministry of Education and Research (BMBF) is funding various lead projects to achieve the expansion targets [42,43].

The EC-CRM is based on data from the last five years. As the German energy transition is a long-term strategy, the second step of this study

* Corresponding author.
E-mail address: a.schreiber@fz-juelich.de (A. Schreiber).

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projects the criticality of the 26 selected raw materials for the years 2035 and 2045, taking into account the targets of the EC's Critical Raw Material Act (CRMA) [6], in order to make the EC-CRM approach more future-oriented.

2. Methods

2.1. European Commission's methodology to assess critical raw materials

In 2011, the EC published its initial report on critical raw materials for the EU [18]. In this first EC-CRM, 14 out of a total of 41 considered raw materials were classified as critical. The EC-CRM is updated every three years [5,19–21]. In the most recent EC-CRM, published in March 2023 [5], 34 raw materials out of a total of 87 (67 individual and three grouped materials, namely platinum group metals, light rare earth elements, and heavy rare earth elements) are defined as critical.

Two indicators, economic importance (EI) and supply risk (SR), are used to determine the criticality of a material for the EU [13]. Raw materials which reach or exceed certain thresholds for EI and SR are classified as critical raw materials (CRMs). An EC expert group set these thresholds to EI $\geq$ 2.8 and SR $\geq$ 1.0 [13]. The latest EC-CRM update in 2023 [5] also defines strategic raw materials (SRMs), which are of major importance for strategic technologies (green, digital, defense, and space applications).

The importance of material for the EU economy is determined by its end uses and the value added to the corresponding EU manufacturing sectors in NACE (Nomenclature statistique des activités économiques dans la Communauté européenne) Rev. 2.0, the statistical classification of economic activities in the EU compiled by the Statistical Office of the EC, EUROSTAT [44,45] and is calculated according to equation (1):

$$EI = \sum_{a} (A_S \cdot Q_S) \cdot SI_{EI} \tag{1}$$

S = Sectors related to NACE Rev. 2.0 classification.
A_S = Share of end use of a raw material in a NACE Rev. 2.0 sector.
Q_S = NACE Rev. 2.0 sector's value added.
SI_{EI} = Substitution index related to economic importance.

The EI parameter prioritizes two political requirements. Firstly, a detailed and transparent allocation of raw material use to the corresponding NACE sectors is carried out. Secondly, a raw material-specific substitution index is used to reduce the potential consequences for the European economy due to insufficient raw material supply [46].

The supply risk indicator SR assesses the risk for material supply disruption in the EU. It is determined by the concentration of primary supply from raw materials producing countries expressed by the Herfindahl-Hirschmann-Index (HHI), considering their governance performance measured by the scaled World Governance Indicator (WGI) as well as import reliance (IR), End-of-Life Recycling Input Rate (EoL_{RIR}), and substitution index (SI) according to equation (2) [13]. SR is measured at the 'bottleneck' stage of the material which presents the highest supply risk. This can be either the extraction of a raw material (stage I) or the subsequent processing (stage II). Substitution by other materials and recycling are considered risk-reducing measures.

$$SR = \left[HHI_{gs} \cdot \frac{IR}{2} + HHI_{EUsourcing} \cdot \left(1 - \frac{IR}{2}\right)\right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR} \tag{2}$$

HHI = Herfindahl-Hirschmann-Index (used as a proxy for country concentration)
gs = Global supplier.
IR = Import reliance.
$EU_{sourcing}$ = Actual sourcing of the European supply.
EoL_{RIR} = End-of-Life Recycling Input Rate.
SI_{SR} = Substitution index related to supply risk.

The IR of a material and its HHI are calculated according to the following equations:

$$IR = \frac{Import - Export}{Domestic\ production + Import - Export} \tag{3}$$

$$HHI = \sum_{c} S_c^2 \cdot WGI_c \cdot t_c \tag{4}$$

HHI = Herfindahl-Hirschmann-Index (used as a proxy for country concentration)
c = country.
S_c = share of a country c in the global supply mix of the raw material considered.
WGI_c = scaled World Governance Indicator of country c (used as a proxy for country governance)
t = trade-related variable of country c for a raw material.

The SR parameter is therefore used to address four political needs: (1) inclusion of trade barriers and agreements, (2) adoption of a systematic approach to the supply chain (including the mining and processing stages), (3) consideration of import dependency, and (4) the prominent role of recycling as a risk-reducing factor in the calculation of SR is highlighted [46].

Fig. 1 presents the results of the 2023 EC-CRM [5]. A total of 87 individual raw materials were assessed, 48 of which are classified as critical. CRMs (red dots) lie within the criticality zone (SR $\geq$ 1.0 and EI $\geq$ 2.8). Materials outside of this zone are classified as non-critical (blue dots). The four materials, copper, nickel, rhenium, and tellurium are not meeting the CRM thresholds, but are classified as SRMs (orange dots). CRMs having a higher SR value in stage II than in stage I are indexed with (II).

2.2. Regionalizing the European Commission's methodology for Germany

2.2.1. Selection of technologies and raw materials

Using the example of 26 selected raw materials required for water electrolysis and wind power technologies, the EC-CRM is regionalized for Germany for the reference year 2023. The technology selection is based on a study published by the German Mineral Resources Agency (DERA) [47]. In this study, DERA defines future technologies as industrially utilizable technologies that can trigger revolutionary innovation impulses far beyond the boundaries of individual economic sectors. Additionally, these technologies must contribute to reaching the 1.5 °C target of the Paris Agreement from 2015 [48] as well as should have a future market in 2040. In total DERA identified 32 future technologies and categorized them into five clusters. Water electrolysis and wind power belong to the "Energy technologies and decarbonization" cluster, which is especially important for Germany's energy transition. Five raw materials are used for both technologies: aluminum, chromium, copper, manganese, and nickel. Cerium, cobalt, iridium, lanthanum, platinum, scandium, titanium metal, yttrium, and zirconium are required for various water electrolysis technologies, e.g., alkaline water electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis. Boron, dysprosium, molybdenum, neodymium, praseodymium, terbium, and zinc are additionally required for wind power plants [47]. Aggregates, coking coal, iron ore, limestone, and quartz sand are components for concrete and steel and, thus, are also needed for wind power.

2.2.2. Methodology of regionalization

Fig. 2 provides an overview of the indicators used for EI and SR calculations according to the EC-CRM.

The data required for regionalizing the indicators for Germany, circled in red, are collected for each of the selected 26 raw materials.

2.2.2.1. EI regionalization.

For EI recalculation, the gross value added for the individual sectors (Q_S) is regionalized for Germany using the national accounting data from the GENESIS online database of the Federal Statistical Office DESTATIS [49]. A detailed overview of the breakdown of the end use of materials and the gross value added of the

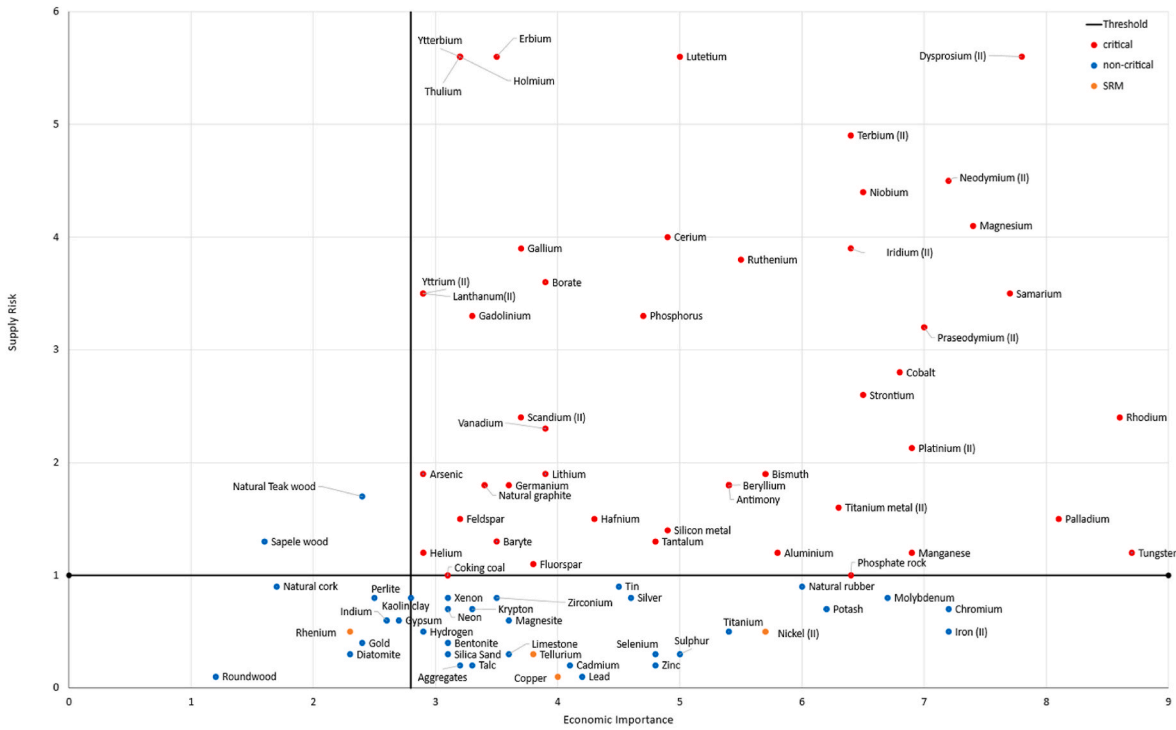

Fig. 1. Results of the latest EC-CRM in 2023 reproduced from the European Commission [5].

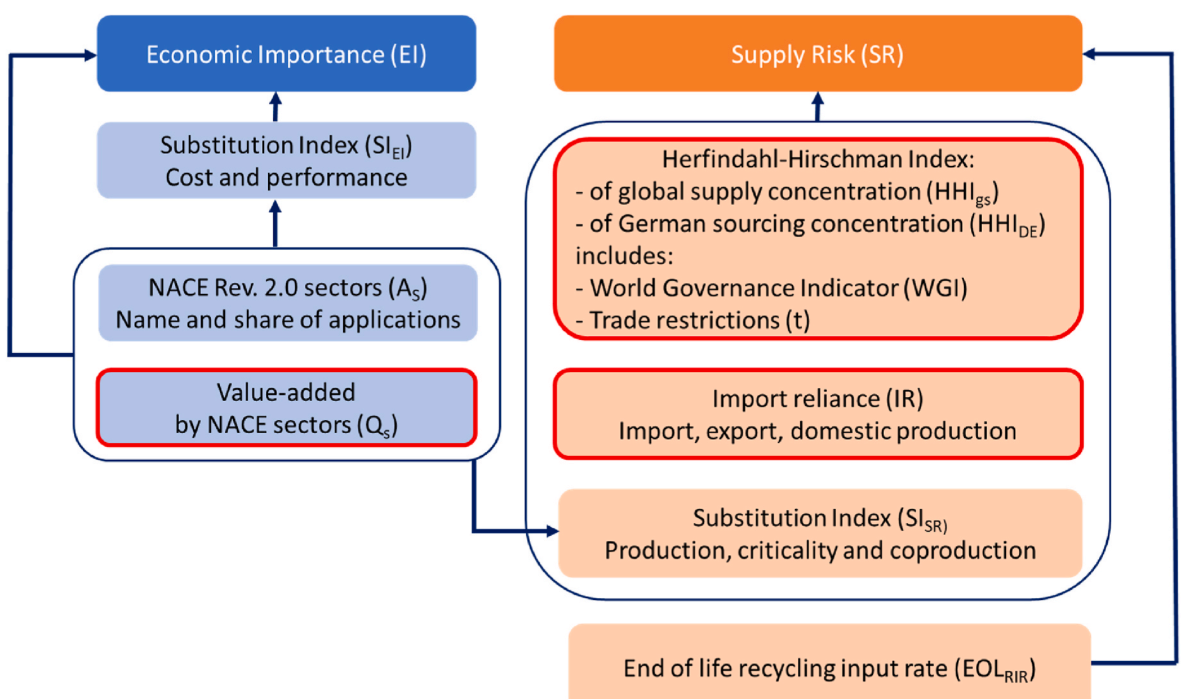

Fig. 2. Overview of the EC-CRM methodology to regionalize raw material criticality for Germany, data for red circled fields are adjusted; figure inspired by European Commission [5]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

individual departments can be found in the supplement material [Additional file 2]. The A_S figures are taken from the latest EC-CRM [5], as rescaling the material shares for entire sectors for Germany is beyond the scope of this paper. Furthermore, it is assumed that the SI_{EI} of a commodity is independent of a specific country, as the share of a raw material in an end-use application, the share of a substitute within an application, and the substitute cost performance parameter used for the SI_{EI} calculation (Additional file 1, equation (3)) are also assumed to be relatively country-independent, especially as Germany is the largest economy in the EU with an economic output of approx. 20 % of the total EU economic output. Finally, EI is obtained by multiplying (A_S * Q_S) for all sectors by SI_{EI} obtained from EC-CRM [5] according to equation (1).

2.2.2.2. SR regionalization. To regionalize the European supply risk for

Germany's economy (SR_{DE}) the IR as well the HHI is adapted (equation (5)) based on the originally EC-CRM methodology (equation (2)):

$$SR_{DE} = \left[HHI_{gs} \cdot \frac{IR_{DE}}{2} + HHI_{DE} \cdot \left(1 - \frac{IR_{DE}}{2} \right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR} \tag{5}$$

HHI_{DE} = Actual sourcing of the German supply.
IR_{DE} = Import reliance of Germany.

The availability and quality of the necessary data are crucial. To regionalize SR, a large amount of data must be collected for Germany, e. g., on Germany's supplier countries for ores and refined products for the 26 raw materials. For the stage of refined products, several products often need to be considered. The products to be included are described in the EC factsheets 2023 [50]. For example, nickel (Ni) data had to be collected for seven different products or product groups (Ni oxide and hydroxide, Ni chloride, Ni sulphate, ferronickel, Ni un-alloyed, Ni alloyed, Ni powders and tinsel). One difficulty when gathering data is that raw material ores or refined products are often not delivered directly from the producer to Germany but pass through several transit countries. In the DESTATIS [49] and EUROSTAT [45] statistics, however, often only the supply from the last transit country is given. The tracking of raw materials can therefore be challenging. In this study, EU data is used if the data basis for Germany is insufficient. Fig. 3 illustrates the data collection process for the SR recalculations.

If there are also data uncertainties or unavailability at the EU level, the analysis will be carried out at the global level. The World Governance Indicator (WGI) is scaled between 0 and 10 using the latest values (2023) from the World Bank [51]. The WGI is updated annually since 1999 and is intended for cross-country comparisons of specific governance indicators such as political stability, absence of violence/terrorism, rule of law and corruption. As Germany is the largest economy among EU member states, it can be argued that the EU's trade relations are comparable to those of Germany. Thus, the trade variable t for calculating the HHI is taken from the latest EC-CRM [5]. Germany's IR (IR_{DE}) is recalculated for each commodity [Additional file 1, equation (1)] as well as the latest data from the DERA [52] and the number codes of the harmonized and standardized system (HS code) of the World Customs Organization (WCO). The IR_{DE} results have a value between 0 and 1, with 1 corresponding to low or non-existent domestic production. IR is linked to the HHI of global producers (HHI_{gs}) as well as Germany's supplier countries (HHI_{DE}). With an IR of 100 % (IR = 1), both HHI values are used to calculate the SR_{DE} according to equation (5). However, if domestic production corresponds to net imports (IR = 0), Germany is independent of imports. In this case, HHI_{gs} is not taken into account and SR_{DE} is calculated entirely on the basis of HHI_{DE}. If Germany is a net exporter ($IR_{DE} < 0$), IR_{DE} is set to 0 for the calculation. SI_{SR} includes three different aspects; (1) global production of the substitutes and the corresponding raw materials, (2) comparison of the criticality of both raw materials, and (3) information on whether the substitute is produced as a by-product of another raw material and is according to equation (4) in Additional file 1. These three indicators are considered to be independent of a region and thus also SI_{SR}. An overview of the EoL_{RIR} and SI factors used is provided in the latest EC-CRM [5] and can also be found in the supplement material [Additional file 2]. Data regarding extraction and producing countries as well as imports and exports are obtained from various data sources [53–55].

2.3. Projection of raw material criticality for Germany in 2035 and 2045

The projections are based on the CRMA targets, which envisage a significant strengthening of the European value chain through the following measures by 2030 [56].

i. at least 10 % of the EU's annual consumption for extraction (ores and concentrate) should be covered by domestic capacities,
ii. at least 40 % of the EU's annual consumption for processing (refined products) should be covered by domestic capacities,
iii. not more than 65 % of the EU's annual consumption of each strategic raw material at any relevant stage of processing should come from a single third country,
iv. at least 25 % of the EU's annual consumption for recycling should be covered by domestic capacities [57].

The CRMA refers only to SRMs, while in this paper the CRMA targets are used for all raw materials.

For the projection of future criticality, EI is assumed to be constant, although technology developments can trigger overall changes in

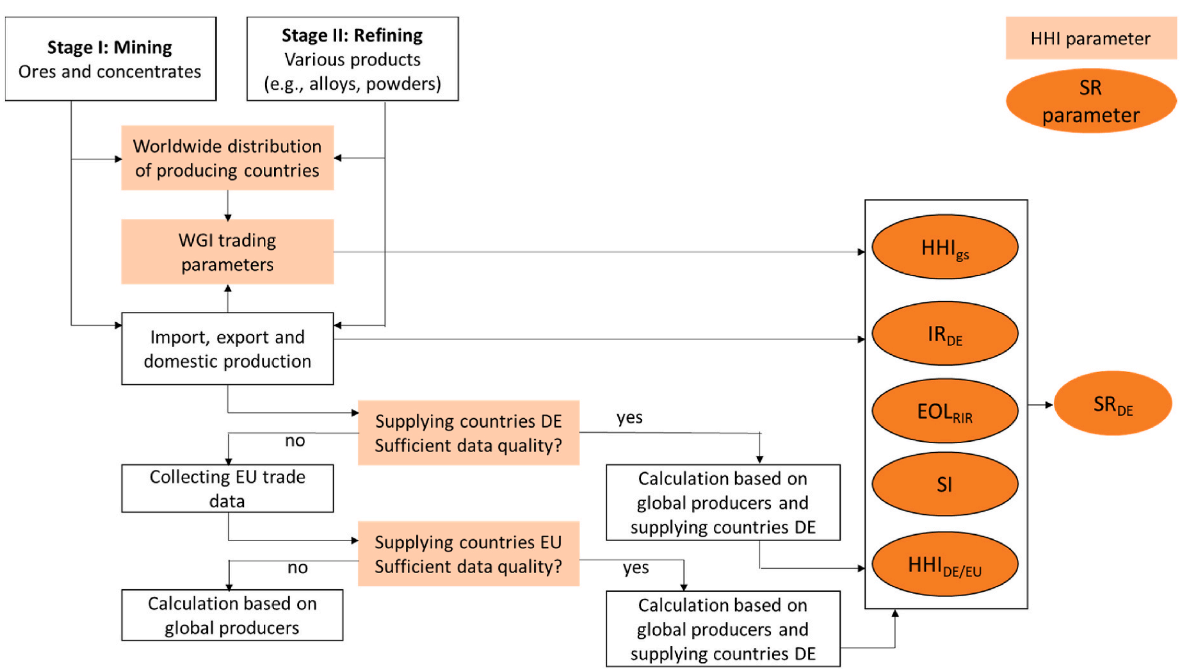

Fig. 3. Procedure for regionalizing the supply risk for Germany (SR_{DE}); EOL_{RIR}: End-of-Life Recycling Input Rate, HHI: Herfindahl-Hirschmann-Index, IR: Import reliance, SI: Substitution index, SR: Supply risk, WGI: World Governance Indicator

various sectors resulting in a shift of gross value added. A future change in value added in the NACE Rev. 2.0 divisions (Q_S) would involve a comprehensive economic forecast, which is beyond the scope of this paper. Changes in the end-use sectors of an individual raw material within the NACE Rev. 2.0 sectors (A_S) are also difficult to estimate, as they are mainly characterized by developments in all divisions of the manufacturing industry. Therefore, the focus in this paper is on the projection of the supply risk indicator SR.

The projection of the future regionalized supply risk ($SR_{DE,2035}$, $SR_{DE,2045}$) requires several assumptions and estimations. First, forecasts on the future country mix of global supplier for the extraction of ores (HHI_{gs} I) and production of refined products (HHI_{gs} II) are compiled (iii). The availability and quality of the data are a crucial factor here. Reliable forecasts on mining extraction rates could only be found for nine of the 26 raw materials: aluminum (including bauxite), cobalt, copper, nickel, zinc, dysprosium, terbium, neodymium, and praseodymium. The data on future forecasts for raw material extraction were taken from a 2022 joint KU Leuven/Eurometaux report for aluminum (incl. bauxite), copper and zinc [58] and from a 2020 Joint Research Centre (JRC) report for rare earths, cobalt and nickel [59]. In a second step, changes in the mix of supplier countries for 2035 and 2045 ($HHI_{DE,2035}$, $HHI_{DE,2045}$) are assumed for all raw materials (iii). Data for future German supplier countries were derived from DERA and DESTATIS [47,49].

As there are doubts as to whether the envisaged increase in domestic mining activities and production of refined products can be achieved by 2030 [60], first the targets for supplier countries will be adjusted for the year 2035. Germany's import countries will be diversified in such a way that a maximum of 65 % of the imported quantity of a raw material comes from a single third country, with the remaining shares being distributed among existing supplier countries. A change in supplier countries has an impact on the HHI_{DE}. Furthermore, the individual country share is multiplied by the country specific WGI, which also influences the HHI.

For 2045, two additional targets of the CRMA are implemented. It is assumed that 10 % of ores and concentrates (i) and 40 % of refined products (ii) will be sourced from EU countries. If available, existing EU suppliers will be used and their import share will be increased. If there are currently no EU suppliers to Germany, EU countries are selected where the relevant raw material is currently being mined but not supplied to Germany or where there is a potential for mining. This applies, for example, to the mining of rare earths in Sweden, which is expected to happen by 2045 [61,62]. If no significant raw material deposits are known within the EU, an average value of the WGI of all EU countries is used for the calculation.

3. Results

3.1. Regionalized current raw material criticality for Germany

First, the current criticality of the 26 raw materials for Germany was recalculated according to the described procedure in section 2.2.2. Depending on the data, raw materials are considered for extraction (stage I), further processing into refined products (stage II), or both stages.

o Stage I: limestone, quartz sand, aggregate, zirconium,
o Stage II: platinum, iridium, scandium,
o Stage I and II: bauxite (I)/aluminum (II), boron, chromium, iron ore, rare earths (cerium, lanthanum, neodymium, praseodymium, dysprosium, yttrium, terbium), cobalt, coking coal, copper, manganese, molybdenum, nickel, titanium, zinc.

Bauxite (I) and aluminum (II) are merged for consistency reasons as in the EC-CRM and hereinafter referred to as aluminum. As platinum and iridium are mainly traded as refined products, only stage II is considered for both. Scandium is exclusively obtained as a by-product from tailings, residues and leaching during the extraction of other metals such as rare earths, titanium, bauxite, and uranium. Therefore, only stage II is considered also for scandium (Table 1).

Fig. 4 plots Germany's current raw material criticality for the 26 selected raw materials required for water electrolysis and offshore wind power in the style of the EC-CRM matrix. For some raw materials, SR was calculated both for the extraction and processing stage. The higher result is always indicated in the matrix of Fig. 4. The number (II) behind the commodity indicates the result of a refined product. Otherwise, the results for the extraction stage are given. The analysis demonstrates that 13 of the 26 raw materials considered are classified as CRMs because they exceed the thresholds for EI and SR. Four other raw materials (boron, cerium, iridium, copper) are also classified as CRMs due to their definition as strategic raw materials by the EC-CRM. The comparison with the 2023 EC-CRM [5] shows seven deviations in which raw materials are classified as critical that were classified as non-critical in the 2023 EC-CRM and vice versa (Table 1). Reasons are higher SR values caused by higher HHI_{DE} and IR_{DE} in the case of chromium and nickel, and lower EI values for boron, cerium, coking coal, iridium, and yttrium, due to lower Q_s values. Detailed interim results on Germany's main suppliers and the recalculated IR_{DE} (according to equation (3)) for stage I and stage II as well as the global (HHI_{gs}) and German HHI (HHI_{DE}) can be found in the supplementary material (Additional file 2). For aggregates, limestone, and quartz sand, IR_{DE} is 0 or <0, which means that Germany is independent of imports. They are therefore not considered for future calculations, as a sufficient supply is ensured.

3.2. Projected raw material criticality for Germany in 2035 und 2045

3.2.1. Germany's raw material criticality in 2035

For the 2035 criticality assessment, as described in section 2.3, the effects of variations in the global mix of producer countries and the diversification of supplier countries in accordance with the CRMA targets [6] are analyzed. First, forecasts of future raw material extraction rates were used for this calculation. Due to the new country distribution, the HHI_{gs} were recalculated (Additional file 2), which has a significant impact on the $SR_{DE,\ 2035}$. Table 2 presents the revised $SR_{DE,\ 2035}$ values for stage I (extraction) and stage II (processing).

A considerable decrease of $SR_{DE,\ 2035}$ (I) can be found for dysprosium, neodymium, praseodymium, and terbium due to the predicted significant reduction in Chinese production, which currently accounts for around 84 % of global ore mining. According to Carrara, Bobba [63], an expert from the JRC, this share is expected to fall to 23 % for dysprosium and 25 % for terbium. Although China will remain the world's largest producer of rare earths, the shares of Canada, the United States, Australia, Russia, Greenland, Sweden, and some African States (e.g., Burundi, Malawi, Angola, Madagascar, Tanzania, Kenia, Namibia, South Africa) will increase to a total of approx. 70 % [62]. Despite a growth in cobalt production of around 45 %, the Democratic Republic of Congo's dominance is expected to decline. The global market share is forecasted to fall from 67 % to 48 % which is reflected in the reduced $SR_{DE,\ 2035}$ (I) of cobalt. The SR_{DE} (I) for nickel is rising most significantly. One reason is the expected concentration of nickel production in Indonesia, which will account for 33 % to 44 % of global production. The second reason is the high Indonesian value for the trade variable t, as part of the HHI, which is caused by the export restrictions on nickel ores imposed by Indonesia in 2020.

In the second step, the effects of diversification of Germany's supplier countries are analyzed. The current situation shows that imports from a single third country exceed the 65 % limit for nine of the 26 raw materials (Additional file 2). These include, for example, bauxite (Guinea 93 %), boron (Turkey 99 %), and rare earths (China 94 %). Germany's supplier countries for these raw materials are reorganized so that the 65 % threshold is no longer exceeded, based on the CRMA target. The recalculated $SR_{DE,\ 2035}$ for stage I is shown in Fig. 5 and the underlying recalculated $HHI_{gs,\ 2035}$ and $HHI_{DE,\ 2035}$ are shown in the

Table 1
Regionalized SR and EI for Germany's current situation compared to the EC-CRM figures [5].

Raw material	EI_{DE}	EI [5]	Stage I			Stage II			Criticality	SRM
			Data origin	SR_{DE}	SR [5]	Data origin	SR_{DE}	SR [5]		
Aluminum	4.0	5.8	GL&DE	2.2	1.2	GL&DE	0.7	0.5	C	No
Boron	1.9	3.9	GL&DE	3.7	3.6	GL	1.9	1.4	NC*	Yes
Chromium	3.8	7.2	GL&DE	1.5	0.7	GL&DE	0.7	0.6	C*	No
Iron	4.5	7.2	GL&DE	0.5	0.5	GL&DE	0.9	0.2	NC	No
Aggregate	1.2	3.2	DE	0.7	0.2	–	–	–	NC	No
Limestone	1.6	3.6	DE	0.3	0.3	–	–	–	NC	No
Cobalt	3.6	6.8	GL	2.2	2.8	GL&DE	1.0	0.5	C	Yes
Coking coal	1.5	3.1	GL&DE	1.8	1.0	GL&DE	1.1	0.4	NC*	No
Copper	3.4	4.0	GL&DE	0.2	0.1	GL&DE	0.2	0.1	NC	Yes
Cerium	2.4	4.9	GL&DE	2.1	3.9	GL	3.2	4.0	NC*	Yes
Lanthanum	3.1	2.9	GL&DE	2.7	2.0	GL&DE	3.7	3.5	C	No
Neodymium	3.8	7.2	GL&DE	2.8	4.5	GL&DE	3.8	3.7	C	Yes
Praseodymium	4.0	7.0	GL&DE	2.7	1.8	GL&DE	3.8	3.2	C	Yes
Manganese	4.6	6.9	GL&DE	1.5	1.2	GL&DE	1.2	1.0	C	Yes
Molybdenum	4.1	6.7	GL&DE	0.9	0.8	GL&DE	0.2	0.2	NC	No
Nickel	3.8	5.7	GL&DE	0.6	0.4	GL&DE	1.0	0.5	C*	Yes
Iridium	2.1	6.4	–	–	–	GL&DE	2.5	3.9	NC*	Yes
Platinum	6.9	6.9	–	–	–	GL	1.5	2.1	C	Yes
Quartz sand	1.4	3.1	DE	0.5	0.3	–	–	–	NC	No
Dysprosium	4.1	7.8	GL&DE	3.1	5.3	GL&DE	4.7	5.6	C	Yes
Scandium	2.8	3.7	–	–	–	GL&DE	4.3	2.4	C	No
Yttrium	1.7	2.9	GL&DE	2.2	1.4	GL&DE	4.3	3.5	NC*	No
Terbium	3.5	6.4	GL&DE	2.0	2.5	GL&DE	4.4	4.9	C	Yes
Titanium metal	4.3	6.3	GL&DE	0.8	0.5	GL&DE	1.6	1.6	C	Yes
Zinc	2.5	4.8	GL&DE	0.4	0.2	GL&DE	0.2	0.1	NC	No
Zirconium	1.5	3.5	GL&DE	0.6	0.8	–	–	–	NC	No

GL = global, DE = Germany, C = Critical, NC = Non-critical, SRM = Strategic raw material, * = different from the EC-CRM [5].

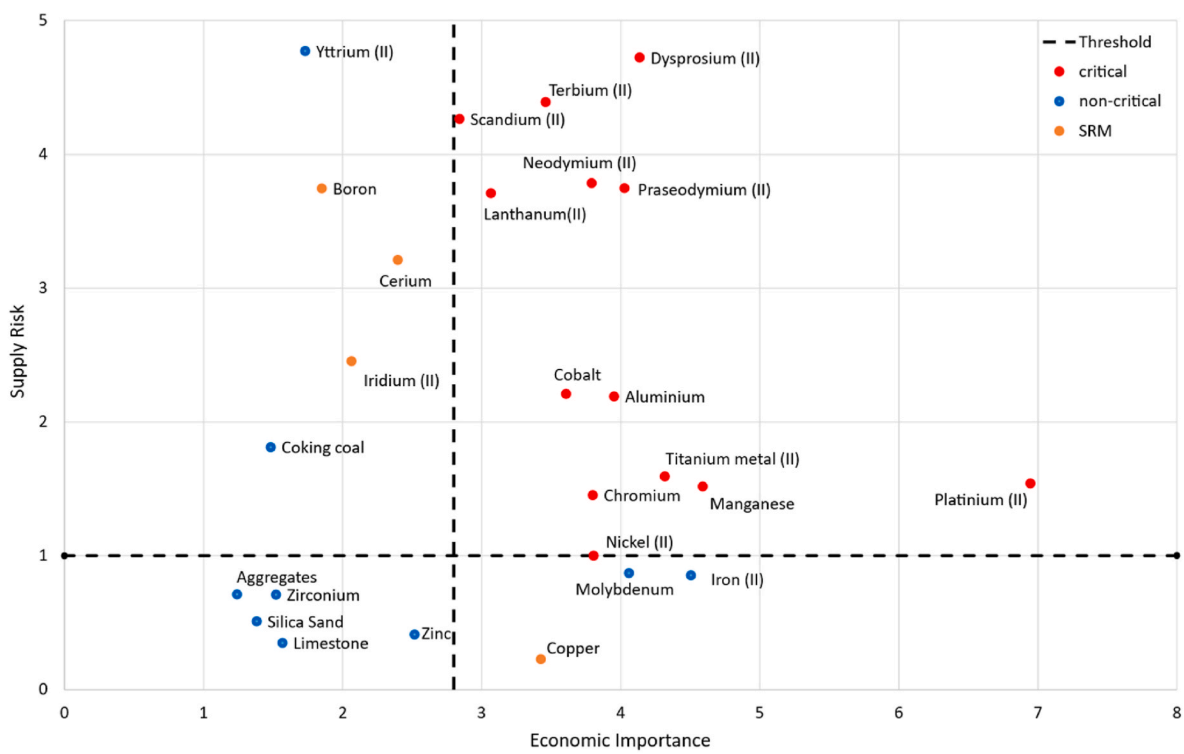

Fig. 4. Current raw material criticality regionalized for Germany for 26 selected materials; SRM: Strategic raw materials

supplementary material (Additional file 2). $SR_{DE,\ 2035\ (I)}$ remains unchanged for nine raw materials, as neither a supply of more than 65 % comes from a single third country nor reliable forecasts of future ore extraction are available. The most significant reduction in $SR_{DE,\ 2035\ (I)}$ caused by the diversification of Germany's supplier countries can be seen for aluminum and boron. For boron, it is assumed that Turkey's share as a supplier country for Germany will be reduced from the current 99 % to the required 65 % with the addition of four new supplier countries (China, Bolivia, Chile, and United States). The same applies to aluminum (bauxite). Here, the share of Guinea's bauxite export to Germany will also fall from 93 % to 65 % and Spain, Guyana, China, and Turkey will be included as new German supplier countries.

Fig. 6 illustrates the corresponding results for stage II. As only rare earths have exceeded the import limit of 65 % (stage II) (Additional file

Table 2
Projected $SR_{DE,2035}$ in comparison to current SR_{DE} (2023)

Raw material	SR (I) 2035	Deviation compared to 2023, %	SR (II) 2035	Deviation compared to 2023, %
Aluminum	1.4	−36	0.7	0
Boron	2.2	−41	1.9	0
Cerium	2.1	0	3.2	0
Chromium	1.5	0	0.7	0
Cobalt	1.6	−27	1.0	0
Coking coal	1.8	0	1.1	0
Copper	0.2	0	0.2	0
Dysprosium	1.5	−52	4.0	−17
Iridium	–	–	2.5	0
Iron	0.5	0	0.9	0
Lanthanum	2.2	−22	3.1	−19
Manganese	1.5	0	1.2	0
Molybdenum	0.9	0	0.2	0
Neodymium	1.4	−50	3.1	−18
Nickel	0.8	25	0.9	−1
Platinum	–	–	1.5	0
Praseodymium	1.4	−48	3.2	−16
Scandium	–	–	2.3	−46
Terbium	1.4	−30	3.7	−14
Titanium metal	0.8	0	1.6	0
Yttrium	2.0	−5	3.6	−16
Zinc	0.4	0	0.2	0
Zirconium	0.7	+17	–	–

2), only $SR_{DE,\ 2035\ (II)}$ for rare earths will fall. Scandium had the highest dependency on China in 2023 (94 %), thus, this value will decrease most in 2035 (−46 %). The reason for the small reduction in $SR_{DE,\ 2035\ (II)}$ of nickel (−1 %) is a minor change in global producer countries in 2035 compared to 2023.

3.2.2. *Germany's raw material criticality in 2045*

After capping the import share at 65 % from a third country for 2035, it is also assumed that EU production for 2045 will increase. A quota of 10 % is envisaged for stage I and 40 % for stage II materials. This increased production within the EU serves as the foundation for Germany's supplier countries. The underlying recalculated $HHI_{gs,\ 2045}$ and $HHI_{DE,\ 2045}$ are listed in the supplementary material (Additional file 2). Except for cobalt, copper, iron, terbium, and zinc, the $SR_{DE,\ 2045}$ (stage I) is reduced slightly compared to 2035. The difference between 2035 and 2045 for refined products (stage II) is higher than for ores and concentrates (stage I) (Table 3). This is due to the expected higher share of EU countries in further processing, which have an average WGI of 3, while the global WGI average is almost 5. Except for nickel, the other twelve materials remain critical even after all the adjustments made for 2035 and 2045, as already stated for 2023 (Fig. 4).

Fig. 7 plots the recalculated SR-EI Matrix for the considered materials for 2045. Again, materials that have a higher $SR_{DE,\ 2045}$ value in stage II than in stage I are indexed with (II).

4. Discussion

The current criticality of seven out of the 26 crucial materials required for the manufacture of offshore wind technology and electrolyzers in Germany differs from the European perspective [5]. For five materials, boron, cerium, coking coal, iridium, and yttrium the EI, regionalized for Germany (EI_{DE}), is below the threshold value defined by

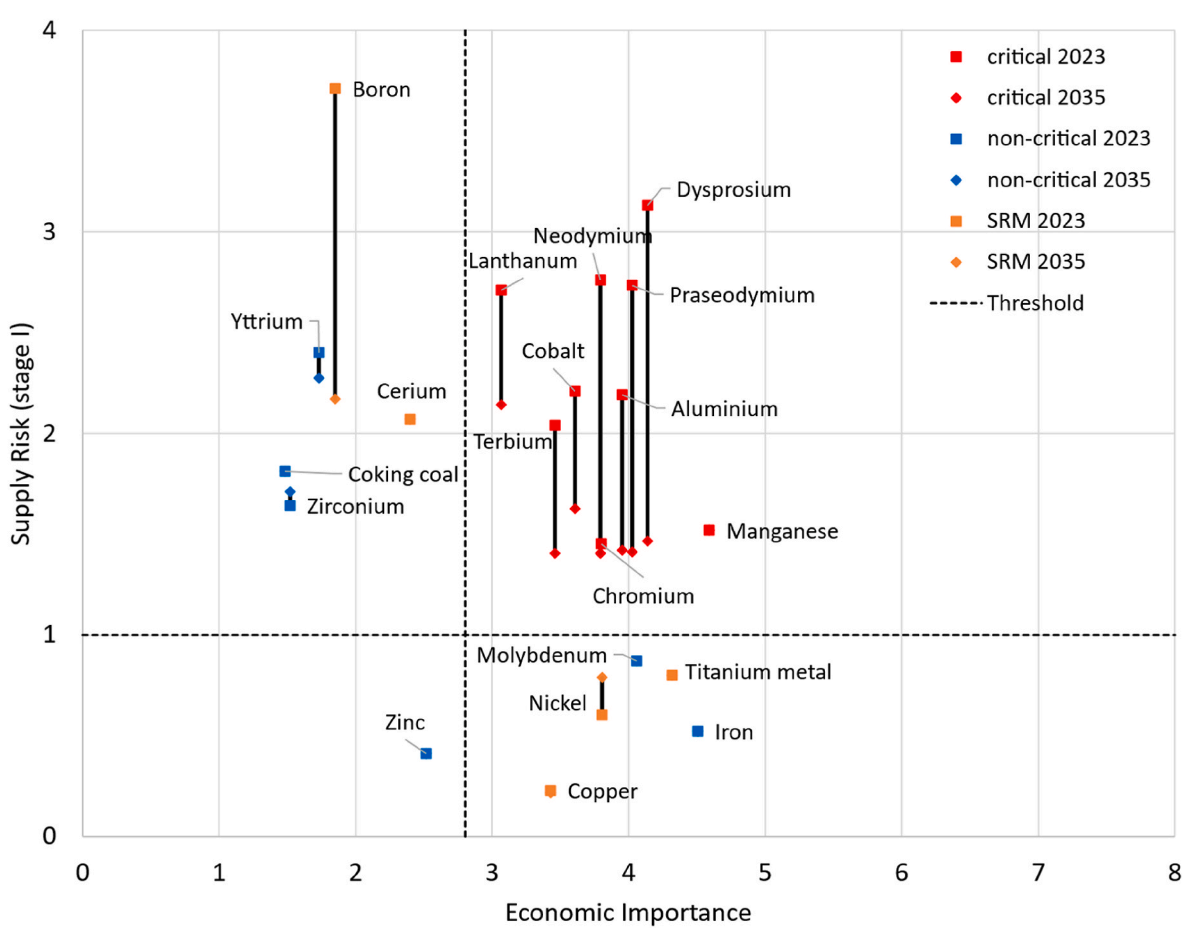

Fig. 5. Change of supply risk from 2023 to 2035 by using future production rates of global producers and diversification of supplier countries for extraction (stage I); SRM: Strategic raw materials

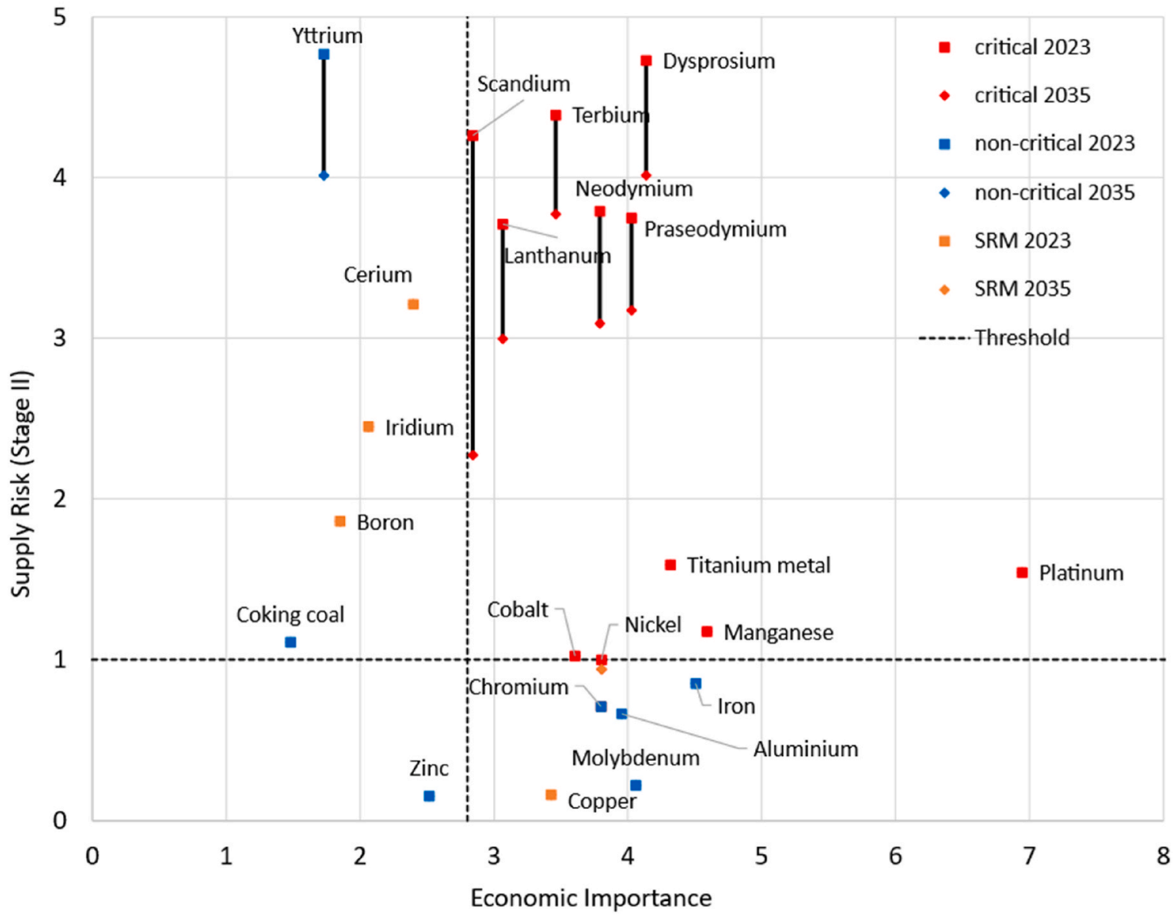

Fig. 6. Change of supply risk from 2023 to 2035 using future production rates of global producers and diversification of supplier countries for processing (stage II); SRM: Strategic raw materials

Table 3
Projected $SR_{DE, 2045}$ in comparison to 2035

Raw material	Stage I		Stage II	
	2045	Deviation compared to 2035, %	2045	Deviation compared to 2035, %
Aluminum	1.2	−16	0.7	0
Boron	1.9	−16	1.9	0
Chromium	1.3	−15	0.7	0
Iron	0.5	0	0.4	−55
Cobalt	1.6	0	1.0	0
Coking coal	1.7	−6	1.1	0
Copper	0.2	0	0.2	0
Cerium	1.9	−11	2.4	−25
Lanthanum	2.0	−9	2.4	−25
Neodymium	1.2	−17	2.5	−24
Praseodymium	1.2	−17	2.5	−28
Manganese	1.3	−15	1.2	0
Molybdenum	0.8	−13	0.2	0
Nickel	0.7	−14	0.8	−13
Iridium	–	–	2.0	−18
Platinum	–	–	1.5	0
Dysprosium	1.4	−7	3.3	−21
Scandium	–	–	1.6	−44
Terbium	1.4	0	3.1	−23
Yttrium	1.9	−7	2.9	−20
Titanium metal	0.8	0	1.6	0
Zinc	0.4	0	0.2	0
Zirconium	0.6	−17	0.0	0

the latest EC-CRM, thus classifying the materials as non-critical. For chromium and nickel, the recalculated supply risk for the current situation in Germany (SR_{DE}) is above the threshold, in contrast to the EU figures.

For the projection of criticality in 2035, the shares of global producing countries were adjusted (HHI_{gs}) and imports from a single third country to Germany were limited to a maximum of 65 % (HHI_{DE}). In addition, imports of at least 10 % from an EU country for ores and ore concentrates (stage I) and at least 40 % EU imports for stage II products were prescribed to project the German situation in 2045. These requirements are based on the CRMA targets. The largest effects in the analysis of the future raw material criticality are seen for rare earths, where a break-up of China's monopoly position is assumed and countries with a lower WGI than China, such as Canada, Australia, and the United States, come to the fore [62]. However, the results show that neither the changed distribution of global producer countries combined with the limitation of Germany's largest supplier countries until 2035 nor the adjustment of the import structure for 2045 can reduce the criticality of today's thirteen critical materials, except for nickel, below the thresholds.

4.1. Supply risk mitigation strategies

Given these unexpected and disillusioning findings, it is important to consider the efforts and actions that are needed to reduce the supply risk to acceptable levels (SR < 1). In its CRMA [6], the EC has addressed various measures in this context and called on the member states to drive them forward and to implement them. Raw materials projects in the fields of extraction, processing or recycling of CRMs can be

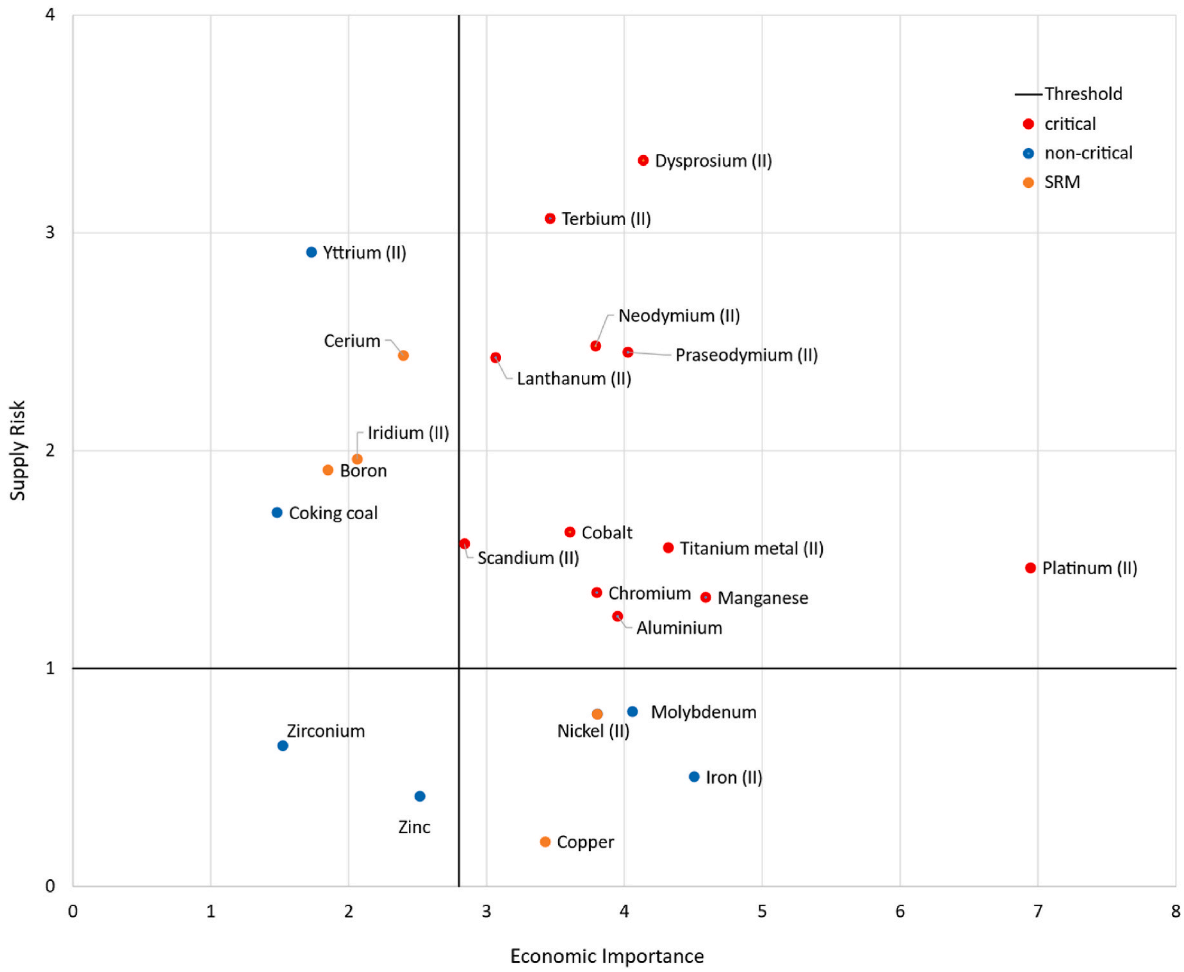

Fig. 7. Projected raw material criticality for Germany in 2045; SRM: Strategic raw materials

recognized by the EC as "strategic projects". This brings many advantages, in particular the acceleration and facilitation of approval procedures. The Swedish mining company LKAB, which recently discovered the largest deposit of rare earths in Europe [61], has applied to the EU for this to be recognized as a "strategic project" [64]. This mining project offers the opportunity to meet future European demand for rare earth minerals. Another prominent project in this context is that of the Zinnwald Lithium GmbH [65,66], which plans to implement one of Europe's largest lithium mining projects near Altenberg in the Ore Mountains, Germany by 2030. The aim is to mine the amount of lithium needed for about 600,000 car batteries per year. Zinnwald Lithium GmbH is also seeking for this project to be classified as a "strategic project", resulting in an approval process off less than 27 months. Furthermore, the member states are requested to set up national exploration programs and circular economy programs. The potential recovery of CRMs from mining waste should be promoted. From 2032, the use of post-consumer recyclates in permanent magnets will be mandatory, which is primarily aimed at ensuring a secure supply of rare earths [60]. Furthermore, the EC is working towards an EU-wide monitoring system for supply risks (e.g. price volatility, supply bottlenecks) and on joint SRM purchasing [60].

At this point, it must be mentioned that raw materials that are not currently defined as strategic by the EC (e.g. aluminum, zinc) may also be exposed to supply risks in the future. For example, Germany imports over 90 % of its bauxite from Guinea alone. Increased energy costs have also caused a decline in smelter production of aluminum and zinc (concerning stage II) in Germany [67]. Therefore, the European Aluminium Association and the German Aluminium Industry Association are appealing to the EC to expand the list of SRMs [68]. Furthermore, strong concerns are expressed about achieving the targets for ore extraction and processing within seven years [69], because the extraction of raw materials is associated with complicated and time-consuming approval procedures and/or a lack of public acceptance [70,71]. As mentioned above, the EC intends to significantly shorten approval procedures with the help of the CRMA. Whether the implementation of the CRMA is successful will play an important role for the future secure supply of raw materials and thus also for the success of the energy transition.

4.1.1. *Diversification and recycling*

In this paper, the analysis focused particularly on two supply risk mitigation strategies. One option is to further diversify the producer and supplier countries, thus reducing the HHI_{gs} and HHI_{DE}. Another option would be to increase the EoL_{RIR} as a risk-reducing measure. Fig. 8 shows by how much either the EoL_{RIR} would have to be increased or the two HHIs reduced in order to bring SR below the criticality threshold of <1 for stages I and II based on the values for 2035. SR is calculated according to equation (5), assuming that HHI_{gs} and HHI_{DE} are reduced by 1 %-point each and that the current EoL_{RIR} is increased by 1 %-point at the same time. The graphs show possible HHI/EoL combinations for which the condition ($SR < 1$) is fulfilled. For better clarity the results for the rare earths are depicted in a separate diagram. Additionally, the current EOL_{RIR} are shown (indicated by a colored diamond). As the EC-CRM states the current EoL_{RIR} for all rare earths to be 1, only one diamond is presented in the rare earth diagram. EI is not changed in this sensitivity analysis. For boron, for example, the current EoL_{RIR} is 1 %. To

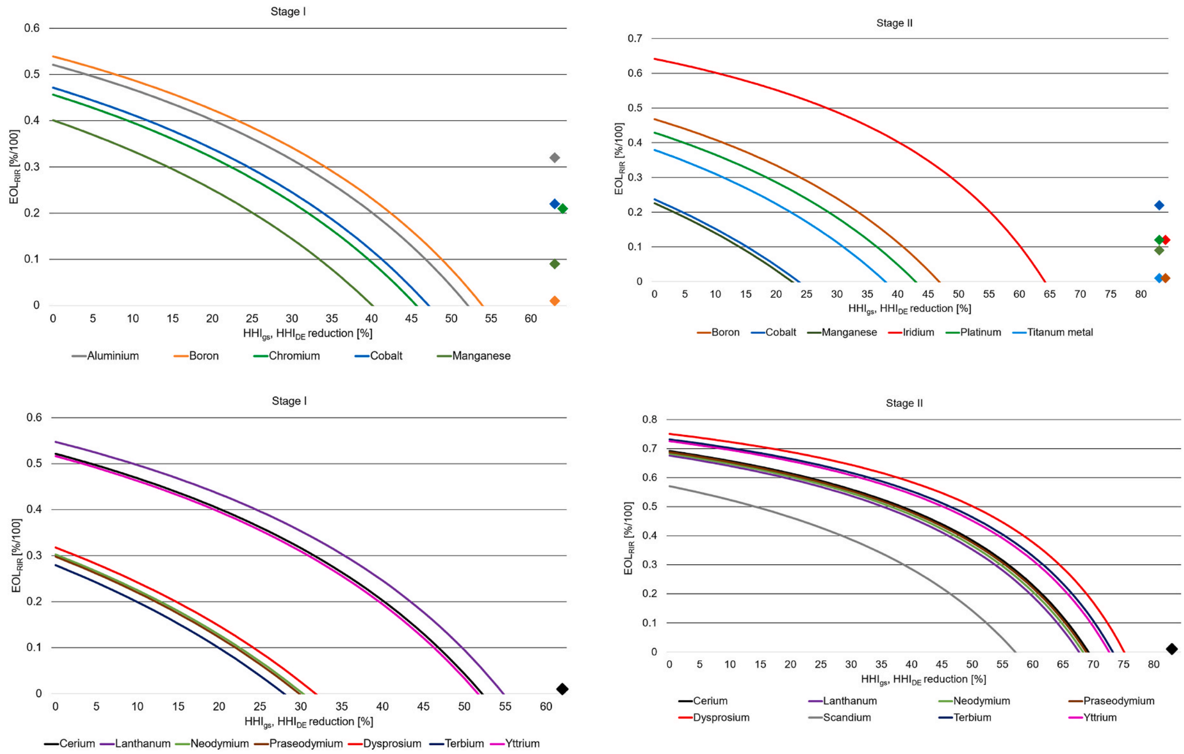

Fig. 8. Results of the sensitivity analysis for a supply risk (SR) < 1; each point on the curve shows a possible HHI/EoL_{RIR} combination; diamonds = current EoL_{RIR}.

bring SR for boron below the threshold of 1 at constant recycling rate, the HHI_{gs} and HHI_{DE} would have to be reduced by 55 %, which is very unlikely, as today only two countries mine borates (Turkey and US) and there are not many known reserves elsewhere. If it were possible to increase the EoL_{RIR} for boron to 20 %, an HHI reduction of 45 % would be sufficient, at 40 % EoL_{RIR} an HHI reduction of 25 % would be sufficient and if a 55 % EoL_{RIR} rate were to be achieved, the HHIs would not have to be reduced any further based on the 2035 values (i.e. no further diversification of producer and supplier countries). Due to the end-use-sectors for boron an increase in recycling is hindered by either loss during the use phase (e.g. fertilizer) or the non-functioning of recycling (e.g. chemicals and cleaning agents). The only promising research activities can be seen in the recycling of NdFeB permanent magnets. This leads to the conclusion that the sufficient supply of boron in Germany will probably continue to be problematic in the future. The situation is quite different for cobalt (stage II), whose EoL_{RIR} is currently already 22 %. An increase in the EoL_{RIR} by 1 %-point to 23 % and a simultaneous marginal reduction in the HHIs by 1 % would be enough to achieve an SR < 1. The situation is similarly promising for manganese (stage II); an increase in EoL_{RIR} by approx. 5 %-points to 14 % and a reduction in the HHIs by 5 % (both seem realistic) would be enough to bring SR < 1. Unfortunately, the graphs for iridium and the rare earth metals show a similar unpromising situation as for boron; the HHIs and the EoL_{RIR} would have to be reduced and increased, respectively, in an unrealistic manner. For rare earths, the degree of geographic concentration in stage II (HHIs) exceeds that found in the extraction (stage I) meaning that the opening of new mines would have only limited benefit in decreasing supply risk.

Furthermore, there are still enormous logistical and technical challenges for recycling. However, EoL_{RIR} efforts have been underway for several years to recycle permanent magnets, e.g., from wind turbines, which contain a significant share of rare earths [72–74]. At this point, the statement on iridium should be supplemented with findings from a recently published study on future demand for iridium [75]. Although the current global EoL_{RIR} of iridium amounts to 20–30 %, an EoL_{RIR} of 40–50 % is already achieved in industrial electrochemical processes [75]. Demand scenarios by Minke et al. [75] result in the depicted cumulative iridium demand for PEM water electrolysis alone of 20 t by 2040 and more than 75 t by 2070. However, less than 10 t per year are currently produced worldwide. Minke et al. [75] show that a recycling infrastructure for iridium catalysts with technical EoL_{RIR} of at least 90 % needs to be developed. The iridium bottleneck is not due to its static range, but to the geographic and socio-economic conditions of exploration and mining, e.g., concentration in South Africa, and the coupling of its production rate to that of the other PGMs, e.g., platinum and palladium [75].

The discussion shows how difficult it will be to achieve even the CRMA targets, let alone even more ambitious ones pointed out by the sensitivity analysis for most materials necessary for the electrolyzer and wind technologies.

Two other important measures to mitigate supply risks are higher material efficiency (e.g. less iridium/kW PEM water electrolysis) and the introduction of alternative technologies (e.g. wind turbine types with fewer rare earth metals such as squirrel cage induction generators and high-temperature superconductors). Neither of these measures is the focus of this paper.

4.2. Limitations

First of all, the method of regionalization and projection of criticality was only applied to materials needed for the manufacturing of water electrolyzers and offshore wind turbines. The manufacturing of both techniques is highly complex. Therefore, not all materials could be included in the analysis. This concerns the rotor blades of the wind turbines and parts of the balance-of-plant of the electrolyzers (e.g. electronics).

A second important point concerns the availability, reliability, geographical coverage and age of the data, as well as how to handle data gaps. The data available for the individual raw materials varies widely. Rare earths are often only considered as a single commodity group in the statistics. The confidentiality of some data was also problematic for the analysis (e.g. data for cobalt exports from the Democratic Republic of

Congo). Trade data often only refer to transit trade and not to the origin of the material. A meaningful interpretation was therefore a central part of the data collection. Whenever possible, we used official, publicly available data that we considered reliable. Mostly, recent data (2020–2024) were used. Here, data from German sources or from EU member states were preferred over international data. If the data situation for Germany was insufficient, available EU data were checked and used if appropriate. If no trade data were available at the EU level either, the analysis was carried out based on global production. It must also be assumed that the forecast data used (e.g. from Roskill, Eurometaux, JRC) is per se characterized by strong uncertainties.

In addition, the entire commodity market is subject to high system dynamics. The widespread production and supply chain, with numerous players from mining companies to processing and recycling, plays a significant role. Raw material prices are also subject to strong volatility, which in turn can affect global demand, production and trade. This high economic momentum is a particular source of uncertainty for the forecasts. Other factors, such as environmental and social aspects that influence the dynamics of raw material supply, were not considered in this paper.

From a methodological point of view, it should be noted that for the regionalization of the EI parameter the gross value added (Q_s) of the individual sectors was recalculated for Germany, but the breakdown of the end use of the materials (A_s) was retained at the EU level (Fig. 2).

As mentioned in Chapter 2.2, imports were split evenly across existing partner countries. However, companies would probably choose the most favorable trading partner. This pattern could be reduced through appropriate political incentives.

Finally, it should be noted that the targets of the CRMA were applied not only to the raw materials defined as strategic by the EC, but to all materials examined in this work.

5. Conclusions

Criticality assessments of raw materials have become increasingly important in recent years. The regular EC-CRM documents the status of today's criticality of raw materials for the EU. However, the underlying data represents an average of the last five years. Looking into the future, which was done in this work, offers great opportunities to identify bottlenecks in the supply of raw materials for emerging technologies at an early stage, even though the assessment of future criticality is associated with large uncertainties due to the dynamics and complexity of raw materials markets. Data quality is a limiting factor for the validity of forecasts. In particular, the origin of imports is difficult to analyze from available statistics. With this in mind, this work presents an initial approach to develop future-oriented criticality assessment using the example of two technologies which are of particular importance for the German energy transition. As we are still in the early stages of this work, we plan to include further technologies and materials in a future study.

The results indicate that significant efforts are needed to ensure that raw materials no longer exceed criticality thresholds. Individual measures are not sufficient; instead, a bundle of them is needed which, for some materials, must go beyond current CRMA's targets.

One of the biggest challenges is diversifying global producer and supplier countries that are crucial for Germany. Equally challenging is strengthening EU mining and refining within the next few years. The point in time at which the CRMA's targets will be achieved depends, among other things, on whether the permitting procedures are accelerated. Currently, there is widespread skepticism about the latter.

The last years have shown the impact of supply chain disruptions and dependencies on imports of raw materials on the economy and society in many countries. Thus, the continuous and secure supply of raw materials is an elementary component of Germany's climate neutrality target by 2045. A comprehensive understanding of future criticality and the effects of possible countermeasures strengthen the transformation of the energy system with limited supply risks.

CRediT authorship contribution statement

Andrea Schreiber: Writing – original draft, Visualization, Methodology, Conceptualization. **Petra Zapp:** Writing – review & editing, Supervision, Conceptualization. **Christina Wulf:** Writing – review & editing, Supervision, Methodology. **Lavinia Reitz:** Visualization, Data curation.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.04.248.

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