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Raw material demand and geopolitical risk in carbon-neutral futures

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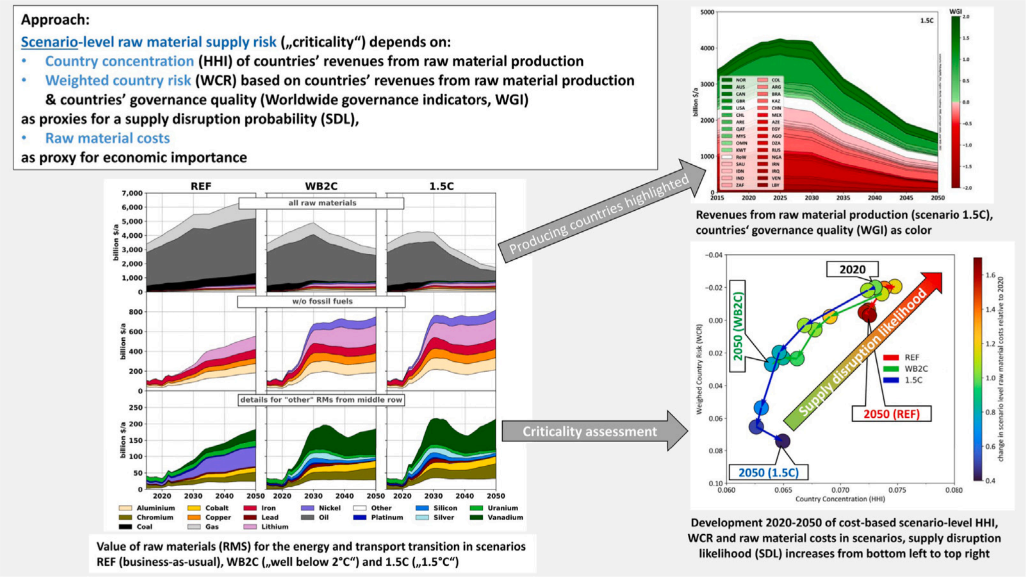
GRAPHICAL ABSTRACT



Approach:

Scenario-level raw material supply risk („criticality") depends on:

- **Country concentration (HHI) of countries' revenues from raw material production**
- **Weighted country risk (WCR) based on countries' revenues from raw material production & countries' governance quality (Worldwide governance indicators, WGI)**

as proxies for a supply disruption probability (SDL),

- **Raw material costs**

as proxy for economic importance

Value of raw materials (RMS) for the energy and transport transition in scenarios REF (business-as-usual), WB2C („well below 2°C") and 1.5C („1.5°C")

Revenues from raw material production (scenario 1.5C), countries' governance quality (WGI) as color

Development 2020-2050 of cost-based scenario-level HHI, WCR and raw material costs in scenarios, supply disruption likelihood (SDL) increases from bottom left to top right

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ABSTRACT

Raw materials are essential for robust global pathways towards carbon-neutral futures. However, many raw materials are subject to geopolitical risks, meaning that potential supply bottlenecks can be an obstacle to a rapid transformation of the energy system towards carbon neutrality. In order to investigate this in more detail, we combine integrated assessment modelling, material flow analysis and a scenario-level geopolitical risk assessment in this study. We show that the total raw material demand for construction and operation of the energy and transport system decreases when considering both, fossil fuels and non-fuel raw materials for the construction of technologies. However, the expected sharp increase in demand for many raw materials in clean energy and transport technologies requires a steep ramp-up of the global raw material production to avoid supply shortages and corresponding price increases. Ambitious system transformation leads to lower total raw material costs compared to a business-as-usual scenario and – depending on assumptions on raw material price development – than today. Finally, scenario-level geopolitical supply risk factors (country concentration

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and weighted country risk of raw material supply) depend only weakly on the degree of defossilization of the energy and transport system. The declining raw material costs are thus the main driver for a considerable reduction in geopolitical-economic dependencies of ambitious climate protection compared to business-as-usual strategies.

Abbreviations	
1.5C	scenario “1.5 °C”
CCS	carbon capture and storage
CdTe	cadmium telluride solar cell
CETT	clean energy and transport technologies
CIGS	copper indium gallium selenide solar cell
CO_2	carbon dioxide
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
GDP	gross domestic product
HHI	Herfindahl–Hirschman index
IAM	integrated assessment model
IEA	international energy agency
IRA	inflation reduction act
ISE	Institut für seltene Erden und strategische Metalle
LFP	lithium ion phosphate batteries
MFA	material flow analysis
NMC	nickel manganese cobalt lithium ion batteries
PV	Photovoltaics
P2X	Power-to-X (electricity-based synthetic gases and fuels)
REE	rare earth elements
REF	scenario “reference”
USGS	United States Geological Survey
WB2C	scenario “well below 2 °C”
WCR	Weighted country risk
WGI	worldwide governance indicator

Nomenclature	
d_r	global demand for raw material r in CETT
d_r^c	demand for raw material r in CETT satisfied by production in country c
d^c	demand for *all* raw materials in CETT satisfied by production in country c
D	global demand for all raw materials in CETT
hhi_r	Herfindahl–Hirschman index for raw material r
HHI^M	scenario-level HHI, based on mass aggregation
HHI^C	scenario-level HHI, based on cost aggregation
p_r^c	production of raw material r in CETT in country c
P_r	global production of raw material r for CETT
pr_r	world market price for raw material r
r_t^c	revenues for raw material r in CETT produced in country c
r^c	total revenues for all raw materials in CETT produced in country c
R	global revenues for all raw materials in CETT
t	time step
t_0	base year of the analysis (2022)
wcr_r	weighted country risk for raw material r
WCR^M	scenario-level WCR, based on mass aggregation
WCR^M	scenario-level WCR, based on cost aggregation
WGI_c	worldwide governance indicator for country c

Units	
bn	billion
kg	kilogramme
Mt	megatonne (10^6 tonnes)
PJ	petajoule (10^{12} J)
t	tonne (10^3 kg)
yr	year
$	US Dollar

1. Introduction

The defossilization of the global energy and transport system goes hand in hand with a complete restructuring of the global energy supply and extensive direct or indirect electrification of the transport and heat sectors (IPCC, 2022). The rapid development of appropriate infrastructures for the generation, storage and transportation of electricity, as well as a rapid decarbonization of energy sources, is essential if the goals of the Paris Agreement are still to be achieved. Wind power and photovoltaic (PV) systems, along with electricity storage, grid infrastructure, and electric vehicles, are anticipated to constitute the foundational components of an integrated carbon-neutral energy system. Though these clean energy and transport technologies (CETT) require less fossil fuels, power generation technologies are generally more material-intensive in their investment phase compared to conventional technologies in a sense that they require more steel, aluminium, or copper per unit of output, *e.g* per kWh of produced power (Hund et al., 2020; IEA, 2021; Schlichenmaier and Naegler, 2022; Liang et al., 2022). In addition, many of these CETT require raw materials that are listed as “critical” by the EU (European Commission, 2023) or the US (Bauer et al., 2023), due to their high economic importance and a high supply disruption likelihood, to which geopolitical risk factors contribute (*e.g* production is concentrated in only a few countries and/or the political stability of the producing countries is low Rosenau-Tornow et al., 2009).

Correspondingly, the energy transition will lead to a shift from fossil fuels (which are central to the *operation* of the current system) to an increased demand in non-fuel raw materials (which are needed for the *construction* of new infrastructures and the built-up of the new vehicle fleet) (Watari et al., 2019; Nijnens et al., 2023). While fossil fuels are not recyclable, the demand for non-fuel raw materials might considerably profit from improvement of recycling processes and could serve – in the future – as a cornerstone of the circular economy (Hagelüken and Goldmann, 2022).

Several studies have analysed the global future raw material demand in specific sectors, *e.g* wind and PV technologies (Carrara et al., 2020) the electricity infrastructure (Deetman et al., 2021), electricity generation technologies, cars, and electronic appliances (Deetman et al., 2018), power generation, storage and transport (Schlichenmaier and Naegler, 2022; Schischke et al., 2023), batteries (Bongartz et al., 2021), electromobility (Jones et al., 2020; Habib et al., 2020), or the energy and transport system (IEA, 2021; IRENA, 2021) (see also overviews in Elshkaki et al. 2016, Watari et al. 2020, 2021). Qualitatively these studies agree in the finding here that the demand for many raw materials, both “critical” materials and major metals like iron, aluminium and copper will increase considerably also as a result of the global energy transition. However, a comprehensive and consistent analysis of the demand of a *broad range of raw materials*, which play an important role *both* for the construction of CETT *and* the operation of a future energy and transport system, is lacking.

The concept of criticality in the context of raw materials has achieved widespread recognition within the academic discourse (Hofmann et al., 2018; Offerman, 2019; Schrijvers et al., 2020) and frameworks for evaluating geopolitical risks associated with these materials have been developed (Santillan Saldivar et al., 2022). Nevertheless, despite its established status, the notion of criticality continues to be the subject of rigorous scholarly debate (Frenzel et al., 2017). However, aggregating the assessment of supply risks from the level of individual raw materials to the technological level presents considerable analytical challenges (Helbig et al., 2016; Santillán-Saldivar et al., 2021; Santillan Saldivar et al., 2022), and geopolitical supply risks on the scenario level have not been quantitatively assessed before. However, China's restrictions on the export of rare earth elements (REE) in 2010, which are required in many CETT and the subsequent multiplication of REE prices (Fernandez, 2017) and Russia's invasion of Ukraine have shown, how vulnerable the current energy system as well as the energy transition is to geopolitical disruptions of the supply of important energy raw materials (Schreurs, 2023). Potential future geopolitical dependencies are also increasingly being discussed for individual raw materials used in CETT (Vakulchuk et al., 2020; IEA, 2021; IRENA, 2023; International Energy Agency (IEA), 2024) and – from a more critical perspective – in Overland (2019).

Qualitative analyses suggest that the clean energy transition will be accompanied by a decline in mining for raw materials for energy and transport and that the associated geopolitical risks may also decrease as a result (Krane and Idel, 2021, 2022). However, a comprehensive *quantitative* analysis of the impact of the global energy transition on geopolitical risks *on the level of entire transformation scenarios* is still lacking. This is particularly true when both the increasing demand for mineral raw materials and the decline in demand for fossil fuels are weighed against each other. This analysis aims to make an initial contribution to this.

Thus, this study pursues the following objectives:

1. Quantify the development of the demand for 34 different raw materials required in different climate mitigation scenarios for the global energy and mobility transition, which differ in their global warming at the end of the century. 30 of those raw materials ("non-fuels") are necessary for the construction of clean energy and transport technologies (CETT) as identified by Schlichenmaier and Naegler (2022) and four "fuels" (gas, oil, coal, uranium) are used to operate the system, (see overview in Table 1).
2. Quantify raw material costs associated with raw material demand.
3. Analyse the risk of short- to medium-term raw material shortages *at the level of individual raw materials*, which may arise due to rapidly increasing global demand and geopolitical risk factors.
4. Identify the development of aggregated geopolitical risk factors *at the level of the scenarios examined.*

2. Materials and methods

2.1. Overview of the analysis workflow

In order answer the research questions identified above, we couple scenario results from the integrated assessment model (IAM) REMIND (Baumstark et al., 2021) with a material flow analysis (MFA) (Schlichenmaier and Naegler, 2022), which assesses the demand for 34 raw materials required to construct and operate the energy infrastructure and vehicle fleet (*i.e.* including fossil fuels and Uranium, cf. Table 1) and estimate raw material costs implied by the scenario results from the IAM.

We focus on three transformation pathways with different degrees of climate protection ambition (see Section 2.2): a reference scenario (Scenario "REF") in which currently energy and climate policies implemented before 2019 are continued without future strengthening of ambition, a second scenario compatible with limiting global warming well below 2° (Scenario "WB2C") and a third scenario which aims at achieving the 1.5° goal of the Paris Agreement (Scenario "1.5C"). We deliberately chose climate change mitigation scenarios featuring fast renewables-based decarbonization of power supply and wide deployment of technology potentials for the large-scale electrification of end-uses sectors (Luderer et al., 2022) for two reasons. First, these represent the subset of climate stabilization pathways that are most consistent with current technology trends (IEA, 2023). Second, such pathways with high deployment of wind and solar power as well as electrification of mobility can be expected to mark the upper end of plausible energy-related critical material demands.

The assessment of raw material demand and costs is followed by a risk analysis which takes into account (a) the pressure to expand raw material production due to increasing demand (b) geopolitical risk factors such as the concentration and the political stability of raw material supplier countries. Fig. 1 gives an overview of different steps of the workflow which are explained in some more detail in the next paragraph and the following sections.

The basis for the Material Flow Analysis (MFA) is a detailed database on the current and expected future specific raw material demands (see step (1) in Fig. 1) which takes into account expected material efficiency gains insofar as the data situation allows. In this data base, the specific raw material demand is given per functional unit (*e.g* per kW generation capacity, per kWh storage capacity, per car) of a broad range of sub-technologies for electricity generation and storage, fuel generation, and for different light duty vehicles classes and powertrain technologies. A full list of all materials can be found in Table 1. System boundaries of the MFA comprise power generation and storage technologies, generation of synthetic gases and fuels (P2X) as well of biogas and biofuels, CCS, and light duty vehicles. An overview of all sub-technologies considered here can be found in the supplementary material (Section 2.1 and Figures 3 and 4). The core of the database was compiled by means of an intensive literature review (Junne et al., 2020; Schlichenmaier and Naegler, 2022) and is available in the supplementary material for Schlichenmaier and Naegler (2022). For the purpose of this study, this database was extended by data on the specific demand of iron, aluminium, and copper from the life-cycle inventory data base Ecoinvent (Version 3.3, built-in raw material amounts only) (Wernet et al., 2016) and an own unpublished analysis on the future demand of those materials in different types of vehicles.

The specific raw material requirements of energy and transportation technologies depend to a large extent on the specific design of the technology. It is therefore not sufficient to look only at the raw material demand for a reference technology within a technology class (*e.g* PV), but it is usually necessary to differentiate between several sub-technologies within a technology class. This may be *e.g* different battery chemistries for stationary or mobile power storage (*e.g* different types of NMC batteries, LFP, lead acid, vanadium redox flow), or different types of PV modules (*e.g* silicon-based vs. this-film modules like CIGS or CdTe). In order to estimate the demand for raw materials in scenarios for the transformation of the energy and transport system, it is therefore necessary to consider scenarios for the development of the market shares of all relevant sub-technologies within a technology class step 2 in Fig. 1, which are referred to as "roadmaps" in this study (see also Junne et al. 2020, Gervais et al. 2021, Dong et al. 2025). The roadmaps used here have been compiled and published by Schlichenmaier and Naegler (2022) and are summarized in the supplementary material (Figures 3 and 4).

The combination of the database for the specific material demand on sub-technology level (step 1) and the sub-technology roadmaps for individual technology classes (step 2) allows estimating the development of the specific material demand on the level of a technology class (step 3 in Fig. 1). Note that the specific raw material demand on the

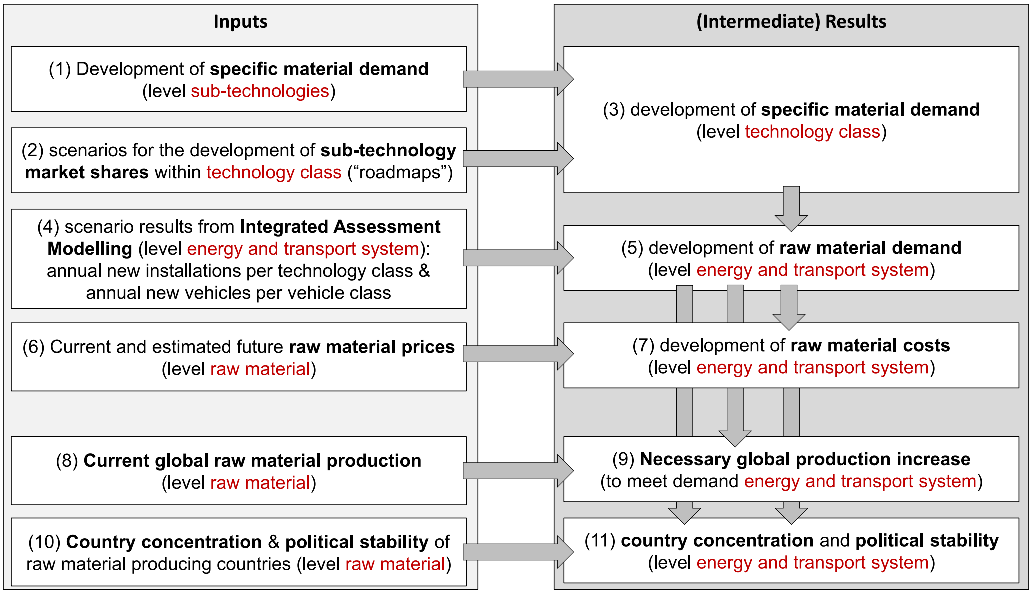

Fig. 1. Overview of the analysis workflow.

level of individual technology classes thus depends on the roadmaps chosen for this technology class.

The raw material demand on the scenario level (step 5 in Fig. 1) is calculated from the specific material demand for each technology class (step 3) and the scenario-specific annual new installations per technology class (step 4) modelled with the integrated assessment model (IAM) REMIND (see Section 2.2). We do not differentiate between primary material and (recycled) secondary material. This implicitly means that the possibilities of a circular economy to reduce the need for primary materials are not taken into account in the analysis. The demand for fossil fuels (coal, oil, and gas) is directly taken from the REMIND results (given in PJ/yr) and converted to mass units. REMIND scenario results relevant for the analysis are documented in the supplementary material (Section 1.2).

A compilation of current world market prices for the raw materials considered and two scenarios for extrapolating prices into the future (see Table 1 and Section 2.3) enable the raw material costs associated with the realization of the scenario to be estimated (steps 6 and 7 in Fig. 1). (Please note that the estimation of raw material requirements and raw material costs is carried out on the basis of the already calculated IAM scenarios. They therefore do not influence the scenario results.)

For many of the raw materials considered here, demand is expected to rise sharply in the future — driven in part by the increasing demand for energy and transport technologies. As global raw material production cannot be expanded at will, it cannot be ruled out that there will be shortages of certain raw materials in the medium term. In order to quantify the pressure to expand the production of individual raw materials, we compare the maximum annual demand for the various raw materials in CETT in the period under review up to 2050 with current raw material production (steps 8 and 9 in Fig. 1), which is summarized in Table 1 and Section 2.4.

Finally, the geopolitical risk assessment of the scenarios is based on (a) two proxy indicators which describe the likelihood of a disruption of raw material supply (SDL), and (b) a proxy indicator for the "economic damage" induced by a supply shortage. The "economic damage" component of the risk assessment is represented by the *value* of the raw materials required in the scenarios. As indicators for the supply disruption likelihood (SDL), the concentration of raw material supplying countries (measured by the Herfindahl–Hirschman Index HHI) and the weighted country risk (WCR) were used. The latter is measuring the political stability of the supplying countries. Both SDL indicators are well established to assess geopolitical risks for individual raw materials. Current values for individual raw materials are summarized in Table 1. As HHI and WCR are generally defined on the level of *individual raw materials*, in this paper, we propose a new approach to aggregate the HHI and WCR for individual raw materials in order to quantify these two indicators on the level of *entire energy scenarios* (steps 10 and 11 in Fig. 1). This approach is described in detail in Section 2.5.

2.2. Integrated assessment model climate mitigation scenarios

The three energy transformation pathways considered in this study were produced with the Integrated Assessment Model REMIND (Baumstark et al., 2021) in its version 2.1.3. REMIND represents the integrated energy-economy-climate system by coupling an macro-economic growth model with a bottom-up representation of energy supply and demand. REMIND includes substantial detail in electricity generation, non-electric energy supply, as well as energy enduse for the industry, transport and buildings sectors. Crucially, REMIND is coupled to the transport model EDGE-T (Rottoli et al., 2021a,b), which models the vehicle stock and technology choice at high granularity. This feature is particularly valuable to estimate raw material demand for electric vehicles. REMIND is also coupled to the landuse model MAgPIE (Dietrich et al., 2019) for bioenergy demands as well as landuse and agricultural emissions. The key criteria for the selection of REMIND were (a) global coverage (b) consistent joint modelling of the transformation of the energy and transport system (c) availability of model results required for resource demand and criticality assessment (new installations power and heat generation/storage or new registration of cars) are available, (d) model is established in the ESM community.

As for the scenarios considered, "REF" describes a continuation of the relatively weak climate policy ambition of individual nations implemented until 2020. It therefore does not account, for instance, for the impact of the inflation reduction act (IRA) of the United States for the Fit-for-55 package of the European Union.

For the other two scenarios, greenhouse gas emissions pricing is assumed to be implemented in all regions such that cumulative CO2 emissions from 2020–2100 are limited to 900 $GtCO_2$ (Scenario "WB2C"), consistent with limiting global mean temperature increase well below 2 °C, or 500 $GtCO_2$, consistent with limiting warming to below 1.5 °C after temporary overshoot (Scenario "1.5C"). These climate stabilization scenarios further assume dedicated policies to accelerate the market introduction of battery-electric vehicles as well as continued rapid learning effects to reduce costs of vehicle batteries and renewable

Table 1

Overview of analysed materials, global production, HHI and WCR (for 2022), prices (for 2023). HHI and WCR were calculated based on data given in the references. For prices for fossil & nuclear fuels as well as additional information for price data see supplementary material (Section 2.5). References: BP: (BP, 2022), IM: (index mundi, 2023), ISE: (ISE, 2024), USGS: (USGS, 2023), RMIS: (Joint Research Centre, 2023), WB: (Kaufmann and Kraay, 2023), WMD: (Reichl and Schatz, 2023).

Raw material	Production [t/yr]	HHI	WCR	Price [$/kg]	References
Aluminium	68,352,000	0.37	−0.07	2.87	USGS, WB
Cadmium	22,594	0.20	0.29	4.10	USGS, WB
Cerium	113,865	0.53	−0.09	3.78	USGS, ISE, WB
Chromium	12,897,711	0.27	−0.09	12.13	USGS, WB
Cobalt	195,940	0.55	−1.20	36.38	USGS, WB
Copper	21,903,000	0.12	0.00	8.67	USGS, WB
Dysprosium	2,725	0.30	−0.27	418.38	RMIS, ISE, WB
Gallium	610	0.97	−0.33	370.00	USGS, WB
Germanium	178	0.57	0.04	1,400.00	RMIS, WB
Indium	999	0.49	0.14	240.00	USGS, WB
Iridium	7	0.83	−0.20	147,895.70	USGS, WB
Iron	1,295,800,000	0.46	−0.13	0.59	USGS, ISE, WB
Lanthanum	62,535	0.38	−0.06	3.66	RMIS, ISE, WB
Lead	4,460,000	0.23	−0.07	2.54	USGS, WB
Lithium	146,450	0.35	0.88	273.31	USGS, WB
Magnesium	1,046,000	0.80	−0.33	7.11	USGS, WB
Manganese	20,109,000	0.22	−0.03	7.02	USGS, WB
Neodymium	40,674	0.42	−0.19	95.46	RMIS, ISE, WB
Nickel	3,269,000	0.27	−0.00	21.80	USGS, WB
Platinum	174	0.53	−0.25	32,151.24	USGS, WB
Potassium	33,986,285	0.20	0.33	0.73	USGS, IM, WB
Selenium	3,307	0.22	0.37	21.00	USGS, WB
Silicon	9,061,000	0.55	−0.21	4.19	USGS, WB
Silver	25,615	0.12	−0.15	752.34	USGS, WB
Sulphur	82,190,000	0.10	0.16	0.10	USGS, WB
Tellurium	585	0.45	−0.04	78.46	USGS, ISE, WB
Vanadium	101,610	0.48	−0.45	36.41	USGS, WB
Yttrium	14,737	0.30	−0.22	32.48	RMIS, ISE, WB
Zinc	12,303,000	0.17	−0.00	2.98	USGS, WB
Zirconium	no data	0.19	0.42	28.00	USGS, WB
Coal	8,364,759,974	0.30	−0.07	see supplement	BP, WB
Oil	4,424,137,161	0.08	−0.06	see supplement	BP, WB
Gas	3,437,500,086	0.10	0.09	see supplement	BP, WB
Uranium	55,972	0.25	0.04	see supplement	WMD, WB

electricity generation in line with historic trends. More detail on these scenarios and the modelling is available from Luderer et al. (2022).

2.3. Raw material price assumptions and price scenarios

The price data used for the present analysis are annual average prices for the year 2023 and were compiled from data from the US Geological Survey (USGS) (USGS, 2023), Institut für seltene Erden und strategische Metalle (ISE) (ISE, 2023), and index mundi (index mundi, 2023). An overview of prices for non-fuel raw materials can be found in Table 1. Prices for fossil and nuclear fuels for the different scenarios are endogenously calculated by the integrated assessment model used to generate the energy and transport system scenarios. They are documented in Section 2.5 in the supplementary material, where also a discussion of the price scenarios can be found as well as a detailed description of the data sources and calculation steps for the material prices.

In the present work, two scenarios for the development of (real) prices are considered: In the standard calculations in the main text, it is assumed that (real) prices for non-fuel raw materials remain constant at the 2023 level over the entire analysis period. The idea behind this so-called “static” price scenario is that price decreases due to ongoing technological learning (Song et al., 2022) in the field of exploration and mining can balance potential price increases caused by the rising demand. For fossil and nuclear fuels prices endogenously calculated by the REMIND model are used, which depend on the development of the global demand and differ between the scenarios.

In a sensitivity test, the “growth” price scenario, an annual increase of the non-fuel raw material real prices by 5% based again on average prices for 2023 was assumed. In contrast, prices for fossil and nuclear fuels in the “growth” scenario are identical to prices in the “static” scenario. The idea of this price scenario is to investigate a case in which non-fuel raw materials have an economic disadvantage in comparison to fossil fuels. The price development of the non-fuel raw materials is in line with Hotelling’s rule (Hotelling, 1931; Livernois, 2009), which assumes that prices for exhaustible resources increases with a standard the discount rate. The selected annual price increase of 5% (which reflects the interest rate and maybe other influences) is close to high historical discount rates (IMF, 2024).

In view of the considerable uncertainty of the future development of commodity prices, these two scenarios only represent extreme cases in the context of a sensitivity test. Under no circumstances should they be understood as a forecast of future commodity prices.

2.4. Current production estimates of fuels and non-fuel raw materials

Estimates of the current production of raw materials including fossil fuels (for the year 2022) are summarized in Table 1. The data is compiled from BP (2022), USGS (2023), Reichl and Schatz (2023), Joint Research Centre (2023). For all further analysis, it is assumed that each country’s share in the global production of a commodity remains constant over the time horizon of the analysis, regardless of increasing or decreasing total demand of each commodity.

2.5. Geopolitical risk assessment on raw material and scenario level

The definition of the term “criticality” in this paper is based on the definition of “risk” from the field of risk assessment: “Risk” (or “criticality in this paper) is defined as the expected value of a loss caused by a specific event (see *e.g* Cox 2009). In our analysis, the “event” that triggers the damage is a supply shortage of certain raw materials. The criticality assessment must therefore include two components: On the one hand, the likelihood of a supply bottleneck and, on the other, the damage caused by it. Both variables – likelihood and damage – must be estimated on the basis of suitable proxy indicators, as a modelling of the interplay between economy, raw material supply, and geopolitics is far too complex. Note that there is no clear definition of "criticality" in the literature. Other approaches use different sets of indicators for the SDL or the damage or even include environmental effects of raw material production as an elementary pillar in an assessment of raw material criticality (*e.g* Graedel et al. (2012), see also critical discussion in Frenzel et al. 2017).

As will be shown in detail below, the supply disruption likelihood (SDL) is estimated in the paper using two sub-indicators, the Herfindahl–Hirschman Index (HHI) and the Weighted Country Risk (WCR). As already mentioned above in Section 2.1, the value of the raw materials is used as a proxy for the potential damage. In the following paragraphs, we present first the method to calculate both indicators *for individual raw materials*, before we show how HHI and WCR *on scenario level* (*i.e.* aggregated over *all* materials) can be calculated.

For assessing the **geopolitical induced supply disruption likelihood on the *level of individual raw materials*** (metals and fossil fuels), two indicators were used (see *e.g* Fig. 4):

First, the Herfindahl–Hirschman-Index (HHI) (Hirschman, 1964) measures the concentration of producing countries as an indicator for the market concentration risk. For a raw material r, the hhi_r is calculated as follows:

$$hhi_r = \sum_c \left(\frac{p_r^c}{P_r}\right)^2 \tag{1}$$

where p_r^c/P_r denotes the fraction of the production of raw material r in country c in the global production P_r of this material. p_r^c/P_r is calculated from current production data (see above).

The second indicator is the Weighted Country Risk of a raw material r (WCR_r) (Rosenau-Tornow et al., 2009; Buchholz et al., 2012), which is a measure for the raw material supply risk due to political instability of the producing countries. The WCR is based on the Worldwide Governance Indicator (WGI) (Kaufmann et al., 2011; Kaufmann and Kraay, 2022) developed by the World Bank. Within the WGI framework, six dimensions of governance are measured: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. The arithmetic mean of all six indicators for the year 2021 is used in the analyses in this paper. The WGI theoretically can have values between −3 (very unfavourable) and +3 (very favourable). However, the WGI (arithmetic mean of all six sub-indicators) for countries that produce relevant quantities of raw materials for energy and transportation technologies is currently (2023) between −1.54 (Democratic Republic of Congo) and +1.74 (Norway). The WGI for these countries is documented in Table 2 in the supplement.

The weighted country risk of a raw material r, wcr_r, is an weighted average WGI, with the country share in global production of the raw material as the weighting factor. wcr_r is thus calculated as follows:

$$wcr_r = \sum_c \left(\frac{p_r^c}{P_r} \cdot WGI_c\right) \tag{2}$$

The HHI and WCR are used both in the scientific literature (Frenzel et al., 2017; Schrijvers et al., 2020) and by national agencies (DERA, 2023) or the European Union (European Commission, 2017) to assess potential geopolitical risks in supply of individual raw materials. However, to our knowledge, there have not yet been any approaches to determine the HHI and WCR indicators for the raw material demand of *entire transformation scenarios*. The approach presented in the following paragraph closes this gap.

The approach presented above to calculate the geopolitical risk indicators HHI and WCR *for individual raw materials* can be extended to obtain a similar assessment for the raw material requirements *for entire energy scenarios*. Scenario level HHI and WCR thus require an aggregation over all raw materials necessary to implement the energy transition described in the scenario. The scenario level indicators then allow (a) the estimation of the change in the country concentration and country risks at scenario level over time due to the temporal development of the demand for individual raw materials in the scenario and (b) a comparison of the risks between different transformation strategies.

The basic idea for scenario level HHI and WCR is to replace the term p_r^c/P_r in Eqs. (1) and (2) which describes the share of a country c in the global production of an *individual* raw material r is replaced by either

1. a country's share in the global *production* (in mass units) of *all* raw materials required to implement the assessed scenario **(mass based approach)** or
2. a country's share in the global *value* (in monetary units) of *all* raw materials required to implement the assessed scenario **(cost based approach)**

In a more formalized manner, these two approaches can be formulated as follows: From the scenario assessment, we obtain the global demand for a raw material r at each time step t ($d^r(t)$). A central assumption in our analysis is that a country's share of global production of a raw material r (p_r^c/P_r) does *not* change over time (*i.e.* remains constant at *current* levels at time step t_0, which is known from published sources), even if global production increases. Then the production of raw material r for clean energy and transport technologies in country c at time step t ($d_r^c(t)$) can be calculated from the global demand in a scenario ($d^r(t)$) and current share of county c in the global production of r as follows:

$$d_r^c(t) = d_r(t) \cdot \frac{p_r^c(t_0)}{P_r(t_0)} \tag{3}$$

The contribution of a country c to the *total* raw material demand in the scenario can thus be calculated as:

$$d^c(t) = \sum_r d_r^c(t) \tag{4}$$

If D(t) denotes the total mass of *all* raw materials required in a scenario at time step t, it follows that a mass-aggregated HHI^M on *scenario level* (index "M" for "mass") can be calculated as:

$$HHI^M(t) = \sum_c \left(\frac{d^c(t)}{D(t)}\right)^2 \tag{5}$$

When comparing Eqs. (1) and (5), it can be seen that the term p_r^c/P_r is replaced with the term d^c/D. A mass-aggregated WCR^M on scenario level can thus be calculated in a similar manner:

$$WCR^M(t) = \sum_c \left(\frac{d^c(t)}{D(t)} \cdot WGI_c(t_0)\right) \tag{6}$$

Please note that it is assumed that the WGIs do not change over time. We thus do *not* assume any development of the governance quality in the producing countries over the course of the scenario.

Cost-aggregated HHI^C and WCR^C can be calculated in a similar way: The share of a country c in the global revenues of a raw material r can be estimated similar to Eq. (3):

$$r_r^c(t) = pr_r(t) \cdot d_r^c(t) = pr_r(t) \cdot d_r(t) \cdot \frac{p_r^c(t_0)}{P_r(t_0)} \tag{7}$$

where $pr_r(t)$ is the price of a raw material r at time t. Here, too, we assume that a country c contributes exactly the same proportion to the demand for a raw material r in the scenario as its *current* share of global production.

The share of a country c to the total raw material *revenues* in the scenario can thus be calculated (analogous to Eq. (4)) as:

$$r^c(t) = \sum_r r_r^c(t) \tag{8}$$

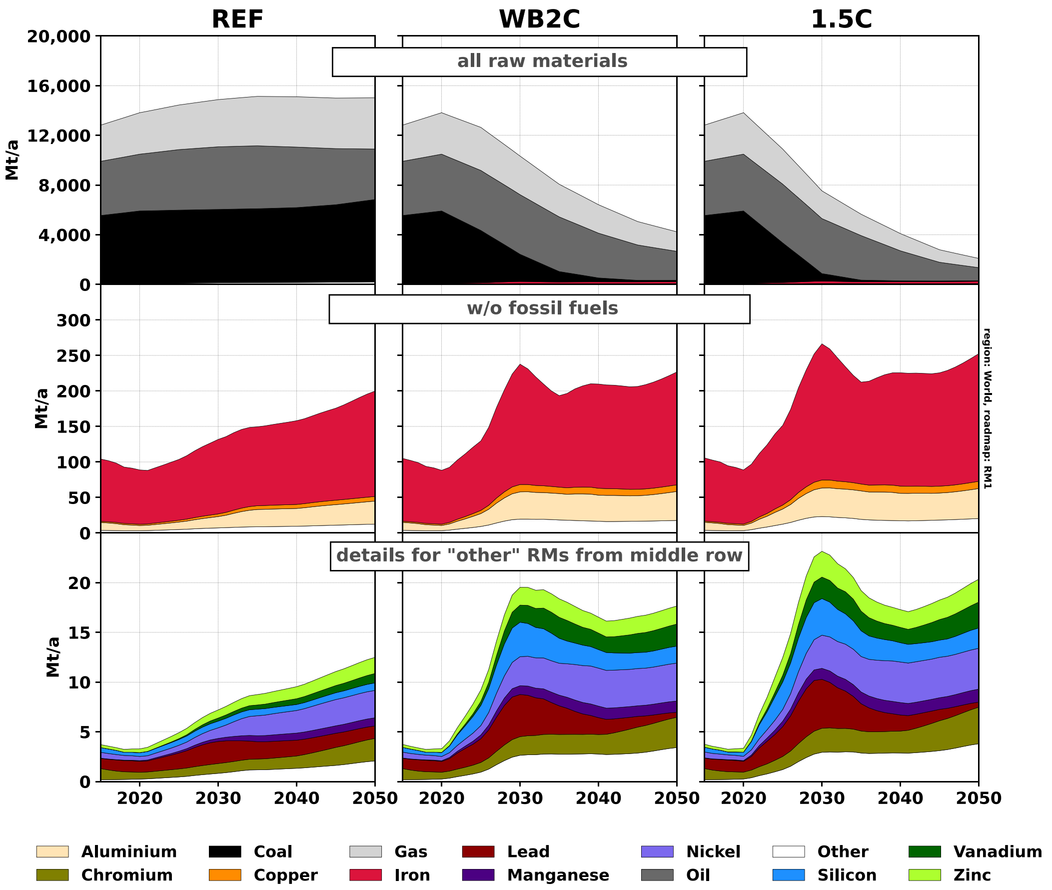

Fig. 2. Annual global raw material demand (in Mt/yr) for the energy system including transport in the scenarios REF (left column), W2BC (middle column), and 1.5C (right column) and for roadmap RM1. In order to show also results for raw materials with a small demand, the figure zooms in from the top row (all materials) over the middle row (all materials except fossil fuels) to the bottom row, which shows details for the "other" materials from the middle row. Results for raw material with very low demand ("other" in bottom row) can be found in the supplementary data (Figures 7ff).

If R(t) denote the total revenues in all countries from all raw materials required to implement the scenario, a cost-aggregated HHI^C (index "C" for "costs") can be defined similar to Eq. (5) as:

$$HHI^C(t) = \sum_c \left(\frac{r^c(t)}{R(t)}\right)^2 \tag{9}$$

and a cost-aggregated WCR^C similar to Eq. (2) as:

$$WCR^C(t) = \sum_c \left(\frac{r^c(t)}{R(t)} \cdot WGI_c\right) \tag{10}$$

3. Results

3.1. Raw material demand (mass units)

The investments in new technologies, encompassing power generation, generation of biogenic and synthetic fuels, storage solutions, and vehicles, enable the calculation of an annual global raw material demand for each of the three scenarios under review (cf. Fig. 2). The analysis includes the remaining demand for fossil fuels such as coal, gas, and oil. As the magnitudes of the demand for the individual raw materials differ considerably, the figure zooms in on the raw material demand from left to right.

In the REF scenario, total raw material demand – fuels and non-fuel raw materials – increases from currently (2020) about 13,800 Mt/yr to about 15,000 Mt/yr in 2050 (upper left panel in Fig. 2). In 2050, fossil fuels constitute 98.7% of the total raw material demand by mass. The demand for iron is projected to be approximately 150 Mt/yr, while the combined demand for all other raw materials examined in this study is estimated at 51 Mt/yr (as shown in the middle row, left column). In the WB2D and 1.5C scenarios, the total raw material demand decreases considerably to about 4200 Mt/yr (WB2D, −69% compared to 2020) and 2100 Mt/yr (1.5C, −85%), mainly due to the largely complete phase-out of fossil fuels in those two scenarios. However, the decarbonization of energy and transport goes hand in hand with a strong increase in the demand for non-fuel raw materials, which is roughly tripling between 2020 (88 Mt/yr) and the interim high in 2030 (238 Mt/yr in WB2D, and 266 Mt/yr in 1.5C) and reaches 227 Mt/yr in 2050 (WB2D; 1.5C: 266 Mt/yr). Iron, aluminium, and copper dominate the non-fuel raw material demand (middle row in Fig. 2), as they are required in many CETT in large quantities. The bottom row highlights the demand for other non-fuel raw materials. Here, we see that considerable up-scaling of nickel and chromium, but also lead, manganese, silicon, vanadium, and zinc are required in comparison to today's level, and much in particular in the decarbonization scenarios. In terms of mass, the demand for other materials analysed here (such as lithium, neodymium, dysprosium etc, see Table 1 and Section 3.1. the supplementary data) is comparatively small.

3.2. Costs associated with raw material demand

The projected global costs associated with the raw material demand are shown in Fig. 3, which has a similar structure to Fig. 2. Here and in the following analyses, current raw material prices are assumed to remain constant until 2050 (see Table 1) unless otherwise stated. The quantitative results for raw material costs shown here are thus probably a lower bound. However, in sensitivity tests (see discussion) we can show that our qualitative results do not depend on the price scenario.

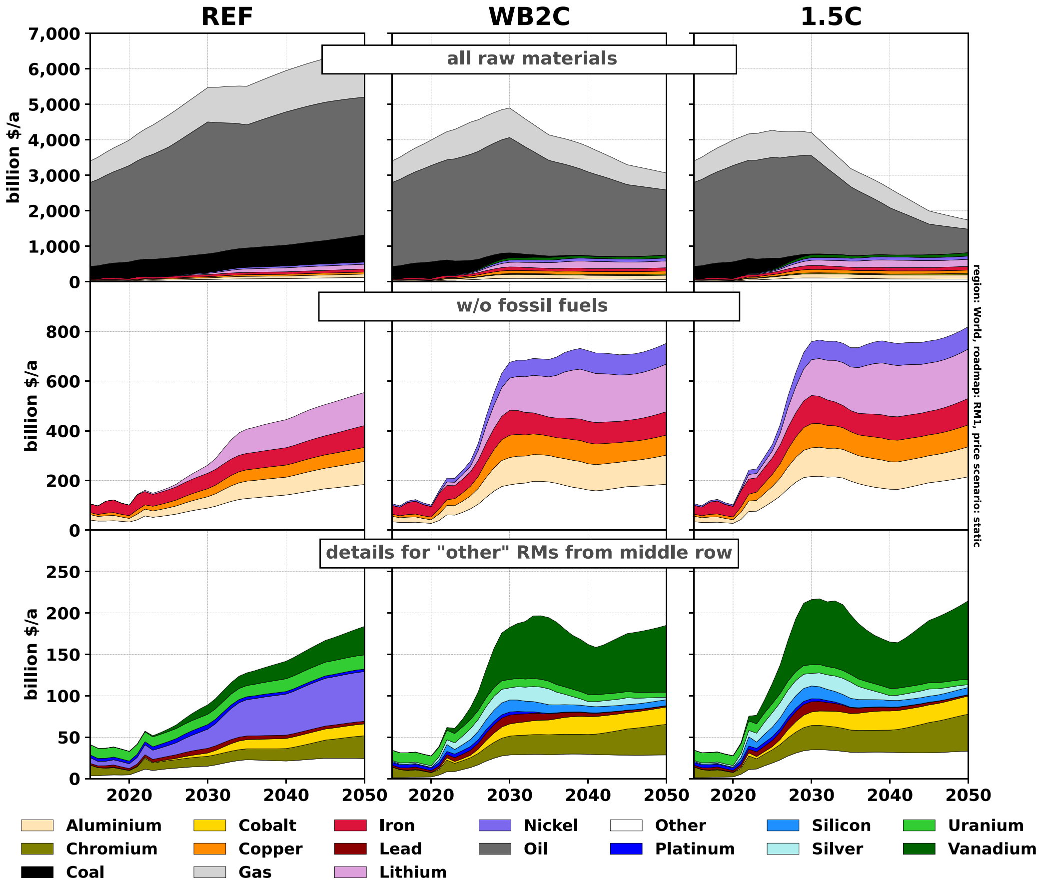

Fig. 3. Annual global raw material costs for the energy system and transport (in billion $/yr) in the scenarios REF (left column), W2BC (middle column), and 1.5C (right column) in roadmap RM1. In order to show also results for raw materials with a small costs, the figure zooms in from the top row (all materials) over the middle row (all materials except fossil fuels) to the bottom row, which shows details for the "other" materials from the middle row.

In the REF scenario, the aggregate costs for raw materials (fuels and non-fuels) increase from currently (2020) about 4000 bn $/yr to more than 5500 bn $/yr in 2035. By 2050, the expenditure to sustain the energy system through the replacement of aging infrastructure and the expansion in regions with growing demand is projected to reach around 6500 bn $/yr. In contrast to the reference case, total raw material costs decrease considerably (after an increase until 2030) in both the WB2D and the 1.5C scenarios: In the WB2D scenario, the costs decrease by almost 25% between 2020 and 2050 (3100 bn $/yr). In the 1.5C scenario, with 1700 bn $/yr in 2050, raw material costs have more than halved since 2020.

The substantial reduction in costs observed in the WB2C and 1.5C scenarios is primarily attributed to the systematic phase-out of fossil fuels. Despite the marked rise in expenses for non-fuel raw materials, the overall costs are considerably mitigated by the savings achieved from reduced fossil fuel expenditures under an ambitious decarbonization strategy. On the one hand, raw materials that are used in large quantities in clean energy technologies (such as steel, aluminium and copper) account for a dominant share of total non-fuel raw material costs: ca. 75% in 2020 and still between 40% and 45% in 2050, depending on the scenario. On the other hand, materials that are required in small quantities but have a comparatively high price per kg (cf. Table 1), such as lithium and nickel (see middle row in Fig. 3), but also chromium, cobalt, lead, platinum, silicon, silver, uranium, and vanadium (bottom row in Fig. 3), contribute considerably to the overall costs for non-fossil raw materials.

3.3. Evaluating raw material supply risks in market and geopolitical contexts

The likelihood of supply bottlenecks for raw materials can be attributed to a variety of factors. A detailed review of indicators used to estimate the supply disruption likelihood can be found, for example, in Helbig et al. (2016), Frenzel et al. (2017), Schrijvers et al. (2020). Fig. 4 summarizes the results for four of the most often used indicators of a potential supply disruption on the level of individual raw materials on the basis of the 1.5C scenario and roadmap RM1 (cf. Figures 3f in the supplement for details). Fossil fuels are not shown in this picture, as they would dominate the cost axis.

Geopolitically related supply risks are assessed here by the concentration of raw material producing countries in the form of the Herfindahl–Hirschman Index (HHI) on the x-axis, and the weighted country risk (WCR, with more negative values indicating higher risk) for each raw material analysed on the y-axis (see methods section and Table 1 for details). The supply disruption likelihood due to geopolitical factors increases from left to right and from bottom to top in this chart.

One market-related aspect shown in Fig. 4 is the necessary expansion of raw material production, which is only possible to a limited extent for many raw materials (Humphreys, 2014); the development of new deposits, for example, takes an average of 8 to 10 years (Hartman and Mutmansky, 2002). Accordingly, the risk of short to medium-term bottlenecks increases if global production cannot be expanded quickly enough to meet rapidly rising demand.

The second market-related aspect shown in Fig. 4 is the cumulative costs for the supply of individual raw materials in the scenario 1.5C indicated by the colour of the circles.

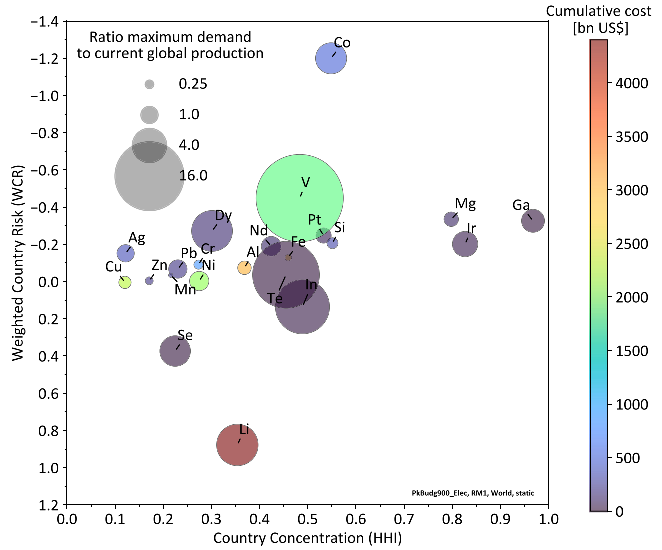

Fig. 4. X-axis: Country concentration (measured by HHI), Y-axis: weighted country risk (WCR), colour: cumulative (2020–2050) raw material costs (billion US$, constant prices), circle size: ratio maximum annual raw material demand (in 2020–2050) to current annual global production, for selected raw materials. Note the reversed order of the *y*-axis, as more negative WCR-values indicate higher risk. The geopolitically related supply disruption likelihood increases from bottom left to top right. Results for scenario 1.5C-RM1.

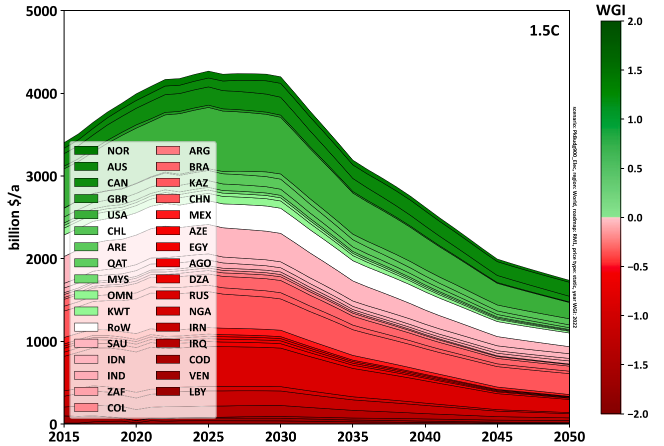

Fig. 5. Annual revenues from raw material production per producing country for the scenario 1.5C (RM1). The colour indicates the country's Worldwide Governance Indicator (WGI). See Table 2 in the supplementary material for numerical WGI values for all relevant countries and explanations of the ISO 3166 country codes. RoW: Rest of world.

Here is a brief example of how Fig. 4 can be interpreted: The light green circle in the centre represents results for vanadium. Vanadium has a comparatively high concentration of supplier countries (HHI on x-axis: 0.48) and a high weighted country risk (WCR on y-axis: −0.45). *In the particular scenario analysed here*, global vanadium production must be expanded by a factor of 25 (indicated by the circle size). The cumulative value of vanadium production is around 1800 billion dollars, indicated by the green colour of the circle (see colour axis on the right).

Concentration of supplying countries is highest for gallium and magnesium (used in some types of PV cells), and iridium (used in electrolysers). However, the country concentration is still high for iron, battery materials such as cobalt, lithium, and vanadium, platinum (fuel cells) and indium (electrolysers), rare earth elements such as neodymium and dysprosium (for permanent magnets in electric motors and wind turbines), aluminium, and others. Cobalt has the highest weighted country risk, followed by vanadium, magnesium, gallium, dysprosium, and others. Particularly for materials used in stationary and mobile batteries, as well as in specific thin-film PV technologies, fuel cells, electrolyzers, and permanent magnets, there exists a substantial exposure to geopolitical risks. Geopolitical risks for fossil fuels (not shown on plot) are comparably low (HHI/WCR for coal: 0.30/-0.07, oil: 0.08/-0.06, gas: 0.10/0.09).

In this scenario shown in Fig. 4, a fast and strong expansion of global production capacities is necessary to match the raw material demand for *CETT alone*. This is in particular true for vanadium (factor of 25), tellurium (factor of 15), indium (factor of 109), lithium and dysprosium (factor of 6), and cobalt (factor of 3). Also the production of iridium, gallium, neodymium, or nickel has to be increased considerably within a short period of time. In contrast, within the analysis period, the maximum annual demand for fossil fuels is only slightly higher than the current production (not shown). Note, however, that in thin film PV technologies (requiring selenium, tellurium) and V-redox-flow batteries (vanadium) could in principle partly be substituted by other PV or battery technologies, thus reducing the necessary production expansion somewhat (see Figures 3 and 4 in the supplement). In terms of cumulative costs, materials that are required in large quantities in many technologies dominate, such as lithium (4400 bn $), aluminium (3,00 bn $), iron (2700 bn $), and copper (2300 bn $). Also battery and PV materials have significant cumulative costs (nickel: 2000 bn $, vanadium: 1800 bn $, cobalt: 500 bn $, silicon: 300 bn $), and alloy elements such as chromium (800 bn $). Cumulative costs for fossil fuels (not shown on the picture), reach almost 58,000 bn $ for oil and 17,000 bn $ for gas and 3100 bn $ for coal, respectively.

3.4. *Geopolitical risk assessment across energy transition scenarios*

In the previous section, supply risks due to geopolitical and market-related factors were discussed *for the individual raw materials* required to built up and operate the energy and transport system. The following sections aim to quantify geopolitical risks *at the level of the overall system*, *i.e.* aggregated across the supply risks for the individual raw materials. Particular attention is paid to the temporal development of supply risks over the course of the transformation process and the comparison of geopolitical risks between different scenarios.

Fig. 5 illustrates geopolitical risk aspects for the 1.5C scenario. It shows the revenues from raw material production (fuels and non-fuels) for the most relevant producer countries.[2] The colour of each country corresponds to its Worldwide Governance Indicator (WGI) (see Table 2 in the supplement for details). The figure illustrates *qualitatively* that, while raw material revenues are considerably decreasing due to the global energy transition, the relative shares of producing countries with a high and low WGI remains similar over the scenario period. Also, the degree of concentration of producing countries does not appear to be changing considerably either. Thus, at first glance, the concentration of supplying countries and the average political stability of those countries do not change considerably until 2050.

These findings are further substantiated *quantitatively* in Fig. 6: It shows the temporal development of scenario-level, cost-weighted country concentration (HHI^C) and weighted country risk (WCR^C, see Section 2.5) on a HHI-WCR plane similar to Fig. 4 and for all three scenarios. Furthermore, the development of the total annual raw material costs of each scenario (relative to 2020) is shown as the colour of the circles. In the REF scenario (red lines), HHI^C and WCR^C hardly changes over time. In contrast, in the ambitious transformation scenarios WB2C (light blue) and 1.5C (dark blue), both geopolitical risk indicators tend

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[2] The total global revenues are identical with the total global costs in Fig. 3, lower left panel.

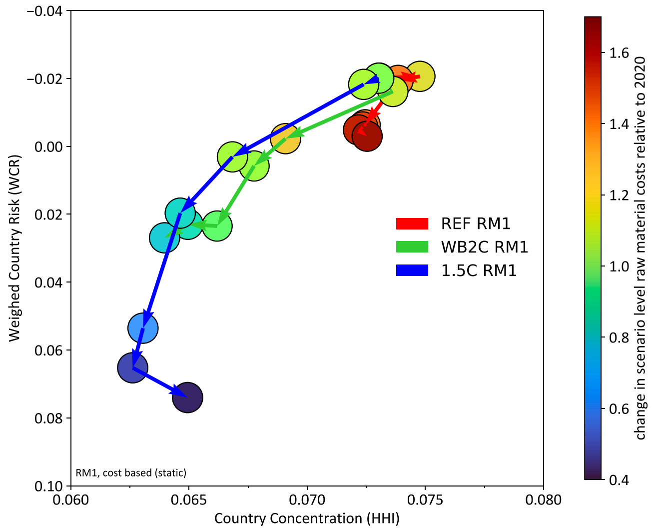

Fig. 6. Temporal development of scenario-level HHI^C and WCR^C in 5-year steps between 2020 and 2050 (cost-based aggregation). The timeline is indicated by the arrows; arrow colours distinguish the three scenarios. The fill colours indicate the total raw material costs relative to 2020 (at static prices). Note the reversed order of the y-axis: The supply disruption likelihood increases from the lower left to the upper right corner.

to decrease, however, only slightly — in particular given the potential range of the HHI (between 0 and 1) and of the WCR (typically between −2.5 and +2.5). As already shown in Fig. 3, in can further be seen that ambitious climate protection (scenarios WB2C and 1.5C) leads to considerably lower costs for fuels and non-fuel raw materials than in the REF scenario with considerably less climate protection. The geopolitical advantages of ambitious climate protection are therefore primarily to be seen in the fact that the dependencies on a few and/or politically unstable producing countries decrease quantitatively (in terms of raw material costs) — both over time and compared to a less ambitious scenario.

4. Discussion

While we address the uncertainty of climate mitigation pathways and the development of sub-technologies through the scenarios presented, it is important to note that these are not exhaustive. There are additional pathways, which we outline below, that could lead to significantly varied material demands.

4.1. Effect of cost assumptions

Estimates of future raw material prices play a central role for the assessment of geopolitical risks in out approach. Raw material prices depend on a complex interplay of drivers like demand growth, mining productivity, resource quality, recycling rates etc. Schischke et al. (2024), Bhuwalka et al. (2023). Although there are estimates of price developments on the raw material markets (Boer et al., 2021; Mauler et al., 2022; Orangi et al., 2023), deriving comprehensive and consistent price scenarios is challenging. To account for this, we perform a sensitivity test with an annual price increase of 5% for all non-fuel raw materials.

Also under increasing prices for non-fuel raw materials, total costs in the REF case are higher than in the WB2C scenario and lowest in 1.5C. The scenario-wide criticality indicators HHI^C and WCR^C show a similar behaviour in the case of increasing prices compared to the static price case (see Section 4 in the supplement). This suggests that the finding that geopolitical risks in the sense analysed here are generally *lower* in the case of ambitious climate protection compared to a business-as-usual strategy is robust for increasing raw material prices.

4.2. Key uncertainties

Analysing the raw material demand and geopolitical risks by energy scenarios is associated with uncertainties in many aspects:

The underlying scenarios are plausible and self-consistent transformation paths for the energy and transportation system without any claim on completeness nor on probabilities. However, other pathways associated with considerably different material demands are possible.

In fast evolving technologies such as batteries (International Energy Agency (IEA), 2023a; Itani and De Bernardinis, 2023), material compositions change dynamically. Even though we have tried to take possible trends into account in the sub-technology roadmaps, it is possible that completely newly developed sub-technologies with a considerably different raw material profile will come to the market in the future and could have a considerable impact on the demand for certain raw materials.

The analysis relies on assumptions also about the future development of specific raw material requirements for most sub-technologies. However, it is difficult to quantify how realistic it is that the expected material efficiency gains can actually be realized. For some technologies, the data situation is so thin that current values for the specific raw material demand must be used for the entire analysis horizon. This might lead to an overestimation of the raw material demand in these sub-technologies.

In a future energy system, international trade with synthetic energy carriers is expected to play a major role (Nuñez-Jimenez and De Blasio, 2022; Fonder et al., 2024; Egerer et al., 2023). As corresponding trade flows are not depicted in the scenario model, the new geopolitical risks arising from the import of these energy carriers cannot be addressed here.

One core limitation of the analysis is its static (with respect to hhi and wcr for individual raw materials) and indicator-based approach which can neither capture the whole complexity of international trade flows (and associated geopolitical risks) nor trends in raw material production market shares and country governance. This analysis therefore cannot and does not intend to replace in-depth analyses of supply risks along the value chains of key raw materials and technologies for the energy transition. However, as it integrates over many technologies and raw materials, it can highlight broad trends and serve as an early guiding system for long-term strategic decisions in the energy sector.

Considering fluctuations in future raw material prices is extremely difficult and only very little studies on the long-term price development of raw materials exist (see *e.g* Sverdrup et al. 2017, Fu et al. 2020, Bajolle et al. 2022, Boer et al. 2023, Bhuwalka et al. 2023). On the other hand, assumptions for commodity costs play an important role in the analysis presented here. As we discussed in more detail Section 4 in the supplement, we assume that our approach has taken into account the majority of the effects of possible price increases. Nevertheless, even more considerable price increases than assumed here cannot be ruled out, even for commodities whose costs make a considerable contribution to overall commodity costs. Therefore, a less generic analysis of potential price risks for individual raw materials would be desirable. However, this was beyond the scope of this study.

This analysis takes a global perspective. Results could be different from the perspective of a specific country or region (*e.g* the EU), taking into account regional raw material production, import shares, countries of origin of imports, regional recycling, etc. In addition, it would be important to analyse not only potential geopolitical bottlenecks for raw material production, but also bottlenecks along the entire value chain from raw material extraction, refining and processing to the production of the actual technology. Furthermore, political relationships and trade relations between raw material producing countries and “end-user” countries could be considered in the analysis.

Finally, a shortage of fossil fuels has different consequences for the energy system than a shortage in materials required for the built up of the energy (and transport) infrastructure. A shortage of fossil fuels directly impairs the operation of the energy and transport system. Furthermore, fossil fuels are not recyclable. In contrast, a scarcity of raw materials required for the built-up of infrastructures slows down the transformation process but does not immediately affect operation. Also, those raw materials can in principle be recycled. Therefore, questions also need to be clarified as to how the different characteristics of fossil fuels on the one hand and raw materials for the construction of new infrastructures on the other can be taken adequately into account in a criticality analysis.

In the present analysis, the possibility of reducing the demand for primary materials (and the resulting geopolitical dependencies) by recycling raw materials was not addressed. However, it is to be expected that the core statements of the analysis will remain qualitatively unchanged even if recycling is taken into account. This is primarily due to the fact that the high geopolitical and economic dependency identified in the REF scenario compared to the two climate protection scenarios is due to a considerable extent to the high consumption of non-recyclable fossil fuels in REF.

4.3. Comparison of results with other studies

As already shown in Section 1, there are many publications on the future development of raw material requirements in CETTs. However, a thorough quantitative understanding of differences between these studies and our analysis is generally difficult, as the various studies make very different assumptions regarding drivers for raw material demand, such as climate protection goals, GDP and population development, sub-technology roadmaps, specific raw material demand, etc. Furthermore, those assumptions are often not well documented. The comparison of our results with results from selected studies in the following paragraphs can therefore only be made qualitatively.

International Energy Agency (IEA) (2024) estimates the demand for cobalt, copper, lithium, nickel, and rare earth elements implied by global scenarios for the global energy and transport transition from the IEA's world energy outlook (International Energy Agency (IEA), 2023b). In general, the estimates from International Energy Agency (IEA) (2024) of the future demand of those raw materials are similar in magnitude as the results here. Furthermore, as found out here, the demand for those materials increase with increasing ambition of climate protection. However, when comparing the demand in individual technology classes, there are some clear differences between (International Energy Agency (IEA), 2024) and this study. They are discussed in more detail in Section 3.2 in the supplementary material, but cannot be fully resolved.

Watari et al. (2020) have compiled previous estimates of the expected raw material demand for clean energy and transport technologies in 2030 and 2050. While the results here in this study are well in the range of demand estimates compiled by Watari et al. (2020) for many materials, for some materials (*e.g* chromium, indium, nickel, silicon, silver, and zinc) the estimates here exceed the range previously found in the literature, in particular for the year 2030 (see Section 3.2 in the supplement for details). One reason for this could be that in scenarios that are limited by a CO_2 *budget* (as in our study), CO_2 emissions must already be reduced considerably already in the next few years. This means that the energy infrastructure and vehicle fleet must be converted more quickly than in scenarios that only achieve climate neutrality in 2045 or 2050.

As in the present study, Krane and Idel (2021, 2022), Nijnens et al. (2023) come to the conclusion that ambitious climate protection requires less mining than a business-as-usual scenario, as the growing demand for non-fuel raw materials is more than offset by the decline in fossil fuel mining activities.

5. Conclusion and outlook

To the best of our knowledge, neither a systematic and comprehensive analysis of the development of geopolitical risks associated with the raw material demand for the energy and transport transformation, nor a comparison of risks of different transformation scenarios, as presented in this paper, has ever been carried out to date. We were able to show that both demand and costs for raw materials required for the energy and transport transition will increase in the coming years — especially in the case of ambitious climate protection. At the same time, the consumption of fossil fuels will fall disproportionately compared to a business-as-usual scenario if the climate protection targets of the Paris Agreement are met. Our study indicates that the reduction in fossil fuel consumption outweighs the increased demand for non-fuel raw materials. This offers reassurance that the shift toward clean energy and transport will not intensify existing geopolitical risks.

Addressing the future scarcity of metals and mitigating geopolitical risks is a multifaceted challenge that should be tackled through a blend of technical and non-technical approaches. Technical options include improving material efficiency (including new sub-technologies that are less reliant on critical materials), extending the lifespan of energy infrastructure and vehicles (Gaustad et al., 2018), and enhancing regional recycling efforts which decrease the dependency from primary material imports. Furthermore, efficiency and sufficiency measures can lead to a reduction in the demand for raw materials, which would help to mitigate geopolitical risks. While these strategies offer promising avenues for long-term sustainability, the transformation process towards climate-friendly energy supply and transport requires first a fast built-up of new infrastructures and electric vehicle stocks (as well as mining and refining capacities), the short-term effect of these measures will be limited.

On the non-technical side, there is a need for policies that diversify resource bases, securing access to materials through new alliances and partnerships as well as long-term supply contracts (IRENA, 2023), and the deployment of alternative and preferably regional resource deposits. In particular the built up a *regional* recycling infrastructure could help reducing raw material imports and the associated geopolitical risks. Largely climate-neutral energy and transport systems, synthetic hydrogen-based energy carriers (P2X) are expected to play an important role. Therefore, new geopolitical risks associated with P2X import strategies must be carefully weighed against economic criteria to avoid new dependencies.

Our paper presents for the first time an approach on how to assess trends in aggregated geopolitical risks related to raw material demand for the global energy and transport transition. Nevertheless, there is of course potential for further development in many areas: On the one hand, analyses of geopolitical risks should be tailored more closely to a focus region in order to take better account of its regional characteristics with regard to transformation strategies, but also to regional raw material production, economic-political relations with raw material-producing countries, etc. Secondly, there is an need to address new potential dependencies due to imports of P2X, but also energy and transport technologies, already at the scenario development stage. Finally, the static, indicator-based approach presented here should be improved to better address the complexity of global supply chains and trends in political-economic relations between countries when attempting to assess geopolitical risks for the future and contribute to the development of resilient, robust transformation strategies for energy and transport.

CRediT authorship contribution statement

Tobias Naegler: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Sebastian Rauner:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Alois Dirnaichner:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Patrick Jochem:** Writing – review & editing, Conceptualization. **Steffen Schlosser:** Writing – original draft, Formal analysis, Data curation. **Gunnar Luderer:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tobias Naegler reports financial support was provided by German Federal Ministry of Education and Research. Gunnar Luderer, Sebastian Rauner, Alois Dirnaichner, Patrick Jochem, Steffen Schlosser reports financial support was provided by German Federal Ministry of Education and Research. If there are other authors, they 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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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enpol.2025.114622.

Data availability

Data will be made available on request.

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