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Research paper

# Raw material risk in clean energy technologies and the power supply system: For which materials should price fluctuations be prioritised?

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ABSTRACT

Transformation strategies for climate-friendly energy systems are often obtained with cost-optimising energy system models (ESMs). Although technology cost assumptions considerably affect model outputs, state-of-the-art ESMs generally do not account for the dependence of technology prices on potential raw material price fluctuations. Owing to the large number of raw materials required in central clean energy technologies (CETs), such as photovoltaics, batteries, offshore and onshore wind power, electrolysers, or fuel cells, any future consideration of raw material price fluctuations in ESMs to derive resilient energy system transformation strategies requires prioritising the raw materials considered. We therefore provide a framework for identifying raw materials whose price fluctuations should be explicitly considered in ESM-based energy scenarios. The materials associated with the highest CET-specific risk are determined based on an estimate of the current contributions of selected raw materials to technology costs as well as their geopolitical and market-based supply disruption likelihood (SDL). The analysis is performed both at the level of individual central CETs and at the level of power supply scenarios, which aggregate over several CETs. From the system perspective, the materials with the highest price risk are steel alloy materials (iron, chromium, nickel), rare earth elements (neodymium and dysprosium), lithium, and silicon. High-risk materials at the level of individual CETs can differ.

## 1. Introduction

Changing the energy system to achieve a transformation to net-zero emissions poses a technical, economic, social, and regulatory challenge. Technical implementation requires the installation of clean energy technologies (CETs) at a large scale while ensuring a safe supply of energy in an increasingly decentralised and complex energy system. The construction of CETs is subject to a high dependence on raw materials (Liang et al., 2022). A wide variety of raw materials is required (Zepf, 2020), and the mass per functional unit[1] is often greater for the construction of CETs than for conventional fossil-based technologies (de Koning et al., 2018). Therefore, continuous access to the required raw materials is crucial for energy system transformation. Previous studies revealed that the global demand for many raw materials will increase substantially due to CETs, mobility, industry, and the expanding overall economy (Tokimatsu et al., 2018; Valero et al., 2018; Schlichenmaier and Naegler, 2022). This increasing material demand has raised concerns about the security of raw material supply and the consequences in the case of supply disruptions (Mancini et al., 2013).

Material supply disruptions do not necessarily imply that a material is entirely unavailable on the market. However, in the case of a material supply disruption, demand exceeds supply, leading to an increase in the price of a considered raw material (Sprecher et al., 2015).

Owing to the comparatively high material requirement and the high specific investment cost per energy output, it is necessary to investigate how sensitive CETs are to increases in the prices of the required raw materials. Potential driving factors for raw material supply disruptions must be analysed as well. On this basis, the materials associated with the highest risk for individual CETs can be identified.

Strategies for the technical implementation of energy system transformation are often obtained from energy system models (ESMs). However, state-of-the art energy system models do not yet consider the impact of changes in raw material prices. Therefore, the materials whose price fluctuations should explicitly be considered in ESM-based energy scenarios must be identified from a wide range of candidate materials. To identify the materials associated with the highest risk for the power supply system, a risk analysis similar to the level of an individual CET must be conducted at the level of the power supply system, which aggregates over several CETs.

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[1] A functional unit is defined as a 'quantified performance of a product system for use as a reference unit' (ISO, 2006).

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## 2. Literature review

In the past, there have been considerable increases in raw material prices. However, the driving factors for price spikes in the future could be quite different from the historical factors (Althaf and Babbitt, 2021). Accordingly, material shortages and price increases that are more drastic than the maximum increases in the past are possible.

There are a small number of elaborate models for estimating future long-term raw material prices; they employ complex model mechanics and consider material demand scenarios (Fu et al., 2020; Sverdrup et al., 2017; Boer et al., 2023; Bhuwalka et al., 2023). These models focus on a limited selection of materials and do not account for the impact of disruptive events on material prices. To analyse the impact of disruptive events on material prices, Santillan-Saldivar et al. estimated the price elasticities of battery materials from historical material price increases after disruptive events (Santillán-Saldivar et al., 2021). However, Santillan-Saldivar et al. do not provide a causal chain model for the translation of supply disruptions into material price spikes. The insufficient knowledge about the future development of material prices, i.e., after disruptive events, indicates that further research on the future development of material prices is necessary. Owing to the high number of potentially relevant materials, screening for materials, which should be prioritised, is required. We propose screening on the basis of material risk for the specific context of central CETs and the power supply system.

The impact of changes in material prices on CETs is dependent on the CET cost structure (Lütkehaus et al., 2022). Technology cost models,[2] which use a bottom-up approach and include raw materials, have been developed in research and industry for different technologies. Examples for battery systems include BatPaC (Nelson et al., 2019), CellEst (Wentker et al., 2019), or the model by PSI (Berg et al., 2015). Such models enable the analysis of detailed price contributions and the testing of the sensitivities to possible material price spikes (Wentker et al., 2019). Owing to the high technology specificity, in-depth industrial knowledge about the production process and access to related data are required to build and utilise bottom-up technology cost models. Therefore, the focus of bottom-up cost modelling is usually on only one technology class or even a single sub-technology. Sub-technologies are variants within a main technology class that fulfil the same function but can differ in the material systems used (Junne et al., 2020). The production processes for a sub-technology produced by different manufacturers can be quite different, leading to different technology costs and raw material price contributions. Owing to their high case specificity, bottom-up technology cost models are able to calculate the price contribution of raw materials to technologies in a precise way, i.e., for their manufacturers. However, analyses aiming to identify implications at the system level utilise expected values for typical technologies or sub-technologies.

Studies that compare the economic competitiveness of different technology systems and consider the impact of raw materials on technology costs are scarce in the literature (Ciez and Whitacre, 2016; Sun et al., 2022; Leader et al., 2019; Wilting and Hanemaaijer, 2014). Leader et al. (2019) investigated the impact of possible increases in the prices of raw materials on technology costs for selected CETs. The technology cost depending on raw material prices was compared to a target cost level, where economic competitiveness is expected. Leader et al. investigated catalysts for proton-exchange membrane (PEM) fuel cells in fuel cell electric vehicles, neodymium permanent magnets (NdFeB) in direct drive wind turbine generators, and cathode materials in Li-ion batteries for electric vehicles (Leader et al., 2019).

The cost changes of a CET following material price changes will subsequently influence the power supply system. Therefore, a perspective shift to the whole power supply system is necessary to understand the systemic impacts of changes in raw material prices.

Technical transformation strategies for energy systems are often obtained with cost-minimising ESMs[3] (Trutnevyte, 2016), such as REMix (Gils et al., 2017; Wetzel et al., 2024), TIMES (Loulou et al., 2016a,b), MARKAL (Kannan, 2011), or PyPSA (Brown et al., 2018). On the basis of the technology cost related to typical functional units of the considered technologies, as well as fixed operation and maintenance costs, fuel costs and emissions costs, the overall system cost is determined in a bottom-up manner. This system cost function serves as the optimisation target (Kotzur et al., 2021), and the system transformation goals, i.e., emission reductions, are typically formulated as constraints. Therefore, cost assumptions play a central role in determining which technologies are preferably installed according to optimising ESMs.

In most state-of-the-art ESMs used to derive technical transformation strategies, the raw materials required to build CETs are implicitly assumed to be available in unlimited quantities and at current prices. Although pioneering approaches outline how the supply disruption likelihood (SDL) associated with CETs can be included in ESMs as a second optimisation target (Cao et al., 2024), they do not yet capture the impact of material price changes on CET costs and the results of optimising ESMs. Relative changes in the costs of the considered technologies can lead to a change in the overall system cost, which leads to a change in the cost-optimal technology mix. Strengthening the resilience of the energy system requires adapting ESMs to evaluate the long-term impact of material price changes on the energy system. Identifying the materials to be prioritised for such an analysis – from an exhaustive range of candidate materials – is a necessary initial step that is still lacking in the literature.

Raw material criticality considerations aim to assess the economic risk associated with a material for a specified target (Frenzel et al., 2017), i.e., individual technologies or an economy. The risk depends on the economic damage in the case of a supply disruption and the likelihood of a supply disruption. There are various criticality assessment methods with different assumptions about the mechanisms, which lead to supply disruptions and subsequently cause economic damage to a system (Graedel et al., 2012; Helbig et al., 2016; Blengini et al., 2017; European Commission, 2017; National Science and Technology Council, 2016; Schrijvers et al., 2020). The choice of the appropriate criticality assessment method depends on the specific research context.

Geopolitical conflicts and the market situation are highly relevant as potential driving factors for supply disruptions. This focus is set due to politically related events such as the rare earth crisis (Sprecher et al., 2015) and the sensitive dependence of the technology sector on a steady supply of certain key materials in a highly competitive market (Hofmann et al., 2018).

The likelihood of geopolitical supply disruptions is affected by the concentration and political stability of the supplier countries (Blengini et al., 2017; European Commission, 2017). The likelihood of market-based supply disruptions can be influenced by various factors. The increase in production required to meet future material demand is highly important. If demand exceeds the available supply from ongoing mining operations, severe supply chain disruptions follow. In such a case, the adaptation of supply requires a stronger exploitation of existing mining projects or investment in the development of new mining projects. The time interval from the start of a mining project to operation is several years, with an expected value of five to thirteen

[2] Bottom-up technology cost models derive the cost of an individual technology or sub-technology from the variable cost of the required inputs (i.e., materials, labour, and energy) and additional fixed costs (Duffner et al., 2021).

[3] An 'optimization energy model identifies the most favorable set of technology [in an energy system, e.g. at a national level] to accomplish a defined target at reduced costs under particular constraints' (Laha and Chakraborty, 2017, p. 102).

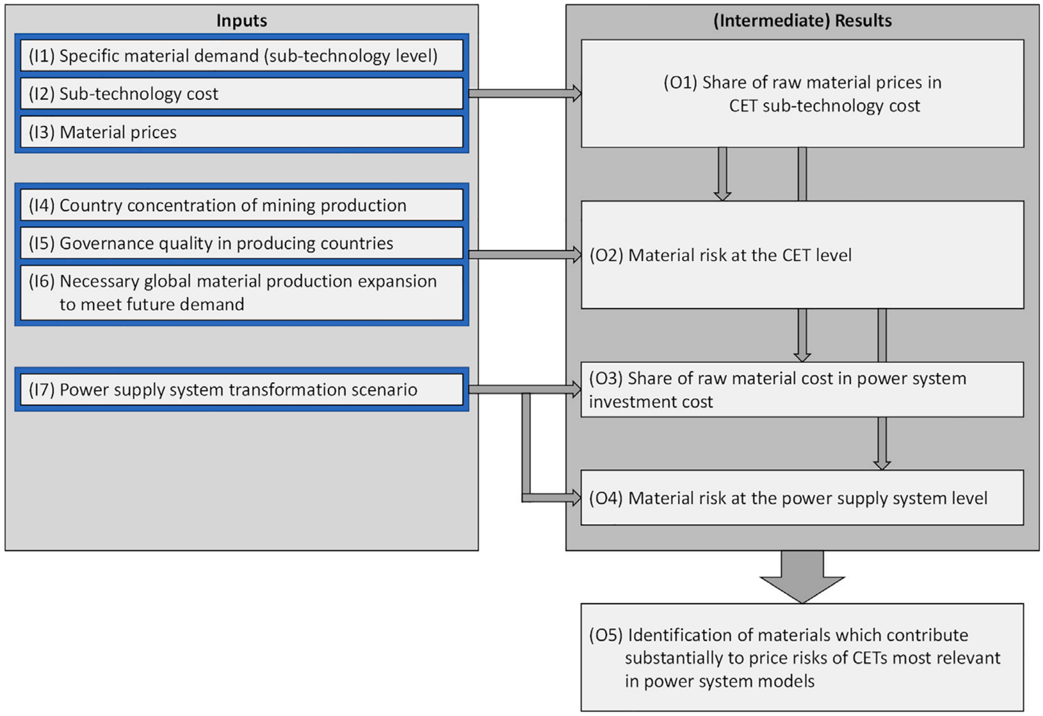


**Fig. 1.** Workflow for identifying the materials to be integrated into optimising energy system models.

years (Hartman and Mutmansky, 2002). In this context, absolute physical abundance is unlikely to be the limiting factor (van Oers et al., 2020).

Supply chain disruptions related to geopolitical factors can lead to drastic short-term price increases. These increases may fall after the conflicts have been resolved and the supply chains have been restored. A persistent mismatch between supply and demand related to market-based factors can lead to continuous price increases over a longer period.

## 3. Research question

An analysis that differentiates the key CETs into their sub-technologies and yields a credible expected value for the cost share of raw materials in each sub-technology, is still lacking in the literature. On this basis, we propose a qualitative framework to identify the materials associated with the highest risk, specifically for central CETs, from an exhaustive range of candidate materials. Furthermore, we propose the transfer of our framework to the global power supply system to identify the materials, the price fluctuations of which should be the focus of energy system analysis.

This analysis spans the range from the CET level to the power supply system level. Furthermore, it provides CET developers with information on which materials should be reduced to lower the cost risk in CETs. To the best of our knowledge, there is no study that covers a similarly broad scope of CETs at a high level of detail with the objective of determining which materials are most economically relevant for the power supply system by combining technology assessment and scenario analysis methods.

Therefore, we address the following main research question:

- For which materials are raw material price fluctuations most likely to have a significant effect on the costs of CETs and, thus, on the results of cost-optimising energy system models?

The following detailed research questions are addressed:

Q1: How much do raw material prices contribute to the overall costs of central CETs?
Q2: For each CET, which materials have the highest geopolitical and market-based SDL?
Q3: Which materials have the greatest contribution to the total raw material costs for the global power supply system?
Q4: Which materials are associated with the highest risk for the global power supply system?

Since energy system modelling and material importance considerations for key technologies are still largely treated separately, this work aims to provide a basis for future work on the optimisation of energy systems that explicit considers potential raw material bottlenecks and their corresponding price increases.

We start with by analysing individual CETs. In Section 5.1, we analyse the contribution of raw material prices to the overall cost of central CETs. In Section 5.2, we identify, for each CET considered, the market-dominant sub-technology and determine the materials associated with the highest risk by including indicators for the geopolitical and market-based SDL. On this basis, we perform an analysis of the power supply system. In Section 5.3, we analyse the raw material cost for the power supply system for a climate-neutral transformation pathway until 2050. In Section 5.4, we address which materials are expected to have the highest risk for the power supply system, taking into account the geopolitical and market-based SDL.

## 4. Methodology

### 4.1. Workflow

To answer the research questions, we combine a technology-specific material risk analysis and a material demand analysis for the global power supply system. The workflow is organised in accordance with the research questions and is visualised in Fig. 1.

First (Q1), we investigate the contribution of raw materials to the cost of a selection of clean energy technologies (CETs) (O1). These

CETs are broken down into their sub-technologies. This analysis draws on the specific material demand of the sub-technologies (I1), the sub-technology costs (I2) and the raw material prices (I3).

Second (Q2), we analyse the technology-specific risk associated with the materials used in CETs (O2). For each CET, the focus is on the sub-technology with the highest market share. The raw material price contribution to the sub-technology cost (O1) is used as an input as well as indicators for the geopolitical and market-based supply disruption likelihood (SDL). The geopolitical SDL is derived from the country concentration (I4) and governance quality (I5). As the market-based SDL indicator, the expansion of the global material production necessary to meet future demand is used. It adds a prospective element to the material risk analysis.

Third (Q3), we investigate the annual share of raw material costs in the power system investment cost (O3) for a selected global power supply system transformation scenario (I7). This analysis is similar to (O1) and accounts for the share of the selected CETs – as well as further energy technologies – in the overall power system.

Fourth (Q4), we evaluate the material risk at the global power supply system level (O4), drawing on the technology level risk assessment and the power supply system transformation scenario. By evaluating the intersection of materials relevant for the technology level and the power system level, we identify which materials are most relevant and should be integrated into energy system models (ESMs) as a potential driving factor of CET costs.

### 4.2. Data collection

#### 4.2.1. Technologies

Photovoltaics, stationary batteries, onshore wind power, offshore wind power, electrolysers, and stationary fuel cells will be the backbone of the future power supply system. Therefore, these CETs are investigated in terms of a material specific risk assessment (Table 1). Within each technology class, different sub-technologies are available. The sub-technologies investigated covered more than 90% of the market share in 2022 (International Energy Agency, 2023; Gervais et al., 2022; Wulf et al., 2020; Wittstock et al., 2019; ERM, 2022). The other technologies shown in Table 1 are used only in the scenario level material demand analysis.

Data for the specific raw material demand per functional unit were obtained from a detailed technology database (Schlichenmaier and Naegler, 2022), complemented by data from Farina and Anctil (2022), Gervais et al. (2022), Gerloff (2021), Li et al. (2022), Schreiber et al. (2019), Vestas (Allekotte and Garrett, 2024; Mali and Garrett, 2022a,b; Razdan and Garrett, 2019) and the Ecoinvent database (Wernet et al., 2016). The raw materials shown in Table 2 are covered, including function-essential minor materials and mass materials. Steel materials were decomposed into alloy materials according to the information available in the respective sources in the literature. If no detailed information was available, the composition of low-alloyed steel from the Ecoinvent database was used for all technologies except wind power. For wind power, the steel compositions of Shammugam et al. (2019) were used. The data for the specific raw material demand of the sub-technologies considered are available in the supplementary information.

The technology cost (Table 1) for CETs refers to 2022 and is based on the literature and our own assumptions (in the supplementary information). The technology cost includes the technology production cost, including the balance-of-system (BoS) and the installation cost. In contrast to conventional energy technologies, maintenance costs are considerably lower in CETs and are therefore not focused on. Fuel costs and emissions costs are not relevant in the operation of CETs.

#### 4.2.2. Materials

We assume that the metals used for CETs are exclusively high-purity metals. We use annual average prices, which are representative of the world market and robust to short-term fluctuations. The price data for 2022, shown in Table 2, were obtained preferentially from the USGS (US Geological Survey, 2024). The price of silicon suitable for PV application was considered. Owing to the high uncertainties of the price of PV-grade silicon, the USGS price was cross-checked with domain knowledge (Ballif et al., 2022). Price data for rare earth elements (REEs) and iron was obtained from the ISE (Institut für Seltene Erden und Metalle, 2024). Potassium price data were obtained from Index Mundi (Index Mundi, 2024). In the scenario analysis, temporarily constant material prices (at the 2022 level) are assumed due to a lack of consistent estimations concerning long-term raw material price development.

#### 4.2.3. Countries

Data on the production and reserves per country were obtained from the USGS (US Geological Survey, 2024), the WMD (Austrian Federal Ministry of Finance, 2023) and Zhou et al. (2017). The Worldwide Governance Indicators ($WGI_c$), which describe the political situation, were obtained from the World Bank (Kaufmann et al., 2011; Kaufmann and Kraay, 2022).

#### 4.2.4. Scenarios

In the system-level assessment, we focus on the global power supply system (electricity) and Power-to-X (P2X) up to 2050. In addition to CETs (PV, stationary batteries, wind power, electrolysers, and fuel cells), the capacity development of the other energy technologies shown in Table 1 is included. The heating and transport sectors are not included in our analysis of the power supply system. However, the transport sector is included as an impact on the requirement to increase material production.

Scenario data on the development of the global power supply system is obtained from Teske et al. (2019). The LDF scenario follows the goals of limiting global warming to 1.5° via a fast expansion of the CET. The ADV scenario follows the goals of limiting global warming to 2.0°. Furthermore, the REF scenario resembles business-as-usual development, which would result in global warming of up to 5.0°. The LDF scenario is used for the main evaluation, while the ADV and REF scenarios are used to cross-check the results. More details on the scenario, i.e., the newly installed capacities per year in the power supply system as well as the new battery capacities in transport per year, and the corresponding visualisations are provided in the supplementary information.

The data described in this section are available in the supporting information.

### 4.3. Qualitative/descriptive analysis

#### 4.3.1. Identification of materials associated with high risk

The extent of economic damage in the case of a material supply disruption increases with the economic importance of the material for a technology. The economic importance of a material is a measure of the CET sensitivity to its price increases—in the case where increasing raw material prices are simply passed on. The economic importance of a material $i$ for a technology is calculated as its price contribution (Eq. (1)) (Lütkehaus et al., 2022).

$$EI_i = \frac{c_i \cdot m_i}{C} \tag{1}$$

where $c_i$ is the price of material $i$ per mass (in \$/kg), $m_i$ is the mass of material $i$ in a functional unit of a technology (in kg/kW or kg/kWh) and $C$ is the cost of a functional unit of a technology (in \$/kW or \$/kWh). The economic importance is a dimensionless value on a scale of 0 to 1.

**Table 1**
The CET classes PV, wind onshore and offshore, electrolysers, fuel cells and stationary batteries, are broken down into their sub-technologies. The CET sub-technology costs refer to the year 2022. These CETs are considered in both technology-specific material risk analysis and scenario analysis. The other technologies are considered only in the scenario analysis and their costs refer to 2020.

| Technology class: | Sub-technology: | Cost: | Unit: | Source: |
|---|---|---|---|---|
| Photovoltaics (PV) | Crystalline Silicon (c-Si)[a] | 692 | $/kW | International Renewable Energy Agency (2023) |
| | Copper Indium Gallium Selenide (CIGS) | 990 | $/kW | International Renewable Energy Agency (2023), Smith et al. (2021) |
| | Cadmium Telluride (CdTe) | 731 | $/kW | International Renewable Energy Agency (2023), Smith et al. (2021) |
| Wind Onshore (W-On) | Gearbox Double-Fed Induction Generator (GB-DFIG) | 1486 | $/kW | Stehly et al. (2023) |
| | Gearbox Permanent-Magnet Synchronous Generator (GB-PMSG) | 1486 | $/kW | Stehly et al. (2023) |
| | Direct Drive Electrically Excited Synchronous Generator (DD-EESG)[a] | 1486 | $/kW | Stehly et al. (2023) |
| | Direct Drive Permanent-Magnet Synchronous Generator (DD-PMSG) | 1486 | $/kW | Stehly et al. (2023) |
| Wind Offshore (W-Off) | Gearbox Double-Fed Induction Generators (GB-DFIG) | 3830 | $/kW | Stehly et al. (2023) |
| | Gearbox Permanent-Magnet Synchronous Generator (GB-PMSG) | 3830 | $/kW | Stehly et al. (2023) |
| | Direct Drive Electrically Excited Synchronous Generator (DD-EESG) | 3830 | $/kW | Stehly et al. (2023) |
| | Direct Drive Permanent-Magnet Synchronous Generator (DD-PMSG)[a] | 3830 | $/kW | Stehly et al. (2023) |
| Electrolyser (Electrol) | Proton Exchange Membrane Electrolyser (PEMEL)[a] | 862 | $/kW | Joint Research Centre (2023) |
| | Alkaline Electrolyser (AEL) | 589 | $/kW | Joint Research Centre (2023) |
| | Solid Oxide Electrolyser (SOEL) | 1901 | $/kW | Joint Research Centre (2023) |
| Fuel Cell (FC) | Proton Exchange Membrane Fuel Cell (PEMFC) | 1208 | $/kW | International Energy Agency (2019), Bruce et al. (2018) |
| | Phosphoric Acid Fuel Cell (PAFC)[a] | 3788 | $/kW | Park et al. (2023), Korkmaz et al. (2023) |
| | Solid Oxide Fuel Cell with Scandium (SOFC Scandium) | 2335 | $/kW | Whiston et al. (2021) |
| | Solid Oxide Fuel Cell with Yttrium (SOFC Yttrium) | 2335 | $/kW | Whiston et al. (2021) |
| Battery (Batt) | Lithium Cobalt Oxide Battery (LCO) | 551 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Iron Phosphate Battery (LFP)[a] | 416 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Ion Manganese Oxide Battery (LMO) | 445 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Nickel Cobalt Aluminium Oxides Battery (NCA) | 393 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Nickel Manganese Cobalt (111) Oxides Battery (NMC-111) | 424 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Nickel Manganese Cobalt (532) Oxides Battery (NMC-532) | 336 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Nickel Manganese Cobalt (622) Oxides Battery (NMC-622) | 392 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lithium Nickel Manganese Cobalt (811) Oxides Battery (NMC-811) | 339 | $/kWh | Mauler et al. (2021), Mongird et al. (2020) |
| | Lead-Acid Battery (Lead-Acid) | 387 | $/kWh | Mongird et al. (2020) |
| | Vanadium Redox-Flow Battery (VRFB) | 473 | $/kWh | Mongird et al. (2020) |
| Other | Biomass Power Plant (Biomass) | 2501 | $/kW | International Energy Agency (2020) |
| | Concentrated Solar Power Plant (CSP) | 5857 | $/kW | International Energy Agency (2020) |
| | Diesel Generator (Diesel) | 900 | $/kW | Teske et al. (2019) |
| | Geothermal Power Plant (Geothermal) | 6647 | $/kW | International Energy Agency (2020) |
| | Hydrogen Co-Firing ($H_2$ co-comb) | 1005 | $/kW | International Energy Agency (2020) |
| | Coal Power Plant (Hard Coal) | 1897 | $/kW | International Energy Agency (2020) |
| | Hydro Power Plant (Hydro) | 3587 | $/kW | International Energy Agency (2020) |
| | Lignite Power Plant (Lignite) | 2973 | $/kW | International Energy Agency (2020) |
| | Gas Power Plant (Nat Gas wo $H_2$) | 823 | $/kW | International Energy Agency (2020) |
| | Nuclear Power Plant (Nuclear) | 3606 | $/kW | International Energy Agency (2020) |
| | Oil Power Plant (Oil) | 404 | $/kW | Danish Energy Agency (2020) |

[a] Sub-technology with the highest market share as of 2022.

Raw material criticality is a function of the supply disruption probability of a material and the related economic impact on a system (Frenzel et al., 2017). Geopolitical and market-based supply disruption probabilities, which are mathematically properly defined and normalised, would be desired. However, such probabilities are not accessible. Instead, geopolitical and market-based supply disruption likelihoods are operationalised as indicator values, where a higher value indicates a greater likelihood of supply disruption. This allows for a relative comparison between materials.

The geopolitical supply disruption likelihood (SDL) is operationalised as the concentration of supplier countries, considering the respective political situation (WGI-weighted Herfindahl–Hirschmann Index (Blengini et al., 2017)) (Eq. (2)).

$$SDL_{geopol,i} = \sum_{c} \left( \frac{p_{i,c}}{P_i} \right)^2 \cdot WGI_c \tag{2}$$

where $p_{i,c}$ is the production of material $i$ in country $c$ and $P_i$ is its global production (Austrian Federal Ministry of Finance, 2023). In our main analysis, we evaluate the concentration at the level of mining production. In the sensitivity analysis, we consider the concentration of the reserves. The Worldwide Governance Indicators ($WGI_c$) have been rescaled linearly so that a value of zero corresponds to the best and a value of ten corresponds to the worst possible political situation.[4] The geopolitical SDL is therefore a dimensionless value on a scale from zero to ten. A more concentrated supply and more politically unstable supplier countries are related to higher values and vice versa. Our operationalisation of the geopolitical SDL is similar to the operationalisation used by the European Commission (EC) (European Commission, 2017). The EC also takes into account broadly defined expected values (including all end-use applications of a material) for recycling and substitutability. However, these broadly defined expected values are not consistent with our focus on specific technologies and are therefore omitted.

The market-based supply disruption likelihood is operationalised as the degree to which the production of a material must be increased with respect to current production. It is an indicator of the pressure to increase production, which in turn points to a potential mismatch of supply and demand. The greater this expansion pressure becomes, the more likely intermediate material availability problems on the market become. The demand increase has been considered in the context of criticality assessments conducted by previous studies (Helbig et al.,

[4] We consider the average of the six specific WGI indicators. The original data are on a scale of approximately −2.5 to +2.5, where −2.5 corresponds to the worst and +2.5 to the best political situation.

**Table 2**
Material prices considered in our analysis and the main CET classes associated with the materials.

| Material: | Symbol: | Price (2022) [$/kg]: | Source: | PV: | W-On: | W-Off: | Electrol: | FC: | Batt: |
|---|---|---|---|---|---|---|---|---|---|
| Aluminium | Al | 3.4 | US Geological Survey (2024) | x | x | x | x | x | x |
| Bismuth | Bi | 8.6 | US Geological Survey (2024) | | | | | | |
| Boron | B | 0.5 | US Geological Survey (2024) | | | | | | |
| Cadmium | Cd | 3.4 | US Geological Survey (2024) | | | | | | |
| Cerium | Ce | 4.4 | US Geological Survey (2024) | | | | | | |
| Chromium | Cr | 18.6 | US Geological Survey (2024) | | x | x | x | x | x |
| Cobalt | Co | 65.7 | US Geological Survey (2024) | | | | | | x |
| Copper | Cu | 8.5 | US Geological Survey (2024) | x | x | x | x | x | x |
| Dysprosium | Dy | 476.4 | Institut für Seltene Erden und Metalle (2024) | | x | x | | | |
| Europium | Eu | 278.5 | Institut für Seltene Erden und Metalle (2024) | | | | | | |
| Gadolinium | Gd | 79.7 | Institut für Seltene Erden und Metalle (2024)[a] | | | | | | |
| Gallium | Ga | 477.0 | US Geological Survey (2024) | x | | | | | |
| Germanium | Ge | 1294.0 | US Geological Survey (2024) | | | | | | |
| Gold | Au | 57,936.5 | US Geological Survey (2024) | | x | | | | |
| Indium | In | 251.0 | US Geological Survey (2024) | x | | | | | |
| Iridium | Ir | 147,314.7 | US Geological Survey (2024) | | | | x | | |
| Iron | Fe | 0.6 | Institut für Seltene Erden und Metalle (2024)[b] | x | x | x | x | x | x |
| Lanthanum | La | 4.1 | Institut für Seltene Erden und Metalle (2024) | | | | | | |
| Lead | Pb | 2.4 | US Geological Survey (2024) | | | | | | x |
| Lithium | Li | 364.2 | US Geological Survey (2024)[a] | | | | | | x |
| Magnesium | Mg | 11.0 | US Geological Survey (2024) | x | | | | | |
| Manganese | Mn | 7.0 | US Geological Survey (2024) | x | x | x | | x | x |
| Molybdenum | Mo | 41.4 | US Geological Survey (2024) | | x | x | | | |
| Neodymium | Nd | 155.1 | Institut für Seltene Erden und Metalle (2024) | | x | x | | | |
| Nickel | Ni | 25.8 | US Geological Survey (2024) | x | x | x | x | x | x |
| Platinum | Pt | 31,075.5 | US Geological Survey (2024) | | | | x | x | |
| Potassium | K | 0.5 | Index Mundi (2024)[a] | | | | | | |
| Praseodymium | Pr | 175.9 | Institut für Seltene Erden und Metalle (2024) | | x | x | | | |
| Samarium | Sm | 14.3 | Institut für Seltene Erden und Metalle (2024) | | | | | | |
| Scandium | Sc | 4310.8 | Institut für Seltene Erden und Metalle (2024) | | | | | x | |
| Selenium | Se | 21.2 | US Geological Survey (2024) | x | | | | | |
| Silicon | Si | 8.0 | US Geological Survey (2024) | x | x | x | | | |
| Silver | Ag | 703.5 | US Geological Survey (2024) | x | | | | | |
| Strontium | Sr | 14.2 | Institut für Seltene Erden und Metalle (2024) | | | | | | |
| Sulphur | S | 0.2 | US Geological Survey (2024) | | | | | | |
| Tellurium | Te | 67.5 | Institut für Seltene Erden und Metalle (2024) | x | | | | | |
| Terbium | Tb | 2303.9 | Institut für Seltene Erden und Metalle (2024) | | x | x | | | |
| Tin | Sn | 32.7 | US Geological Survey (2024) | x | | | | | |
| Titanium | Ti | 11.1 | US Geological Survey (2024) | | | | x | | |
| Vanadium | V | 36.4 | US Geological Survey (2024)[a] | | x | x | | | x |
| Yttrium | Y | 39.7 | Institut für Seltene Erden und Metalle (2024) | | | | | x | |
| Zinc | Zn | 3.8 | US Geological Survey (2024) | | x | x | | | |
| Zirconium | Zr | 30.0 | US Geological Survey (2024) | | | | x | x | |

[a] The price of the raw material was derived from the price of a chemical compound, considering the stoichiometric ratio.

[b] The price of cast iron was assumed.

2021). Our approach is novel in terms of its high specificity for selected energy transformation scenarios.

The production increase required for a large selection of materials was calculated using a material demand analysis (Schlichenmaier and Naegler, 2022). Material demand analysis focuses on the assessment of the material demand for the global energy and transport transition system, but it includes an – albeit coarse – estimate of the demand for other applications on the basis of an extrapolation of current demand in line with assumptions about global economic growth (GDP). These aspects are briefly introduced in Section 4.3.2. The expansion pressure is introduced as a measure for the market-based SDL (Eq. (3)).

$$SDL_{market,i} = \frac{p_{max,i}}{p_{current,i}} \tag{3}$$

where $p_{max,i}$ is the maximum annual raw material demand in the period to 2050 that results from the scenario considered. Therefore, the market-based SDL indicator integrates a prospective element into the technology-specific material risk analysis.

Combining the price contributions of the raw materials and SDL indicators allows for a qualitative assessment of the technology-specific material criticality.

To identify whether a material is associated with a substantial risk for a CET, we take a qualitative approach. For each CET, we identify the materials that are most problematic regarding the individual criteria of economic importance, the geopolitical SDL, and the market-based SDL in terms of a relative ranking. The materials considered most problematic are those ranked highest in each of these criteria.

A cut-off for the number of materials is applied based on the relative differences in the criteria values. However, one exception is made: If the criteria values of the materials ranked highest correspond to a rather unproblematic situation in practice, these materials are not evaluated as critical due to this criterion.

If a high-SDL material has low economic importance, the overall risk can still be moderate, as even high price increases would lead to a minor economic damage. In these cases, an individual decision about the related risk is made based on knowledge from the literature about the sub-technology specific substitutability of the material. If a material that is always used in conjunction with a set of other materials (i.e., alloys or compound materials), is associated with a substantial risk in a CET, we consider all conjuncted materials to have a high risk as well. The same principle is applied if materials are from the same source, i.e., the same geological origin or co-production.

The raw materials associated with the highest risk for the power supply system are identified analogously, with the total material cost as the economic importance.

#### 4.3.2. Raw material demand analysis at the scenario level

The raw material demand analysis to determine the annual raw material requirements in the power system and non-energy applications was conducted as described in Schlichenmaier and Naegler (2022).

In the power supply system, material demand $md_i^j$ in year $a$ for raw material $i$ in technology $j$ is calculated according to Eq. (4).

$$md_i^j(a) = nc_j(a) \cdot \left( \sum_k s_j^k(a) \cdot smd_i^k(a) \right) \tag{4}$$

where $nc_j(a)$ is the new capacity, which is derived mainly from new installations and the replacement of old capacities after the end of their technical lifetime. Additionally, early decommissioning and lifetime expansion are taken into account. This calculation requires data on the expected annual capacity change in the power system, i.e., power system transformation scenarios. The scenarios evaluated are described in Section 4.2.4. In addition to the power supply system, we include the transport sector in the material demand analysis.

Additionally, $k$ refers to the sub-technologies. $s_j^k$ is the share of sub-technology $k$ in the new capacity of technology $j$. $smd_i^k$ is the specific demand of material $i$ in sub-technology $k$. Different sub-technologies within a CET class can greatly differ in terms of the specific material demand. Therefore, the development of the sub-technology distribution is accounted for in technology roadmaps. The roadmaps used assume a development of the sub-technology distribution in accordance with the current trend.[5]

The demand for material $i$ is subsequently calculated as the sum of the demand for material $i$ in all technologies $j$ (Eq. (5)).

$$md_i(a) = \sum_j md_i^j(a) \tag{5}$$

The annual material cost of material $i$ is calculated on the basis of the annual material demand and the specific cost of material $i$ per mass (Eq. (6)).

$$mc_i(a) = md_i(a) \cdot c_i \tag{6}$$

For non-energy applications, the material demand is extrapolated on the basis of the expected GDP growth. In the main analysis, we consider a GDP scenario with an annual growth of 3.2% (HI). In the sensitivity test, we consider a GDP scenario with an annual growth of 2.5% (LO).

## 5. Results

### 5.1. Material price contribution to total technology costs

The contributions of the raw material prices to the costs[6] of the most relevant sub-technologies of the main CET classes PV, stationary batteries, wind power (onshore and offshore), electrolysers, and fuel cells are displayed in Fig. 2. All materials with a price contribution of less than 2.0% are summarised as ‘Other materials’ for purposes of visual display. The focus is to identify the overall price contributions and the materials with the highest economic impact potential.

For photovoltaics, the overall price contribution of materials varies between 8% and 15% for the different sub-technologies (Fig. 2). Aluminium, used in the frames, and copper, used in the cabling, are economically relevant for all sub-technologies due to their similar peripheries. The PV subtechnologies differ in the material systems used in their active layers. For c-Si, the silicon wafers and silver contacts have a substantial effect on the cost. For thin-film-based CIGS and CdTe, the active layer materials have a considerably smaller price contribution than do the mass materials in the frames and cabling.

For stationary batteries, there is a considerable variance of approximately 13% to 38% in the overall price contribution of materials for the different sub-technologies (Fig. 2). Lithium has the highest price contribution to all Li-based sub-technologies. Lithium-Cobalt-Oxide (LCO) batteries are the only exception, as cobalt has a higher price contribution than does lithium. In lead–acid and vanadium redox-flow batteries, the highest price contributions are from lead and vanadium, respectively. For all battery sub-technologies, the function-essential materials have a considerably higher price contribution than do the mass materials used in the peripheries.

For onshore wind power, the overall price contribution of materials varies between 13% and 17% (Fig. 2). Steel alloy materials (iron, chromium, and nickel), used for structural elements, and zinc, used for anticorrosive coatings, have the highest combined price contribution to all sub-technologies. Gearbox-based turbines and directly driven wind turbines differ significantly in their price contributions of raw materials since directly driven turbines have larger nacelles and are therefore more material intensive. Rare earth elements (REEs), used in permanent magnets for generators, are economically relevant in directly driven wind turbines. Nevertheless, their price contribution is significantly lower than that of mass materials.

For offshore wind power, the overall price contribution of materials varies between 9% and 10% (Fig. 2). On a qualitative level, the findings for raw material price contributions are similar to those for the corresponding onshore wind turbine types. However, offshore wind turbines have a higher cost because they are installed in a demanding environment. Therefore, the raw material cost is lower than that of onshore turbines.

For electrolysers, the price contributions of raw materials vary considerably from 8% to 39% (Fig. 2). The construction and functional material systems used differ strongly for the electrolyser sub-technologies. The highest price contribution to PEMEL is from the PGM metal iridium. The raw material costs for AEL and SOEL electrolysers are dominated by nickel and chromium.

For fuel cells, the material price contributions vary between 13% and 20% (Fig. 2). Iron, chromium, and nickel are economically relevant for all sub-technologies. For PAFC, platinum has the highest price contribution. Scandium is economically relevant for the scandium-based solid oxide fuel cell (SOFC). However, yttrium has a minor price contribution of less than 0.5% for the yttrium-based solid oxide fuel cell.

Among the more than forty materials used in the CETs considered, fourteen have a contribution of more than 2.0% to the total sub-technology cost of any of the CETs considered. There are considerable variations across the technology classes. Installation in different environments can have an impact on the material price contribution, i.e., for on- and offshore wind power. Variations within technology classes can be attributed to different material systems and complexities in production chains. For all technology classes, with the exception of batteries, the price contribution of the steel alloy materials iron, chromium, and nickel as well as from other mass materials such as aluminium and copper exceeds the price contributions of function-essential minor materials.

### 5.2. Technology-specific material risk assessment

Having identified the price contributions of raw materials to the main CET classes (Section 5.1), we shift the focus to analysing the risk associated with raw materials for the market-dominant sub-technology in each CET (Table 1). The risk associated with a material is a function of its supply disruption likelihood (SDL) and the associated economic damage. Drawing on the raw material cost analysis, we additionally evaluate the geopolitical and market-based SDLs. The geopolitical SDL considers the level of material production and the market-based SDL considers the ambitious LDF power system transformation scenario and high GDP growth.

All materials contributing over 0.1% to the technology cost of the sub-technologies considered are accounted for in this analysis to provide a holistic risk analysis. Materials with price contributions smaller

[5] Visualisations of the roadmaps are provided in the supplementary information.

[6] Abbreviated as price contributions in the following.

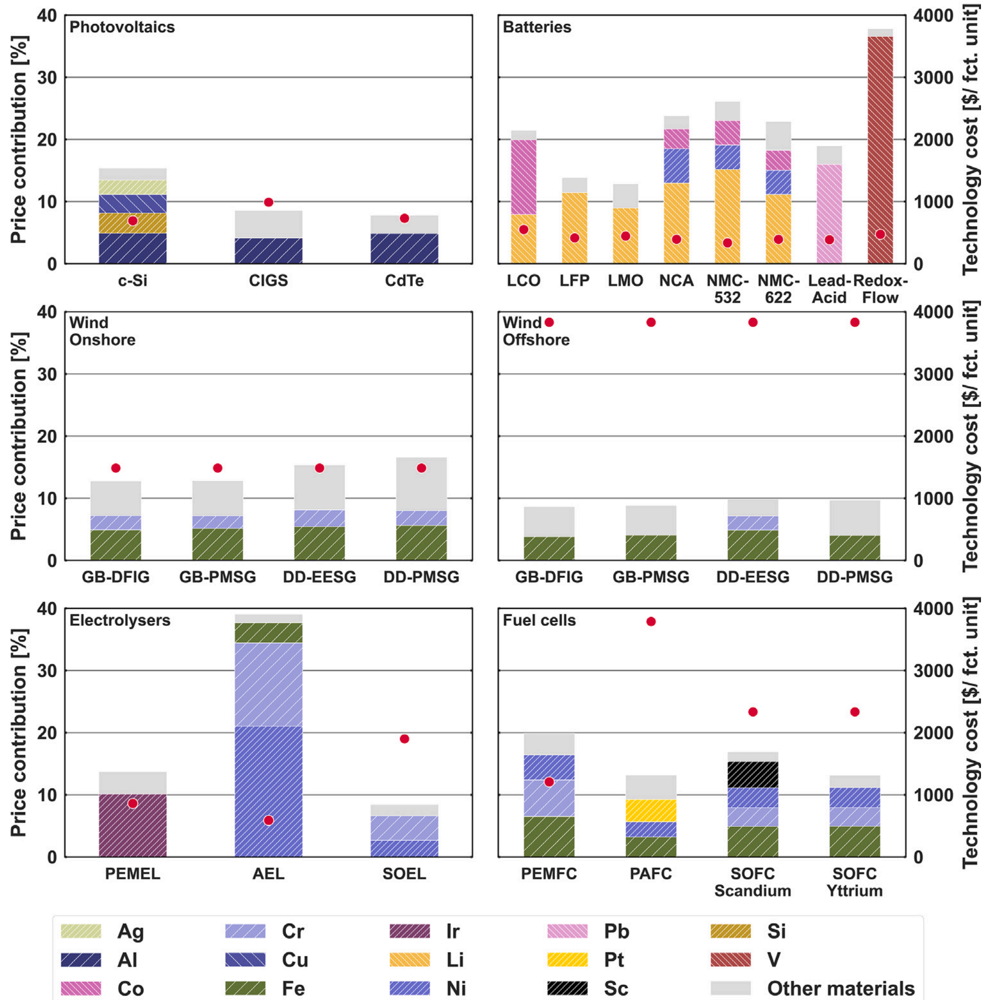


**Fig. 2.** Price contributions of economically relevant materials to technology costs, indicated by stacked bar plots (left y-axis). The technology cost per functional unit is indicated by red dots (right y-axis). Materials with a contribution of less than 2.0% are summarised as 'Other materials'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than 0.1% are omitted, since even drastic increases in their prices would result in a minor impact on technology costs.

This analysis is conducted in a semi-qualitative manner based on indicator data[7] and technology-specific expertise. The aim is to identify the materials related to the highest risk for each CET class. All materials not elaborated on explicitly have low price contributions and are moderate in terms of the SDLs; thus, the related risk can be considered low.

Crystalline silicon (c-Si) solar cells accounted for approximately 94% of the PV market in 2022. For c-Si, the total material price contribution is approximately 15%. The dominant price contributions of raw materials stem from aluminium (5%), silicon (3%), copper (3%), and silver (2%) (Fig. 3). Aluminium is used for structural elements, silicon is used for wafers, copper is used for cabling, and silver is used for the contacts. All of these materials are geologically abundant. Their market-based SDLs are moderate since an increase in current production by a factor of approximately two to four (Fig. 3) is required in the future. While silver and copper have a low geopolitical SDL, indicating diversified production in rather politically stable countries, aluminium and silicon have a higher geopolitical SDL. PV developers rate the risk related to silver as high (Hallam et al., 2023). To mitigate this risk, reducing the specific silver demand is a major objective in PV research (Chang et al., 2024). Magnesium, which is used in small quantities in the contacts of the module, has a low price contribution of approximately 0.7%. However, even though magnesium is geologically highly abundant, the geopolitical SDL is high, as more than 80% of the global production is located in China, and a production increase of approximately four will be required in the future.

LFP is the dominant stationary battery sub-technology, with a market share of 42% in 2022. The price contribution of raw materials to LFP is approximately 14%. Lithium has a price contribution of approximately 11%, and chromium has a price contribution of approximately 1% (Fig. 3). For these materials, the geopolitical SDL is rather low. For lithium, the market-based SDL is extraordinarily high because the expected maximum annual demand until 2050 – mainly for electric vehicles – is almost nine times greater than current production. Therefore, major market-based supply problems are possible for lithium (Fig. 3). Chromium will require a moderate increase in production by a factor of approximately four in the future.

Wind turbines with a directly driven electrically excited generator (DD-EESG), without permanent magnets, are the dominant onshore wind sub-technology, with a market share of approximately 88% in 2022. The total material price contribution of materials to DD-EESG is approximately 15%. The main price contributions are from iron (5%), nickel (2%), chromium (3%), and manganese (under 1%) for steel structural elements (Fig. 3). Copper, with a price contribution of 2%, is used for magnet coils and cabling. Zinc, with a price contribution of

[7] The indicator data are provided in the supplementary information.

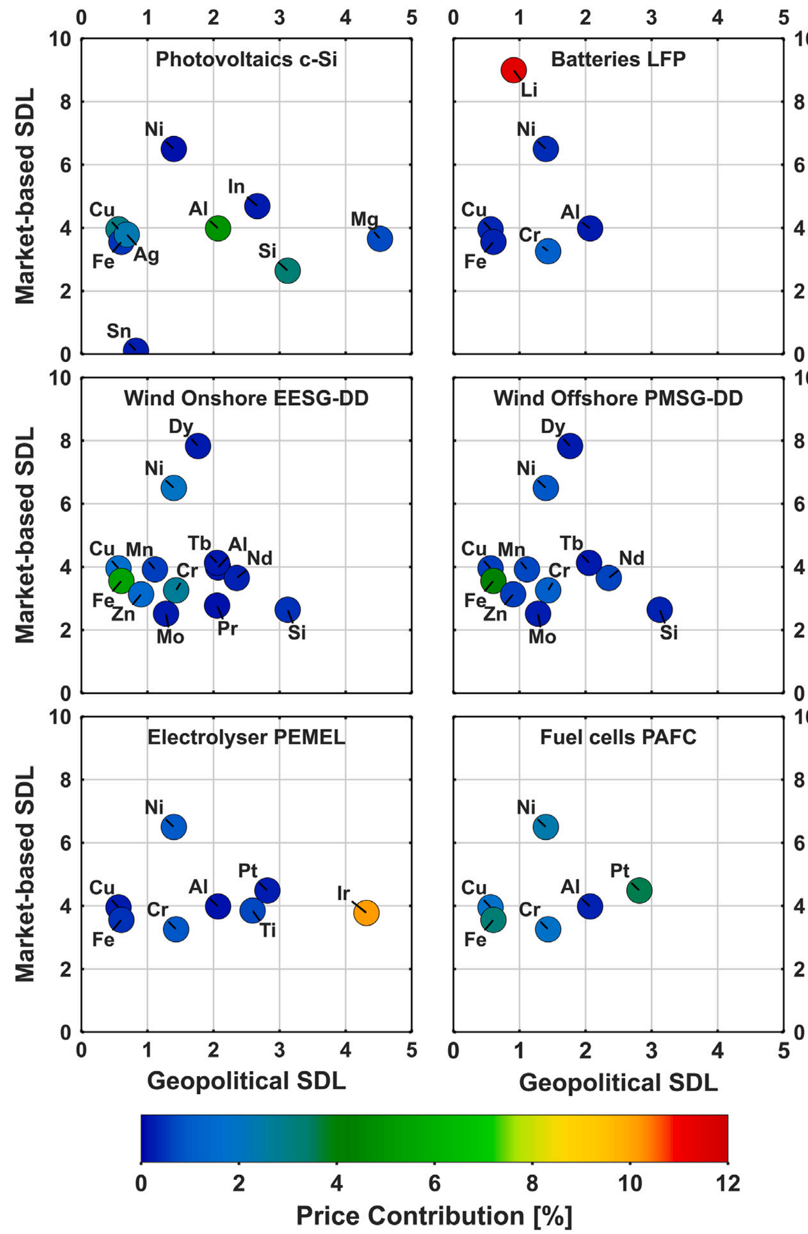


**Fig. 3.** CET-specific material risk analysis. The geopolitical SDL (dimensionless with possible values from 0 to 10) and the market-based SDL (dimensionless with possible values from 0 to infinity) are used as the x- and y-axes. The price contributions are indicated by the colour bar. Materials with a price contribution over of 0.1% are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

over 1%, is used for the coatings. The mass materials required for steel, coils, and coatings have a rather low geopolitical SDL and a moderate market-related SDL. Due to a required increase in production by a factor of approximately four to six, the market-based SDL appears to be a stronger problem than the geopolitical SDL. The REEs used in DD-EESG are minor fractions, since the generator does not use permanent magnets. Accordingly, the REE-related risk is low for DD-EESG onshore turbines.

Directly driven turbines with permanent magnets (DD-PMSG) are the dominant offshore wind sub-technology, with a market share of approximately 67% in 2022. They have a simpler construction compared to geared wind turbines, which minimises the probability of major maintenance work in the demanding offshore environment. For DD-PMSG wind turbines, the total material price contribution was approximately 10%. The main price contributions are from the steel materials iron (4%) and chromium (1%) for structural elements and copper (under 1%) for the cabling. The price contributions of manganese and nickel are lower than 1%. The REE neodymium used in permanent magnets has a price contribution of approximately 0.6%. Furthermore, the REEs terbium and dysprosium have price contributions lower than 0.5%. For offshore wind power, the findings for mass materials are similar to those for onshore wind power in terms of the SDL (Fig. 3). However, their price contributions are considerably smaller compared to wind turbines with the same generator type installed onshore because of the higher installation costs required for offshore wind power. REEs, used in permanent magnets, have a relatively high geopolitical SDL. Furthermore, the high concentration of refinement and the economic challenge of launching new rare earth mines and refinement facilities strongly aggravate geopolitical concerns. Among REEs, neodymium has the highest economic importance but requires only a moderate production expansion. Although dysprosium has a small price contribution, the high expansion pressure aggravates the risk. Overall, the risk associated with rare earths is high for permanent magnet-based offshore wind turbines.

Proton exchange membrane electrolysers (PEMEL) constitute the market-dominant electrolyser sub-technology, with approximately half of the market share in 2022. The price contribution of materials is approximately 14%. Iridium contributes 10% to the technology cost. Therefore, there is a strong dependence on iridium with a high geopolitical SDL and a required increase in production by a factor of four in the future (Fig. 3). Nickel, chromium, and titanium have considerably lower price contributions of less than one percent and are moderate in terms of their geopolitical and market-based SDLs.

Phosphoric acid fuel cells (PAFC) constitute the market-dominant fuel cell sub-technology, with a market-share of 46% in 2022. For PAFC, the overall material price contribution is approximately 13%. PAFC is strongly dependent on platinum, with a price contribution of approximately 4%. Other relevant price contributions are from iron (3%), as well as chromium, nickel, and copper (2%). For platinum, the market-based SDL is moderately high, at approximately four (Fig. 3). However, the geopolitical SDL of platinum is relatively high. For the other materials, the SDL is as described previously.

To determine whether the risk associated with a material in a CET is substantial, we focus on the market-dominant sub-technologies shown in Fig. 3. Additionally, alternative sub-technologies are considered if their market share is substantial. The most technology-critical materials for the selected CETs are as follows:

- PV: Aluminium, silver, silicon, and magnesium
- Batteries: Lithium
- Onshore wind: Steel alloy materials (iron, chromium, nickel)
- Offshore wind: Steel alloy materials (iron, chromium, nickel), REEs (i.e. neodymium)
- Electrolysers: Iridium
- Fuel cells: Platinum

For technology developers, improving the production processes involving these materials to reduce the mass required per functional unit is recommended.

As a sensitivity test, material risk analysis was also conducted with a geopolitical SDL calculated on the basis of reserves and a market-based SDL under a low-ambition power system transformation scenario (REF) and GDP growth (LO). The geopolitical SDL at the level of reserves indicates a lower concentration for all materials except indium and iridium. This finding confirms that risk currently originates mainly from the production stage. Adapting the location of production to the location of reserves could lead to a diversification of supply and a lower material-related risk in the future. Furthermore, for some key materials, such as lithium and dysprosium, the ambition of power system and transport transformation significantly affects the need to increase production and is a stronger driving factor than GDP growth. For most other materials, however, the need to increase production is determined mainly by the GDP growth. The corresponding results are included in the supplementary information. Overall, these findings confirm that the ambitiousness of power system and transport transformation is a potential driving factor for disruptions in the supply of raw materials.

### 5.3. Material and technology costs in the power supply system

Following the technology-specific assessment, the economic importance of the raw materials for the power system is investigated for the LDF scenario, which is in line with the goal of limiting global warming to 1.5 °C (Teske et al., 2019). Fig. 4a shows the annual technology investment cost, and Fig. 4b–d shows the annual material costs. Materials that contribute more than 0.5% of the total material cost are displayed.[8]

[8] The complete scenario timeframe is considered for this calculation.

The annual system-level costs for the installation of energy technologies increase strongly in the LDF scenario (Fig. 4a). They will reach approximately 2200 billion $USD_{2022}$ in 2030 and peak at approximately 2600 billion $USD_{2022}$ in 2037. Afterwards, they will decline again and amount to 1900 billion $USD_{2022}$ in 2050. The total cost for raw materials used for the power system will rise to over 300 billion $USD_{2022}$ per year in the medium term (2030) (Fig. 4b). The total annual costs for metals will peak in 2037 at approximately 350 billion $USD_{2022}$ and significantly decline thereafter (although the electricity demand will still increase). In the long term (2050), more than 200 billion $USD_{2022}$ will be expected.

The strong increase in technology investment and raw material cost until 2037 is explained by the LDF scenario design, where CETs must be installed at a large scale in a limited amount of time to limit global warming to 1.5°. For the materials shown in Figs. 4c and 4d, which are mainly function-essential materials, the material cost curve shows a similar trend. The overall contribution of raw materials to technology installation costs is already relevant at approximately 10% in 2020 and will reach as high as approximately 14% because of more material-intensive CETs.[9]

Iron, chromium, nickel, copper, and aluminium are the most economically relevant materials, as displayed in Fig. 4b. In comparison, the annual cost for function-essential technology materials is considerably lower, as displayed in Figs. 4c and 4d. Among the materials displayed in Fig. 4c, lithium and silicon are the materials that are most important from an economic perspective. The rare earth elements (REEs) neodymium (Fig. 4c) and dysprosium (Fig. 4d) have a smaller economic importance. Iridium, used in electrolysers, is also economically relevant (Fig. 4d). However, platinum, which is relevant for PAFC fuel cells, is not economically relevant due to the small number of installed units.

The large-scale installation of wind power is the main driver of the demand for steel alloy materials. Furthermore, wind power is the exclusive driver of the demand for the REEs neodymium and dysprosium. PV installations drive the demand for silicon, and stationary batteries drive the demand for lithium. The demand for iridium is driven by electrolysers. Overall, the materials identified as most critical from the technology-specific assessment are economically relevant at the systems level.

The findings from the ADV scenario (refer to the supplementary information) are consistent with those from the LDF scenario. This outcome serves as proof of the plausibility of the results. In contrast, the business-as-usual REF scenario has substantially smaller material costs. The ratio of the overall contribution of the material price to the technology cost is also substantially smaller in the REF scenario with approximately 7% to 8% throughout the timespan considered. The comparison with the REF scenario confirms the increase in raw material demand as well as the increase in the economic importance of raw materials in a CET-based and increasingly decentralised power supply system.[10]

### 5.4. Material risk in the power supply system

Drawing on the previous results, the materials associated with the comparatively highest risk at the scenario level are identified. The scenario specific criticality assessment is depicted in Fig. 5. The economic indicator is the cumulative material cost. The materials contributing over 0.1% of the total material cost are considered.

Iron, chromium, and nickel, which are used mainly in steel alloys for structural elements, have the greatest economic impact. Although their geopolitical and market-based SDLs are low, their high economic impact generates a substantial material-related risk. Lithium and the REE

[9] The ratio of the annual material costs to the annual investment costs into new energy technologies is shown in the supplementary information.

[10] The economic importance of raw materials in the other power system transformation scenarios is shown in the supplementary information.

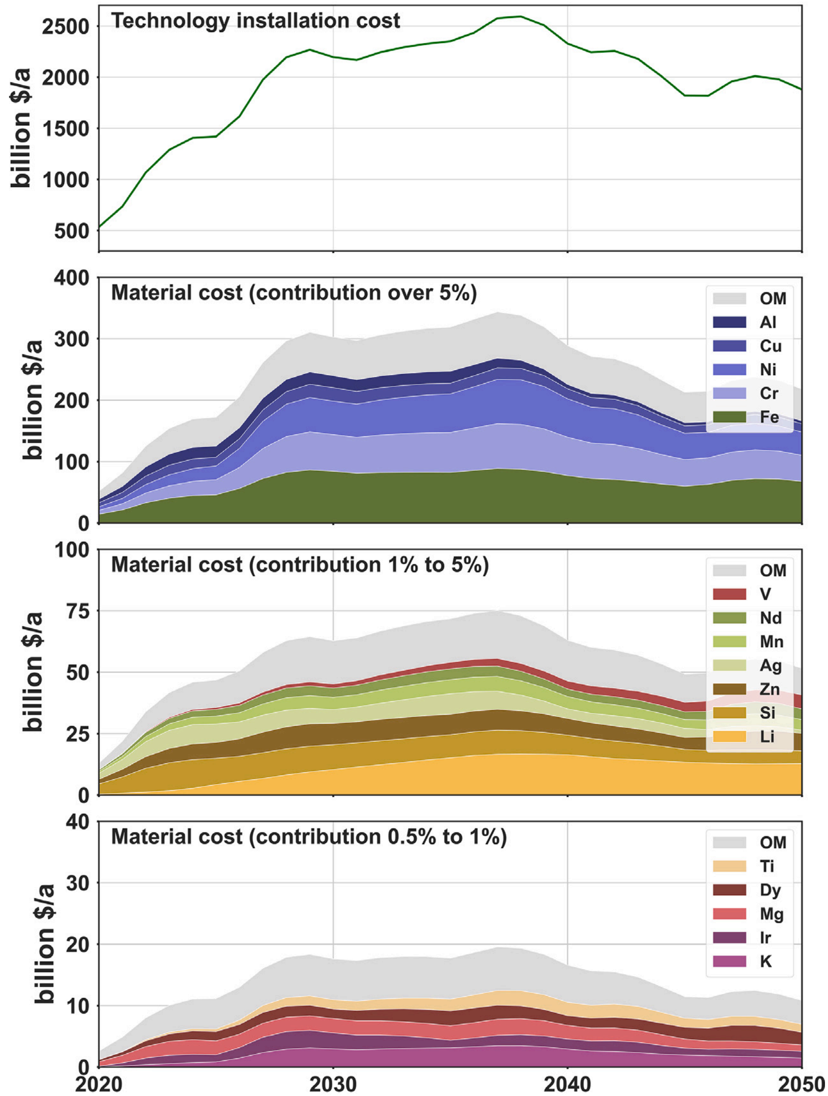


**Fig. 4.** Scenario-level costs for the LDF scenario. In (a), the technology investment cost is shown. In (b), all materials are depicted and the materials contributing less than 5% to the total material costs are summarised as 'Other materials'. In (c), the 'Other materials' from (b) are broken down, and the materials contributing less than 1% are summarised as 'Other materials'. In (d), the 'Other materials' from (c) are broken down, and the materials contributing less than 0.5% are summarised as 'Other materials'. The order of the materials in the graphs and legends reflects increasing economic importance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dysprosium have the highest market-based SDL, i.e., high production expansion pressure. Since they provide essential product functionality, they cannot easily be substituted and should therefore be focused on. Additionally, neodymium, praseodymium, and terbium should be focused on because they are economically and geopolitically important and are rare earth elements with geological origins similar to that of dysprosium. Geopolitically, silicon is relatively problematic and should be focused on in terms of the price risk. Although iridium and magnesium have even greater problems in this respect, their low economic relevance leads to a lower risk. Cobalt has both a high geopolitical SDL and a high market-based SDL. The economic importance is low due to the market dominance of lithium-based batteries without cobalt.

On the basis of the scenario risk analysis, we recommend focusing on steel alloy materials, REEs, as well as lithium and silicon in terms of price scenarios and considering them in optimising ESMs as potential drivers of CET costs.

As a sensitivity test, material risk analysis was also conducted for the less ambitious scenario (REF) and low GDP growth (LO). We observe that ambitious power system and transport transformation drives the risk associated with materials such as lithium, dysprosium, and nickel, which are not relevant or associated with a minor risk in the REF scenario. These results are included in the supporting information.

## 6. Discussion

### 6.1. Summary

In this work, the materials whose price fluctuations should be prioritised in energy system modelling are identified. This identification was achieved by combining a technology-specific materials risk analysis that distinguishes the most important sub-technologies in each major CET class and an ex-post material demand analysis of the global power supply system.

The steel alloy materials iron, chromium, and nickel are highly economically relevant for the power system. Their demand is driven mainly by wind power. Although their geopolitical SDL is low and their market-based SDL is low to moderate, increases in the price of these materials would have a considerable effect on power system costs. In addition to mass materials, a selection of function-essential minor

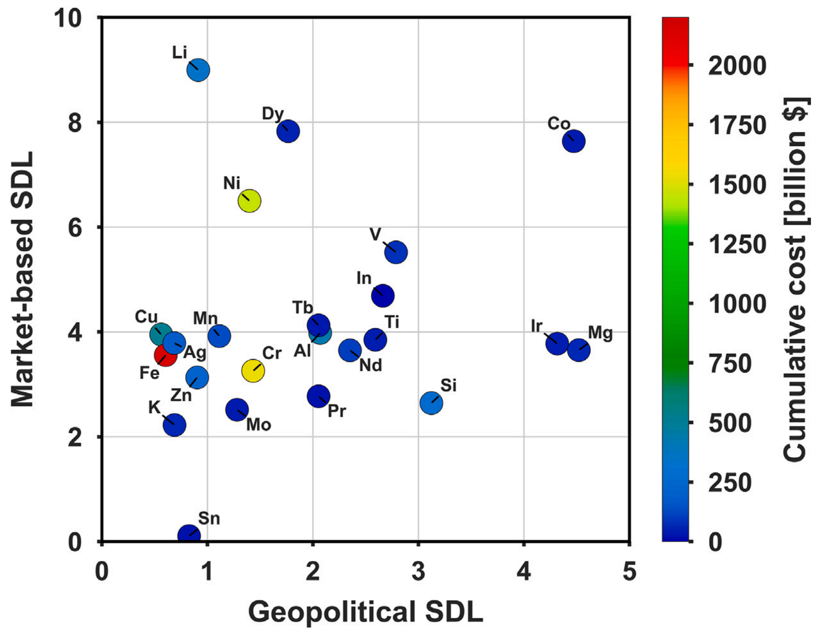


**Fig. 5.** Material-related risk for the LDF scenario. The cumulative material costs are used as the economic impact and are indicated by the colour bar. The geopolitical SDL (dimensionless with possible values from 0 to 10) and the market-based SDL (dimensionless with possible values from 0 to infinity) are used as the x- and y-axes, respectively. The SDLs are assumed to remain stable over the scenario timeframe. The materials contributing more than 0.1% to the total material cost are displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

materials poses a considerable risk to the power system. The materials that are especially problematic because of production expansion pressure are lithium and the rare earth element dysprosium. Owing to its similar mining origin, neodymium should also be considered problematic. Lithium demand is driven by batteries, and rare earth element demand is driven by wind power. The materials that are especially problematic because of their geopolitical concentration are silicon as well as iridium and magnesium. Silicon demand is driven by PV. PV-grade silicon has been of high concern because of high price changes in the past. Although iridium and magnesium are even more concentrated, the high geological abundance of magnesium and the low number of electrolysers, which drive iridium demand, mitigate the related problems.

Our study sharpens the focus on which materials should be prioritised in terms of future price scenarios and be considered a potential driving factor of clean energy technology costs in energy system models. This knowledge is crucial for streamlining efforts to develop material price models and to extend ESMs.

### 6.2. Key uncertainties

For the specific material demand per functional unit, an average value that covers a broad range of data from various sources in the literature was used. Accordingly, we are able to identify the economic impact of the raw materials for typical sub-technologies, but lose the specificity achieved with detailed bottom-up cost models. Steel materials introduce uncertainty, since the chemical composition of the steel used in a CET is not always documented precisely and assumptions from the literature must be used.

The data on CET costs and material prices both refer to 2022; thus good validity of the raw material price contributions within this temporal scope is achieved. However, long-term price changes are possible; thus, future raw material price contributions to CET costs could differ substantially.

Furthermore, the material-related risk within the sub-technologies was investigated by drawing on indicator values for the supply disruption likelihood. The geopolitical SDL captures the concentration at the mining production level as of 2022. It is a state-of-the-art geopolitical indicator used in various studies. As the market-based SDL indicator, production expansion pressure was considered. It is focused on the demand side. The material demand in non-energy applications was assumed to grow with GDP. This leads to a default production expansion pressure of approximately 2.5 for all materials used in non-energy applications. A sector-specific material demand analysis for technology metals was conducted for the global power supply and transport system. Therefore, production expansion pressures over 2.5 are driven by the demand in the power supply and transport system. However, other raw material-dependent technology sectors could also grow stronger than the overall economy. An example is the electronics and communications industry, where the demand for raw materials is driven by increasing consumer demand and short product lifetimes. Accordingly, a production expansion pressure higher than that estimated in the present study is possible for technology metals. Furthermore, uncertainties regarding the material supply side remain. The geopolitical abundance and even the currently available reserves are not bottlenecks limiting the material supply because of the exploration of new reserves and technological progress in mining (Jowitt et al., 2020). The more pressing problem is the material-specific capability to scale up production. If a timely adaptation of material production to increased demand were possible, material supply problems could be avoided. However, models for the expansion of production capacity, i.e., the Hubbert model, which was developed for oil production, have limited validity for metals (Riondet et al., 2023).

The assessment at the power system level includes a prospective element. The aspects that can change over the timeframe considered are the geopolitical and market-based SDLs, material prices and the power supply system. We deliberately limited the prospective element to technology installations by focusing on a technologically feasible ambitious transformation scenario. The other aspects were assumed to remain stable. Our objective was to identify the materials that are most problematic under an ambitious power supply system transformation from the present perspective. We provide a knowledge basis for the materials related to the highest risk for CETs and the power supply system.

### 6.3. Comparison with other studies

In this work, we add to the limited number of studies investigating the economic competitiveness of different technology systems, including the impact of raw materials on technology costs. The study by Leader et al. (2019) partially follows a similar approach. However, Leader et al. set different system boundaries and focused on the materials that provide essential product functionality. Instead, we focused on complete functional units, which can be installed in the power supply system.

Most other studies on CET costs focus on one CET class or individual sub-technologies. In comparison with these bottom-up cost models, our results have less specificity regarding the economic impact of a material for a sub-technology. However, we cover a considerably larger scope of CET classes and sub-technologies. In our comparison with other studies, we focus on recent studies and the market-dominant sub-technologies and materials that we identified as most relevant.

For crystalline silicon solar cells, the price of silicon is a major concern. A recent study by Chang et al. revealed that the contribution of polysilicon to the module cost is approximately 12% in 2025[11] (Chang et al., 2022). In our study, we assumed that the module cost is approximately half of the installed cost. Considering this correction, our value of approximately 3% for the contribution of silicon to the total installed cost is still considerably smaller than the value reported by Chang et al. emphasising the importance of silicon price changes.

There is a broad range of literature on battery cost modelling. Interestingly, Ciez and Whitacre (2016) reported in their 2016 study that lithium price changes were associated with only minor technology cost changes in lithium manganese oxide spinel ($LiMn_2O_4$) and lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$) at that time. This finding is explained by the low 2016 lithium price of 7.5 $/kg assumed by Ciez et al. Sun et al. reported that the costs of lithium, cobalt, and nickel in battery packs for electric vehicles contribute approximately 25% (Sun et al., 2022). The numeric findings appear to be consistent with our findings for lithium-based batteries, although the sub-technologies are not identical. However, Sun et al. interpreted their findings in a different way. Drawing on domain knowledge, Sun et al. expected cost declines in other components to compensate for even strong lithium price increases. Leader et al. reported that a 100% increase in the price of lithium leads to an approximately 11% increase in the price of LFP battery cathode active materials (Leader et al., 2019). However, Leader et al. did not include any other components. Overall, the volatile lithium price strongly affects the results of related studies.

For wind power, there are few recent studies on the impact of materials on costs. Elia et al. (2020) estimated the contributions of the mass materials iron, aluminium, and copper to the onshore wind power turbine cost to be approximately 15% in 2017.[12] This value is consistent with our findings despite the time interval between the studies. Elia et al. neglected rare earth elements. While Pavel et al. (2017) identified price increases in rare earth elements as potential drivers for shifting from REE-based turbines to REE-free turbines, they did not disclose the actual price contributions of rare earth elements. Leader et al. estimated that a 100% increase in the prices of neodymium, dysprosium, and terbium leads to price increases of 3.5%, 2.6%, and 2.4%, respectively, in direct-drive wind turbines with permanent magnets. However, the impact would be considerably smaller when considering the full functional unit, including tower, rotor, and balance-of-system costs. Therefore, the results of Leader et al. appear to be consistent with our findings. Most recently, Baron et al. (2024) investigated the economic value of the rare earth elements neodymium, dysprosium, and praseodymium in a small wind farm generator. Baron et al. disclosed a market value of approximately 500 $/t of neodymium, 280 $/t of dysprosium, and 160 $/t of praseodymium in the generator.

For PEMEL electrolysers, Badgett et al. (2024) reported an economic value of approximately 80 $/kW for the iridium in the anode catalyst. The anode – the cost of which we expect to be dominated by iridium – contributes about 15% to the manufactured cost of a functional unit.[13] Hemauer et al. (2023) reported that the anode, the economic value of which is dominated by iridium, contributes approximately 17% of the state-of-the-art PEMEL stack costs (approximately 300 €/kW[14]). Considering the total installed costs depending on plant capacity (approximately 2600 €/kW to 1300 €/kW[15]), an iridium price contribution of approximately 2% to 4% would be expected. While our results for the iridium price contribution in PEMEL are smaller than those reported by Badgett et al. Hemauer et al. disclose a smaller iridium price contribution.

For PAFC fuel cells, there has been little coverage by recent studies and even comprehensive reviews do not focus on the price contributions of raw materials (Cigolotti et al., 2021; Qasem and Abdulrahman, 2024).

Overall, the results from most related studies are in line with our findings. However, there are differences in specific cases, mainly resulting from the temporal interval between the studies. This emphasises the importance of continuous monitoring of material price contributions in CETs. Furthermore, including specific domain knowledge can lead to other conclusions about the relevance of raw materials for technology costs.

Although different studies have analysed raw material demand for the power system (Schulze et al., 2024), a similar ranking of the economic importance and risk of raw materials to the power system has thus far not been conducted.

### 6.4. Future work

Our objective in this work was to take an initial step towards identifying the materials associated with the highest risk for CETs from a large number of candidate materials. Therefore, an analysis with a qualitative approach was conducted. On this basis, the next step could be to derive price scenarios for the high-risk materials identified. This could also include in-depth probabilistic modelling to gain a more comprehensive understanding of the supply disruption likelihoods of individual high-risk materials.

Here, we briefly describe our expectations concerning the factors influencing future raw material price changes.

Recycling and substitution are two factors expected to impact material prices in the long term. Currently, recycling is relevant mainly for mass materials used in structural elements. However, recycling still has a minor impact on reducing the demand for CET-grade function-essential materials from primary production. Depending on the specific material and lifetime of the associated CETs, the main impact of recycling to reduce the demand for CET-grade function-essential minor materials is expected after our considered scenario timeframe. The substitution of problematic materials is already an option today. If material-for-material substitution in a sub-technology is not possible, shifting to sub-technologies based on different material systems in the same CET class is required. Substitution on a large scale can lead to interactions between CET prices.

Furthermore, intersectoral dependencies between the power supply system and other sectors could be relevant. For some key materials,

[11] This value was estimated from Figure 3b in the study by Chang et al. (2022).

[12] This value was estimated from Figure 7 in the study by Elia et al. (2020).

[13] This value was calculated from Table 10 in the study by Badgett et al. (2024).

[14] This value was estimated from Figure 5 in the study by Hemauer et al. (2023).

[15] These values were estimated from Figure 6 in the study by Hemauer et al. (2023).

such as lithium and dysprosium, the need to increase production is strongly driven by power supply system and transport transformation. We expect that the increasing demand for these materials in the CET sector could lead to higher market prices in the future. In this case, other sectors, such as electronics, which rely on the same materials, would be affected as well. If CETs with lithium and dysprosium face price changes originating from factors other than changes in the price of lithium or dysprosium, a lower demand for these CETs would follow. This could lead to a lower demand for lithium and dysprosium, thus lowering prices. The need to increase the production of other materials is influenced mainly by GDP growth and is rather insensitive to the ambitiousness of the CET sector. Therefore, we expect that the demand from CETs does not significantly affect the prices of these materials. Rather, CETs are subject to the material price changes from the main economy.

Subsequently, how these price scenarios change CET costs and, thus, the results of cost-optimising ESMs can be investigated. State-of-the-art ESMs based on cost optimisation focus on the technology mix, which minimises the system cost within the constraints. The most important constraint is that the electricity feed-in equals the electricity demand at any time. Material price increases can change the economically preferred sub-technology within a technology class if the material price increase leads to strong cost increases for the reference technology but causes smaller cost increases for alternative sub-technologies. This can be the case if the initial technology costs are similar for the reference and alternative sub-technologies and if the initial material price contribution of the considered material is higher in the reference technology. Sub-technology shifts could significantly alter the systemic demand for function-essential materials.

Furthermore, also changes across technology classes induced by material price increases are possible. Even the attractiveness of clean energy technologies as a whole, measured against conventional energy technologies with less material dependence, can change.

Our study illustrates the complexities associated with energy system transformations that are dependent on raw materials with varying prices. It provides a strong indication that including material considerations into optimising energy system modelling is required to understand how material price changes affect the structure of the energy system. For this analysis, the materials that should be focused on have been identified.

Furthermore, suitable policy measures are required to ensure a stable long-term supply of the materials associated with the highest risk for CET and the energy system. While the energy transformation mitigates old fossil fuel dependencies (Schreurs, 2023), its feasibility depends on a continuous and just access to these materials.

In our analysis, we address a global scope and therefore prioritise policy measures that are in line with a globally just energy transition. Increasing material efficiency and strengthening efforts to recycle End-of-Life (EoL) CETs are beneficial for all countries pursuing a green transition. Despite the technical nature of these approaches, policy measures are required for their implementation. Targeted innovation funding, such as that offered by the European Innovation Council (EIC) (European Innovation Council, 2024), could be used to improve the material efficiency and recycling processes of CETs. On the other hand, recycling requires regulation to implement design for circularity (König et al., 2024) and mandatory disclosure of the functional materials contained in EoL CETs. Domestic recycling can be a means of supporting access to raw materials and mitigating the geopolitical dependencies of countries with few resources in the long term. The Critical Raw Materials Act (CRMA) passed by the European Union is one such initiative (European Commission, 2023), setting goals for recycling in the EU. Furthermore, the CRMA sets goals for domestic extraction and production. Owing to the unequal distribution of raw material reserves, the environmental externalities of extraction, and the long-term effects of recycling, additional measures will be necessary. From a single economy perspective, diversifying the supply of raw materials and engaging in long-term trade contracts are the preferred measures (Righetti and Rizos, 2025). To avoid the green transition from leading to competition for raw materials among major economies and aggravating existing inequalities (Schreurs, 2024), close global cooperation is required.

## CRediT authorship contribution statement

**Steffen J. Schlosser:** Writing – original draft, Investigation, Data curation, Conceptualization. **Tobias Naegler:** Writing – review & editing, Project administration.

## Declaration of competing interest

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

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## Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2025.03.051.

## Data availability

The data will be made available upon request.

## References

Allekotte, L., Garrett, P., 2024. Life cycle assessment of electricity production from an offshore V236-15 MW wind plant. URL https://www.vestas.com/en/sustainability/environment/lifecycle-assessments [accessed 1 July 2024].

Althaf, S., Babbitt, C.W., 2021. Disruption risks to material supply chains in the electronics sector. Resour. Conserv. Recycl. 167, 105248. http://dx.doi.org/10.1016/j.resconrec.2020.105248.

Austrian Federal Ministry of Finance, 2023. World mining data. URL https://www.world-mining-data.info/ [accessed 14 February 2024].

Badgett, A., Brauch, J., Thatte, A., Rubin, R., Skangos, C., Wang, X., Ahluwalia, R., Pivovar, B., Ruth, M., 2024. Updated manufactured cost analysis for proton exchange membrane water electrolyzers. URL https://www.nrel.gov/docs/fy24osti/87625.pdf [accessed 8 April 2024].

Ballif, C., Haug, F.-J., Boccard, M., Verlinden, P.J., Hahn, G., 2022. Status and perspectives of crystalline silicon photovoltaics in research and industry. Nat. Rev. Mater. 7 (8), 597–616. http://dx.doi.org/10.1038/s41578-022-00423-2.

Baron, R., Kowol, D., Matusiak, P., Lutyński, M., Nowińska, K., 2024. Assessment of the risk of the loss of supply, the recycling rate and the degree of substitutability of elements in the NdFeB magnets of a small wind farm generator. Energies 17 (3), http://dx.doi.org/10.3390/en17030671.

Berg, E.J., Villevieille, C., Streich, D., Trabesinger, S., Novák, P., 2015. Rechargeable batteries: Grasping for the limits of chemistry. J. Electrochem. Soc. 162 (14), A2468. http://dx.doi.org/10.1149/2.0081514jes.

Bhuwalka, K., Kirchain, R.E., Olivetti, E.A., Roth, R., 2023. Quantifying the drivers of long-term prices in materials supply chains. J. Ind. Ecol. 27 (1), 141–154. http://dx.doi.org/10.1111/jiec.13355.

Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., van Maercke, A., Solar, S., Grohol, M., Ciupagea, C., 2017. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. Resour. Policy 53, 12–19. http://dx.doi.org/10.1016/j.resourpol.2017.05.008.

Boer, L., Pescatori, A., Stuermer, M., 2023. Energy transition metals: Bottleneck for net-zero emissions? J. Eur. Econ. Assoc. jvad039. http://dx.doi.org/10.1093/jeea/jvad039.

Brown, T., Hörsch, J., Schlachtberger, D., 2018. PyPSA: Python for power system analysis. J. Open Res. Softw. 6 (1), 4. http://dx.doi.org/10.5334/jors.188.

Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P., 2018. National hydrogen roadmap. URL https://www.csiro.au/en/research/environmental-impacts/fuels/hydrogen/Hydrogen-Roadmap [accessed 7 November 2024].

Cao, K.-K., Martens, L., Arellano Ruiz, E.S., Schlosser, S.J., Buschmann, J., Naegler, T., 2024. Multi-criteria energy system optimization: Costs vs. Critical materials. In: 18. Symposium Energieinnovation 2024. URL https://elib.dlr.de/202888/.

Chang, N.L., Newman, B.K., Egan, R.J., 2022. Future cost projections for photovoltaic module manufacturing using a bottom-up cost and uncertainty model. Sol. Energy Mater. Sol. Cells 237, 111529. http://dx.doi.org/10.1016/j.solmat.2021.111529.

Chang, Y.-C., Zhang, Y., Wang, L., Wang, S., Wang, H., Huang, C.-Y., Chen, R., Chan, C., Hallam, B., 2024. Silver-lean metallization and hybrid contacts via plating on screen-printed metal for silicon solar cells manufacturing. Prog. Photovolt., Res. Appl. http://dx.doi.org/10.1002/pip.3799.

Ciez, R.E., Whitacre, J.F., 2016. The cost of lithium is unlikely to upend the price of Li-ion storage systems. J. Power Sources 320, 310–313. http://dx.doi.org/10.1016/j.jpowsour.2016.04.073.

Cigolotti, V., Genovese, M., Fragiacomo, P., 2021. Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems. Energies 14 (16), http://dx.doi.org/10.3390/en14164963.

Danish Energy Agency, 2020. Technology data. URL https://ens.dk/en [accessed 7 May 2024].

de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G., Tukker, A., 2018. Metal supply constraints for a low-carbon economy? Resour. Conserv. Recycl. 129, 202–208. http://dx.doi.org/10.1016/j.resconrec.2017.10.040.

Duffner, F., Mauler, L., Wentker, M., Leker, J., Winter, M., 2021. Large-scale automotive battery cell manufacturing: Analyzing strategic and operational effects on manufacturing costs. Int. J. Prod. Econ. 232, 107982. http://dx.doi.org/10.1016/j.ijpe.2020.107982.

Elia, A., Taylor, M., Ó Gallachóir, B., Rogan, F., 2020. Wind turbine cost reduction: A detailed bottom-up analysis of innovation drivers. Energy Policy 147, 111912. http://dx.doi.org/10.1016/j.enpol.2020.111912.

ERM, 2022. The fuel cell industry review 2022. URL https://www.erm.com/solutions/climate-net-zero/the-fuel-cell-industry-review/ [accessed 23 October 2024].

European Commission, 2017. Methodology for establishing the EU list of critical raw materials – guidelines. http://dx.doi.org/10.2873/769526.

European Commission, 2023. Proposal for a regulation of the European parliament and of the council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160 [accessed 1 March 2025].

European Innovation Council, 2024. EIC 2025 work programme. URL https://eic.ec.europa.eu/eic-2025-work-programme_en [accessed 2 February 2025].

Farina, A., Anctil, A., 2022. Material consumption and environmental impact of wind turbines in the USA and globally. Resour. Conserv. Recycl. 176, 105938. http://dx.doi.org/10.1016/j.resconrec.2021.105938.

Frenzel, M., Kullik, J., Reuter, M.A., Gutzmer, J., 2017. Raw material 'criticality'—sense or nonsense? J. Phys. D: Appl. Phys. 50 (12), 123002. http://dx.doi.org/10.1088/1361-6463/aa5b64.

Fu, X., Beatty, D.N., Gaustad, G.G., Ceder, G., Roth, R., Kirchain, R.E., Bustamante, M., Babbitt, C., Olivetti, E.A., 2020. Perspectives on cobalt supply through 2030 in the face of changing demand. Environ. Sci. Technol. 54 (5), 2985–2993. http://dx.doi.org/10.1021/acs.est.9b04975.

Gerloff, N., 2021. Comparative life-cycle assessment analysis of power-to-methane plants including different water electrolysis technologies and $CO_2$ sources while applying various energy scenarios. ACS Sustain. Chem. Eng. 9 (30), 10123–10141. http://dx.doi.org/10.1021/acssuschemeng.1c02002.

Gervais, E., Betten, T., Shammugam, S., Graf, R., Müller, M., Schlegl, T., 2022. Material requirements for the energy transition - energy technology profiles and environmental impacts. http://dx.doi.org/10.24406/publica-427.

Gils, H.C., Scholz, Y., Pregger, T., Luca de Tena, D., Heide, D., 2017. Integrated modelling of variable renewable energy-based power supply in europe. Energy 123, 173–188. http://dx.doi.org/10.1016/j.energy.2017.01.115.

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M.-y., Zhu, C., 2012. Methodology of metal criticality determination. Environ. Sci. Technol. 46 (2), 1063–1070. http://dx.doi.org/10.1021/es203534z.

Hallam, B., Kim, M., Zhang, Y., Wang, L., Lennon, A., Verlinden, P., Altermatt, P.P., Dias, P.R., 2023. The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050. Prog. Photovolt., Res. Appl. 31 (6), 598–606. http://dx.doi.org/10.1002/pip.3661.

Hartman, H.L., Mutmansky, J.M., 2002. Introductory Mining Engineering, second ed. John Wiley & Sons, Inc., Hoboken, New Jersey.

Helbig, C., Bradshaw, A.M., Kolotzek, C., Thorenz, A., Tuma, A., 2016. Supply risks associated with CdTe and CIGS thin-film photovoltaics. Appl. Energy 178, 422–433. http://dx.doi.org/10.1016/j.apenergy.2016.06.102.

Helbig, C., Bruckler, M., Thorenz, A., Tuma, A., 2021. An overview of indicator choice and normalization in raw material supply risk assessments. Resources 10 (8), http://dx.doi.org/10.3390/resources10080079.

Hemauer, J., Rehfeldt, S., Klein, H., Peschel, A., 2023. Performance and cost modelling taking into account the uncertainties and sensitivities of current and next-generation PEM water electrolysis technology. Int. J. Hydrog. Energy 48 (66), 25619–25634. http://dx.doi.org/10.1016/j.ijhydene.2023.03.050.

Hofmann, M., Hofmann, H., Hagelüken, C., Hool, A., 2018. Critical raw materials: A perspective from the materials science community. Sustain. Mater. Technol. 17, e00074. http://dx.doi.org/10.1016/j.susmat.2018.e00074.

Index Mundi, 2024. Potassium chloride monthly price - US dollars per metric ton. URL https://www.indexmundi.com/commodities/?commodity=potassium-chloride [accessed 22 October 2024].

Institut für Seltene Erden und Metalle, 2024. Metallpreise. URL https://ise-metal-quotes.com/ [accessed 12 July 2024].

International Energy Agency, 2019. The future of hydrogen: Sizing today's opportunities. URL https://www.iea.org/reports/the-future-of-hydrogen [accessed 2 April 2024].

International Energy Agency, 2020. Projected costs of generating electricity: 2020 edition. URL https://www.iea.org/reports/projected-costs-of-generating-electricity-2020 [accessed 7 May 2024].

International Energy Agency, 2023. The role of critical minerals in clean energy transitions. URL https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions [accessed 27 November 2023].

International Renewable Energy Agency, 2023. Renewable power generation costs in 2022. International Renewable Energy Agency, Abu Dhabi, URL https://www.irena.org/Publications/2023/Aug/Renewable-power-generation-costs-in-2022 [accessed 15 March 2024].

ISO, 2006. ISO 14044: 2006, Environmental management — Life cycle assessment — Requirements and guidelines. Dtsch. Und Engl. Fass. EN ISO 14044, URL https://www.iso.org/standard/38498.html [accessed 11 February 2025].

Joint Research Centre, 2023. Water electrolysis and hydrogen in the European Union: Status report on technology development, trends, value chains & markets. URL https://setis.ec.europa.eu/water-electrolysis-and-hydrogen-european-union_en [accessed 27 March 2024].

Jowitt, S.M., Mudd, G.M., Thompson, J.F.H., 2020. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. Commun. Earth & Environ. 1 (1), 13. http://dx.doi.org/10.1038/s43247-020-0011-0.

Junne, T., Wulff, N., Breyer, C., Naegler, T., 2020. Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt. Energy 211, 118532. http://dx.doi.org/10.1016/j.energy.2020.118532.

Kannan, R., 2011. The development and application of a temporal MARKAL energy system model using flexible time slicing. Appl. Energy 88 (6), 2261–2272. http://dx.doi.org/10.1016/j.apenergy.2010.12.066.

Kaufmann, D., Kraay, A., 2022. The worldwide governance indicators, 2022 update: Aggregate governance indicators 1996–2021. URL http://www.govindicators.org/ [accessed 10 February 2024].

Kaufmann, D., Kraay, A., Mastruzzi, M., 2011. The Worldwide Governance Indicators: Methodology and analytical issues. Hague J. the Rule Law 3 (2), 220–246. http://dx.doi.org/10.1017/S1876404511200046.

König, K., Mathieu, J., Vielhaber, M., 2024. Resource conservation by means of lightweight design and design for circularity—A concept for decision making in the early phase of product development. Resour. Conserv. Recycl. 201, 107331. http://dx.doi.org/10.1016/j.resconrec.2023.107331.

Korkmaz, S.A., Erginer, K.E., Yuksel, O., Konur, O., Colpan, C.O., 2023. Environmental and economic analyses of fuel cell and battery-based hybrid systems utilized as auxiliary power units on a chemical tanker vessel. Int. J. Hydrog. Energy 48 (60), 23279–23295. http://dx.doi.org/10.1016/j.ijhydene.2023.01.320.

Kotzur, L., Nolting, L., Hoffmann, M., Groß, T., Smolenko, A., Priesmann, J., Büsing, H., Beer, R., Kullmann, F., Singh, B., Praktiknjo, A., Stolten, D., Robinius, M., 2021. A modeler's guide to handle complexity in energy systems optimization. Adv. Appl. Energy 4, 100063. http://dx.doi.org/10.1016/j.adapen.2021.100063.

Laha, P., Chakraborty, B., 2017. Energy model – a tool for preventing energy dysfunction. Renew. Sustain. Energy Rev. 73, 95–114. http://dx.doi.org/10.1016/j.rser.2017.01.106.

Leader, A., Gaustad, G., Babbitt, C., 2019. The effect of critical material prices on the competitiveness of clean energy technologies. Mater. Renew. Sustain. Energy 8 (2), 8. http://dx.doi.org/10.1007/s40243-019-0146-z.

Li, C., Mogollón, J.M., Tukker, A., Dong, J., von Terzi, D., Zhang, C., Steubing, B., 2022. Future material requirements for global sustainable offshore wind energy development. Renew. Sustain. Energy Rev. 164, 112603. http://dx.doi.org/10.1016/j.rser.2022.112603.

Liang, Y., Kleijn, R., Tukker, A., van der Voet, E., 2022. Material requirements for low-carbon energy technologies: A quantitative review. Renew. Sustain. Energy Rev. 161, 112334. http://dx.doi.org/10.1016/j.rser.2022.112334.

Loulou, R., Goldstein, G., Kanudia, A., Lettila, A., Remme, U., 2016a. Documentation of the TIMES model: Part i. URL https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf [accessed 3 April 2024].

Loulou, R., Lehtilä, A., Kanudia, A., Remme, U., Goldstein, G., 2016b. Documentation for the TIMES model: Part II. URL https://www.iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-II_July-2016.pdf [accessed 3 April 2024].

Lütkehaus, H., Pade, C., Oswald, M., Brand, U., Naegler, T., Vogt, T., 2022. Measuring raw-material criticality of product systems through an economic product importance indicator: A case study of battery-electric vehicles. Int. J. Life Cycle Assess. 27 (1), 122–137. http://dx.doi.org/10.1007/s11367-021-02002-z.

Mali, S., Garrett, P., 2022a. Life cycle assessment of electricity production from an onshore V136-4.2 MW wind plant. URL https://www.vestas.com/en/sustainability/environment/lifecycle-assessments [accessed 1 July 2024].

Mali, S., Garrett, P., 2022b. Life cycle assessment of electricity production from an onshore V150-4.2 MW wind plant. URL https://www.vestas.com/en/sustainability/environment/lifecycle-assessments [accessed 1 July 2024].

Mancini, L., Pennington, D., de Camillis, C., 2013. Security of supply and scarcity of raw materials – Towards a methodological framework for sustainability assessment. Joint Research Centre, Institute for Environment and Sustainability, Publications Office, Ispra, Italy, http://dx.doi.org/10.2788/94926.

Mauler, L., Duffner, F., Zeier, W.G., Leker, J., 2021. Battery cost forecasting: A review of methods and results with an outlook to 2050. Energy & Environ. Sci. 14 (9), 4712–4739. http://dx.doi.org/10.1039/D1EE01530C.

Mongird, K., Viswanathan, V., Alam, J., Vartanian, C., Sprenkle, V., Baxter, R., 2020. 2020 Grid energy storage technology cost and performance assessment. URL https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf [accessed 15 March 2024].

National Science and Technology Council, 2016. Assessment of critical minerals: Screening methodology and initial application. URL https://www.govinfo.gov/content/pkg/GOVPUB-PREX23-PURL-gpo67429/pdf/GOVPUB-PREX23-PURL-gpo67429.pdf [accessed 24 November 2023].

Nelson, P.A., Ahmed, S., Gallagher, K.G., Dees, D.W., 2019. Modeling the performance and cost of lithium-ion batteries for electric-drive vehicles.

Park, H., Jung, Y., Park, C., Lee, J., Ghasemi, M., Alam, A., Kim, H., Kim, J., Park, S., Choi, K., You, H., Ju, H., 2023. Performance evaluation and economic feasibility of a PAFC-based multi-energy hub system in South Korea. Energy 278, 128055. http://dx.doi.org/10.1016/j.energy.2023.128055.

Pavel, C.C., Lacal-Arántegui, R., Marmier, A., Schüler, D., Tzimas, E., Buchert, M., Jenseit, W., Blagoeva, D., 2017. Substitution strategies for reducing the use of rare earths in wind turbines. Resour. Policy 52, 349–357. http://dx.doi.org/10.1016/j.resourpol.2017.04.010.

Qasem, N.A.A., Abdulrahman, G.A.Q., 2024. A recent comprehensive review of fuel cells: History, types, and applications. Int. J. Energy Res. 2024 (1), 7271748. http://dx.doi.org/10.1155/2024/7271748.

Razdan, P., Garrett, P., 2019. Life cycle assessment of electricity production from an onshore V117-4.2 MW wind plant. URL https://www.vestas.com/en/sustainability/environment/lifecycle-assessments [accessed 1 July 2024].

Righetti, E., Rizos, V., 2025. Reducing supply risks for critical raw materials: Evidence and policy options. URL https://circulareconomy.europa.eu/platform/sites/default/files/2024-01/CEPS-InDepthAnalysis-2024-01_Reducing-supply-risks-for-critical-raw-materials.pdf [accessed 2 February 2025].

Riondet, L., Suchet, D., Vidal, O., Halloy, J., 2023. Applicability of Hubbert model to global mining industry: Interpretations and insights. PLOS Sustain. Transform. 2 (4), e0000047. http://dx.doi.org/10.1371/journal.pstr.0000047.

Santillán-Saldivar, J., Gaugler, T., Helbig, C., Rathgeber, A., Sonnemann, G., Thorenz, A., Tuma, A., 2021. Design of an endpoint indicator for mineral resource supply risks in life cycle sustainability assessment: The case of Li-ion batteries. J. Ind. Ecol. 25 (4), 1051–1062. http://dx.doi.org/10.1111/jiec.13094.

Schlichenmaier, S., Naegler, T., 2022. May material bottlenecks hamper the global energy transition towards the 1.5° C target? Energy Rep. 8, 14875–14887. http://dx.doi.org/10.1016/j.egyr.2022.11.025.

Schreiber, A., Marx, J., Zapp, P., 2019. Comparative life cycle assessment of electricity generation by different wind turbine types. J. Clean. Prod. 233, 561–572. http://dx.doi.org/10.1016/j.jclepro.2019.06.058.

Schreurs, M.A., 2023. Implications of the Russian war on Ukraine for climate policy and the geopolitics of energy. Can. J. Eur. Russ. Stud. 16 (2), 90–113. http://dx.doi.org/10.22215/cjers.v16i2.2765.

Schreurs, M.A., 2024. Jockeying for climate leadership amidst rising global tensions: China, USA and the European Union. In: Biba, S. (Ed.), Europe in an Era of US-China Strategic Rivalry: Challenges and Opportunities from an Outside-in Perspective. Springer Nature Switzerland, Cham, pp. 243–264. http://dx.doi.org/10.1007/978-3-031-48117-8_12.

Schrijvers, D., Hool, A., Blengini, G.A., Chen, W.-Q., Dewulf, J., Eggert, R., van Ellen, L., Gauss, R., Goddin, J., Habib, K., Hagelüken, C., Hirohata, A., Hofmann-Amtenbrink, M., Kosmol, J., Le Gleuher, M., Grohol, M., Ku, A., Lee, M.-H., Liu, G., Nansai, K., Nuss, P., Peck, D., Reller, A., Sonnemann, G., Tercero, L., Thorenz, A., Wäger, P.A., 2020. A review of methods and data to determine raw material criticality. Resour. Conserv. Recycl. 155, 104617. http://dx.doi.org/10.1016/j.resconrec.2019.104617.

Schulze, K., Kullmann, F., Weinand, J.M., Stolten, D., 2024. Overcoming the challenges of assessing the global raw material demand of future energy systems. Joule 8 (7), 1936–1957. http://dx.doi.org/10.1016/j.joule.2024.05.016.

Shammugam, S., Gervais, E., Schlegl, T., Rathgeber, A., 2019. Raw metal needs and supply risks for the development of wind energy in Germany until 2050. J. Clean. Prod. 221, 738–752. http://dx.doi.org/10.1016/j.jclepro.2019.02.223.

Smith, B.L., Woodhouse, M., Horowitz, K.A.W., Silverman, T.J., Zuboy, J., Margolis, R.M., 2021. Photovoltaic (PV) module technologies: 2020 Benchmark costs and technology evolution framework results. URL https://www.nrel.gov/docs/fy22osti/78173.pdf [accessed 15 March 2024].

Sprecher, B., Daigo, I., Murakami, S., Kleijn, R., Vos, M., Kramer, G.J., 2015. Framework for resilience in material supply chains, with a case study from the 2010 rare earth crisis. Environ. Sci. Technol. 49 (11), 6740–6750. http://dx.doi.org/10.1021/acs.est.5b00206.

Stehly, T., Duffy, P., Mulas Hernando, D., 2023. 2022 Cost of wind energy. URL https://www.nrel.gov/docs/fy24osti/88335.pdf [accessed 15 March 2024].

Sun, X., Ouyang, M., Hao, H., 2022. Surging lithium price will not impede the electric vehicle boom. Joule 6 (8), 1738–1742. http://dx.doi.org/10.1016/j.joule.2022.06.028.

Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2017. Integrated modelling of the global cobalt extraction, supply, price and depletion of extractable resources using the WORLD6 model. BioPhysical Econ. Resour. Qual. 2 (1), 4. http://dx.doi.org/10.1007/s41247-017-0017-0.

Teske, S., Pregger, T., Simon, S., Naegler, T., Pagenkopf, J., van den Adel, B., Meinshausen, M., Dooley, K., Briggs, C., Dominish, E., Giurco, D., Florin, N., Morris, T., Nagrath, K., 2019. Methodology. In: Teske, S. (Ed.), Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5° C and +2° C. Springer International Publishing, Cham, pp. 25–78. http://dx.doi.org/10.1007/978-3-030-05843-2_3.

Tokimatsu, K., Höök, M., McLellan, B., Wachtmeister, H., Murakami, S., Yasuoka, R., Nishio, M., 2018. Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2° C target with 100 percent renewable energy. Appl. Energy 225, 1158–1175. http://dx.doi.org/10.1016/j.apenergy.2018.05.047.

Trutnevyte, E., 2016. Does cost optimization approximate the real-world energy transition? Energy 106, 182–193. http://dx.doi.org/10.1016/j.energy.2016.03.038.

US Geological Survey, 2024. Commodity statistics and information. URL https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information [accessed 2 April 2024].

Valero, A., Valero, A., Calvo, G., Ortego, A., 2018. Material bottlenecks in the future development of green technologies. Renew. Sustain. Energy Rev. 93, 178–200. http://dx.doi.org/10.1016/j.rser.2018.05.041.

van Oers, L., Guinée, J.B., Heijungs, R., 2020. Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. Int. J. Life Cycle Assess. 25 (2), 294–308. http://dx.doi.org/10.1007/s11367-019-01683-x.

Wentker, M., Greenwood, M., Leker, J., 2019. A bottom-up approach to lithium-ion battery cost modeling with a focus on cathode active materials. Energies 12 (3), http://dx.doi.org/10.3390/en12030504.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The Ecoinvent database version 3 (part i): Overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230. http://dx.doi.org/10.1007/s11367-016-1087-8.

Wetzel, M., Ruiz, E.S.A., Witte, F., Schmugge, J., Sasanpour, S., Yeligeti, M., Miorelli, F., Buschmann, J., Cao, K.-K., Wulff, N., Gardian, H., Rubbert, A., Fuchs, B., Scholz, Y., Gils, H.C., 2024. REMix: A GAMS-based framework for optimizing energy system models. J. Open Source Softw. 9 (99), 6330. http://dx.doi.org/10.21105/joss.06330.

Whiston, M.M., Lima Azevedo, I.M., Litster, S., Samaras, C., Whitefoot, K.S., Whitacre, J.F., 2021. Paths to market for stationary solid oxide fuel cells: Expert elicitation and a cost of electricity model. Appl. Energy 304, 117641. http://dx.doi.org/10.1016/j.apenergy.2021.117641.

Wilting, H., Hanemaaijer, A., 2014. Share of raw material costs in total production costs. URL https://www.pbl.nl/sites/default/files/downloads/pbl-2014-share-of-raw-material-costs-in-total-production-costs_01506.pdf [accessed 10 April 2024].

Wittstock, R., Pehlken, A., Peñaherrera, F., Wark, M., 2019. Assessment of the demand for critical raw materials for the implementation of fuel cells for stationary and mobile applications. In: Pehlken, A., Kalverkamp, M., Wittstock, R. (Eds.), Cascade Use in Technologies 2018. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 111–121.

Wulf, C., Zapp, P., Schreiber, A., 2020. Review of Power-to-X demonstration projects in Europe. Front. Energy Res. 8, http://dx.doi.org/10.3389/fenrg.2020.00191.

Zepf, V., 2020. Chapter 4 - The dependency of renewable energy technologies on critical resources. In: Bleicher, A., Pehlken, A. (Eds.), The Material Basis of Energy Transitions. Academic Press, London, United Kingdom, pp. 49–70. http://dx.doi.org/10.1016/B978-0-12-819534-5.00004-0.

Zhou, B., Li, Z., Chen, C., 2017. Global potential of rare earth resources and rare earth demand from clean technologies. Minerals 7 (11), http://dx.doi.org/10.3390/min7110203.