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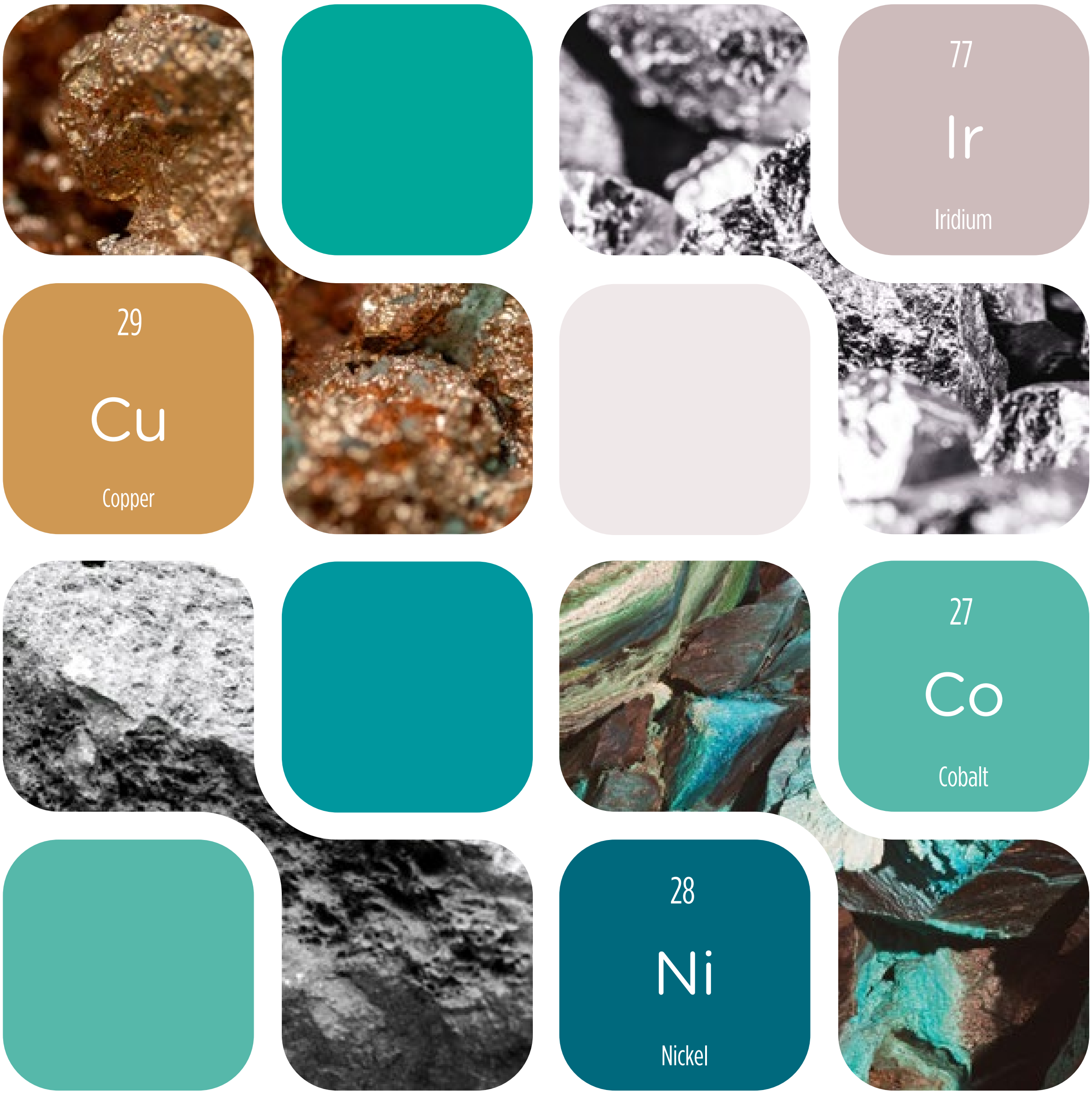

Constructing a ranking of critical materials for the global energy transition

A brief from the Collaborative Framework on Critical Materials for the Energy Transition

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

About NUPI

The Norwegian Institute of International Affairs (NUPI) was established by the Norwegian Storting (parliament) in 1959 and is an independent research institution. NUPI carries out research on international issues, including the global energy transition and climate policy.

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Abbreviations

CCS	carbon capture and storage
CSP	concentrated solar power
EU	European Union
EV	electric vehicle
HHI	Herfindahl-Hirschman Index
IRENA	International Renewable Energy Agency
LFP	lithium iron phosphate (battery)
NUPI	Norwegian Institute of International Affairs
OECD	Organisation for Economic Co-operation and Development
PEM	polymer electrolyte membrane
PGMs	platinum group metals
PV	photovoltaic
REEs	rare earth elements
SIB	sodium ion battery

Chemical symbols

Al	aluminium
B	boron/borate
Be	beryllium
Cd	cadmium
Ce	cerium
Co	cobalt
Cr	chromium
Cu	copper
Dy	dysprosium
Eu	europium
Fe	iron/steel
Ga	gallium
Gd	gadolinium
Ge	germanium
Gr	graphite
In	indium
Ir	iridium
K	potassium
La	lanthanum
Li	lithium
Mg	magnesium
Mn	manganese
Mo	molybdenum
Nb	niobium
Nd	neodymium
Ni	nickel
P	phosphorus
Pb	lead
Pd	palladium
Pr	praseodymium
Pt	platinum
Re	rhenium
Rh	rhodium
Ru	ruthenium
Se	selenium
Si	silicon
Sm	samarium
Sn	tin
Sr	strontium
Ta	tantalum
Tb	terbium
Te	tellurium
Ti	titanium
V	vanadium
W	tungsten
Y	yttrium
Zn	zinc
Zr	zirconium

Executive summary

Many lists of critical materials exist, but most are not focused on the renewable energy transition and include materials that are primarily used for medical, military and even fossil fuel purposes. Those lists that do focus on renewable energy have limitations in terms of energy technologies covered, critical materials included or geographical scope. This report develops a methodology to comprehensively identify and rank critical materials specifically needed for the global transition to renewable energy, based on a two-pronged approach, outlined below.

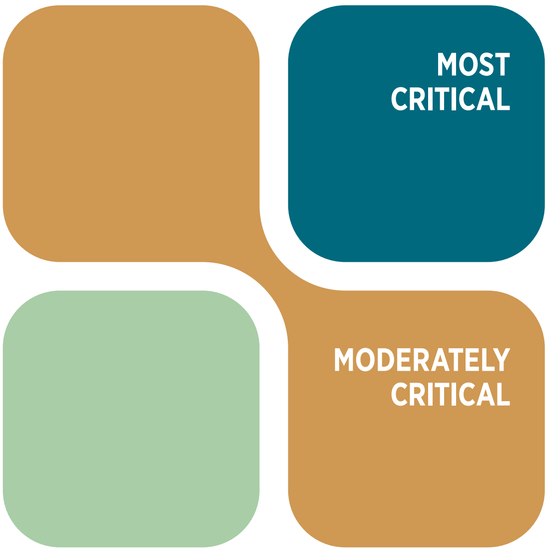
First, a meta-list of critical materials is compiled based on existing lists of materials deemed critical for renewable energy. This is based on how frequently the materials appear in the underlying lists. Second, a composite index of criticality is created based on six indicators: trends in the listing of critical materials, diversification of materials markets, abundance of minerals in the Earth's crust, demand scenarios, recycling potential and substitution potential.

The composite index is combined with the renewable-energy materials meta-list to generate final criticality scores that provide the basis for the global ranking of critical materials.

Based on this methodology, the materials ranked as "most critical" for the energy transition in a global context are (in order of criticality): lithium, cobalt, gallium, rare earth elements (REEs), neodymium, indium, platinum group metals (PGMs), dysprosium, nickel, tellurium, praseodymium, graphite, manganese, copper and germanium.

The materials ranked as "moderately critical" are: silver, strontium, platinum, phosphorus, chromium, rhodium, lanthanum, ruthenium, aluminium, boron/borate, selenium, palladium, cerium, vanadium, titanium and silicon.

The materials ranked as "least critical" are: molybdenum, magnesium, yttrium, cadmium, terbium, zinc, iridium, zirconium, samarium, tungsten, beryllium, tin, iron/steel, europium, potassium, niobium, tantalum, gadolinium, lead and rhenium.



Lithium, cobalt, gallium, rare earth elements (REEs), neodymium, indium, platinum group metals (PGMs), dysprosium, nickel, tellurium, praseodymium, graphite, manganese, copper and germanium.

Silver, strontium, platinum, phosphorus, chromium, rhodium, lanthanum, ruthenium, aluminium, boron/borate, selenium, palladium, cerium, vanadium, titanium and silicon.

In addition to the global ranking of critical materials, this report generates several findings. First, geopolitical, regulatory and technological changes and their impacts on the various stages of mineral supply chains constantly alter the supply and demand for materials, making it hard to predict the exact set of materials that will be considered critical in the future.

Second, this means that the mining and mineral-processing industries face fundamental uncertainties about future demand for critical materials. This could reduce or delay investment, in turn destabilising supply.

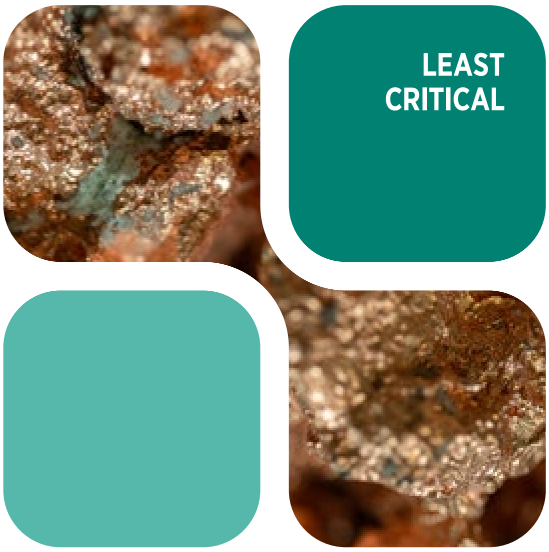
Third, a narrow focus on scarcity carries a risk of overlooking other constraints, opportunities and technological developments.

This report makes several policy recommendations. To begin with, definitions of criticality and lists of critical materials should be used with caution. Any list of critical materials will be influenced by the outlook of the authors, state or organisation that produced the list and the specific circumstances at the time the list was produced.

Next, rankings of critical materials such as those compiled in this report should be updated every two to three years to reflect evolving technologies and policies affecting supply and demand.

One of the main possible enhancements of the ranking and an area for further research would be to further develop its forward-looking aspect by including more complex scenarios for future technological developments.

Finally, if governments implement measures to reduce risks for investors involved in critical materials they should be careful to avoid micromanaging supplies of specific materials because the materials that are seen as critical may change.



Molybdenum, magnesium, yttrium, cadmium, terbium, zinc, iridium, zirconium, samarium, tungsten, beryllium, tin, iron/steel, europium, potassium, niobium, tantalum, gadolinium, lead and rhenium.

1. Introduction

The number of critical materials lists published by states is growing. However, most of these lists are not focused on materials used in the production of renewable energy technologies and are often dominated by materials used for fossil fuel extraction, military, medical, electronics and other purposes. For example, the European Union's (EU's) list of critical materials includes coking coal (used for steelmaking), and the United States' (USA's) list includes lutetium (mainly used for petroleum cracking in oil refineries) (Grohol and Veeh, 2023). This report fills the gap by compiling a ranking of critical materials used specifically for renewable energy technologies around the world.

The identification of a material as "critical" is important for several reasons.[1] This designation can attract capital to the supply chain for the material, trigger initiatives to promote higher environmental and social standards for its mining and processing, generate pressure for more transparent supply chains and enhanced international collaboration on its supply, and help avoid potential supply-demand imbalances that could delay the energy transition. However, such a designation also carries risks: it can lead to geopolitical and social tensions, resource nationalism, rent-seeking, corruption, speculation and hoarding (Sturman *et al.*, 2022). Bearing in mind both the potential positive and negative effects of classifying materials as critical, this report sets out to build a global ranking of critical materials for renewable energy applications.

1.1 Scope and design

The analysis in this report is limited to materials that are critical for renewable energy development as defined by IRENA. Thus, carbon capture and storage (CCS), energy efficiency, nuclear power, natural gas and blue hydrogen are not covered (Table 1). However, technologies that are not directly involved in generating renewable energy but are important for facilitating the expanded use of renewable energy, such as electricity grids, energy storage and electrification of transport, are included.

The overarching methodology is explained in Figure 1. First, meta-list of critical materials for renewable energy purposes was constructed based on multiple existing lists from academic publications, government documents and reports published by international and non-governmental organisations. Second, the meta-list is complemented by a composite index consisting of various factors relevant for critical materials globally (see Figure 1). Adding these factors helps ensure that the list includes a global perspective and is forward-looking rather than retrospective.

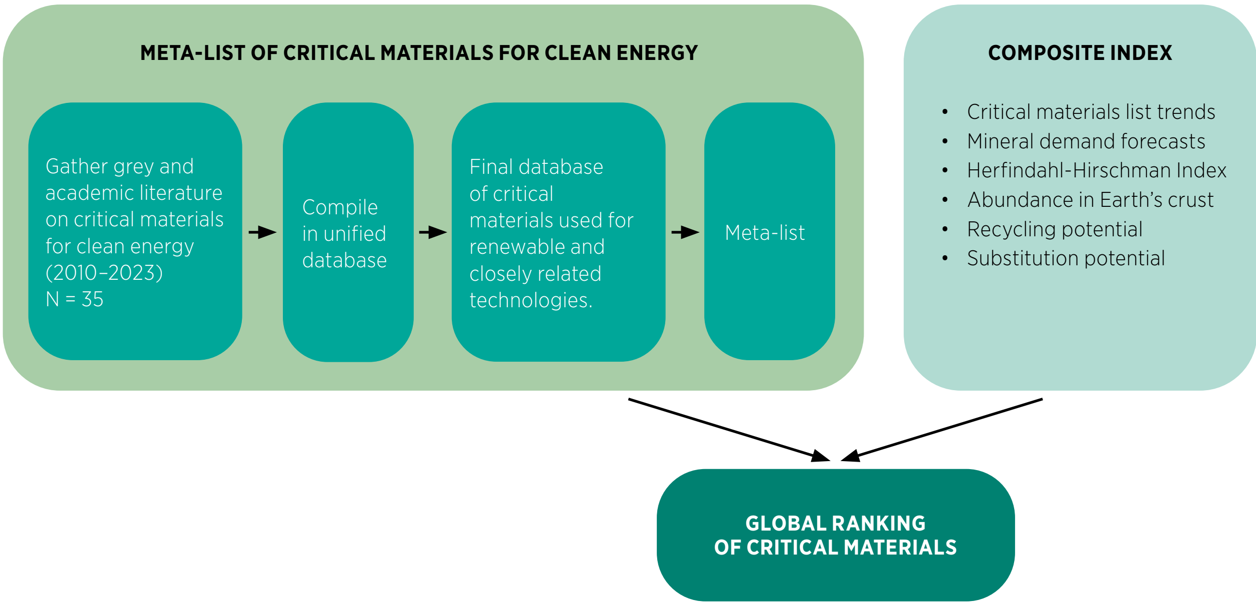
The combination of the meta-list and the composite index constitutes a compromise between a bottom-up and a top-down approach. The meta-list represents a bottom-up approach, drawing on the extant assessments of which materials are critical for renewable energy applications and related technologies. The composite index represents a top-down approach by which indicators with overarching validity for the whole world are identified and which make it possible to look forward in time. By combining these two approaches with equal weights, the objective is to make the ranking reflect current thinking around the world and make optimal use of existing lists of critical materials.

[1] Some publications use the terms "strategic materials" or "conflict minerals" rather than "critical materials". The vast majority of publications were found to use the term "critical materials", and this term is therefore also used in this report.

TABLE 1 Decarbonisation technologies included and excluded from the analysis

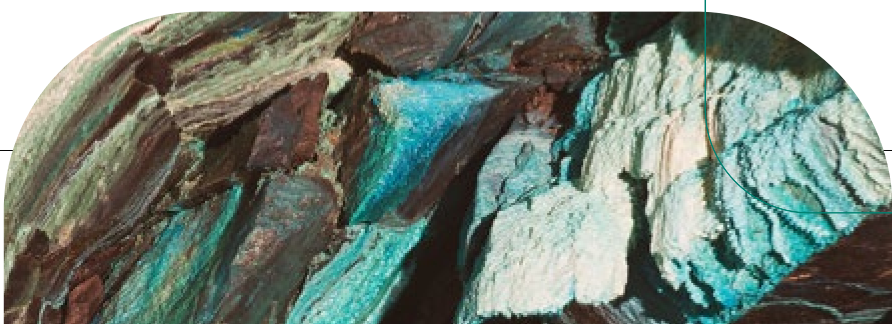
Included	Excluded
• **Renewable energy** o Wind power ▪ Offshore ▪ Onshore o Solar power ▪ Photovoltaic (PV) ▪ Concentrated solar power (CSP) o Bioenergy ▪ Biogas ▪ Biomass, waste ▪ Biomass, co-firing ▪ Biomass, solid o Geothermal power o Hydropower o Tidal and wave power • **Electrification** o Electrification of transport o Energy storage o Electricity grids • **Green hydrogen**	• **Non-renewable energy** o Coal o Natural gas o Nuclear power • **Other decarbonisation strategies** o Blue/pink/purple/turquoise/grey hydrogen o Carbon capture and storage (CCS) o Energy efficiency

FIGURE 1 Flowchart of methodological and empirical steps in the compilation of the ranking of critical materials for the global renewable energy transition



In the process of this research a second meta-list was also compiled. It covered the national lists of critical materials published by 24 national governments, including the EU. However, this meta-list was found to be of limited use in a renewable energy context because most states lump together critical materials for renewable energy with critical materials for other purposes. The national meta-list was therefore left out and only the renewable energy meta-list has been used as a basis for creating the global ranking of critical materials.

Methodological details are provided along with the presentation of the ranking components in the next sections.



2. Meta-list

As a basis for the meta-list of critical materials for renewable energy applications, 35 existing lists were collected from academic publications, reports from international and non-governmental organisations, and government documents (see detailed overview of lists in Appendix A, Table A.1). The collection covered 2010-2023 and was limited to lists specifically concerned with materials for renewable energy applications. The following terms were used in the search for relevant publications: "(critical materials OR critical minerals OR critical metals) AND (energy transition OR renewable energy OR clean energy OR batteries OR electric vehicles OR EVs)".

This resulted in the identification of 57 critical materials that appear on one or more of the collected lists. Since the scope of the lists varies and some cover the broad concept of "clean energy" and/or include technologies such as nuclear power or blue hydrogen, materials linked to technologies unrelated to renewable energy as defined by IRENA were subsequently removed (see Table 1). This resulted in a meta-list of 49 critical materials, presented in Figure 2.

In addition to 49 individual materials, 2 larger groupings were included: REEs and PGMs. Some lists name specific minerals within these groups, while others list only the higher-level groups. The aim of the methodology is to capture all instances without inflating the degree to which the lists focus on a material. When a listing of an individual mineral was encountered (but not the group it belongs to), this was counted both as a hit for the mineral in question and for the group it is part of. (However, if several individual materials of the group were mentioned in the list, the group received only one hit, to avoid overcounting.)

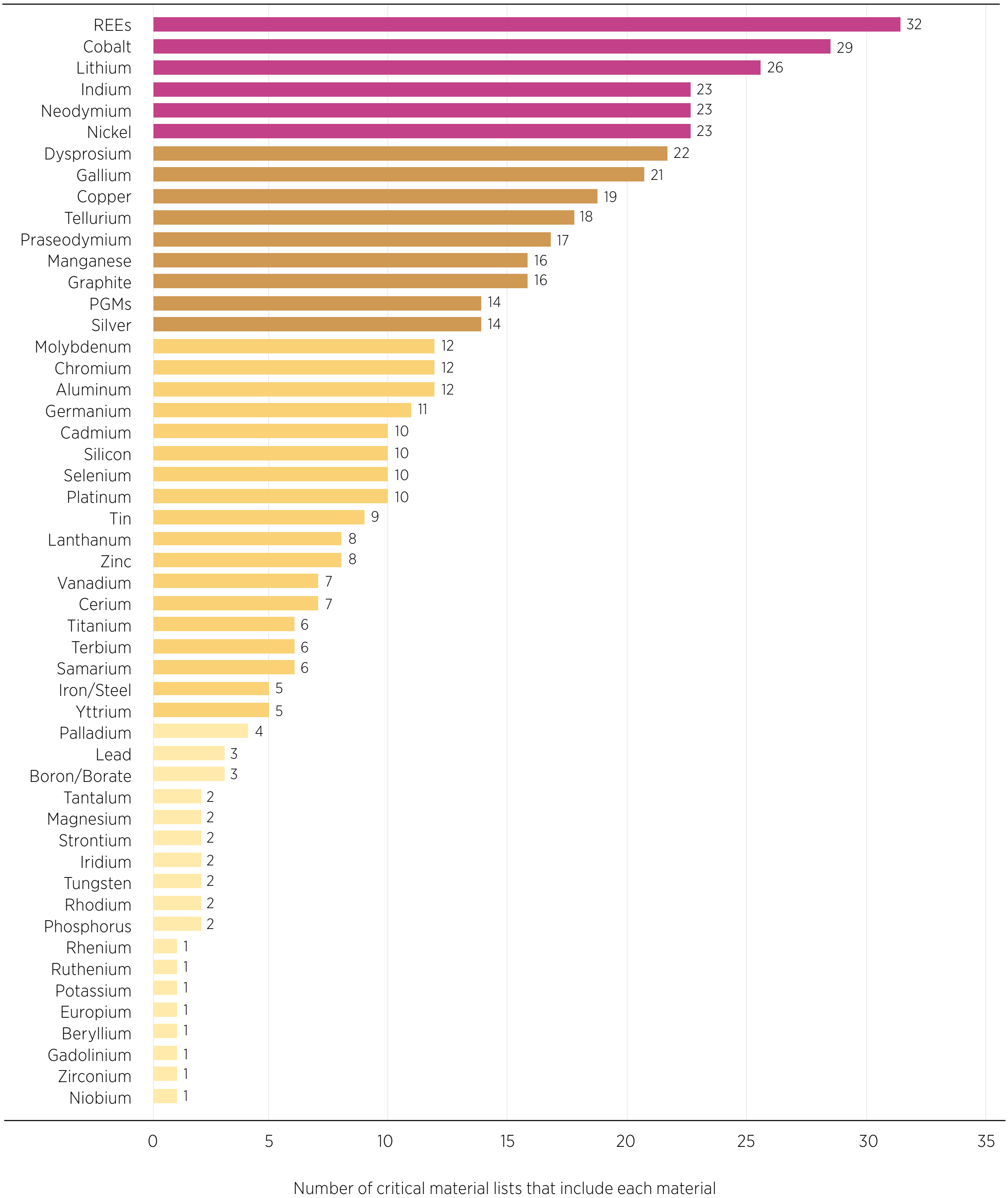
The collected critical materials lists define criticality in different ways. Although this is a limitation, it is an intrinsic feature of the current empirical investigation. The meta-list compiled here is meant to sum up and bridge the existing approaches to critical materials for renewable energy, taking into account the diversity of those approaches.

The resulting meta-list is presented in Figure 2 and shows the full range of materials identified as critical for renewable energy technologies in different lists. The frequency of inclusion of each material across the gathered lists is used as an initial indication of the degree to which materials are considered critical. Figure 3 shows the various materials included in the meta-list and which technologies they are linked to.

An important limitation of such a meta-list is that it has a retrospective element. This is because the existing lists on which it builds come from different years between 2010 and 2023. The time lag caused by the process of writing, peer reviewing, revising and publishing those lists potentially makes them further outdated.

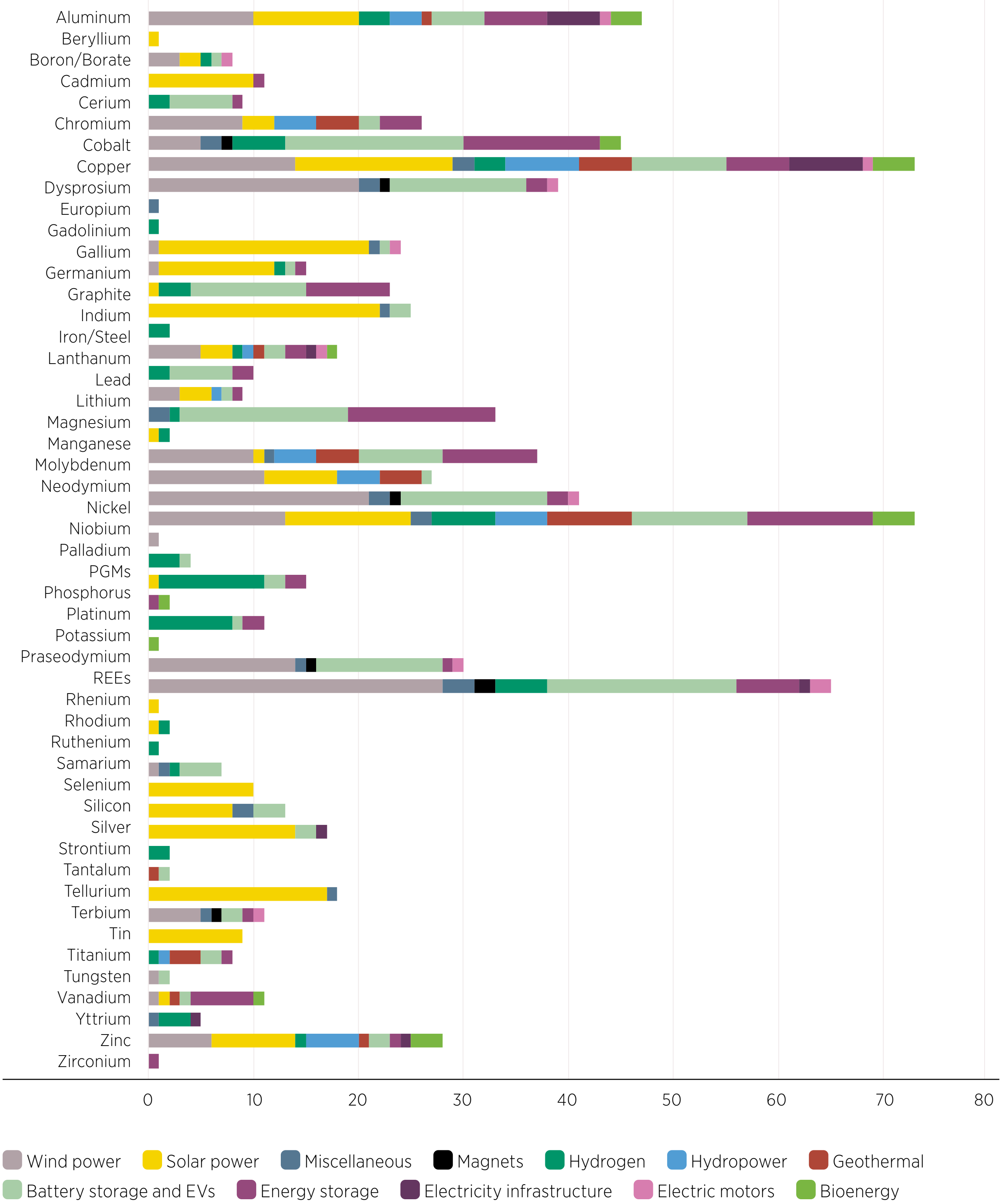
An additional challenge is that such lists tend to be based on the available technologies and supply-demand situation at the time they were compiled. Even if all lists reflected the situation today, geopolitical, regulatory and technological changes will inevitably affect the future supply and demand for these materials (see Figure 4). Technological changes are especially probable and salient. The only thing that is certain about innovation and renewable energy technologies is that many technologies will evolve, and some will be replaced, leading to changes in the demand for critical materials. For example, perovskite solar photovoltaic (PV) panels and sodium ion batteries (SIB), both of which are currently subject to innovation races, may dramatically alter demand for several materials.

FIGURE 2 Meta-list of critical materials after removal of materials unrelated to renewable energy



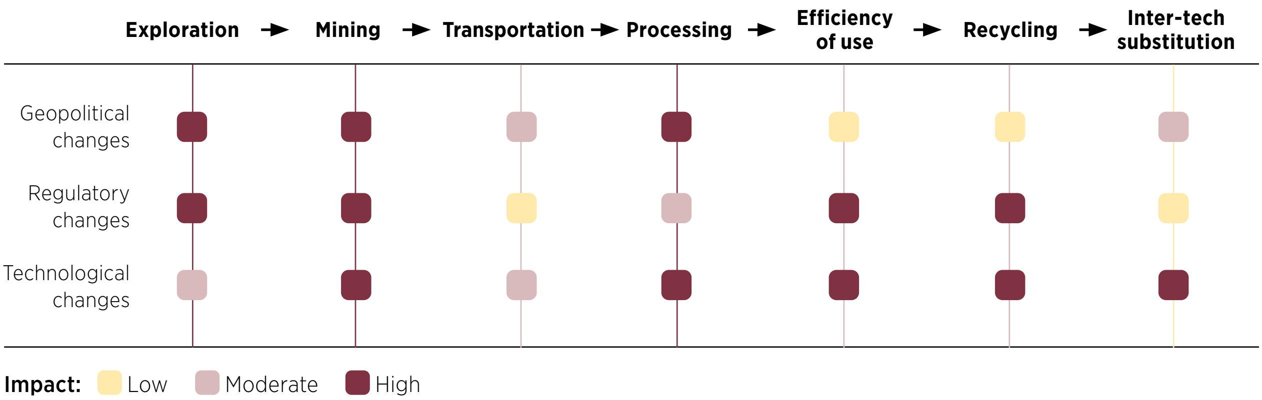
Notes: REEs = rare earth elements; PGMs = platinum group metals; the mineral groups REEs and PGMs include occurrences of these group categories as well as occurrences of individual minerals that are part of these groups.

FIGURE 3 Number of critical materials lists each critical material appears in, with uses for specific energy transition technologies colour coded



Note: "Miscellaneous" includes items that could not be classified into one specific technology type: infrastructure, energy transition, energy infrastructure, energy generation, clean energy.

FIGURE 4 Geopolitical, regulatory and technological changes may affect all stages of mineral supply chains, changing the availability and cost of minerals



Note: This purely theoretical representation aims to illustrate the complexity and unpredictability of changes and their impacts on the mineral life cycle.

Innovation can change not only the uses of materials, but also their discovery, extraction and processing. The rise of shale oil and gas – unexpected by proponents of peak oil – illustrates how (even relatively modest) innovation and recombination of existing technologies can change the accessibility and usability of already-known reserves.[2] Similar developments could happen with other natural resources, including many of the minerals considered critical today. However, the timing and extent of such technological changes and how they would affect the supply and demand for materials are difficult to predict. Many lists of critical materials are therefore based on currently available technologies and are not forward-looking. There will be innovation throughout material supply chains.

[2] Peak oil proponents take a neo-Malthusian view of oil reserves and believe that the world will imminently run out of oil and gas, causing extraction to decline and leading to competition and potentially conflict over the dwindling resources.

3. Composite index

A composite index was created and used to rebalance the meta-list into the final ranking of critical materials for global renewable energy. This was done to ensure that the ranking of critical materials has some forward-looking aspects and reflects a balanced view overall. The index makes use of indicators that are forward-looking and/or relevant for the whole world: trends over time in the identification of critical materials, demand scenarios, market diversification, estimated abundance in the Earth's crust, recycling potential and substitution potential. Inevitably, the choice of indicators is subject to data availability, timeliness and measurability. See Table 2 for the specifications and justifications for the inclusion of the indicators. The next subsections discuss each indicator individually.

All indicators were measured on a continuous scale and rescaled to have the same range (0-1) using min-max normalisation

$\times = (\times - \min) / (\max - \min).$

Where necessary, the scale of variables was reversed so that a greater value indicates a higher degree of criticality.

TABLE 2 Indicator specifications for composite index

Indicator	Specification	Justification for inclusion in index	Data sources for indicators
Critical materials list trends	The compound annual growth rate (CAGR) of the number of appearances of material per year across critical materials lists from the earliest year a material appears in a list until 2022.	The trends show which materials are on the rise and which are declining in importance at the global level, and thus provide a partial pointer to the future.	Report's data and calculations; see Table B.3
Demand scenarios	Forecasted demand growth for materials based on multiple sources. Forecasts for 2050 estimated via an exponential trend line based on all available scenarios for all years. Scenarios for 2050 were used because this was the year for which most forecasts were available, and it adds a long-term look into the future to the analysis. However, the horizon of the ranking developed in this report is limited to 2030 because the more long-term the forecast, the more uncertain prospects become.	Renewable energy technologies are projected to require much higher volumes of materials in the future (Roelich *et al.*, 2014), particularly wind and solar power and batteries.	(Calderon *et al.*, 2020 a; Calvo and Valero, 2022; Dominish *et al.*, 2019; Gregoir, 2022; Hund *et al.*, 2020; Karali and Shah, 2022; Sturman *et al.*, 2022)
Diversification	Herfindahl-Hirschman Index (HHI) values for production of materials by country. Based on data on final processed materials.	When the production of a certain material is monopolised and/or oligopolised, leaving no room for alternative suppliers to enter the market in cases of supply disruption, fears can be raised among the importing countries and contribute to criticality (De Ridder, 2013; Sharova *et al.*, 2020; Wilson, 2018).	(Reichl and Schatz, 2022)
Abundance	Abundance of materials in Earth's crust.	"A metal is perceived critical if it is crucial for green energy technologies and if it is scarce by its geological occurrence" (Grandell *et al.*, 2016). Along with geopolitical tensions between supplying countries and importing countries and trade restrictions, geological scarcity of a mineral is a significant factor that increases its criticality (Nate *et al.*, 2021; New Zealand Government, 2019).	Web Elements, 2007)
Recycling	Feasibility of recycling with available technology.	A low recyclability rate is an important factor in defining the criticality of a material (Chadha and Sivamani, 2021; German National Academy of Sciences Leopoldina, 2016; Graedel and Reck, 2018). Low recyclability makes importing countries more dependent on primary producers.	(Li *et al.*, 2022)
Substitution	Ease of substitution, ranges from 0 to 1.	Limited substitutability of a material narrows the options for alternative sources of supply and makes dependency on a material and its supply more acute (Dominish *et al.*, 2019; Poulizac, 2013; Söderman *et al.*, 2013).	(Grohol and Veeh, 2023).

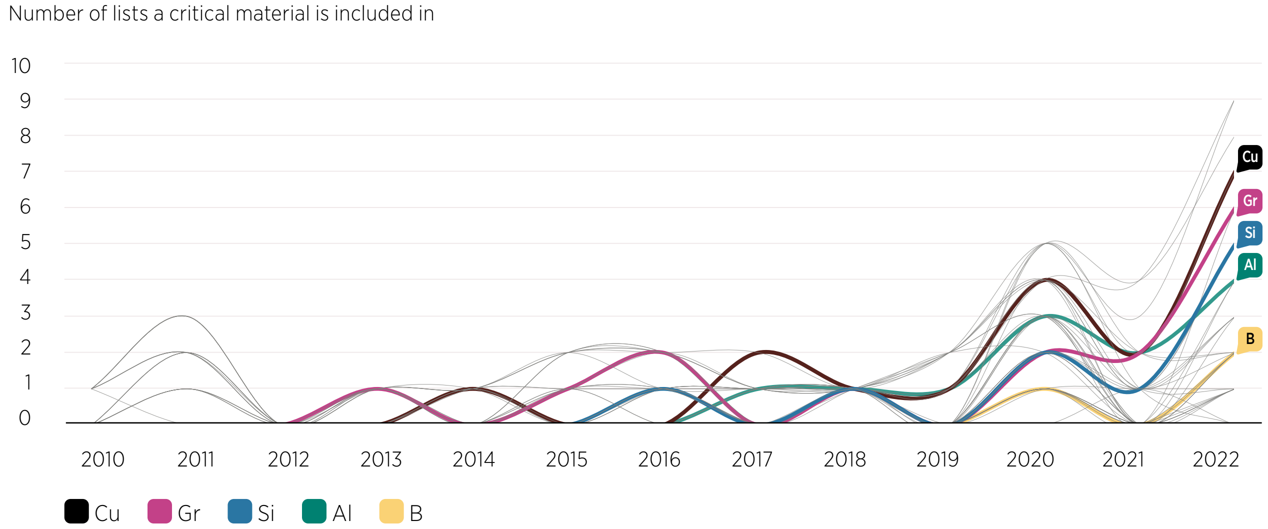
3.1 Trends over time in the identification of critical materials

In attempting to make the selection of critical materials more forward-looking, the first step was to look at the trends within the data underlying the renewable energy meta-list. If a material appeared with increasing frequency over time in the underlying lists, this was interpreted as rising criticality. Conversely, if the appearance of a material declined over time, this was taken as a sign that the criticality of the material is in decline. Not all trends will extend into the future, but many will, and this metric allows us to compensate for the retrospective aspect inherent in the underlying lists.

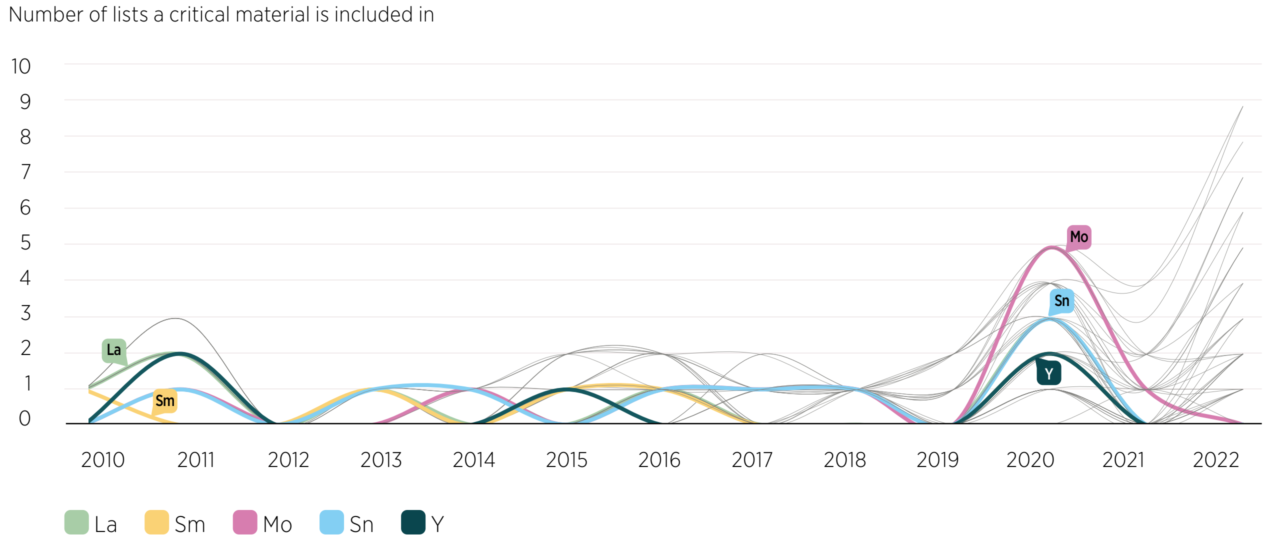
The trend indicator was calculated as the compound annual growth rate (CAGR) in the number of lists that mention a critical material from the first year it is included in a list until 2022. For illustrative purposes, Figure 5 shows five materials whose frequency across the underlying lists rose most, and five materials whose frequency declined most. The five main rising materials were aluminium, boron/borate, silicon, copper and graphite (Panel A). The five main declining materials were lanthanum, molybdenum, samarium, tin and yttrium (Panel B). (The underlying CAGR numbers are provided in Appendix B.)

FIGURE 5 Five materials on the rise and five materials on the decline in terms of criticality

A. The five materials whose frequency of appearance in critical materials lists is increasing most: aluminium, boron/borate, silicon, copper, graphite.



B. The five materials whose frequency of appearance in critical materials lists is decreasing most: lanthanum, molybdenum, samarium, tin, yttrium.

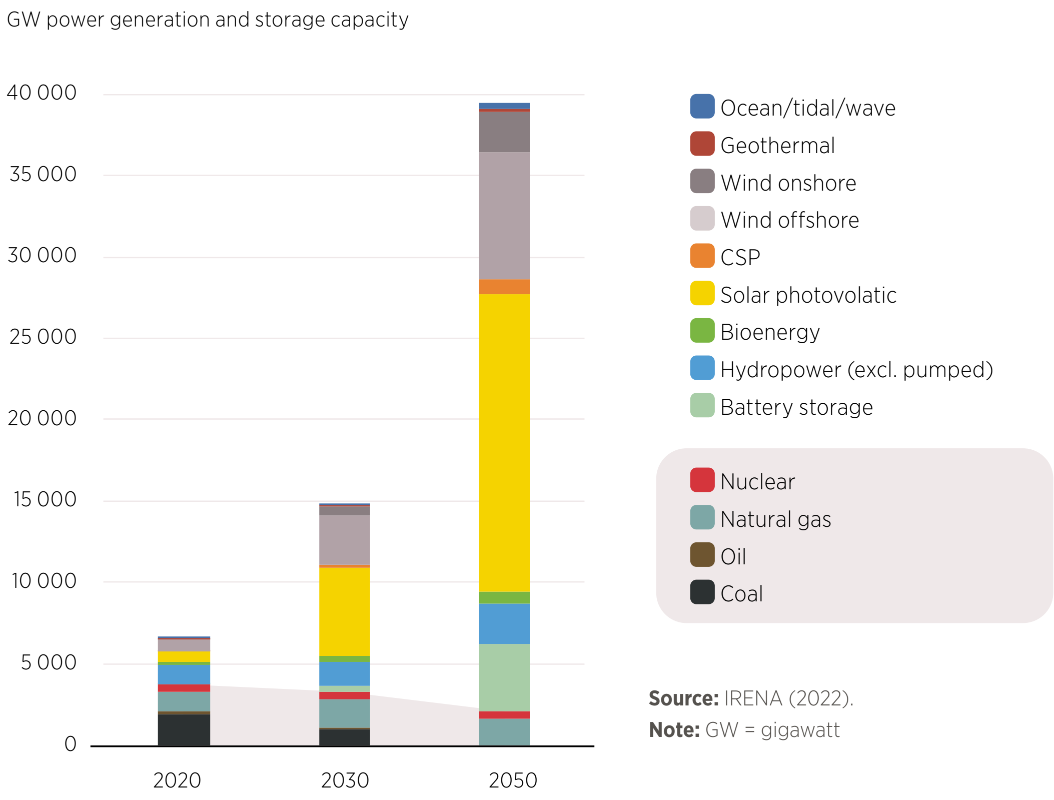


3.2 Demand scenarios for materials

One way of looking at the future demand for materials is to examine the future energy mix. Figure 6 indicates that solar PV power installations will have the largest power generation capacity in 2030 if IRENA's 1.5°C Scenario is achieved (IRENA, 2023). There are several reasons for this, including the dramatic decline in the cost of solar panels. Another reason is that the modularity of solar power makes it highly scalable: it can be used for anything from the smallest unit, such as a watch or a single-family household, to large utilities. Furthermore, population density tends to be highest in parts of the planet with high levels of solar radiation. Finally, deserts have very high levels of solar radiation combined with large amounts of space and low usage for other human activities (Overland and Sabyrbekov, 2022). Far more space is available for solar power in deserts than is needed to address global energy needs (though some deserts are subject to indigenous land rights and have significant cultural heritage value).

Wind power installations (both onshore and offshore) are expected to have the second-largest power generation capacity – slightly more than half as much as solar PV in 2030. This is reflected in Figure 6, which is based on the most recent electricity-mix scenarios (IRENA, 2022). (Note that generation capacity does not equal actual generation, which depends on the capacity factor, which is normally higher for wind than for solar power.)

FIGURE 6 Global installed power generation by energy source and storage capacity in the 1.5°C Scenario



Source: IRENA (2022).
Note: GW = gigawatt

Energy storage, for both stationary and transportation purposes, could become an even more important driver of materials demand than wind and solar power. However, there is considerable technological diversity, scope for innovation and uncertainty about demand for energy storage compared to electricity generation. Some underlying uncertainties are the balance between private electric vehicles (EVs) and public transport/micro-mobility, the evolution of aviation technology, the large number of competing emerging battery chemistries, the balance between hydrogen and batteries within both transportation and grid-level storage, and a possible slower growth of storage over time due to regional grid integration.

However, the level of aggregation of the solar, wind and battery outlooks discussed so far in this section does not enable it to be used as a basis for detailed demand scenarios for critical materials. Therefore, scenarios and forecasts for the future demand for specific critical materials were gathered from multiple sources and combined into composite estimates (see Figure B.1 in Appendix B). These scenarios implicitly or explicitly incorporate assumptions about the future energy mix and technology pathways. Various sources calculate demand scenarios based on different base years; eight sources were used that project annual demand for renewable energy technologies in relation to total production in the base year (Calvo and Valero, 2022; Dominish *et al.*, 2019; Gregoir, 2022; Karali and Shaw, 2022; Calderon, *et al.*, 2020 b; Sturman *et al.*, 2022; Watari *et al.*, 2018). (Also see Table B.1 in Appendix B.)

3.3 Diversification of materials markets

The degree of market concentration is commonly measured using Herfindahl-Hirschman Index (HHI) values. This metric is often used in economics, antitrust and competition analysis to quantify the level of market concentration and the potential impact on competition and market dynamics. It can also be used as an indicator of supply security and vulnerability to disruption (see Figure 7).

The HHI is calculated by summing the squares of the market shares of all firms within a market. In mathematical terms:

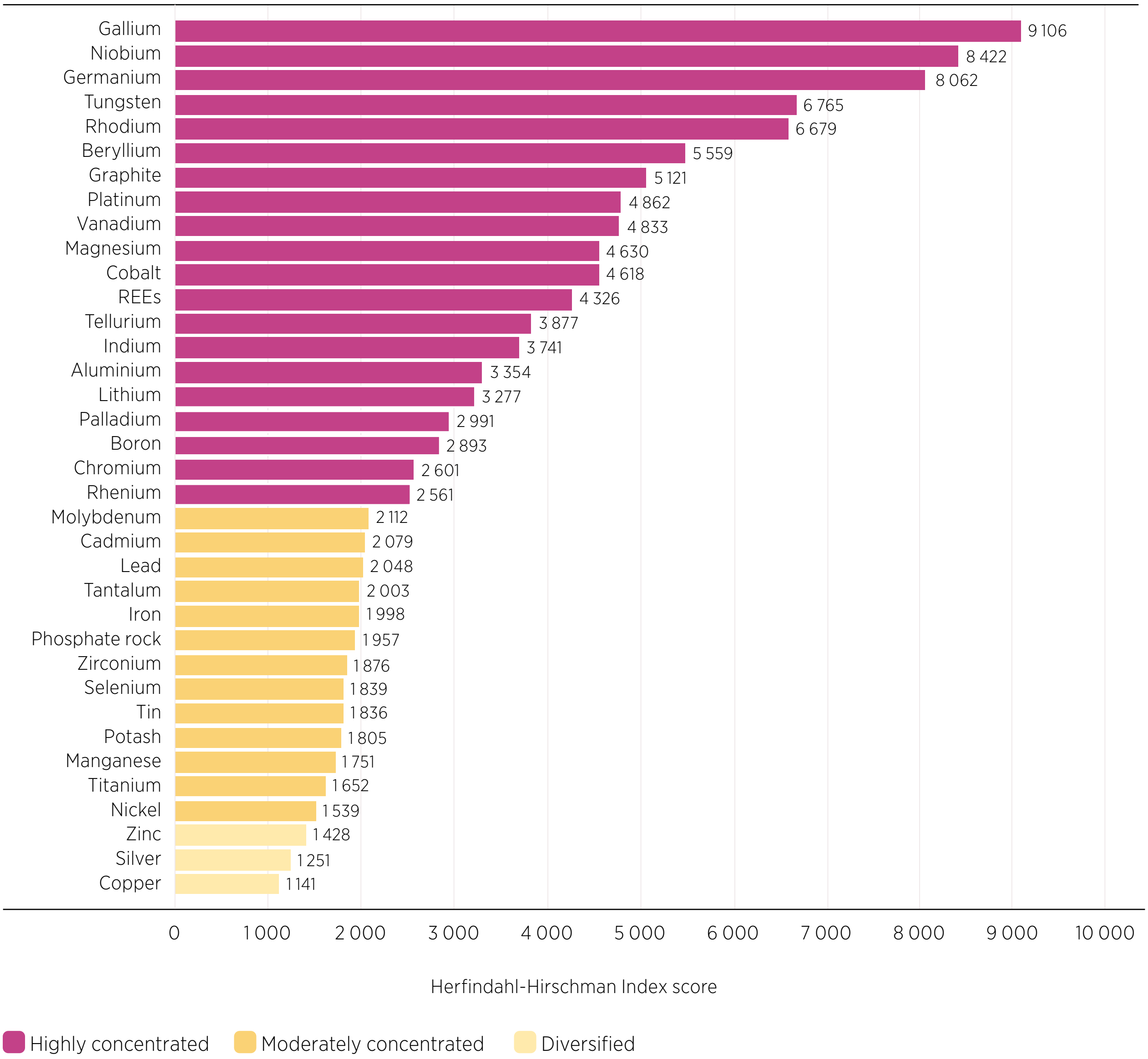
$$\text{HHI} = (\text{Market Share of Firm 1})^2 + (\text{Market Share of Firm 2})^2 + \ldots + (\text{Market Share of Firm N})^2$$

where: “Market Share of Firm 1” represents the percentage of the total market held by the firm and “N” is the number of firms in the market. For the purposes of this report, firms are replaced with countries.

The resulting HHI value can range from 0 to 10 000. The higher the index value, the more concentrated the market, and the greater the vulnerability to supply or price shocks. An index value above 2 500 is considered highly concentrated, 1 500 to 2 500 is moderately concentrated, and below 1 500 is diversified (Department of Justice, 2010).

Gallium is ranked as the most concentrated material because 95% of processed gallium is produced by China. Molybdenum is considered “moderately concentrated” since its production is shared among a number of countries, including China (34%), Chile (21%), the United States (18%), Peru (11%) and Mexico (7%). The production of copper is the least concentrated because it is produced by 56 countries, with the largest producers being Chile (28%) and Peru (10%).

FIGURE 7 HHI scores for global production of critical materials



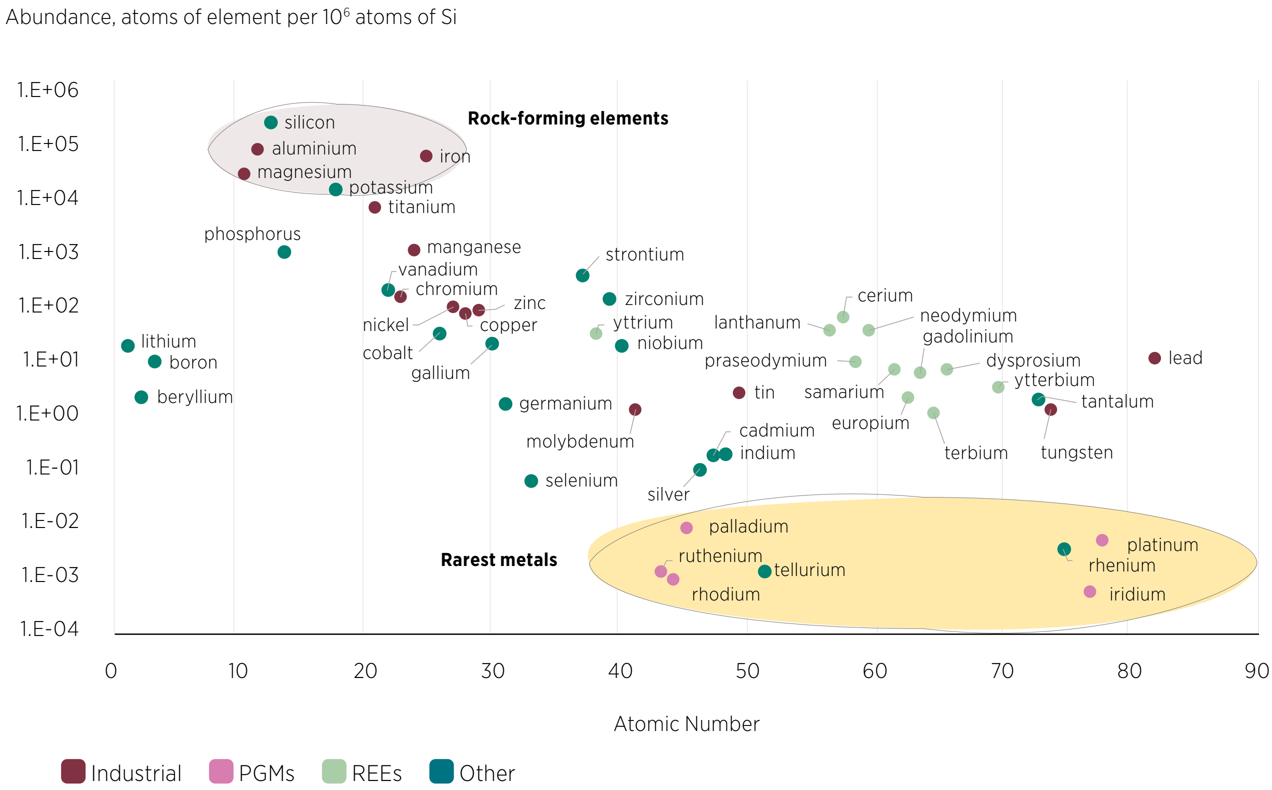
Source: Reich and Schatz (2022).

Notes: The figure includes both ore and concentrate and is based on market shares of producing countries. Higher scores represent less diversified markets on the producer side. Only those materials for which data were available are included in the figure.

3.4 Abundance of minerals in the Earth's crust

An important aspect of critical materials is their physical abundance in the Earth's crust. For example, silicon, aluminium, magnesium, iron and potassium are among the most abundant elements on Earth, whereas platinum, rhenium, iridium, palladium, ruthenium, rhodium and tellurium are among the rarest (see Figure 8). However, the physical abundance of minerals does not necessarily equate to availability and ease of access. For instance, although copper is not all that rare, the average lead time for a new copper mine is about 20 years, which means that it takes a long time to translate geological reserves into market availability and to obtain government permits (see Figure 9).

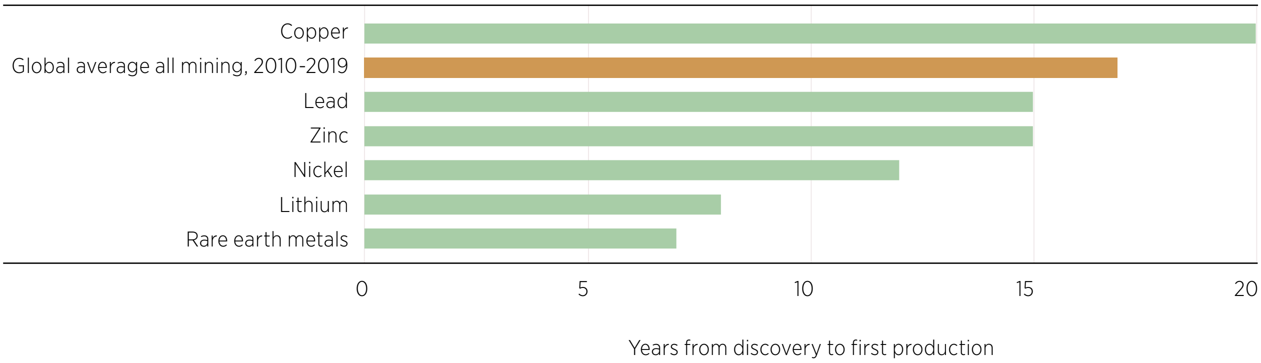
FIGURE 8 Estimated abundance of critical materials in the Earth's crust



Based on: Web Elements (2007).

Notes: PGMs = platinum group metals; REEs = rare earth elements.

FIGURE 9 Average lead times for new mining



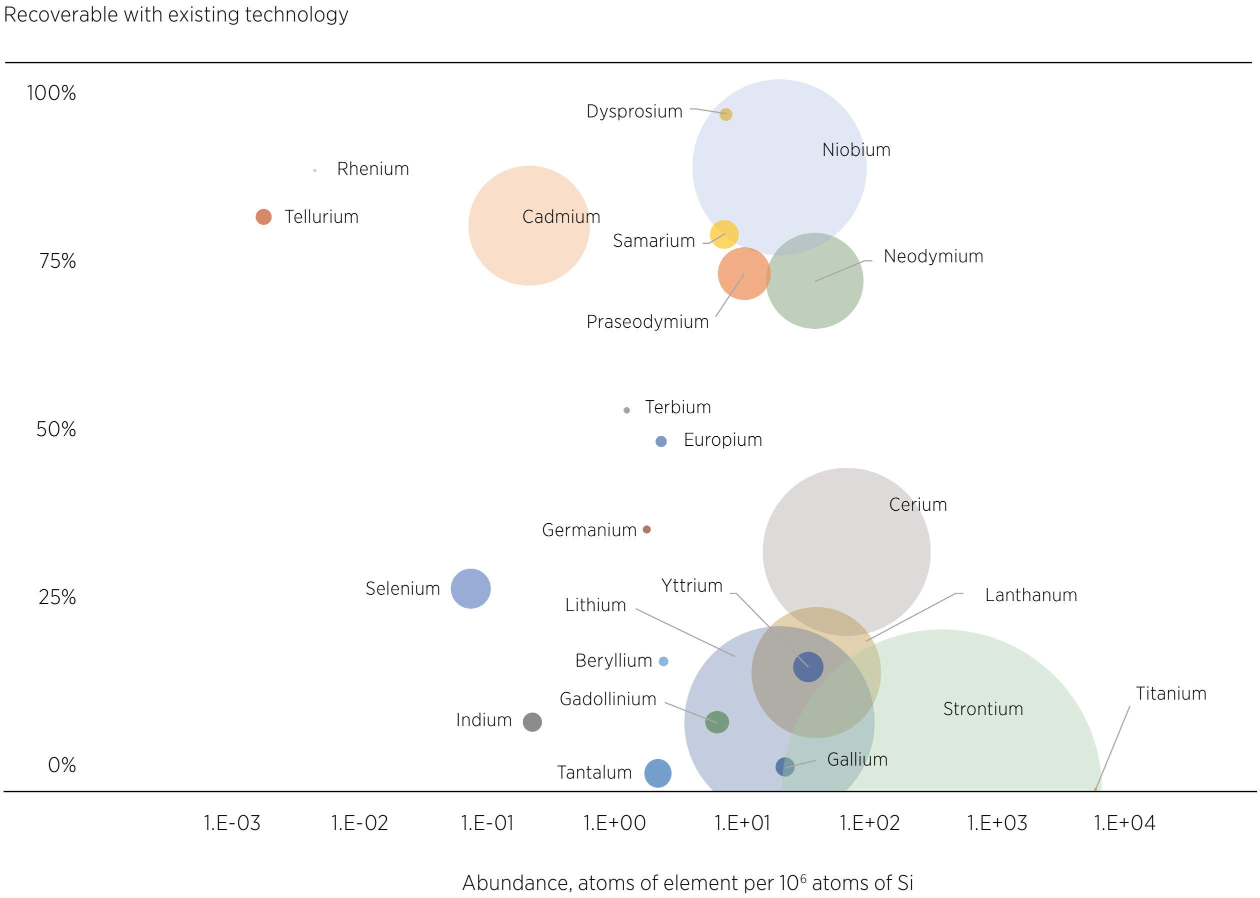
Sources: GlobalX (2016), Heijlen *et al.* (2021), IEA (2022), MiningDigital (2020), Statista (2022) and World Bank (2016).

Notes: The global average includes the average of lead times for 35 minerals mined globally during 2010-2019 and is from the International Energy Agency (2022). Lead time includes: discovery, exploration, feasibility studies, extraction planning and first production.

3.5 Recycling potential

Many critical materials for renewable energy applications have previously been subject to limited demand and have only come into focus because of the vertiginous rise of renewable energy. Consequently, technologies and infrastructure for their recycling are underdeveloped relative to current demand. In anticipating future criticality, a key question is therefore what ratio of a material could be recycled. The greater share of a material that can be recycled, the less critical it is likely to become. Figure 10 shows what ratio of various critical materials can be recycled using existing technologies. Due to rising demand and long product lifetimes, additional mining may still be required to satisfy demand even in cases where high recycling rates are achievable.

FIGURE 10 Recycling of end-use flow in 2018 for selected materials

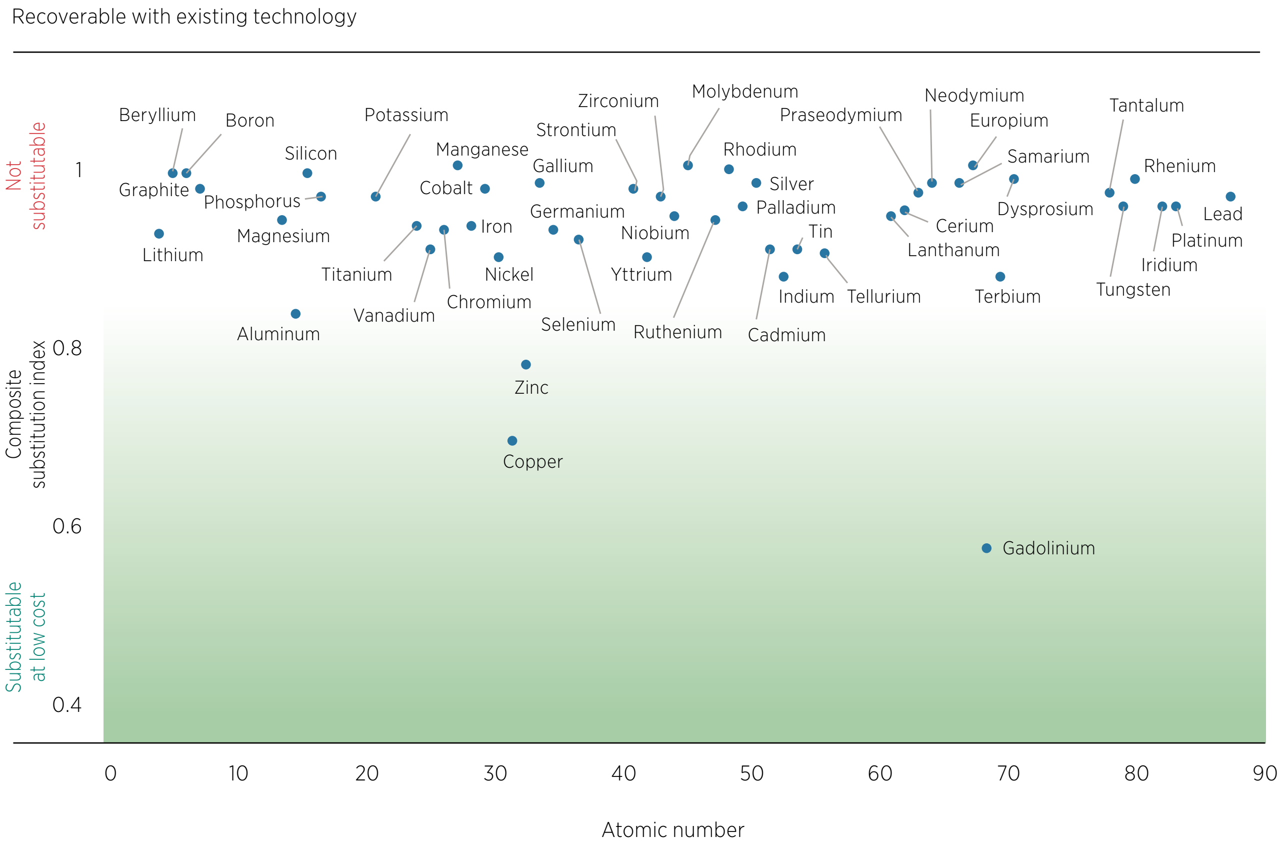


Source: Li *et al.* (2022).
Note: The size of bubbles represents the new volume of each material available on the market in 2018, in tonnes.

3.6 Substitution potential

One of the main aims of innovation in the renewable energy sector is to find ways to substitute materials that are scarce, geographically concentrated, or prone to significant human and environmental impacts with more widely dispersed or abundant materials. Such innovations are frequent, cumulative and can have far-reaching consequences for the criticality of materials. Estimates of the substitutability of materials are included in Table B.3 in Appendix B and visualised in Figure 11. The values are taken from Grohol and Veeh (2023) and are a composite of their economic and supply risk substitution estimates.

FIGURE 11 Substitutability of critical materials



Source: Grohol and Veeh (2023).

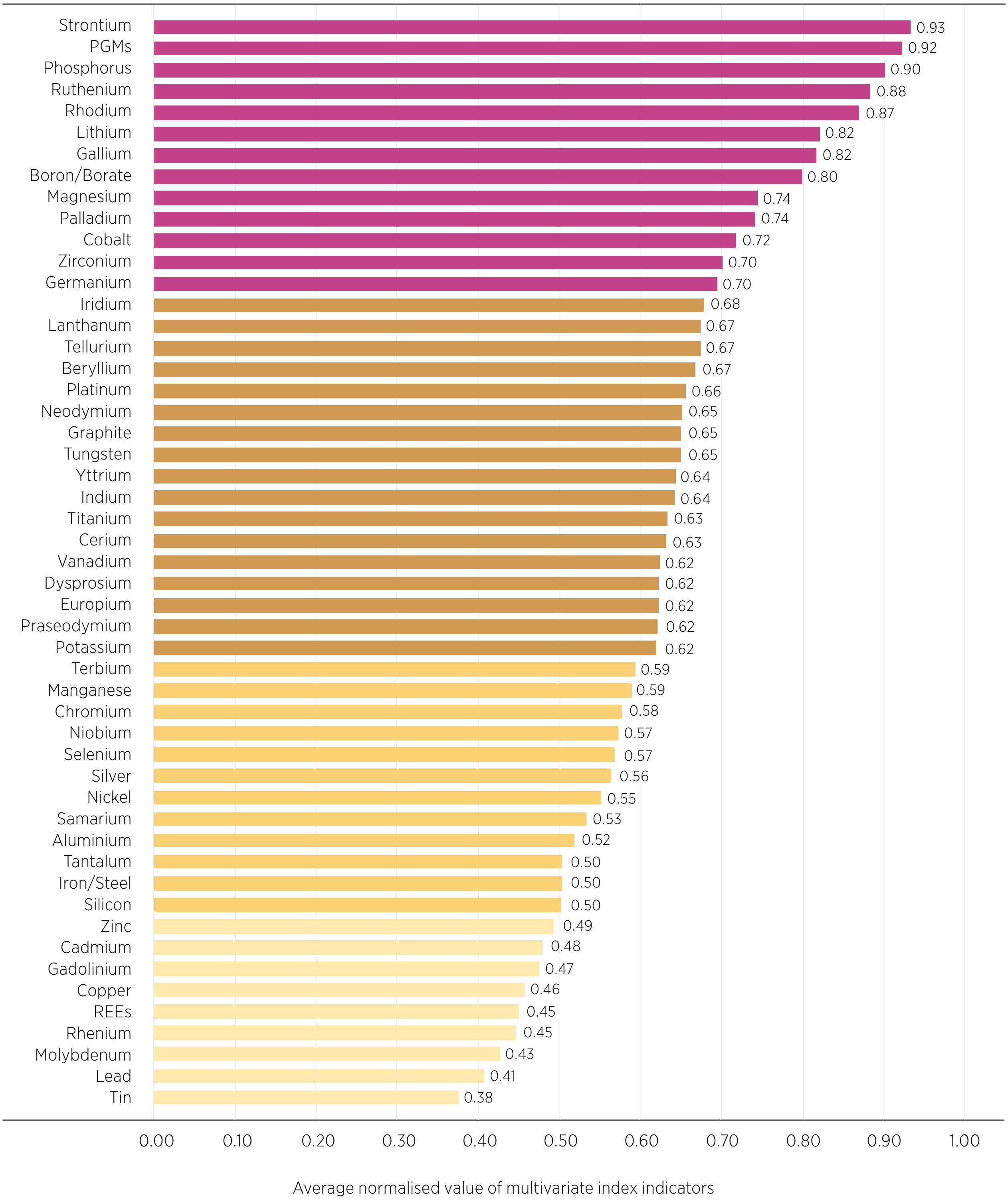
Notes: Substitutability within all usage areas, not only renewable energy. This figure highlights material substitution within a technology, rather than technology substitution, which involves developing new technologies that do not require the same critical materials as existing ones. Substitutability is dynamic and subject to change with innovation.

3.7 Combining the indicators into the composite index

Since there was no *a priori* or theoretical reason to differentiate the weighting of the indicators presented in the subsections above, they were given equal weights, in accordance with established practices for composite index creation (Becker *et al.*, 2017; Overland and Sabyrbekov, 2022). The development of a system or argument for differentiated weighting in the future could be introduced.

All indicators were normalised to a range of 0-1, and the average of all the indicators taken as the composite index value. If an indicator lacked data on a material, that indicator was omitted for that material and the average taken of those indicators which were available.

FIGURE 12 The composite index, the forward-looking element of the global ranking of critical materials



Notes: PGMs = platinum group metals; REEs = rare earth elements.

4. A ranking of critical materials

This section presents a global ranking of critical materials based on, and exemplifying the application of, the report's methodology. The ranking of critical materials was created by combining the renewable energy meta-list and the composite index. These were brought together with equal weights to form scores ranging from 0 to 1, with a score of 1 representing the highest level of criticality. The materials were divided into three groups: most critical (≥0.50), moderately critical (0.4-0.50) and least critical (0-0.39). The results of the ranking are presented in Table 3.

TABLE 3 Global ranking of critical materials for renewable energy

MOST CRITICAL		MODERATELY CRITICAL		LEAST CRITICAL	
Lithium	**0.81**	Silver	**0.49**	Molybdenum	**0.39**
Cobalt	**0.81**	Strontium	**0.48**	Magnesium	**0.39**
Gallium	**0.73**	Platinum	**0.47**	Yttrium	**0.39**
REEs*	**0.72**	Phosphorus	**0.47**	Cadmium	**0.38**
Neodymium	**0.68**	Chromium	**0.47**	Terbium	**0.38**
Indium	**0.68**	Rhodium	**0.45**	Zinc	**0.36**
PGMs*	**0.67**	Lanthanum	**0.45**	Iridium	**0.36**
Dysprosium	**0.65**	Ruthenium	**0.44**	Zirconium	**0.35**
Nickel	**0.63**	Aluminium	**0.44**	Samarium	**0.35**
Tellurium	**0.61**	Boron/borate	**0.43**	Tungsten	**0.34**
Praseodymium	**0.57**	Selenium	**0.43**	Beryllium	**0.33**
Graphite	**0.57**	Palladium	**0.42**	Tin	**0.32**
Manganese	**0.54**	Cerium	**0.41**	Iron/Steel	**0.32**
Copper	**0.52**	Vanadium	**0.41**	Europium	**0.31**
Germanium	**0.51**	Titanium	**0.40**	Potassium	**0.31**
		Silicon	**0.40**	Niobium	**0.29**
				Tantalum	**0.27**
				Gadolinium	**0.24**
				Lead	**0.24**
				Rhenium	**0.22**

Notes: Rankings are based on their criticality scores, with the theoretical range of criticality score 0-1.
* The mineral groups REEs and PGMs and the individual minerals that are part of those groups are treated separately. This is because of the scoring system for the renewable energy meta-list, which is designed to accommodate the fact that some critical materials lists include only the group names, while others refer to individual minerals that belong to the groups. This also explains why the scores between the groups and their individual minerals diverge.
PGMs = platinum group metals; REEs = rare earth elements.

The "most critical" group includes most of the materials that are familiar from discussions of critical materials in the academic and grey literature and the media. Lithium and cobalt stand out as the most critical of all, followed by large gaps of 0.08 and 0.09 points down to gallium and the REEs, respectively. A key question moving forward is whether cobalt could move down the ranking as lithium iron-phosphate (LFP), solid state lithium batteries and SIB – none of which contain cobalt – capture greater shares of EV markets. The same question applies to nickel, which is also not required for most LFP and SIB batteries. This also illustrates some of the difficulties with estimating material criticality for rapidly evolving technologies and that it could be misleading to focus too much on what is used for some of today's technologies rather than current and near-term substitutes.

Another important question is whether graphite should be even higher on the ranking, being a critical material that is utilised in the anode of lithium-ion batteries of EVs today that lacks diverse supply. China dominated the market with 79% of global graphite production in 2021 (NRCan and ISED, 2022). However, growing graphite mining in Canada and Mozambique, the development of advanced recycling technologies, and competition between natural and synthetic graphite (which have different strengths and weaknesses) can contribute to supply diversification and increased availability of graphite, which in turn can determine its criticality.

The group of materials classified as "moderately critical" mostly contains materials that are less frequently mentioned in the literature and are of less acute importance or scarcity. However, they are still worth watching since some may rise in importance. For example, should vanadium-flow batteries be widely adopted for grid-level electricity storage, demand for vanadium could rise dramatically. Platinum demand is linked to hydrogen production through polymer electrolyte membrane (PEM) electrolysis; its criticality may therefore increase significantly under assumptions of higher hydrogen deployment (the same applies to iridium in the "moderately critical" group).

In the "least critical" group, many materials have similar index values. Materials such as iron/steel, lead, tin and zinc are widely used for purposes other than renewable energy and therefore have large and diverse resource bases and markets that can help cushion supply issues.

5. Conclusions and recommendations

The aim of this report was to develop a methodology for a global ranking of critical materials for renewable energy technologies. An example demonstrating the application of this methodology was presented in the previous section. This section presents additional findings, implications and recommendations.

- The high probability of geopolitical, regulatory and above all technological changes and their impact on the various stages of mineral supply chains (illustrated in Figure 4) may alter the supply and demand for materials in a variety of ways that it is hard to predict the exact set of materials that will be considered critical ten years into the future. Many of those identified as critical today may also be critical in the future, but it is hard to say exactly which ones those will be.

- This means that the mining and mineral-processing industries face fundamental uncertainties about future demand for critical materials and dilemmas with regard to investment. These uncertainties could reduce or delay investment, in turn destabilising supply. On the one hand, clearly, large volumes of metals and minerals will be needed for the energy transition, and large investments are urgently needed to avoid severe bottlenecks. On the other hand, due to the many factors and uncertainties involved, such investments will carry significant risks.

- This report has shown that definitions of critical materials and assessments of their criticality vary among countries and change over time.

- It is risky and can be misleading to rely on national lists of critical materials for identifying which materials are critical for renewable energy, because most materials included in national lists are linked to fossil fuels or other sectors that are not relevant to renewable energy technologies.

- Malthusian scarcity perspectives may not always be helpful for understanding critical materials supply chains and markets. Some important materials will be scarce at some points in time and some actors may derive advantages or disadvantages from such scarcity – but it is less likely to dominate the energy transition to the extent that some actors expect. Focusing too narrowly on perceived geological scarcity carries a risk of overlooking other constraints and opportunities.

Taking into account these findings, policy makers and market actors could consider the following policy recommendations.

First, **definitions of material criticality and critical materials should be approached in a relativistic manner and their diversity and positionality recognised**. Any list of critical materials produced by a state or an organisation will be influenced by the outlook of that state or organisation and the specific circumstances at the time the list was produced.

Second, considering the frequent changes in critical materials classifications around the world, **the ranking of critical materials and the weighting should be updated every two to three years** to reflect changing technologies and policies affecting supply and demand.

Third, the role of evolving technologies as a driver of changes in material criticality means that one of the main possible enhancements of the ranking and an area for further research would be to **further develop its forward-looking aspect by including technology forecasts or scenarios**. However, such forecasts are notoriously difficult to get right. Such work therefore requires serious consideration.

Fourth, **governments should be aware of the uncertainties faced by market actors**. If governments want reliable supplies of critical materials, they may need to implement measures to reduce risks for investors. However, governments should also avoid going too far in securing supplies or the production of specific materials, as governments face the same uncertainties themselves. How to optimally calibrate such measures is another important area for future research and policy development.

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Appendices

Appendix A. Additional materials for renewable energy meta-list

Table A.1 Sources used for renewable energy meta-list

Reference	Year	Title	Publication type	Minerals covered
(Nate *et al.*, 2021)	2021	*Mineral policy within the framework of limited critical resources and a green energy transition*	Academic article	17
(Karali *et al.*, 2022)	2022	*Bolstering supplies of critical raw materials for low-carbon technologies through circular economy strategies*	Academic article	15
(Wang, *et al.*, 2020)	2020	*The availability of critical materials for China's renewable energy development: An analysis of physical supply*	Academic article	25
(Wang *et al.*, 2019)	2019	*Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition*	Academic article	8
(Wang, *et al.*, 2020)	2020	*Metal-energy nexus in the global energy transition calls for cooperative actions*	Academic article	34
United States Department of Energy (DoE, 2010)	2011	*Critical materials strategy*	Report	18
(Leader, 2020)	2020	*Critical material supply risks and mitigation strategies in clean energy technologies*	PhD Dissertation	29
European Commission (EC, 2015)	2015	*Materials for energy*	Report	14
World Wide Fund for Nature (WWF, 2014)	2014	*Critical materials for the transition to a 100% sustainable energy future*	Report	27
(Sturman *et al.*, 2022)	2022	*Mission critical: Strengthening governance of mineral value chains for the energy transition*	Report	14
International Renewable Energy Agency (IRENA, 2022)	2022	*World energy transitions outlook 2022: 1.5°C Pathway*	Report	6
International Energy Agency (IEA, 2022)	2022	*The role of critical minerals in clean energy transitions*	Report	13
(Fromer *et al.*, 2011)	2011	*Critical materials for sustainable energy applications*	Report	19
(Vranken, n.d.)	2020	*Critical raw materials in Li-ion batteries*	Report	4
(Clean Energy Canada, 2017)	2017	*Mining for clean energy: How the global rise of solar power will drive demand for Canadian metals and minerals*	Report	19
(Patrahau *et al.*, 2020)	2020	*Securing critical materials for critical sectors: Policy options for the Netherlands and the European Union (Tables 2–7)*	Report	18
(Miller *et al.*, 2023)	2023	*The stumbling block in 'the race of our lives': Transition-critical materials, financial risks and the NGFS climate scenarios*	Working Paper	9
(Simandl *et al.*, 2015)	2015	*Which materials are 'critical' and 'strategic'*	Survey Paper	16

Reference	Year	Title	Publication type	Minerals covered
(Azevedo *et al.*, 2022)	2022	*The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition*	Report	21
(Moss, 2013)	2013	*Critical metals in the path towards the decarbonization of the EU energy sector: Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies*	Report	32
(Rietveld *et al.*, 2022	2022	*Strengthening the security of supply of products containing critical raw materials for the green transition and decarbonization*	Report	33
United States Department of Energy (DoE, 2010)	2010	*Critical materials strategy*	Report	14
(Chadha *et al.*, 202	2021	*Critical minerals for India: Assessing their criticality and projecting their needs for green technologies*	Working Paper	10
(Bermack *et al.*, 2022)	2022	*Mine 2022: A critical transition*	Report	15
(Dominish *et al.*, 2019)	2019	*Responsible minerals sourcing for renewable energy*	Report	14
(Growth Analysis, 2017)	2017	*Innovation-critical metals from extraction to final product: How can the state support their development?*	Report	33
(Gielen, 2021)	2021	*Critical materials for the energy transition*	Report	6
(OECD, 2022)	2022	*Security of supply for critical raw materials: Vulnerabilities and areas for G7 coordination*	Report	17
(Moss *et al.*, 2011)	2011	*Critical metals in strategic energy technologies: Assessing rare metals as supply chain bottlenecks in low carbon energy technologies*	Report	14
(Church and Crawford, 2018)	2018	*Green conflict minerals: The fuels of conflict in the transition to a low-carbon economy*	Report	24
(Hund *et al.*, 2020)	2020	*Minerals for climate action: The mineral intensity of the clean energy transition*	Report	17
Gregoir	2022	*Metals for clean energy: Pathways to solving Europe's raw materials challenge*	Report	29
World Bank Group and EGPS	2017	*The growing role of minerals and metals for a low carbon future*	Report	16
European Academies Science Advisory Council and Deutsche Akademie der Naturforscher Leopoldina	2016	*Priorities for critical materials for a circular economy*	Report	24
Vahle *et al.*	2022	*Critical raw materials for the energy transition in the EU: How circular economy approaches can increase supply security for critical raw materials*	Report	8

Appendix B. Additional materials for composite index

Table B.1 Demand growth projections for 2050

Mineral	Demand growth projections for 2050, %
Aluminium	14
Beryllium	N/A
Boron/borate	N/A
Cadmium	20
Cerium	N/A
Chromium	1.5
Cobalt	584
Copper	33
Dysprosium	533
Europium	N/A
Gadolinium	N/A
Gallium	250
Germanium	24
Graphite	438
Indium	175
Iridium	63
Iron/Steel*	9
Lanthanum	N/A
Lead	20
Lithium	2120
Magnesium	N/A
Manganese	12.5
Molybdenum	15
Neodymium	327
Nickel	150
Niobium	N/A

Mineral	Demand growth projections for 2050, %
Palladium	N/A
PGMs	N/A
Phosphorus	N/A
Platinum	64
Potassium	N/A
Praseodymium	110
REEs**	15.5
Rhenium	N/A
Rhodium	N/A
Ruthenium	N/A
Samarium	N/A
Selenium	150
Silicon	62
Silver	65
Strontium	N/A
Tantalum**	13
Tellurium	2000
Terbium	62
Tin	26
Titanium	0
Tungsten	N/A
Vanadium	181
Yttrium	N/A
Zinc	7
Zirconium	N/A

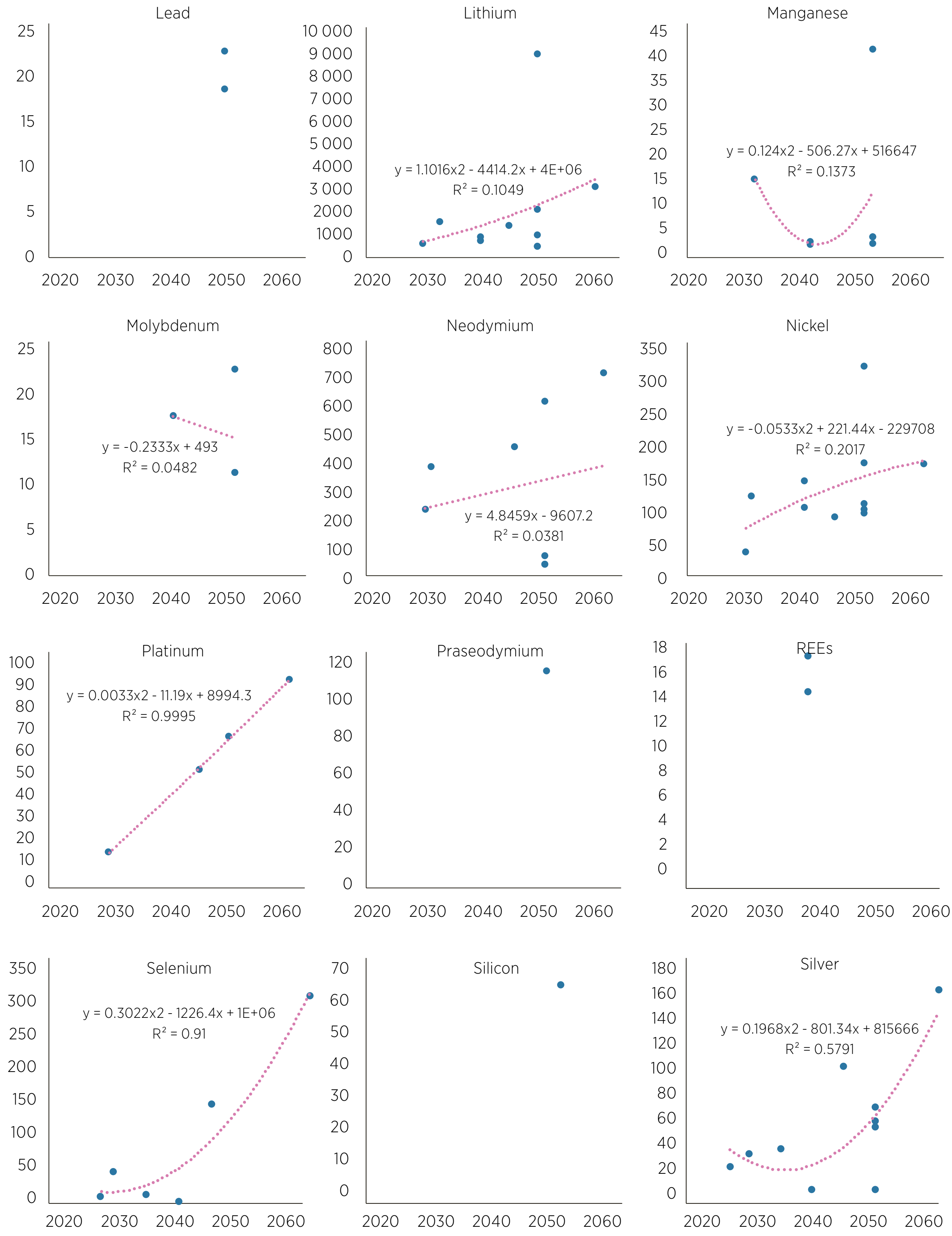
*As iron and steel were merged, their demand forecast for 2050 was taken as an average of both.
**The forecast is given for 2040 but here it is taken as a reference value for 2050.

Figure B.1 Demand growth projections (blue dots) as a share of base year production

Sources: Calvo and Valero (2022), Dominish *et al.* (2019), Gregoir (2022), Hund *et al.* (2020), Karali *et al.* (2022), Calderon *et al.* (2020 b), Sturman *et al.* (2022) and Watari *et al.* (2018).

Note: The y-axes are %. Fitted lines (dotted red) represent compromises between different projections, not trend lines, and are based on highest R^2.

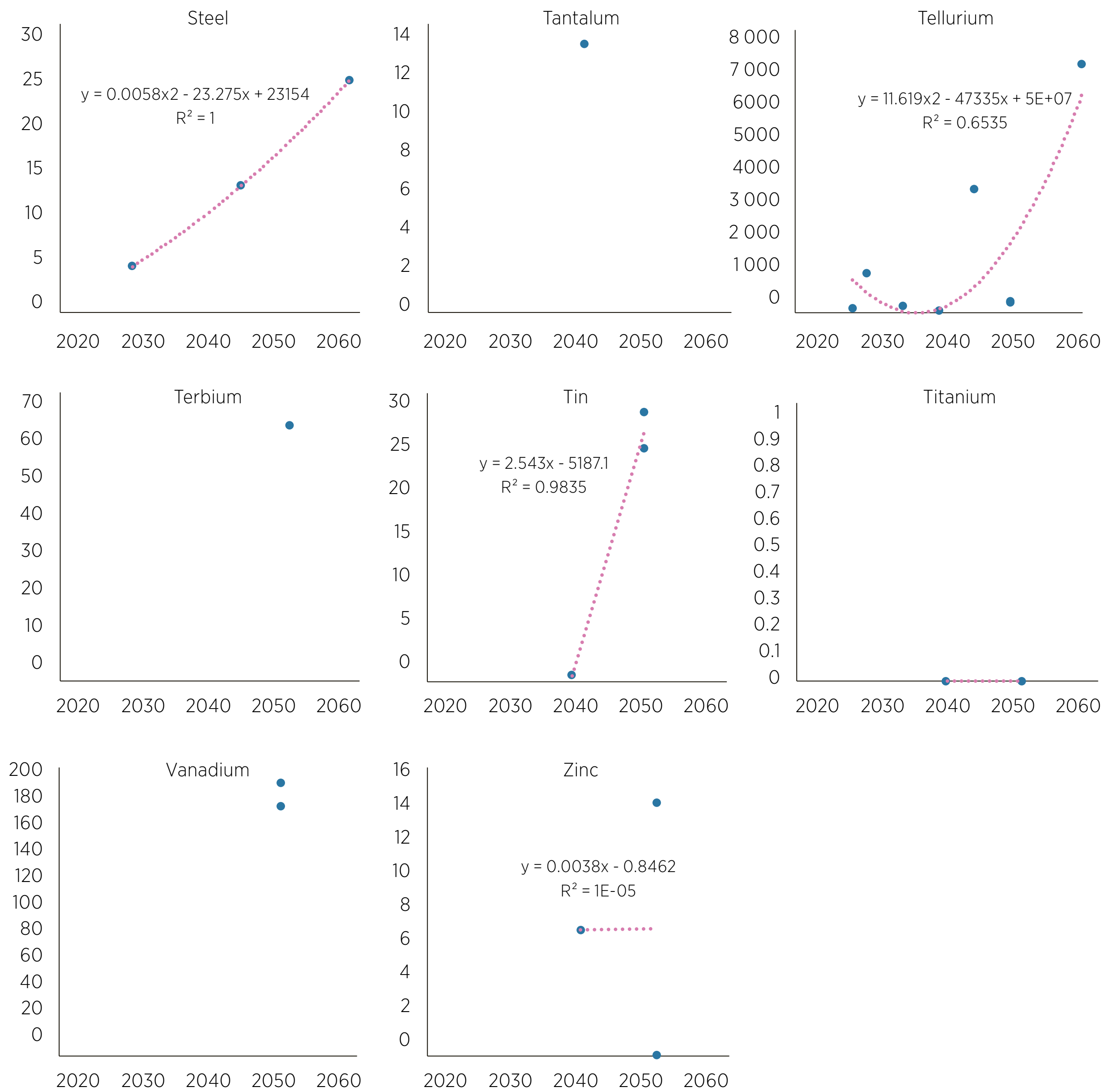
Figure B.1 Demand growth projections (blue dots) as a share of base year production (continued)



Sources: Calvo and Valero (2022), Dominish *et al.* (2019), Gregoir (2022), Hund *et al.* (2020), Karali *et al.* (2022), Calderon *et al.* (2020 b), Sturman *et al.* (2022) and Watari *et al.* (2018).

Note: The y-axes are %. Fitted lines (dotted red) represent compromises between different projections, not trend lines, and are based on highest R^2.

Figure B.1 Demand growth projections (blue dots) as a share of base year production (continued)



Sources: Calvo and Valero (2022), Dominish *et al.* (2019), Gregoir (2022), Hund *et al.* (2020), Karali *et al.* (2022), Calderon *et al.* (2020 b), Sturman *et al.* (2022) and Watari *et al.* (2018).

Note: The y-axes are %. Fitted lines (dotted red) represent compromises between different projections, not trend lines, and are based on highest R^2.

Table B.2 CAGR of critical materials mentioned in critical materials lists analysed for this paper

Mineral	CAGR, %
Aluminium	26
Beryllium	-100
Boron/Borate	26
Cadmium	0
Cerium	-100
Chromium	10
Cobalt	17
Copper	24
Dysprosium	13
Europium	-100
Gadolinium	-100
Gallium	9
Germanium	6
Graphite	20
Indium	5
Iridium	0
Iron/Steel	0
Lanthanum	-100
Lead	-100
Lithium	18
Magnesium	0
Manganese	10
Molybdenum	-100
Neodymium	13
Nickel	11
Niobium	-100

Mineral	CAGR, %
Palladium	6
PGMs	16
Phosphorus	0
Platinum	12
Potassium	-100
Praseodymium	11
REEs	18
Rhenium	-100
Rhodium	0
Ruthenium	0
Samarium	-100
Selenium	-6
Silicon	26
Silver	3
Strontium	0
Tantalum	-100
Tellurium	5
Terbium	0
Tin	-100
Titanium	15
Tungsten	-100
Vanadium	0
Yttrium	-100
Zinc	20
Zirconium	0

Table B.3 Substitutability of critical materials

Mineral	Substitution index
Manganese	1.00
Molybdenum	1.00
Europium	1.00
Rhodium	1.00
Silicon	0.99
Beryllium	0.99
Boron	0.99
Dysprosium	0.99
Rhenium	0.99
Neodymium	0.98
Gallium	0.98
Silver	0.98
Samarium	0.98
Cobalt	0.98
Graphite	0.98
Strontium	0.98
Praseodymium	0.97
Tantalum	0.97
Lead	0.97
Phosphorus	0.97
Zirconium	0.97
Potassium	0.97
Palladium	0.96
Platinum	0.96
Tungsten	0.96
Iridium	0.96
Cerium	0.95

Mineral	Substitution index
Lanthanum	0.95
Niobium	0.95
Magnesium	0.94
Ruthenium	0.94
Titanium	0.94
Iron	0.94
Chromium	0.93
Germanium	0.93
Lithium	0.93
Selenium	0.92
Cadmium	0.91
Tin	0.91
Vanadium	0.91
Tellurium	0.91
Nickel	0.90
Yttrium	0.90
Indium	0.88
Terbium	0.88
Aluminium	0.84
Zinc	0.79
Copper	0.71
Gadolinium	0.59
REEs	N/A
PGMs	N/A
Borate	N/A
Steel	N/A

Source: Grohol and Veeh (2023).

Notes: 0.0: Easily and completely substitutable at no additional cost; 0.3: Substitutable at low cost; 0.7: Substitutable at high cost and/or loss of performance; 1.0: Not substitutable. Index values are averages of economic and risk substitution scores.

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