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Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity

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ABSTRACT

The demand for raw materials, in particular, for those classified as critical materials, has increased considerably due to the ongoing energy transition and the corresponding surge in the use of renewable energy technologies. In this context, this review paper analyses literature on reserves, resources, and production data of critical materials, which are required for the energy transition, to understand the connection between the present criticality definition and long-term sustainability. The link to long-term sustainability was studied by applying bell curve production projections. The analysis shows that the present criticality concept and classification is predominantly a reflection of a short-term local political construct, which may be consumption- or production-driven, or a mixture of both, depending on the classifying country. Based on material databases and the corresponding logistic production bell curves, severe limitations of primary supply could emerge from materials, such as antimony, cadmium, chromium, cobalt, copper, indium, molybdenum, nickel, silver, and zinc within two decades. Furthermore, all studied materials are projected eventually to be severely critical. Thus, local efforts will likely have a limited capability to effectively address the long-term risk associated with the production and use of critical materials. Moreover, without concerted global effort, the present criticality concept may not be effective in addressing even the short-term supply bottleneck, particularly for the accelerating energy transition, that it aspires to address. Hence, applying the criticality concept at the global level carries special potential to mitigate the supply risk by mobilising all stakeholders based on a well-informed understanding of materials flows.

1. Introduction

The growing awareness of the global climate crisis (IPCC, 2021) has increased interest in finding ways of mitigating its impact (UNFCCC, 2016). The ongoing energy system transition to achieve net zero or negative greenhouse gas emissions is broadly recognised as a necessary step to avoid irreversible planetary scale aftereffects (Bogdanov et al., 2019; Breyer et al., 2022; Hansen et al., 2019; Jacobson et al., 2019; Luderer et al., 2021; Pursiheimo et al., 2019). The rapid capacity growth of renewable energy (RE) technologies, which are required for the energy transition, such as solar photovoltaic (PV) modules (Bogdanov et al., 2021; IRENA, 2019a; Sens et al., 2022; Victoria et al., 2021), wind turbines (IRENA, 2019b; Sens et al., 2022), and battery electric vehicles (BEV) (Greim et al., 2020) raises questions on whether the available volumes of new primary (fresh raw) materials are sufficient to build the whole new energy system (Valero et al., 2018a). Even though there is no consensus on future capacities of solar PV, wind power, and BEV (Sens et al., 2022), several studies show a strongly increasing trend of installations for all of these technologies. Solar PV and wind power capacities grow several folds from the current (as of 2020) 760 GW and 743 GW (REN21, 2021), respectively, to approximately 14 TW and 8 TW by 2050 according to the net zero emission scenario requirement of studies by International Energy Agency (IEA) (2021a) and International Renewable Energy Agency (IRENA) (2021, 2019b, 2019a). Other studies analyse various capacity projections and report a substantially sharper capacity increase by 2050 to a median-maximum values range of 20.5–70 TW and 8–18.2 TW for Solar PV and wind power technologies, respectively (Sens et al., 2022). In turn, the fleet of electric vehicles is projected to grow from 10 million cars in 2020 (IEA, 2021b) to more than 300 million cars by 2030 according to different estimates (Greim et al., 2020; IEA, 2021c; Walton et al., 2020) with the potential to grow to more than two billion around 2050 (Greim et al., 2020; Khalili et al., 2019). Such a rapid capacity growth is projected to result in a surge of raw materials demand and may even lead to potential shortages of materials in the decades to come (EC, 2020a; Giurco et al., 2019; Junne et al., 2020; Watari et al., 2019).

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Nomenclature

AEL	alkaline electrolysers
a-Si	amorphous silicon
BEV	battery electric vehicles
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CSP	concentrating solar thermal power
c-Si	crystalline silicon
EOL-RIR	end-of-life recycling input rate
EV	electric vehicles
GaAs	gallium arsenide
LED	light-emitting diode
PEM	polymer electrolyte membrane
PGE	platinum group elements
PHEV	plug-in hybrid electric vehicles
PMSMs	permanent magnet synchronous motors
PV	photovoltaics
RE	renewable energy
REE	rare earth elements
SOEL	solid oxide electrolysis
URR	ultimately recoverable resources
BGS	British Geological Survey
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
USGS	United States Geological Survey
WBG	World Bank Group
t	ton (metric)
kt	kiloton (metric)
Mt	Megaton (metric)

The expected increase of material demand has attracted the attention of various studies over the past decade. The studies come in various forms, i.e., those evaluating (i) material demand related to an increase of installations in some specific technology (Cristóbal et al., 2020; EC, 2020a; Elshkaki, 2020; Greim et al., 2020; ICMLR, 2016; Jones et al., 2020; Kim et al., 2015; Lennon et al., 2022; Wilburn, 2011), (ii) material demand for energy transition scenarios (Arent et al., 2014; Calvo and Valero, 2021; Elshkaki and Shen, 2019; Giurco et al., 2019; Grandell et al., 2016; Hund et al., 2020; IEA, 2021d; Junne et al., 2020; Månberger and Stenqvist, 2018; Turner et al., 2013; Valero et al., 2018a; WBG, 2017), and (iii) those dealing with the requirement for the green and digital "twin" transitions (EC, 2020b, 2020c). In most of these studies, material requirements for the energy transition and related energy technologies take the centre stage on a regional scale (Arent et al., 2014; EC, 2020b; Kim et al., 2015; Turner et al., 2013; Wilburn, 2011). The remaining studies then deal with the requirement on a global level (Grandell et al., 2016; Hund et al., 2020; IEA, 2021d; Junne et al., 2020; Månberger and Stenqvist, 2018; Valero et al., 2018b, 2018a; Watari et al., 2019; WBG, 2017;). In general, these studies show that the demand for materials increases over the coming years due to the enormous capacity ramping of technologies for the energy transition.

A study by European Commission (2020a) that analysed the material demand for wind power and solar PV from now (2018) up to 2050 found that the material demand increases considerably as the capacity of these technologies grows for both Europe and the world. The growth in material demand for both technologies could lead to raw material demand stress during the energy transition. The European transition to green energy technologies as stipulated by the European Green Deal could be endangered by supply security of several related materials such as gallium, germanium, indium, selenium, silicon, tellurium and rare earth elements (REE) (EC, 2020a). It is crucial to mention that this study anticipates only about 12.5 TW of PV capacity by 2050, less than expected by the IEA and IRENA net zero scenarios. Goldschmidt et al. (2021) examined material demand for a higher PV capacity growth, specifically in a range of 20–70 TW by 2050, which is in line with various studies (Bogdanov et al., 2021, 2019; Haegel et al., 2023). The authors concluded that in order to be resource efficient and to avoid potential supply shortages, upholding the present high rate of technological innovation will be as necessary as investing in PV manufacturing capacity. Lithium demand and supply was also studied in connection with the anticipated fast demand growth for battery applications, and mandatory establishment of efficient recycling was reported to overcome the projected short-term supply shortage as well as to ameliorate the long-term sustainability risks to the global energy transition up to the end of this century (Greim et al., 2020). In short, the rate of increase in demand for a given material is dependent on various factors, such as, an assumed transition pathway and technology-specific material demand. Nevertheless, in all cases, the discussion on the group of materials that are classified as "critical" receives emphasis as a potential source of risk in the coming decades.

Several materials, which are relevant for the energy transition, are generally classified as critical (EC, 2020b; Hund et al., 2020; IEA, 2021d; Junne et al., 2020; WBG, 2017). In this study the term "material" includes geological minerals or compounds as well as various other organic and inorganic, metal and non-metal elements, minerals, rocks, and materials. The criteria for classifying a material as critical is, however, dependent on the focus of the evaluating body and does not necessarily assume materials, which are relevant for sustainable technologies and the energy transition. In general, a group of such factors as resource availability, possible supply risks and import reliance, economic importance, substitution possibility, environmental implication, and others (EC, 2020d; USGS, 2018) contribute to this classification. The concept of criticality is rather complex and lacks a unified methodology (IRENA, 2023). There is neither a general and globally accepted list of critical materials nor a complete data on the production, reserves, and resources of such materials. For example, both, the United States (FREO, 2020; USGS, 2018), and the European Union (EC, 2020d) define critical materials as the ones that are important for the local economy. The European Commission (2020d) acknowledges the importance of critical raw materials for the future, noting that the need for such materials will replace the current dependence on oil. This somehow differs as compared to the criteria that considered the global framework as in the studies of the IEA (2021d) and World Bank Group (WBG) (2017).

The uncertainties related to the local criticality rankings and their connection to the global economic sustainability emphasise the fundamental questions on the use of the term criticality and its practical implication to the achievement of sustainable energy system transformation. Understanding of the long-term and short-term sustainability risks associated with critical materials on the global level as well as the required potential global warming mitigation techniques to be followed at both the point of extraction and at the point of use is essential to create a global framework that can limit the risk to the global economy and associated local concerns. Thus, understanding the way materials flow through the global economy will be fundamental in giving sustainability risks a proper perspective.

There are two important aspects in developing understanding of material sustainability risks globally. The first aspect is the quantifying of the global material resources in general and the expected demand for production with the expected change in our economic activities. The two well-known databases, which comprise such data, are the United States Geological Survey (USGS) (2021) and the British Geological Survey (BGS) (2021). The second aspect is understanding the use of each specific material and exploring the possibilities to achieve its circularity. Materials extracted from the ground are important to maintain and improve our standard of living as they are required for the production of goods. Their flow in the economy occurs in various forms as they become part of different products, which, as a consequence, affects the manner of their disposal and/or their ability to be recovered. Thus, understanding how much material circularity may address material criticality might be very helpful.

This review paper explores the research gaps on a lack of a unified criticality methodology and investigates the connection of local criticality rankings to the global long-term economic sustainability and to the ongoing energy system transition. Thus, the paper presents a list of critical materials for the energy transition based on their linkage to the renewable energy technologies. Possible long-term issues for critical materials are addressed by analysing various literature sources and databases on material reserves, resources, and production. Additionally, logistic bell curve production projections are applied in frames of the supply side approach to understand to what extend the concept of criticality highlights risks for global sustainability and its implication on materials extraction and use. Even though the supply of critical materials will be largely driven by future energy or broad demand scenarios, the point of the logistic bell curves is not to project the future supply, but to analyse resource management possibilities by estimating theoretical production trends and peaks based on the historical production data and resources. Moreover, the paper examines whether the local concept of criticality is consistent with the global resources and the traded goods depending on it, and the role that material circularity will play if the criticality concept is properly implemented on a planetary level.

Following this introduction, Section 2 outlines various critical materials lists, presents classification and analysis of their methodological basis, and reviews their suitability for the global long-term materials availability investigation defining critical materials for the energy transition. A review of the global databases of materials, data on materials production and global material flow, reserves, resources, and recycling, and assumptions to fill statistical data gaps are presented in Section 3. Besides that, this section also includes our projections of the production peaks of materials, the time of depletion of their deposits, the role of recycling, and possible primary materials supply bottlenecks using the bell curve method. A literature review of materials that are critical for the energy transition, is presented in Section 4. Conclusions are presented in Section 5.

2. Overview of critical materials classifications

The analysis of data found in literature shows that the term criticality is applied to materials in a broad context (Andersson, 2020; Bartekova and Kemp, 2016; EC, 2017a; Greim et al., 2020) that has been changing as it undergoes regular re-evaluation over time as the concern for raw material supply increases due to the growing demand and tightening of supply (Graedel et al., 2015; Hund et al., 2020; IEA, 2021d; JRC, 2011; Valero et al., 2018a; Watari et al., 2020; WBG, 2017). However, the present use of the term could be categorised into two broader groups, each with possible subcategories based on the methodologies used for material classification. The first group follows experts' opinions, while the second one bases its classification dominantly on global supply and demand analyses. Despite the difference in methods of material classification showing a widely varying meaning of the term "critical mineral", it is clear that all emphasise that the term refers to materials that performs essential functions for which there is an identified risk of supply restriction of some kind (be it due to availability, political, or environmental factors). For example, an executive order from the US president (FREO, 2017) states that "critical mineral" is a mineral (i) identified as a non-fuel mineral or mineral material essential to the economic and national security of the United States, (ii) having a supply chain vulnerable to disruption, and (iii) that serves an essential function in the manufacturing of a product, the absence of which would have considerable consequences for the economy or the national security. Similarly, the 2020 communication of the European Commission (2020e) identified critical minerals as raw materials that are most important economically, due to their essential functioning and integrity to industry, and have a high risk of supply shortage. Even though both definitions are essentially the same, differences in local contexts leads to different list of materials as can be seen in Table 1.

2.1. Criticality classification using experts' opinions

The criticality classification made by the European Union (2020d), USGS (Schulz et al., 2017; USGS, 2018), the governments of China (Andersson, 2020), Japan (Austrade et al., 2019; Hatayama and Tahara, 2015), Canada (2021), Australia (Austrade et al., 2020), and various researchers (Bartekova and Kemp, 2016; Eheliyagoda et al., 2020; Harper et al., 2015; Machacek, 2017; Nassar et al., 2015, 2012; Panousi et al., 2015) fall under this category.

The European Commission's list of critical materials (2020d) is based on two indicators that evaluate their economic importance and the associated supply risk factors in the context of the EU. Materials that meet or exceed the threshold values for these parameters are defined as critical for the EU. The "economic importance" parameter is evaluated by considering other factors such as a materials' end use share in the manufacturing industry sector, the value added for the economy, and the possibility and the cost for substitution in end use applications. In turn, the supply risk parameter comprises factors representing the global supply mix of countries together with their associated political and trade risk, EU sourcing, its import reliance, the end-of-life recycling possibility, and the possibility of supply substitutions. However, while the European Commission follows the detailed guidelines to estimate the criticality-related parameters and subfactors, there is no unified and quantitative methodology presented to estimate the threshold values (EC, 2017b). So-called "candidate materials" are compared to each other based on their impact on the EU economy. Although the materials' importance to renewable energy technologies is marked as a leading criterion for defining criticality of materials, the EU's criticality is based on a broader consideration of other sectors of the European economy. Similarly, the US definition of critical materials (Fortier et al., 2018) excludes uranium from the list of critical materials since it is a fuel material. However, its local importance for national defence was one of the reasons for its inclusion in the list of critical materials (Table 1).

Critical materials for the US are defined by the USGS using indicators related to the materials supply disruption risk and importance to the national economy and defence (Fortier et al., 2018; USGS, 2018). On the first stage of the analysis, three parameters, namely, supply risk, production growth, and market dynamics factors related to selected materials are evaluated, normalised, and combined into a criticality score. At this initial stage of screening, the authors of the study intend to identify materials with risk of security of supply from a global perspective. In the second stage, which includes a closer evaluation of each specific material, a more specific look at the US condition is considered by including indicators, such as US import reliance and importance to specific sectors of the local economy and defence. Similar to the EU, the US methodology suggests a quantitative assessment to define critical materials by meeting threshold values for chosen parameters (Nassar and Fortier, 2021). Even though the quantitative methodology itself differs from the one in the EU, the factors it includes generally follow the similar ideas and principles with exception of the negligible attention given to issues of substitution in the US methodology.

The government of Japan defined its list of so-called "strategic minerals" following similar to the EU and US principles. The similar parameters are also accounted for the Canadian list of critical materials (Government of Canada, 2021) even though provincial governments appear to emphasise the importance of possible material substitutions and clean technology development (Gouvernement du Québec, 2020). Australia forms the local list of critical materials by applying the existing criticality lists and methodologies from the EU, the US, and Japan on the local material deposits (Austrade et al., 2020). The critical material list

Table 1
Materials' criticality and relevance to the energy transition. Green markings stand for the materials, which were identified as relevant to the energy transition and chosen for a further analysis. (See below-mentioned references for further information.)

Material	Symbol	Criticality classification (Andersson, 2020; Austrade et al., 2020, 2019; EC, 2020d; Government of Canada, 2021; Hatayama and Tahara, 2015; Hund et al., 2020; IEA, 2021d; USGS, 2018)								EOL-RIR [%] (EC, 2020d)	Application (EC, 2020a; Fortier et al., 2018; Ganguli and Cook, 2018; IEA, 2021d; Kiemel et al., 2021; Shah et al., 2021; Valero et al., 2018a; Zhou et al., 2017)	
		EU	US	China	Australia	Japan	Canada	IEA	WBG		End-use	Energy specific use
Aluminium (bauxite)	Al	x	x	x			x		x	12	Automotive and transport, building and construction, packaging, consumer goods (kitchen appliances, electronics)	Solar PV, solar thermal, wind power, grids (structural), batteries, EV, electrolysers
Antimony	Sb	x	x	x	x	x	x			28	Flame retardants, lead-acid storage batteries hardener, chemicals, ceramics, decolorising agents in glass for electronics, heat stabilisers, catalyst in lead alloys and plastics	Batteries
Arsenic	Ar		x					x		0	Lead-acid storage batteries, antifriction additive for bearings, herbicides and insecticides, semiconductors for solar cells, space research, telecommunications, optical materials, short-wave infrared technology	Solar PV (gallium arsenide (GaAs))
Barite	Ba	x	x							1	Weighting agent in oil and gas drilling fluids, filler in paint and plastics, sound reduction in engine compartments, coating automobile finishes to increase corrosion resistance and smoothness, friction products for vehicles, construction of bearing alloys in an elemental barium form	Oil and gas drilling fluids
Beryllium	Be	x	x		x	x				0	Part of copper beryllium alloy in electronics, telecommunication, transport, energy and military; parts of industrial components such as moulds, ceramic, metal bars	Stopping leaking during oil spills by copper beryllium
Bismuth	Bi	x	x		x		x			0	Cosmetics and pharmaceutical application, manufacturing of ceramic glazes, crystal ware and pearlescent pigments, substitute lead in plumbing, and many other applications, including fishing weights, hunting ammunition, lubrication greases and soldering	
Boron (borate)	B	x						x		1	Agricultural fertiliser, wood preservatives, additives in detergents and other chemical and fluids, in steel and other ferrous metals such as permanent magnet.	Wind power, EV (permanent magnet synchronous motors (PMSMs))
Cadmium	Cd							x		30	Ni-Cd batteries, cadmium pigments, cadmium stabilizers, cadmium coating, cadmium alloys cadmium electronic compounds	Solar PV (cadmium telluride (CdTe), crystalline silicon (c-Si), copper indium gallium selenide (CIGS))
Caesium	Cs		x				x				Caesium compounds, infrared detectors, optics, photoelectric cells, scintillation counters, spectrophotometers, energy conversion devices, magneto-hydrodynamic generators, and polymer solar cells	
Chloride	Cl										Disinfectant, plastics, organic chemistry, pharmaceuticals applications	
Chromium	Cr		x	x	x	x	x	x	x	21	Chromium chemicals, stainless-steel and heat-resisting-steel, superalloys	Wind power (direct drive, gearbox), CSP, hydropower, EV
Cobalt	Co	x	x	x	x	x	x	x	x	22	Batteries, super alloys, catalysts, pigments, magnets	Wind power (generator), batteries, electrolysers, EV, Fischer-Tropsch
Coal (coking)		x		x						0	Metallurgical coke production, heating of steel slabs, heating of blast air, drying of ceramics, drying of coal, production of electricity	
Coalbed methane				x							As a fuel (heating, cooling, cooking, drying, lightning)	
Copper	Cu			x		x	x	x	x	17	Building construction, electrical and electronic products, industrial machinery and equipment, transportation equipment, electricity distribution networks	Solar PV (c-Si, CIGS, CdTe), wind power (direct drive, gearbox), structural: solar, wind, CSP, hydro, bio, grids, EV (PMSMs), batteries, electrolysers
Fluorite (fluorspar)		x	x	x		x	x			1	As a flux for smelting, in the production of certain gases and enamels, in the production of hydrofluoric acid, fluorine-containing fine chemicals	
Gallium	Ga	x	x		x	x	x	x		0	Integrated circuits, light-emitting diode (LED), alloys, batteries, magnets, solar PV	Solar PV (CIGS, GaAs, c-Si), EV
Germanium	Ge	x	x		x	x	x	x		2	Semiconductors, infrared optics, fibre optics, catalysts, solar PV, high-speed integrated circuits	Solar PV (amorphous silicon (a-Si)), EV
Gold	Au			x		x				29	Jewellery, physical bar, coins and medals, electrical and electronics	
Hafnium	Hf	x	x		x			x		0	Super alloys, nuclear control rods, plasma cutting tips, electronics, catalysts, thin films, optics	
Helium	He		x		x		x			1	Magnetic resonance imaging, laboratory applications, welding, engineering applications, leak detection and semiconductor manufacturing	
Indium	In	x	x		x	x	x	x	x	0	Flat-panel screens, car and aircraft windshields, solar PV, solders and alloys, batteries	Solar PV (CIGS), EV
Iron	Fe			x					x	31	Construction, transportation, machinery, equipment, energy, appliances	Wind power (structural), EV (PMSMs), solar thermal
Lead	Pb					x		x	x	75	Lead-acid batteries for automobiles, computer and telecommunications networks, and motive power	PV (coating, perovskite), wind power, batteries
Lithium	Li	x	x	x	x	x	x	x	x	0	Glassmaking, ceramics, batteries, aluminium electrolysis, air conditioning systems, medicines	Batteries, EV
Magnesium	Mg	x	x		x	x	x	x		13	Aerospace and automotive industry, bicycles and other sporting goods equipment, medical applications, electronics, underground pipelines, storage tanks, water heaters	Batteries, solar PV (c-Si)
Manganese	Mn		x		x	x	x	x	x	8	Metallurgy batteries, electronics, fertilisers and animal feed, water treatment chemicals, colorants	Wind power (direct drive, gearbox), CSP, hydropower, batteries

(*continued on next page*)

Table 1 (*continued*)

Molybdenum	Mo			x		x	x	x	x	30	Steel alloys, corrosion resistant alloys, super alloys, magnets	Wind power (direct drive, gearbox), solar thermal, solar PV (CIGS, CdTe), EV
Natural gas				x							As a fuel (heating, cooling, cooking, drying, lightning)	
Natural graphite		x	x	x	x	x	x	x	x	3	Refractories, batteries, friction products, lubricants	Batteries
Natural rubber		x								1	Tyres, industrial and consumer products, latex	
Nickel	Ni			x		x	x	x	x	17	Alloys, stainless steel production, transport, chemical processing, construction industries, liquid gas storages, batteries, aerospace, military applications, turbines	Wind power (direct drive, gearbox), solar PV (c-Si), CSP, hydropower, batteries, AEL and SOEL electrolysers
Niobium	Nb	x	x		x	x	x	x		0	Alloys, steels, high-pressure pipeline construction, building sector, components in the automotive industry	EV, batteries
Oil				x							Fuels, plastics, textiles, cosmetics, medical supplies, household products	
Platinum group elements	PGE	x	x		x	x	x	x		11-28	Jewellery, automobile catalysts, fuel cells, electronics, chemistry, glass, medical applications	Pt, Ir: PEM electrolysers; Pt: fuel cells, Pt, Pd: EV
Phosphate rock		x								17	Mineral fertiliser, food additives, fireworks and detergents, microchips, flame retardants	
Phosphorus	P	x		x		x				0	Chemical industry, electronics, metal products, flame retardants lubricant additives, feed detergents	
Potassium (potash)	K		x	x			x			0	As a fertiliser for chloride sensitive crops, agricultural and chemical applications, pharmaceuticals, medical application, batteries compounds	
Rare Earth Elements	REE	x	x	x	x	x	x	x	x	0-38	Permanent magnets, catalysts, glass polishing, metallurgy and alloys, battery alloys, phosphors, ceramics	Nd, Pr, Dy, Tb, Y: wind power (direct drive, gearbox); Nd, Dy, Ce, Er, Eu, Gd, La, Sa, Pr: EV, PMSMs; Sc, Y: PEM electrolysers
Rhenium	Rh		x		x	x				50	High-temperature superalloys, aviation sector, power generation applications, catalysts, electrical contact points, flashbulbs, heating elements, vacuum tubes, X-ray	
Rubidium	Ru		x								Biomedical applications (antishock agents, tomographic imaging, antidepressants), research (quantum-mechanics-based computing devices), electronics (motion-sensor devices, night vision devices, photoelectric cells, photomultiplier tubes), specialty glass (fibre optic telecommunications networks), pyrotechnics	
Scandium	Sc	x	x		x		x			0	Additive in the aluminium alloys, metal-halide lamps in TV and computer monitors ion activators	
Selenium	Se							x		1	Glass manufacturing, agriculture, chemicals and pigments, electronics	Solar PV (CIGS, c-Si)
Shale gas				x							As a fuel (heating, cooling, cooking, drying, lightning)	
Silicon	Si	x						x		0	Aluminium alloys, manufacture of silicones, semiconductor and solar energy industries (chips for computers and c-Si PV cells)	Solar PV (c-Si, a-Si), batteries
Silver	Ag					x		x	x	19	Jewellery, coins and bars, silverware, PV systems, electronics	Solar PV (c-Si), CSP, EV
Strontium	Sr	x	x			x				0	Ceramic ferrite magnets, pyrotechnics and signals, drilling fluids, electrolytic production of zinc, master alloys, pigments and fillers, glass	
Tantalum	Ta	x	x		x	x	x	x		0	Alloys, automotive capacitors, mobile phones, personal computers, glass lenses (improving flexibility, sharpness, and weight), cutting tools.	
Tellurium	Te		x				x	x		1	Metallurgical alloying, solar cells, thermoelectric production, rubber application	Solar PV (CdTe, c-Si), EV
Tin	Sn		x	x		x	x	x		31	Solder, chemicals, tinplate, lead acid batteries, copper alloys, computing and robotics, energy generation, autonomous and electric vehicles, energy storage and energy infrastructure.	PV (perovskite)
Titanium	Ti	x	x		x	x	x	x	x	19	White pigment, metal and alloys, aircraft sector, geothermal energy production facilities, engines	Bioenergy, solar thermal, wind power, batteries, PEM electrolysers
Tungsten	W	x	x	x	x	x	x	x		42	As the raw material for cemented carbides, high-speed steels and heat-resistant alloys	
Uranium	U		x	x			x				Nuclear reactions	
Vanadium	V	x	x		x	x	x	x	x	2	High-strength low-alloyed steels, special steels, super alloys, chemicals, cast iron, certain types of stainless steels	Batteries, solar thermal, EV
Zinc	Zn					x	x	x	x	31	Galvanizing, brass and bronze, zinc-based alloys	Wind power (direct drive, gearbox), solar thermal, solar PV (CIGS)
Zirconium	Zr		x	x	x	x		x		12	Ceramics, foundry sand, opacifiers, refractories, abrasives, chemicals, metal alloys, welding rod coatings	AEL and SOEL electrolysers

in Australia has a different meaning compared to the material consumption-based connotation of countries discussed above. In this case, the list has a supplier-based connotation and provides technical details of Australia's critical material development projects. This list is focused on achieving Australia's national interest of making considerable contributions to meeting the increasing material demand and enabling the diversification of the global upstream supply chain.

The Chinese classification appears to merge materials categorised by the local supply risk with those that are dominantly produced in China. Like the other countries, its criteria emphasise the importance to the local economic development, security, defence and supply risk (Andersson, 2020). The Chinese "strategic materials list" shows that the criteria have a weak connection to renewable energy technologies and contradicts the consensus that critical materials refer to the forward-looking non-fuel materials because of the inclusion of fossil fuel materials. Contrary to the concept of critical materials of the EU, the US, Japan and Canada, the Chinese "strategic mineral list" also includes six materials that China has in abundance, namely tungsten, tin, antimony, REE, crystalline graphite, and fluorite. Unlike others, the Chinese classification was not driven by the interest to mitigate supply risk but by the interest to gain competitive advantage over other countries. Consequently, China has introduced a resource policy that uses export taxation and applies production and export quotas to regulate and restrict the use of some materials. Most of the materials that are designated as critical by the EU, the US, and Japan are also materials that are dominantly produced in China. According to the criticality evaluation methodologies of those countries, highly concentrated material production is linked to higher supply disruption risk. Summing up, the localised criticality designation concepts are intended to promote the interests of the specified nation or region and, as such, is the reason for the lack of the globally identified critical material list.

In general, these classifications are rather influenced by policy makers and relevant experts of specific countries than by an objective classification aimed to achieve both a short-term and long-term sustainable global economy. These classification methodologies can be characterised as: (i) relying on historical and present data, (ii) using no indicators that may link criticality to material availability using resource and reserve values, and (iii) reflecting political constructs, created based on experts' opinions of the country's future materials demand and associated risk, and influenced by public financing in the short-term. Consequently, these classification techniques have more of a short-term, in the order of a decade, local risk aversion role rather than a goal to achieve a long-term solution. The localised criticality concepts may jeopardise the ability to mitigate the challenge of material supply if global cooperation cannot be achieved.

However, the following three reasons make a global concerted effort to understand and mitigate the challenge crucial: (i) unlike fossil fuels, which lose their initial properties by the end of their lifetime, most metallic materials can be used to form new useful compounds to manufacture various products. Some materials can be recovered through recycling techniques without losing their initial physicochemical properties after the end of the life of the associated products. (ii) Materials are traded as part of the product that utilises it, which could be utilised anywhere on the planet. As a result, if efficient end-of-life recycling of the product is achieved, these materials could eventually flow back through a reverse loop as part of a new product or even a material commodity. Thus, conceptualizing a new circular business model that can enforce responsible use of these resources throughout the planet is much more advantageous in enabling a prosperous long-term global economy. (iii) The global economy is highly interconnected so that a shockwave at one place can propagate to other places easily (Gałaś et al., 2021). In this regard, the local strategy may help in understanding risks. However, it may not be an effective strategy in solving long-term problems as improper material use and management could eventually derail the long-term sustainability of the global economy (IEA, 2023; IRENA, 2023). Thus, the discussion of criticality should be centred on the understanding of material flows and of the advantages it creates to the long-term sustainability of the global economy insofar as it is guided by just and common long-term purpose. The present problem of this group of classification is that it partly follows short-term local conditions.

2.2. Criticality classification based on resource and demand analysis

This classification is predominantly based on supply and demand analysis and comes mostly from academic literature and some international organisations such as WBG (Hund et al., 2020; WBG, 2017) and IEA (2021d). Such a group of academic literature and international organisations reports does not necessarily create a classification but determines criticality of some materials based on an analysis that sometimes may contain experts' opinions. The criticality analysis comes in the form of detailed long-term economy-wide analyses of specific materials or as an analysis that undertakes the demand for key economy sectors or technologies.

The WBG (Hund et al., 2020; WBG, 2017) approaches the question of the role of materials in the future carbon-constrained economy from a broad angle. The first study by the WBG (2017) analyses material demand for the energy system under various climate change targets by taking wind power, solar PV, and energy storage technologies as a proxy. A later study by the WBG (Hund et al., 2020) deepens the subject by expanding the number of energy technologies and improving the methodology. Among the most relevant advances in methodology is their consideration of the impact of the reuse of recycled materials and the creation of a demand risk matrix to identify the level of impact of a given material on the energy system based on their assumed scenarios. The study excludes several materials due to various limitations and thus the corresponding list provided in Table 1 is not yet comprehensive.

However, two important lessons can be learned from such studies. First, critical materials in this context can be understood as materials that have the potential to become a bottleneck to the global economy (taking the implication to the energy industry as a proxy) due to possible supply risk to arise in the event of material production shortage. However, it is worth noting that the link of criticality to material availability is still weak due to the limitation of this analysis, which uses only 2018 production values as a reference for those materials even though production is not a static value and changes with time depending on various factors. Second, if more comprehensive approaches are pursued globally, then the discourse of criticality can be used to create an environment where long-term and short-term sustainability of the global economy receives attention. Simultaneously, the risk and opportunities for all stakeholders, namely miners, manufacturers, consumers and recyclers can be properly identified. This would have a much-needed impact, compared to the presently localised views that are driven either by the perspective of consuming or producing countries.

Similarly, the IEA (2021d), which also uses the term "mineral security" along with "critical mineral", studied the availability and reliability of material supply to achieve the energy transition. Thus, the materials included in its study are identified based on their relevance to emerging and fast scaling energy technologies. As compared to the WBG, the IEA includes a greater number of materials, which are assumed to have substantial security implications to energy sectors. Although aluminium was classified as a high impact critical material by the WBG due to its application in several energy technologies, the IEA remains vague as it excludes it from their study by claiming that it is regularly projected as a part of other IEA studies (IEA, 2021d, 2021a). In addition to this, the IEA also analyses material demand for other sectors to better understand the overall contribution of energy technologies to the demand and related supply-side challenges by selecting five focus materials: copper, lithium, nickel, cobalt, and neodymium (as a representative for REE). It is crucial to mention that the selected energy scenarios of the IEA and the WBG may not reflect the level of severity related to transition options that more rapidly transition to renewables (see Section 4).

Another group of global studies are those conducting overall demand and supply analysis of selected materials, as for lithium in Greim et al. (2020) and silver in Li and Adachi (2019). The results of these studies show that these materials could become bottlenecks to the energy transition without further measures such as the establishment of efficient recycling for the case of lithium and substituting silver in PV manufacturing (Victoria et al., 2021; Zhang et al., 2021). These materials also carry long-term sustainability risks to the energy transition and the economy in general. Summing up, the global criticality concept has the potential to directly link to the material availability and related short-term bottleneck as well as its long-term sustainability risk. The global criticality concept also has the special capability to identify the problem in global material markets and provide remedy as compared to the localised concept.

Table 1 provides the list of critical materials according to seven different sources, five countries, and two international organisations. The table also includes the data on the end-of-life recycling input rate (EOL-RIR) in Europe, and the materials area of applications together with their specific use in sustainable energy technologies like solar PV, concentrating solar thermal power (CSP), wind power, electric vehicles (BEV and plug-in hybrid electric vehicle (PHEV)), batteries, bioenergy, hydropower, and electrolysers (EC, 2020a; IEA, 2021d; Valero et al., 2018a). Green markings in the table stand for materials, which were identified as relevant to the energy transition based on their application in renewable technologies and thus chosen for a further analysis. Even though coal, methane, natural and shale gas, and uranium are listed as critical materials in some of the above-mentioned assessment regions, fossil fuels are not the focus of this study because they contradict with the transition towards a 100% renewable energy system (Bogdanov et al., 2021).

In summary, the foregoing discussion and Table 1 show that the critical material list changes depending on location due to the difference in the needs of local economies, available resources, and related politics. Only a handful of materials, namely antimony, cobalt, lithium, natural graphite, REE, and tungsten, are included in all five governments critical materials lists. The lists presented by the IEA and the WBG are based on the need of the energy system, shortening the list further. In general, the foregoing discussion shows that the term criticality is very fickle and constantly changing with time and location. Consequently, the local criticality criteria are formulated (by considering different sectors of economy, environmental targets, local supply risks, and political reasons) leading to the difference in the critical material lists. The localised interpretation of criteria typically has nothing to do with the global material criticality. In the next section, the global databases of materials that are critical to the energy transition are studied to gain more in-depth knowledge about the global versus local criticality context.

3. Materials production, reserves, resources, and recycling

Materials can be supplied from primary and secondary material flows. Primary production refers to materials directly mined from geological bodies whether or not it requires further processing methods (EC, 2019). Secondary production indicates materials extraction from end-of-life products, waste, and scrap by recycling (EC, 2020d, 2019). Since most geological deposits are heterogenous, such formations consist of a few materials that can be extracted alongside a primary product of mining, and, hence, other materials become its by- or co-products. While co-products carry the same value as a primary material, which can cover its mining expenses, by-product materials are not the planned products of an initial mining process and are not included in the cost of mining formation (Keller and Anderson, 2018).

Materials that are currently available on our planet for further extraction are usually reported as material resources or reserves depending on the level of geological knowledge and confidence (Gandhi and Sarkar, 2016). Natural deposits that have an accumulation of materials in quantities that are technologically extractable and economically viable are called ore deposits or reserves. The remaining deposits constitute those that may become economically viable as extraction technologies improve or as economic conditions change as the demand for that material increases (Haldar, 2013). Reserves and resources of any material are not a constant value and can change over time. When some part of resources becomes profitable to mine, it becomes a reserve, and when new deposits are found, both quantities (reserves and recourses) may change (Wellmer, 2008). Typically, information on reserves and resources is available from specific national sources on mining, for example from statistical data of national geological surveys, ministries, and industrial associations. International sources, such as USGS (2021) and BGS (2021) provide both global and local data compiled based on official national statistics while also validating other sources.

Due to high uncertainty and disparity of the data on reserves and resources, three scenarios, namely Low, Medium and High production scenarios, were defined for all researched materials having the appropriate data (Table 2). In this study, reserves and resources are assumed to be depleted when reaching its total extraction share of 99% and 95%, respectively, due to the specific differences of its geological confidence.

Table 3 presents the production type, 2020 production values, corresponding reserves and resources estimate, years of production left until reserves and resource depletion, and production peak years for materials that are assumed to become relevant to the energy transition.

Analysing the data of materials related to the energy transition provides a better understanding of the connection between the criticality concept and the long-term sustainability. Historical production data and reserve and resources estimates corresponding to the identified materials were derived from the USGS (2021) and BGS (2021) databases. Even though USGS and BGS databases were used as the main data sources in this study, other literature data was also used to fill in the data gaps for some materials and for some parameters, which were used in the calculation, as stated in the remarks of Table 3. The data on the share of each individual rare earth element in the total REE oxides production is presented in Supplementary Table S1.

3.1. Global flows of materials

The BGS database (BGS, 2021) provides annual data on the world materials production by country starting from the beginning of the 20th century as well as statistical data on materials' import and export. Moreover, the database provides geological information, extraction and processing methods, end-use data, and prices for a limited number of material commodities. Similar data on the materials production is published in the USGS database (USGS, 2021) on an annual basis. In addition, the USGS database includes annual global data on materials reserves and/or resources by country, a global interactive map of REE deposits, as well as annualised information on recycling and substitution possibilities, global material-related events, and the US specific material end-use, trades, consumption, and prices.

Both databases provide similar values of materials annual production. However, in case of some by-product elements due to their dependence on primary commodities, some missing data exists. Since by-products are typically associated with the primary products of their mining, it is difficult to estimate the volumes of their production, and, moreover, their reserves and resources. The same applies to elements, which are often found in groups, such as platinum group elements or rare earth elements. For these groups of elements, the data on both production and reserves and/or resources is often published for the whole range of elements combined, making it complicated to estimate specific values for individual elements. In such cases, to fill the statistical data gaps, several assumptions were made in this study (Table 3 and Supplementary Table S1).

The data, which was derived from databases and other sources also comprises regional material production values, ore grades, ore types, secondary production, and by-product dependencies. Fig. 1 presents the local production distribution by top countries for selected materials taken as examples as a share of global production in 2020. Similarly, Fig. 2 presents local shares of reserves compared to the global data for the same materials. Top 9 countries (if available) are presented for each of the selected materials' production and reserves, while the rest and the ones with shares lower than 2%, are combined into the "Other" category.

As seen from the figures, materials are not necessarily produced relative to their known reserves in a specific location, neither reserves are equally distributed across the globe. These factors make the global coordination on materials flow even more complicated because such location-related limitations are not only formed by the geological distribution but also affected by politics and vice versa. This elucidates how focus on the global data and related projections conceal some of the localised challenges that originally contributed to the concern of criticality. For example, the major factors of the cobalt's criticality are based on the political stability of the country with the largest known reserves and also the present largest production. On the contrary, the driving factor of the silver's criticality is the overall material's deposits limitation caused by the overexploitation and diminishing of the resources. Thus, even though detailed location-based analysis is challenging for a large group of minerals, application of the global data can provide a global overview of the long-term conditions for several materials at once.

This paper is focused on the supply side approach of the materials production projection due to a number of existing limitations. The reason for this is that the full material demand is practically impossible to estimate due to the uncertainty in the expected technological demand for more than a century. Moreover, to estimate the total material

Table 2
Scenarios of the logistic bell curve calculation.

Scenario	Low scenario	Medium scenario	High scenario
Quantity base (2020)	Reserves	Average of reserves and resources	Resources
Depletion rate	0.99	0.95	0.95

Table 3
Critical materials' geological data, and reserves, resources and its depletion estimates.

Material	Dominant production(BGS, 2011, 2009; Moss et al., 2013; Peiró et al., 2013; USGS, 2021)		Production (2020) [kt]	Reserves [kt]	Resources [kt]	Years until depletion based on				Bell curve peak		Remarks, specific to each material/data. n/a – stands for not available data
						2020 production		Bell curve				
	Type	Primary commodity				reserves	resources	Low scenario	High scenario	Low scenario	High scenario	
Aluminium	Primary		65,100	12,000,000*	30,000,000*	184	461	76	86	2061	2079	* assumed 40% Al content in bauxite (The Aluminum Association, 2021)
Antimony	Primary		111	2,000	n/a	18	n/a	18	n/a	2026	n/a	
Cadmium	By-product	Zn	24	690*	5,700*	29	238	34	107	2034	2089	* assumed 0.03% Cd content in Zn ores (Scoullos et al., 2001; IEA, 2021d)
Chromium	Primary		37,000	570,000	12,000,000	15	324	17	62	2027	2061	
Cobalt	By-product	Cu, Ni	142	7,600	25,000	54	176	40	58	2039	2057	
Copper	Primary		20,600	880,000	5,600,000	43	272	39	91	2038	2079	
Gallium	By-product	Al	0.33	1,513*	13,845**	4,625	42,339	90	103	2079	2102	* estimated assuming 50 ppm Ga content in bauxite and 40% extraction rate (ICMLR, 2016); ** calculated using Ga content in bearing ores (Lu et al., 2017)
Germanium	By-product	Zn	0.14	n/a	36*	n/a	257	n/a	98	n/a	2085	* Gunn (2014)
Indium	By-product	Zn	0.96	21*	356*	22	371	22	62	2029	2063	* estimated assuming 50 ppm and 10 ppm In content in Zn and Cu ores, respectively (Gunn, 2014); ** Werner et al. (2017)
Lithium	Primary		83	22,000	89,000	267	1,079	45	49	2046	2057	
Manganese	Primary		18,900	1,500,000	17,273,000*	79	914	60	137	2048	2115	* Mn global deposits data (Schulz et al., 2017)
Molybdenum	Primary/by-product	Cu	298	16,000	25,400	54	85	39	42	2040	2046	
Nickel	Primary		2,510	95,000	300,000	38	120	37	57	2036	2056	
PGE*	Primary/by-product	Magmatic Ni-Cu-PGE sulphide deposits										* average concentrations of each element in ores were estimated on the basis of approximate individual element grades and ore types (Mudd, 2012; Mudd et al., 2018)
	Pt		0.17	31	42	183	248	227	167	2057	2068	
	Pd		0.21	24	41	116	197	92	84	2051	2065	
	Rh		0.018	3.98	5.01	226	284	95	86	2061	2068	
	Ru		0.024	6.98	8.28	287	340	99	95	2072	2082	
	Ir		0.006	1.65	2.02	268	329	87	77	2069	2073	
	Os		0.005	1.52	1.77	290	338	98	84	2072	2075	
REE*	By-/co-product/ primary	Cu, Au, U, P, Fe, Ti, Zi, Zn	*	**	***							* estimated based on the data in Supplementary Table S1; ** estimated based on individual element composition in advanced deposits (Zhou et al., 2017); *** Weng et al. (2015)
	La		54	25,325	139,805	472	2,604	98	119	2076	2107	
	Ce		90	46,227	243,399	516	2,715	98	119	2077	2108	
	Pr		10	4,718	19,847	452	1,901	97	115	2075	2104	
	Nd		34	16,070	62,433	472	1,832	94	109	2074	2099	
	Sm		2.72	1,552	7,707	571	2,837	94	114	2075	2104	
	Eu		0.47	249	1,757	533	3,768	103	134	2080	2119	
	Gd		2.17	1,145	5,143	528	2,373	100	122	2078	2109	
	Tb		0.31	102	827	325	2,636	89	104	2063	2096	
	Dy		1.12	544	4,009	485	3,575	124	133	2076	2110	
	Ho		0.32	105	695	325	2,155	102	115	2066	2099	
	Er		0.63	262	2,554	416	4,053	130	150	2076	2117	
	Tm		0.15	105	310	681	2,009	102	108	2074	2095	
	Yb		0.46	263	2,486	570	5,383	122	136	2077	2115	
	Lu		0.15	106	389	687	2,531	148	141	2085	2109	
	Y		6.42	3,118	32,329	485	5,033	108	124	2071	2109	
Selenium	By-product	Cu	3.12	100	n/a	32	n/a	39	n/a	2035	n/a	

(continued on next page)

Table 3 (*continued*)

Material	Dominant production (BGS, 2011, 2009; Moss et al., 2013; Peiró et al., 2013; USGS, 2021): Type	Dominant production: Primary commodity	Production (2020) [kt]	Reserves [kt]	Resources [kt]	Years until depletion based on 2020 production: reserves	Years until depletion based on 2020 production: resources	Years until depletion, Bell curve: Low scenario	Years until depletion, Bell curve: High scenario	Bell curve peak: Low scenario	Bell curve peak: High scenario	Remarks, specific to each material/data. n/a – stands for not available data
Silver	By-/co-product/primary	Pb-Zn deposits, Cu, Au	24	530	1200*	23	51	25	38	2030	2040	* estimated as a difference between the ultimately recoverable reserves of Ag at present, and the amount that have been extracted by the humanity (Sverdrup et al., 2014)
Tellurium	By-product	Cu, Pb	0.56	31	n/a	55	n/a	26	n/a	2034	n/a	
Titanium	Primary		5,154*	449,506*	599,341**	87	116	73	68	2056	2061	* estimated based on molar mass ratio of Ti and TiO_2; ** estimated assuming 50% TiO_2 content in the bearing ores (Mindat.org, 2021)
Vanadium	By-/co-product/primary	Fe, U	105	24,000	63,000	229	600	120	110	2073	2096	
Zinc	Primary		12,000	250,000	1,900,000	21	158	24	78	2029	2068	
Zirconium	By-/co-product/primary	Ti, Sn	595*	51,824*	n/a	87	n/a	60	n/a	2050	n/a	* estimated assuming 67% Zr content in zircon (Zircon Industry Association, 2021) and using molar mass ratio of Zr and ZrO_2

General remark: the decrease in the "year until depletion" for some elements is due to the application of a 5% limit to the resource depletion value that has not much difference from reserve values, to which only 1% was applied.

demand, not only the demand for the energy system is needed, but also the overall material demand for all human activities is required. Besides that, any kind of non-gradual technology development is very complex if not impossible to anticipate for that long period of time. Hence, the supply side approach is chosen as an appropriate tool from the basis of the existing knowledge on the materials' production and usage.

In this study, in order to analyse the long-term sustainability risk associated to critical materials and understand ways to ameliorate the anticipated challenge of materials supply constraint, the following steps were performed based on existing data and literature sources: (i) model long-term material production (material supply projection), (ii) estimate depletion years based on various conditions, (iii) synthesise the present role of recycling, its link to critical materials, and factors affecting its use.

3.2. Production trends and projections of critical materials

In order to understand resource management challenges of each material overtime, the simplest way is to study the possible production trends, peaks of production and depletion time of each material by extending the typical trend in the historical production and materials' quantity using some mathematical model. The growth curve method is a simple method to project materials production and to identify potential resource limitations, which is widely used in resource management (Höök et al., 2011). The logistic bell-shape curve, which is calculated from the growth curve, described by Vikström et al. (2013) and adopted by Greim et al. (2020), is applied for the present study. The specific curve of each material was computed by applying the logistic curve formula given in Equation (1). The corresponding parameters of the equation were identified by fitting the curve to the historical annual production data while extending the projections to future years using the material's reserves or resources data. The historical data of materials includes all the available data from the datasets from the early 20th century onwards.

In this approach, the model determines parameters that represent the past production activities and, moreover, it is able to estimate future material production volumes, if sufficient past historical data is applied. Applying the curve fitting to historical data may also minimise the effect of missing data, especially for those materials that are typically produced as by-products. To obtain the parameters, each raw material bell curve is compared to historical annual production data that was obtained from the USGS (2021) and BGS (2021) databases, while adjusting coefficients in the Equation (1) until the production difference, the cumulative historical production difference, and difference between published and projected reserves or resources are minimised. The application of bell-shaped curves was found to be suitable based on the available data and thus calculated until the time of materials' quantity depletion. In that case, the presented diagrams show the trend for centuries to come, even though the short-term analysis of material's production should include the supply–demand analysis for materials.

$$f(t) = A + \frac{K - A}{\left(1 + Qe^{-B(t-M)}\right)^{\frac{1}{v}}} \quad (1)$$

where $f(t)$ – cumulative production in a year t; K – upper asymptote of the curve (which is usually an estimate of ultimately recoverable resource (URR) of a given material); A – the lower asymptote of the curve (practically, the cumulative mass of resources previously extracted by the initial year); Q – the scaling parameter; B – the growth rate parameter of the curve; M – year of maximum growth (peak year); v – a parameter of the peak year asymptote.

The fact that the URR value includes all historical production as well as the future extraction potential and the yet undiscovered resources, makes its' estimation rather challenging. Due to this, the upper value of the curve or *K-value* was set to the known reserves or resources depending on the scenario as of 2021, while assuming parameter A as

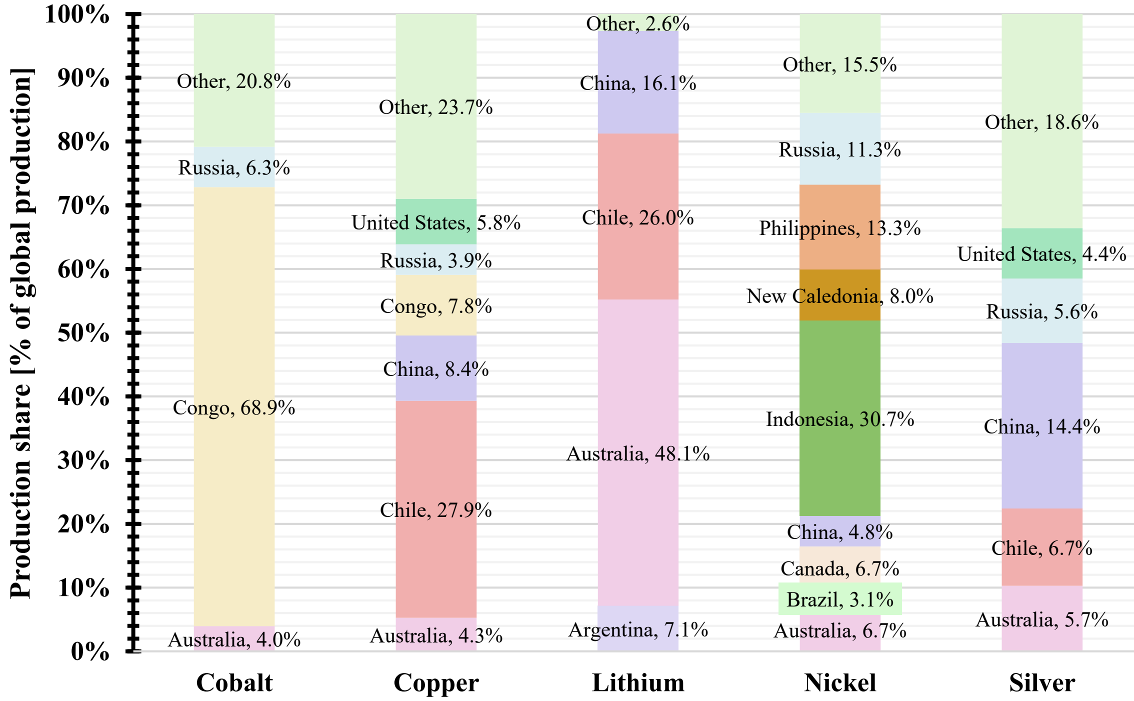

Fig. 1. Selected materials' production distribution by country in 2020.

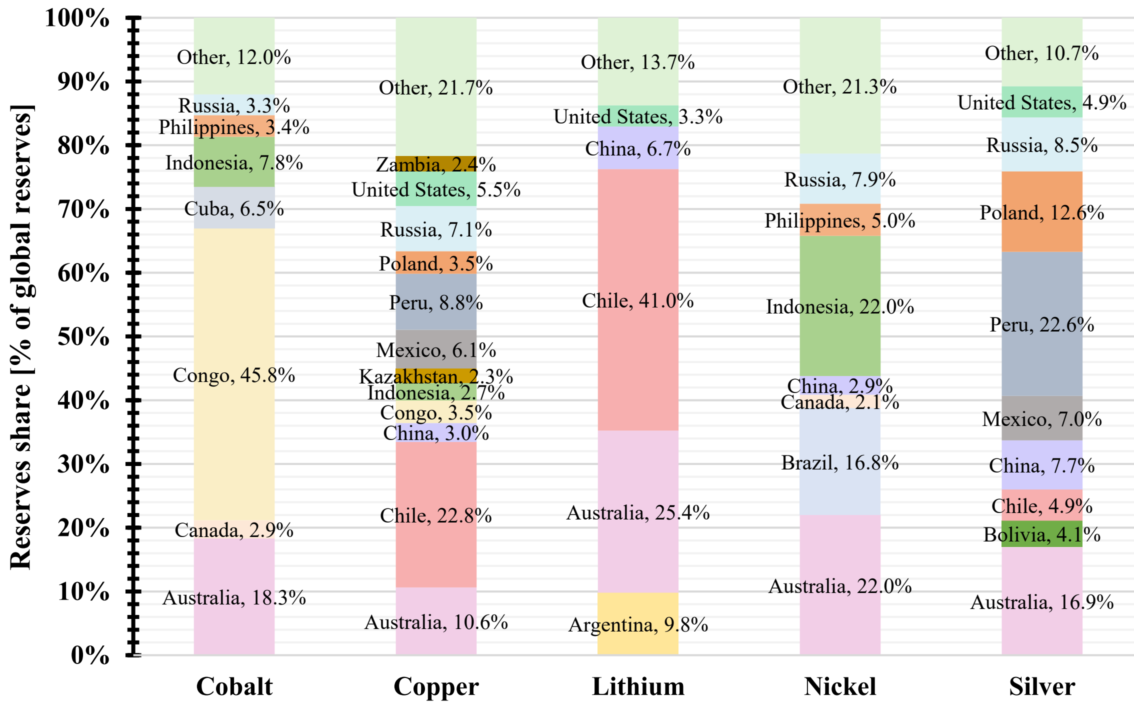

Fig. 2. Selected materials' reserves distribution by country in 2020.

the total historical production of a material by the year 2021. The parameter *A* was adjusted to such a negative value to make the curve fit the known historical production and further project the production from 2021 until the known reserves and resources are depleted. In this study, the cumulative projected production from 2021 to the depletion, which follows the bell curve, was estimated to deviate from the actual reserves or resources values by less than 1%. Since the historical data is fluctuating for most of the materials, the bell curve is adjusted to corresponding trendlines based on the historical data (Supplementary Fig. S1 and Fig. S2). In such cases, even though the annual difference between the historical data and the projections may be high, the error between the overall cumulative historical production and projections are minimised.

In most cases, as demand for materials increases, reserves are depleting, and mining prices rise, the reserve amount also expands by including the more expensive resources. However, the resource potential may be the most optimistic potential and unrealistic estimate. Thus, the Medium production scenario may better represent the higher range of the recoverable quantity for the corresponding materials. Using Equation (1) the peak years of materials' production were estimated based on the relevant K-values of the three scenarios and corresponding production rates, which were then recalibrated due to the circular dependence of Equation (1) and Equation (2).

$$M = t_{ref} + \frac{\ln\left(\frac{K}{\hat{f}(t)} - 1\right)}{B} \tag{2}$$

where t_{ref} – reference year of historical production values (2020); $\hat{f}(t_{ref})$ – annual material production in a year t_{ref}.

The applied parameters for the growth curve for all the energy-critical materials are presented in Supplementary Table S2. The annual data of material production projection was then derived from the corresponding cumulative production curve.

Material production curves considerably vary depending on the mineral abundance, which can be linked to the corresponding reserve or resource quantity. As a result, depending on the corresponding reserve quantity, eight material groups were formed for the Low scenario, two for each of REE and PGE (based on low and high group shares), and four groups for other materials based on the annual production peak values, namely those with low abundance (1.6–3.9 kt), medium abundance (30–651 kt), high abundance (1,034–9,484 kt), very high abundance (15,500–290,000 kt). Similarly, the same eight groups were formed for the High scenario. The REE group generally falls in the highly abundant minerals but the elemental share in the group is different thus leading to two groups depending on their overall share.

Figs. 3-6 present the production curves of the selected materials, highlighting production peak values and years. Figs. 3 and 4 present the Low and High scenario curves for selected REE, while Figs. 5 and 6 present the Low and High production scenario curves for selected PGE. Other figures are provided in the Supplementary (Figs. S3-S14). The figures show the potential changes in resource production related to each material, with the curves growing depending on the specific scenarios' maximum material quantity and the fit to the historical production. Although the curve fitting approach is able to achieve a good short-term (up to a decade) material production projection, its ability to accurately describe the long-term projection will still be limited due to continues market changes. It should be noted that the curves are showing production projections from the supply-side perspective. Practically, it means that the curves allow to research the productions, which is possible if there is a corresponding demand for any specific material. However, if demand for materials will be lower in the future, such peaks may not be ever reached within the specified time range. The bell curves of most materials for the low scenario show that with the present production rate, the material production will reach its peak production in less than five decades (see Table 3).

Table 3 provides the estimated peak year and the depletion year for materials related to the energy transition. For the Low production scenario, some materials such as antimony are already on or near their peak. Some studies, such as Calvo et al. (2017), which implement a similar to this study analysis that uses reserve data, confirm that antimony has already attained its maximum production values. Other materials, such as selenium and silver are projected to reach their production peaks in 2035 and 2030, respectively. Similar to the case of antimony, the projection of selenium production is based on only reported reserves values; therefore, a longer production period may be expected taking in mind possible higher resources. Besides that, apart from empirical estimations of silver resources, other official geological data was not available. The production of zirconium is expected to peak in 2046. Such values on zirconium repeat the trend of other projections, which were based on a low value of reserves.

In turn, the cadmium and molybdenum production projections are expected to peak in 2034 and 2040, respectively, due to their natural occurrence as by-products of zinc and copper bearing ores mining. The projected production of cobalt reaches a peak in 2039 and tellurium peaks in 2034. Both elements are mined as by-products. In turn, copper (primary commodity of cobalt, molybdenum, selenium, silver, tellurium, PGE, and REE), nickel (primary commodity of cobalt and PGE), and zinc (primary commodity of cadmium, germanium, indium, silver and REE) production projections climb to the peaks before 2040, even

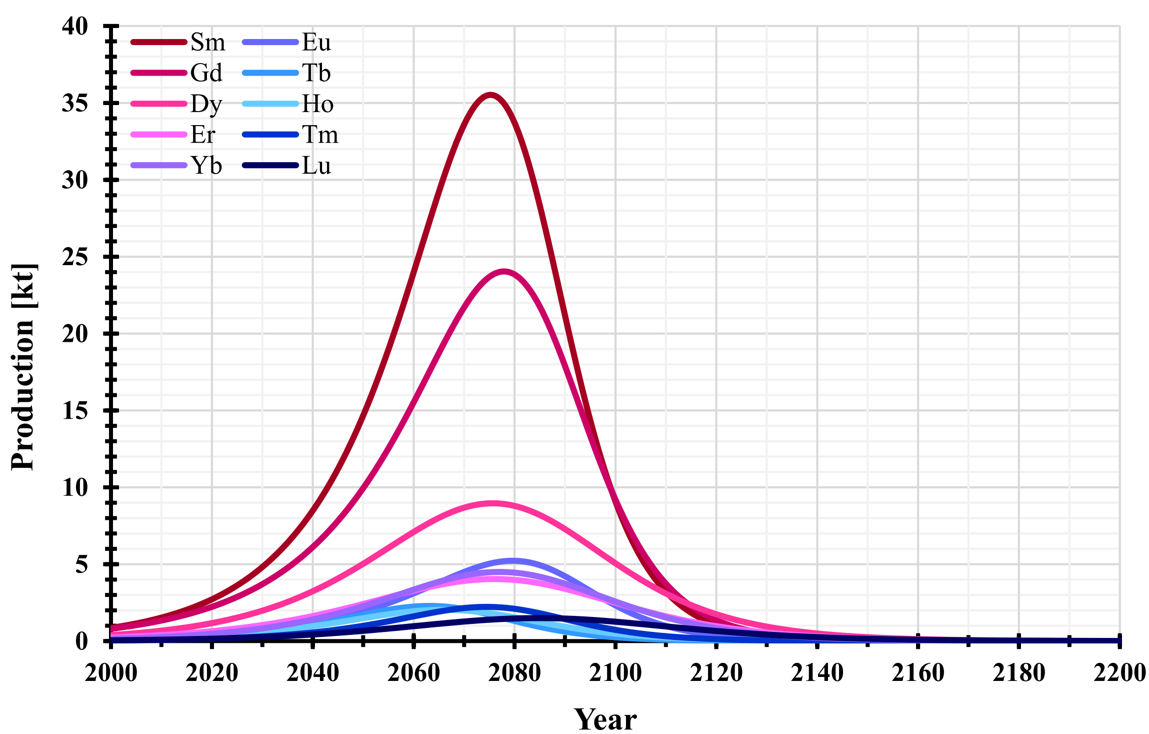

Fig. 3. Low scenario material production projection for REE with the low group share.

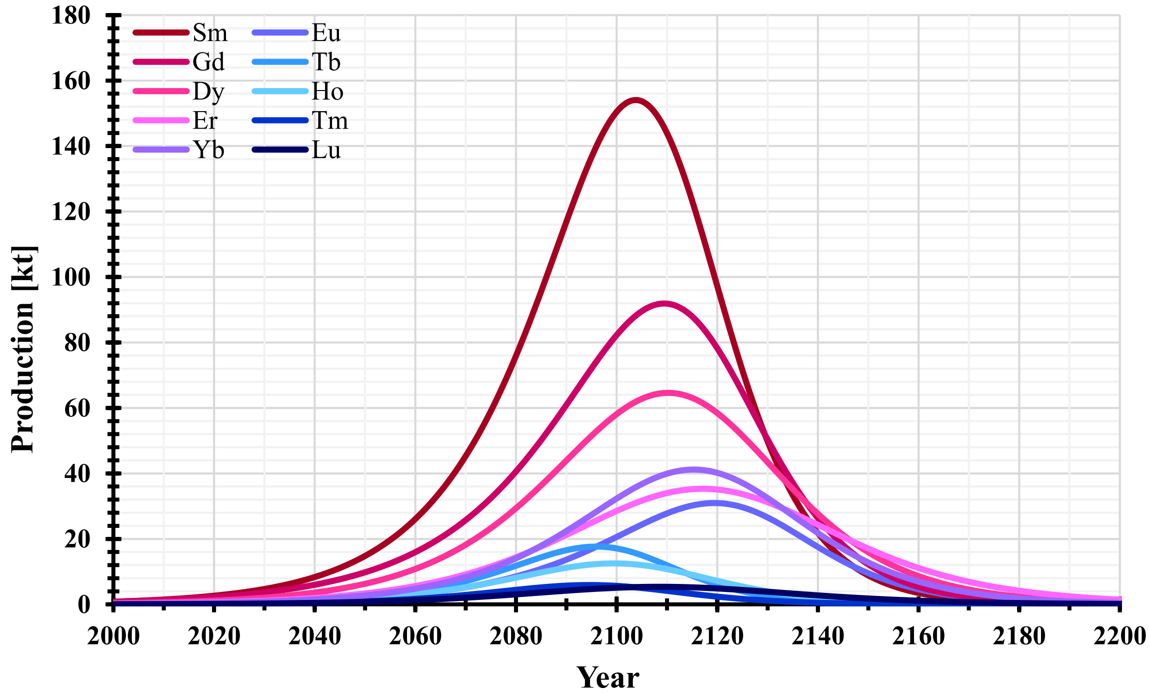

Fig. 4. High scenario material production projection for REE with the low group share.

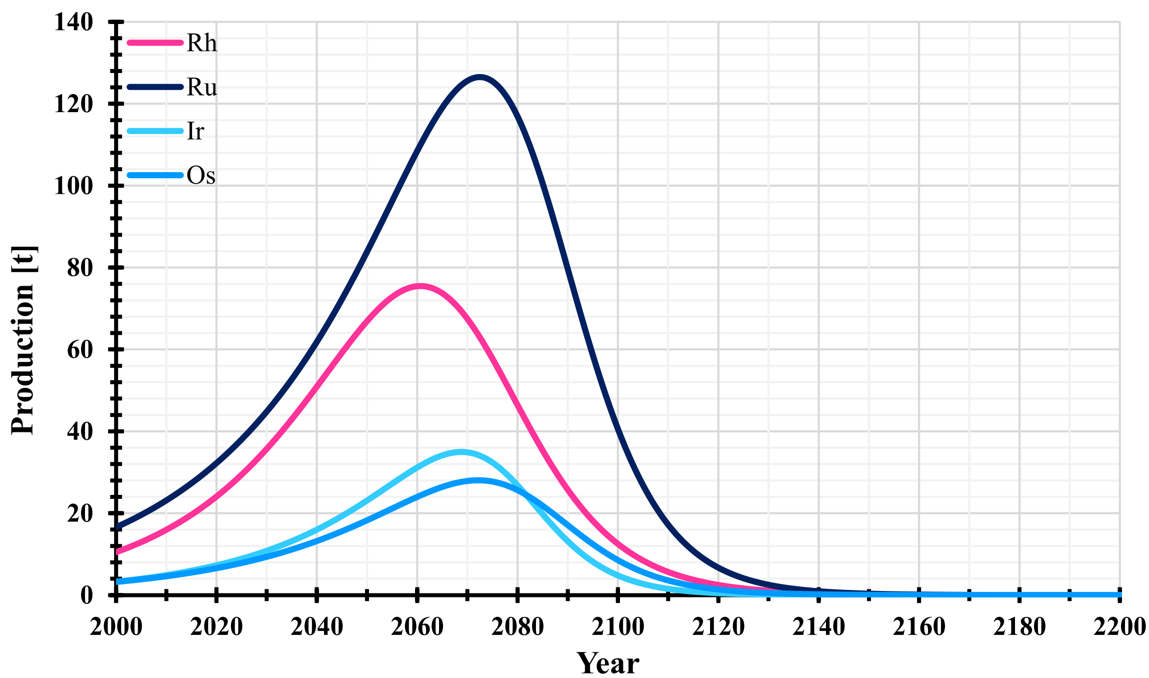

Fig. 5. Low scenario material production projection for PGE with the low group share.

though these three materials are used in many applications across various sectors of the economy. It should be also noted that the present supply of some of these materials, such as copper, nickel and zinc, contains significant secondary production flows via recycling of used goods and scraps (USGS, 2021). In turn, the corresponding bell curves are fitted to mine production data and thus capture only the primary supply conditions.

Calvo et al. (2016) state that the peak production of copper has been continuously receiving research interest and its deposits values have been adjusted continually since the last century to be sufficient to cover the production for the following 8–20 years at any given year (Kerr, 2014). Both groups of elements, REE and PGE, have shown a good potential for further expansion of production. REE are not scarce from the geological perspectives, and their resources are enough for the production growth before peaking in the end of the 21st century. Thus, the designation of REE as critical at present time emanates from political concern related to the country that produces the largest amount and also has the largest reserves and resources, which is China. Among six elements of PGE, only platinum and palladium are expected to reach production peaks in 2050 s, while the others seeing production peaks later

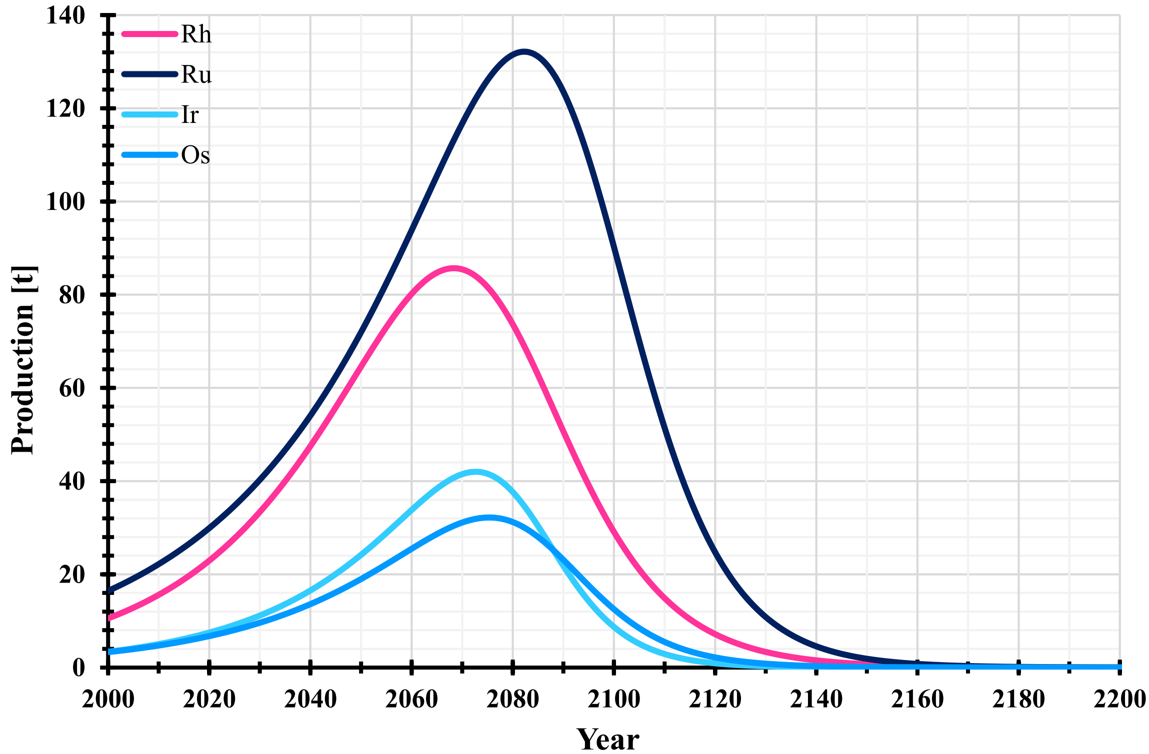

Fig. 6. High scenario material production projection for PGE with the low group share.

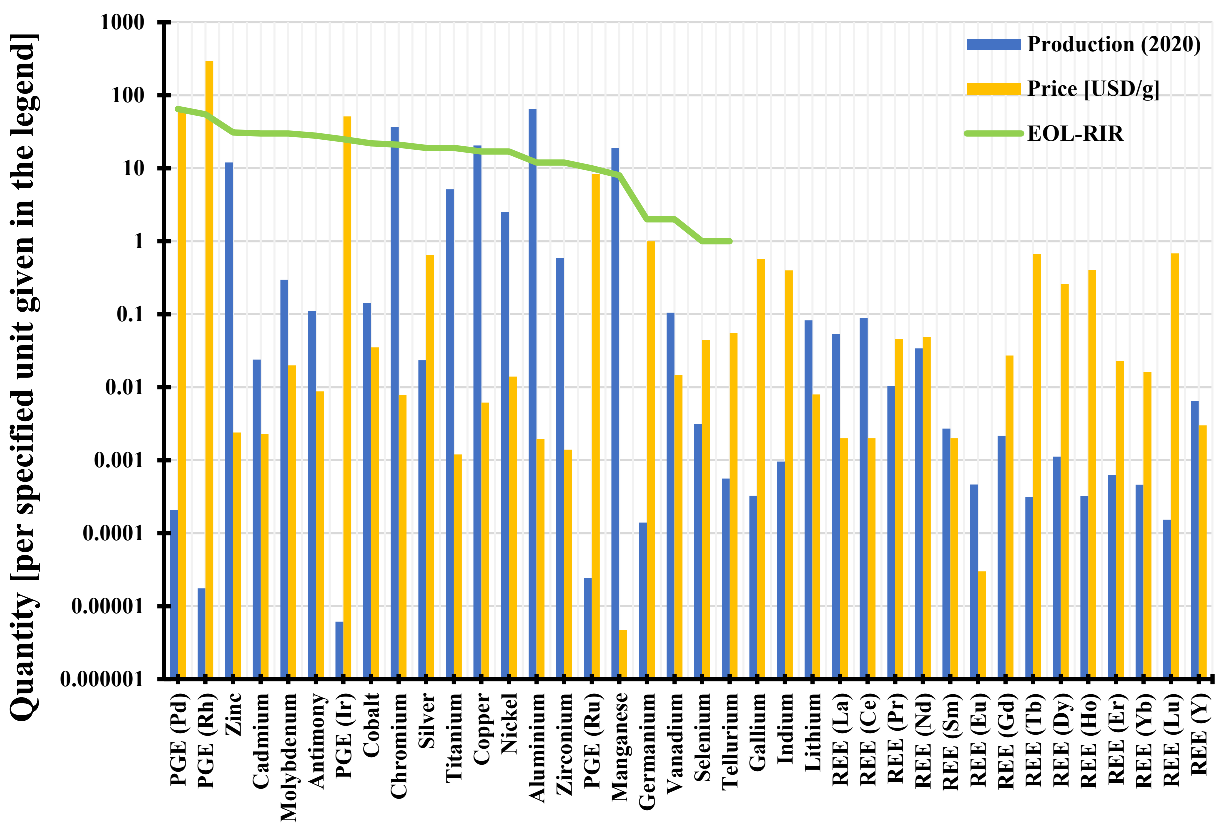

Fig. 7. EOL-RIR in Europe, 2020 global price and production of various materials. Values provided in Supplementary Table S3. Data source: EC (2018) and USGS (2021).

in the 21st century. Hence, these materials can be treated as critical from the point of the growing demand, political reasons, and geographical distribution of resources, but not because of their diminishing resources and production rates.

3.3. Depletion year and the role of recycling

The other important aspect to examine is the material depletion year. In this study, the material depletion year was estimated by assuming a constant rate of production at the 2020 level and by using bell curves. The results of our investigation using both estimation techniques show that many materials could be depleted before the end of this century. However, it is crucial to mention that these results may demonstrate rather "optimistic" scenarios as demand for some of the material may increase faster than what the past data suggest. Such a fast demand growth can affect the material price, which may lead to an exploitation of other more expensive deposits then those that are currently provided in the resources databases. This may delay both the depletion and peak production year for many materials. Moreover, the development of efficient recycling may also have an added role of its own in ameliorating the problem of the material demand growth. However, regardless of the substantial criticality of minerals with low abundance, the results illustrate that all these materials will eventually be severely critical.

Currently, most of the fresh material demand comes from the primary production of the corresponding materials, with negligible secondary material flow for most materials. However, recycling plays a crucial role in addressing the challenges associated with critical materials, as it offers means to recover valuable resources and reduce dependency on primary production. The present global recycling condition values are not available, thus the European recycling rates are taken. The latest EOL-RIR, green curve in Fig. 7, reflects the share of material input into production that was obtained from secondary sources or recycled end-of-life consumer scrap.

Fig. 7 shows that quite a few materials that are critical to the energy transition are currently being recycled. The values of the EOL-RIR are high for the PGE group with 65%, 65%, 55%, 25%, and 10% for platinum, palladium, rhodium, iridium, and ruthenium, respectively. The EOL-RIR values for other valuable critical materials such as cobalt, silver, copper, nickel, manganese, lithium, and REE are 22%, 19%, 17%, 17%, 17%, 8%, 0%, and 0%, respectively. The reason for the small recycling role is attributed to: (i) low economic benefit of recycling; (ii) lack of suitable recycling technologies; (iii) long lifetime of end-of-life products; (iv) the growing demand for materials that continually exceed the recycling output (EC, 2018; UNEP, 2013, 2011; Wang et al., 2021).

Moreover, as studied by Liu et al. (2012), rocketing demand for fresh materials (and aluminium in particular) by 2050 can substantially decrease the role of recycling in material supply due to a negligible amount of scrap available for the recycling. This is potentially possible because of the lifetime lag between the raw material production and its decomposition for recycling. Nevertheless, the study mentions that recycling will play a significant part in reducing the fresh material demand for aluminium after 2050, when much higher volumes of scrap will be available for recycling. Another study by Lennon et al. (2022) states that the use of recycled aluminium will be critical to reach the required installed capacities of RE technologies for the energy transition while shortening mining emissions.

Recycling is a crucial and valuable part, but it is just one factor of the solution to the materials availability for the energy transition. As stated above, the available scrap materials for the recycling correlates to the new installed capacities of the RE technologies with the time lag of their lifetime. Due to the expected rocketing demand for RE capacities in the foreseen future by 2050, the available scrap materials in 2050 then correspond to the RE capacities of the 2020 s, where the capacities are much lower in most cases compared to the ones in 2050. In contrast, the situation after the year of 2050 in this discussion to the very long-term outlook up to the end of the century may be promising since there is a realistic chance to enter a high stability of material demand on the very long term (Keiner et al., 2023) and that shall enable very high recycling rates (Lopez et al., 2022).

The present recycled materials either fall into the group of precious materials, as platinum, or of those related to materials in high volume application, as chromium in stainless steel, which is recycled as part of steel scrap (USGS, 2021). Similarly, the bulk of recycled antimony is recovered as "antimonial lead" through lead smelting and finally consumed by the lead-acid battery industry (USGS, 2021). Fig. 7 also reveals that the recycled materials are high-cost materials or those related in the form of an alloy to high volume application materials such as copper, aluminium, lead, and iron. Materials with low or no present recycling, such as REE, are typically characterized by the low volume of production and long-life application, which limits its business attractiveness.

4. Materials for the energy transition and research outlook

4.1. Possible material supply bottlenecks

In the short-term perspective up to 2030, rare earth elements (Nd, Pr, Dy), In, Ag, Co, natural graphite and Li (EC, 2016) may face supply bottlenecks in the EU due to the growing demand for RE technologies. Besides that, in the upcoming two decades, REE, Cu, Ni, Co, and Li are estimated to see the highest increase in demand (IEA, 2021d). The IEA (2021d) projects that meeting the climate goals set by the Paris Agreement and reaching the needed capacities of RE technologies would result in four times higher critical materials demand for energy technologies in 2040 than today. In turn, reaching the net-zero emissions scenario (IEA, 2021e) would result in material requirement rise by a factor of six in 2040. Shares of specific materials needed for clean energy technologies in the projected total material demand for copper, lithium, nickel, cobalt, and rare earth elements (neodymium) may rise, accordingly, to 45%, 90%, 60%, 66%, and 40% by 2040, respectively (IEA, 2021d). Another study by Calvo and Valero (2021) presents an analysis of materials availability estimations for the energy system by 2050 using specific material demand per RE technology obtained from Valero et al. (2018b). Using the production projection curves derived from Valero et al. (2018a) and based on the results of the demand analysis for the energy system, cobalt, nickel, lithium, and tellurium were marked as the most critical elements with high risk of becoming a bottleneck in the medium and long-term perspective, for which the annual demand is expected to exceed the projected annual production. However, such estimations were based on the rather conservative IEA scenarios, which project lower renewables capacities than needed for the net-zero emissions scenario. Cobalt, nickel, lithium, tellurium plus neodymium, dysprosium, and terbium are identified as "strategic" for the automotive industry and as valuable strategic components of electric vehicles (Iglesias-Émbil et al., 2020; Ortego et al., 2020). The overall materials demand of transitioning to 100% RE may be considerably higher (Goldschmidt et al., 2021; Greim et al., 2020; Junne et al., 2020; Li and Adachi, 2019), and considerable effort may be required to enhance efficiency of mineral production and use.

Mining is a very risky industry that could result in huge financial and ecological losses, and consequently, a mining project has a lead time of up to 30 years, to reach material production (IRP, 2020; MiningNews, 2020). Conversely, the need to counter the climate crisis requires a faster energy transition, which, in turn, requires increasing material supply. Thus, addressing the conflicting demand of both sides will require a coordinated global effort, so that material supply will not become a bottleneck to the global energy transition (IEA, 2023; IRENA, 2023; Lèbre et al., 2020; Sovacool et al., 2020). In this regard, clear understanding of current production volumes, resources, and reserves is required for appropriate energy system scenarios projections that are linked to the materials resource base, and, especially, for identifying potential limits and bottlenecks from a geological perspective. Any global-level criticality concept should focus on the sustainable energy system. The materials needed for such a transition should be defined as critical based on factors of its global reserves and resources availability, recycling and substitution opportunities, and production rates. Practically, the existing local methodologies to define critical materials can be adopted on the global level by shifting the focus to the global demand, sustainable development, and ambitious climate targets.

4.2. Research outlook

A further research should examine the links between raw material production and the growth of key technologies, emphasising that faster-growing RE capacity scenarios carry a serious risk of supply insufficiency or cross-sectoral competition for materials.

Addressing these challenges requires a proactive and comprehensive approach. Diversification and substitution of materials, coupled with advanced technology development, can help mitigate the risks associated with material shortages. Furthermore, embracing recycling and circular economy practices can enhance resource efficiency and reduce dependence on primary resources. Long-term cross-sectoral planning and international collaboration are essential to minimise the impact of material limitations and ensure a balanced and sustainable transition.

Therefore, to effectively address the challenges of material criticality, it is imperative to adopt a holistic approach that encompasses diversification, substitution, recycling, advanced technology development, and international collaboration. By doing so, one can mitigate the risks and create a more resilient and resource-conscious energy system. Continued research and analysis will play a crucial role in refining and informing these countermeasures as societies strive towards a sustainable and successful energy transition.

5. Conclusion

The need for the energy transition has increased the interest in the group of materials that are classified as critical. In this paper, the concept of criticality and its link to global long-term sustainability was analysed based on its relevance for the energy system transition towards sustainable energy technologies. The analysis was made using existing literature data as well as the material reserves, resources and historical production data collected from various sources. The logistic bell curve production projection was applied to understand the possible long-term issues for materials relevant to the emerging energy transition. The overall analysis shows that the present criticality concept is mainly driven by local short-term political concerns. As a result, the criticality list may be formed based on local consumer-centred policies as in the case of Japan and European countries or producer-centred policies as in China and Australia. This factor has contributed to the absence of a globally agreed critical material list. Besides that, it also compromises the possibility of mitigating the challenge of materials supply shortage for the transitioning towards sustainable energy technologies as it lacks the potential to create a unifying perspective for all stakeholders.

The analysis of the logistic bell curve production projections of selected materials shows that the long-term sustainability potential for antimony, cadmium, chromium, cobalt, copper, indium, molybdenum, nickel, silver, and zinc are severely threatened. However, irrespective of the material abundance, it can be concluded that all studied materials will eventually be severely critical. Such criticality challenges cannot be addressed using the localised short-term criticality concepts. However, the global criticality concept has the potential to coordinate all stakeholders by creating a new model that can enable material circularity based on proper understanding of material flows throughout the global economy. At the same time, due to the inherent risk associated to mining and availability of materials, the energy transition could be compromised.

A further analysis identifying a supply–demand balance of the energy-critical elements and possible short- and long-term bottlenecks based on well informed understanding of the role of all sectors is crucial. The competition for critical materials among different sectors of the economy should also receive proper attention to understand the overall risk to the global economy.

CRediT authorship contribution statement

Vitalii Lundaev: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **A.A. Solomon:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Tien Le:** Formal analysis, Investigation. **Alena Lohrmann:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Supervision. **Christian Breyer:** Conceptualization, Methodology, Validation, 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.

Data availability

I have shared the link to my data at the Attach File step

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Appendix A. Supplementary material

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