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Review article

Critical elements for a successful energy transition: A systematic review

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ABSTRACT

The transition to a low-carbon energy future requires large amounts of many raw materials. Some of these materials are deemed critical in terms of their limited availability, concentrated supply chain networks, associated environmental impact, and various social issues. Acknowledging the significant dependency on raw materials for future energy scenarios, this paper presents a systematic review of the existing literature to identify the barriers, solutions proposed and the current research gaps associated with the supply of a range of critical chemical elements. The focus was mainly on evaluating supply risk in light of raw material availability and contemporary extraction technologies. Results indicate that a transition to a low-carbon energy system is possible, but will require efforts to address supply concerns, and strategic planning. A key risk mitigation strategy is increasing material circularity, especially to cope with the growth in demand for cobalt in lithium-ion batteries, platinum used in fuel cells and electrolysers, iridium used in electrolysers and dysprosium used in permanent magnets. Copper was found to be possibly the most concerning critical element due to the expected demand from developing nations in addition to the demand for the energy transition. The geopolitical, social, and environmental risks for lithium, cobalt, rare earth elements and platinum group metals could also hinder future energy security, as demand for these elements continues to grow.

Introduction

There is growing global consensus that, to prevent the worst-case future climate scenarios and attempt to limit global warming to below 2° Celsius over pre-industrial temperatures, the industrialized world needs to rapidly embark on an ambitious twin transition to low-carbon electricity generation, and the simultaneous electrification of all energy-intensive sectors, first amongst which is the transport sector. However, key technologies to generate renewable electricity (e.g., wind and solar photovoltaics (PV)), and to store it for delayed use in multiple applications (e.g., lithium-ion batteries (LIBs)), are dependent on the supply of a range of specific chemical elements. As a result, the global demand for the latter is expected to surge in the coming decades. Specifically, the following groups of elements are recognized as essential to the functioning and integrity of a range of key energy technologies:

1. Lithium, Cobalt, and Nickel – used in varying proportions in most cathode formulations for LIBs.
2. Neodymium, dysprosium, and other "rare earth elements" (REEs) – used in permanent magnets (PMs) for electric motors and wind turbines.
3. Silver, Tellurium, Selenium, Gallium, Indium, and Cadmium – used in a range of PV technologies, including crystalline silicon (c-Si), and CdTe and CIGS thin films.
4. Platinum and other "platinum group metals" (PGMs) – used in catalysts for water electrolysis and "green" hydrogen production.
5. Copper – widely used in virtually all electrical applications.

With the transition to a low-carbon energy system, the current demand for and contributions (Fig. 1) of these elements to energy generation, storage, and transport technologies are expected to increase

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Abbreviations: BGS, British Geological Survey; B&C, Bars and coins; BEV, Battery electric vehicle; C&G, Ceramics and glass; CRM, Critical raw material; c-Si, Crystalline silicon; CdTe, Cadmium telluride; CIGS, Copper indium gallium diselenide; DFIG, Doubly fed industrial generator; DRC, Democratic Republic of Congo; EoL, End of life; EV, Electric vehicle; FCEV, Fuel cell electric vehicle; HREE, Heavy rare earth element; ICEV, Internal combustion engine vehicle; IEA, International Energy Agency; IEA – 2D, IEA "2-degree" scenario; IEA – B2D, IEA "beyond 2-degree" scenario; IEA – PVPS, IEA PhotoVoltaic Power Systems programme; LED, Light emitting diode; LIB, Lithium-ion battery; LREE, Light rare earth element; NdFeB, Neodymium-iron-boron; PEM, Polymer electrolyte membrane; PGM, Platinum Group Metals; PM, Permanent magnet; PV, Photovoltaic; REE, Rare earth element; TIM, Thermal interface material; USGS, United States Geological Survey.

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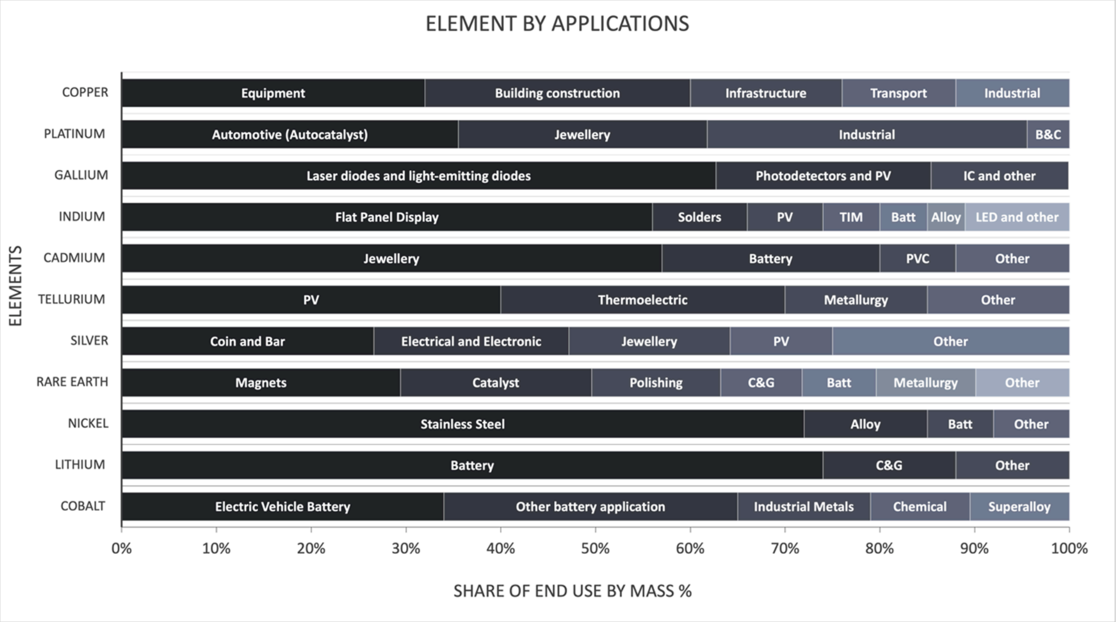

Fig. 1. Recent shares of end uses for each element under consideration here (except selenium, for which such information was not available). B&C = bars and coins, C&G = ceramics and glass and TIM = thermal interface material. Data year for cobalt, lithium, silver, tellurium, and platinum: 2021; for nickel, rare earth elements, and copper: 2020; for cadmium and gallium: 2019; for indium: 2012. Adapted from [12–19].

Table 1
Four main categories of risk associated with critical elements for the energy transition.

Category	Description
Geological availability risk	Issues related to the global supply of the elements (resource & reserve base).
Geopolitical/regional risk	Issues related to the element supply chain, its geographic distribution, and potential disruptions; vulnerability concerns for meeting demand in specific regions (also affected by price fluctuations).
Environmental risk	Issues related to associated air emissions and pollution to water and land.
Social risk	Issues related to miners and local communities (including: health & safety, financial risk).

significantly, leading to intensive competition with many other sectors. As discussed in a growing number of recent high-level reports published by a range of reputable organizations, amongst which the IEA [1], the EC [2–4], CSIRO [5], TNO [6] and the U.S. Geological Survey [7], a rapidly growing global demand for these chemical elements (and the natural resources in which they are found) runs the risk of triggering a series of associated supply chain “criticalities”.

First and foremost, amongst these criticalities is the risk of critical raw material (CRM) shortages globally, if the yearly demand outstrips supply capacity due to either limitations in total reserves, or in the maximum rate at which the parent resources can be extracted and processed using existing mining and refining infrastructure. Related to dwindling resources and the often-long lead time of mining projects, are then further geopolitical risks, often rooted in frictions caused by the specific geographical localization of ore deposits, and/or processing capacity. These geopolitical risks apply to many CRM supply chains, and are in many cases expected to increase supply pressure and limitations, potentially even escalating to open conflicts [8–9]. Furthermore, the mining industry is intrinsically highly polluting, and its expansion to keep pace with the surging demand for CRMs has justifiably led to significant environmental concerns. Also, relatedly, in many of the countries where CRM extractive activities are concentrated, health and safety regulations are lacking or not strictly enforced, resulting not only in contamination of ecosystems, but also direct health impacts on workers and communities [1,10]. The mining industry is also known to lead to increases in violence, child labour and other human right violations as the sector is weakly governed [11].

This paper presents and discusses the results of a systematic review of the available scientific literature on the four main categories of risk discussed above, and synthesized in Table 1, as they pertain to the critical elements required to enable a successful transition to a low-carbon energy future. Based on the evidence found in the reviewed literature, the authors will then attempt to provide preliminary answers to three related, overarching research questions, namely:

1. Which are the currently identified barriers in CRM supply for a transition to a low-carbon energy future?
2. To what extent are these barriers likely to constrain or otherwise affect the energy transition?
3. Which potential solutions have so far been identified to overcome these barriers?

Materials and methods

Literature collection

The primary aim of this review is to identify the challenges, barriers and potential solutions to a sustainable supply of the critical elements required to deploy low-carbon technologies on a global scale. The term “sustainable supply” is hereby intended to comprise both its literal root meaning (i.e., a supply which can be sustained in the medium-long term without disruption), and its extended connotations in terms of environmental and social impact. The systematic review process was structured following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology as far as possible [20], which allows for the transparent and unbiased collection of studies related to a set of research questions. The PRISMA Statement includes a flow chart and 27 items in the form of a checklist; these items are given in the Supplementary Materials 1 and 4, respectively. The sources were selected to guarantee the quality of the returned articles. Specifically, two main search engines were selected and used to retrieve peer-reviewed journal papers and editorials: Google Scholar (GS) and Web of Science (WoS). In addition, three publisher-specific search engines relevant to the field were also identified and used in parallel: Science Direct (SD), Nature Publishing Group (NPG), and MDPI.

The literature collection strategy used search keywords/phrases related to minerals, metals and energy, in line with the research questions presented in Section 1 and combined using Boolean operators. It is acknowledged that the very choice of search keywords/phrases inevitably influences, to some degree at least, the results of the search in terms of the articles that are returned, and hence also of the breadth of the information covered therein. In order not to pre-emptively bias the process in favour of any particular resource, the choice was made to employ general search terms such as, e.g., “critical mineral”, “strategic mineral” and “key mineral” instead of specific named elements, metals or minerals (the sole exception to this rule was the inclusion of the phrase “rare earth element”, due to the fact that, despite the specific chemical meaning of this phrase, referring to Lanthanides, the phrase is sometimes also used loosely to refer to other scarce elements in the earth’s crust). Also, the choice was made to mandate the inclusion in each search of either of the terms “energy transition” or “energy system”, in order to guide the literature collection towards those articles that specifically dealt with these core aspects of the intended focus of this review and reduce out-of-scope bycatch. At the same time to reduce the irrelevancy of search results, filters were applied. Given the different nature of each search engine, it was not possible to apply the same search strategy. The papers from research area of physics, biology and chemistry were excluded from the WoS search engine process to filter out papers related to experimental and laboratory-scale works.[1] In the case of MDPI, searches were done in four relevant journals: Energies, Sustainability, Minerals and Resources. In GS, where it was not possible to limit the search through options, certain words were explicitly excluded from the search (i.e., “biology” and “physics”[2]) to limit the number of irrelevant papers returned and reduce the burden of the subsequent manual screening stages. The asterisk (wildcard) symbol was used to target the same root keywords with different suffixes (not supported by SD and MDPI at the time of search). Searches were done using the “topic” field where possible (WoS and SD), which includes title, abstract and keywords. GS and NPG restrict searches to either the “title” or “article” fields, and hence for better comprehensiveness, the latter field was used in these cases; finally, MDPI is limited to the “keyword” and “title” fields, both of which were employed.

The initial results from the search engines were subject to a three-stage screening process; the methods of the screening process, inclusion/ exclusion criteria and data extraction process are provided in the Supplementary Material 1 and 2. Table 2 synthesizes the literature collection and screening process, including the list of keywords used and the paper tallies per search engine, at each stage of screening. A full list of the resulting 100 papers is provided in the Supplementary Material 3. A very few additional sources were later added during the data analysis and writing up stages, to fill in specific gaps in the reviewing process. The latter comprise 11 reports from geological surveys, raw material institutes and critical material reports, which are also reported in the

Table 2
Literature identification/collection process and subsequent screening stages.[1,2,3].

Search engine	Google Scholar	Web of Science	Science Direct	MDPI[2,]	Nature Publishing Group
Date of search (last updated)	13/Jan/22	14/Jan/22	14/Jan/22	14/Jan/22	14/Jan/22
Search fields → Search keywords/ phrases ↓	Article	Topic	Topic	Keywords and Title	Article
(“Critical Mineral*” OR “Critical Metal*”) AND (“Energy System” OR “Energy Transition”)	365	21	18	20	6
(“Strategic Mineral*” OR “Strategic Metal*”) AND (“Energy System” OR “Energy Transition”)	167	0	4	1	0
(“Key Mineral*” OR “Key Metal*”) AND (“Energy System” OR “Energy Transition”)	71	3	5	37	2
(“Mineral Supply*” OR “Metal Supply*”) AND (“Energy System” OR “Energy Transition”)	495	3	7	6	7
(“Mineral Availability” OR “Metal Availability”) AND (“Energy System” OR “Energy Transition”)	151	0	5	3	1
(“Rare Earth Element*”) AND (“Energy System” OR “Energy Transition”)	450	25	2	4	2
Total results from searches	1699	56	37	71	18
First Screening *Titles and Abstracts only*	208	34	10	12	7
Second Screening *Full text*	179	32	7	12	7
Duplicate removal	161				
Third Screening *Papers that fall under the research question*	100				

[1] Search phrases in GS excluded certain terms to reduce the subsequent manual screening burden, i.e., (“Critical Mineral*” OR “Critical Metal*”) AND (“Energy System” OR “Energy Transition”) -physics -biology.

[2] The search phrases did not include the use of asterisk (*) as this was not supported by Science Direct and MDPI at the time of search, e.g., (“Critical Mineral” OR “Critical Metal”) AND (“Energy System” OR “Energy Transition”).

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[1] It is however acknowledged that the WoS classification system into designated “research areas” may not be entirely faultless, and that as a result, in some rare instances, it may result in the inadvertent exclusion of individual papers which might in fact be relevant to the intended scope of this review.

[2] The word “chemistry” was not used as an exclusion criterion in GS because it was considered that doing so might have led to the loss of potentially relevant papers, since in this case the exclusion criteria apply to all instances of the use of the word itself within the article. This is different from the exclusion criteria applied in WoS, where the terms “biology”, “physics” and “chemistry” refer to the WoS’ own classification of the papers in the respective “research areas” (which pertain to experimental sciences and were therefore deemed out of scope).

[3] Searches were conducted in four specific MDPI journals: Energies, Sustainability, Minerals and Resources

Supplementary Material 1.

Statistical analysis of the screened literature

The collected literature, post-screening, was first analysed in terms of year of publication, with interesting results. As illustrated in Fig. 2, there was a sharp rise in interest in these topics beginning in 2018, and indeed it turns out that over half of the relevant literature was published during just 2020–2021. This is a remarkable finding because it clearly highlights how current and urgent the identified research questions are perceived to be in the wider scientific community, and it also indirectly underscores the timeliness of this review.

The papers were then categorized according to the four types of "criticalities" defined in Section 1, namely: supply risk on the global scale, supply risk on the regional scale (linked to geopolitical concerns), environmental concerns and social concerns. Given that several papers addressed more than one of these categories, the sum of the four individual paper counts is larger than the total number of papers remaining post-screening. As reported in Fig. 3, this second step of the statistical analysis highlighted a comparative larger emphasis on supply risk vs. the associated environmental and social concerns. This may in part be due to the sheer difficulty of collecting reliable quantitative information on the latter, but it also points to potentially significant knowledge gaps in terms of these important issues.

The third and final step of the statistical analysis involved categorizing the papers according to the elements taken into consideration, grouped according to their key roles in specific applications, as

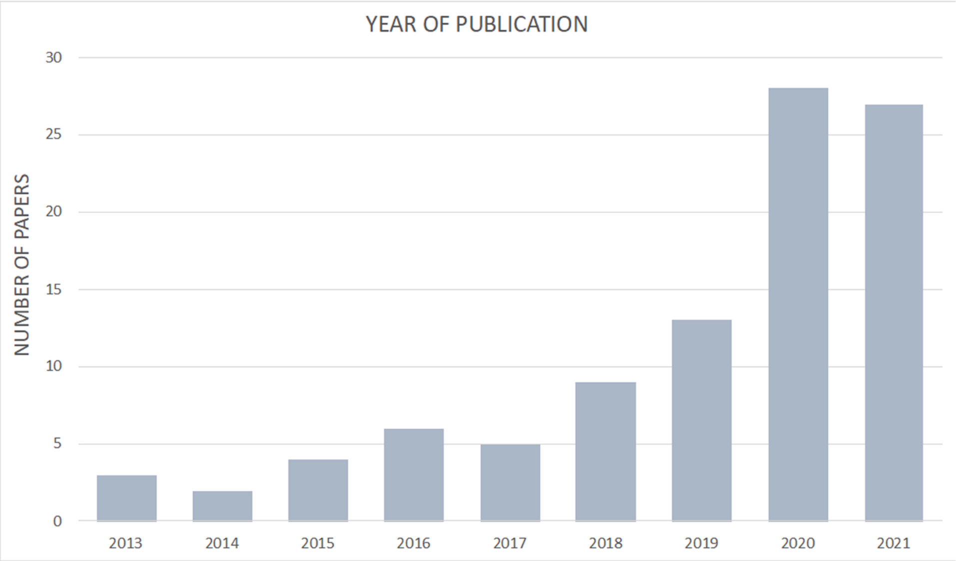

Fig. 2. Number of papers per year of publication.

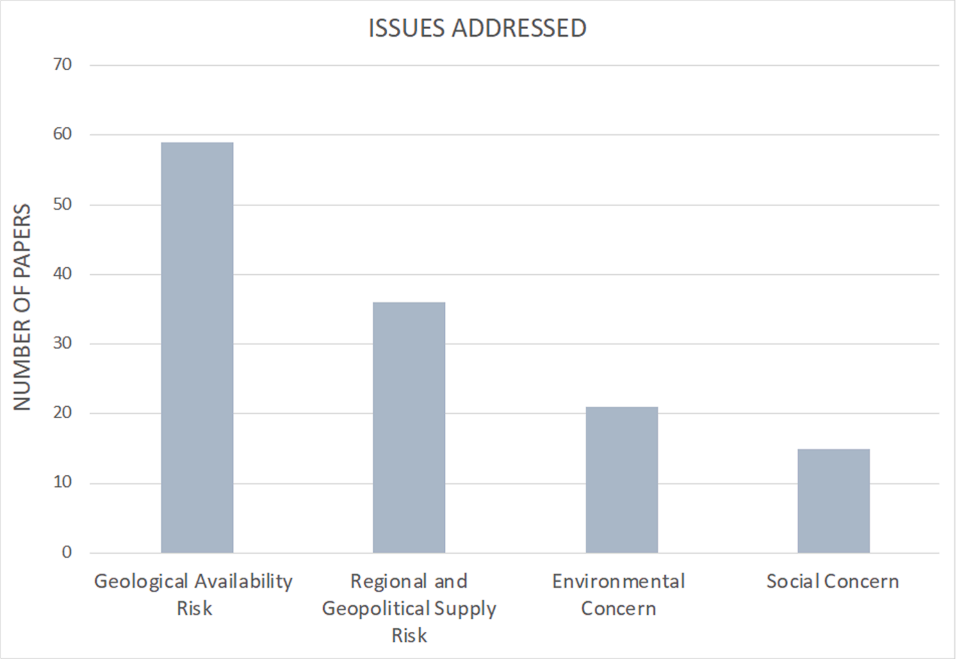

Fig. 3. Number of papers addressing each of the four types of issues/barriers identified in Section 1, some papers take into consideration more than one type of risks.

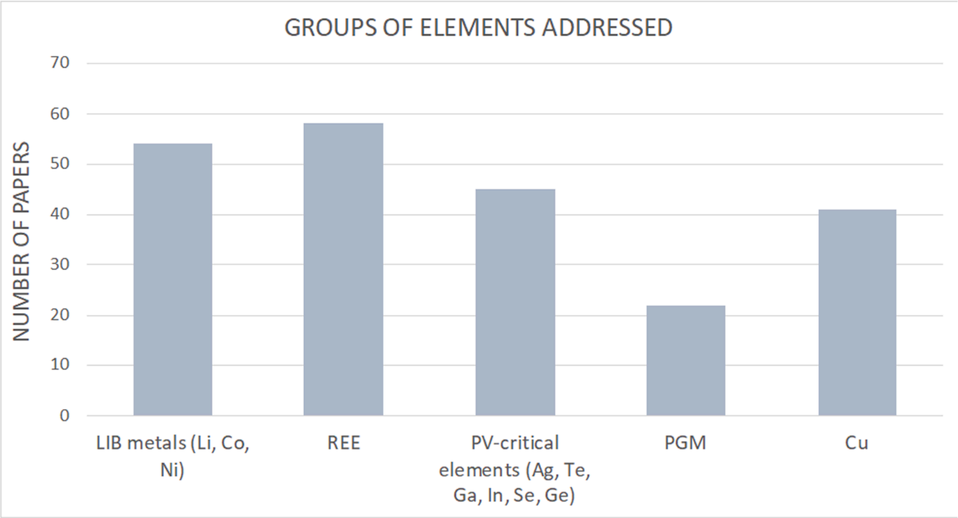

Fig. 4. Number of papers addressing each of the six groups of elements considered, some papers take into consideration more than one type of element category. REE = Rare Earth Elements; PGM = Platinum Group Metals.

discussed in Section 1, namely: elements for battery storage (Li, Co, Ni, Mn); elements for permanent magnets used in wind turbines and electric motors (REE); elements for photovoltaics (Ag, Te, Ga, In, Se, Ge); elements for catalysts used in "green" hydrogen production (PGM); and copper (used in all electrical applications). The resulting group-specific tallies are reported in Fig. 4. The two groups of elements that appear to have attracted the most attention thus far are the battery elements and the REE; it is noteworthy that both are key to enable the transition to electrical mobility.

Critical elements by key application

Elements for battery storage

With the transition to low carbon energy and transport systems there will be considerable demand for battery metals. The metals discussed in this section are lithium, cobalt and nickel, which are considered critical for the development of LIBs used for battery electric vehicles (BEVs) as well as stationary storage applications.

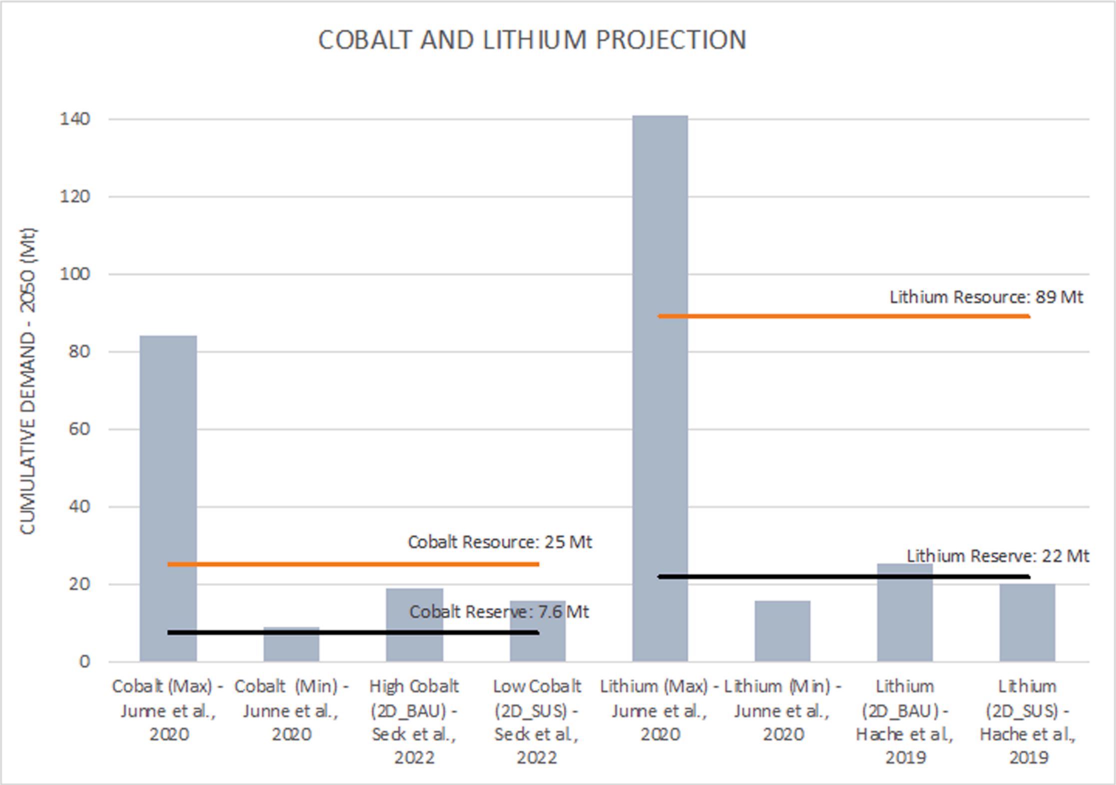

Fig. 5. Resource and reserve estimates and cumulative demand projections up to 2050 for lithium and cobalt in all sectors, adopted from [31,47]. 2D_BAU: 2-degree climate projection with "business as usual" and high mobility scenario; 2D_SUS: 2-degree climate projection with a shift to sustainable mobility and reduced number of private vehicles (both 2D BAU and 2D_SUS scenarios assume a recycling rate of 80.8% for cobalt used in EV batteries and no recycling for lithium).

Cobalt

Cobalt is extracted in 14 countries; more than 70 % of it is supplied from sedimentary deposits in the Democratic Republic of Congo (DRC), which represent almost 46 % of the global reserves, followed by reserves in Australia, Indonesia, and Cuba [21]. For clarification, the term "reserve" refers to the economically mineable mineral from discovered deposits, which depends on the technology used and the market value of the mineral, whereas "resource" refers to the estimated total amounts of discovered and yet-undiscovered deposits. Given that in most cases cobalt is a by-product of the extraction of copper or nickel, the processing is not optimised for cobalt recovery, therefore some of the cobalt ends up in tailings and slags after ore processing and refining. It is estimated that around 40–60% of cobalt content is lost during the concentration step, and specifically for the ores found in Australia, it is estimated that the recovery of cobalt is 40 % [21]. Cobalt, along with other battery elements, may also potentially be sourced from deep sea mining. Deep sea mining in the Clarion-Clipperton Zone (a geological submarine fracture zone of the Pacific Ocean, with a length of around 7000 km) could contain 5 times the cobalt reserves on land while potentially causing significantly lower carbon emissions per mass of metal extracted [22,23]. However, the full extent of environmental implications of deep-sea mining are still unknown and the biodiversity in the zone is insufficiently assessed [23].

Cobalt is often considered a critical element for EV development in the automotive sector [24,25], since it has been key in achieving higher gravimetric energy densities in LIBs (NMC and NCA cathode formulations). However, the large dependency on its centralised production in the DRC (a country with a long history of instability) and subsequent concentrated refinement in China has led to geopolitical concerns [26–29]. China is also a major manufacturer hub for EVs and LIBs, representing 45 % of global EV sales in 2020, followed by Europe and the USA [30]. These three regions will be the largest net consumers of cobalt without sufficient domestic production; hence it is important for these regions to implement recycling systems, not only to prevent wastage of material but also to mitigate supply risks [31].

Globally, the future demand for cobalt may grow nine-fold from 2020 to 2050, by which time up to 64.5 % of cobalt could be required by the transport sector [31]. In terms of geological availability, studies that conducted supply vs. demand analyses for cobalt showed that, without considering the on-going reduction in cobalt content in batteries and the role of recycling, the future demand for cobalt would undoubtedly exceed its current reserve level before 2050 [31–34]. When considering the future reduction of cobalt content in batteries (up to NMC 811), Seck et al. (2022), estimated that around 26 % (350kt) of cobalt can be saved by 2050 [31]. According to their analysis, the yearly demand for cobalt could decrease by 13 % by moving towards public and non-motorized transport; however, when considering the demand for cobalt from multiple end uses, the reserve is still expected to be exceeded by 2050, and 61.2 % of cobalt resources in 2013 would be depleted by 2050 (Fig. 5). Klimenko et al. (2021), examined the availability of cobalt by comparing future reserve estimates using historical trends. They analysed the requirement for cobalt considering both recycling, and the shares of cobalt-free and low-cobalt EV batteries. Under these conditions, the demand for cobalt in BEVs would hardly exceed a quarter of the prospective reserves by 2050, and by the year 2100 recycling would limit the demand to 55 % of the prospective reserves (if the recycling rate for cobalt is improved to 50 % by the middle of the century, from the current 30 %) [34]. According to the same authors, the future availability of cobalt will not just depend on aggressive reductions in cobalt content, but also on a move towards more sustainable mobility modes (including shared mobility and public transport), development of new mining technologies, exploration and increase in efficient recycling facilities.

Lèbre et al. (2020) carried out a global assessment of environmental, social and governance (ESG) risks associated with energy transition metals. Their findings indicated that these risks are significantly higher for cobalt than for lithium, mainly due to the social impact associated with cobalt mining [35]. The social concern for cobalt mainly stems from artisanal mining, which makes up 20–40 % of cobalt production in the DRC [19,21]. Without establishing responsible sourcing practices, artisanal mining can lead to compromising the well-being of workers for the short-term economic prosperity of the mining and trading industries. To reduce mining health and safety risks and avoid child labour, mining companies are being required to formalise artisanal mining, to provide standards for human security and ensure a more ethical and sustainable supply of cobalt [8]. In two recent formalization projects of artisanal mining in the DRC, namely Kasulo and Mutoshi, corporate engagement with artisanal miners increased their ability to source cobalt legally; however, these projects also shifted the risk of price fluctuation to artisanal miners, who are paid based on production output [36–37]. According to Jones et al. [38], cobalt being a by-product of nickel and copper makes supply and prices more volatile; this can cause the number of artisanal miners registered with mining cooperatives to fluctuate dramatically, depending on the market price of cobalt. Formalised artisanal miners are also paid lower incomes compared to trading professionals, and this is usually justified by the need to provide them with training, free personal protective equipment (PPE) and health systems (although safety is sometimes still not ensured, like in the case of Kasulo [37]. In terms of environmental and health risks, a survey conducted by Sovacool (2019) highlighted serveral issues, amongst which the contamination of rivers by washing of cobalt or waste dumping by artisanal miners, tailings from large mining site causing both air and water pollution, and the spread of diseases in mining camps due to lack of ability to maintain hygienic conditions [39].

Lithium

The major lithium resources are found in the so called "lithium triangle", which comprises regions of Bolivia, Argentina, and Chile that are rich in brine deposits, followed by regions with hard rock lithium deposits: Australia and China. In recent years, hard rock deposits have come to dominate the production of lithium, in the form of lithium concentrate which is then converted in a refinery plant to either lithium carbonate or lithium hydroxide [40]. This was not the case a few years back, when lithium from brine deposits represented the primary source of lithium, commonly traded as lithium carbonate. Lithium hydroxide has higher lithium content over lithium carbonate; hence it is preferred by LIB manufacturers; however, converting lithium carbonate from brine into lithium hydroxide adds extra cost to the refining [41]. China currently refines 75 % of hard rock lithium from Australia and 25 % of brine from lithium triangle countries. However, the shift in production from brines to hard rock, and the very concentrated refinement in China, entail an increased risk of supply chain disruption for other region planning on expanding their own battery manufacturing capacity [27,41–43]. Significant additional lithium resource is known to be available in Europe and Central Asia, diversifying production and bringing refinement closer to battery manufacturing could help increase productivity and reduce dependency on a few selected countries [44].

The demand for lithium for rechargeable batteries is expected to increase quite significantly in the coming years. Viebahn et al.(2015) estimated lithium demand for stationary storage and found that the demand is relatively low and not critical [45]; however, the growing demand for lithium for BEVs may create shortages. Based on multiple studies on material demand projections, it was found that lithium demand for BEVs may exceed the resource level by 2100, or the reserve and production level by 2050 [42,46–48]. In the short term, lithium supply and demand could be matched by increasing the production rate and scale, thereby reducing the near future supply risk, but new production start-up, which could take up to 10 years, and additional strategies would have to be implemented to cope with long-term demand [42,49]. Authors suggest that key factors in balancing lithium supply and demand in the long term will be: developing an efficient recycling system, increasing material utilization efficiency, substituting demand for lithium by diversifying transportation technology such as developing new battery chemistries, and, lastly, limiting light duty vehicle stock growth by spatial planning and promoting improved public transportation and shared mobility [34,38,47,49]. Klimenko et al. [34] pointed out that the current lithium recycling rate is around 3 %, and that it should be increased to at least 30 % by the middle of the century to overcome lithium shortage. Watari et al. [50] indicated that, by considering recycling and technology advancements, the divergence between lithium supply and demand can be reduced significantly. Imposing policies on producers to recycle could encourage markets for further recycling [51].

In terms of environmental issues, concerns over the intensive water use for lithium brine extraction and purification processes have been raised by several authors [35,42,43,52,53]. Water use is also seen as a significant social issue due to the pre-existing water stress around salt lakes experienced by local and indigenous communities. The extraction of brine water from surface and underground deposits to fill the evaporation ponds has led to ongoing groundwater depletion; the conversion from lithium brine to lithium carbonate is a further concern due to chemical leakage into the groundwater [41,43]. Based on a social study on lithium brine extraction conducted by Liu and Agusdinata [53], curbing mining water demand could significantly reduce the impact on local communities. Mulvaney et al. [52] suggested mining industries must aim to eliminate the use of freshwater and waste discharges. This can be done by employing alternative processes such as using more efficient materials, additives, or techniques to concentrate lithium such as through ionic exchange before sending the brine to the evaporation ponds [53]. Also, new projects are on-going to find alternative, more environmentally sustainable ways to extract lithium, i.e., using geothermal water in the UK, and using salt to extract lithium from clay deposit in US [53]. Lithium activity developed within the lithium triangle states also raises concerns by local and indigenous communities in terms of access to safe drinking water, land rights of communities, fair compensation and access to a safe environment [41,53]. The increase in social stress may result in strikes that could have far-reaching impacts on the supply chain [53].

Nickel

Nickel reserves have increased by more than 10 Gt since 2012 [19,54]. In terms of production, Indonesia is the largest producer of nickel, accounting for 37 % of total global nickel production in 2021, followed by the Philippines at 13 % [19]. China, Korea, Australia, and Indonesia are the most relevant countries for the nickel supply chain network [55]. Nickel is an essential element for LIBs used in BEVs, and battery chemistries are moving to higher nickel content. Wind turbines will also demand nickel in large amounts, but less than for the growth of the EV sector [56].

Studies examining the demand for nickel based on energy technology and vehicle projections found that nickel availability is not a constraint for the transition to a low-carbon energy future [46,57]. However, as for most materials with structural applications (currently, two-thirds of the nickel produced is used for stainless steel [58]), the increase in demand will not only depend on the energy transition but also, possibly primarily, on population and economic growth in developing countries [59]. Hence, neglecting to take account of the potential increase in Nickel requirement in developing countries may result in underestimating the total demand for this element. Guohua et al. [60] estimated the growth in nickel demand in China to 2050 for energy technologies, the vehicle fleet and other applications based on historical trends in population and economic growth, and they found that the cumulative demand in China is expected to reach between 59 and 79 %, or between 21 and 55 %, of global reserves in 2050, respectively without or with consideration of secondary supply (scrap and recycling). More than 50 % of the global reserve being consumed by a single region clearly suggests that nickel is critical in terms of geological availability.

In terms of social and environmental impacts, nickel causes higher

Table 3
Summary of key barriers/challenges and suggested solutions for battery storage elements (cobalt, lithium and nickel).

Category	Issues	Elements	Potential Solutions	References
Geological Availability Risk	Insufficient reserves and resource	Cobalt	Increase recycling and shift towards sustainable transport modes. Reduce the use for cobalt in batteries, improve material efficiency. Increase exploration and development of mining technologies.	[31,33,34,38,46,47,48,49]
	Reserves constraint	Nickel Lithium	Increase recycling and scrap supply. Shift towards sustainable transport modes.	[60]
	Low recovery of cobalt during extraction	Cobalt	N/A	[40,63]
Geopolitical and Regional Risk	Mining and/or refinery concentrated in a single region	Cobalt, Lithium	Increase and develop recycling in major consuming countries. Tailor trade strategies to reduce supply risk.	[26,28,29,41-43]
Environmental Risk	Contamination of water (lakes, rivers, or groundwater)	Cobalt, Lithium	Implement water management system such as water recycling process; aim to reduce wastewater discharge.	[39,35,43,52]
	Waste discharge to air and land	Cobalt, Lithium	Implement better tailings management; aim for waste reduction and recovery.	[52,39]
	Water scarcity and intensive water use for brine extraction process	Lithium	Recycle water, minimizing waste products; improve recovery efficiently by alternative materials and technologies such as pre-concentration using ion exchanger.	[35,43,52,53]
Social Risk	Health, well-being and safety risks of artisanal mining	Cobalt	Improve the provision of basic health and safety requirements at mining sites. Provide support	[35-37,39,52]

(*continued on next page*)

Table 3 (*continued*)

Category	Issues	Elements	Potential Solutions	References
			and training for other livelihood incomes. Establish community benefit agreements and integrate artisanal and large-scale miners.	
	Violation of local communities' rights: -Access to safe drinking water -Land rights of communities -Access to a safe environment	Lithium	N/A	[43]

land disturbance during mining, compared to lithium or cobalt [35]. Furthermore, the decreasing nickel ore grades are another significant concern, requiring more energy investment in the extraction process, and higher emissions and water use [59]. However, some authors have pointed out that thanks to an increasing secondary supply of nickel for energy transition technologies, the overall envionmenal impacts and water demand would decrease significantly [60–62]. The water consumption for nickel production in China could be reduced by 31–50 % when considering secondary supply. Currently, the end-of-life recycling rate for nickel is only 60 %, where more than 95 % of nickel is recycled in alloy form to produce stainless steels; however, such recycled nickel is not pure enough to be used in battery manufacturing [58,59].

Summary of elements for battery storage

Fig. 5 presents the demand projections for battery elements according to the roadmaps and technological improvement assumptions assumed in the reviewed studies, vs. the respective reserve and resource estimates. Table 3 summaries the key review findings.

Rare earth elements for permanent magnets in wind turbines and electric motors

Rare earth elements, especially neodymium and dysprosium used in neodymium-iron-boron (NdFeB) PMs, are critical for mainly offshore wind turbine generators and electric mobility motors. Their ability to provide high magnetic flux density and performance makes them suitable for the use in vehicle applications which call for lightweight and compact magnets, as well as for wind turbines, by allowing for a lighter turbine design, requiring less structural materials, and consequently fewer efficiency losses specially at low wind speeds [64]. The shares of REEs in NdFeB are mainly dominated by neodymium, which represents 29–31 % of the magnet mass, followed by dysprosium for higher temperature stability and sometimes in small quantities also praseodymium and terbium [64]

There is known to be no to very little economic extraction currently outside southern China and Myanmar for heavy rare earth elements (HREEs) such as dysprosium and terbium [65]; this is mainly due to the very low content of HREE in ores, usually less than 1 % outside of southern China [19]. Light rare earth elements (LREEs), on the other hand, like neodymium and praseodymium, are extracted more globally [66]. Overall, China is the largest producer for all REEs, accounting for 60 % of the production in 2021 [19,67]. Hence, the implementation of any domestic REE policies in China could have a significant impact on the stability of the wind turbine and EV markets, and potentially hinder their expansion outside of China; an example of this mechanism already played out during the global price spike due to the reduction in China REE export prior to 2012 [68,69]. Furthermore, Chinese mines usually operate at much lower metal price points than in the rest of the world, mainly due to the reduced costs of labour and environmental repercussion compared to foreign competitors, which makes it difficult for mining companies outside of China to financially survive without agreements to secure revenues for their future output of REEs [66,67]. In terms of resource availability, however, North America and India actually have large REE deposits; in particular, Greenland is also characterised by very low geopolitical risk, making it an attractive region for future REE production [69,70]. OECD Europe region has a limited amount of REE reserves and very low production capacity, making this region highly dependant on imports [69]. Authors that have investigated vulnerability and potential conflicts between REE demand and supply have suggested that it is vital to be able to diversify the supply chain outside of China to prevent a monopolistic structure, especially with the growing demand for energy technologies, as this could intensify geopolitical and environmental constraints [69,71].

Studies that have focussed on the simultaneous growth expected in the wind turbine and EV sectors found that the supply for REEs is expected to be dominated by road transport due to the high market share of EVs utilising permanent magnet motors [34,47,71]. A significant scale up in production volume is required to support the future growth of wind turbines and EVs, by a factor of up to 35 for HREEs and 9 for LREEs, relative to current production rates [47,69]. Furthermore, studies considering the simultaneous growth in both sectors have found that the demand for dysprosium is expected to exceed the current known reserves, making this element a potential bottleneck for the energy transition in lack of an effective and adequate recycling infrastructure [64,47]. Junne et al. [47] suggested the need for a recycling rate of 80 % to prevent dysprosium bottlenecks. The only major market for dysprosium is permanent magnets and hence it should be relatively manageable to target this element for recycling (e.g., recovering it from recycling hard drives) [72]. However, considering the current low recycling rates for REEs in general (15 %), significant improvements will be required to meet the desired proportion of demand through recycling, such as: reducing the energy consumption associated with the recovery, increasing the purity of recovered materials, recovering from residues and scrap, imposing responsibility for collection and recycling [51,73,74]. According to Klimenko et al. [34], ongoing efforts in exploration and improvements in mining practices, coupled with technological advancements, may enable continued growth in REE reserves, following historical trends, which would mean that global demand for REEs would not be an issue.

Other authors have suggested substitution to reduce the REE demand for energy technologies [45,75]. For the case of onshore wind turbines, doubly fed induction generator (DFIG) wind turbines could easily replace PM-based turbines, but this would not be economical for the case of offshore installations, because DFIG turbines require more costly maintenance. According to Smith and Eggert's study based on expert responses [68], moving to new production processes to reduce the dysprosium content in the magnet by 40– 50%, such as the use of dual-alloying or grain boundaries diffusion, would be the most favourable strategy. Substitution between HREEs is also possible to achieve magnetization over a wider temperature range; for instance, terbium can completely substitute for dysprosium. According to a study done by Rollat et al. [66] and Elshkaki [76], as light emitting diodes (LEDs) take over from fluorescent lamps in the coming years, the demand for terbium will decrease, in which case the ensuing excess supply of terbium could replace dysprosium in NdFeB magnets as a possible strategy in the near future, thereby helping to cope with a possible dysprosium shortage. Similarly, it is possible to reduce the supply constraint on neodymium by increasing the praseodymium content using didymium (i.e., unseparated NdPr alloy) [68]. Another type of

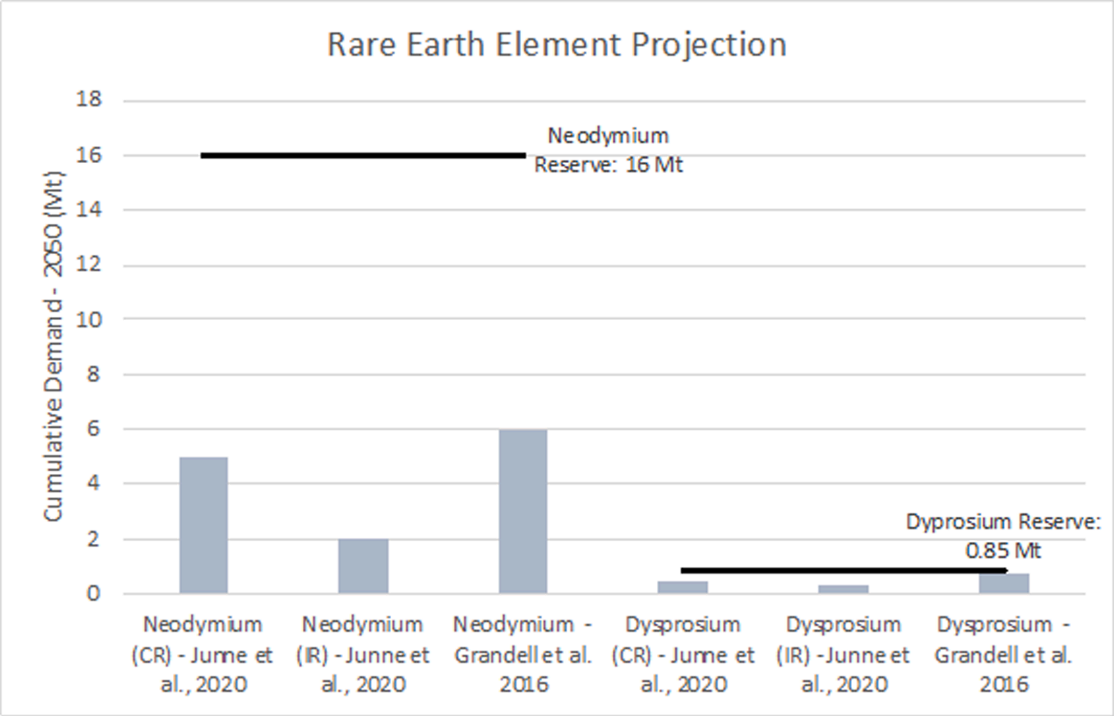

Fig. 6. Reserve estimates and cumulative demand projections for Neodymium and Dysprosium in all sectors, adapted from [47,64]. CR: Current recycling rate; IR: Improved recycling rare. Resource estimates are not available in the literature for REEs.

substitution is using ferrite magnets, relieving the geopolitical risk associated with REEs altogether; however, this is considered to be the least viable option for wind turbine manufacturers, as ferrite magnet are much heavier, and they would require a lot more materials for the structural support for the wind turbine, with adverse economic effects [68,75,77]. Also, for the case of EVs, switching to ferrite magnets would be unfavourable as it would constrain the travel range of the vehicles. Some automotive companies have already started to reduce the use of permanent magnets in EVs by using induction motors or round-wound design based on copper [47].

In terms of environmental and social implications, there have been serious concerns related to the extraction and refining of REEs, mainly due to the co-presence of radioactive elements, and due to the chemicals used in the leaching process, which result in radioactive waste and other toxic pollutants leaking into the wastewater, waste gas and land during the extraction and refining process [78–80]. These issues are also amongst the reasons hindering the production of REEs in many regions of the world [69,76,81]. However, the environmental impacts in most categories were found to be more intense for Chinese deposits compared to deposits in other regions [76]. Recent health impacts of REE processing and illegal mining in China have raised major concerns due to contamination of water and land, and also a REE refinery plant in Malaysia is facing closure due to public concern on radioactive waste [69,80,82,83]. Microbial processes are currently used for the removal of several harmful substances in mining waste; similar processes could be used in the future to also extract and recover REE from waste streams

Table 4
Summary of key barriers/challenges and suggested solutions for rare earth elements.

Category	Issues	Elements	Potential Solutions	References
Geological Availability Risk	Insufficient reserves	Dysprosium	Increase recycling of magnets by imposing legal responsibility and improving recycling efficiency. Replace production process by dual alloying or gain boundary diffusion to reduce dysprosium content; replace dysprosium by terbium. Improve efficiency of mining and chemical processing to maximize metal output from ores Possible recovery of dysprosium from dilute ores or industrial and other waste streams Exploration and development of REE mining.	[34,48,64,68, 69,74,82]
Geopolitical and Regional Risk	HREE mining limited to mostly China and Myanmar LREE mainly concentrated in China Lack of reserve availability in Europe	Dysprosium, Neodymium	Increase investment in REE mining outside of China. Increase recycling and substitution.	[66,68,69,70, 71,82]
Environmental Risk	Co-presence of radioactive elements; contamination of water and land Lack of environmental investment in Chinese mining	Dysprosium, Neodymium	Implement and monitor proper waste and safety regulations to ensure appropriate prevention of exposure to workers and communities. Extraction of REE and harmful substances from waste stream using bioleaching techniques to reduce harmful accumulation.	[69,73]
Social Risk	Illegal production in China Health problems associated with mining and refinery of REE	Dysprosium, Neodymium	Enforce strict regulation and stable pricing of REEs. Protect labour rights and provide a safe working environment.	[78–80]

[73]. Proper waste and safety regulations would need to be implemented and monitored to ensure appropriate prevention of exposure to the workers and communities, as well as prevention of contamination of wastewater and release of tailings to the environment [69,79]. Furthermore, measures to prevent illegal mining in China still need to be implemented, such as strict regulation and stable pricing to discourage illegal activities and associated social and environmental implications [83].

Summary of rare earth elements

Fig. 6 shows the demand projections for neodymium and dysprosium, according to different scenarios assumed in the reviewed studies, vs. the respective reserve estimates (resource estimates are not available in the literature for REEs). Table 4 summaries the key review findings.

Elements for photovoltaics

This section discusses some of the key elements used in PV technologies and their implications on the potential for future growth of these technologies. The elements discussed are silver used in crystalline silicon (c-Si) solar cells; tellurium and cadmium used in cadmium telluride (CdTe) solar cells; and indium, gallium and selenium used in copper indium gallium diselenide (CIGS) solar cells. Currently, c-Si makes up the majority of the PV market share, whereas CdTe and CIGS thin films comprise less than 10 % of the total PV market [84]. Other, third generation PV technologies such as perovskites are not discussed in this paper since it is still unclear whether they will become a commercial reality.

Silver

Silver is used as part of a conducting paste in c-Si cells to provide high electrical and thermal conductivity to improve the cell efficiency. Silver reserves have declined since 2015 from 570 kt to 530 kt [19], and this could be a concern if the demand for silver continued to grow. Currently, 11 % of global silver demand is used by the PV sector [14]. In the production of c-Si cells, however, the demand for silver per unit of PV peak power has been reduced from 82 t/GW in 2010 to 35.6 t/GW in 2014, and it is expected to be further reduced in the coming years, or even substituted by other less critical or cheaper metals such as copper, nickel or zinc-copper alloys [19,85,86]. 70 % of Silver is mined as a by-product of copper or lead-zinc deposits [14,19], mainly in Mexico, China, and Peru. Silver production and known reserves are more regionally distributed as compared to other critical elements used in the PV sector.

The current global demand for silver used in solar technologies is low compared with current production and reserves [32,86]. However, based on the reviewed studies, there is disagreement on future silver availability. A recent review by Lee et al. [28] indicated that the demand for silver may reach 70 % of current reserves by 2050, whereas other studies indicated that silver availability will not be a hinderance to PV growth [87]. It is noted, though, that those studies that indicate reserve constraints are often based on obsolete estimates of high silver content in c-Si (133 t/GW–80 t/GW), and have not considered the ongoing reductions in silver content [33,88]. Other studies that do consider such reduction in silver content, instead, indicate that the availability and production of silver will not be a constraint for PV industry through to 2060. Davidsson & Höök [87] estimate that the total global requirement for silver for c-Si PV could decrease from 66 % to 12 % of the 2015 reserve, assuming that silver intensity is reduced from 35.6 kg/MW to 1 kg/MW by 2050. Similarly, for PV growth in China, reducing silver intensiy would lead to only using a small proportion of the total reserve, approximately 6% [85]. Furthermore, it was found that future changes in the lifetime of PV would only have a small impact on reducing the cumulative silver demand [85]. Davidsson & Höök further estimated that if recycling of silver takes place from PV panels, it will provide 32 % of cumulative silver demand by 2050; additionally, most silver from recycling will only become available when the demand for silver for new c-Si PV is significantly reduced, or even when silver has already been phased out altogether [87]. Hence, according to these authors, there could even be a possibility of oversupply of silver for the future of the PV industry. In terms of environmental impact, silver is burdened by the highest global warming potential and cumulative energy demand per unit of mass, compared to all other elements discussed in this section. However, silver is used in very small quantities in c-Si PV, which reduces its contribution to PV's overall impact [89].

Tellurium

Tellurium is extracted as a by-product of copper through the refinement of anode slimes, with a low recovery rate of 30–50 % [90]. Decreasing copper grade ores could hinder the future supply of tellurium by further reducing its recovery rate from copper refinement, or because of a shift to more economical ways of refining copper which may not involve the recovery of tellurium at all. According to USGS, in this latter case gold deposits with high-grade tellurium could become the new primary source of tellurium [90]. Current global tellurium production is estimated to be 580t/yr, of which China represents almost 60 %. China is also the main exporter of raw tellurium, followed by exports from Canada, the USA, Japan and the EU. Canada plans to produce ultra-high-purity (99.9 %) tellurium in the coming years [19]. Since copper ore is mined all over the globe, tellurium supply concentration is not a major concern at present. However, it is uncertain what the supply risk would look like in terms of possible constraints on the recovery rate. Tellurium is used in various applications beside thin film CdTe PV, such as in thermo-electrics and as an alloying additive (representing 45 % of the tellurium demand). Most tellurium applications are highly dispersive, and the element is barely recovered, except for tiny amounts from older plain-paper copiers and from CdTe solar cells [19]. Both the future CdTe PV market share and metal intensity play a vital role on the future availability of tellurium [32,86,87]. With recent technological improvements, current tellurium intensity in CdTe PV is estimated to be approximately 60 t/GW, based on First Solar's Series 6 CdTe PV panels with a module efficiency of 19% [84,91] and lower values have been projected for the future with maximum decrease in the literature from 20 to 12 t/GW by 2050 [86,87,92]. Studies based on the "2-degree" IEA projection indicated that if CdTe PV market share increases to 15–25 % (out of 4 TW by 2050), improvement in tellurium intensity could prevent reserve depletion, however when considering demand from other sectors improvement in intensity will not be enough to prevent reserve constraint. Caution should be exercised considering possible competing demand for other applications and limitations in production capacity [32,86,87].

Cadmium

Cadmium is extracted as a by-product from smelting zinc and lead-zinc ores [19,93]. Almost 60% of cadmium is produced mainly in East Asia, and the global production of cadmium is around 24 kt, out of which less than 1% is used for manufacturing CdTe solar cells [19,94]. The estimated total reserve has not been reported by USGS [19]. Past and current predictions on cadmium intensity in CdTe in the literature range between 21 and 138 t/GW [45,86,87]. The latest industry-vetted information reported in the IEA PVPS report on LCI of PVs indicates a cadmium intensity of approximately 50 t/GW, based on First Solar's Series 6 CdTe PV panels [91]. Calvo and Valero's review [57] stated that in the medium term, problems related with cadmium availability are unlikely. The amount of cadmium production from 1900 to 2014 has been found to be far greater than the projected amount of cadmium requirement for CdTe PV up to 2050, indicating that a significant share of cadmium demand could be met with secondary resources [87]. However, at the moment only a small amount of cadmium is reported to have been recovered from NiCd batteries [19]. According to Calvo and Valero, cadmium is not usually considered critical as its use in the future may be further restricted, like in the case of mercury [56]. However,

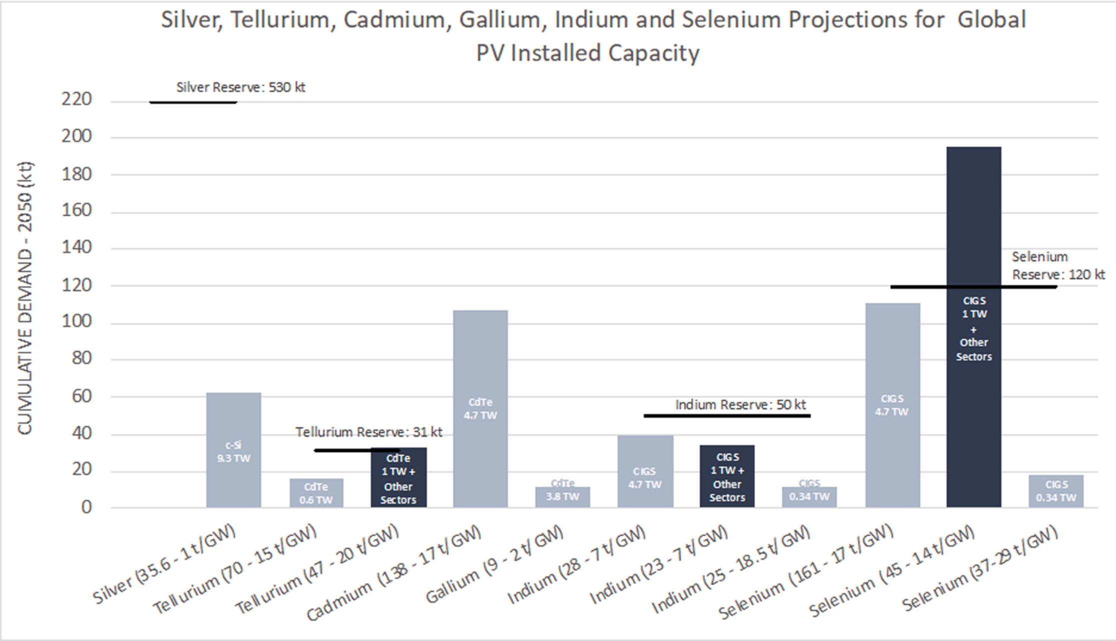

Fig. 7. Reserve estimates and cumulative demand projections for silver, tellurium, cadmium, gallium, indium, and selenium based on decreasing intensities in PV manufacturing (indicated along the x-axis, in brackets) and expected installed capacities to 2050 (indicated within each bar), adapted from [32,87,92,106]. Reserve estimates for cadmium and gallium are unavailable. Resource estimates are not available in the literature for any of these elements.

Elshkaki and Shen [95] argue that as CIGS PV market penetration grows, the demand for germanium and indium extraction from zinc production will also increase, and hence consequently cadmium production too, as a companion metal.

In terms of environmental considerations, cadmium is a highly toxic metal and cadmium disposal is connected to environmental hazards and may lead to serious health risks due to Cd exposure [85,93]. However, since cadmium is contained in zinc ores and it is inevitably mined with them and generated as a by-product or waste product of Zn production, the increased use of cadmium in CdTe PV may end up being beneficial to the global environment by allowing its sequestration from otherwise potentially harmful left-over stockpiles at mining sites [96].

Indium

Indium is an important metal for CIGS solar cells and flat panels displays, specifically in the form of indium tin oxide (ITO), of which CIGS represent 8 % of total demand [97]. A small amount of indium is also used for the electronic components of passenger vehicles and in nuclear power plants, representing on average 0.4 g/vehicle and 1.6t/GW respectively [56,88]. Indium production is similar to its companion metal cadmium and is also a by-product of zinc refining [93,98]. Around 80 % of the current indium supply is mostly concentrated in East Asia and has a high degree of concentration by country (the same applies to tellurium and gallium) [19,98]. The main reason for this is that not all countries use their refinery potential for these elements that are extracted as by-products [99]. China represents the main share of global indium reserves, however in the future China's domestic demand for indium may outstrip its domestic reserve before 2050 [52,85]. This is not only likely to hinder supply in China but in other nations relying on indium imports from that country.

There have not been any official figures in term of global indium reserves published recently, but reserves used in some studies are estimated to range between 11 and 50 kt [33,87]. Based on a 2014 study, indium intensity in CIGS PV may range between 9.8 and 23.1 t/GW [100]. The latest IEA PVPS LCI report [91] indicates 2.82 g/m^2, which at 16 % module efficiency translates to 17 g/kW (= t/GW). Watari et al. (2018) examined indium requirement for CIGS PV based on the upper end of the range, and they found that assuming IEA "beyond-2-degree" projections, the demand would exceed the reserve and resource base by 2050, if CIGS were to even represent 20 % of the total installed PV capacity [33]. Even if the indium intensity were to decrease to around 7.5 t/GW, it was also found that 4.65 TW of installed CIGS PV would still either exceed or be close to the current known reserve by 2050 [87]. Therefore, securing indium demand for CIGS PV seems to be a challenge, and coupled with competing demand for other applications, it seems likely that indium will be a high supply risk element [45,94,99,101]. There is very little information presented in the literature on end-of-life indium recovery. In Japan and Korea, indium is mostly recovered from ITO scraps [19]. However, end-of-life recycling of indium is less than 1 % overall, and this can be explained by the small quantities of indium used which makes it difficult to separate for recycling [33,99]. Another possible recovery route is from mine waste [85]. It is reported that around 60 % of the Indium or more is lost during mining and processing, mainly due to low recovery from smelting facilities [99,102,103]. Additionally historical mine waste contains large amount of Indium, for example, lead smelting in Namibia's Tsumeb mine between 1963 and 1996, contain 490 t of indium, but historical mines are reported inaccessible due to environmental concerns [101]. Indium is known to be hazardous to human health, and there are reports of lung disease from exposure to indium in manufacturing processes [103].

Gallium

The main applications of gallium are semiconductors of which less than 3 % of total gallium production was used by CIGS solar cell in 2019 [104]. EVs also contain gallium but in very small amounts [56]. Gallium is produced as a by-product of bauxite processing and the rest comes from zinc residue processing. There are no published reserve estimates for gallium; the resources for gallium are quite abundant, but they occur in very small concentrations: the average gallium content of bauxite ore is quite low, between 0.003 and 0.008 %, out of which only 10 % of gallium is recoverable [19,93]. The global production for gallium in 2021 was around 430 kt, China being the largest and only major producer representing 98 % of Gallium. However, Australia, Brazil, Guinea and India represent significant production shares of bauxite, and could be future sources of gallium [19]. Studies have shown future gallium production though to 2050 for CIGS could be around 3 times 2017

Table 5
Summary of key barriers/challenges and suggested solutions for PV-critical elements. No social risks were provided within the literature for PV critical elements.

Category	Issues	Elements	Potential Solutions	References
Geological Availability Risk	Insufficient reserves	Tellurium Selenium Indium	Increase recovery from electrolytic copper and zinc refineries. Increase recycling and scrap supply from mine waste.	[48,87]
	Low recovery during extraction	Tellurium, Selenium, Gallium Indium	Improve recovery rates and refine mine waste (significant quantities available in tailings, slags, smelting, and refining processes for recovery of host metals). Have smelters with indium recovery capabilities to reduce losses.	[19,63,101,102]
	Recycling Barriers: -High dispersion losses for tellurium gallium and selenium -Low concentration uses in end products for indium	Tellurium Gallium Selenium Indium	Improve recycling and collection of EoL products (e.g., LCDs for indium).	[19,103]
Geopolitical and Regional Risk	Mining and/or refinery concentrated in a single region	Tellurium, Indium Gallium	Diversify supply by increasing refining and treatment at host element extraction.	[99,106]
Environmental Risk	Highly toxic	Cadmium	Increase use of waste cadmium to prevent harmful accumulation of cadmium in ecosystem.	[85,93]
	Mildly toxic, exposure hazardous to human health	Indium	N/A	[103]

production or 3–11 times the cumulative historical production between 1973 and 2014, if gallium utilization intensity in CIGS were to remain constant in the future [87,92]. If demand starts to increase, gallium production can be started at many bauxite and zinc refineries [94,99]. For example, Germany announced restarting primary gallium production in 2021 due to the recent increase in gallium prices [19]. Thus, gallium availability is far from its maximum production levels. In terms of recycling, similar to tellurium, the recovery of gallium is negligible due to its high dispersion because it is used in very small amounts in many applications, making it difficult to recover [56]. The only exception is the recovery of gallium from scrap generated during the manufacturing of GaAs devices [19].

Selenium

Selenium is mainly used in metallurgical processes, whereas less than 10 % of global production is used for CIGS solar cells [97]. Selenium is extracted in the same way as tellurium through copper refining, and China and Japan make up more than 50 % of selenium production [19]. However, much like silver, selenium is mined in many different countries. According to Buchholz and Brandenburg (2018), market concentration is moderate, and selenium has a low risk associated with country-specific supply [97]. The global reserve for selenium is estimated as 100 kt based on copper deposits. Additionally, very small quantities are also processed as a by-product of nickel, iron, and zinc refineries [92,97]. Current selenium content in CIGS PV is reported by the latest IEA PVPS LCI report [88] as 5.6 g/m^2, which at 13 % module efficiency translates to 43 g/kW (= t/GW). It has been calculated when taking account of other end uses and if the intensity of selenium in CIGS PV were to drop to 14 t/GW, for 1 TW installed capacity of CIGS PV by 2050, this will well exceed reserve [91]. Even if new metal refineries for selenium production could be built to alleviate some of the availability constraint, this is unlikely to be enough to overcome selenium requirement. Currently selenium is recovered from old photocopiers and printers [19,105]; however, like gallium and tellurium, most selenium consumed is dissipated into the environment and is not recoverable [105].

Summary of elements for photovoltaics

Fig. 7 presents the selections of demand projections for PV-critical elements, according to different scenarios assumed in the reviewed studies, vs. the respective reserve estimates (resource estimates are not available in the literature for these elements). Outdated/obsolete assumption on metal intensity for PV are omitted. Table 5 summaries the key review findings.

Platinum group metals for catalysts used in hydrogen production

Platinum group metals (PGMs) are currently widely used in catalytic converters of internal combustion engine vehicles (ICEVs) operating on fossil fuels, to remove harmful combustion chemicals from their tailpipe emissions: around 39 % of platinum, 50 % of palladium, and 83 % of rhodium are used by the automotive industry for catalytic converters [107]. With the move towards low carbon transport systems and EVs, the demand for PGMs for automotive catalytic converters is expected to drop; however, at the same time PGM use in water electrolysers for the production of “green” hydrogen to be used in fuel cell electric vehicles (FCEVs) and for stationary storage is expected to increase significantly in the coming decades [108,109]. Looking into the geopolitical findings, PGMs suffer in terms of concentrated production in politically unstable countries, which may lead to large price fluctuations and shortages [107,110,111]. For instance, in 2014, a strike by 70,000 workers due to a labour dispute in South Africa led to a 40 % decrease in global PGM supply [108]. The largest PGM reserves are found in South Africa, accounting for almost 90 % of the total reserve, and the production of platinum and palladium specifically is mostly dominated by South Africa and Russia, accounting for 40 % of palladium and 72 % of platinum [19]. Zimbabwean production of iridium has increased by 40 % over the past 5 years due to their on-going mine expansion; however, Zimbabwe is also associated with political instability [112]. Platinum and palladium can be substituted for one another in catalyst applications, in response to changes in their individual market prices, and it is expected that the same may apply to fuel cell applications too [29,107]. Furthermore, significant amounts of PGMs are also lost during extraction; for platinum this represents almost 32 % of the total loss [108]. Long term strategies are needed not just to diversify supply, but also to

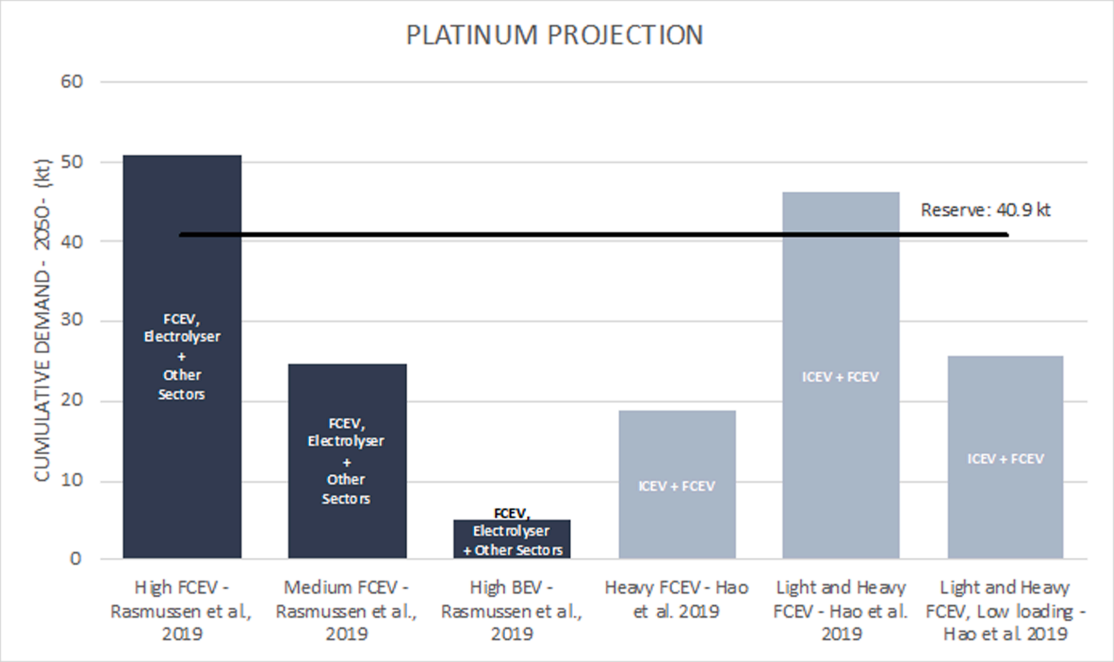

Fig. 8. Reserve estimate and cumulative demand projection for platinum up to 2050, adapted from [107,108]. ICEV = Internal combustion engine vehicles, FCEV = Fuel cell electric vehicles and BEV = Battery electric vehicle. High FCEV = 30% of the vehicle share is FCEVs. High BEV = 80% of the vehicle share is BEVs and the rest is ICEVs. Resource estimates are not available in the literature for PGMs.

improving co-production rates and better utilization of mine waste [108].

One of the most concerning issues in fuel cells and water electrolyzers is the actual PGM content in the electrodes. PGMs are used in polymer electrolyte membrane (PEM) electrolyzers, mainly in the form of platinum cathodes and iridium anodes [109,111]. In terms of potential future supply constraints for water electrolysers, platinum is regarded as a medium-high supply risk, and iridium a high supply risk [113]. Rasmussen et al. [108] estimated the future demand for platinum based on different scenarios for both fuel cell growth and electrolysers, while taking account of other end uses; they indicated that future platinum supply could face a geological availability constraint if the share of FCEVs rises over 30 %. Currently, around 10 g of platinum is needed in a FCEV, which is quite high compared to 1.24 g used in an ICEV [109]. An initial transition of ICEVs to BEVs could provide a surplus in platinum outflow, enabling early platinum demand for FCEV adoption. Subsequent achievement of a closed-loop recycling rate of 90 % for platinum could meet up to 75 % of gross FCEV demand for this metal through to 2100, hence alleviating supply risk [107,109]. This seems to point to a potential synergistic strategy in transitioning first light duty vehicles (LDVs) to battery electric power trains, and then heavy-duty vehicles (HDVs) to fuel cell electric power trains. As for other PGMs, demand for palladium and rhodium will decrease due to the phase out of ICEVs, which could potentially be used to substitute platinum and iridium in many applications [108,109]. Minke et al. [111] investigated the demand for iridium in electrolysers up to 2070, and they suggested a minimum 90 % closed-loop recycling and a reduction in iridium content to 0.05 g/kW to prevent a possible iridium bottleneck. Currently, recycling accounts for around 11 % of platinum supply, mainly from industrial uses and the jewellery sector [52,109]. Although PGM recycling rates from the automotive sector have reached up to 50–60 %, collection losses are still high at 30 %. Also, PGM recycling rates in many countries are still low, like e.g., less than 10 % in China [108,109]. Hence, there needs to be significant improvement in establishing better collection and recycling infrastructure, especially in developing nations [108,109]. A study conducted by McLellan et al. [114], assuming a higher reserve of 81kt by taking account of deep-sea deposits, found that there would be no supply constraints; however, that study did not consider the demand for FCEVs. Furthermore, when compared to other metals, PGMs are already known to cause the highest environmental impacts during their production, and in the case of deep-sea mining, the additional environmental implications is likely to cause hinder [52,114]. Social concerns of PGMs stem from high labour-intensive extraction processes and declining ore grades, coupled with unfair wages and safety issues in South Africa, which often give rise to disputes and violence in the region [108,112].

Summary of platinum group metals

Fig. 8 presents the demand projections for platinum, according to different scenarios assumed in the reviewed studies, vs. the respective reserve estimate (resource estimates are not available in the literature for PGMs). Table 6 summaries the key review findings.

Copper

Copper plays a vital role in the development of the on-going energy transition, from building new cables for expanding grid infrastructure to supporting the growth of energy transition technologies [80]. Copper demand is expected to grow due to the demand for new power distribution lines and its intensive use for wiring in most low carbon energy generation and transport technologies, in addition to the expected increase for copper in developing countries for various applications [28,56,59,94,106,114]. Switching from ICEVs to EVs would require more than three times the amount of copper per vehicle, whereas a solar power plant requires up to four times more copper for the same installed capacity than a thermal plant and wind turbine would require six times more copper than a nuclear power plant [33,115]. Furthermore, Henckens and Worrell [59] pointed out that although copper demand is stabilizing in developed countries, primary copper production is still increasing rapidly with a 2.8% annual increase. Copper is also a host metal for other by-product metals (cobalt, tellurium, silver, molybdenum, and germanium) which are used in the manufacturing of solar panels and EVs. Therefore, copper availability plays a major role in future energy transition.

Table 6
Summary of key barriers/challenges and suggested solutions for platinum group metals.

Category	Issues	Elements	Potential Solutions	References
Geological Availability Risk	Insufficient reserves and resource	Platinum Iridium	Deep sea mining (but with potentially significant environmental implications). Improve extraction rates and increase secondary production from mine waste. Significantly increase closed-loop recycling and end-of-life collection rates. Strategic mix of BEVs and FCEVs Reduce PGM content in fuel cells and electrolysers. Substitute with other PGMs.	[52, 107-109, 111,114]
	Significant losses during extraction process			
	Declining ore grade in South Africa			
Geopolitical and Regional Risk	High proportion of mining in politically unstable regions	Platinum Iridium	Increase exploration and secondary supply to reduce dependency	[108,111]
	Price fluctuations	Platinum Iridium	Substitute with other PGM	[108]
Environmental Risk	High environmental impact associated with PGM mining and processing	Platinum Iridium	Increase secondary supply of PGMs from end-of-life products, scraps and wastewater streams	[71,109, 114]
Social Risk	Labour disputes and safety concerns	Platinum	N/A	[112]

Over the period of 2010–2021, the copper reserves, this is resources that are currently economically extractable have increased by 250 Mt, which reflects the economics for copper mining, exploration, and technological advances [16,19,116]. Copper mining is driven by many different countries. Chile represents the major share of 23% of the total estimated reserves. In terms of refinery production, China represents almost half of refined copper, and it is also the major producer of copper end products. Both Chile and China are expected to play a major role in the future evolution of the copper market [19]. Copper is internationally traded in many different forms across the supply chain. The literature identified no major geopolitical concerns related to copper supply, although there has been mention that increasing copper demand growth rates may make it expensive for future generations, especially in less wealthy nations, to obtain [59].

When looking at the future copper growth, there has been a wide range of demand projections, ranging from 31 to 102 Mt/yr in 2050 [63, 94,117]. According to Vidal et al. [94], if copper demand stabilizes at about 30 Mt/yr from 2030 onwards, it may be possible to avoid a production peak, whereas an increase to 102 Mt/yr by 2050 would result in most of the known resources to be depleted with an assumed recycling rate of 45 % [117]. The recycling rates of copper currently range from 42 to 65 %, with collection rates of 40–50 %, so there is significant potential to improve in terms of both [59,63]. Watari et al. (2022) considers a high collection rate of 90 % and improved lifetime of copper products by 2050; based on their projection of 60 Mt/yr copper demand in 2050, current reserves will still not be sufficient, and 40 % of the resources would have to be extracted, out of which 4 % increase is due to renewables and 14 % increase is due to EVs [63]. Ren et al., 2021, calculated the copper requirement for China; based on their analysis wind turbines alone could consume near half of the domestic copper reserve, despite China being amongst the major copper producers [118]. This is not only concerning for copper markets but also highlights the vast requirement of copper by renewable technology alone. The grid network and other sectors such as building and construction would still represent the major shares of copper demand [63,117]. Furthermore, in most applications copper tends to stay in use for decades: two thirds of the copper produced since 1900 was still in use in 2010 [94,117]. Hence the long-lived nature of copper products coupled with the increasing growth for copper means recycling alone cannot solve the availability concern [94]. Henckens and Worrell [59] point out that at the current recycling rate, at least 10 Gt copper need to be available to support 10 billion people for the next 200 years. Further mitigation strategies, such as increasing material efficiency, improving grid efficiency, substitution, increased collection of copper products, and shared activities would also need to be considered [29,59,63,115,119]. A significant amount of copper in underground cables remains uncollected due to economic reasons and hence provide an opportunity as a secondary resource [120]. As for substitution, it is noted that fibre optics and aluminium are already being used to replace copper in data transmission infrastructure and transmissions lines in grid network respectively; aluminium can also be used to replace copper in other electrical equipment such as power cables, refrigerators, and radiators; in water pipes, drainpipes and plumbing fixtures, copper can instead be replaced by plastics [29,59, 115].

The ore grades for copper have been in gradual decline for the past 30 years, requiring more efforts for concentration and therefore higher energy requirement, emissions, water use, and tailings [52,103]. It is expected that ore grade decline could increase future environmental impacts by 10–20 % by 2050 [60]. This increase in pollution and lack of environmental compensation results in heightened social unrest which has already caused mine operation suspensions in Kazakhstan, Philippines and one of the largest mining sites in Peru [44,121]. Furthermore, changes in mining ownership have caused disorganized displacement of communities in Peru and Laos, and they can sometimes also lead to a lack of social and environmental commitments by the new mining cooperation [121]. Copper mining already generates as much waste as gold mining, although the former is six orders of magnitude less valuable in economic terms [52]. It is estimated that declining ore quality could increase by 2 – 7 times the energy requirement for copper production in 2050 compared to today [80]. The greenhouse gas emissions of the copper cycle could account for approximately 2.7 % of the total 1.5 C emissions budget by 2050, up from 0.3 % today [62]. In Chile, the consumption of fossil fuels in the copper industry is as high as the electricity demand [122]. Haas et al. 2020, investigated the use of solar generation for copper mining in Chile, and found that solar copper mining is economically attractive in sunny regions and the low cost and cleaner production of solar energy can compensate for the increased demand of declining ore grades [122]. Further improvement in energy efficiency of mining and heat recovery, improvement in recycling, electrification of low- and medium-temperature processes such as the use of compression heat pump and electric boilers, could help reduce energy investment and emissions in the copper sector [63].

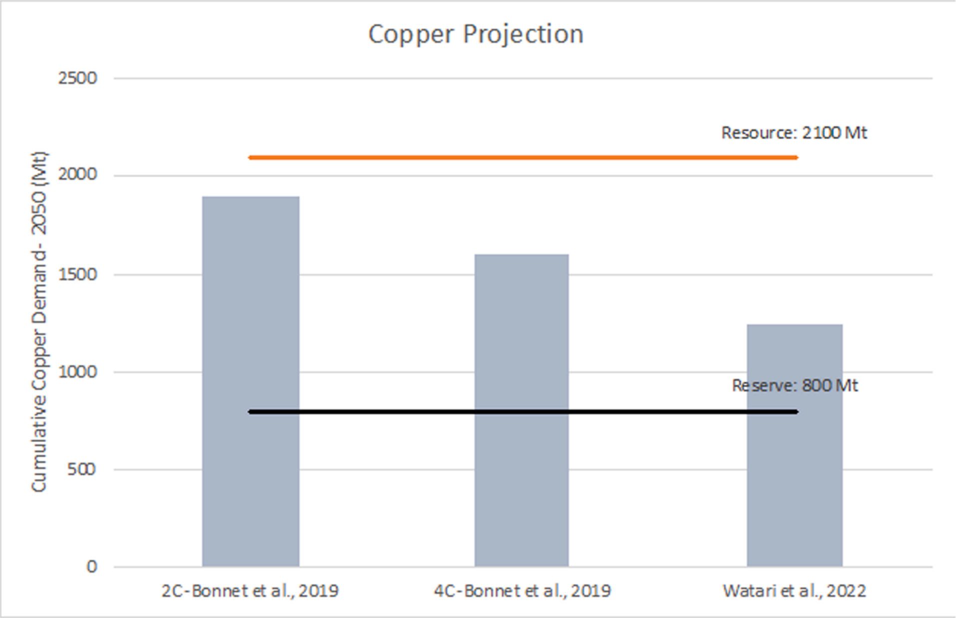

Fig. 9. Resource and reserve estimates and cumulative demand projections for copper up to 2050, adapted from [117] (assuming current recycling rate = 45 %) and [63]. 2C: 2-degree climate scenario; 4C: 4-degree climate scenario.

Summary of copper

Fig. 9 presents the demand projections for copper, according to different scenarios assumed in the reviewed studies, vs. the respective reserve and resource estimates. Table 7 summaries the key review findings.

Discussion

This systematic review has allowed identifying the main challenges associated with a range of critical elements for the energy transition (summarised in Fig. 10), and the strategies that have been proposed to maintain their reliable and secure supply, and to reduce environmental and social implications. It has also highlighted many knowledge gaps (summarised in Table 8). It is acknowledged that the scope of the review in terms of the specific elements discussed, and the issues addressed, are inherently dependant on the information present in the literature returned by the specific searches undertaken and selected keywords (Section 2.1). Hence, certain other elements that have also previously been listed as critical (European Union, 2020; IEA, 2021) could not be reviewed, such as e.g., high-grade quartzite needed for c-Si PV, or natural graphite for LIB. Also, new battery chemistries that require lower amounts of these critical elements per unit of storage capacity – such as all solid state batteries (ASSBs) – or which even avoid these elements altogether and rely instead on much more abundant ones – such as sodium-ion batteries (NIBs) – are being developed, and recent news announcements by automotive OEMs appear to indicate that they may be nearing commercialization sooner than previously thought possible [123,124]. However, quantitative estimates of the impact of the large-scale phase-in of these new technologies on global, medium-to-long term material demand scenarios are not yet to be found in the scientific literature, and therefore these potential effects are not captured by this review. Finally, the extent of information available in the various literature sources differs for each element, and therefore some challenges could be discussed more in detail than others.

Global resource availability and recycling

Overall, it was found that copper, cobalt, platinum, and iridium could suffer in terms of availability. All known global copper resources could be depleted by 2050 unless actions are taken to reduce this risk. Additionally, nickel, lithium, dysprosium, tellurium, indium and selenium could exceed current reserves by 2050, hindering the potential uptake of BEVs, FCEVs, CIGS and CdTe PVs, electrolysers and off-shore wind turbines, unless sufficient progress is made in reducing utilization of these elements in these technologies, together with investments in exploration and design for recycling, improvements in mining efficiency, and increased recovery and re-use of production as well as end-of-life scrap. For copper, reduction in use needs to happen in other high consuming sectors as well, such as the building sector and grid networks [63,117].

As green energy technology demand grows, so will the inevitable deterioration and reduction in resources, which will lead to an increase in the complexity of mining [98]. However, unlike fossil fuel sources, minerals and metals can be reused many times with technological efforts. Thus, recycling and reuse provide a great opportunity to slow down the depletion of resources. However, collection and recovery of these materials may be hampered by insufficient economic interest, as is the case for currently uncollected end-of-life copper cables and LCDs containing indium [19,120]. Recycling of some metals will be more challenging than others, such as recycling tiny amounts of platinum from fuel cells, compared to REEs from large permanent magnets [33]. Some elements that are critical for thin film PVs are also used in very small quantities in various other applications and may be difficult to recover. Policies could be implemented to provide economic incentive to encourage markets of secondary resources. Historical mine waste is also a potential source of accumulated by-product metals waiting to be exploited, for example Indium Corporation identified 15 kt of indium as residue reserves [101]. In the long run, recovering critical elements from mine waste would turn accumulated harmful waste stockpiles into useful products, delay resource decline and the need to resort to more complex methods of extraction. However, simultaneously, opening these mine waste sites for exploitation also raises environmental and social concerns, and requires careful treatment and tailing management [101]. More environmentally sound techniques for recovery are gaining momentum. For example, using less aggressive solvents or microorganisms to extract useful metals from ore and waste streams [73,125]. Except for the case of indium, the challenges and benefits of waste mining have so far received very little attention in the literature.

Table 7
Summary of key barriers/challenges and suggested solutions for copper.

Category	Issues	Elements	Potential Solutions	References
Geological Availability Risk	Insufficient reserves and resource	Copper	Improve copper production efficiency (copper smelting and refining). Significantly increase recycling and end-of-life collection rates of copper products and scraps. Improve material efficiency and substitution. Encourage shared practices of certain copper end products. Deep sea mining (but with potentially significant environmental implications).	[29,59,63,106,115,117]
Environmental Risk	Increase in energy demand and emissions due to decline in copper ore grade.	Copper	Electrify mining processes, improve energy efficiency, and use renewable generation for mining. Increase recycling and end-of-life collection of copper end products and scraps.	[63,80,121,122]
Social Risk	Social unrest due to increase in pollution, lack of environmental compensation and inconsistent displacement of local communities	Copper	N/A	[44,121]

It was found that most studies that evaluated reserve constraints, focused on the current reserve for further growth, whereas only a few studies considered potential increase in reserves, which was limited to cobalt, nickel and REEs [32,59]. Also, when investigating supply risks for PV elements, PGMs and nickel, very few studies included other end uses, beyond energy technologies. This may sometimes lead to underestimating future demand, such as the potential increase in demand for indium for flat panel displays, or the significant use of platinum in other sectors, which collectively represent more than 50% of the total (Fig. 1). Deep-sea mining could provide an opportunity to address availability concerns related to copper, REEs, PGM and battery elements; however, the full extent of the associated environmental threats is still not explored [67,109,119,126], with preliminary studies indicating the possibility of significant impacts [23,127]. Furthermore, environmental regulation on deep sea mining could differ significantly from country to country, unless they are mined outside the exclusive economic zone [126], which could lead to a lack of proper monitoring and mitigating of environmental impacts, possibly to a worse extent than for terrestrial mining. For areas beyond exclusive economic zone, the International Seabed Authority is responsible for mining activities and protection of the ecosystem; however, mining in these areas could greatly impact many species that live on potential mining nodules, which could result in permanent loss of certain ecosystem functions of which the consequences are still unknown [23].

Geopolitical risk

In terms of geopolitical risk, it was found that the supply of most of the elements reviewed is either concentrated at a single region or is limited in terms of trade networks, which makes other consumers of these elements dependant on a few selected countries. This may result in political instability, lack of regulations being followed, critical minerals being used for political strategy, or simply their production and refining to maximize regional economic interests, with lack of consideration for ethical sourcing. These considerations apply to cobalt, lithium, dysprosium and PGMs. For cobalt, this is due to its heavy concentrated mining and refining in the DRC and China respectively; for lithium, to its concentrated refining in China; for dysprosium, to its concentrated mining in China; and for PGMs, to their concentrated production in South Africa. Efforts could be made in diversifying supply but, for the case of dysprosium, the ore content is found to be less than 1 % outside China. Therefore, reducing the actual dysprosium use in target applications would be the best strategy; this could be accomplished by moving to more efficient production processes requiring less dysprosium, or by replacing dysprosium with terbium, as more of the latter becomes available thanks to the gradual phasing out of fluorescent lamps containing terbium in the coming years (discussed in Section 3.2). It was also found that the extraction of most critical elements for thin film PVs (e.g., tellurium, indium, and gallium) is concentrated in few regions, and their supply may also be limited by the production of the respective host elements [95]. Since these elements are by-products of zinc, lead, copper, and bauxite which are extracted globally, production can be diversified and expanded by building further refineries [99]. However, cheaper supply in other developing or less developed regions makes it difficult for mines in developed regions to operate, since labour and environmental cost are higher; this is the case for gallium in EU and REEs in the USA and Australia [66,110]. Furthermore, this also gives an illusory sense of security about the supply of minerals, such as in the case of REEs during China export restriction; although these restrictions could be imposed for environmental protection reasons or to secure domestic supply, they can also be used for price manipulation, leading to further risk of shortages in supply [128]. Nevertheless, in this case, the increase in world price also fuelled interest in REE investment. Although the increase in demand from energy technologies may likely attract mining investments, the long lead times of mining projects could pose short-term supply risks if such projects are not planned well ahead of time. Critical mineral recovery from mine wastes could also reduce the reliance on the few current producing countries. Global trade is an important aspect to consider in supply risk studies to prevent failures or disturbance in the supply chain. Geopolitical supply risk beyond the point of extraction was not considered in the reviewed literature, with the partial exception of battery metals only [55]. The use of a GIS-based quantitative mapping tool such as the one recently introduced under the name “LAYERS” [129] would be of significant value in estimating this extended risk.

Environmental and social aspects

The booming demand for both niche and common elements provides new opportunity for economic and social development in producing countries, but at the same time it can have disastrous consequences unless social and environmental impact are managed properly.

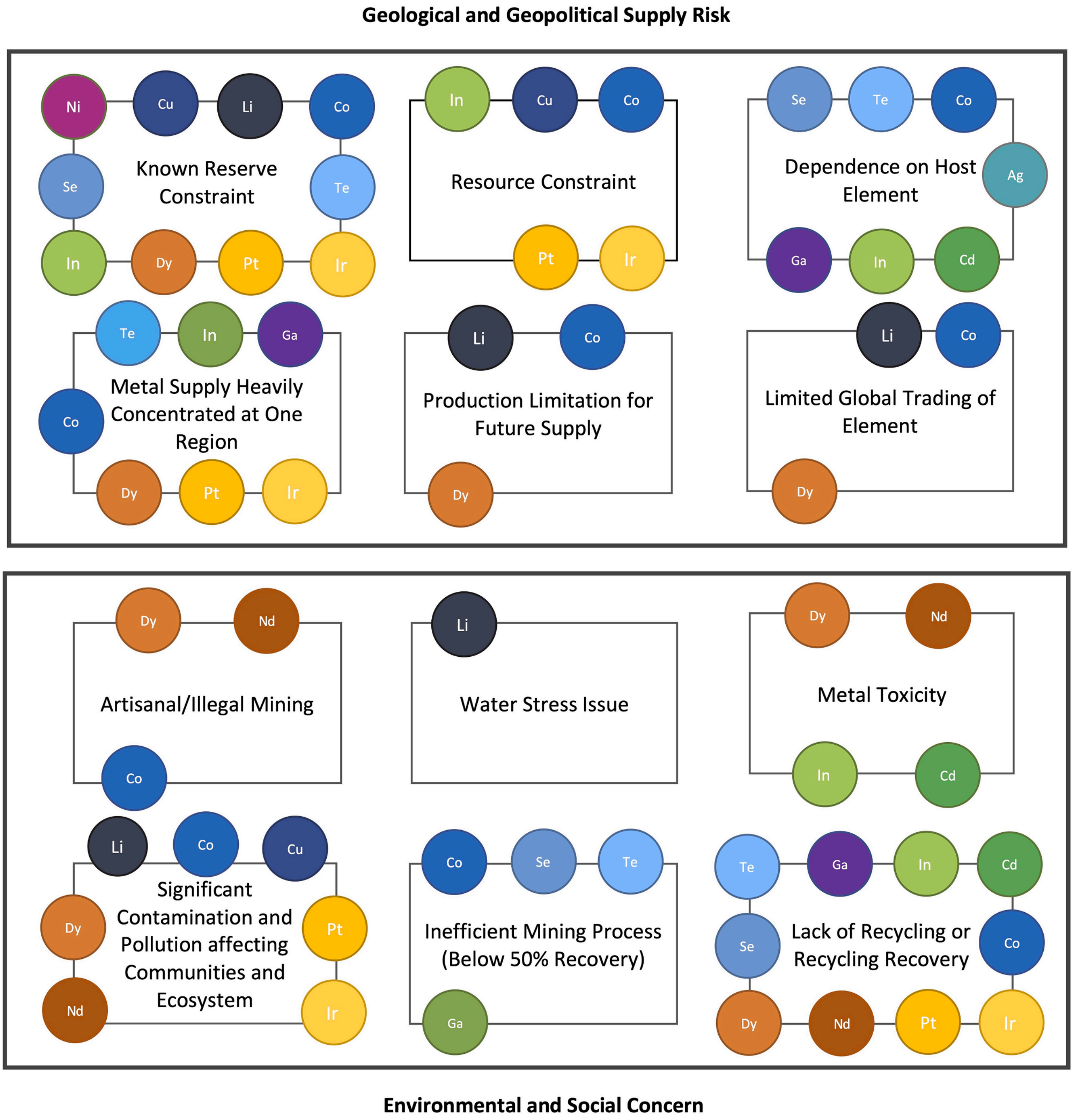

Fig. 10. Issues highlighted for each element based on findings from the systematic literature review. Shades of similar colour represent common ore deposits.

Only very few of the reviewed studies evaluated or discussed the environmental and social aspects of the supply of critical elements, with isolated exceptions, mainly for the cases of cobalt, lithium and REEs. None of the studies addressed post-mining scenarios, such as end-of-life management strategies of mining sites, or considerations of restoring communities and ecosystems [130]. One reason could be due to the lack of transparency of mineral supply chains, which makes it difficult to assess both environmental and social impacts [77]. Authors that did investigate the environmental and social impacts associated with the extraction of these elements suggested the need for tailing, chemical leakage and water management, enforcement of safety regulations, increased use of wastewater and using alternative techniques in mining to reduce ecosystem contamination, water stress and harm to the local communities [33,38,51,66,77]. Further issues have been identified for cobalt, HREEs and PGMs, to do with exploitation of workers, or lack of other livelihood incomes, which translates to unfair wages and leads to violence amongst workers, and insufficient safety and health provisions [34,35,66]. To ensure stability in supply chains, environmental and societal costs should be internalised before starting mining projects. Mining companies should be required to provide due diligence in supply chains to regulate material flows, and prevent illegalities, including possible funding of armed conflicts and violation of rights [131]. Efforts need to be made to also provide workers with better working conditions and expanding livelihood opportunity beyond mining in those mining countries [37].

Concluding remarks on supply concerns and material circularity for specific applications

Overall, this systematic review has indicated that most critical

Table 8
Identified knowledge gaps based on systematic review.

Category	Knowledge gaps	Elements
Global Supply Availability	Demand projection is mostly limited to energy sector only	PGMs, PV elements
	Outdated information on improvements made on element loading for low carbon energy technology	Selenium, indium
	Limited studies on potential mining from waste and historical mine sites	PV elements, PGMs
	Limited number of studies on supply and demand projections	Nickel, iridium
Geopolitical	Limited findings on geopolitical risk beyond mining	PGMs, REEs, PV elements, Copper
Environmental	Limited findings on environmental evaluation of extractive activities	PV elements, REEs, PGMs
	Limited findings on environmental benefits and challenges of using mine waste	All
	No discussion of restoring ecosystems at end of mining operations	All
	Limited findings on environmental impact of deep-sea mining	Cobalt, lithium, nickel, PGMs
Social	Limited findings on societal impacts of mining on local communities and workers	Nickel, REEs, PV elements, copper, PGMs

elements have the potential to meet the demands of the transition to a global low-carbon energy system, but doing so requires considerable efforts to address supply concerns and a careful, strategic planning of the mix of energy technologies to be deployed. For instance, based on the findings of this review, it does not appear likely that silver will represent a significant constraint to the growth of c-Si PV; however, it is acknowledged that there is still significant uncertainty on this particular point [132], which primarily stems from the wide range of projections on future PV growth overall [133]. Conversely, the competing demand of indium and selenium will probably hamper the large-scale uptake of CIGS PV. Instead, the indium requirement for EVs and nuclear power plants is unlikely to be an issue, as these technologies only require very small amounts of this critical element. Gallium is also used in small quantities in EVs, and moreover there is potential to expand bauxite refinery for gallium production. For offshore wind and electric motor technologies, there should be significant efforts to reduce the dysprosium content and increase circularity in the permanent magnets market. Significant improvements will also need to be made in general for REEs in terms of environmental safety regulation, the lack of which has been shown to hinder further investments in their supply chains.

To support the mass transition to EVs, on-going improvements will need to continue in reducing or eliminating the cobalt content in batteries and improve circularity for both lithium and cobalt. This is where developments in future battery chemistries that use more abundant materials, like lithium iron phosphate and sodium ion formulations, may be significant. There is also a growing consensus in the literature to recommend shifting light duty ICEVs to BEVs first, followed by heavy duty ICEVs to FCEVs, to reduce long term supply risk and meet most of the early demand for platinum through EoL ICEVs. Improvements also need to be made on reducing significant losses of valuable electrical materials in the EoL collection of vehicles and improving recycling, especially for PGMs in developing nations. Indeed, the co-location of battery recycling facilities with battery manufacturing would significantly enhance the potential for recovery of valuable materials for reuse. The mining industry requires vast investments, and producing regions are likely to focus on maximizing economic gains, which is prone to lead to both social injustice and lack of enforcement of environmental regulations, both of which can be seen currently in the case of PGMs, cobalt and lithium. These pressures, coupled with the political instability in those regions where extraction is concentrated, conspire to make the supply of elements for BEVs and FCEVs more vulnerable to disturbance. Therefore, social and environmental impacts need to be made a primary focus of attention to ensure a reliable and sustainable supply of these critical elements, as well as to avoid creating new impacts in the pursuit of reducing GHG emissions.

Author contribution

Mashael Kamran and Marco Raugei: Conceptualization. **Mashael Kamran:** Literature collection and screening. **Mashael Kamran and Marco Raugei:** Writing of original draft. **Marco Raugei and Allan Hutchinson:** Supervision, Internal reviewing and editing.

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

No data was used for the research described in the article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2023.100068.

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