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Review

Resourcing Future Generations Requires a New Approach to Material Stewardship

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Abstract: The paper aims to examine sector policies for securing mineral resources for future generations in ways that are economically, environmentally and socially responsible, guided by the Sustainable Development Goals by 2030 and carbon neutrality by 2050. This study proposes a roadmap for responsible mineral production, looking at drivers and goals, trends in resource demand and supply, technological and responsibility issues as well as current solutions. We conclude that while adopting the principles of a circular economy by minimizing waste, improving design for recovery, recycling alone will not be sufficient to meet the demand for an increasingly complex range of metals, and consequently primary mining will be needed for the foreseeable future. Various authors have proposed top-down approaches for sustainable mineral sourcing and co-ordination of global supply, but there is no evidence of these being taken up. Instead, to accelerate the transition towards sustainable, responsible and low-carbon mineral production, we suggest there is a role for 'material stewardship' defined and implemented through the actions of various players in the life cycle or value chain of specific minerals and metals. That bottom-up process has begun, though there is as yet no common definition of the term.

Keywords: sustainable development goals; mineral production; E-minerals; climate change; circular economy; material stewardship; metal and mineral accounting

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1. Introduction

Mineral production is an important part of the global economy that not only supplies the much-needed raw materials for manufacturing, construction and infrastructure development as well as other industries, but also plays an integral part in nation building and maintaining global security. Global economic development relies upon the extraction and use of mineral resources, and, for that reason, mineral resource exploitation has a significant role in fulfilling the UN Agenda 2030 and its 17 Sustainable Development Goals [1].

The future of global mineral production is conditioned by two major overarching policy imperatives that form a vision of global development, decarbonization and sustainable development [1,2]. There are other pressing political and economic issues including security of supply to break away from hydrocarbon dependency and move towards renewable energy generation and use. The minerals industry will have a pivotal role in ensuring this transition [2].

In this paper, we aim to examine potential issues and challenges for the minerals industry and its stakeholders on this transitory journey towards a carbon neutral and sustainable development. We consider specific elements of a minerals industry roadmap towards fulfilling global policy imperatives such as drivers, goals, trends, issues, and opportunities. This analysis will allow us to outline potential challenges and opportunities for the minerals industry.

Underlying that, there are a series of regional and other drivers, policy directions and technological trends that influence the development of mineral production. Most importantly, we want to examine what could be important issues that may arise during this new opportunity for the minerals industry and what are the implications for the industry's stakeholders. Thus, in this paper, we review major themes and challenges that the minerals industry and its stakeholders will have to face to respond to these two major policy imperatives identified above.

The paper examines a major question: How do we secure mineral resources for future generations in ways that are economically, environmentally and socially responsible in the context of the Climate Change Convention [2] and the agreement at COP 26 to work towards a target date of 2050 for global carbon neutrality [3]? To answer this question, the paper reviews the existing academic and policy literature using an adapted roadmap framework that looks at drivers, goals, trends in demand and supply, issues and opportunities for technological change [4,5].

The following section presents an overview of the materials and methods; followed by the presentation of results; and the discussion and conclusions. The paper is based on an analysis of trends, perspectives and issues in the minerals industry that was conducted as part of editing and preparing the Routledge Handbook of the Extractive Industries and Sustainable Development (2022) [6].

2. Materials and Methods

As an industry, minerals production is a business-to-business activity which services the needs for raw materials by downstream industries such as manufacturing and construction [6]. The demand for these raw materials is conditioned by the consumption of these materials by existing and emerging technologies [7]. In order to envisage the future of the minerals industry and to examine the issues and challenges for the industry managers and their stakeholders, in this paper we employ methods used in foresight studies such as a technology roadmap [4,5,8].

Roadmapping is a method for the analysis of technological development used by companies, governments and the non-governmental sector to identify, evaluate and select alternatives for market-driven technological development [4,5,8]. As a method of technology planning and coordination, it offers opportunities to examine critical technologies, gaps, and alternatives [5,8]. It is widely used for analysis of technology as an integrated system; it aids the consideration of alternative pathways for technological development and allows the examination of perspectives for stakeholders [5,8].

In the minerals industry, roadmapping developed by the US Department of Energy's Office of Industrial Technologies and the National Mining Association on Mining Industry Roadmap for Crosscutting Technologies [9] featured the following elements:

(a) Keystones (environment, health and safety, and energy); and
(b) Goals of the mining industry's exploration activities (reduction of environmental impact of mineral exploration and resource characterization, reduction of cost of mineral exploration and resource characterization, increasing the value of run-of-mine products, increasing exploration efforts).

The roadmap was designed to identify:

(a) Barriers for mineral exploration and mineral processing;
(b) Research & Development needs for mineral exploration and mineral processing;
(c) R&D priorities;
(d) Performance targets for the efficient mining;
(e) Barriers for safe and efficient mining and mineral processing; and
(f) Additional challenges (which were defined as Environment, Safety, Education, Technology Transfer, Operating Environment, and Funding).

As a result of the analysis, the roadmap can help common issues in the minerals industry such as Environment, Safety, Education/Training, Mining Lower Grades and Remote Sensing [9].

Other recent roadmaps for the minerals industry include the Industrial Minerals Association—Europe's Industrial Minerals Roadmap 2050, published in 2014, and the Australian Government's road map on Resources Technology and Critical Minerals Processing National Manufacturing Priority published in 2021 [10,11]. The European roadmap aimed to examine the role of industrial minerals in the economy and demand for industrial minerals in response to the European Commission's policy on moving to a competitive and low-carbon economy by 2050. The roadmap analysed innovative, sustainable and resource-efficient steps for the industrial minerals industry to fulfil this vision and identified the policy support required. The roadmap consisted of the following elements: role of industry, policy vision, targets, innovative technologies and sustainable products, and overview of economic, environmental, social and institutional themes:

a. Contributing to resource efficient economy;
b. Protecting and promoting biodiversity;
c. Engaging with local communities and workforce; and
d. Partnering with policy makers.

In this paper, we adapt the roadmapping methodology for the examination of the responsible production of mineral resources for future generations that aids the sustainable development agenda and decarbonization of the global economy. Our paper is based on the use of publicly available data such as academic research and policy documents.

3. Roadmap for Responsible Minerals Production

This section examines the elements of a proposed roadmap for the minerals industry. The overview of the roadmap is presented in Table 1. Each element of the roadmap is examined in turn below.

3.1. Drivers and Goals

At the global level, besides the market and investment drivers, there are two top-level policy priorities that guide economic development, including the minerals industry, which are:

1. International climate change policy and the need to move away from reliance on hydrocarbon sources of energy (i.e., oil, gas, and coal) and transition towards generation and use of renewable energy in all sectors including agriculture, manufacturing, transport and service sectors as defined by the United Nations Framework Convention on Climate Change [2]; and
2. The United Nations Sustainable Development Agenda 2030 with its detailed 17 Sustainable Development Goals that aim to improve the wellbeing of all countries and communities around the world [1].

Beyond these top-level policy priorities, we observe an overall shift in thinking that the future economy will be circular. As policy and industry move towards adopting the principles of circular economy, this will not only influence the demand for minerals but will also set the expectations for implementation of circular economy principles in the exploration, extraction, processing and transportation of minerals. The notable tenets of the circular economy include: waste management with application of the principles of reduce, reuse and recycle; use of renewable energy; industrial symbiosis; eco-design; and search for alternative materials and technologies [12–14], though critics point to the limitations of metal recycling and impediments in product design [15,16].

The circular economy is an umbrella concept that promotes an economic system with closed-loop production with increased reuse and recycling of waste and materials, improved resource and energy efficiency, and serves as an alternative to unsustainable linear production of produce-use-dispose model [17–19]. Research finds that the circular economy is still at early stages in the mining industry, based on the content analysis of sustainability reports by leading mining companies [20]. However, it is clear that circular economy principles can be applied to the entire life cycle of minerals from production, smelting and refining, manufacturing, consumption, and waste management [21,22]. Metal and mineral recycling is only one part of the model, the other is with efficient use of metals and minerals [22]. Also, metal recycling or extraction of metals from secondary sources requires energy input and leads to carbon emissions, but values are often lower than the extraction of primary mineral resources [21]. Research demonstrates that the primary metal industry currently contributes to 10% of global greenhouse gas emissions and accounts for 8% of global energy demand [23]. World Bank estimates that CO_2 emissions of renewable energy production with associated mining will be lower than the business as usual [24].

Table 1. Roadmap for responsible minerals production for future generations.

Roadmap Elements	Details
Drivers	• UN Climate Change Policy • UN Sustainable Development Agenda 2030 • Circular economy policies • Intermediate political pressures (such as reduce reliance on oil and gas from Russia)
Goals	• Sustainable production of minerals, including health and safety in production • Safeguarding availability of mineral resources for future generations • Reduction of carbon emissions in mining, mineral and metals production and improvement of material recycling
Trends in demand and supply	• Trends in resource demand ○ Increase of the overall volume of resource demand ○ Use of wide range of metals and minerals • Trends in resource supply ○ Decrease in ore grades ○ Increased competition with other land uses
Technological issues	• Mining is going deeper • Ore grades are declining • Discovery rates are falling • Cost of exploration are increasing
Responsibility issues	• Human rights • Child labor • Gender equality • Indigenous peoples • Environmental conduct • Artisanal mining
Current solutions	• Ethical supply chain management (e.g., labelling, fair trade, traceability and transparency) • Social license to operate [25–27] • Regional policy • Global governance
Future opportunities	• Sustainable mineral sourcing • Sustainable Development Licence to Operate [28,29] • Material and metal security of low-carbon energy transitions • Sustainable minerals and metals for a low-carbon future • Material stewardship, and metal and mineral accounting

Source: Authors' own.

We also see a rise of intermediate political pressures that further push towards accelerating the move towards decarbonization, and there is currently discussion, especially in the European Union, UK and USA, of a need to address critical mineral supply chain vulnerability by placing less reliance on a single or few suppliers, and specifically on reducing imports of Russian oil, gas, and coal [30]. A move from hydrocarbon energy sources would require greater development of renewable energy, transport and infrastructure technologies and their scaling up [24]. Nations and regions such as the European Union are concerned about the availability of critical raw materials that would support their renewable energy, transport and strategic industries and in turn enable their economic development [31–33].

When we think about the goals for the mining industry in the context of specific, identified drivers of sustainable development, decarbonization, and circular economy (see Table 1), we should look at how mining can respond to these drivers. The major goals for the mining industry in the long and medium term are to:

1. Promote sustainable production of minerals including maintaining health and safety;
2. Safeguard the availability of mineral resources for future generations; and
3. Reduce carbon emissions in mining, mineral and metals production and recycling [21,34].

3.2. Trends in Demand and Supply

3.2.1. Trends in Resource Demand

We can define two major trends in resource demand:

1. Increase of the overall volume of resource demand; and
2. Use of a wider range of metals and minerals.

Since the end of the Second World War, improvement in the standard of living of many of the world's poorest countries has been driven in large measure by technological development. That development has depended on the use of an increasingly wide range of metallic elements. Demand for all raw materials has risen dramatically, but substitution, recycling and usage efficiency improvements will not be enough on their own. Projections for energy technology, urbanization and economic growth will dramatically increase demand for all raw materials [7,35].

World population is predicted to reach about 10 billion by the end of this century and then to stabilize [36]. Assuming the UN Sustainable Development Goals are successful in eradicating poverty and improving the wealth of all, emerging economies, increasing human population, growth in the global middle-class (which some estimate could reach 6 billion by 2100) and increasing demand for white goods coupled with continuing urbanization will increase demand for metals and minerals.

The 20th century and early part of this century saw a dramatic increase in living standards and improvement in the quality of life for many of the world's poorest. That improvement has been underpinned by the ubiquitous use of metal and mineral resources in infrastructure and technology, resulting in increased per capita consumption. By the beginning of the 21st century almost all of the elements of the Periodic Table were used in one way or another to the extent that a typical mobile or cell phone contains up to sixty elements [35].

Demand for all raw materials has risen dramatically. The transition to a low-carbon energy system required to tackle climate change implies a steep increase in the metals intensity of the energy system, which in turn will cause a substantial increase in the demand for metals [37].

Wind turbines require rare earth elements for magnets, copper for the generator, and steel and cement for the tower and base. Photo voltaic cells require silver for silicon-based cells, and cadmium, tellurium, indium, gallium, germanium and ruthenium. Energy crops require steel for agricultural machines and mineral inputs for fertilizers. Finally, the transmission of more renewable energy would require more copper and steel for the electricity power lines and pipelines, and specialty metals for catalysts and storage [37].

3.2.2. Trends in Resource Supply

Mineral deposits are irregularly distributed and their occurrence is controlled by geology, which means that they are not necessarily where we would wish them to be. At the risk of oversimplifying matters, some major trends can be identified that have a bearing on resource supply. Firstly, mines are going deeper, creating greater environmental impact, using more energy and creating more emissions as material is hauled for greater distances to the processing plant. Secondly, lower grades are being worked, increasing operational costs and environmental impact because of the greater volume of material being dug and, as a result of the increased use of water in processing, potentially increasing the risk of conflict with local communities over water rights. Thirdly, after a period when the rate and of discovery of new deposits was lagging behind the rate of exhaustion of worked deposits [38], currently discovery of resources and reserves in keeping pace with increased rates of extraction [39]. Fourthly, discovering and developing new mineral resources is a lengthy process and even under the best circumstances it can be 10~20 years from initial survey to opening of a mine. Fifthly, mining is in competition with other land uses such as agriculture, amenity, ecological protection, safeguarding of water supplies, urbanization and so on. As a result, increasingly operations are delayed or prevented by problems in receiving permits and licenses, or because of social conflicts. In many jurisdictions, community and legal barriers cause more than 50% of delays resulting in many millions of tons per year loss in supply [40].

3.3. Issues

3.3.1. Technological Issues

There are various styles of mining—open cast pits and quarries, underground mines reached by shafts and adits, and brine pumping involving the injection of fluids to dissolve the sought-after material and recover it to the surface and in situ recovery of uranium. In addition, considerable amounts of gold, cobalt and tantalum, diamonds and other gemstones are produced informally by Artisanal and Small-scale Mining (ASM), while highly mechanized offshore dredging is used to recover diamonds and tin [40].

3.3.2. Responsibility Issues

Whereas large- and medium-size mining companies are regulated, ASM is not, which creates a range of issues from use of child labor, gender equality, health and safety and the uncontrolled use of cyanide or mercury in processing extracted material. In addition, in some countries ASM is controlled by warlords who subvert the proceeds of mining to fund their activities, giving rise to so-called conflict minerals [41].

Whereas it is relatively easy to track the ethical sourcing of commodities such as gold and diamonds, for other materials which require complex processing, such as cobalt and tungsten, it is more difficult to do so [25,42].

Considerable attention has arisen recently over the rights of Indigenous peoples and the desecration of native aboriginal lands. Not all countries recognize the rights of Indigenous peoples in Statute, an example being Peru, or acknowledged in decision making, an example being the nomadic peoples who cross national boundaries, such as the Sami of northern Norway and Finland, and decisions are made at national level without recognition of their views [43].

There is growing community opposition to mining around the world [26]. Researchers cite environmental impacts, displacement, community participation and compensation as some of the factors contributing to this trend [26]. The consumption in developed countries of sophisticated manufacture is dependent on metals and minerals from the developing world, where environmental oversight, post-mining reinstatement, workforce health and safety and gender equality may be poor or non-existent. Is it ethical for the developed world to export such problems?

Many argue for the formalization of artisanal mining, perhaps without knowledge of it. For many artisanal miners the work is seasonal, done by farmers during agricultural slack times, and the work can involve whole families in mining with women and children processing recovered material. Various attempts have been made to formalize ASM, including licensing, but usually at a cost unaffordable to the miners. More success may come from the formation of co-operatives providing a mechanism for the miners to buy equipment and then sell the results of their labor at a fair price [41].

3.4. Current Solutions

3.4.1. Corporate Social Responsibility Solutions

For the responsibility challenges in the mining industry, several evolving solutions are being offered including ethical supply chain management, social license to operate, and other corporate social responsibility tools and instruments [25,27,44,45].

Ethical supply chain management aims to deal with environmental issues such as reduction of greenhouse gases, and social issues associated with metal and mineral supply such as conflict, violence, exploitation, and crime [25]. Over the past 20 years, the international community has been developing principles and guidance to deal with ethical issues in metal and mineral supply chains such as revenue transparency, traceability of products to avoid association with conflict and violence, due diligence to demonstrate environmental and social standards, stopping the supply of minerals from conflict zones to fund violent regimes and groups, and consideration and protection of human rights in business [25]. Various private sector initiatives have sprung up in response to international policies and government legislation to regulate ethical issues in metal and mineral supply chains; these include responsible sourcing standards, industry guidelines and certification schemes [25]. Bingham Chee [25] reports that significant responsible sourcing initiatives have been created for precious metals, gemstones, tin, tantalum, and tungsten. The list of metals that has received further attention is expanding to include cobalt, copper, aluminum, iron-steel, zinc, and mica [46].

At a local project level, even when mining enterprises obtain government licenses to conduct exploration and extraction activities, local communities and stakeholders can be discontented with mining projects. The concept of "social license to operate" (SLO) has become significant in the mining industry since the late 1990s. SLO is the community's social acceptance of industrial or extractive projects [27]. It implies that companies need to consider local community needs, interests, and approval beyond legal licenses [25]. The operationalization of SLO also presents problems when communities may grant SLO to mining companies and offer expressed support for mining projects, but in the process can overlook or ignore potentially negative environmental or health safety concerns under pressure to enhance economic development in the communities [27]. Demajorovic and Pisano [27] suggest documenting and recording the progress and maintenance of SLO with a use of social impact assessment. They recommend using social constructivist and social capital approaches for the study of community perceptions of mining projects and combine them with technical and scientific approaches applied in environmental impact [27].

The remit of corporate social responsibility (CSR) in the mining industry is influenced not only by the industry challenges and issues, but the global action to improve corporate social responsibility in business. SLO is not to be confused with CSR. Whilst SLO is about community acceptance, CSR is about strategies and actions of corporations directed at improving their social, environmental, and ethical conduct [47]. The range of CSR instruments and tools available is growing, as well as their complexity, and can be applied depending on project-level factors and stages in the mining cycle [45].

3.4.2. Regional Policy and Global Governance Measures

In 2009, the African Heads of State and Government of the African Union adopted the Africa Mining Vision (AMV) with the long-term goal of attaining "Transparent, equitable and optimal exploitation of mineral resources to underpin broad-based sustainable growth and socio-economic development" [48].

The AMV is not about mining as such, but about development. It essentially seeks to use Africa's natural resources sector to transform the continent's social and economic development by tying permission to mine to the development of the necessary infrastructure to allow mining products to be processed in-country rather than be exported for refining overseas. In this way, more of the wealth generated by mining products might be retained, particularly if used as feed stock in new local manufacturing industries.

The AMV raises issues regarding continuity of supply and sustainable development, intergenerational equity, resource conservation and more equitably sharing the wealth generated by mining. Where does responsibility for use lie?—With individuals? Consumers? Mining companies? National governments? The international community? Will the African Mining Vision influence other governments?

In 2019, the United Nations Environment Programme International Resource Panel published a report entitled Mineral Resource Governance in the 21st Century. It concluded that the mining sector, if carefully managed, presents enormous opportunities for advancing sustainable development, particularly in low-income countries; that international action is needed to consolidate existing rules and regulations in the mining sector, and to agree on international standards on transparency and codes of conduct; that despite a plethora of instruments, these have not succeeded in promoting shared benefits and creating links to local economies [28].

The report introduces the concept of a Sustainable Development Licence to Operate designed to function as a reference point for the multiple actors concerned with the extractive sector, enabling them to act in a coordinated and cooperative manner that supports the achievement of the 2030 Agenda for Sustainable Development. This involves building on the wider suite of relevant priorities, obligations and standards that are compatible with the SDGs. The report also proposes new taxation and accounting practices [29].

3.5. Future Opportunities

It is evident that policy enhancement work is being conducted at various levels to address major technological and responsibility challenges in the mining industry. Furthermore, the circularity and net-zero ambition in relation to mineral production cannot be solved in isolation. There is a need for a systems approach to searching for possible opportunities to improve sustainability, responsibility and reduce carbon emissions associated with production and consumption of metals and minerals. There are four broad opportunities explored in the existing literature for improving the sustainability, responsibility and climate change in mineral production [28,49–51] (see Table 2). These recommendations focus on international policy and governance [28,49], mineral supply chains [50], industry research and development and innovation in finance [51].

In their papers, Ali et al., 2017 [49] propose six specific measures for sustainable mineral sourcing. Pedro et al., 2017 [47] propose a Sustainable Development Licence to Operate. Lee et al., 2020 [51] set out a research agenda, while Sovacool et al., 2020 [50] argue that that there is a need for policy coordination of global supply chains and make four policy recommendations (see Table 2). Perhaps it is too early to judge, but there is no evidence of these top-down approaches being taken up, possibly because many would require international agreement and a suspicion of treaty exhaustion. Such thoughts beg the effectiveness of existing institutional frameworks. Perhaps a bottom-up approach driven by company imperatives of future-proofing the sourcing materials needed to sustain manufacturing could be more effective?

Table 2. Future opportunities for sustainable, responsible, low carbon mineral production.

Future Opportunities	Details	Notes
Actions for sustainable mineral sourcing (Ali et al., 2017) [49]	• Reach consensus on international targets for global mineral production. • Monitor impacts of mineral production and consumption. • Improve coordination of mineral exploration. • Support investment and research into new mineral extraction technologies. • Harmonize global best practices for responsible mineral resource development. • Develop maps and inventories showing the availability of recyclable metals.	These proposals are global, require collaboration with various parties across sectors of society (public, private and civil society) and different geographical scales.
Sustainable development licence to operate (Pedro et al., 2017) [28]	• Built on principles such as national and regional policies such as Africa's Mining Vision; international conventions on environment, climate change, human rights, trade and investment; and industry best practice such as GRI and EITI. • Incorporate diverse individual and institutional actors from public, private and third sectors. • Considers formal and informal norms, e.g., laws, policy, standards, cultural and professional norms, etc. • Participation of stakeholders in decision-making for coordinated and collaborative action to enhance the contribution of the extractive industry to sustainable development.	Multi-level and multi-stakeholder governance framework that aims to enhance the contribution of the mining sector to sustainable development.
Material and metal security of low-carbon energy transitions (Lee et al., 2020) [51]	• Further analytical work on the role and scale of metals and minerals in a low-carbon future. • Technology research to addressing bottlenecks, design of substitute materials, improved recycling, new technologies. • New financial instruments in commodity markets to mitigate and manage risks and increase transparency. • Developing technologies in the mining industry (e.g., Blockchain, artificial intelligence, autonomous mining, and mining engineering). • Researching and developing a harmonized framework for carbon accounting and science-based climate target-setting along minerals supply chains.	Set of recommendations targeting the minerals industry and stakeholders to improve efficiency, low-carbon development using research and development of technologies and innovation in financial instruments.
Sustainable minerals and metals for a low-carbon future (Sovacool et al., 2020) [50]	• Diversify mining enterprises for local ownership and livelihood dividends. • Acknowledge the limits of traceability. • Explore new resource streams. • Incorporate minerals into climate and energy planning.	Policy recommendations have a focus on global supply chains of metals and minerals.
Material Stewardship (ICCM, 2006; International Zinc Association; International Lead Association) [52–54]	• Maximize the value of minerals and metals to society. • Focus on supply chain collaboration and communication with stakeholders. • Enhance durability and recyclability of minerals and metals. • Increase the efficiency of their production and use. • Minimize associated health and safety and environmental risks. • Foster responsible sourcing and producer responsibility.	Bottom-up industry-led approach involving actors and stakeholders in metal and mineral value chains.

Source: Author's own.

3.5.1. Material Stewardship

In the context of these comprehensive studies, we suggest that to accelerate the transition towards sustainable, responsible and low-carbon mineral production, there is a role for "material stewardship". In 2006, the International Council on Mining and Metals (ICMM) released a publication, "Maximizing Value: Guidance on implementing materials stewardship in the minerals and metals value chain" [52]. This guidance is offered to maximize the value of minerals and metals to society with a focus on supply chain collaboration and communication with stakeholders. Materials stewardship is an evolving concept that aims to enhance the "durability and recyclability of minerals and metals, increase the efficiency of their production and use, and minimize associated risks." [52] (p. 1) ICMM proposes that the concept "will ultimately be defined and implemented through the actions of various players in the life cycle or value chain of specific minerals and metals" [52] (p. 1).

The International Zinc Association [53] suggests that material stewardship in practice involves: (1) understanding the social, environmental, and economic impacts of materials as they move through life cycle from mining to the end of life; (2) developing a relationship with actors along the metal/mineral life cycle to maximize use and minimize human health and environmental risks; (3) implementing stewardship activities within the life cycle parts under direct control. The International Lead Association [54] (p. 1) similarly outlines their vision of material stewardship that focuses on ensuring "that lead is manufactured and used responsibly, minimising environmental and health impacts." This association specifies that the objectives of material stewardship initiative are to: (1) promote responsible sourcing and protect public health and the environment; (2) encourage producer responsibility for collection of batteries at end-of life and recycling under environmentally-sound conditions; (3) encourage continuous improvement in the environmental and health and safety performance in the value chain; (4) support improvements in health and environmental standards in low- and middle-income countries; and (5) enhance transparency to stakeholders through reporting on progress.

In 2012, the Aluminium Stewardship Initiative was launched as an industry-led initiative that aims to promote sustainability and commitment to social, environmental, and ethical standards amongst industry and users in the aluminum value chain through certification. The initiative's mission is to "foster responsible production, sourcing and stewardship of aluminium" and particularly advance the "material stewardship as a shared responsibility in the lifecycle of aluminium from extraction, production, use and recycling" [55] (p. 1).

Material stewardship has entered the language of mining companies. Notably, mining giants such as Anglo American and Rio Tinto as well as other companies such as Boliden have started to communicate about material stewardship, allocate resources to material stewardship in companies and join industry initiatives on material stewardship [56–58].

The emerging concept of material stewardship has its roots in environmental management, sustainable development, life cycle assessment, systems thinking and circular economy. Material stewardship is strongly influence by considering the dimensions of sustainability and triple bottom line thinking. It is "concerned with managing the flow of materials into society to improve its sustainability by mitigating environmental, economic, and societal impacts and maximizing its efficiency and durability." [59], and borrows from circular economy principles. For instance, Williamson recommends four strategies to pursue material stewardship, called 4D's approach: dematerialization, durability, design for multiple lifecycles, and diversion of waste stream through industrial symbiosis [59]. The business case for the development of material stewardship can be examined by further research.

3.5.2. Metal and Mineral Accounting

To improve the transparency and efficiency of metals and minerals in the value chain, information exchange between different stages of production, consumption and recycling would be encouraged. Such a metal and mineral accounting system could guide decision-making on mineral consumption, rates of primary mineral production, metal and mineral recycling and planning projects. The system where stocks of metals and minerals could be accounted for, and the time and movement of materials are recorded, in order to identify how and when these materials become available to be transformed into productive inputs for the economy.

Metal and mineral accounting can raise awareness of the impacts of mineral consumption from source to product, and environmental consequences, as well as local community impacts and economic development. It could encourage individuals and nations to be accountable for their resource use, including that of mineral products. Being accountable for the use of non-renewable resources would address the intergenerational principle of sustainable development, whereby current generations can meet their needs and let future generations also access ample mineral resources (see Table 3).

Table 3. Resource Accounting.

Resource Accounting	Details
Accounting for mineral resources as natural capital (global level)	US Department of Commerce Bureau of Economic Analysis (1994) [60] asserts that the failure to account systematically for mineral resources as a form of capital has been blamed both for over- and under-exploitation.
Total global resource estimation (global level)	The UNFC for Energy and Mineral Resources, introduced first in 1992 [61] recognizes total resources in place, in terms of produced quantities, remaining recoverable quantities and additional quantities remaining in place with its main focus on remaining recoverable quantities.
Classifying resources and reserves (deposit level)	Most economic geologists use a scheme, first devised by McKelvey (1972) and subsequently developed by the USGS, to classify resources on their degree of certainty, which can vary overtime, and distinguish between discovered commercial resources as proven, probable or possible from undiscovered resources which can be hypothetical or speculative or sub-commercial [62]. The original scheme has been developed considerably by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO). CRIRSCO identifies a number of reporting codes of which the most significant are the JORC Code (Australasia), SAMREC Code (South Africa), PERC Reporting Standard (Europe), CIM Guidelines (Canada), SME Guide (USA) and Certification Code (Chile).
Reporting of metal stocks in annual audit (manufacturer level)	Corporate governance assurance on metallurgical processes, in particular stocks and losses during metallurgical processing (SmartMin, 2022) [63].
Metals from recycling (recycling level)	Johnson Matthey in partnership with European Metal Recycling, one of the world's largest material recyclers and a leading recycler of end-of-life vehicles, is to develop an efficient value chain in the UK for recycling lithium-ion batteries and cell manufacturing materials [64].

Source: Authors' own.

There is considerable discussion in the literature about accounting for mineral resources as natural assets in traditional accounting systems. The US Department of Commerce Bureau of Economic Analysis in its 1994 survey of current business [60] asserts that the failure to account systematically for mineral resources as a form of capital has been blamed both for the over- and under-exploitation. More recently, metal accounting is said [63] to be a growing focus in the fulfilment of corporate governance practices and to provide assurance on metallurgical processes, in particular stocks and losses during metallurgical processing [63]. Metal accounting is the estimate of (saleable) metal in a mine and subsequent process streams over a defined period [63].

The UNFC for Fossil Energy and Mineral Resources, introduced first in 1992 [61], goes further in recognizing total resources in place, in terms of produced quantities, remaining recoverable quantities and additional quantities remaining in place, with its main focus on remaining recoverable quantities.

Clearly, to know how much resource remains in the ground and what might be available from, for example, manufactured goods, buildings, spoil dumps or landfill may be an intrinsically 'a good thing', but is it attainable? The more immediate need and focus of this paper is how the future need for technology, or so-called critical materials for the energy transition, can be met.

4. Discussion

Issues surrounding the demand, supply, processing, use, and end-of-life recovery of metals and minerals stretch well beyond the expertise of geoscientists and mining engineers and involve many other disciplines, including but not limited to metallurgists and process engineers, economists, political and behavioral scientists and many other branches of social science, product designers, manufacturers and so on. Forums that encourage experts, policy makers and mining industry stakeholders to collaborate, examine interdependencies of sustainability, responsibility and circular economy issues in supply chains and develop joint solutions suitable for metal and minerals products and cycles should be promoted further. A notable example of such forums includes the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) [65]. Industry associations for individual metals and minerals are also very relevant to fostering focused and sustained discussion on material stewardship.

The Brundtland Report [66] introduced the concept on intergenerational equity, that future generations should not be disadvantaged by the actions of previous generations, and the circular economy is built on similar concerns—to minimize the use of materials and energy and to ensure maximum reuse through end-of-life recycling.

With globalization, materials that we use in building infrastructures are not extracted locally but are sourced internationally. Today, outreach and policy work can promote public awareness and recognition of sourcing, treatment and management of mined materials to ensure global availability of resources for future generations. Much of this work concerns global supply chains. If the extractive industries are to secure and keep social acceptance, consumers need to better understand their role and ethical consequences of material consumption.

In an exercise of peak modelling, Northey et al. [67] predict that expected demand for copper can be met from known deposits until about 2030 and would then decline unless new deposits are being brought into production. But another feature of the figure is to consider when recycling will cause primary production to decline. The concern here is that stocks of copper remain locked away in hard wiring, electric motors and other goods for considerable periods of time, possibly 40 or more years, and will not be sufficiently large or available for recycling to offset the need for primary production. That said, many uses are dissipative or cannot be recycled [68]. A similar story applies to iron and steel used in buildings, which may have a life of 100 or more years, and materials were used in ways that do not favor easy recovery, reuse or recycling.

Besides, however efficient the collection of materials for recycling, there is a loss of material through each cycle with a progressive build-up of trace metals used as 'hardeners,' such as V, Ni and so on.

Using less through better product design so that materials are recoverable, research on substitution and promoting recycling all have a role to play.

Klein [32] illustrates that the switch to renewal electric power generation will require considerable amounts of a diverse range of metals. Sovacool et al. [50] build on the work of Klein by looking at the demand for lithium and other metals which would arise by electrifying the global vehicle fleet, and provide estimates of increased demand in 2050, relative to 2017 production, for a range of metals and materials including lithium (965%), cobalt (585%), graphite (383%), indium (241%) and vanadium (173%).

The Russian invasion of Ukraine has brought into sharp relief both the over-dependence of many European countries on Russian oil and gas and the benefits of diversity in supply. Perhaps too much reliance has been placed on 'just in time' supply chains and lowest cost. For some time, there has been a growing conversation about the dangers of 'just in time' and the desirability in shortening supply chains 'just in case' [69].

Through their understanding of Earth processes, geoscientists have developed predictive models which help identify prospective areas for exploration and near-surface mining, and increasingly, the merge of large geophysical datasets with the results of surface geochemical and geological and structural surveys is providing useful data about the likely occurrence of as yet undiscovered ore deposits at depths of 3 km or more, which would need new mining technologies for recovery.

Mining of whatever kind requires societal consent, which cannot be presumed. In many countries the concerns of Indigenous peoples who may hold certain lands sacred or, if nomadic, traditional grazing areas, are not recognized in the mine application planning process, and the income generated by mining does not always appear in the national accounts, giving rise to concern that the wealth generated is not shared equitably. The recently published report by the UNEP IRP which argues for a SDLO might help address these concerns.

Are existing institutional frameworks fit for purpose? In late 2021, COP 26 agreed the procedures and protocols to consider actions agreed six years previously at the Paris COP meeting. What can be done about global resource governance and how might it be achieved? Putting aside such questions, is there a need to better conserve what we have by considering some form of 'metal accounting'? Should manufactures be responsible for recycling white goods? The Kyoto Protocol introduced a global ban of chlorofluorocarbons and led to the requirement that manufacturers were required to 'take back' refrigerators for safe disposal of CFCs. Is this a precedent that might require manufactures of electric vehicles to recycle both the vehicle and battery?

How do you educate consumers to make more informed purchasing decisions and to bring about behavioral changes that will be needed as society learns to use less raw materials? We suggest that building a system of mineral accounting, setting and maintaining standards of material stewardship along with the development of related transparency and accountability for the use of metals and minerals in the supply chain and through sharing information with the consumers and stakeholders can help consumer decision-making and inform consumer behaviour.

5. Conclusions

Notwithstanding growing levels of recycling, the current trends in material consumption will increase demand for metals and minerals worldwide [7] and build on top of a long-term upward trend in primary metal production because of increased per capita consumption. Mitigation of climate change and development of new energy-generating and transmission technologies will add to that demand. There may be shortages in supply, given it can take 20 or more years from discovery to bringing a mine into production, and the current lack of investment in exploration could exacerbate the problem.

New international agreements on resource governance are needed to allow exploration and mining to continue in existing areas and to open up new frontiers. The SDLO may provide a way ahead. More recycling and new technologies to improve the rates of recovery will help but, nevertheless, there will still be a need for primary mining for the foreseeable future and possibly into the next century. New mechanisms to account for our mineral wealth and stewardship of resources that we extract and process could contribute to planning and assessing the needs for extraction and recycling to ensure preservation of natural resources and reduction of environmental and social impact. A transition to a sustainable, responsible and circular future would require multi-stakeholder international effort and coordination with the development of both technological, policy and social innovations to cater for the needs of present and future generations.

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