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Metal Sourcing For a Sustainable Future

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Drastic measures are required to meet the standards of the Paris Agreement and limit the increase of global average temperatures well below 2˚C compared to pre-industrial levels. Mining activities are typically considered as unsustainable but, at the same time, metals such as cobalt and lithium are essential to sustain the energy transition. Several sustainability goals defined by the United Nations (UN) require large quantities of raw materials. Exploration and extractives activities are required in order to contribute to meeting sustainability standards. Future sourcing of metals will need to implement procedures that go well beyond current ecological, economic, and social requirements and practices. In this paper we assess the usual sustainability criteria and how they apply to the extractives sector. Sustainability can only be achieved if one accepts that the natural capital can be substituted by other forms of capital (so called weak concept of sustainability). Sourcing the raw materials increasingly demanded by our societies will need transparent and inclusive stakeholder participation as well as a holistic understanding of the impact of extractives activities to reach this weak sustainability status. Our analysis shows that the sustainability of mining cannot be reached without harmonized political instruments and investment policies that take the three pillars of environmental, economic, and social sustainability as a major priority.

Keywords: sustainable mining operation, environmental impact analysis, socio-economic consequences of mining, mining regulation, sustainability governance

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INTRODUCTION

Ambitious measures are required to meet the standards and targets of the Paris Agreement, in particular to keep the increase of global average temperatures well below 2˚C compared to pre-industrial levels (Bleischwitz, 2020). On the other hand, metals such as cobalt and lithium are essential to sustain the energy transition (e.g., Junne et al., 2020) and several of the sustainability goals defined by the United Nations (UN) require large quantities of raw materials (Ali et al., 2017). For example, copper remains a primordial metal to ensure electrical conduction and is the cornerstone of power distribution. In addition, many other elements such as indium, gallium, germanium or rare earths are required for wind turbines and solar panels. Many of these materials can be recycled and reused under certain conditions (e.g. concentration, identification) if the discarded end-product is systematically collected. However, mineral processing and metallurgical processes are getting technically and economically challenging the more society demands to recycle increasingly complex end-of-life products. Reuse and recycling are possible under certain conditions if the discarded end-product is collected but remain limited by technical factors and organizational constraints (e.g., Korhonen et at., 2018). In fact, it seems that extraction, mining, and processing of raw materials currently remain a necessity to ensure the transformations that could lead into a more sustainable future.

Mining is often described as ecologically destructive and socially unacceptable. Local communities and representatives of the civil society have been increasingly objecting to present practices of mining and influenced political agendas (e.g. Mercer-Mapstone, 2018). The main barrier to mining is currently not the scarcity of material or the emergence of economic monopolies but public acceptance (Weber and Stuchtey, 2019).

There is no doubt that mineral resources have intrinsic characteristics that make them difficult to manage sustainably. The popular notion that the extraction of mineral raw materials will inevitably lead to a reduction of primary resources over time is, however, misleading if all the waste management options that could be pursued, including recycling, are considered and future exploration is taken into account (Meinert et al., 2016). However, there is no doubt that mining has and will have an impact on the environment. A program for improving the sustainability performance of mining is needed. Improved ecological performance and an inclusive approach must govern the transformation of the mining industry. The stakeholders need to examine the main challenges, identify potential actions to address the deficits, develop strategies to create or regain trust and incite the mining sector to commit to sustainable development by embracing diversity for identifying problems and finding more environmentally and socially friendly solutions (Littleboy et al., 2019).

The following article is an attempt to provide one of the first comprehensive analyses of the impact of mining on crucial criteria of sustainability and outline the potential requirements for more sustainable operations. The main argument is, that *1*) it should be possible to reduce the burden to the environment by a substantial order of magnitude; *2*) like any other industry, the mineral sector can offset some of its negative impacts by means of compensation and ensure an equitable sourcing; *3*) the mining industry can significantly contribute to the principles of a circular economy and, finally; *4*) a more sustainable extractive industry is a cornerstone to the fulfilment of the UN Sustainable Development Goals.

CRITICALITY OF MINERAL RAW MATERIALS

Our technological societies rely more and more on mineral raw materials and with an expanding variety (Graedel et al., 2015). Problems of access to mineral resources as well as several political crises have been subsumed under the term "mineral criticality." The degree of criticality depends not only on geological abundance, but also on factors such as the potential for substitution, the degree to which ore deposits are geopolitically concentrated, the state of mining technology, the amount of regulatory oversight, geopolitical initiatives, governmental instability, and economic policy (Poulton et al., 2013). There are now a few quantitative assessments of mineral criticality (e.g. Graedel et al., 2015; COM, 2020) that provide lists of mineral resources ranked by demand and supply risk. While the demand is quite easily determined, further research is required to assess supply risk and current assessments of raw material criticality might not be realistic (Frenzel et al., 2017). In fact, and contrary to common views, global reserves for most metals have not significantly decreased relative to production over time (Meinert et al., 2016; Jowitt et al., 2020). This is mainly due to the extension of global reserves as mineral exploration progresses. Despite the strong demand and increase in production and consumption, the supply of mineral raw materials has continued to meet the needs of industry and society, and the assessment of global reserves seem to remain constant (Arndt et al., 2017). It has become apparent that socio-environmental parameters are becoming the prime variables governing criticality (Mudd and Jowitt, 2018; Jowitt et al., 2020). It implies that the discovery and exploration of mineral resources, and their sustainable extraction, will demand a careful selection of potential exploration sites and will increasingly require creative inputs from geoscientists (Herrington, 2013). It is becoming more and more important to secure a diverse range of acceptable sources for the needed raw materials using innovative approaches (Herrington, 2021). It is also required to assess the potential of mined wastes and also to refocus exploration in areas where sustainability criteria are easier to implement (e.g., Vidal et al., 2013). It also implies that a global coordination is needed to ensure that minerals are produced in the most ecologically and economically efficient way (Ali et al., 2017).

PROSPECT AND LIMITATIONS OF SUSTAINABLE MINING

The term "sustainability" is understood here as a guiding concept to ensure the long-term preservation of our environmental foundations and to secure humane living conditions for all people in all regions, in the present and future. The pathway to reach such a state of sustainability is called sustainable development. This term also indicates that sustainability will remain a target that is never fully reached but only approximated over time. It is the main task of sustainability science and sustainability research to create the necessary knowledge base for the implementation of this normative concept and to test its validity, reliability and practicability (Renn, 2022).

FIGURE 1 | The 17 Sustainability Development Goals of the UN (courtesy of Research Gate).

Sustainable development (WCED 1987) allows humankind to meet the needs of the present without compromising the ability of future generations to meet their own needs. This goal of sustainable development has inspired the United Nations 2020 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) (United Nations 2020). The 17 goals are illustrated in **Figure 1**.

Sustainable development promises to integrate economic activity and environmental integrity, include social concerns and implement effective and transparent governance systems. In the debate about sustainable development, a relevant issue for the mining sector is the distinction between "weak" and "strong" sustainability. It highlights that the key question regarding sustainable development is whether Natural Capital (diverse natural resources such as water, air, mineral resources, but also ecosystem services) can be substituted by other forms of capital (technical, human, social or financial capital). While proponents of "weak sustainability" maintain that manufactured or human-made and natural capital may be substitutable in the long term, those in favour of strong sustainability believe they are not, and that scarce resources belong to the natural capital should be preserved because they cannot be replaced by other (human-made) alternatives.

In the first case ("substitutability paradigm" or "weak sustainability"), sustainability is achieved when the total stock of capital is grown or at least sustained for future generations; in opposition to this, in the "strong sustainability concept," human-made capital is not completely interchangeable with, but limited by natural capital, introducing environmental limits that have to be observed in order to ensure environmental sustainability ("non-substitutability paradigm"). In this perspective, the loss of certain forms of natural capital can threaten the survival of humanity as they provide basic life-support functions (Neumayer, 2003). In this debate, the concepts of resource renewability and the occurrence of irreversible processes are fundamental, as well as the concept of planetary boundaries (O'Neill, et al., 2018; Röckström et al., 2013).

Strong sustainability is currently an ideal, technically impossible to accomplish for the mining industry and cannot serve as a realistic goal in this domain. Weak sustainability, however, can realistically be achieved when the total stock of capital is at least sustained if not enriched for future generations. Mining can meet this sustainability criteria if it compensates the net capital loss. While a quantification of natural capital is difficult, the concept of net benefit for sustainable transformations can serve as a guideline for the mining industry. In this sense, the degree to which mining contributes to sustainability can only be evaluated when looking at the purpose of mining (Ali, 2013).

Many examples within the industry, private and public leading institutions and academia show how the mining sector has been working towards sustainability and this has led to an important deployment of tools to conform a higher degree of responsible mining protocols and frameworks to take control of its social and environmental impacts (Ruokonen, 2020; Salonen, 2020). Of course, there is a need to differentiate metallic minerals from others, due to its renewability for operational purposes, defined by the design products that can retrieve minerals in a usable form with relatively low energy expenditure. This means that the energy needed to balance the entropy generated during the mineral's use and its recycling is the main metric to evaluate whether that material's use is sustainable or not. In other words, the ideal scenario would be to be able to recycle and reuse all minerals and metals on the premise that the energy utilized for recycling comes from renewable sources and land use is compensated by rehabilitating otherwise dilapidated landscapes. Supporting this idea of sustainability from an economic perspective, proponents of weak sustainability claim that the extraction process of a finite resource from the Earth's crust can still lead to overall sustainable development so long as part of capital generated is invested in building a diversified economy.

Even under weak sustainability, it is quite unlikely that all negative impacts to the natural capital can be compensated or

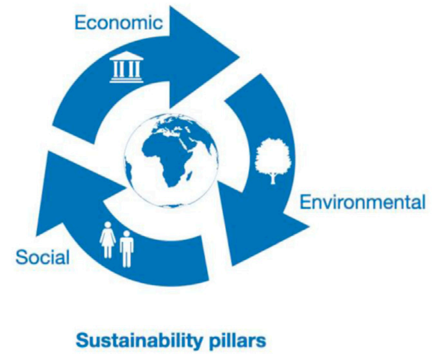

FIGURE 2 | Sustainability objectives illustrated by Renn et al. (2021).

substituted. Yet, the mining sector needs to adapt and consolidate good practices designed for responsible mining.

The classification developed by Renn et al. (2021; cf. **Figure 2**) provides a framework to establish sustainability objectives. *1*) The environmental pillar includes the notions of decarbonisation, dematerialisation and rehabilitation of used land (re-naturalisation). *2*) The economic pillar includes circular economy and sustainable welfare. *3*) The social pillar considers a fair distribution of risks and benefits, personal and social opportunities for co-determination of decisions and social well-being, including health. These three classic pillars of sustainability are further diversified in the UN Sustainable Development Goals (SDG) (UNDP, 2016). Mines supply key raw materials for building infrastructure (SDG 9) and the manufacturing of wind and solar PV technologies (SDG 7; Carrara et al., 2020). Mineral exploration and mining can be made safer and more energy-efficient (SDG 7), produce less waste and greenhouse emissions (SDG 13), improve wastewater treatment (SDG 6) and reduce land consumption for mining waste as well increase well-being of local communities and improve environment (SDG 15). Mining operations spur economic growth and lower the unemployment rate (SDG 8) and, when properly governed, can contribute to mitigate inequalities and discrimination (SDG 1, 5, 10). Mining companies are called upon a responsible supply of raw materials, promoting peace, justice, and strong institutions (SDG 16) and should contribute to territorial development and to creating a long-term diversified economy based on the local endogenous resources (Polo, 2006).

THE ENVIRONMENTAL DIMENSION OF SUSTAINABLE MINING

The environmental impacts of mining depend on the attributes of the local environment and on the type of mining activity conducted (Spitz and Trudinger, 2009). They can be quantified and are often even predictable. These impacts depend, firstly, on the attributes of the local environment and, secondly, on the type of mining activity conducted. A mining area usually consists of either underground or open-pit mine, side-stone heaps and soil removal masses, tailing area, concentrator, other buildings, and infrastructure (roads, water and electricity lines, maintenance buildings), machinery and equipment, landfill sites and wastes. The dimension of the direct impacts relies on the geochemistry, ore position, selected mining method, using local water sources, and chemicals used in mineral processing and management of wastes as well as the sensitivity of the environment (e.g., Spitz and Trudinger, 2009). Direct impacts include, for example, wastewater discharges from mine affecting the quality of the surrounding water as well as changes in relief and landforms, erosion, and dust emissions. Increasing the extent and density of mining areas will cause additional threats to biodiversity as already now 8% of the global mining areas coincide with nature protection areas, 7% with key biodiversity areas and 16% with remaining wilderness reserves (Sonter et al., 2020). These direct impacts can be numerically assessed and modelled.

Quantification is much more difficult and often even impossible for indirect impacts. They are often insidious and difficult to identify and measure. Environmental risks need to be evaluated separately at each site and stage of the mine life cycle, from exploration to exploitation and mine closure and reclamation. For example, the operational phases of a mine have an impact on water (mineral processing and gas emissions), air (emissions), soil (land use and possible contamination), biota (destruction of habitats and displacement of fauna) and climate (energy consumption). While mining infrastructure impacts the habitats and biodiversity by environmental fragmentation, the unused elements and substances, left in tailings and other side-products of the ore processing can notably affect the ecological systems. The re-naturalisation of the mined areas also needs to be considered at the very beginning of the project with the introduction of a sound and justifiable ecological compensation plan. Environmental accidents have a wider impact that spreads across the ecology domain and the indirect impacts are usually much more profound than the direct ecological effects. Decarbonization requires the use of innovative technologies to reduce consumption of fossil fuels. This, in turn, requires securing additional raw material supply which introduces an apparent contradiction with dematerialisation (McKinsey Company et al., 2020). However, under the interpretation of weak sustainability, the contribution of mineral extraction to decarbonization can outweigh its negative impacts.

Ecological sustainability thus must include three major objectives: *1*) to drastically reduce the amount of carbon in the atmosphere (climate protection), *2*) to significantly reduce the amount of material that is used for production thus limiting emissions and waste and *3*) develop land-use practices that ensure high biodiversity and the preservation of natural landscapes.

To ensure these targets, companies need to create funds during the operation of the mine for this purpose and be accountable. Independent environmental monitoring during the whole mine life cycle and during a sufficiently long period after the mine closure is a required instrument to keep the mining activities under control, reduce the impact to the environment and improve mining reputation. Responsible mining activities inspired by a concept of weak sustainability could drastically reduce greenhouse gases and wastes and offset natural capital deficits. Mines will develop land use patterns that ensure high biodiversity and territorial integration.

The development of innovative recycling processes is an opportunity for mining companies since the technology is similar to recovery. From a legislative/system perspective, opportunities lie in the domain of stimulating the mining industry in countries that have strict mining and environmental legislation (that is actually implemented and controlled) and transfer those good-practice cases into areas where this has not been a current practice. Operating a mine creates greenhouse gas emissions, but also provides materials for providing carbon-neutral energy.

THE ECONOMIC DIMENSION OF SUSTAINABLE MINING

The current business model is designed to maximise profits for the company and its shareholders. There is little incentive for the company to invest in sustainable performance beyond the minimum that is required. It is the state's responsibility to ensure that taxes and royalties are fairly distributed to society (Franks 2020). There is no guarantee of benefits to the community, other than an *expectation* that the mining company will do so. Benefits that are delivered to the community are often localised. There is also the risk that monetary as well as non-monetary benefits received by the state from the mining company are not distributed appropriately or fairly or are not perceived to be. By investigating the interactions between environmental, economic, and social impacts of mining instruments and tools developed for accounting, assessing and balancing benefits and risks may serve as guidance to analyse investments and quantify overall impacts to the natural and social environment. The main objective of the economic dimension of sustainability is to create a circular economy in which economic incentives are present and effective to reduce material and energy input, promote recycling and minimize emissions. These goals need to be internalized into the pricing system as an obligation for all direct investments into sustainable pathways.

What are the immediate requirements for meeting the goals of economic sustainability? *1*) life cycle assessments providing a numerical estimate of all environmental costs from cradle to grave (Pelletier et al., 2019); *2*) environmental management accounting studies that assess the accumulated costs of resource mining, use and disposal (Latan et al., 2018); *3*) eco-efficiency assessments of circular economy highlighting the most efficient operations for mining and material recycling (e.g.,Liu et al., 2019). McLellan et al. (2009) demonstrated that the biggest opportunity for impact reduction of mining operations lies in the design phase, rather than in operation or post-closure. Based on new technological advancement in manufacturing and waste treatments, more efficient and environmentally friendly operations of the mining industry have been introduced and demonstrate often economic advantages in conjunction with energy savings and less material use (Kagermann et al., 2013). These new technologies will transform the operational mining business towards smarter and sustainable exploration procedures (Kesselring et al., 2020), autonomous mining (Roberts and Duff., 2002; Gao et al., 2020) and a more effective remediation of mining areas. Technology-driven and recycling-oriented business models will also change operations on and off-site (Tayebi-Khorami et al., 2019). At the same time, the implementation of novel procedures requires high investments (Pimentel et al., 2016). This is even more pronounced for new technologies that increase environmental performance without decreasing production costs. For promoting the use of innovations that minimize environmental damage, it seems wise to pursue a program based on the obtainment of a social license to operate (SLO) (Hilson and Nayee, 2002; Nikolaou and Evangelinos, 2010). This business model could be developed either by the global mining industry as a whole or by a coalition of governments granting operational permits which would include prescriptions for mining operations. This model may be attractive for commercial investors, in particular for those, who favour sustainability-oriented financial investments (Azapagic, 2004), or banks that are eager to improve their image (Baumgartner and Rauter, 2017).

THE SOCIAL DIMENSION OF SUSTAINABLE MINING

The failed relationships between communities and mining corporations represent one of the single biggest market risks to the extraction sector in 2020 (Ernst and Young, 2020). A sharp rise in conflict between communities and companies has been observed between 2000 and 2013 (Andrews et al., 2017). In that respect, accidents are seen as "focusing events" that attract the attention of the public and lead to changes in public opinion but also public policy (Birkland, 1997). Conflicts around mining touch upon competing concepts of space. All of the critical actors need to share the same vision of sustainability if mining is going to be accepted. The Social Licence to Operate (Cooney, 2017) is only attained when a mine gets or retains community acceptance. Contextual social sustainability as defined by Suopajärvi et al. (2016) refers to the positive conditions for communities, defined as social coherence (Littig and Griessler, 2005), creation of social capital, preservation of socio-cultural characteristics (Vallance et al., 2011) or valued and protected local cultures (McKenzie, 2004) and quality of life (e.g., Littig and Griessler, 2005; Partridge, 2005). The objective of social sustainability is achieved when the negative impacts of mining are mitigated and the compensatory schemes for impacted communities are equitable. The main goal is to achieve a fair distribution of benefits and risks within an overall framework of minimizing impacts.

The reality is, however, different. Sustainability accounting is still dominated by the belief in financialization or commodification of social and environmental impacts based on purely economic thinking. This is then often accentuated by the physical and economic displacement of a host community, resulting in a shift from a traditional economy to a purely cash-based economy and the rupturing of community (MacCallum, 2016; Proctor and MacCallum, 2019). There are significant failures embedded within this and similar approaches, not least in that it designates value on identifiable "things"- so it works better with rivers, trees and tangible assets. It does not work at all for cultural artefacts, because they are difficult or impossible to be translated into monetary values. How can one place a value on losing a family farm which has been in the family for 400 years and all the social connection that entails? Is it 10% over the land value as set by a surveyor?

Sustainable development practice focuses on the assets and strengths within a community that can be built on to reduce poverty, instead of focusing on perceived needs. The mining sector is well placed, as a strategic investor, to benefit from the lessons learned in the development sector and to combine responsible practice with effective relationships (Franks, 2020). What either the mining sector or the regulators must do, is both engage with those that are opposed or might be opposed in the future to mining operations in their locality. Knowing where the ore is enables all actors to conceptualize a proactive approach to engagement. Dealing with issues such as concerns, fears, poor information, the need for host communities' economic gain from the extraction process and scoping whether it is a 10-year project or a 50-year project as well as closure issues, can be and need to be addressed. Building the societal capacity to undertake such a far reaching and complex set of engagement requires significant time and investment. In analysing the future of mining, all actors involved need to move beyond the traditional twentieth century business model of economic growth, with taxes and royalties through mining carved up with spin-off opportunities for states, regional governments, and certain businesses. If the COVID-19 pandemic has taught society anything, it is that if we do not address our problems strategically and collectively as early as possible, it can be very costly. Ignoring the EU's need for access to strategic minerals, to decarbonize our economy, will leave everyone vulnerable in dealing with climate change and, also, at the mercy of those controlling critical minerals in jurisdictions where the human and environmental costs are less regulated, much higher and outside of society's control. Furthermore, leaving the issue of fairness and just distribution unresolved will result in a major withdrawal of support and loss of acceptance by the local and regional communities. Changes are urgently needed.

In conceptualizing sustainability to investigate barriers to mining, we need to assure that all critical actors can be brought to a shared vision of sustainability. This goal oblieges those with resources to support the engagement of those without, namely the host community. Mining needs to look at the social contract around mining. Due to the increasing concern about access to and the governance of the extraction of raw materials and the need to decarbonize and dematerialize production, European actors may take the lead in becoming powerful change agents. Europe could promote the initiative for developing improved operational guidelines, promulgating effective concepts of social licences to operate and generate new and fair models for citizen involvement in local operations.

There are also other issues within social sustainability beyond fairness and shared vision that need to be addressed. Of special importance is the notion of procedural fairness. This refers to political participation, participatory processes, equity, justice, inclusion, access and sense of common ownership (Partridge, 2005). The key issues are related to the availability of open information, transparency and participation in the different decision-making processes that occur before and after the mine has been established. What is perceived as socially sustainable in one place might differ in another. This is strictly related to the expectations and needs that the local people have for mining instead of the concrete impacts (Suopajärvi et al., 2016). The local communities set their own standards for that and stay in the area after the mine is gone, which highlights the need for them to participate in the governance of their own lands. These frameworks provide a way to link what might be called, established views of sustainability. The challenge in relation to the procedure, is the temporal aspect. It is useless talking to communities about a mine once plans have already been finalised and the finances raised. How long does it take and what mechanisms could be used to enable citizens' capacity to challenge and negotiate with a mine corporation? How long would this up-front and ongoing investment need to be assured for? If the financial investment is from the EU how does it recoup that investment and what about sovereign wealth rules? There are no easy answers, but it does point to a restructuring of the current mining business model given that mine operators can sell and transfer ownership, potentially collapse and dissolve and it is unlikely they want to commit to 10 years investment up front, without a guaranteed return. Currently, the present coalescence of groups opposing mining in their own locality, offers an opportunity to engage with and to explore what are the pivotal factors driving both their opposition and their coming together. There will be no sustainability for mining without citizens' consent. A new social contract for mining and wider public dialogue is essential.

BALANCING THE RELATIVE CONTRIBUTIONS OF MINING FOR SUSTAINABILITY

The three objectives of environmental sustainability can be met by the mining industry if all actors involved actively pursue this goal. Starting with the objective of decarbonization, the mining industry is still far away from being carbon-neutral. Mining is currently responsible for 4–7 percent of greenhouse gas (GHG) emissions globally but could fully decarbonise (excluding fugitive methane) through operational efficiency, electrification, and renewable-energy use. Capital investments are required to achieve most of the decarbonisation potential, but certain measures, such as the adoption of renewables, electrification, and operational efficiency, do pay off for many mines within a reasonable time span.

The second objective of dematerialisation is a basic approach to reduce the pressure on the resources and environment and to realise sustainable development (Qiu et al., 2020). Even if dematerialisation is hardly consensual, its narrative - the over-use of the natural resources of the Earth and achieving or already transcending planetary boundaries - receives increasing approval (Müller et al., 2017). Sustainability in a material-economical system needs to be designed that the most efficient methods for energy use and the most effective methods for material reduction are chosen as main targets of operation.

The third objective, renaturalization, is particularly challenging for the mining industry. Changes in land use are inevitable in mining. The direct changes in the landscape and the footprint of mining and exploration activities expands during the life cycle of a mine. Therefore, the closure plans are most essential and need to be addressed before the mine starts operation. It is not possible to restore a mining site to a situation comparable pre-mining state, especially in cases of open pits. However, re-naturalization is an important part of the closure of a mine. By specifying the closure measures and procedures in advance, the former mine site can be recultivated for safe and environmentally benign use in the future and new land use options (Sonter et al., 2020). The rehabilitation of, for example, an acid generating mining site and tailings bonds depends on a thorough understanding of the geo-chemistry at the site. Passive treatments are needed to avoid oxidation and acid generation of the tailings or open pits. It is essential to forward the knowledge of chemistry of the site, directions of water flows and methods of closure to the following land users along with the site-specific restrictions for the use of the site (Räisänen and Juntunen, 2004). The concept of ecosystem services may offer an application for landscape planning at the post-mining site, but improved indicators are needed to describe the optimal future uses of a mine site (Larondelle and Haase, 2012). The choice of accounting methodology and the setting of targets should be guided by policy objectives (Mancini et al., 2015).

Turning to the economic aspects of sustainability, in particular circular economy, is closely related to the ecological objectives described above. The most important instrument for circular economy in the mining industry is the capacity building for reuse and recycling. Although metals cannot be recycled for ever, the average period of metals and minerals in us can be expanded for decades if properly recycled. This is not only a task directed to the mining industry but also a task for all manufacturers that use minerals or metals in their products.

When we turn to the social aspects of sustainability it has become obvious that societies face an increase in awareness of the importance of social aspects of mining. Based on the survey done by Ernst and Young (2020) for the executives in mining, social license to operate is seen as the top challenge/risk related to the mining projects. This means that the companies, from small junior exploration to larger mining companies, must put effort and increased resources into the social engagement in the very early stages of the project. This means hiring a professional in the fields of social sciences into the companies. Furthermore, the role of the mining-related professional, in particular the geologist, mining-related engineers and other "technical" staff, is an important crucial asset to the company and can act as "billboard" of the company to the local stakeholders. Especially, the geologists, who are among the first with their boots on the ground in greenfield exploration projects, have the opportunity to "make or break" and be sensitive to the needs and concerns of the local population depending on how they engage with the locals (e.g., Mckenzie., 2004; Moffat and Zhang, 2014). This responsibility means that communication skills and social concern assessment (Florin and Bürkler, 2017) are important educational components for technical higher education (universities) and continuing life-long-learning for the mining-related professionals (e.g. Mckenzie., 2004). This type of evolution in the education has already begun in Europe and is led by European Union-funded projects such as INFACT (Horizon 2020) and EXplORE (EIT RawMaterials Academy; *see* Jansson et al., 2020).

One major social concern of communities and affected citizens is perceived fairness, in particular between local, regional, national and global interests. Robertson (1992, 1996) defined the term "glocal" to describe this difficult relationship. Mining operations should have shared benefits not only for the shareholders but also for the stakeholders, including communities with their prior approval (Littleboy et al., 2019). In addition to the positive engagement of the company personnel and local stakeholders, Moffat and Zhang (2014) pointed out that procedural fairness is an important aspect of gaining public trust and acceptance. This includes empowerment of local actors to have a voice in the decision-making process. When individuals feel that they are actively participating in the decision-making process, they regard the whole procedure as fair and are more likely to develop a sense of affiliation with the mining operations.

GOVERNANCE AND POLICY IMPLICATIONS

The integration of ecological, economic, and social sustainability within a context of globally interlinked economic systems includes enormous challenges for the design of effective policy instruments and governance

FIGURE 3 | Beneficial governance structure for responsible mining (SDG, Sustainability Development Goals as defined by the United Nations).

mechanisms. Societal and political demands for such instruments have grown since the 1980s, when the liberalization of the mining industry coincided with the rise in global environmental awareness (Warhurst, 1999). The global climate movement urging climate action has caused both proactive and defensive reactions from governments and industries alike (Rosewarne et al., 2013). Actual policy design and implementation are characterized by complexities such as market structure, lobbying power, asymmetric information, risks and uncertainties (Sterner et al., 2019) are hardly visible (Venghaus et al., 2019) driven by vested interests (Obersteiner et al., 2016). Overcoming opposing interests often requires integrative policies that internalise societal and environmental costs (Pizzol et al., 2014). A notable change is expected when the incorporation of negative external effects will affect the budgets of both private and public households.

Figure 3 is an attempt to visualize the linkages between actors and impacts. It provides a systematic compilation of potential consequences of mining operations and distinguishes between monitoring, assessment, and implementation. Whenever possible, impacts that are monitored, assessed, and managed should be quantified. Impacts that can only be qualitatively characterized should be included in a balanced assessment of opportunities and risks.

As corporate environmental responsibility is more driven by "internal pressure" (Annandale and Taplin, 2003a; Annandale and Taplin, 2003b), the improved environmental performance relies on leadership, organisational learning and capacity building. Over the past decades, the polluter pays principle has been widely accepted as a basis for shifting the burden of pollution prevention to industries, including mining companies. This shift has occurred at a differing pace in different countries, with the globally active mining companies, operating across jurisdictions, leading the way. Simultaneously, the growth in traditional forms of top-down, prescriptive regulation has increasingly been accompanied by new policy instruments such as economic instruments (taxes, fees, subsidies) and performance standards. These types of instruments can be beneficial in promoting innovative, cost-effective environmental technologies. Such advances have been made in managing water and waste metal toxicity, mine closure, land rehabilitation and biodiversity protection (UNDP and UN Environment, 2018). Furthermore, programs that integrate environmental, geo-technical and social sustainability objectives are also envisioned but need further refinement.

Preliminary steps towards such goals were proposed for exploration (**Figure 4**). A Theory of Change was produced in 2019 and then refined by INFACT partners based on subsequent research and developments within the project to produce a Discovery Roadmap. This is the first attempt to our knowledge to propose a process of strategic engagement across all stakeholders. The roadmap was intended for exploration activities and only covers the preliminary stages of a mining project.

The greater recognition of social impacts has led to the increasing adoption of community consultation revolving around the concept of free, prior, and informed consent (FPIC), with large players in the mining industry increasingly involved (UNDP and UN Environment, 2018). National regulatory instruments may include instruments such as taxes, waste charges, and establishing new protected areas (Sterner et al., 2019). Globally, the policy scope for mining remains somewhat divided. Leading companies play a large role, setting examples beyond geographically defined jurisdictions. In the policy domain, it implies that one set of policy instruments does not fit all jurisdictions equally. For instance, the utilization of new market and performance-based instruments set high knowledge requirements for both mining companies and regulatory agencies. In countries where mining operators are relatively small and inexperienced, setting clear,

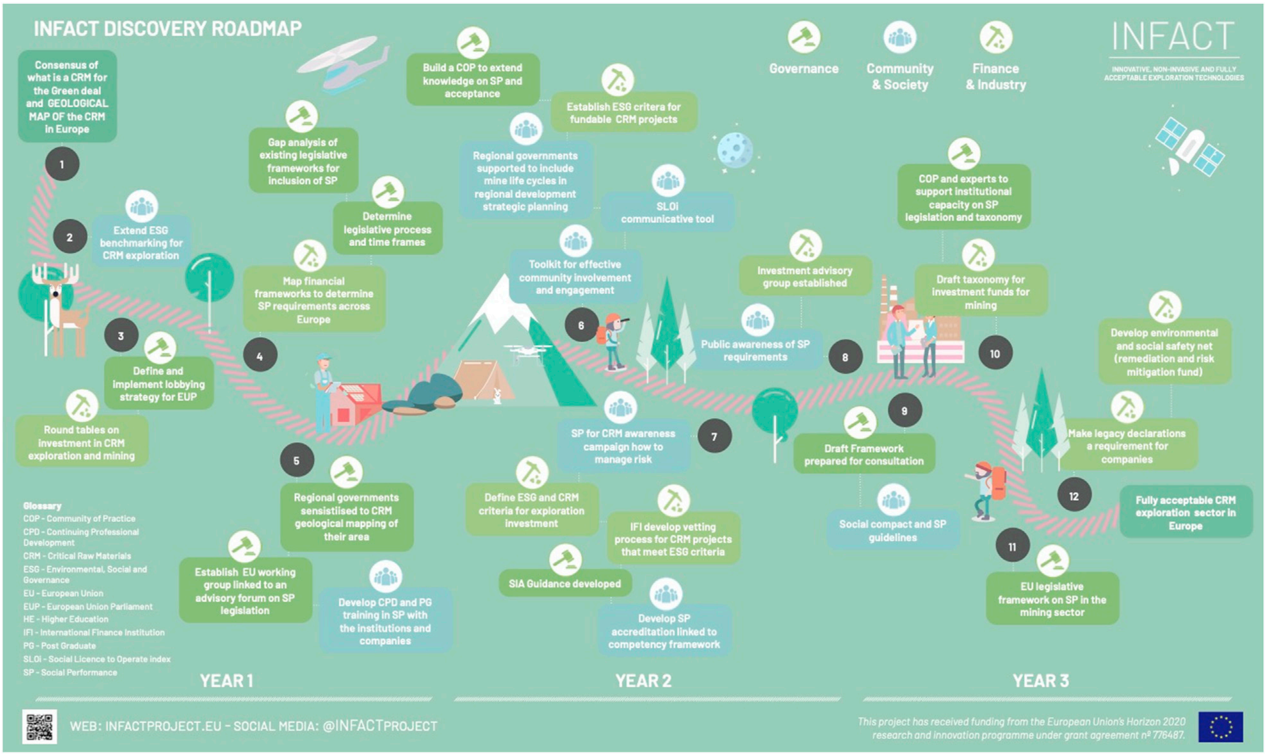

FIGURE 4 | INFACT discovery map based on the recognized need to include all stakeholders at an early stage. It assumes that Europe's exploration and mining sector should become fully acceptable by focussing on three long term goals: *1*) The European Commission develops a legislative framework for improved social performance. *2*) International Finance Institutions, banks and private equity consider investment opportunities for critical raw material exploration, with companies that actively consider the ESG risk profile of their proposed activities. *3*) Achieving and /or maintaining a SLO is considered from the outset of a project with effective engagement of potentially affected communities to improve awareness and trust, understanding of the local context and values and socio-economic shared value through collaborative planning.

unambiguous technology standards might achieve better outcomes (UNDP and UN Environment, 2018). Also, gaps and loopholes between nationally defined regulatory systems, such as mining in sea-bed areas need to be closed (Van Dover, 2011). Voluntary initiatives such as company disclosure (Christopher et al., 1997; Mudd, 2010), or consortia (e.g., IRMA - Initiative for Responsible Mining Assurance) and hybrid forms that merge top-down regulation and voluntary measures, such as the African mining vision, attempt to connect mineral resources policies with inclusive development. At the same time, however, only few countries have expressed a need for geoinformation in mining policies or set parameters to buffer environmental and social variables.

The lack of geospatial data infrastructures and their use in mining projects act as impediments to implementing sustainable mining policies. The lack of geoinformation may result in poor benefit-sharing, poor understanding of environmental risks, and a lack of integrated land use planning in resource-rich African countries. There is a need to expand awareness on the value of and to enhance access to geoinformation, establishing a space for geoinformation in Country Mining Visions, and to strengthen local capacity for handling these data. Mineral-rich African countries must optimise benefits derivable from emerging Earth Observation technologies and associated spatial data for measuring contributions of the mining sector to specific SDGs (Moomen et al., 2019).

Urged by new policies such as the Green Deal of the European Union, the United Nations Guiding Principles on Business and Human Rights, the Extractive Industry Transparency Initiative (EITI), the Dodd-Frank Act and others, a transition of the mining industry towards a low-carbon and circular economy has started and gains momentum. However, their implementation may be hampered by corruption and limited transparency in governmental oversight (Sturesson et al., 2015). In recent years green bonds, e.g. finance schemes that are linked to good environmental performance, received growing attention (Ehlers and Packer, 2017) and might have effects on sustainability gains (Maltais and Nykvist, 2020). Green bonds enable capital-raising and investment for projects with proven environmental benefits. The green bond principles support environmentally sound and sustainable projects that foster a net-zero emissions economy and protect the environment. By recommending that issuers report on the use of green bonds it triggers a transparency that facilitates the tracking of funds to environmental projects and their estimated impact. Green bonds have a relatively large share in sectors related to environmentally induced credit risks, but mining is hardly recognized in green bond investment portfolios. The effectiveness of private and public financial instruments and green investment strategies are therefore still controversial. While structural challenges on the public level (e.g., corruption) are often hard to counteract, the emergence of sustainable investment and voluntary schemes are a leverage to impact supplier and consumer side. Sustainable governance will need to rely partly on the active role of the industry and especially international companies.

CONCLUSION

Sustainable exploration and mining must reach environmental, economic, and social development goals; the alternative–mining is never sustainable–would result in intolerable negative environmental and social impacts. The sector needs transparent and inclusive stakeholder participation as well as a holistic understanding of the impact of their activities to meet the principle(s) of weak sustainability.

There is a plethora of domestic, regional, and international legal and regulatory frameworks, as well as formal and informal initiatives and instruments (including at company level), which are all aimed at improving governance of the extractive industry for increased economic prosperity and environmental protection. Based on our analysis, we would recommend the following concrete steps towards a more sustainable mining governance:

1) *Planning and management at organizational level:* here the companies and the investors that provide capital to these companies have prime responsibility to place sustainability indicators into their decision-making and controlling activities. If sustainability is not part of the accounting system, it will not be advanced.
2) *Regional and national regulations (legal instruments, permitting);* All mining operations are embedded in a context of regional and national regulations and requirements. These regulations should be guided by the three dimensions of sustainability. In particular, they should provide incentives (tax reductions for excellent sustainability performance or penalties for violations of sustainability goals) that may offset the financial burden for investing in sustainable operations. Furthermore, regional regulation should ensure the empowerment and involvement of local communities and actors in shaping the operating conditions (as for example specified in the license for operation).
3) *Voluntary agreements and certification systems in the industries*: The most important instrument here is the license to operate. This could be facilitated by mining associations but also by large standardization organizations such as the ISO. The main goal is to include the objectives of ecological, economic, and social sustainability as major benchmarks for operation with clear provisions for measurement, monitoring, and compliance management.
4) *Global governance structures:* It would be a major step forward if regional and national regulations were to be harmonized world-wide so that all mining operations are bound to the same sustainability criteria and rules regardless of where they operate. Such a global agreement could still include adjustments for considering regional conditions. Yet, as long as such a global accord is missing, it is important that all nations that are willing to cooperate promulgate legislation that provides incentives for sustainable practice. It may be worth-while creating a UN secretariat or even a new unit at the UN for governing world-wide mining operations. The more sustainability evolves into a key driver for change the more the global community needs a forum where rules for mining can be developed, negotiated, and implemented.
5) *Financial instruments (green investment funds):* As part of the triangulation of measure to ensure the compliance with sustainability goals the financial sectors could include sustainability indicators when banks make decisions about loans or when rating agencies assign grades to the performance of companies.

In addition, new policy instruments and approaches, e.g., hybrid forms of governance and consumer-oriented measures (demand management) may play a role in the governance of mining and mineral extraction. In addition, customary law and land tenure are important regulatory mechanisms, especially in indigenous territories.

Regardless which governance measures are introduced there will always be trade-offs between opportunities such as facilitating the energy transition, innovative battery design and e-mobility on the one side and risks for ecosystem and social communities on the other side. It is important to find the right balance that ensures shared benefits and reduces the risks. But there is no zero-risk solution, and one can only speak about risk reduction, not elimination. As political pressure on industry will increase due to the climate crisis, the economic risks for energy-consuming industrial sectors will increase respectively. This pressure on the mining industry might be amplified because of existing mutual interaction between the natural environment, mining industry, society, and economy. Decision making authorities need to balance public opinion, objective information about real consequences of mining activities, sustainable development goals, a necessity for climate change mitigation and economic development.

Our analysis shows that the sustainability of mining cannot be reached without harmonized political instruments and investment policies that take the three pillars of sustainability as a major priority. There is no one-size-fits-all single innovation concept that will resolve the challenges of the mining industry, let alone provide positive contributions to the sustainable development goals of the UN (SDGs). Societal innovations are mainly positive for advancing the goals of sustainability, but they are often accompanied by negative implications on the direct economic viability of mining operations. However, in the long-term, these innovations and reforms are absolutely necessary for making mining a future-proof activity.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Overall architecture and structure of the paper, coordinator, contributor (OR and RG), Revisions and contributions (OR and RG), Organization and contributions (CB), all others contributions by the other co-authors.

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CONFLICT OF INTEREST

VDR and JG are employed by Asistencias Técnicas Clave, Seville, Spain, and JR is employed by SRK Exploration Services, Cardiff, United Kingdom.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Ali, S. H. (2013). *Can Mining Be Sustainable?* University of Minnesotas's Institute on the Environment. Available at: https://ensia.com/articles/mine-over-matter/.

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., et al. (2017). Mineral Supply for Sustainable Development Requires Resource Governance. *Nature* 543, 367–372. doi:10.1038/nature21359

Andrews, T., Elizalde, B., Billon, P. L., Oh, C. H., and Thomson, D. R. (2017). *The Rise in Conflicts Associated with Mining Operations: What Lies beneath?* Vancouver, Canada: The Canadian International Resources and Development Institute (CIRDI), 1–127.

Annandale, D., and Taplin, R. (2003a). Is Environmental Impact Assessment Regulation a 'burden' to Private Firms? *Environ. Impact Assess. Rev.* 23, 383–397. doi:10.1016/S0195-9255(03)00002-7

Annandale, D., and Taplin, R. (2003b). The Determinants of Mining Company Response to Environmental Approvals Regulation: A Report of Australian Research. *J. Environ. Plann. Manage.* 46 (6), 887–909. doi:10.1080/0964056032000157651

Arndt, N. T., Fontboté, L., Hedenquist, J. W., Kesler, S. E., Thompson, J. F. H., and Wood, D. G. (2017). Future Global mineral Resources. *Geochem. Persp.* 6 (1), 1–171. doi:10.7185/geochempersp.6.1

Azapagic, A. (2004). Developing a Framework for Sustainable Development Indicators for the Mining and Minerals Industry. *J. Clean. Prod.* 12 (6), 639–662. doi:10.1016/s0959-6526(03)00075-1

Baumgartner, R. J., and Rauter, R. (2017). Strategic Perspectives of Corporate Sustainability Management to Develop a Sustainable Organization. *J. Clean. Prod.* 140, 81–92. doi:10.1016/j.jclepro.2016.04.146

Birkland, T. A. (1997). *After Disaster: Agenda Setting, Public Policy, and Focusing Events*. Washington, D.C.: Georgetown University Press.

Bleischwitz, R. (2020). Mineral Resources in the Age of Climate Adaptation and Resilience. *J. Ind. Ecol.* 24, 291–299. doi:10.1111/jiec.12951

Carrara, S., Alves Dias, P., Plazzotta, B., and Pavel, C. (2020). *Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy systemEUR 30095 EN*. Luxembourg: Publications Office of the European Union. doi:10.2760/160859

Christopher, Th., Hutomo, S., and Monroe, G. (1997). Voluntary Environmental Disclosure by Australian Listed Mineral Mining Companies: An Application of Stakeholder Theory. *Int. J. Account. Business Soc.* 5 (1), 42–66.

COM (2020). *Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability Document, Dated 03/09/2020*, 474..

Cooney, J. (2017). Reflections on the 20th Anniversary of the Term 'social Licence'. *J. Energ. Nat. Resour. L.* 35 (2), 197–200. doi:10.1080/02646811.2016.1269472

Ehlers, T., and Packer, F. (2017). *BIS Q. Rev.* 9, 89

Ernst and Young (2020). Top 10 Business Risks and Opportunities – 2020. Available at: https://www.ey.com/en_gl/mining-metals/10-business-risks-facing-mining-and-metals (Accessed April 8, 2022).

Florin, M. V., and Bürkler, M. T. (2017). *Introduction to the IRGC Risk Governance Framework (No. REP_WORK)*. Lausanne: EPFL.

Franks, D. M. (2020). Reclaiming the Neglected Minerals of Development. *Extractive Industries Soc.* 7 (2), 453–460. doi:10.1016/j.exis.2020.02.002

Frenzel, M., Kullik, J., Reuter, M. A., and Gutzmer, J. (2017). Raw Material 'criticality'-Sense or Nonsense? *J. Phys. D: Appl. Phys.* 50 (12), 123002. doi:10.1088/1361-6463/aa5b64

Gao, Y., Ai, Y., Tian, B., Chen, L., Wang, J., Cao, D., et al. (2020). Parallel End-To-End Autonomous Mining: An IoT-Oriented Approach. *IEEE Internet Things J.* 7 (2), 1011–1023. doi:10.1109/JIOT.2019.2948470

Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P., and Reck, B. K. (2015). Criticality of Metals and Metalloids. *Proc. Natl. Acad. Sci. U.S.A.* 112, 4257–4262. doi:10.1073/pnas.1500415112

Herrington, R. (2021). Mining Our green Future. *Nat. Rev. Mater.* 6, 456–458. doi:10.1038/s41578-021-00325-9
Herrington, R. (2013). Road Map to mineral Supply. *Nat. Geosci* 6, 892–894. doi:10.1038/ngeo1947
Hilson, G., and Nayee, V. (2002). Environmental Management System Implementation in the Mining Industry: A Key to Achieving Cleaner Production. *Int. J. Mineral Process.* 64 (1), 19–41. doi:10.1016/s0301-7516(01)00071-0
Jansson, N., Ranta, J. P., Berthet, T., and Suopajärvi, L. (2020). From Oil Digger to Energy Transition Enabler: The Critical Role of Exploration Geosciences Education in Europe. *Eur. Geologist* 50, 57. doi:10.5281/zenodo.4311695
Jowitt, S. M., Mudd, G. M., and Thompson, J. F. H. (2020). Future Availability of Non-renewable Metal Resources and the Influence of Environmental, Social, and Governance Conflicts on Metal Production. *Commun. Earth Environ. Nat.* 1, 11. doi:10.1038/s43247-020-0011-0
Junne, T., Wulff, N., Breyer, C., and Naegler, T. (2020). Critical Materials in Global Low-Carbon Energy Scenarios: The Case for Neodymium, Dysprosium, Lithium, and Cobalt. *Energy* 211, 118532. doi:10.1016/j.energy.2020.118532
Kagermann, H., Wahlster, W., and Helbig, J. (Editors) (2013). *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group* (Munich: Acatech - Deutsche Akademie der Technikwissenschaften e.V).
Kesselring, M., Wagner, F., Kirsch, M., Ajjabou, L., and Gloaguen, R. (2020). Development of Sustainable Test Sites for Mineral Exploration and Knowledge Spillover for Industry. *Sustainability* 12 (5), 2016–2017. doi:10.3390/su12052016
Korhonen, J., Honkasalo, A., and Seppälä, J. (2018). Circular Economy: the Concept and its Limitations. *Ecol. Econ.* 143, 37–46. doi:10.1016/j.ecolecon.2017.06.041
Larondelle, N., and Haase, D. (2012). Valuing post-mining Landscapes Using an Ecosystem Services Approach-An Example from Germany. *Ecol. Indicators* 18, 567–574. doi:10.1016/j.ecolind.2012.01.008
Latan, H., Chiappetta Jabbour, C. J., Lopes de Sousa Jabbour, A. B., Wamba&Shahbaz, S. F. M., and Shahbaz, M. (2018). Effects of Environmental Strategy, Environmental Uncertainty and Top Management's Commitment on Corporate Environmental Performance: The Role of Environmental Management Accounting. *J. Clean. Prod.* 180, 297–306. doi:10.1016/j.jclepro.2018.01.106
Littig, B., and Griessler, E.. (2005). Social Sustainability: a Catchword between Political Pragmatism and Social Theory. *Int. J. Sust. Develop.*, 8, 65. doi:10.1504/IJSD.2005.007375
Littleboy, A., Keenan, J., Ordens, C. M., Shaw, A., Tang, R. H., Verrier, B., et al. (2019). A Sustainable Future for Mining by 2030? Insights from an Expert Focus Group. *Extractive Industries Soc.* 6 (4), 1086–1090. doi:10.1016/j.exis.2019.11.005
Liu, X., Guo, P., and Guo, S. (2019). Assessing the Eco-Efficiency of a Circular Economy System in China's Coal Mining Areas: Emergy and Data Envelopment Analysis. *J. Clean. Prod.* 206, 1101–1109. doi:10.1016/j.jclepro.2018.09.218
MacCallum, C. S. (2016). *A Social License for Sustainable Development through Mining. Mining and Communities Solutions*. Vancouver, Canada. June 6-8, 2016 Published by InfoMine, © 2016 InfoMine.
Maltais, A., and Nykvist, B. (2020). Understanding the Role of green Bonds in Advancing Sustainability. *J. Sust. Finance Investment* 1 (20), 1–20. doi:10.1080/20430795.2020.1724864
Mancini, L., Benini, L., and Sala, S. (2015). Resource Footprint of Europe: Complementarity of Material Flow Analysis and Life Cycle Assessment for Policy Support. *Environ. Sci. Pol.* 54, 367–376. doi:10.1016/j.envsci.2015.07.025
McKenzie, S. (2004). *Social Sustainability: Towards Some Definitions*. Magill, South Australia: Hawke Research Institute Working Paper Series No27, University of South Australia.
McKinsey Company,Delevingne, L., Glazener, W., and Grégoir&Henderson, L. K. (2020). *Metals & Mining and Sustainability Practices. Climate Risk and Decarbonization: What Every Mining CEO Needs to Know. Building a Climate Strategy Won't Be Quick or Easy—But Waiting Is Not an Option*. Amsterdam: Report McKinsey & Company.
McLellan, B. C., Corder, G. D., Giurco, D., and Green, S. (2009). Incorporating Sustainable Development in the Design of mineral Processing Operations - Review and Analysis of Current Approaches. *J. Clean. Prod.* 17 (16), 1414–1425. doi:10.1016/j.jclepro.2009.06.003
Meinert, L. D., Robinson, G. R., and Nassar, N. T. (2016). Mineral Resources: Reserves, Peak Production and the Future. *Resources* 3, 14. doi:10.3390/resources501001410.3390/resources5010014
Mercer-Mapstone, L. D. (2018). *The Role of Dialogue in Social Licence to Operate in the Extractives sectorPhD Thesis*. Sustainable Minerals Institute: The University of Queensland. doi:10.14264/uql.2018.544
Moffat, K., and Zhang, A. (2014). The Paths to Social Licence to Operate: An Integrative Model Explaining Community Acceptance of Mining. *Resour. Pol.* 39, 61–70. doi:10.1016/j.resourpol.2013.11.003
Moomen, A.-W., Bertolotto, M., Lacroix, P., and Jensen, D. (2019). Inadequate Adaptation of Geospatial Information for Sustainable Mining towards Agenda 2030 Sustainable Development Goals. *J. Clean. Prod.* 238, 117954. doi:10.1016/j.jclepro.2019.117954
Mudd, G. M., and Jowitt, S. M. (2018). Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. *Econ. Geol.* 113, 1235–1267. doi:10.5382/econgeo.2018.4590
Mudd, G. M. (2010). The Environmental Sustainability of Mining in Australia: Key Mega-Trends and Looming Constraints. *Resour. Pol.* 35 (2), 98–115. doi:10.1016/j.resourpol.2009.12.001
Müller, F., Kosmol, J., Keßler, H., Angrick, M., and Rechenberg, B. (2017). Dematerialization-A Disputable Strategy for Resource Conservation Put under Scrutiny. *Resources* 6 (4), 68. doi:10.3390/resources6040068
Neumayer, E. (2003). *Strong versus Weak Sustainability*. Cheltenham: Edward Elgar.
Nikolaou, I. E., and Evangelinos, K. I. (2010). Classifying Current Social Responsibility Accounting Methods for Assisting a Dialogue between Business and Society. *Soc. Responsibility J.* 6, 562–580. doi:10.1108/17471111011083446
Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., et al. (2016). Assessing the Land Resource-Food price Nexus of the Sustainable Development Goals. *Sci. Adv.* 2 (9), e1501499. doi:10.1126/sciadv.1501499
O'Neill, D. W., Fanning, A. L., Lamb, W. F., et al. (2018). A Good Life for All within Planetary Boundaries. *Nat. Sustainability* 1, 88–95. doi:10.1038/s41893-018-0021-4
Partridge, E. (2005). Social Sustainability': a Useful Theoretical Framework?." in Australasian Political Science Association Annual Conference 2005. Dunedin, New Zealand. Available at: http://cfsites1.uts.edu.au/find/isf/publications/partridge2005socialsustainability.pdf.
Pelletier, N., Bamber, N., and Brandão, M. (2019). Interpreting Life Cycle Assessment Results for Integrated Sustainability Decision Support: Can an Ecological Economic Perspective Help Us to Connect the Dots? *Int. J. Life Cycle Assess.* 24 (9), 1580–1586. doi:10.1007/s11367-019-01612-y
Pimentel, B. S., Gonzalez, E. S., and Barbosa, G. N. O. (2016). Decision-support Models for Sustainable Mining Networks: Fundamentals and Challenges. *J. Clean. Prod.* 112, 2145–2157. doi:10.1016/j.jclepro.2015.09.023
Pizzol, M., Smart, J. C. R., and Thomsen, M. (2014). External Costs of Cadmium Emissions to Soil: a Drawback of Phosphorus Fertilizers. *J. Clean. Prod.* 84, 475–483. doi:10.1016/j.jclepro.2013.12.080

Polo, C. (2006). *Los ejes centrales para el desarrollo de una minería sostenible. Serie Recursos*. Madrid: SEPAL.

Poulton, M. M., Jagers, S. C., Linde, S., Van Zyl, D., Danielson, L. J., and Matti, S. (2013). State of the World's Nonfuel mineral Resources: Supply, Demand, and Socio-Institutional Fundamentals. *Annu. Rev. Environ. Resour.* 38, 345–371. doi:10.1146/annurev-environ-022310-094734

Proctor, M., and MacCallum, C. (2019). The Canary in the Cage : Community Voices and Social License to Operate in Central Eastern Europe. Available at: http://www.gecaminpublications.com/sustainable-mining-2019/ (Accessed April 8, 2022).

Qiu, R., Lin, M., Ruan, J., Fu, Y., Hu, J., Deng, M., et al. (2020). Recovering Full Metallic Resources from Waste Printed Circuit Boards: A Refined Review. *J. Clean. Prod.* 244, 118690. doi:10.1016/j.jclepro.2019.118690

Renn, O. (2022). Anforderungen an ein tragfähiges Konzept der Nachhaltigkeitswissenschaften. *Nachhaltigkeitsrecht* 2 (6), 601. doi:10.33196/nr2022010.33196/nr202201000601

Renn, O., Beier, G., and Schweizer, P.-J. (2021). The Opportunities and Risks of Digitalisation for Sustainable Development: a Systemic Perspective. *GAIA - Ecol. Perspect. Sci. Soc.* 30 (1), 23–28. doi:10.14512/gaia.30.1.6

Roberts, J. M., and Duff, E. S. (2002). Reactive Navigation and Opportunistic Localization for Autonomous Underground Mining Vehicles. *Inf. Sci.* 145 (1-2), 127–146. ISSN 0020-0255. doi:10.1016/S0020-0255(02)00227-X

Robertson, R. (1996). Globality, Globalization and Transdisciplinarity. *Theor. Cult. Soc.* 13 (4), 127–132. doi:10.1177/0263276496013004008

Robertson, R. (1992). "Globalization," in *Social Theory and Global Culture (Theory, Culture & Society Series)* (London: SAGE).

Rockström, J., Sachs, J. D., Öhman, M. C., and Schmidt-Traub, G. (2013). "Sustainable Development and Planetary Boundaries," in *Background Paper for the High-Level Panel of Eminent Persons on the Post-2015 Development Agenda* (Sustainable Development Solutions Network). Available at: https://www.jstor.org/stable/pdf/resrep16114.pdf?acceptTC=true&coverpage=false&addFooter=false.

Rosewarne, S., Goodman, J., and Pearse, R. (2013). *Climate Action Upsurge: The Ethnography of Climate Movement Politics*. Milton Park: Routledge. doi:10.4324/9780203594520

Ruokonen, E. (2020). Preconditions for Successful Implementation of the Finnish Standard for Sustainable Mining. *Extractive Industries Soc.* 7 (2), 611–620. doi:10.1016/j.exis.2020.03.008

Salonen, A. (2020). Sustainable Mining in Northern Finland: Standardization and Current Practices. Available at: https://lutpub.lut.fi/handle/10024/161881 (Accessed April 8, 2022).

Sonter, L. J., Dade, M. C., Watson, J. E. M., and Valenta, R. K. (2020). Renewable Energy Production Will Exacerbate Mining Threats to Biodiversity. *Nat. Commun.* 11 (1), 4174–4176. doi:10.1038/s41467-020-17928-5

Spitz, K., and Trudinger, J. (2009). *Mining and the Environment: From Ore to Metal*. Milton ParkRoutledge: CRC Press.

Sterner, T., Barbier, E. B., Bateman, I., van den Bijgaart, I., Crépin, A.-S., Edenhofer, O., et al. (2019). Policy Design for the Anthropocene. *Nat. Sustain.* 2, 14–21. doi:10.1038/s41893-018-0194-x

Sturesson, A., Zobel, T., and Zobel, T. (2015). The Extractive Industries Transparency Initiative (EITI) in Uganda: Who Will Take the lead when the Government Falters? *Extractive Industries Soc.* 2 (1), 33–45. doi:10.1016/j.exis.2014.11.006

Suopajärvi, L., Poelzer, G. A., Ejdemo, T., Klyuchnikova, E., Korchak, E., and Nygaard, V. (2016). Social Sustainability in Northern Mining Communities: A Study of the European North and Northwest Russia. *Resour. Pol.* 47, 61. doi:10.1016/j.resourpol.2015.11.004

Tayebi-Khorami, M., Edraki, M., Corder, G., and Golev, A. (2019). Re-Thinking Mining Waste through an Integrative Approach Led by Circular Economy Aspirations. *Minerals* 9 (5), 286. doi:10.3390/min9050286

UNDP and UN Environment (2018). *Managing Mining for Sustainable Development: A Sourcebook*. Bangkok: United Nations Development Programme.

UNDP (2016). *Mapping Mining to the Sustainable Empowered Lives*. Nairobi: United Nations Development Programme. Resilient nations. Development goals: An atlas. White Paper Available at: www.undp.org/content/dam/undp/library/Sustainable%20Development/Extractives/Mapping_Mining_SDGs_An_Atlas_Executive_Summary_FINAL.pdf.

United Nations (2020). *Transforming Our World: The 2030 Agenda for Sustainable Development*. New York: United Nations Press. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld.

Vallance, S., Perkins, H. C., and Dixon, J. E. (2011). What Is Social Sustainability? A Clarification of Concepts? *Geoforum* 42, 342. doi:10.1016/j.geoforum.2011.01.002

Van Dover, C. L. (2011). Tighten Regulations on Deep-Sea Mining. *Nature* 470 (7332), 31–33. doi:10.1038/470031a

Venghaus, S., Märker, C., Dieken&Siekmann, S. F., and Siekmann, F. (2019). Linking Environmental Policy Integration and the Water-Energy-Land-(Food-)Nexus: A Review of the European Union's Energy, Water, and Agricultural Policies. *Energies* 12 (23), 4446. doi:10.3390/en12234446

Vidal, O., Goffé, B., and Arndt, N. (2013). Metals for a Low-Carbon Society. *Nat. Geosci* 6, 894–896. doi:10.1038/ngeo1993

Warhurst, A. (1999). The Mining and Energy Research Network: Aims and Scope of the Project. *Minerals Energ. - Raw Mater. Rep.* 14 (3), 3–5. doi:10.1080/14041049909362532

WCED (1987). *Our Common Future*. Oxford, UK: Oxford University Press.

Weber, T., and Stuchtey, M. (2019). *Pathways towards a German Circular economyLessons from European Strategies Preliminary Study*. Munich: Acatech.