Innovation opportunities through circular economy in mining – proactive handling of ESG factors and sustainability-oriented regulation

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Abstract. Mining companies provide the required materials for the energy transition and green technologies. The question which emissions and waste are generated to produce these technologies attracts growing interest throughout the society. Investors, governments, customers, and other stakeholders have recognized that the mining and metals industry is the key to many sustainability issues. One of the greatest challenges for miners - short- to midterm - lies in increasing scrutiny, complex requirements from investors (Environmental, Social and Governance criteria, ESG) and stringent regulation. Consequently, two-third of the world's largest mining companies have defined net-zero or carbon neutrality goals. However, which paths must miners take to achieve these ambitious goals? How can they overcome the reactive phase and integrate sustainability into their core activities? Sustainable business model innovation is considered the prime technique for miners to outperform in this context. Circular business models belong to the most promising approaches beyond them. Based on a literature review, the paper points out potential circular strategies along the mine's life cycle and discusses drivers and barriers towards a circular transition of the sector. It aims to provide a solid information basis and starting point for sustainability strategists in mining.

Keywords: Circular economy, Circular transition factors, Mining and metals, Circular business models, ESG integration.

1 Introduction

Achieving climate change goals is dependent on and driven by the mining and metals sector to a large extent. The transition to wind energy, solar photovoltaic or e-mobility known to be 'clean energy technologies', requires a wider range and quantity of materials compared to fossil-fuel-based electricity generation technologies (Hund, La Porta, Fabregas, Laing, & Drexhage, 2020). At least 23 key minerals - beyond them iron, copper, aluminum, nickel, lithium, cobalt, platinum, silver, and rare earth metals – will

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be critical to the development and deployment of clean energy technologies (Church & Crawford, 2018); (Lèbre, et al., 2020). Hence, it is obviously, that the low-carbon transition also enlarges the material footprint. Any potential shortages in mineral supply have the power to delay the diffusion of these technologies (Hund, La Porta, Fabregas, Laing, & Drexhage, 2020). This finding also depicts the unsustainable aspect of mining and metals: The sector leaves fewer resources for future generations. Does that mean, humanity must act unsustainably to combat climate change? Alternatively, does a workaround exist?

So far, only 8.6 % of the resources that are extracted return to the production system as input into new everyday essential products (CGR, 2022). The figures of critical raw materials, the clean energy technologies described above, heavily rely on, are even worse. For instance, the End-of-Life-recycling rate for rare earths is estimated to be below 1% (Graedel, et al., 2011a); the same rate is evaluated for the global lithium recycling (Swain, 2017). Engaging in a low-carbon future is resource-intensive and a transition can only be realized through a combination of mining of primary and secondary materials.

Critical stakeholders, especially regulators, and more and more investors show growing awareness for the impact, the mining and metals industry has on its environment. Regulation is exerting pressure by dictating tough time schedules and strict requirements (e.g. EU taxonomy regulation, Corporate Sustainability Reporting Directive), with the aim to channel capital flows into sustainability-oriented economic activities (Wunder, 2022). The mineral resource investment landscape is reshaped by climate change issues (Svobodova, Owen, Harris, & Worden, 2020). So far, more than 100 major financial institutions worldwide have already divested from thermal coal and now focus on opportunities and growth tied to investments in the energy transition (Buckley, 2019). Environmental, social, and governance (ESG) criteria are not new to the board-level but become increasingly critical for the company's success and therefore should be linked to its strategy, core operations and business model. Originally introduced as market-led initiative encouraged by the United Nations in 2004, ESG integration is now amplified by regulatory pressure and considered as one of the most widely adopted 'sustainable yardsticks' on a global level, linking corporate governance and social and environmental sustainability (Câmara, 2022). Circular finance is also winning pace - describing any form of financial service or instrument integrating circular economy indicators into the business or investment decisions, in order to enable and accelerate the circular transition (PwC, 2021); (FinanCE, 2018). Related investments already exist in many sectors. Vehicles like circular bonds, public equity funds, venture capital for circular projects are already available on the market and are recording high growth rates (EMF, 2022); (Koumbarakis, 2021).

The mining and metals board levels are aware of the development and quote environmental, social, and governance (ESG) criteria as their number one challenge (EY, 2022). According to a recent CEO study, 72% of mining and metals CEOs agree that sustainability issues (including decarbonization) are very important to important when it comes to their company's future success (compared to an average of 54% throughout all industries) (Lacy, Hughes, & Hull, 2022). 63% of investors would avoid investing in mining companies that fail to meet their decarbonization targets (Jacobs, Keenan, & Cranmer, 2022). Several leading mining companies (e. g. BHP, Rio Tinto, Vale, Glencore, Anglo American) have already committed themselves to become carbon neutral by 2050 by the latest (Kuykendall, 2021). However, the investments required along the way must be financed. The mining and metals managers must develop strategies and innovate their business models sustainably to meet the requirements of strict regulation and investment criteria that ensure their capital flows, and at the same time satisfying diverse stakeholders to achieve and retain their ‘social licence to operate’. Taking on these latest developments in legislation and the investment landscape, as well as the current public debate on the key words ‘circular economy’ and ‘low-carbon transition’, opens the question, how a key sector like mining and metals can innovate towards this end and profit. How can it meet investor, policy and societal requirements, still earn enough money to stay profitable and provide long-lasting benefits to communities, and therefore be a driving force especially for people’s prosperity in emerging and developing countries?

Based on an extensive literature review of academic and grey literature, the following subsections shed light on the corporate context in mining and metals (chapter 2) to provide a clear understanding of what must be considered when positioning the company for the future. Following the aim to support sustainable development and combat climate change, it focuses on the circular economy concept. Therefore, it suggests a sectoral definition and circular strategies (chapter 3) and investigates influencing factors (internal and external) that drive/hinder the circular transition of the sector (chapter 4). Eventually, potential business model patterns are derived (chapter 5) to guide practitioners in the innovation process and implementation of circular initiatives.

2 ESG relevance and sustainability-oriented regulation

The ESG discussion depends in many aspects on the kind of products and services, a company offers to its stakeholders, and how those products are manufactured within the entire value chain with respect to climate change and sustainability issues (Dathe, Dathe, Dathe, & Helmold, 2022). According to a recent investor study of ESG in the mining sector, the top five attributes that would drive a significant valuation premium with regard to sustainability-oriented initiatives, are: (1) low scope emissions; (2) invests in revolutionary technology; (3) improving efficiency and costs; (4) best in class independent ESG score and (5) production of energy-critical metals (Jacobs, Keenan, & Cranmer, 2022).

ESG governance is highly effective due to the ‘cascade effect’. Namely, its power to affect several types of entities and persons in four successive stages. First, starting from the asset manager making investment decisions; second, over the companies invested in (or not) to engage in responsible business activities; third, through further influencing the company’s supply chain or network; and fourth via further downstream consumers and the public, and thus also potential workforce (Câmara, 2022). Withholding ESG criteria in sustainability reporting harms the company’s valuation, access to capital, and its (brand) reputation (Castanón Moats, Herman, DeNicola, DiGuiseppe, & Brown, 2022) which is very critical for a capital-intensive industry like mining and metals. Regulators of many countries have started to mandate the inclusion of certain ESG data like targets and policies in favor of sustainable development.

The Corporate Sustainability Reporting Directive (CSRD) develops its full political impact through a combination with the EU taxonomy regulation ((EU) 2020/852) and the Sustainable Finance Disclosure Regulation (SFDR). Applying these three key elements, the EU is using the regulated financial market to channel capital flows into sustainability-oriented economic activities. The availability of clear, ambitious, and comparable sustainability information as intended by the CSRD, should provide greater certainty for sustainable investment and financing decisions by investors and banks in the near future and avoid greenwashing. The EU taxonomy requires additional disclosure of the environmentally sustainable share of the company's sales revenues, its capital expenditures (CapEx) and its operational expenditures (OpEx) in the management report. The identification of relevant company's business activities is enabled through screening in order to identify 'taxonomy-compliant activities'. Economic activities herein can be those, which are practiced by the company itself, enabling activities for other companies (as in networks) or transitional activities in case no sustainable alternatives are available due to technical or economic reasons. Further – to determine the taxonomy quotas, compliance with defined 'technical screening criteria' (TSC) (threshold values and performance criteria) must be checked for each taxonomy-eligible activity. These represent minimum requirements for the taxonomy conformity of economic activities, and decide whether their contribution is substantial enough, so that they can be allocated to green sales shares, investments or operational expenses. An economic activity is ecologically sustainable if it contributes significantly to the achievement of one or more of the six environmental goals, at the same time does not significantly impair the achievement of the other environmental goals and minimum social standards (Wunder, 2022).

The six environmental objectives, the taxonomy regulation defined are: (1) climate change mitigation; (2) climate change adaptation; (3) sustainable use and protection of water and marine resources; (4) transition to a circular economy; (5) pollution prevention and control; and (6) protection and restoration of biodiversity and ecosystems (EC, 2021). In the future, a further planned 'EU social taxonomy', will address aspects relating to human and labor rights and an appropriate standard of living for consumers (Wunder, 2022).

In the US, the direction also leads toward the expansion of mandatory ESG reporting obligations. The Securities and Exchange Commission (SEC) has adopted a fragmented approach with a focus on climate change (Scope 1 and 2 GHG emissions reporting, as well as Scope 3, material; climate risks, strategy impacts, climate governance, and risk management) and cybersecurity reporting rules starting from the financial year 2023. Further rules are expected in terms of human capital and board diversity disclosures during the year 2023 (Bichet, Eastwood, & Mencher, 2022).

3 Defining circular economy in mining and metals

Generally, circular economy (CE) describes an economic system that is based on business models replacing the 'end-of-life' concept seeking to reduce, alternatively reuse, recycle, and repurpose materials in production, distribution, and consumption processes. CE complements the conceptual basis of the 'industrial ecology' framework (Walmsley, Ong, Klemes, Tan, & Varbanov, 2019) and offers a systemic umbrella concept (Blomsma & Brennan, 2019); (Homrich, Galvão, Gamboa Abadia, & Monteiro de Carvalho, 2018) for a wider range of circular strategies.

Circular strategies - also known as ‘Re-strategies’ - are oriented towards achieving three core objectives:

(1) They aim at extending the productive life of resources to keep materials and products in the system and at their highest utility for as long as possible to optimize their values.

(2) They strive for designing waste and pollution out of the economic system through fully costing their impacts and generating additional values by recycling, reusing and repurposing the materials.

(3) They look for ways to regenerating natural systems to protect essential functions (clean water and air, healthy soils, carbon storage and flood protection) (Blomsma & Brennan, 2019); (Barreto, Barreto, & Chovan, 2021).

Mining and metals operations include mining, mineral processing, and metallurgical extraction. The fascination of mining and its processes lies in increasing very low concentrations of minerals and metals to supply core raw materials to most global supply and value chains enabling production of our everyday essentials. However, low concentrations of material come along with the production of a huge amount of mine wastes. In some cases, gold ores for example, about 99% of mined material is considered waste. Due to significantly dropping ore grades of a variety of extracted minerals and metals, waste volumes will rise further. Mine wastes occur as solid, liquid or gaseous by-products, in the forms of tailings, waste rock, or contaminated fresh water. They consume land, create dust storms and silt streams, contaminate surface water and groundwater (Kalin-Seidenfaden & Wheeler, 2022). Altogether, the mining and metals industry is among the world’s greatest generators of waste with approx. 10 billion tonnes a year, which amounts to 40-55% of the global total. Per annum, the global mining industry generates approx. 6.5 million tons of tailings (Lacy, Long, & Spindler, 2020). Currently about 85 per cent of the energy consumed by mines originated from fossil fuels (Colwell, 2017). With declining ore grades, the demand is expected to rise further. An analysis of copper mines for instance, showed that the average ore grade has decreased by 25 % over one decade leading to an increase of 46 % in the total energy consumption (Calvo, Mudd, Valero, & Valero, 2016). Given the three core objectives of the circular economy concept, the mining and metals sector is clearly a driving force towards achieving a circular transition and at the same time in supporting sustainable development.

Striving for the 3R waste reduction alone - in the strict sense of a circular economy - would allow for a significant contribution of the sector through:

- Improved water and material reuse by implementing cyclic systems.
- Maximized reuse of waste and the mine’s by-products.
- Collaboration with the manufacturing sector for circular product design (Bakker, Den Hollander, van Hinte, & Zijlstra, 2019).
- Enabled tracking and tracing of materials and alloys at the End-of-Life (EoL) status with aid of information technologies to facilitate subsequent reusing, recycling and repurposing.

- Acting with the usual objective of efficiency, a part of CE-oriented measures could already be considered: Improving recovery rates both in mining and mineral processing through technological progress, minimizing waste generation (tailings, gas emissions and waste water), developing feasible approaches for lower grade ores, amongst others (Tayebi-Khorami, Edraki, Corder, & Golev, 2019); (McCarney, et al., 2021).

Frequently cited conceptualizations describe the CE as a circular flow of resources in production, manufacturing and consumer product markets, thereby demonstrating a downstream focus and depicting a 'part-value chain CE model'. According to this interpretation, the stages of raw material extraction and material waste/landfill of the system are limited to flows that should be minimized (McCarney, et al., 2021); (Lèbre, Corder, & Golev, 2017); (EMF, 2013). This perspective excludes extraction and import of natural resources as well as the outflows of waste materials from the core of the model, leading to the situation, that the primary sector is overlooked in most circular value chains (McCarney, et al., 2021) despite its huge potential for circular business cases. A content analysis of sustainability reports of large-scale mining companies also states that circular economy initiatives are not explicitly addressed in most cases. Concept-related processes (recycling measures) were addressed implicitly, but without proof for increase in either communication or practice (Upadhyay, Laing, Kumar, & Dora, 2021). A Finnish study confirms that circular economy efforts are lacking in environmental programs of mining companies (Ruokonen & Temmes, 2019).

CE practices, potentially, also can contribute directly to achieving a considerable number of Sustainable Development Goal (SDG) targets, with the strongest relationships to SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) (Schroeder, Anggraeni, & Weber, 2018). Shortly summarized, three main interpretations exist in terms of the relationship between CE and sustainability, according to which CE is either considered as a condition for sustainability, as a beneficial relation, or a trade-off (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). Given the sector's relation to sustainable development and considering current ESG and stakeholder requirements, the focus on circular ambitions in mining and metals should be laid on achieving a beneficial relation between circular approaches and sustainable development. Defining sustainability as balanced integration of the economic, ecological and social dimension benefitting current and future generations (Geissdoerfer, Savaget, Bocken, & Hultink, 2017), it becomes clear that circular approaches in mining and metals must entail social value creation, especially for the local communities the mining operations (in)directly impacts.

Based on the general CE and sustainability definitions and derived CE strategies, the following key principles can be identified to operationalize circularity in the mining and metals context in accordance with ESG and regulation requirements:

(1) Optimize stocks through extending the value of materials.
(2) Be eco-efficient and eco-effective in daily operations.
(3) Eliminate waste by extending value of resources.
(4) Implement 'Extended Producer Responsibility' (EPR).

(5) Design products and processes circular (‘Material Stewardship’).
(6) Create social (‘shared values’) for the local communities and beyond (Barreto, Barreto, & Chovan, 2021).

Further investigation of circular opportunities should take into account the entire life cycle of the mine with the phases of prospecting, exploration, development, extraction, closure and reclamation. This perspective is endorsed by the European Union (EU) Circular Economy Action Plan, which also examined best practices in its ‘Extractive Waste Management Plans’. (EC, 2019). Depending on the status (‘greenfield’ or ‘brownfield’) of the mine project, the degree of management influence on the application of circular aspects varies.

Generally, circularity at the mine site can be achieved in two ways: First, miners are material suppliers and initiate the most product value chains. Second, they are industrial buyers/users of products and services at the mine site (technical operating system including physical infrastructure, equipment, and further assets that are created and/or utilized at the mine site). With this dual perspective, a bunch of CE opportunities evolves at the mine site and also beyond, if the mining company engages in collaborations, e. g. with local mining operators, upstream supply vendors, other key partners in the downstream value network (Barreto, Barreto, & Chovan, 2021). Depending on the type of resource, location of the deposit, and available options to collaborate, circular initiatives can be implemented at the ‘micro level’ (throughout the mine site - involving material and company aspects), the ‘meso level’ (within ‘eco-industrial parks’ engaging in industrial symbiosis) and the macro level (across the local community, region for optimized infrastructure and energy use).

As mining and metals sites are often located in emerging and developing countries, approaches like ‘creating shared value’(CSV) are advantageous. Through CSV the social dimension can be integrated in the circular initiative and ensures that a sound business case exists. Shared value results from “[…] policies and operating practices that enhance the competitiveness of a company while simultaneously advancing the economic and social conditions in the communities in which it operates” (Porter & Kramer, 2011). The three distinct ways to create shared value as described by Porter and Kramer, namely (1) reconceiving products and markets; (2) redefining productivity in the value chain; and (3) enabling local cluster development (Porter & Kramer, 2011) are reflected both in circular strategies and business models, particularly through the following opportunities:

- Support fair and equitable access to mineral resources.
- Prolong the mine’s life and thus create long-term job opportunities.
- Combat climate change through investing in a ‘zero-carbon mine’.
- Engage in socio-cultural and biodiversity protection, community health and education measures.
- Source responsibly, particularly in terms of social aspects in supply chains.
- Use renewable energy and support relevant infrastructure in local communities.

- Consider the future use of residual mineral deposits in the post-mining phase and rehabilitation aiming to eliminate the contamination on- and off-site (Barreto, Barreto, & Chovan, 2021).

Further shared value opportunities are generated through networks and clusters/eco-industrial parks, for instance by direct recycling of pre-consumer manufacturing scrap/residues, urban mining of post-consumer EoL-products, e. g. recovery of metals from electronic waste, and landfill mining (LFM) of historic (and future) urban waste streams (Jones, et al., 2013). The more the collaboration in networks progress, and the more the mining and metals sector is integrated, the more business opportunities arise.

4 Factors influencing the circular transition of the mining sector

Many studies have investigated drivers and barriers of the circular economy cross-sectoral, using different research methods (literature reviews, group discussions with stakeholders, expert interviews, international case studies) (de Jesus & Mendonca, 2017); (Houston, Casazza, Briguglio, & Spiteri, 2018); (Ranta, Aarikka-Stenroos, Ritala, & Mäkinen, 2018); (Tura, et al., 2019). Due to the fact, that CE influencing factors do not act in isolation, but are intertwined, their interrelationships have been examined - on a regional level (EU) (Kirchherr, et al., 2018) and by mapping causality networks from the macro-level perspective (Gue, Promentilla, Tan, & Ubando, 2020). Interestingly, a number of studies already exist for the mining and metals sector, which investigate different stages of the mining and metals value chain. Barriers and their intensity were evaluated (Singh, Kumar, Garza-Reyes, & de Sá, 2020), interrelationships were identified in an emerging economy context (Gedam, Raut, Lopes de Sousa Jabbour, & Agrawal, 2021), an insight was given on the status quo of large-scale mining companies (Upadhyay, Laing, Kumar, & Dora, 2021). Technological issues - with a focus on mine wastes - have been reviewed many times, e. g. by (Lottermoser, 2011); (Gaustad, et al., 2019); (Kinnunen & Kaksonen, 2019); (Kinnunen, Karhu, Yli-Rantala, Kivikytö-Reponen, & Mäkinen, 2022). Also further downstream some studies exist, especially with a focus on critical raw materials and derived products (Prats Raspini, Bonfante, Cúnico, Alarcon, & Campos, 2022); (Jensen, Purnell, & Velenturf, 2020). The identified factors can often both be drivers and barriers - depending on their 'direction of action'. Thus, they are considered as 'CE influencing factors' hereafter. For the mining and metals context - viewed from a corporate perspective – six clusters of influencing factors can be identified (Table 1) and subcategorized in (1) internal factors and (2) external factors, sometimes overlapping. For instance, ESG investments are influenced from inside and outside.

Miners can positively contribute to investments by innovating their business models towards acknowledging ESG requirements (internal). On the other hand, they cannot influence the development of investment criteria (external). According to this classification, internal factors can directly be influenced by management decisions and workforce behavior - towards progress or regression. External factors have an impact on the company (and the industry) from 'outside'. The highest system level, the macro-level, has the greatest distance to the actions of a mining manager. This level can hardly be influenced by the company. Internal factors entail the categories ‘organizational’, ‘operational’, ‘financial’ and ‘technological’; external factors comprise the clusters ‘government policies and regulations’, and ‘market’. Characteristic for the mining sector is, that some internal conditions exist, which can hardly be influenced (e.g. location of deposit).

Based on the sectoral definition of CE, derived principles and identified influencing factors, it becomes clear that achieving the circular transition of the mining and metals sector entails redistributing resources, opportunities, and power among actors and thus, will be a mid- to long-term project, contested and conflict-ridden. Shifting to a CE system requires overcoming barriers. In many cases radical innovation and socio-institutional change is necessary. Innovation on companies’ side relates to technology, product and process design and revenue models, and will therefore entail holistic business model innovation and the courage to do so. The major paradox managers are facing is, that the current (linear economic) system that still enables success with today’s business models, reinforces behaviors that are inconsistent with engaging in the needed circular economic system. This paradox is not new - it accompanies innovation in general (Anthony, Cobban, Nair, & Painchaud, 2019).

Table 1: Overview of internal and external factors influencing the progress of the CE transition in mining and metals (Own illustration based on literature cited in chapter 4)

(Mainly) Internal factors				External factors	
Organi-zational	**Operational**	**Financial**	**Techno-logical**	**Policies & regulations**	**Market**
Manager mindset, expertise & commitment	Adjusted mine life cycle	ESG investments	Maturity of processing technology (lower-grade materials)	Regulations (e.g. EU taxonomy)	Product standardization
Corporate culture ('stewardship')	Adjusted product life cycle	Initial capital for CE initiatives	Handling of sidestream technologies	Promotion/ Incentives; Fees/taxes	Trade-offs between primary and secondary material
Workforce training	Implemen-tation of circular value chain (collaboration especially downstream)	R&D budget for process & product adjustment and optimization	Tailings valorization: Hetero-geneity/impurities & refinery issues; Knowledge gaps on mineralogy, concentration	Compliance mechanisms	Consumer awareness and consumption patterns (sufficiency, willingness to pay more)
Decision-making & planning horizons	Integration of functions	Training funds	'Balance problem' (between abundance of elements and market demand)	Maturity/ existence of infrastructure	Stock exchange instruments
Implementation of CE measures		Funds for CE operations	Risk management (e.g. opening old heaps)	Consumer information campaigns	Diverse stakeholder interests
		Invest in additional CE marketing	Availability of EoL-products		

	Profitability of CE initiatives	Quality requirements	
		Traceability of material	

5 Circular business model innovation

Apart from the economically and politically motivated measures building pressure, described in section 2, there is an adequate strategic response, supporting the circular shift and enabling additional value creation. Business model innovation has been argued to be a key enabler for circular economy - reaching from basic innovations in operational efficiency upstream to radical innovation of all business model elements, including new forms of collaboration downstream the value chain, for example. Generally, business models describe the organizational value creation, defined by three key elements: (1) the value proposition (the benefit offered to customers and further stakeholders); (2) the value delivery, explaining how value propositions target and unfold for customers and further stakeholders; and (3) the value capture revealing how the company generates net value from its interaction with customers and stakeholders (Breuer & Lüdeke-Freund, 2017); (Osterwalder & Pigneur, 2010). Business model innovation not only generates higher returns than mere product or process innovations but is also a means to build market entry barriers and to achieve a competitive advantage (Magretta, 2002).

The traditional business model in mining and metals is under pressure due to market disruption. Companies should adapt and innovate their business models towards circular objectives, applying circular strategies and principles that fit in their individual context. Circular business models describe the rationale of how an organization creates, delivers, and captures values with and within closed material loops addressing resource and impact decoupling for the sake of current and future generations. Thus, it can be subcategorized under the concept of sustainable business models (Osterwalder & Pigneur, 2010); (Mentink, 2014); (Geissdoerfer, Pieroni, Pigosso, & Soufani, 2020). Sustainable business model innovation aims to improve the company’s financial, social and environmental performance and aims to integrate societal issues at the core of company’s strategy and activities, not at the periphery (Porter & Kramer, 2011).

The path towards (circular) business model innovation may entail the extended coexistence between current and new business models (Chesbrough, 2010) to manage holistic change in a profitable, ‘healthy’ manner. Principles to support the circular business model innovation process in the mining and metals sector have been discussed in subsection 3. Put in a contextual perspective, circular business models should consider potentials within the full value chain, that result from the integration of primary resource producers and regions into circular value chains, the application of circular policies and practices to extraction and processing stages, as well as the consideration of linkages between emerging innovations in downstream consumer markets and upstream actors (McCarney, et al., 2021). The circular strategies implemented in the individual company context define which types of circular business models are applicable and how they are executed (Casadesus-Masanell & Ricart, 2011). A circular business model does not need to close material loops itself (within its internal system boundaries) but can also be a part of a system of business models which in collaboration close a material loop (Mentink, 2014). For instance in bridging the concepts of the usual circular concept with a focus on production, manufacturing, and consumer markets on the one hand and that one of raw material extraction towards landfill on the other (McCarney, et al., 2021).

Table 2: Overview of contextual circular business models based on the ReSOLVE framework (Own illustration based on *(EMF, 2015)*; *(Lewandowski, 2016; Barreto, Barreto, & Chovan, 2021; Drusche, Krause, Kretschmann, Mischo, & Ayres da Silva, 2021)*; *(Bocken, Short, Rana, & Evans, 2014)*.

Framework classification criteria	**Description (contextual)**	**Business model patterns based on *(Bocken, Short, Rana, & Evans, 2014)***	**Link to ESG criteria, regulation**
Regenerate	• Shift to renewable energy and decarbonization; alternate powered vehicles; sustainable fuels	Substitute/use of renewable and digital processes	ESG; EU Taxonomy, SEC
Share	• Reuse materials • Resource-Service Systems (RSS) • Prolong life through maintenance, design for durability, etc. • Ensure fair and equitable access to mineral resources • Industrial Symbiosis	Deliver functionality - not ownership Adopt a stewardship role Inclusive value creation Repurpose for society/environment Encourage Sufficiency Closing resource loops	ESG
Optimize	• Increase efficiency/ performance of products • Prolong mine life • Enable potential future use of residual mineral	Maximize material and energy efficiency Adopt a stewardship role	ESG

	deposits in post-mining phase • Optimize tracking and tracing of materials through digitization • Reduce/remove waste		
Loop	• Implement restorative loops of material stock from mining waste • Recycle materials	Closing resource loops	ESG, EU Taxonomy
Virtualize	• Dematerialize directly (paper, business trips) and indirectly (online sourcing)	Adopt a stewardship role	ESG
Exchange	• Replace old with advanced non-renewable materials • Apply new technologies (e. g. 3D printing for spare parts)	Adopt a stewardship role	ESG

Circular business model patterns facilitate the innovation process by providing simple and conveniently formatted problem-solution combinations. Hence, it is not surprising, that a high percentage of new business models is not new in the proper sense, but results from a recombination of patterns, like creative transfer from other industries (Drusche, Krause, Kretschmann, Mischo, & Ayres da Silva, 2021). Table 2 depicts sustainable business model patterns identified by Bocken et al. that are suitable in the circular economy based on the contextual definition, classified according to the frequently cited ReSOLVE framework (EMF, 2015). The ESG and legislation relevance of circular activities that are tied to the listed patterns can be taken from Table 2. It visualizes that tough external requirements can induce further value creation opportunities.

6 Discussion and Conclusion

Even with increased rates of material recovery, reuse, and recycling, there is no doubt about the current and further increasing demand for primary minerals and metals during the decades to come – due to the low-carbon transition, emerging economy material demands and secondary material supply constraints in the near- to medium-term time horizon. Achieving the low-carbon transition is resource-intensive and must build on a combination of mining of primary and secondary materials. Sustainable business model innovation is considered the prime technique for miners to outperform in this context. Circular business models belong to the most promising approaches beyond sustainable business models. They should be based on the full-circle circular economy interpretation linking the mining and metals' circle from raw material extraction towards waste/landfill applications with the consumer goods circle. Studies reveal that the implementation of circular economy is successful when it is flanked by a sound business case (Ghisellini, Cialani, & Ulgiati, 2016). Addressing ESG issues and emerging regulations will then become core business and not a further obligation. A growing number of companies across industries have identified circular economy and its strategies as enabler of cost reduction, generator of additional revenues, and means of risk management, especially in terms of climate change issues. For practitioners, the most pressing question is how a business case for circular economy can be created, as it usually does not happen by accident. The information in the previous sections in terms of context, sectoral definition, suitable CE strategies and circular business model patterns should support decision-makers in planning their path towards circular transition. Further research is needed in terms of CE transition conditions for individual resources and how far these conditions can be generalized.

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