TOWARDS A CIRCULAR ECONOMY APPROACH TO MINING OPERATIONS

Key Concepts, Drivers and Opportunities

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NOTE TO READERS

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List of Abbreviations

CE	Circular Economy
CMIC	Canada Mining Innovation Council
CMMP	Canadian Minerals and Metals Plan
CSM	Critical and Strategic Minerals
EPR	Extended Producer Responsibility
ESG	Environmental, social and governance
EV	Electric vehicle
GHG	Greenhouse gas
Gt	Giga tonnes
MAC	Mining Association of Canada
MVFW	Mining Value from Waste
NRCan	Natural Resources Canada
SD	Sustainable Development
SDGs	Sustainable Development Goals
WBCSD	World Business Council on Sustainable Development

Executive Summary

The minerals sector is receiving increasing international attention for the role it plays as a supplier of materials necessary to build the infrastructure for a low carbon energy future. While contributing to climate change solutions, it must also address mounting pressures from stakeholders and supply networks to tackle serious environmental and social impacts. Combined, these trends present a moment of opportunity and challenge for the mining industry.

There is a growing interest globally in the benefits associated with the integrated, zero waste/low carbon Circular Economy (CE). CE concepts and strategies focus on transformative approaches that design waste and pollution out of products and services, while capturing greater economic value throughout supply networks, by rethinking conventional “take-make-waste” linear business models.

Relatively little has been discussed about the implications of CE transition strategies for mining operations. Aside from their irreplaceable role in renewable energy infrastructure, minerals have unique properties of durability, recyclability and adaptability, making them ideal materials for the closed loops of production associated with CE systems.

Canada’s established history of mining innovation positions it well to address and benefit from these challenges. With the Canadian Minerals and Metals Plan (CMMP) identifying CE strategies as a way to advance a sustainable future for the industry, there is an opportunity to demonstrate leadership that builds on domestic strengths and larger global trends, both of which seek to capture greater value while reducing negative impacts.

Core CE Objectives and Principles

Regardless of sector, CE is guided by three core objectives:

- Design waste and pollution out of the economic system, by fully costing impacts and identifying potential for value in materials recycling, reuse and repurposing.
- Keep products and materials in the system and at their highest utility for as long as possible to optimize value.
- Regenerate natural systems to protect essential ecosystem services such as clean water, clean air, healthy soils, carbon storage, and flood protection.

Several principles inform CE solutions and define an approach to problem-solving using integrated and systemic strategies to address root causes of ongoing negative environmental and social impacts. The CE approach seeks to overcome siloed harm reduction tactics when dealing with environmental, social and governance (ESG) problems that address symptoms but not the underlying conditions or activities that lead to those problems.

Key CE principles relevant to the mining industry explored in the report include:

- Stock optimization – extending the value of materials;
- Eco-effectiveness – going beyond eco-efficiency;
- Eliminating the concept of waste by extending resource value;
- Extended Producer Responsibility (EPR);
- Circular product and process design; and,

- Creation of social value for everyone.

This report demonstrates these principles applied to mining operations throughout the mine life cycle.

CE Applications at the Mine Site

For mine operators, CE involves the minimization of waste generation, through all stages of extraction and processing, and the focused preservation of natural resources and their value by extending the life of extracted minerals. The emphasis is on maximizing value wherever possible but is not exclusively reliant on producers to bear this responsibility. Under CE scenarios, other market players may be drawn in to capture and share value (see Figure below, *Process and Product Stewardship in Minerals Value Chain*).

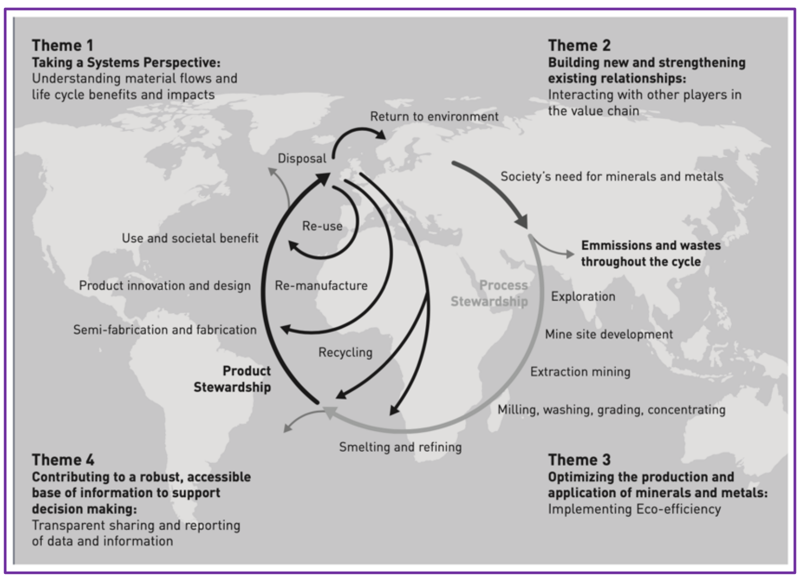
Mines are understood not only as suppliers of materials but also as major purchasers and users of products and services, themselves subject to principles of optimal use. Thus, mining companies engage with "closed loop" systems that contribute to a CE of minerals-related products, and feed new materials into those systems as needed to meet growing demand.

Opportunities also occur when the mine operator partners with others not involved in the operations. This can include co-development of regional infrastructure, processing or utilizing others' process residuals to the benefit of each party and regenerating lands and transitioning ownership of assets for post-mining uses.

Mine operators can engage various strategies in the practice of CE smart mining. Mine development viewed from a "cradle-to-cradle" perspective re-imagines such possibilities for all the materials extracted, the assets and infrastructure constructed, and the land reformed and supports responsible design and decision-making.

This report describes a hierarchy of categories of circular practice that an operating site or mining organization can consider. These practices fall into two areas of influence and activity:|

1. The technical operating system of infrastructure, equipment and assets created or utilized at a mine site; and
2. The natural resources that mining operations disturb, extract, consume, use and/or otherwise manage.



Process and Product Stewardship in Minerals Value Chain. Source: ICMM. (2006). Maximizing Value, Guidance on implementing materials stewardship in the minerals and metals value chain, p. 7.[1]

[1] The graphic was adapted by ICMM, from NRCan. (1995). *Sustainable Development and Minerals and Metals: An Issues Paper*, p.10.

Adapting Technical Systems to Maximize Value Creation at the Mine Site

The technical system considers the physical infrastructure, equipment, and assets that a mining company purchases, establishes, or utilizes to operate the mine. These systems are present from development and excavation of the deposit, through comminution, extraction, and tailings production, and through packaging and transport to the customer (whether they be refiners, smelters, semi-fabricators, fabricators and/or manufacturers). Key CE principles in this area include:

- *Whole systems design for inter-related CE strategies:* start with a system wide review of how different elements of the mine cycle can be designed to advance zero waste, low carbon, and social objectives.
- *Safely dispose*: re-think “end of life/waste” definitions and practices to explore new value capture opportunities.
- *Recycle, upcycle, reuse, redeploy*: get the maximum value possible from products already on site.
- *Refurbish, remanufacture*: reimagine/recreate on-site products to extend value.
- *Share, rent, prolong, maintain*: re-think supply and ownership to optimize use and value.

This report contrasts the use of incremental adjustments to linear processes with the implementation of a combination of inter-related changes from the outset to achieve system-wide targets in the pursuit of efficiency and economic gain.

Reducing Impacts, Maximizing Value of Natural Resources and Disturbed Lands

Several CE strategies focus on optimizing natural resource management and deriving the greatest value from the resources that are disturbed, extracted, used and/or otherwise managed. Key activities in the mining sector would be to:

- *Consider lower impact options:* use mine-impacted waters from the site instead of fresh water; capture and use waste energy or geothermal energy via heat transfer or converted power from exhausts, circulating fluids (processing or water); replace fossil fuel-based power systems with renewable energy and hybrid electric options; exchange toxic consumables with safer options; and purchase refurbished, used or consumables bearing recycled content.
- *Extract embedded value from mining wastes making the most out of stored geological resources:* repurpose, redirect, reprocess on-site and local off-site resources; develop re-valuations for new markets or buyers; discover new value-add uses.
- *Extend materials life and industrial symbiosis: creating value through waste exchanges with others:* engage separate industries in a collective approach to competitive advantage – industrial symbiosis – involving physical exchange of materials, energy, water, and/or by-products.
- *Re-think mine reclamation from harm reduction to value generation:* reclaim and regenerate land for recreational, commercial, agricultural purposes and to natural ecological systems as appropriate.

CE Business Models and Business Case Considerations

Most CE mining approaches have the potential to be deployed, in some capacity, in all mines, for all commodities, for any scale of mine, and at any life cycle stage of a mine. However, the greatest benefits derive when all CE strategies are considered, and circularity is "designed and built in" to new developments and implemented at the earliest phase of the mine's life cycle.

Responsible mining standards address questions of carbon, waste reduction and/or social development (e.g., *Climate Smart Mining*, World Bank, *Towards Sustainable Mining*, Mining Association of Canada (MAC), *Initiative for Responsible Mining Assurance*, IRMA, and *Green Mining Innovation,* CanmetMINING, Natural Resources Canada [NRCan]). Because these initiatives relate to issues under the umbrella of CE in mining, operators in the mining space already may be at various points within this spectrum and, without knowing it, on the circular agenda. For example, many companies long ago began improvements in social and environmental performance beyond specific regulatory requirements, and many of these goals align with CE objectives. Energy efficiency and process optimization efforts aimed at cutting operational costs, and climate-smart mining, have led the sector along the path of low carbon developments. As a result, aspects of circularity may now fall within core business practices.

This report proposes that opportunities for savings, for systems value generation, and for creating benefits beyond the mine border exist in transformational innovation. Benefits of a move towards CE are reflected at the mine site and beyond and are realized through increased partnership and collaboration, as summarized in this and the next three sub-sections.

Benefits for the Mine Site and Beyond

Circular practices introduce mechanisms to reduce water and energy consumption and CO_2 emissions, and to eliminate the generation of waste. These lead to reductions in costs related to operational risk management and consumption in general. Stored waste materials exposed to climatic conditions may cause environmental problems over time, often well after operations have ceased. The costs of rehabilitation of impacted lands and water can be substantial. Circular practices lessen the risk of potential environmental impacts because fewer waste materials accumulate on the site during operations and over the longer term. Therefore, potential liability and associated closure and financial assurance costs are reduced.

The introduction of circular actions demonstrates an operator's commitment to sustainable and responsible production. It improves the organization's reputation, upholding its social license to operate and inviting preferential market access, responsible investment interest and improved ability to attract and retain personnel aligned with these corporate and professional values.

Building on the foundation of responsible mine strategies, the implementation of CE practices in the mining sector would reduce greenhouse gas (GHG) emissions and environmental impacts over the longer term. CE seeks to maximize value from resources, increase resource security, and restore or regenerate natural capital and ecosystems. Because some CE strategies will require innovation, new technology and exchange capabilities, CE will lead to jobs in diversified value chains (e.g., specialized processors, systems designers, land and infrastructure repurposing planners and specialists, technology and digital developers, technical operators, and more). CE activities will also attract investment, relieve pressure on municipal budgets, and demonstrate technological leadership.[2]

Local Partnership Models

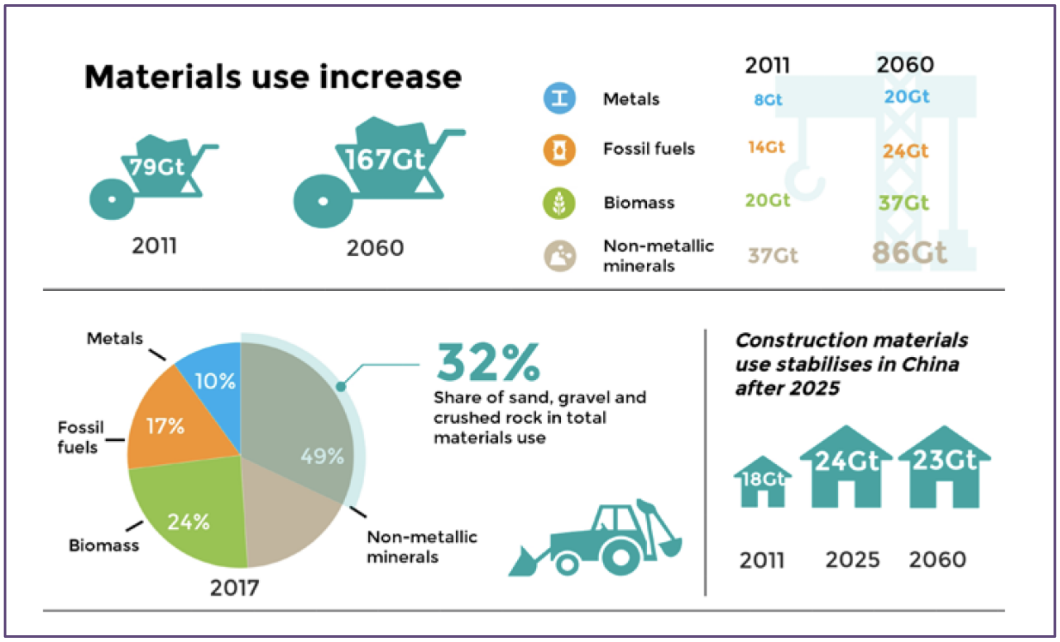
Mines can partner to facilitate circular benefits beyond the mine by utilizing excess materials and planning for mine closure. The first opportunity comes when there are excess materials or resources

[2] Responsible Mining Foundation. (2020). *Mining and the SDGs: a 2020 status update*. https://www.responsibleminingfoundation.org/app/uploads/RMF_CCSI_Mining_and_SDGs_EN_Sept2020.pdf

generated by the mine (deemed uneconomic under conventional accounting methods) that could be utilized by others within the region - during operations or after the mine has closed. The second opportunity involves transition planning in preparation for mine closure. When a mine is a primary contributor to the local economy, it can be difficult for local communities to sustain economic health or growth beyond the mine. This report defines this transition with a CE lens. For example, infrastructure assets developed to support the mine can be designed with consideration of the longer-term needs of the community.

Engagement, Collaboration and Partnership Considerations

CE business benefits for the mining sector include increased supply chain security; additional value from products and materials; and mitigation of risk from volatile commodity prices.



Materials Use Increase. Source: OECD (2019). [Global Material Resources Outlook to 2060: Economic drivers and environmental consequences.](#)

With respect to the supply network and markets, CE activities could be furthered by:

- Engaging the supply network with an emphasis on greater transparency and flexibility;
- Engaging with local communities, Indigenous rights holders, regional planners and government to optimize value creation and local economic benefits; and,
- Applying systems-based, life cycle assessments to enable better understanding of value network potentials for all aspects of mining operations upstream, downstream and adjacent.

An investigation of CE opportunities should start with regionally located mining operators, upstream supply vendors, local stakeholders, and then with players in the downstream value network. Most companies are already focused on operational efficiencies, and sourcing equipment and new technologies which may require engaging the supply network or finding new vendors who can meet new requirements. Some of the biggest potential gains, however, exist in local partnerships and on the downstream side of the value chain – in the segregation and development of secondary or tertiary products, or continued use of assets over the long term.

CE and Minerals: Drivers, Demands and Market Opportunities for Mining Companies

The current trajectory of population and economic growth, with its associated materials consumption, is sobering in terms of potential environmental and social impacts. In an already stressed human and environmental context, global materials use is projected to more than double from 79 Giga tonnes (Gt) in 2017 to 167 Gt in 2060 (see figure below, *Materials Use Increase*). Growth in demand for motor vehicles and electronics in turn is driving increased demand for a range of minerals.

In addition to these consumer market trends, the minerals required for the expansion of renewable energy generation, transmission and storage will result in unprecedented increases in demand for minerals. At the same time, addressing carbon emissions associated with meeting these needs is imperative but is a substantial challenge.

CE Approaches Reduce Carbon and Address Responsible Mineral Demands

Addressing climate risks is an ever-increasing priority for the mining industry, under pressure from governments, investors and consumers to develop strategies for carbon emissions reduction. Many companies have begun to set ambitious emission-reduction goals ranging from zero to 30 percent by 2030, though below the broadly defined national objectives associated with the Paris Agreement goals. In theory, mines *can* fully decarbonize (excluding fugitive methane) through operational efficiency, electrification, and renewable energy use.[3] They can do so even in the context of increasing market demand for mineral commodities.

To highlight the importance of ambitious strategies around climate solutions in addressing mineral development challenges, the World Bank, among others, has proposed an integrated CE approach to address waste reduction, carbon emissions and socio-economic value generation.

In parallel to the focus on carbon emissions reduction, consumer and investor attention to negative impacts from mining is growing, with companies concerned about stigmatizing certain products (e.g., automobiles, electronics, and jewelry) and increasing interest in the idea of responsible sourcing of mineral products. These sourcing concerns are expressed through procurement policies that provide criteria and standards for suppliers to insure against specified impacts.[4] Responsible/ethical procurement strategies have been adopted by both public and private sector organizations and present opportunities for market differentiation for low impact operations.[5]

CE strategies show the potential for a coherent and comprehensive approach to dealing with these challenges and supply chain opportunities. By applying CE systematically, early adopters benefit from preferential access to responsible sourcing markets and investors. Related criteria focus on carbon and

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[3] Delevingne, L., Glazener, W., Grégoir, L., & Henderson, K. (2020, January 28). Climate risk and decarbonization: What every mining CEO needs to know. *McKinsey Sustainability.* https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know

[4] van den Brink, S., Kleijn, R., Tukker, A., & Huisman, J. (2019). Approaches to responsible sourcing in mineral supply chains. *Resources, Conservation and Recycling*, *145*, 389-398. https://doi.org/10.1016/j.resconrec.2019.02.040; Responsible Minerals Initiative. http://www.responsiblemineralsinitiative.org

[5] European Commission. (2017). *Public Procurement for a Circular Economy*. https://ec.europa.eu/environment/gpp/pdf/Public_procurement_circular_economy_brochure.pdf

waste reduction that can help shape the nature of the dialogue on how a CE for minerals can be defined and realized.

As we move towards a future powered by "green metals", circular closed loop industrial models will become the norm. This shift invites a reimagining of the linear mineral extraction business. While raw extraction isn't going away any time soon, opportunities for new business models, including integrated materials companies, mineral solutions providers, and closed-loop metal-as-a-service offerings, will emerge. These are opportunities that mining companies are well-positioned to seize. Lose or acquire market share, disrupt ourselves, or be disrupted. The choice is ours.[6]

Government Policy Support for CE in the Mining Sector

Market and civil society forces are aligning around CE strategies, such as integrated carbon and waste reduction. Governments are articulating policies to frame and support CE strategies for mining companies.

Canada is in the early stages of exploring applications of CE strategies in various sectors of the economy. Aside from its commitment to host the World Circular Economy Forum in 2021,[7] there has been an initial emphasis on deploying CE strategies to engage public, private and civil society institutions in addressing the issues associated with plastic waste.[8] Other areas of CE strategy interest across Canada include urban design, agriculture and food, and energy transitions.

In the mining and minerals sector, there are emerging opportunities associated with the green energy revolution that can capitalize on Canada's unique geological resources, mining capacity and regional economies. For example, the CMMP identifies extracting valuable residual minerals from existing mine waste as an area of focus.

Another track having significant potential synergies with a CE mining strategy is the increasing focus on the supply chains for Critical and Strategic Minerals (CSM). Canada has established policy and trade-related programs with the EU, USA, Japan and Australia, to promote innovation in extraction, recovery, processing, and manufacturing related to minerals essential for green energy transition infrastructure.

At the provincial level, the Quebec government has taken an aggressive approach to advancing a circular CSM development strategy.[9] To stimulate responsible sourcing of minerals, the province made an initial investment of $68M to build a regionally coordinated business innovation hub for the rapidly expanding large-scale and electric vehicle (EV) battery market, as well as telecommunications, aerospace, renewable energy production, the medical sector and transportation electrification. These are high-growth sectors in

[6] Cheadle, A, & Freele, E. (2020, December 4). Quo Vadis? Mining, metals and minerals in a circular economy. *The Northern Miner, 106*(26). https://www.northernminer.com/commentary/quo-vadis-mining-metals-and-minerals-in-a-circular-economy/1003825693/

[7] Government of Canada. (2021). *World Circular Economy Forum 2021.* https://www.canada.ca/en/services/environment/conservation/sustainability/circular-economy/world-forum-2021.html

[8] Environment and Climate Change Canada. (2021). *Government of Canada invests in reducing plastic waste and supporting the transition of a circular economy for plastics.* https://www.canada.ca/en/environment-climate-change/news/2021/04/government-of-canada-invests-in-reducing-plastic-waste-and-supporting-the-transition-of-a-circular-economy-for-plastics.html

[9] Mining [Dot] Com. (2020, November 3). *Québec unveils $68m plan to promote critical and strategic minerals sector growth*. https://www.mining.com/quebec-unveils-68m-plan-to-promote-csm-sector-growth/

which the CSM supply is vital and to which CE supply networks could add substantial economic and environmental benefit.

Linking the interest in CSM with CE systems supports value-creation and supply chain efficiencies, which are integral to the commitment to environmentally and socially responsible mining. Establishing well-defined and resourced CSM strategies, federally and provincially, in partnership with the private sector, invites strategic investments to exploration programs, research and development. This advances the “circular use of critical minerals” (including increased blending of both primary and recycled sourcing) and boosts domestic refining and manufacturing capacities capable of drawing on domestic mineral supplies and feeding international market demands.

Building CE Capacity – Gaps and Recommended Next Steps

Advancing Industry Awareness, Alignment and Capacity

Challenges to advancing the CE agenda within the mining sector are awareness and understanding of what it is, how it applies, and the key benefits of doing so. Another challenge comes with mindset and culture, and the behavioural shifts required to meet new expectations for performance, or to perform business under new operating models.

Changing the culture may prove to be a greater challenge than implementing new and effective operational performance technologies.

The report focuses on the meaning of CE for mining, and how the sector can participate in the CE, and/or practice it internally. The information can be utilized to educate and engage industry and its workforce to identify and prioritize opportunities that each site could advance. However, for an organization to be successful, it is not enough to raise awareness levels – internal company change and industry-wide change need to be supported.

Internal Change

Keys to advancing CE strategies and tools include:

- Establishing CE goals, metrics and incentives;
- Building internal awareness and engagement of CE innovation potential;
- Mainstreaming CE resourcing and evaluation strategies; and,
- CE progress tracking and communications.

Industry-wide Change

A pre-competitive approach to enabling and accelerating greater CE benefits for mining includes:

- Evaluating geological resources beyond primary/conventional target commodities focus;
- Conducting comprehensive waste materials and assets classification throughout the mine cycle;
- Revising closure objectives guidance to enable future CE strategies; and,

- Providing active support for CE information sharing and innovation collaboration (within the mining sector and with other extractive sectors).

Recognition by industry of the potential value of CE strategies to achieve economic, social and environmental objectives is needed. If agreement can be established then information sharing, identification of opportunities, experimenting, technology development, co-development of synergistic plans, and execution should follow.

Towards CE Supportive Policy, Regulations and Incentives

Governments can accelerate the adoption of CE strategies and systems for mining operations. Public policy and regulations play a role in enabling value creation and liability reduction associated with applied CE practices. Government can help reduce obstacles to innovation in mineral extraction processing by incentivizing investments in new technologies and practices, and by encouraging CE through infrastructure support, network development, and procurement policies.

Including CE as an element of the CMMP represents an important opening that could be expanded beyond the current focus on tailings waste recovery and liability reduction. By employing an integrated CE framework, governments can leverage trends such as the growing concerns around CSM and the increasing market interest in climate, environment and social performance measures.

Governments can take steps along the road to CE for the mining sector, engaging with other actors as appropriate to:

- Establish a dedicated Secretariat and a multi-stakeholder technical committee to advance the Mining Value from Waste (MVFW) initiative to address identified institutional and knowledge gaps, regulatory and financial barriers and areas for investment.
- Capitalize on synergies between CE and CSM strategies by actively integrating the policies to:
    a. Support technological innovations and associated CE value network partnerships needed to extract and refine CSM;
    b. De-risk investments in new projects to attract a broader array of financiers to non-conventional mineral projects;
    c. Review, identify and reform mining regulations to address barriers to operationalizing non-conventional primary and waste extraction projects (where they exist); and,
    d. Examine strategies to support integration and economic feasibility of primary and secondary source processing capacity and infrastructure to optimize potential for producing blended CSM products for market.

Enabling Emerging ESG/CE Markets

To support industry's transition to a CE model, governments could:[10]

- Provide incentives to level the playing field for CE practices by accounting for environmental externalities and supporting the creation of new value chains.

[10] World Business Council for Sustainable Development (WBCSD). (2019). *Policy enablers to accelerate the circular economy.* https://circulareconomy.europa.eu/platform/sites/default/files/wbcsd_policy_enablers_to_accelerate_the_circular_economy.pdf

- Promote private and public sector partnerships that promote knowledge sharing, experimentation, and skills-building to create effective CE policies.
- Align and integrate CE policies with mainstream policies to promote mutual learning and complementary objectives and goals.
- Work with industry to set traceable actions and targets to guide and generate tangible results and hold stakeholders accountable for their progress.

Integrated Knowledge and Data Platforms, and Technology Supporting CE Opportunities

The mining sector is shifting towards digitization for improved data analysis and decision-making. Operational sites are optimizing information collection efficiencies and performance, spanning the "pit to product" value chain. Organizations are investigating the use of digital twins[11] to assess and optimize design of future processing systems. These advances can help identify opportunities for reducing inefficiencies, optimizing re-circulation of resources, and for decreasing waste generation overall.

Other useful information worth tracking and reporting on include the types of technologies available (commercialized and proven at pilot scale) to support CE processes, their capabilities and relevant applications, supporting research and technology development in progress, and any organizations interested and/or participating in CE strategies. Mapping the ecosystem of stakeholders in CE, with an ability to sort by region, commodity, and by service offering, would help support companies willing to explore CE to find solutions to meet their needs, and identify gaps in the ecosystem.

Embracing a Pragmatic, Collaborative, Systems Approach

Finally, while the report covers a wide range of concepts and issues that outline what CE can mean for mining operations, the path to CE can be launched with a few core principles and goals in mind.

- Break out of silo thinking on problem solving to explore and embrace a full systems approach to challenges (regarding carbon/water/tailings/wastes/social license). This is key to unlocking new value generation.
- Catalyze new forms of collaboration among interested parties in the mineral supply ecosystem. These new relationships apply to both the industrial use of products and services for extraction, and the opportunity to feed new responsibly sourced materials into systems that are managing growth in demand.
- Create new value networks in the mining and minerals sector by:
    a. Finding new markets for waste products;
    b. Identifying suppliers of products and services who can help monetize social and environmental objectives; or,
    c. Seeking innovators who can re-design extraction and processing systems for critical minerals.
- Focus on using these tools and approaches to realize reductions in risks and impacts. A fulsome suite of public policies and incentives will take time to design and deploy, but in the meantime, companies can re-examine conventional practices that generate waste and miss potential value, both on the mine site and with their upstream and downstream stakeholders.

[11] Digital twins are virtualized representations of physical things, which are used to simulate and experiment with conditions and behaviours to enable design and process innovation in everything from machinery design to building and industrial systems.

Key Messages

How is CE mining different from or related to green or climate smart mining (and related "responsible" or "sustainable" mining initiatives)?

CE complements and builds on "responsible mining" programs by bringing disparate initiatives under an integrated strategy. By solving for mine waste, water risks, energy use and carbon emissions, disturbed and impacted lands, and social impact concerns through a systems-based integrated strategy, CE contributes to responsible mining.

Further, it seeks to add value by (a) looking for synergies and efficiencies between different green mining reforms, and (b) focusing on capturing greater value in the marketplace, including for communities and ecosystems. The World Bank refers to this integrated approach as a "Climate Smart Mining" framework.

How can the adoption of CE strategies and practices affect cost-effectiveness and global competitiveness?

CE strategies aim to increase cost-effectiveness by revenue generation. They are rooted in the goal of maximizing economic returns by: reducing consumption, reducing waste, increasing efficiency, and expanding valuable relationships throughout all stages of the mineral life cycle. They also help to retain market share in areas where increased scrutiny of carbon footprints, waste reduction and ESG issues need to be managed in a more systematic and integrated way.

Additionally, sensitivity to supply chains of CSM currently rooted in China, for example, present an opportunity and imperative for other regions to use CE strategies to differentiate and consolidate market relationships.

CE adopts a systems approach to analyze where potential value is being lost, and where avoidable liabilities are accumulating. (e.g., consider the "un-extracted" value from mine waste, where extraction processes could be better designed, environmental risks avoided, and by-products or used assets be re-used by others.)

This report outlines the growing interest of investors and downstream mineral buyers in ensuring that mined materials do not contribute to environmental and social harm. The ability to access these markets will be predicated on a demonstrated ability to solve for a range of concerns, including carbon emissions, mine waste and human rights. A solid CE strategy provides a coherent means to plan for and execute these kinds of programs in a coordinated and efficient manner.

Is a CE mine possible in and of itself or does it require the establishment of extensive CE-oriented "support" systems throughout the Canadian and global economies?

CE strategies imply and encourage engagement with supply network partners upstream, downstream, and adjacent to the actual mine operations, to reduce waste and increase opportunities to generate greater value from materials and assets.

Application of CE strategies and practices can vary in scale and scope, depending on the technical characteristics and location of mining operations. Opportunities to engage with suppliers to the site and potential partners (e.g., for waste products) will differ significantly between remote operations and those in a region with multiple mines and associated infrastructure, industrial services, manufacturing and commercial centres, and potential community/municipal partners. Nevertheless, CE system design principles identified in this report can yield benefits in a variety of circumstances. In the absence of supporting systems (market or regulatory), companies can still seek opportunities to apply CE strategies internally and within their own supply networks and build from there.

What role do markets play vis-à-vis the supply and demand for primary versus secondary materials?

Demand for minerals to meet renewable energy generation, transmission and storage needs will drive increases in primary and secondary minerals production over the next 2-3 decades at least. In addition, green energy-oriented demand for strategic materials and global mineral demands are being driven by population growth, urbanization and increased levels of consumption in expanding economies.

While there is a substantial opportunity and imperative to expand recycled minerals production from "urban mines" and responsible producer "take-back" programs, this increase in secondary minerals will not offset growth in demand for primary minerals. As has occurred in the forestry sector, blending primary and recycled materials increasingly will be expected. In fact, recycled and primary mineral resources are already blended in smelters and foundries in Canada and around the world. Recovered metals will be essential to EV battery production demands over the next decade.

Demand for commodities of any type is guided by material specifications. Historically, the use of secondary feedstock was constrained by industrial specifications that favoured primary or virgin inputs (e.g., in road construction). Progressive markets accept recycled materials with the understanding that: (a) it is good for the planet; and (b) product performance will not be undermined. In addition, the metallurgical expertise for removing impurities from all material inputs has greatly improved.

What are the impacts and risks of adopting (or not) CE practices in the Canadian mining sector?

With growing market and investment attention paid to how minerals are extracted and managed throughout their life cycles, companies who are engaged with zero waste, low carbon CE strategies will be well positioned to gain market share and maintain competitive positions. Whether associated with the supply of critical and strategic materials for the green energy transition, supplying materials to consumer-sensitive markets like electronics or automobiles, or creating new specialty materials to develop circular products, CE strategies are efficient and effective ways to manage complex customer demands.

Retaining conventional mining practices without innovating to keep pace with market demand and opportunities could result in Canada losing its competitive advantage in the mining industry. It is also about being prepared to participate in market disruptions that may influence future production and purchasing patterns. Canada has the potential to continue to lead in this rapidly evolving market environment if it embraces the application of CE principles across its industry. However, other nations, like Australia, Chile and even China, are already moving in this direction guaranteeing strong competition in this space over the coming decades.

1. Introduction: Mining, Minerals and the Circular Economy (CE) Opportunity

1.1 Context

The minerals sector is receiving increasing international attention for its role as a supplier of materials necessary to build the infrastructure of generation, transmission and storage for a low carbon energy future. While playing a central role in contributing to climate change solutions, it must also tackle serious socio-environmental impacts.[1] Combined, these trends present a powerful, unprecedented moment of opportunity and challenge for the mining industry.

As pressures mount to address social, environmental and economic challenges across a range of sectors (e.g., food, apparel, plastics, transportation, green energy) there is a growing interest globally in the concurrent benefits associated with integrated, zero waste, low carbon circular economy (CE) strategies. These focus on transformative approaches that design waste and pollution out of products and services, while capturing greater economic value throughout supply chains, by rethinking conventional "linear" business models characterized by "take-make-waste" patterns of production and consumption.[2]

The World Business Council on Sustainable Development
described CE as "…the biggest opportunity to transform production and consumption since the First Industrial Revolution 250 years ago. By unleashing circular innovation, we can boost the global economy's resilience, support people and communities around the world and help fulfill the Paris Agreement and the UN Sustainable Development Goals…"[3] *https://docs.wbcsd.org/2017/06/CEO_Guide_to_CE.pdf*

Aside from their irreplaceable role in renewable energy infrastructure, minerals have unique properties of durability, recyclability and adaptability, making them ideal materials for the closed loops of production associated with CE systems. Yet the implications of this CE transition for mining operations remains relatively unexplored.

To date, CE analyses have emphasized consumer-facing commodities and industries, examining ways to decouple economic growth from increased material use, and to transition away from the unsustainable levels of resource use and waste generation that feed the linear economy model.

Canada's established history of mining innovation positions it well to respond to and benefit from these challenges. From the multi-sectoral *Whitehorse Mining Initiative* that addressed sustainable development and social license issues in the early 1990s, to the Mining Association of Canada's (MAC) *Towards Sustainable Mining* benchmarking system, to the Canada Mining Innovation Council's (CMIC) *Zero Waste Mining* strategy and NRCan's Mining Value from Waste (MVFW) initiative[4], Canada has shown leadership on mining reform and movement towards new business models and value chains.

Most recently, the Canadian Minerals and Metals Plan (CMMP) has established a significant and new policy framework for the mining sector. The CMMP vision and framework is based on six strategic directions: economic development and competitiveness, advancing the participation of Indigenous Peoples; the environment; science, technology and innovation; communities; and global leadership. Area of interest for the CE, and many of the actions that are explored in this report, are mainly found in the environment direction. Where the future of the sector is concerned, an opportunity exists to leverage the CMMP vision and build on larger global trends to realize greater value and reduce impacts through the adoption of CE strategies for mining and minerals.

1.2 Report Outline

This report explores global implications and opportunities for the mining industry, primarily in Canada – as a resource-based economy with a high capacity to address these challenges and opportunities – as trends indicate growing demand for integrated strategies to address carbon, waste and socio-economic parameters across a range of sectors, including minerals. Trends that are explicitly framed in terms of the CE can be seen in the EU's comprehensive *Circular Economy Action Plan*,[5] the Nordic nations' regional CE collaboration,[6] China's extensive investments in CE policies and practices,[7] and even in middle-income (mining) nations like Chile.[8]

This report focuses on the mechanics and logistics of the extractive process in the context of a CE framework that is informed and shaped by an analysis of:

- products and services purchased by the mining operation;
- benefits and risks to the stakeholder community affected by the mine; and,
- relationships with the downstream purchasers of the products of the mine (Figure 1).

The strategic interrelationship between these elements of the mining operation will yield the greatest potential gains for companies, for the economy, and for society.

This report is intended to orient the mining sector to the nature and value of applying key CE concepts, drivers and practices.

- A full definition of CE is provided at the beginning of Section 1.
- Section 2 gives an overview of CE concepts and principles as they relate to mining operations.
- Section 3 focuses on operational applications of CE-related practices through different stages of the mining life cycle, with examples.
- Section 4 examines how to integrate CE business innovation into mining operations and addresses business case benefits, considerations and barriers to achieving a zero waste, low carbon circular mine site.
- Section 5 describes external drivers for change in the mining industry and how the industry can address these pressures, such as carbon emissions reduction goals and waste management liabilities, by using an integrated CE lens.
- Section 6 examines CE-related government programs and policies in Canada and the growing international attention to responsible, secure sourcing and potential new markets for CSM.
- Section 7 identifies further actions to bridge gaps, strengthen understanding, undertake research and advance application of CE practices in the sector.

Figure 1: Interrelated Environment, Social and Market Challenges and Solutions. Source: MERG/Enviro Integration Strategies Inc.

This report explores how CE principles and practices could be applied by an operation, regardless of its location and situation within the mining cycle.

Ideally, this will spark uptake for industry innovations and collaboration across Canada and internationally and help advance these practices in an integrated and coordinated manner.

2. Key Mining-Related Principles for a CE

The CE framework takes a systemic approach to re-calibrating the conventional "take-make-waste" industrial model. CE also seeks to address economic and financial effects associated with increasing demands for waste and emissions reductions through supply chain and value innovations while relieving unsustainable levels of stress on biodiversity, water quality and quantity, climate stability, and their associated impacts on the human population.

Focusing on innovation to generate society-wide benefits, a CE framework re-thinks the traditional measurement of economic growth by revealing then phasing out negative externalities and gradually decoupling economic growth from unsustainable consumption of natural resources. It is underpinned by a transition to renewable energy sources and is premised on a commitment to strategies that build economic capital, social stability and healthy ecosystems.

CE covers three main focus areas:

- Designing out waste and pollution by fully costing impacts and identifying potential for value in materials recycling, reuse and repurposing
- Keeping products and materials in use to optimize value to the economy
- Regenerating natural systems to protect essential ecosystem services such as clean water, clean air, healthy soils, carbon storage, and flood protection.[9]

The following sections will outline both the generic and mining-specific principles that can guide the design and implementation of strategies across these three areas of focus.

2.1 Core CE Principles

The following six principles applied in an integrative framework guide the design of CE solutions. Together, these principles aim to solve root causes of waste generation and environmental impacts, displacing the tendency to employ harm reduction tactics that address symptoms but not the underlying conditions associated with negative environmental, social and governance (ESG) outcomes.

A vital issue for the sector is securing the social license that allows for permitting and ongoing operations. Taking a piecemeal "harm reduction" approach can be costly and confusing. Adopting a systematic CE approach allows for coherent and efficient deployment of responsible and sustainable mining initiatives.

2.1.1 Stock Optimization - Extending the Value of Materials

The longer-term value of products, materials and resources is recognized by re-evaluating the design and use of existing economic structures, products, and materials. The goal is to maximize value creation of each link in the system.[10] The principle of stock optimization relates to the durability of minerals and metals that allows them to be re-used almost indefinitely after extraction, affecting their value throughout the economy. It also applies to mine sites as major consumers of products and services that can be optimized to save costs and reduce impacts (see Section 3.2).

2.1.2 Eco-effectiveness: Beyond Eco-efficiency

The principle of eco-effectiveness addresses the design of products, and their associated material flows, with respect to the health of ecological and economic systems. Eco-effectiveness advances the principle of eco-efficiency with a focus on minimizing the volume, velocity, and toxicity of the material flow system.

"Eco-effectiveness moves beyond zero emission approaches by focusing on the development of products and industrial systems that maintain or enhance the quality and productivity of materials through subsequent life cycles. The concept of eco-effectiveness also addresses the major shortcomings of eco-efficiency approaches: their inability to address the necessity for fundamental redesign of material flows, their inherent [albeit unintended] antagonism towards long-term economic growth and innovation, and their insufficiency in addressing toxicity issues."[11]

For the mining sector, this principle should guide the design of the technical systems at the mine site throughout different phases of the mine cycle, including mine closure (see Section 3.3).

2.1.3 Eliminating the Concept of Waste by Extending Resource Value

The supporting principle of stock optimization extends to rethinking the concept of waste, turning it instead into a resource. The "R" strategies – Reduce, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover – in combination with eco-effectiveness of products and processes, can eliminate waste and pollution while generating economic value and protecting communities, workers and environmental values.

This principle is relevant for mineral resources because of their unique properties of durability and recyclability that allow for ongoing value retention. Design for recovery and market incentives for secondary minerals feedstock are important to this principle in the minerals sector. Both Sections 3.2 and 3.4 cover various strategies to implement this principle.

2.1.4 Extended Producer Responsibility

Under the principle of Extended Producer Responsibility (EPR), the producers (manufacturers or "brand owners") are responsible for the supply chain and life cycle of products, including their take-back, recycling and final disposal. Since the early 1990s, EPR has focused on the end-of-use treatment of consumer products, the primary aim being to increase product recovery and minimize environmental impacts of waste materials. This CE concept incorporates any product or material in the supply chain of minerals and materials. This principle can account for all environmental costs associated with a product and indirectly promotes eco-products and process design that returns value to the producer.

For the minerals sector, EPR provides a mechanism to recuperate essential materials that may be in limited supply for manufacturing of products such as batteries and other renewable energy technologies.

2.1.5 Circular Product and Process Design

The objective of the principle of circular product and process design is to optimize function and materials use in product, process or service delivery while minimizing negative impacts along the whole life cycle.[12] This represents a change from a product- to a system-based focus.

The premise of this principle is that design (writ large) is key in eliminating waste and pollution and in promoting viable new services to optimize and extend the life of resources and to advance business arrangements that improve economic, social and environmental values.

In the case of mining, circular design thinking would apply to the entire processing system, which includes the operating site infrastructure, and working with natural ecosystems to create a product.

As it relates to minerals, the key challenge is to find ways that mined materials can be used to add long-term value and avoid collateral damage. A classic example is lead. Lead used as an additive in gasoline was dispersed as toxic waste. When used in lead acid batteries, it is one of the most highly recycled substances on record in which all potential risks are appropriately managed. It will be important to consider all minerals in the context of their product life cycles and potential to recapture value and minimize harm.

Several strategies can be applied to the circular design of mining processes, materials and products (discussed in Section 3.1):

- *Design for Product Attachment and Trust* targets consumer behaviour by creating long-lasting products that are valued and trusted. In the mining sector, conflict diamonds and gold have had a strong impact in this regard. This strategy is also being factored into consumer products such as cars and electronics (see Section 4.4);
- *Design for Product Durability* creates high quality, durable and recoverable products. Here, the material choice is crucial in overcoming functional obsolescence. For minerals, complex trade-offs are made in optimizing for functions (e.g., alloys for weight reduction in vehicles, or electric vehicle (EV) battery efficiency) versus the ability to recover and re-use individual materials which may be difficult to recover from certain alloys/materials blends or product designs.
- *Design for Ease of Maintenance and Repair* counters functional obsolescence with simplified maintenance, repairs and parts replacement. These objectives may be addressed through a service/lease model for equipment that incentivizes service providers to maintain high product performance levels.
- *Design for Upgradability and Adaptability* avoids systemic obsolescence by allowing product upgrades, adaptation and modification to address changing user needs.[13] Again, the service/lease model creates potential for mutual benefit between service provider and user by coordinating evolving needs and technological advances.
- *Whole System Design for Systems Change* focuses on reducing environmental pollution for the entire value chain (zero waste and zero harm) and on creating regenerative systems (design for biomimicry and design for biological and technical cycles).[14] As will be discussed in Sections 3 and 4, the greatest return on investment comes from applying CE principles at the systems level, allowing companies to re-define the value chain for services and products.

2.1.6 Creation of Social Value

The aim of CE is to improve the well-being of all members of society. Resources, products, processes and policies should combine to create social value, in addition to economic value

Developing products and services for customers while connecting to social and environmental issues, such that the competitiveness of the company and the health of the community in which it operates are mutually dependent, relates to the concept of shared values.

For the minerals sector, community benefits (and impacts) can manifest in many ways. A key challenge for Canada is to ensure that there is a consistent application of lessons learned from exemplary projects across the country.[15]

2.2 CE Principles Specific to the Mining Sector

Cross-referencing these six CE principles with the operationally focused principles of mining sector activities highlights their implications. Section 3 will analyze how these sector principles could be deployed by mining operations of different scale and stages of development.

Table 1 provides a high-level view of correlations between core CE principles and key mining-specific principles. For example, the principle of creation of "social value for everyone" can be considered a cross-cutting principle.

	Core CE Principles					
Mining Sector-Specific Principles	Stock optimization	Eco-effectiveness	Eliminate the concept of waste	Extended producer responsibility (EPR)	Circular product and process design	Creation of social value for everyone
Fair and equitable access to mineral resources	●					●
Prolonging mine life as key concept of mine design	●					●
Minimize and create value from mining waste and reject materials originating from the extraction and processing processes: waste rock, tailings, slag, leached ore, mine water	●					●
Extraction, processing and facility engineering improvements in design and technology to promote CE objectives (zero waste, efficiency in resources and energy use, safety and working conditions, community health and socio-cultural protection, etc.)		●			●	●
Incorporate social and environmental dimensions throughout all phases of the mine development process, including prospecting and exploration phases		●			●	
Procurement policies related with machines, equipment and products that incorporate key circularity attributes (e.g. recyclability, carbon neutrality, longevity, extended producer responsibility, etc.)	●		●	●		
Shift to renewable energy and decarbonization		●		●		
Implement restorative loops of material stock from mining waste present in both closed/abandoned and currently operating mines			●			
Enable potential future use of residual mineral deposits after primary mine life closure	●				●	
Rehabilitation of mine site to eliminate contamination on-site and off-site		●			●	●

Table 1: Relationships between mining sector-specific principles and core CE principles. Source: MERG/Enviro Integration Strategies Inc.

The correlations in Table 1 underscore that core principles underpinning CE are broadly applicable and present various opportunities to capture value and reduce waste throughout the full mining life cycle, from planning to procurement, operations, and mine site rehabilitation. It is the commitment to a systemic and integrated application of core CE principles throughout all parts of the mining operation that is key to achieving the greatest benefits (see Sections 3 and 4 of the report).

2.2.1 An Integrated Working Definition of CE

As the concept of CE develops and is used by governments to define policies and programs that emphasize specific areas or sectors, it should be noted that varied definitions of CE appear in the literature.

Nevertheless, CE has the potential to evolve from an umbrella term to a definition of a new socio-economic paradigm. To orient the reader to core parameters, while inviting consideration of the transformative potential of that concept, this report proposes a working definition adapted from Kirchherr (et al.)[16] in which the CE:

> … involves reducing, alternatively reusing, recycling and recovering energy and materials in production, distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is facilitated through a combination of novel business models, (including technological innovation) responsible producers, consumers and investors, supported by enabling policies and regulatory frameworks.[17]

For the mining sector, there are many ways to capitalize on the inherent recyclability and durability of minerals as key materials contributing to a CE. New supply chain relationships for mineral products and associated services present opportunities to eliminate waste and expand value per unit of mined material while increasing social license. These opportunities are compounded and made urgent by the expanding demand for minerals to build the physical infrastructure of the low carbon economy.

3. CE Applications in Mining

With clear trends in market, investment and policy drivers favouring the move towards elimination of waste and the reduction of carbon emissions, mining operators will face increasing pressure to demonstrate circular/closed loop strategies at the mine site. The upside of these trends is that they are associated with new and growing markets and access to different sources of capital representing a chance for new partnerships to be developed and new talent to be attracted to the industry.

In 2006, the International Council on Mining and Metals (ICMM) published a document titled "Maximizing Value", and then in 2016, another report titled "Mining and Metals and the Circular Economy".[18] Figure 2 indicates four primary ways (or "themes") that the value of mining products can be maximized, and the associated study showcases organizations that are practicing circularity via vertically integrated business models. These reports also highlight some key considerations and strategies for exploring circularity in mining.

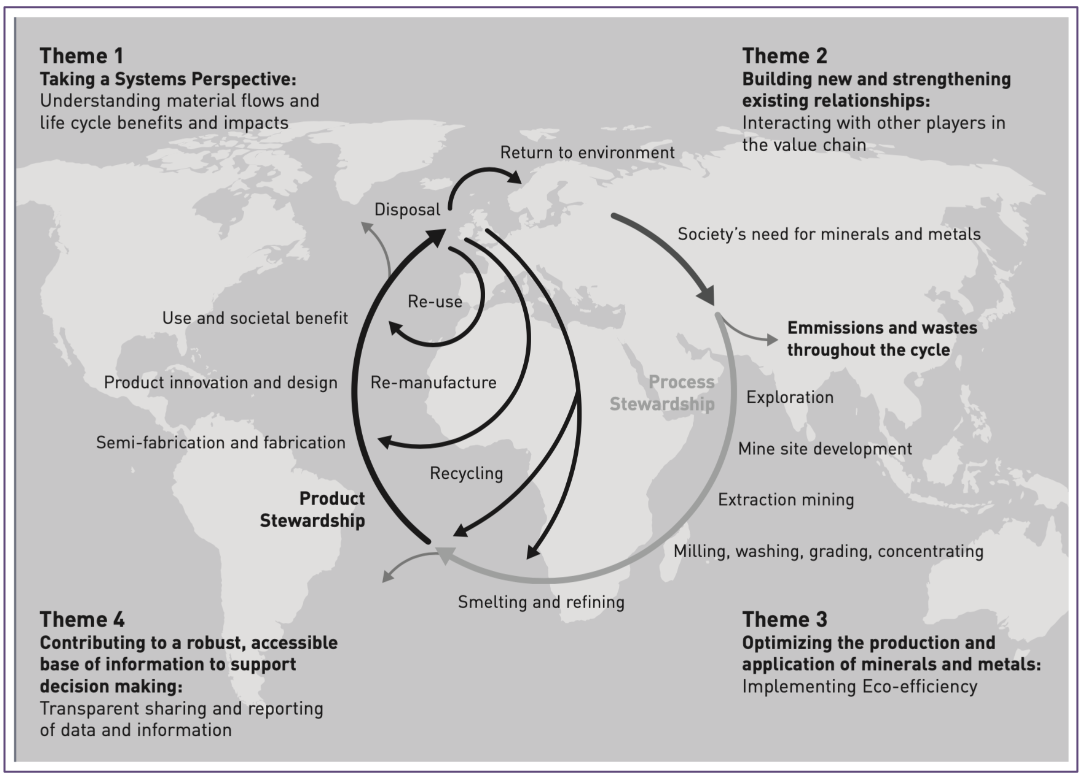


Figure 2: Process and Product Stewardship in Minerals Value Chain. Source: ICMM. (2006). NRCan. (1995).[19]

However, most mining organizations are not vertically integrated in the value chain, limiting their ability to participate in the downstream stewardship of the materials they produce. In fact, except in unique situations, mining organizations cannot control what use is made of their products. Unlike downstream manufacturers, mining companies have little ability to directly recover those product materials, even if they might have the capability in some cases to reprocess the recovered materials.

For mine operators, CE involves the minimization of waste generation and preservation of natural resources and their value by extending the life of extracted minerals. While EPR regulations could introduce incentives to manufacturers to prevent wastes at the source, to design for the environment and to support the achievement of public recycling and materials management, CE principles are not founded solely on ownership of materials or assets or how that ownership may change over time.

The emphasis is on maximizing value however possible. Producers and other market players bear this responsibility and may be drawn in to capture value.

A primary CE concept as applied to mining is that materials extraction and asset creation are to be done responsibly and with minimal land disturbance. The value of all materials and assets should be maintained and utilized effectively. In this context, mines supply materials and are also major purchasers and users of products and services, which themselves are subject to principles of optimal use.

Mine operators can engage various strategies in the practice of CE smart mining. A "cradle-to-cradle" perspective re-imagines possibilities for the materials extracted, the assets and infrastructure constructed, and the land reformed at each site and supports responsible design and decision-making. It adds to the CE focus on post-manufacturing product stewardship, and to mining's focus on responsible supply and operations and environmental stewardship. It applies circular practices to all aspects of a mine development, throughout the mine's life cycle.

Figure 3 delineates the life cycle of a mine development, overlain by overarching circular strategies (and discussed in subsequent sections) that can be applied at or across various life cycle stages. It also shows where products and by-products, or used assets, move from the development stewardship cycle to the product stewardship cycle, and where lands and infrastructure can be repurposed. All these aspects should be considered during the planning and design phases, and even during exploration and economic evaluation studies.

Other value-adding opportunities occur when the mine operator partners with other regional mine operators, and/or others not involved in the mine operation. As will be explained, this can include co-development of regional infrastructure to the benefit of many, reprocessing or utilizing others' process residuals to the benefit of both parties, and regenerating lands and transitioning ownership of assets for post-mining uses.

A hierarchy of value generation and preservation focused on the mine system, including strategies that can be used by the mine operator, is introduced. This hierarchy includes approaches that engage others within the value chain and/or region to maintain and transfer value over time.

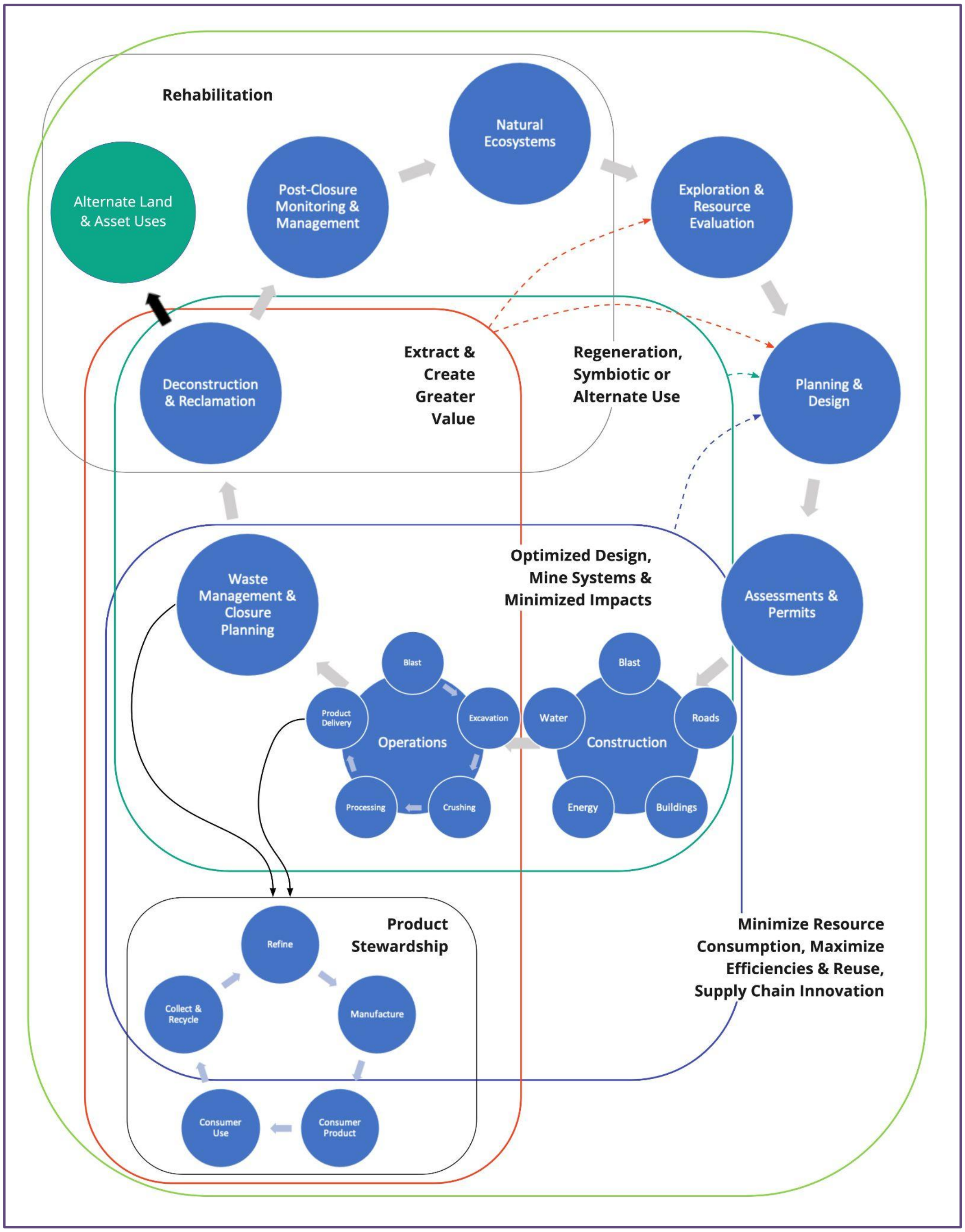


Figure 3: Development Stewardship and the Circular Mine. Source: MERG/Enviro Integration Strategies Inc.

3.1 Proposed Hierarchy of Mining CE Opportunities

Mine operators can engage with circularity via many strategies. This section describes categories of circular practice that an operating site or mining organization can consider. Figure 4 illustrates a range of circular strategies, as applied to two primary categories, and was developed with typical waste-resource management hierarchies in mind.

Categories:

- The natural resources that mining operations disturb, extract, use and manage; and,
- The technical operating system of infrastructure, equipment and assets created or utilized at a mine site.

Waste-resource management hierarchies:

- At the top/outer rims (largest circles), strategies involving regeneration of disturbed lands, recovery of residual asset or material value for alternate uses, and those that safely manage residuals with no recoverable value, are included. These strategies involve the transfer of residual value to other stakeholders engaging with the mine operator in support of CE.
- Progressing into the middle (mid-sized circles), strategies covered involve reduction of resource use and maximized efficiencies, conversion of wastes to value, maintenance and/or extension of the useful life or value of materials, to transfer of value through repurposing.
- The centre (smallest and co-joined circles) is aligned with the highest levels of circularity: refuse/prevent, rethink, redesign. In other words, within both systems (natural resources and technical), the greatest value (and least waste) is derived with strategies at the centre of the figure, and by combining the opportunities available to optimize both systems.

Section 3.2 focuses on the technical system, starting with lowest value/linear strategies and progressing through circular strategies that derive greater value from materials and assets.

Section 3.3 focuses on the integration of both the technical and natural resources systems and discusses strategies to rethink performance objectives and redesign for circularity.

Section 3.4 concentrates on the natural resources system and how operations can work with existing wastes, used assets, and disturbed lands to reduce waste generation and recover embedded value from those materials and assets, and/or transfer value (in terms of continued usefulness) to others.

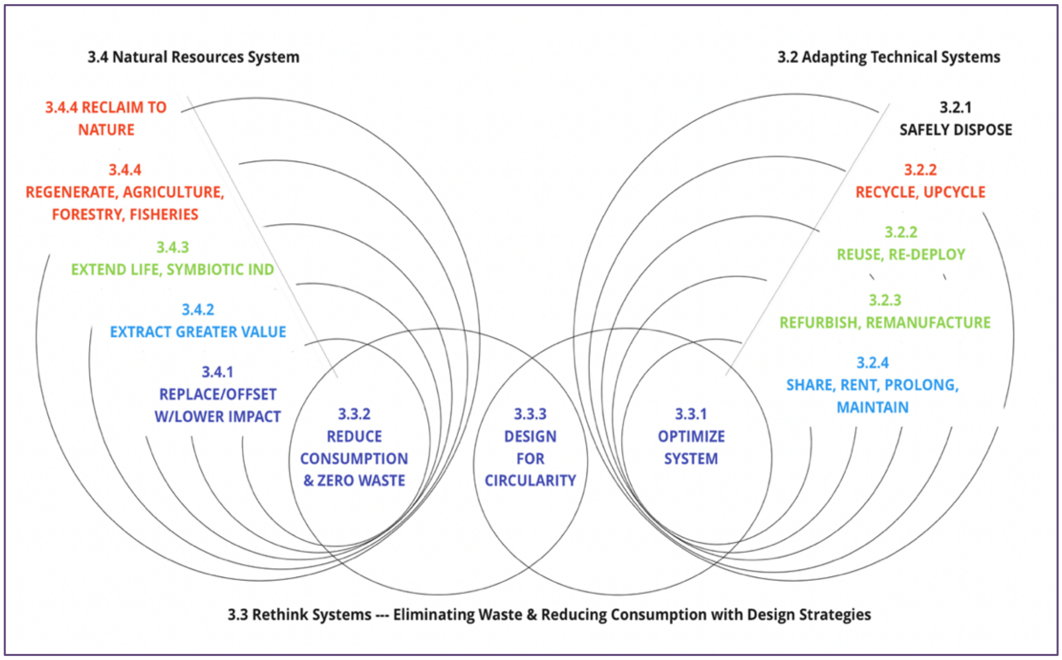


Figure 4: Proposed Mining CE Hierarchy. Source: MERG/Enviro Integration Strategies Inc.

3.2 Adapting Technical Systems to Maximize Circular Value

The technical system considers the physical infrastructure, equipment and assets that a mining company purchases, establishes or utilizes to operate the mine. It considers the full value chain, from development and excavation of the deposit, through comminution, extraction and tailings production, and packaging and transport to the client, whether they be refiners, smelters, semi-fabricators, fabricators and/or manufacturers.

Maximizing the efficiencies and lifespan of these assets has been a long-time focus within industry. But the greatest outcomes arise by implementing all the CE strategies together, rethinking performance objectives and design strategies. This includes maximizing the utilization of every piece of equipment, operating facilities at peak efficiency, extending asset life, and ensuring source materials can be recycled by others. For new systems, it also includes use of innovative technologies that allow the elimination of system components and/or generation of wastes, to design and build only what is needed for the proven resources, and/or use of scalable and interchangeable modular systems.

3.2.1 Re-thinking “End of Life/Waste” Definitions and Practices

It is common to see old equipment, infrastructure, retired assets and out-of- date consumables stored on-site until they can be permanently placed underground – into mined-out pits, buried in waste rock, or tailings facilities. Smaller items are frequently landfilled on the mine property. Although this seems easiest and least costly, this practice should be reconsidered. A particular asset may no longer be useful to its owner, but the embedded value of the materials remains and may be of value to others.

When assessing the feasibility of recycling or off-site repurposing vs. disposal:

- Ensure that all costs are assessed; compare the combined market value, cost of disassembly, and shipping offsite for recycling, with the cost of lifting, moving and burying the associated end-of-life items underground, in-pit, or in a landfill (with no recycled return).
- Consider that landfills are becoming more difficult to license, and underground space itself has an associated cost (construction, management and closure). The smaller the landfill or waste repository on-site, the smaller the footprint, the lower the capital cost of construction, and the lower the cost of closure.
- Identify, evaluate and consider these risks in decision-making: disposal of such items could introduce a risk of longer-term impacts, even within a lined facility.

Other materials to manage appropriately include hazardous substances, such as waste oils, lubricants, reagents and discharges from upset plant conditions or major maintenance programs. These materials cannot be stored and disposed of as-is on site indefinitely – they need to be stabilized chemically and managed in a safe manner, often shipped to off-site facilities. Due to existing regulations, there are many waste handlers available to support industry on this front. Specialty management services costs may be offset by down cycling and/or capturing additional value.

The growth of extended producer responsibility programs[20] and requirements and “product as a service” models (see section 3.2.4) likely soon will have a direct impact on the alternative opportunities associated with many wastes.

3.2.2 Maximizing Value from Products Already On-Site

With the advent of more responsible practices, large equipment and tools are being disassembled and sent off-site for recycling, upcycling, reuse or use for parts, or otherwise redeployed, by sale or donation, to other potential users.

At the lowest level of value recovery, recycling destroys an end-of-life product to create something new, whereas upcycling takes product materials and creates something new from them without material transformation. Where the assets are not yet worn out but are no longer required, they can be transferred to another operating site, or redeployed to extend the asset’s life.

Some examples of down cycling through to reuse include:

- *Down cycling:* Rubber tires are shredded and tire chips re-used for feedstock for gasification (energy recovery) systems, or used in playgrounds, landscaping and wastewater treatment filters – these items are eventually replaced and disposed of.
- *Recycling:* Metals from shredded tires are recovered, and finely ground crumb rubber can be reprocessed to make rubberized asphalt, playground flooring (where permitted), welcome mats, anti-fatigue mats and vehicle mudguards, etc.[21]
- *Upcycling:* Using parts or portions of the materials to create something else – like welding nuts and bolts into art or cutting belts up into smaller pieces as new products.[22]
- *Reuse:* Equipment, tools, parts or other assets are donated to local businesses. Old tires can be used in their current form for other purposes.

The mining company may not gain much from these CE activities, but the operator gains the means to clean up the site and reduce longer-term liabilities.

These practices also can benefit existing local or regional waste handlers and suppliers, or spin-off new business opportunities within the local region. This also establishes the mining company as a good corporate citizen for the host community.

3.2.3 Reimagining/Recreating On-site Products

Both refurbishment and remanufacturing offset or reduce the cost of purchasing new items.

Refurbishment includes the distribution of unused products that have been returned to a manufacturer or vendor for various reasons, such as when a mine alters a system and returns stocked parts no longer of use at the site. Refurbished products are normally tested for functionality and defects before they are re-sold on the market.

Remanufacturing is an industrial process by which a previously sold, worn, or non-functional product can be rebuilt to perform as originally designed and then redeployed. Through the disassembly, cleaning, repair and replacement of worn out and obsolete components, the piece can be returned to a “like-new” or “better-than-new” condition. An example of parts remanufacturing would be a service that retreads large industrial tires for reuse on the site.[23] Use of remanufactured goods and services may be considered of greater value for operating equipment, such as pumps, and larger processing or construction equipment.

3.2.4 Re-thinking Supply and Ownership

This category is about maximizing utilization and prolonging the life of assets in their current form with appropriate maintenance programs and operational practices to reduce wear and tear, and by ensuring careful storage and tracking of excess parts.

In many cases, consideration should be given to renting the necessary assets or contracting with service providers who will take their equipment away when tasks are complete. This approach is very important for larger equipment or assets that are needed only for specific, short-term, or seasonal projects. Underutilized tools and equipment can be shared on site amongst several users, including employees and contractors, by optimizing and coordinating schedules to avoid duplicating equipment needs.

Taken one step further, some suppliers offer products or parts as a service.[24] A usage rate is charged but the supplier maintains the equipment – monitoring and optimizing its performance, efficiency and lifespan – and arranges its eventual takeback for refurbishment, redeployment, or disassembly and recycling, as appropriate. This can be an attractive model for mine operators that are looking to retrofit, renovate or shift from older traditional equipment to automated or more efficient models. Modular operating systems can be included within this category if they are offered as rentals or provided as a service.

*“**Major players operating in the [equipment] market** are investing in research and development activities for upgradation in equipment in order to provide efficient equipment for industry...effectively trying to tighten up this equipment supply chain and achieve higher efficiencies… As a result, rental services of machineries are growing substantially.”* [25]

3.3 Eliminating Waste and Reducing Consumption with New Design Strategies

A company can achieve the greatest efficiencies for both the technical operating system, and the natural resources system, by going back to the drawing board and rethinking performance objectives, and the subsequent means to achieving waste reduction. A harm reduction and efficiency-based model cannot meet the deeper goal of waste elimination envisioned by a CE. There is an opportunity to move to a higher level at which systems can be designed for circularity and minimal environmental impact, and where wastes can be designed out.

For existing operations, improvement options might seem limited due to presumed costs of retrofit, space constraints within existing buildings, permit allowances, and more. However, opportunities surface when an owner is willing to replace an entire operating unit or system with newer technologies, rather than smaller retrofits, additions and/or upgrades. To facilitate such decisions for change, it is critical to perform holistic evaluations of the trade-offs between capital costs of new tech or infrastructure, and longer-term operational savings, including lower environmental impacts.

For new projects, this is the opportunity for multi-disciplinary design teams to come together to re-think mine development, including the supporting infrastructure and the intersecting operational processes. It would include optimizing flow through the entire value chain and across the full mine life cycle, including activities associated with waste management and closure, and would consider how these processes or activities on site change throughout its life cycle. Overarching objectives would include making the entire system value driven and efficient while minimizing resource use, footprint disturbance and waste generation. There is significant tangible value in the reduction of future waste management requirements, activities and liabilities. The more that can be "designed for circularity" from the start, the better the outcomes will be, as discussed in the following sub-sections.

3.3.1 Technical System Improvement through Design Strategies

Many system design strategies can generate desired outcomes. The following list of strategies is based on equipment, technologies, operations, and partnerships:

- Selectively target and extract only the ore, vs. ore and waste;
- Reduce the interception, intake of and/or the need for fresh water;
- Reduce the demand for energy, and the consumption of high-carbon energy;
- Improve free flow of materials, reducing the need for excess or handling of materials;
- Eliminate repetitive motion where one movement can perform the intended action;
- Revise processes to reduce the general wear and tear of system components;
- Eliminate the generation of wastes in the system, such as process scales or crud;
- Extract and segregate multiple value-add metal and/or mineral by-products from "mine waste";
- Allow the capture and reuse of waste heat, energy, water, mineral residuals and reagents;
- Reduce the risks of residuals that must be stored;
- Reduce potential for spills;

- Optimize transport/shipping circuits; and,
- Reduce packaging wastes brought to the site.

The best outcomes for CE practice occur when strategies are combined (see Section 3.3.2). Examples of combined-systems improvements are provided in Section 3.3.3.

3.3.2 Natural System Conservation and Value Creation Outcomes

Desired outcomes of the improvements include:

- Reduced risk mitigation costs and liabilities;
- Smaller disturbed physical footprint;
- Smaller plant size, reduction in "owned" assets;
- Significantly reduced waste volume, handling and storage;
- Reduced draw of freshwater, reduced volume of mine-impacted water to handle and treat;
- Reduced energy demand, reduced fossil fuel use and emissions generation;
- Reduced and less toxic reagents and consumables;
- Reduced environmental risks to manage;
- Creation of poly-metal and mineral products and/or possible value-added manufactured products;
- Value-added use, extended life and/or value recovery of the disturbed land and used assets and infrastructure following orebody depletion; and,
- Responsibly reclaimed and closed sites, according to planned end-use goals.

There are many success stories of large-scale changes to operations that have helped to improve efficiencies, costs and reduce environmental impacts at the same time. The next sub-section highlights a few innovative approaches and applications in industry and indicates that broader changes and future technological uptake are coming.

3.3.3 New Technology for System-based Improvements

Under consortia programs like the Canada Mining Innovation Council's *Towards Zero Waste Mining*[26] goals, several technologies to facilitate reductions in waste generation, energy consumption and water use are being assessed, developed and tested. These solutions support green, climate smart mining and CE principles. (See Table 2)

The projects in this section exemplify the use of introducing a major change in technology for one application, or combined technology changes, to realize benefits across a larger system. If these examples had been assessed using only linear process improvement and other beneficial aspects not been considered (i.e., comparing the costs and efficiencies of one technology to another), they might not have been advanced.

ACTION	**Target ore extraction and separation from non-ore-bearing materials in situ**
Benefit	Extract ore, not waste for reduced: • handling • processing • energy and water consumption • long-term risk management activities
Examples	• Potash: In situ selective dissolution • Uranium: Well-field circuits or jet- and raise-boring extraction[27] • Oil sands: Steam-assisted gravity drainage[28]
ACTION	**Industry collaborates to investigate technologies to reduce energy demand**
Benefit	Energy Demand Drops: Front-end reductions in waste generation and energy consumption
Examples	Technologies enabling • Efficient comminution[29] • Combining refined crushing mechanisms with ore-sorting[30] • Dry-processing or water-less extraction strategies[31] reducing waste-to-mill volumes and management of water • Continuous mining to replace drill and blast operations, producing materials off the back of the cutter that are immediately amenable to sorting • Dewatering leading to water reuse; reduction of mine waste handling, storage costs and risks; and scale of containment infrastructure • Waste energy recovery • Emissions abatement • Capture, recirculation, stabilization/conversion of valuable resources for repurposing
ACTION	**Advance Electric Mines and Fleets**
Benefit	• Reduce fossil fuel use and greenhouse gas (GHG) emissions • Reduce underground ventilation needs • Improve worker health and safety
Examples	Newmont* Borden Lake, Ontario gold project • built Canada's first all-electric underground mine** • recognized by ICMM as a mine of the future • all project vehicles and equipment are battery powered, reducing "annual GHG emissions by more than 7,000 tons or a 70% reduction over a baseline mine."[32] Kirkland Lake Gold • finding gains to the broader scope of the operation, particularly in deep mines. Glencore's Onaping Depth project • calculates that using EVs would create 44 percent savings for ventilation, 30 percent savings for cooling equipment and a 44 percent reduction in GHG emissions.[33] *previously Goldcorp **with partners Sandvik Mining and MacLean Engineering

Table 2: Examples of combined-systems improvements. Source: MERG/Enviro Integration Strategies Inc.

The difference with respect to circularity comes with
looking at the entire mining development and processing system, assessing all the relevant impacts of each option (positive and negative) and "designing for circularity" outcomes.

3.4 Reducing Impacts, Maximizing Value of Natural Resources and Disturbed Lands

Section 3.4 presents strategies to optimize natural resources use and to derive the greatest value from the resources that are disturbed, extracted, consumed and/or otherwise managed. Section 3.4.1 and part of Section 3.4.2 discuss options available to the mine operator, through retrofit with new technologies, supplies, or integrated new processes, without the requirement of external partnerships. Section 3.4.2 leads into a discussion of CE opportunities for natural resources in which non-mining partners and stakeholders – such as communities, regional planners, government, technology and service providers, and/or adjacent industrial or commercial players – can collaborate to derive multi-party benefits. Sections 3.4.3 and 3.4.4 continue with opportunities involving partnerships and end with discussion regarding reclamation to re-establish passive natural ecosystems.

3.4.1 Replace or Offset with Lower Impact Options

An owner of an existing operation may not be in a position to optimize the entire mine system but shifting focus to reducing waste generation and choosing less impactful and more sustainable options for the raw resources and consumables required could include activities such as:

- Replacing use of clean fresh water with mine-impacted, or recycled waters from the site;
- Using waste energy or geothermal energy in the form of heat transfer or converted power captured from exhausts, circulating fluids (processing or water), or other sources;
- Replacing fossil fuel-based power systems with renewable energy and hybrid electric options;
- Replacing toxic consumables with safer options;
- Purchasing refurbished or used equipment, and/or consumables bearing recycled content; and,
- Choosing processes or technologies that eliminate potential risks of discharges, i.e., associated with wastewater streams or tailings slurries.

Dewatered Tailings
Ways to reduce the risks and inefficiencies of managing slurry tailings, including high-density thickeners, centrifuge thickeners, paste plants, filter-press technologies, and co-disposal solutions are being investigated. For example, Goldcorp partnered with FLSmidth, a global engineer company, to create EcoTails®, "a new system to dramatically improve tailings and waste rock disposal while economically processing mine waste and increasing water recovery and reuse by as much as 90–95%." [34]

Renewable or Low Carbon Energy

Renewable and low carbon energy solutions have been used at many mining operations to replace the use of petroleum fuels for all mill processes and camp facilities. Several remote mines have integrated renewable energy systems into their operations. In 2014, Glencore's Raglan nickel mine partnered with Tugliq Energy Co. to install a wind turbine to reduce its GHG emissions from diesel usage. Over its first 18 months of operation, the turbine achieved 97.3 percent availability, displacing 3.4 million liters of diesel and 9,110 tons of GHGs. In 2015, a storage system was installed to better implement wind power to its actual grid.[35]

Some replacements seem obvious and can reduce operating costs in addition to having environmental benefits, but caution is advised when assessing replacement options especially for energy supply. A full life cycle, systems-based and site-specific analysis should be considered.

For example, switching to all-electric fleets may reduce on-site fuel consumption and site-based emissions, reducing ventilation needs and improving health and safety for underground applications. However, net emissions may not be reduced if the electricity source is based on fossil fuel consumption elsewhere or if infrastructure costs to support electric fleets replace operational savings. Similarly, there are life cycle impacts of renewable energy due to the materials consumed in their production. Designers or analysts assessing options should consider a full systems-based, life cycle assessment that includes Scopes 1, 2 and 3 emissions,[36] and other impacts throughout the supply chain, to make the best decisions for an organization. "To foster the sustainable development of metal-containing products, the metal industry has embraced the use of LCA as described by the international standards ISO 14040 (2006) and ISO 14044 (2006) to evaluate and communicate the environmental impacts of its products."[37] Several standards and guides are available on implementing LCA, however the referenced paper on "Harmonization of LCA methodologies" recommends that key elements of the evaluation in metals and mining include:

- Ensuring that the "boundary" of the system analysis contains the end-of-life disposal, recycling, recovery, or rehabilitation aspects related to each option;
- Investigation of alternative uses of assets, and co- or by-products that may be created from wastes; and,
- Estimating potential impacts in the following categories: global warming, acidification, eutrophication, photochemical oxidant creation, and ozone depletion.

Shifting impacts from an operational site to elsewhere does not solve the problem of overall impacts to people and planet.

3.4.2 Extract Embedded Value from Wastes: Using Stored Geological Resources

On-site Repurposing of Resources

Operators have utilized mine wastes on-site for years. Clean waste rock and overburden aggregates have been used for foundations, construction of site infrastructure, road maintenance, capping of closed waste disposal facilities and for reclamation. Finer waste rock and tailings have been used for backfilling and "shotcreting" in underground operations. Equivalent to the sustainable and circular concept of "reuse" these practices can offset operating costs of aggregate supply and shipping.

Off-site Local Repurposing, Refurbishment, Remanufacturing of Resources

The use of mine wastes off-site is less prevalent. Overburden waste rock has been diverted for use in roads and construction of infrastructure in the vicinity of the site, where these materials are of value to local or regional communities and developers. Similarly, there are examples of mine sites diverting, pumping, and/or treating water for use at nearby local communities. As an alternative to discharging the diverted and/or treated streams, a mutually beneficial and shared-value option is to direct that clean water to communities that may otherwise struggle to access clean water for drinking, agricultural use, and potential growth of bio-energy crops.[38] Such examples equate with "refurbishment and remanufacturing" practices but applied to natural resources rather than manufactured consumable products. Depending on the degree of processing and refining necessary for separation and extraction of materials for specific uses, these options take more effort than simple reuse and redistribution. But they utilize resources that the site is already managing, and incurring costs in doing so, thereby providing benefit to others at little to no additional cost – a social return for the organization.

Re-valuation for New Markets or Buyers

The recovery of value from the mining sector's process residuals is an area of growing interest within the research and technology development spaces, for both metal extraction and for the repurposing of more inert material. These have both been a focus of CanmetMINING's MVFW initiative[39] and others as shown by the many papers published over the past 60 years on the use of mine wastes for construction, with exploratory cases significantly growing over the last decade.[40] There has also been a global upswing in the reprocessing of historic mine wastes and impacted mine waters to extract residual metal value,[41] driven by both rising market demand and value of ores previously considered uneconomic or just not considered at all.[42]

Additional value has been found in these hibernating stocks of non-metal residuals:

- For use as aggregate for concrete or off-site construction projects further afield;[43]
- Through the production of higher-value industrial consumables such as interlocking flooring, structural concrete blocks, sealing blocks, concrete plates, shackles, and others;[44]
- Through downstream extraction, refinement and conversion of minerals into high-purity specialty materials; and,
- For use in soil amendment and agricultural applications.[45]

This is interesting because of the assumption that low-value materials cannot travel far before their repurposing becomes uneconomic. Under certain conditions, a low-value aggregate can become a highly sought commodity. A buyer may be willing to pay more to ship a lower value product farther if it is difficult or more costly to obtain within their local region.[46] "Giving away" unneeded, low-value materials that would otherwise incur storage management costs for the seller, and assuming the buyer pays for the handling/shipping, could generate wins on both sides.

Technological solutions to liberate and extract valuable metals and minerals from ore deposits or hibernating waste piles are applicable at many sites. The challenge is finding local buyers for the inert residuals. There is typically a disconnect between metal commodity producers, specialty materials producers, industrial or development mineral producers, and even commercial manufacturers who may be able to utilize raw materials with just a small amount of processing. It is likely that the residual minerals of a metal producer could be utilized by non-metal mineral producers - the awareness of potential synergies must be raised, and transactional agreements established where feasible.

Re-visioning and Discovery of New Value-add Uses

Another way to assess the value in waste materials is in their potential to solve complex challenges related to costly environmental impacts such as acid rock drainage and metal leachates or changing risks such as climate change and CO_2 emissions. For example, research by Teck has found that biological processes within various types of waste rock can be enhanced to help capture contaminants previously being released to the environment. They can establish water treatment systems using waste rock as the treatment medium host.[47] Agnico Eagle's Goldex mine uses some of its thickened tailings as backfill to fill underground voids and is pumping the remainder of its tailings to the old Manitou mine site 23 km away, which is managed by the Quebec government and requires reclamation. The neutralizing tailings are being used to cap severely acid-generating historic wastes, and the alkaline tailings fluids also help stabilize geochemical activity of underlying acidic porewaters, reducing further impacts from the Manitou site.[48]

With respect to climate change challenges, an interesting case has demonstrated that mine tailings have carbon-absorption capacity. The potential exists to use mine tailings in mineral carbonation, or enhanced weathering, to capture and store CO_2 from the air. Additional benefits could include stabilizing tailings piles and reducing the amount of dust generated on mine sites. "The current scale of mining of commodities hosted in magnesium silicate rocks would be sufficient to trap 100 to 200 million tonnes of CO_2 per year if all their waste streams were fully reacted." [49]

The potential is high for extracting greater value out of the wastes stored on operating and closed sites, with the added benefits of reduced long-term environmental risks/liabilities, and reduced waste volumes to manage, reclaim and monitor over the long haul. There is truth in the saying that "one man's waste is another man's treasure". Industry needs to explore the opportunities and make the necessary connections between those with excess and those in need (and who are armed with innovative, cost-effective solutions).

3.4.3 Create Value through Waste Exchanges: Industrial Symbiosis

Section 3.4.3 discusses CE opportunities that go beyond more common mining sustainability practices and measures, where external and non-traditional collaborations are necessary for success. These are areas of significant growth and value-sharing potential and, although they are implemented towards the end of the mine life cycle, they can be investigated at any stage of development. There may be mutually beneficial opportunities in looking outward for partners to utilize and gain value from industry wastes, and in looking inward for ways in which mine operators might utilize others' wastes as well.

What is Industrial Symbiosis and What Makes it Work?

Industrial symbiosis engages traditionally separate industries in a collective effort to reach competitive advantage, involving physical exchange of materials, energy, water, and/or by-products. It describes how a network of diverse organizations can foster eco-innovation and long-term culture change, create and share mutually profitable transactions, and improve business and technical processes.

The keys to industrial symbiosis are: systems thinking; collaboration and consideration of the synergies offered by geographic proximity; and/or the complementary needs and unwanted resources or residuals (waste) of each collaborating party. To explore potential opportunities requires strategic thinking, an openness to sharing information, and an inclination towards holistic value optimization. In production, coordination of logistics and operations and the formation of mutually beneficial, risk-sharing agreements may be required. The outcomes of these symbiotic relationships are that resources remain in productive use in the economy for a longer period.

The Metal Tech Alley (MTA) initiative, based in Trail, British Columbia, *presents a regional example in which commercial and industrial businesses and research entities frequently meet and explore intersecting opportunities to advance the CE.[50] The project began when local mining producer Teck started looking for solutions for over 35 materials they had identified that had potential to be diverted and converted from wastes to value. The MTA initiative has brought together digital fabrication and advanced materials/metallurgy, recycling and circularity, technology and innovation, and the service supply chain to create business opportunities and to start addressing waste challenges, such as those introduced by Teck, and from others in the network.*

Symbiotic opportunities during operations

For the mining sector, symbiotic partnerships may seem far-reaching. However, there are many existing interdependent relationships including: (a) toll-milling agreements between competing producers (often referred to as co-opetition); (b) contracts with producers of other commodities for extraction of secondary products from a poly-metallic stream; or (c) co-location of renewable energy grids on an existing operating site. Further, it is not unreasonable to consider establishing downstream manufacturing directly on a mine site, particularly if the manufacturer can modularize and easily relocate its production plant/equipment and use a large volume of a producer's raw resources. For example, consider utilization of 3-D printing and construction of transportable modular homes or wall units, built from residual tailings materials, which could be used for regional development.

At early exploration phases, or even after operations have commenced, the deposit (and/or wastes) can be fully assessed to understand its value potential. This information can be used with longer-term economic development objectives within the local region to discover potential business or value-add opportunities. During the operational phases of ore extraction, there are opportunities to adapt and/or add modular circuits to the processing plant, and to investigate alternative uses of land or infrastructure no longer being utilized. In planning for closure, and at sites never appropriately closed, there are vast possibilities depending on the state and location of the site and the desires of local communities and regional planners.

Symbiotic Opportunities Post-Mining Operations

In cases where symbiotic exchanges cannot be considered during mine operations, similar thinking can be applied to the mine's assets when approaching and planning for closure. There have been many examples of alternative uses of disturbed and reclaimed lands, and of immobile or more permanent infrastructure no longer needed on-site, including pits and underground workings, stick-built buildings, and utilities such as connections to existing power and water distribution systems.

Regarding renewable energy systems, it has been highlighted that several mine sites have installed on-site solar and wind energy infrastructure. These systems can be transferred to new owners at mine closure, or if not installed for mine operations, the site can be utilized for the same post-closure, as in the case of the Kidston Gold Mine located in Far North Queensland.[51] Another energy-production option, where water management infrastructure already exists, includes pumped hydro energy storage and generation systems,[52] producing power for both on-site in-production use, and for off-site use by the local region both during and then after mine operations cease. Other interesting symbiotic relationships are ones that create several large-scale regional benefits – cleanup and reclamation of historic wastes/impacted sites, use of wastes from other sectors, productive use of brownfield sites, and job creation and clean energy production for the region.[53,54]

Underground infrastructure can be utilized in several industrial and commercial ways, for example:

- High-tech laboratories,[55] experimentation chambers, and testing sites for research and for development of innovative tools;[56]
- Greenhouses and aquaculture systems for various products, due to the ability to control the climate;[57]
- Training centres, e.g., for rescue, use of remote equipment or blasting;
- Climate-controlled data storage servers and analytical systems,[58] or possibly bitcoin operations which require ongoing cooling; and,
- Museums and tourist attractions.[59]

Transitions in site and infrastructure use typically involve a transfer of ownership of assets. In cases where the operator would remain liable for wastes, infrastructure and/or reclaimed lands on the site (i.e., until designated safe for declassification), agreements would need to be established enabling joint land-use or lease of the land or infrastructure.

The symbiotic strategies listed so far have been considered from an outward looking perspective, that is, how to optimize operating systems, become more circular with alternate practices, or by engaging others inside of the operator's supply chain, or within other industries.

Mines using Others' Wastes

An additional view is looking inward and considering where mine operators can utilize the wastes of others, including from other sectors altogether, as feed or another resource for development, operations, or closure phases. Some of the typical ways to do this include buying used or refurbished equipment and infrastructure. Purchasing and processing, or toll-milling, tailings or slags from other sites to recover residual minerals are also great examples.

Wastes from other industries may be appropriate for reclamation and regeneration of disturbed lands. For example, process residuals from wastewater treatment, pulp and paper, or agricultural wastes, can be used to help re-fertilize and establish new plant growth and healthy ecosystems.

There is no shortage of opportunities within the symbiotic realm. Interested operators can initiate this with engagement, sharing of information, and asking questions. What assets are no longer required? Who can use them? What does a region want in the long-term? Who might be interested in partnering to create new circular products and services? How to move forward?

3.4.4 Re-thinking Mine Reclamation: from Harm Reduction to Value Generation

Regeneration is a critical component of CE. It applies to agricultural producers and the forestry sector who can, over time, degrade the land upon which their business is founded. Mining similarly has impacts on the land, and has requirements to both minimize them during operations, and to restore disturbed sites. Social license commitments involve mining organizations in establishing post-mine economic and environmental sustainability for the region. This category of CE compels mining companies to be environmentally, socially, and economically responsible, even for closing operations.

Reclaiming for Recreational and Commercial Purposes

While closed mine sites should be reclaimed so that plants and wildlife do not require ongoing management, certain business opportunities could thrive, for example tourism:

- Seasonal sports, e.g., hiking, biking, golf, zip lining, skiing, tobogganing;
- Fishing and hunting grounds, camping resorts/retreats; and,
- Nature observatory parks, specialty gardens, etc.

In Alberta and British Columbia, there are examples of abandoned and closed coal pit lakes being transformed into busy recreational and fisheries sites.

> In Alberta, about 25 open cut coal mine pits have been converted into pit lakes that are now used as recreational fisheries and as central features around which hiking trails have been created… Quarry Lake, an abandoned coal mine on the edge of the Rocky Mountains, is a popular destination for angling and hiking… and in British Columbia, former mine pits and tailings ponds at a copper mine have been converted into sport fisheries that now host a popular fishing derby.[60]

Aimed at productively repurposing the Sullivan Mine, Teck and the community focused on a few projects when planning for closure.

> The first component was the development of a golf and ski resort that could help mitigate the impact of lost mining revenues on the city. The second was providing land for residential real estate... where a 'land swap' was arranged between the city – which owned a parcel of land that was well suited for real estate development – and Teck – which owned a parcel of parkland the city was interested in obtaining. This 'land swap' facilitated the construction of seasonal and permanent residences marketed to out-of-town buyers… Teck also collaborated with a solar developer and the City of Kimberley to construct SunMine, a pilot solar panel project on Sullivan land and the first solar power plant in Western Canada to connect to the power grid.[61]

Regenerating Land to Healthy Agro-Ecosystems

In the category of regenerative value creation, there are opportunities to actively reclaim and regenerate disturbed land areas to create – where climatically possible – productive agricultural, forestry and/or fisheries sites to support the surrounding region. There are many cases in which mining companies have supported the development of farming operations and facilitated the training and upskilling of local community members to manage such operations. This has often included the energy and water distribution systems to cultivate and grow sustainable, productive crops within a region. There have also been cases where mine tailings have been utilized for soil amendments and fertilizers for regional agricultural projects,[62] further demonstrating the potential for on-site land use in this capacity, depending on the mineralogy of the materials.

Mine sites have energy and water infrastructure that would otherwise be decommissioned, and open land space that requires reclaiming. Combining both brings longer-term benefits to the region in terms of skills, jobs, and revenue for individuals, lower-cost and locally produced food, livestock or energy feedstock, and economic prosperity, well after the mining company has departed.

Regenerating and Reclaiming to Natural Ecological Systems

Assuming active end of operations land-use strategies have not been selected, the final stage of a mine site's life cycle is to return the disturbed site to a naturally productive, self-sustaining ecosystem, where flora and fauna can flourish. This is currently the typical endpoint, land-use objective of most current mining developments, and what is proposed in nearly all environmental assessment studies.

One great example where mining operations have been reclaimed to self-sustaining ecosystems is in Fort McMurray at the Syncrude operations. Realizing the long-term impact that the oilsands operations would have on the existing environment, Syncrude established reclamation research programs to create landscapes equivalent to what existed prior to disturbance.

> Significant progress has been made over the last 50 years with approximately 4,400 hectares of former mine sites either reclaimed or prepared for re-vegetation activities, and more than eight million tree and shrub seedlings planted throughout reclaimed areas… Syncrude approached Elk Island National Park to participate in the Wood Bison Recovery Program, run by the Canadian Wildlife Service, and in 1993, 30 wood bison were released onto reclaimed land. 25 years later, the herd has now grown to 300, who graze on 300 hectares of land reclaimed from oil sands mining operations at the Beaver Creek Bison Ranch, which is managed in partnership with the Fort McKay First Nation.[63]

In addition, Syncrude has also created productive "peat-forming, groundwater-fed wetlands, known as a Fen. Today, the Sandhill Fen Research Watershed Initiative is home to more than 28 kinds of thriving wetland plants." [64]

These examples demonstrate the ability of an operator to regenerate lands to facilitate regeneration of other natural systems - in this case, the wood bison populations at risk and natural peat-forming wetland habitats. Alternatively, the land can be returned to an ecologically stable state for the sole purpose of allowing nature to take over, where wildlife will use the land as it will.

4. CE Business Models and Business Case Considerations

As discussed in Section 3, various circular approaches can be applied in mining. Most of these approaches have potential to be deployed, in at least some capacity, in all mines, for all commodities, for any scale of mine, and at any life cycle stage of a mine. The greatest benefits come when all CE strategies are considered, when circularity is "designed and built in" to new developments and implemented at the earliest phase of the mine's life cycle.

Given the many initiatives that relate to circularity in mining, operators in the mining space may be at various starting points within this spectrum or already on the circular agenda (without knowing it). These include the World Bank's Climate Smart Mining and various responsible mining standards that seek to address carbon, waste reduction and social development issues. For example, many companies embarked long ago on the path towards improvements in social and environmental performance beyond specific regulatory requirements, and many of these goals align with CE objectives. Energy efficiency, and process optimization efforts, have aimed to cut operational costs, and climate-smart mining has led the sector down the path of low carbon developments. As a result, many aspects of circularity may now fall within core business practices. The benefit of the CE framework for mining is the focus on maximized value creation and the sustained value of materials, as well as the regeneration of impacted ecosystems and the reduction of harm.

Section 4 discusses stages of business model innovation, and how implementation of advanced CE strategies correlate with these levels of change adoption.

4.1 Innovation Ambition

In 1957, H. Igor Ansoff developed the Innovation Ambition Matrix, which describes three fundamental levels of innovation ambition: *Core*, *Adjacent*, and *Transformational*. The levels are divided by the combination of change complexity and the impacts or potential value of making changes, where core ambitions are the least complex but bring less value than transformational changes, which may be very complex and bring with them significant value. It is suggested that all businesses engage in a spectrum of innovative opportunities to remain competitive and increase performance. *Harvard Business Review* found that "companies that allocated about 70% of their innovation activity to core initiatives, 20% to adjacent ones, and 10% to transformational ones outperformed their peers." [65]

Applying this matrix to the business of mineral extractives, the work to incrementally optimize, or make more efficient, existing product development processes lies in *Core*; expanding into adjacent markets, applying new technologies, or expanding into "new-to-you" products and processes belongs to *Adjacent*; and inventing new products or processes, or creating new markets, is at the *Transformational* level.[66]

Within core business, the focus is on using existing assets and processes, and continuing to serve existing markets. Moving into adjacent opportunities, the business looks to serve adjacent markets, possibly upstream or downstream of its value chain, or simply within its existing network of stakeholders, and the focus is on larger step changes of processes to do so. To understand transformational opportunities, the business must look to serve entirely new markets, meet new societal needs, and implement completely new inventions or business models.

Aligned with the three levels of innovation ambition, graduated stages of CE implementation relate to the numerous circular strategies described in Section 3, and as shown in Figure 5.

The implementation stages are valid for any scale of operation and any commodity. The challenge for implementation is more a matter of culture change, starting with the leadership setting and aligning on new objectives, planning the path forward, and investigating potential partners to advance change. The life cycle stage of the operation may limit opportunities since economics of change factor into the equation. For the greatest value, it is best to implement changes as early in the life cycle as possible.

Existing operations face additional financial costs, compared to new developments, to change or upgrade infrastructure. The behavioural aspects of change also tend to be more difficult than technology shifts, especially for larger and older organizations. Two facts stand out. First, industry proponents have suggested that upgrades happen frequently enough for most operators to consider and adopt new strategies and technologies once they are already in production. Second, industry has shown its ability to adjust to rapidly changing conditions (e.g., rapid operational changes in response to the 2020 pandemic and sharing best practices), and to collaborate on a large scale, particularly in a pre-competitive context, where the technologies will improve performance for many.

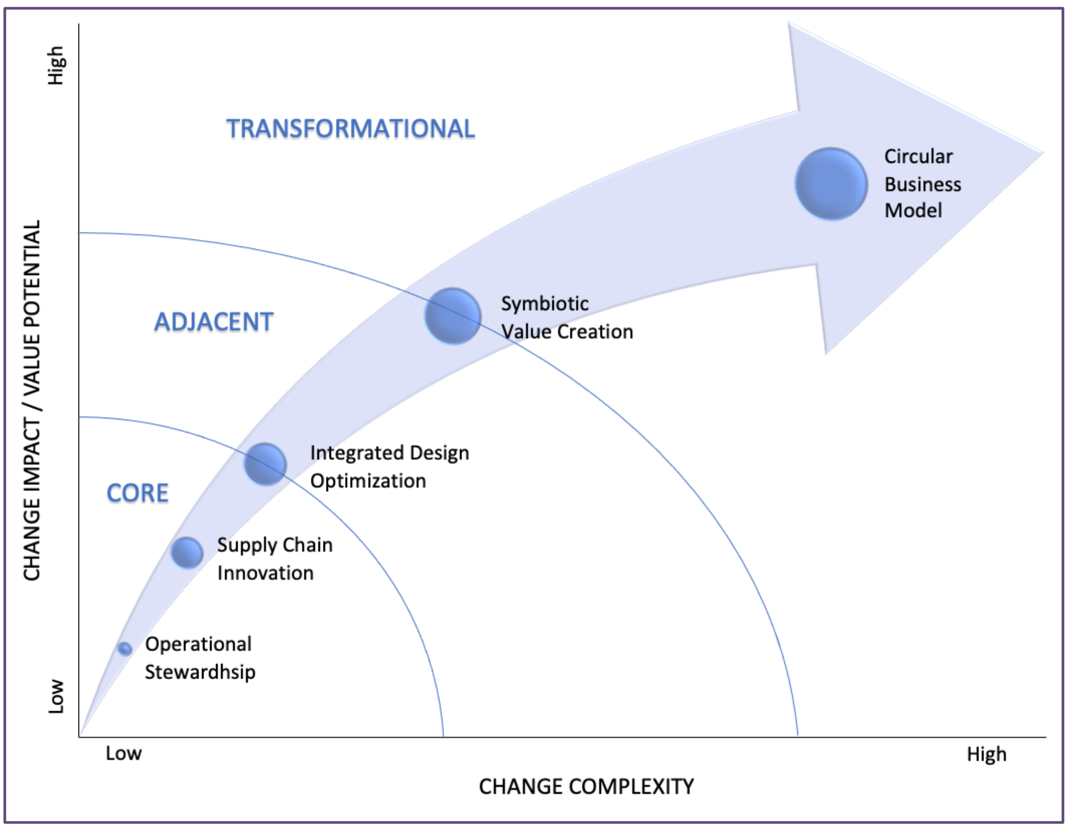


Figure 5: Innovation Ambition and CE Implementation Stages. Source: image adapted from H. Igor Ansoff's Innovation Ambition Matrix.

It is understood that greater opportunities for savings, for systems value generation, and for creating benefits beyond the mine border, fall into areas of transformational innovation, where collaboration is a necessity. And while these shifts involve greater complexity when it comes to change, there are several innovation consortia that have proven successful in tackling complex industry-wide challenges. In fact, the Canada Mining Innovation Council suggests that open innovation collaboration models can:

- Create networking and working group environments ripe for idea generation;
- Provide access to highly experienced and knowledgeable industry leaders;
- Decrease risks associated with investments in innovation;
- Create larger fund pools to devote towards higher benefit-yielding projects;
- Ensure resources are allocated through process structure and operating protocols; and,
- Provide access to resources and to rapid solution generation and implementation.[67]

According to the British Standards Institution, some organizational principles can turn the concept and theory of CE principles into action.[68] Sections 4.1.1, 4.1.2 and 4.1.3 explore these stages of innovative change.

4.1.1 Core Optimization

Under *Core* changes, and as illustrated in Figure 5, the spectrum ranges from driving everything internally to opening problem-solving to people and companies upstream and downstream of various processes on the site, typically involving providers of equipment, services and design. A company may engage in formal partnerships with vendors, or simply transact suppliers to produce solutions that meet a broader span of performance requirements. Two implementation stages are included under *Core*: operational stewardship and supply network innovation.

Operational Stewardship

Operational stewardship includes the fundamentals of the most prevalent Rs (reduce, reuse, remanufacture, and recycle), and typical optimization/efficiency improvements of extraction, processing and material transport logistics. Such improvements are often driven by cost reduction or "excellence" initiatives, compliance requirements, and/or pending changes in regulations. These measures can be implemented at any life cycle stage, for any operation, including mine-only developments to full mine and mill operations.

Most operators are already focused on operational stewardship, where identifying opportunities and implementing such improvements is enabled by having a full understanding of operational processes, and a review of waste generation, flow-barriers and related inefficiencies, as well as areas of impact and risk. Benefits of implementation include efficiency gains, reduced risk and operational cost savings, better environmental performance, and an improved reputation in the eyes of external stakeholders.

Supply Network Innovation

Supply network innovation includes refurbishment, rental, packaged supply and maintenance as service arrangements, sharing of assets, and customized design of products or services by suppliers who partner with the operator. Again, these measures can be implemented at any life cycle stage, for any scale of operation, however, the earlier these strategies are adopted, the greater the opportunity for savings and efficiencies.

Supply network innovation is enabled by expanding thinking upstream and downstream of distinct operational or production processes and having flexibility while working directly with solution providers. There must be a willingness to adapt existing design standards to performance-based ones, and consideration of parts or brands that differ from “asset favourites” (i.e., “go-to” brands that have always been used). The site must also establish integrated scheduling capabilities (e.g., for equipment sharing), and be willing to consider cost- and risk-sharing models. Benefits can include lower asset capital and management costs, lower contractor costs, shared risk, shared costs, and/or extended guarantees on performance of equipment.

4.1.2 Adjacent Expansion

As shown in Figure 5 under *Adjacent* shifts, the spectrum moves from viewing the operational system as a standalone or siloed unit, to gradually involving and/or partnering with proponents upstream and downstream of the value network ecosystem. Adjacent expansion includes collaborating with other mining stakeholders, and/or service or technology providers, who may offer alternative and innovative solutions, or who can support the development of new technologies to solve a particular challenge. It could also include working with those who have needs or challenges of their own, such as buyers in other industries, which can be met through partnering, and/or creating opportunities to generate value from what would otherwise be classified as waste.

One example in which wastes were converted to value because of revaluation and partnerships with new potential buyers is the Anaconda Mining Point Rousse site (Newfoundland & Labrador). Anaconda, Shoreline Aggregates and Phoenix Bulk Carriers worked together to repurpose approximately 3M tonnes of mine waste rock as construction aggregate product to a project in South Carolina. This project generated $2 million in gross revenue with no capital investments required.[69] A significant volume of stored rock was removed along with its potential long-term liability, such that monitoring, management and reclamation costs were no longer being incurred.[70]

Degrees of Partnership and Technology Development

On the lower end of the scale, an organization may simply seek out (relatively) new technologies or technical capabilities or adopt higher-performance standards that have been proved elsewhere. Or it may contract an engineering firm or technology developer to pilot, and then scale up promising technologies on offer. At the upper end of the scale, risk-sharing partnerships, initiating research and co-development of technologies that serve the needs of two or more collaborating partners, and transparency and information sharing within problem-solving networks will enable more opportunities. Such collaborative co-development of technology can be done pre-competitively where it will serve a large group of operators, or it can be done post-competitively, where the solution will benefit only the specific collaborators. Costs per collaborator and the risks of developing new technology diminish significantly, and the new technologies or strategies developed in the process can be later shared into the broader industry pool, enabling sector-wide improvements over the longer-term.

Integrated Design Optimization

Integrated design optimization, as discussed in Section 3.3, takes a full systems’ approach to rethink and redesign operational processes, whereby core objectives include reduction of waste generation, emissions, and potential for impacts, all the while maximizing flow and value creation through innovative design. Since many of the opportunities for this ambition include new technology, altered system and/or process design, the best life cycle stages for its application are during the conceptual and early feasibility study stage, prior to detailed engineering or construction. This can be considered in the case where a new development is being proposed, or when major upgrades, infrastructure replacements, or expansions are being considered.

Some of the key requirements for best outcomes include systems thinking, and engagement of multi-discipline expertise, including vendors, non-engineers, local stakeholders, and thinkers from outside of the mining industry. Another critical approach includes conceptual comparison of different combinations of technologies within the system. Performance and overall evaluation must include sustainability metrics, and there must also be an openness to investigating, modeling and assessing new ideas. Greater performance gains can be achieved if material flows are optimized for internal recycling, minimized emissions, and other measures eliminating risks that would otherwise require containment, governance, and risk or environmental management systems.

As shown in Figure 5, integrated design has been positioned between *Core* and *Adjacent* ambitions, primarily because there are different strategies to improve outcomes. For example, a company may find new processing strategies of their own accord, using internal researchers and/or contracted technology developers, or they may take a broader outlook and partner with solution providers in the supply network, or work within an innovation consortium to co-develop new processes and operational strategies.

One great example of an operation developed with full optimization, and footprint minimization, which aligns with a systems-based CE approach, is GenSource Potash. This vertically integrated operation will produce potash at significantly lower cost than traditional potash developments, using a closed-loop method called selective extraction (or selective solution mining) that has little environmental impact. It works like this: a hot salt (NaCl) brine is injected into horizontal caverns in the ore body, which selectively dissolves potash (KCl) leaving salt in place. The KCl-rich brine is then processed (KCl "drops out" through cooling crystallization) and the NaCl brine is reheated and re-circulated back to the cavern to repeat the process. This process will use 75 percent less water than conventional potash production, can use brackish water, creates no salt tailings, no brine ponds, has a very small physical footprint, and the product can be extracted on demand and loaded straight into trailers to be delivered to partnered buyers.[71]

4.1.3 Transformational Change

In the third innovation ambition level, *Transformational* change, the company reviews and completely changes the fundamental business model and performance objectives to become a proponent of CE. This moves beyond looking at ethically producing a primary ore or a suite of polymetallic products, to include the optimized use of all materials moved and assets operated to liberate their maximum embedded value.

On a site-specific approach, this might bring new development models framed around materials extraction and management, aimed at minimizing waste generation and energy and water wastes associated with excess materials handling. For example, some companies are exploring new technologies to target small-scale orebody development (without extracting wastes), at-face processing, or continuous mining combined with immediate bulk sorting (to separate and leave wastes in place, reuse them for backfill, or redirect them to create alternate products).

On a company-level approach, this might bring the creation of new vertically integrated companies (or new business units), with the focus of assessing new ways to reprocess hibernating waste stocks to create by-products of value for industrial or consumer markets. This is like waste management firms that long ago converted from waste collection and disposal to materials diversion solutions, and the newer services offered by Geocycle under the umbrella of LafargeHolcim.[72]

A broader approach might involve the creation of a regional collaborative of vertically and laterally integrated production, processing and manufacturing services, and end-users to optimize materials. Such measures require multiple buyers or co-processing partnerships, formal or informal, for optimal exchange of materials and assets to maximize the realization of long-term embedded value.

Symbiotic Value Creation or Creating Value for Stakeholders

Symbiotic value creation occurs when the organization considers the value that can be derived from what is commonly believed to be "necessary" waste generation and footprint impacts. It allows expansion from the production of a particular ore to extracting a suite of polymetallic or polymineral products from residual "waste" materials, also known as "gangue". It also considers the bulk residual materials, assets, disturbed land, and infrastructure of an operation as potential sources of value - if not for the organization itself, then for other partners, communities, or buyers of adjacent commodities.

An example of maximized symbiosis occurs when an exporting metal producer collaborates with local industrial mineral producers to derive the embedded value of the materials extracted. Minerals that are mined, processed, manufactured and used domestically include potash, sand and gravel, dimension stones, quartz, etc. Referred to as industrial minerals (or development minerals) they provide crucial inputs for infrastructure, manufacturing, construction and agriculture.

Metals producers often use non-metallic residual materials on-site, but otherwise consider them of low to no value. However, these industrial minerals can be important economically to others located nearby so this potential should be investigated. Symbiotic value creation can also occur if the metal producer supports local developers by sharing training and risk management programs and equipment and/or by establishing supply agreements that benefit both operators.

Several examples of symbiotic value creation were presented in Sections 3.4.2 through 3.4.4. As involvement and partnering with local businesses, regional developers and landowners increases, so does the potential for social benefits to be created within the local region.

Three examples of frameworks with which to build synergistic networks:

Vale's Pico Block Plant in Brazil

A pilot plant for local civil construction products made from tailings from mining activities, it is the first company initiative of its kind to reuse tailings. "In addition to making our operations safer and more sustainable [and ergonomically designed for inclusivity - it has been implemented and will be operated by women], we want to encourage the development of innovative solutions that create value for neighboring communities and society... The company also combines efforts with more than 30 organizations including universities, research centers and Brazilian and foreign companies to develop solutions for reusing mining tailings in different industrial sectors." [73]

RESOLVE's Salmon Gold project

This project brought together miners, communities, conservationists, agencies, restoration experts and manufacturers to produce gold and demonstrate the benefit of restoration. RESOLVE's Salmon Gold project is an innovative approach to sourcing gold responsibly and restoring fish habitats in Alaska, the Yukon Territory, and British Columbia.[74] Salmon Gold is a voluntary partnership to re-mine historical placer gold mine sites for the supply chains of Tiffany & Co. and Apple, and to restore fish habitat using sustainable techniques in regions with globally significant habitat for salmon and other anadromous fish species. This example presents a group of stakeholders working together to solve a challenge related to historical mining practices.

Quebec Circulaire[75]

In Quebec, a group of leaders came together to accelerate the transition to the CE for all types of material waste. The initiative aims to assemble initiatives, tools and expertise to engage in circular strategies and localize the broader benefits, such as jobs, new technological development, economic development, and resource savings.

Timing of Implementation

Synergistic opportunities can be implemented at various life cycle stages, including after mining operations cease, such as for abandoned, orphaned and inactive sites, during closure planning, and when options are being assessed for decommissioning a site. Value can be created for and by others if a mining company does not choose to stay on as an "operator" upon depletion of the primary orebody, but the responsibility remains with establishing and permitting risk mitigation and closure scenarios.

Considering these strategies during the conceptual design phase or during major infrastructure changes provides potential for secondary value creation throughout the operational phase, for streamlining and reducing handling or necessary retrofits later, and for establishing partnerships to share costs and risks in longer-term pursuits.

As shown in Figure 5, symbiotic value creation is positioned along the threshold between the *Adjacent* and *Transformational* innovation stages. A company investigating opportunities in this category will require, at a minimum, either vertical integration in the value chain, or partnership with additional parties, new customers and/or external-to-their-business collaborators. However, there may not be an entirely new business model created by the primary organization to execute the final transactions.

Circular Business Model

Companies considering transformational shifts test the feasibility of the change with a small fraction of the business. The Circular Business Model is about innovating. In mining, this can be done by perhaps looking at one site out of a suite of operations or focusing on one or two types of materials or assets to manage in a circular fashion. This is design of a closed-loop system, with an eye to creating long-term recoverable, re-deployable value within the products, and in everything that is developed, purchased, built and managed. This concept differs from that of taking a small fraction of value from a significant amount of material handled, and the associated and accepted creation of risks that last indefinitely.

A key difference in circular business models is a shift from a focus on singular-commodity value only and its return for the initiating company or its invested shareholders, to looking at value creation for a number of stakeholders, including partners in other commodities or sectors, suppliers, and communities within the region. It also looks at creating value on and from a particular site, beyond the timeline to depletion of the primary ore body. Rather, consideration is given to the extended use of the land, infrastructure, assets, and residual resources associated with the mining operation for alternate needs. This model is achievable only through collaboration amongst interested parties, regardless of the formality of the partnership established.

4.2 CE Business Case Considerations

Key to advancing the circularity agenda within the mining sector is to promote awareness and understanding of CE, its application to mining, and the benefits of doing so. The report thus far has attempted to raise awareness of the opportunities and applications at each level of adoption (Sections 2.1 through 2.4), and those greater potential rewards correlate with increasing levels of implementation of CE. Section 4.2.1 explores the scope of benefits of circularity in mining, plus other factors to consider in a business case analysis. Section 4.2.2 discusses benefits beyond the mine site.

4.2.1 Benefits for the Mine Site

Circular practices introduce mechanisms to reduce water and energy consumption, CO_2 emissions, and to eliminate waste generation showing a clear connection to their role in reducing future potential liabilities and operational costs. Most materials that the mining industry handles are considered waste, including overburden and waste rock, tailings and other process residuals, impact water, leachates and seepages, spent reagents, hazardous materials, air emissions, and more.

Generating less waste means that less material is handled, transported and managed, which reduces fuel consumption and emissions, thereby contributing to climate change objectives. Less waste sitting in landfills, waste piles, or in storage, also means fewer potential risks to manage, monitor, and to report on. Capturing and reusing some of these streams also helps to offset the costs of inputs otherwise required, such as freshwater, and non-renewable energy fuels. Reprocessing or remanufacturing wastes has the potential to generate additional revenues, while reducing the overall impacted footprint. Finally, these actions demonstrate an operator's commitment to sustainable and responsible production, improving the reputation of the organization, and upholding the social license to operate.

4.2.2 Benefits Beyond the Mine

There are other positive outcomes from circularity in mining operations. Through strategies like *Climate Smart Mining* (World Bank), *Towards Sustainable Mining* (MAC), and *Green Mining Innovation* (CanmetMINING, Natural Resources Canada [NRCan]), CE practices in the mining sector bring benefits to governments and society, including reduced GHG emissions, and fewer and smaller environmental impacts over the longer term. It maximizes value from resources, increases resource security, and restores or regenerates natural capital and ecosystems. CE activities create resilient jobs, attract investment, and relieve pressures on municipal services or budgets. It also creates the opportunity to leverage innovation and demonstrate technological leadership.[76]

The World Business Council on Sustainable Development (WBCSD)
described CE as "…the biggest opportunity to transform production and consumption since the First Industrial Revolution 250 years ago. By unleashing circular innovation, we can boost the global economy's resilience, support people and communities around the world and help fulfill the Paris Agreement and the UN Sustainable Development Goals [SDGs]…"

With respect to CE benefits to communities, there are opportunities for diverse employment, bringing increased disposable income, improved quality of life, and an alleviation of social inequalities. Because circularity also stimulates new innovative thinking, it brings the potential for the development of a rich and diverse local economy, and some critical socio-economic benefits, offering the promise of long-term sustainable prosperity through partnered developments and transferred assets over time.

As discussed, there are positive and direct impacts of mining-related CE activities aligned with several environmentally relevant SDGs. Secondary, indirect impacts are aligned with socially relevant SDGs, in which synergies and partnerships are made with local small-scale and artisanal-scale producers and local communities, and the concerns of local stakeholders are heard and addressed. See further details of specific links of mining circularity with the SDGs in Section 5.4.

4.2.3 Local Partnership Models

There are two direct ways that mines can partner to facilitate circular benefits beyond the mine. The first involves transition planning in preparation for mine closure. When a mine has become a primary contributor to the local economy, it can be difficult for the local communities to diversify its economy beyond the mine. The second opportunity comes when there are excess materials or resources generated by the mine that could be utilized by others within the local region - either during operations or after the mine has closed.

For example, the Sullivan Mine was critical to the social and economic fabric of the Kimberley, BC community for over 100 years.[77] At the time of closure, it was the largest single contributor to Kimberley's tax base and the city's largest employer. In planning for closure, Teck facilitated employee transition planning and worked with the city to accelerate development and diversification initiatives to give the City of Kimberley a foundation upon which it could build its future. In the 20 years since the mine closed, Kimberley has transformed from a mining community to a booming tourist and retirement destination. Some of the changes were initiated by Teck and turned over to the community. Other partners also brought forth ideas and business plans to advance with Teck.

The secondary case has been studied closely for developing countries but is also relevant and applicable for remote communities in northern Canada, where jobs and infrastructure are often lacking, and for industrial centres where industrial or development minerals (primarily non-metal aggregates) are both produced and used by different and adjacent players. Research by Professor Daniel Franks, University of Queensland, suggests that if metals mining projects can be directly linked with development minerals projects, particularly in developing countries or remote regions, there are some unique synergies. He highlights that:

> Metals are usually mined for export, where locally, they have a relatively strong fiscal linkage, average consumption linkages, but poor [downstream] production and poor utilisation linkages. Development minerals are mined and used domestically, having

[locally] low fiscal linkages, but strong consumption, strong production, and strong utilisation linkages. [78] (Figure 6.)

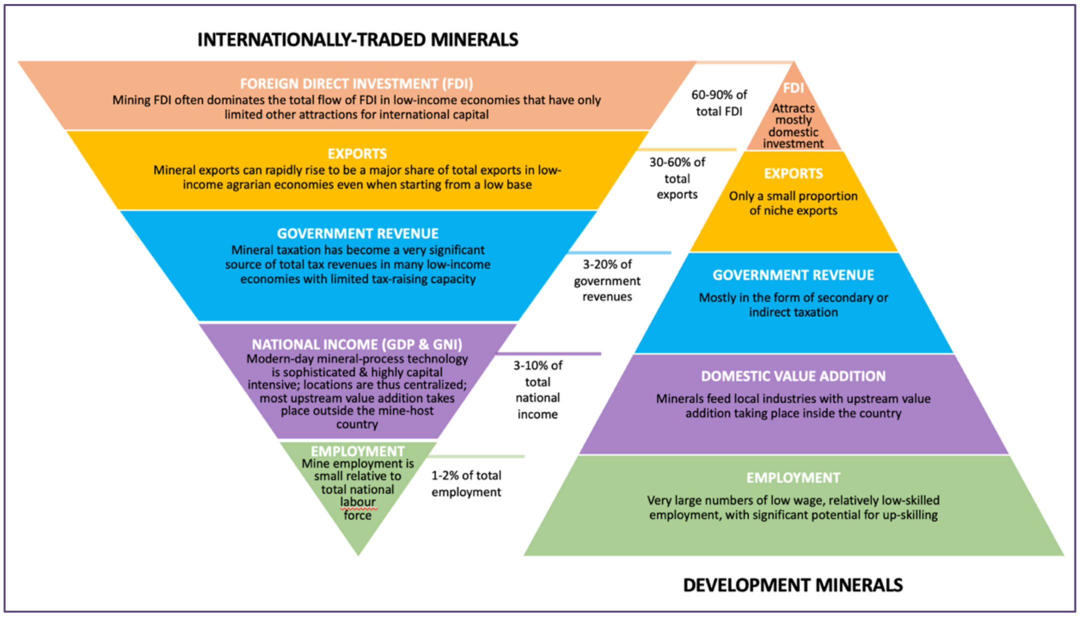


Figure 6: Comparison of benefits from internationally traded high-value minerals and local lower-value industrial/development minerals in developing countries.[79]

The benefits of internationally traded minerals, as documented by ICMM,[80] and locally utilized industrial minerals are inversely related. Given that such industrial minerals come with all metal mine operations, there may be an opportunity to bring developers of both internationally traded and locally utilized minerals together to maximize the benefit of every mine development for both producers and local constituents (business owners, regional developers, and citizens).

Industrial minerals are important in all countries, making up the vast majority of global mineral production. Though often classified as waste by metal producers, their use could, where feasible, be a prominent CE strategy.

For example, Lafarge, a member of the global group LafargeHolcim, is Canada's largest provider of diversified construction materials employing 6,000 employees at 400 sites across the country. Their products include cement and aggregates, ready-mix and precast concrete, and asphalt. They also offer paving, construction, and waste management services through their subsidiary Geocycle. LafargeHolcim has enacted a net zero climate pledge[81] aiming to lead the industry in reducing carbon emissions and shifting towards low carbon construction. Aligned with their carbon-reduction ambitions, they are focused on three initiatives:

1. Raw materials recycling for cement production – scouring recycled waste resources for iron, silica and aluminum instead of using raw resources.
2. Thermal energy fuel bases – using construction and industrial wastes, such as shingles, tires, plastics, etc., as alternatives to fossil fuels for cement production and operations (in jurisdictions that allow it).

3. Closure solutions for ash and other sludge ponds, including use of the waste materials – working with customers needing solutions for full turnkey options to deal with contaminated soils treatment, materials transfers, management of responsibilities, and more.

Lafarge indicated that they are going beyond the traditional 3Rs practice by using a circular approach to business, and that approximately 20 percent of their profits are a direct result of the circularity projects already under way. A growing number of mining companies and large corporations have been working with them in the past 12-18 months regarding material solutions and new business developments.

4.2.4 Engagement, Collaboration and Partnership Considerations

The WBCSD asserts that CE business benefits include increased supply chain and resource security, additional value from products and materials, and mitigation of risk from volatile material prices and supply. With respect to the supply network and markets, this section discusses enabling CE activities:

- Engaging the supply network - being transparent and flexible;
- Engaging with local communities, Indigenous rights holders, regional planners and government; and,
- Applying systems-based, life cycle analyses.

In a recent North American Circularity in Mining session, Anglo American CEO Mark Cutifani stated:

> As a mining company, becoming a metals and mining company, and wishing to become a materials solution company, we're thinking about our business in every dimension... the importance of collaboration and partnerships is critical [with suppliers, customers, adjacent players]...overall we need to better understand and examine our markets and customers, as well as their customers and what expectations they're facing today and moving forward...This approach enables us to identify new opportunities be they within the existing mine products or in related areas where we can leverage existing core skills and capabilities or creating completely new business areas.

The investigation of CE opportunities should start with nearby mining operators, vendors within the upstream supply network, local stakeholders, and then with players in the downstream value chain. Most companies are already focused on efficiencies of operations and sourcing equipment and new technologies, including use of sensors and automated controls to adjust processes. All of these require engaging within the supply network or looking for new vendors who can meet new requirements. Some of the biggest potential gains, however, exist in local partnerships and on the downstream side of the value chain, in the segregation and development of secondary or tertiary products, or continued use of assets over the long-term.

Engaging the Supply Network – Transparency and Flexibility

Engaging specialists from outside the organizational workforce in a multi-disciplinary fashion can enhance the efficacy of systems changes targeting multiple goals for new business or performance models. Systems-based improvement opportunities can be missed if development projects are divided into discipline-specific work packages, with only selected information provided to each discipline.

An alternate way to start, after bringing together designers, process vendors, and equipment suppliers, is to be transparent - sharing with the group relevant targets, performance data and challenges, and then using a workshop approach. This transdisciplinary planning approach, where relevant experts interact, can help the group to find solutions that address multiple goals, unique opportunities for larger changes to the system and more beneficial strategies and outcomes than traditional approaches.

When redesigning a specific process, supply network vendors offer time efficiencies, are aware of new available technologies, and can provide support to find good-fit solutions.

Vendors working in mining may be able to leverage knowledge from other sectors and recommend assets and unfamiliar technologies that are suitable as is, or which might be adapted to meet new requirements, or to improve the system. Conversely, vendors working outside of the mining sector may offer technologies or expertise applicable to the mining sector but be unaware of this potential.

Mining companies can explore arrangements to share risk and costs with vendors who might offer newer, or new-to-mining, technologies that need further testing or in-situ validation. Given the potential opportunity to improve and showcase their technology within industry, technology developers may work with potential buyers to pilot and scale at reduced rates.

Engaging with Local Communities, Indigenous Rights Holders, Regional Planners and Government

It is now common that mining companies work closely with the host community so that their intentions for a project's development and operations do not come as a surprise. However, opportunities to build shared value outcomes in the proposed development are much greater if the stakeholders are engaged in the planning and decision-making process as early as possible. Social engagement ensures that all stakeholders are abreast of possible technical issues and that stakeholder views can be incorporated into the outcomes of technical assessments. Such direct involvement should be applied to new developments, when considering major changes to an operation, and when planning for closure of an operating mine.

Some opportunities may simply involve post-mining transfers of assets and/or supporting a transition from mining operations to new land and infrastructure uses. In other situations, there may be opportunities to partner throughout the mining operational life and co-develop business offerings:

- to maximize the utilization of extracted resources;
- to encourage synergistic use of equipment and material movement processes, employment and local economic returns; and,
- to share education, training and personnel development within a region.

Collaborative engagement with local communities and businesses, Indigenous rights holders, and regional planners allows for the identification of regional partnerships that benefit the local region and lower the cost of material exchanges requiring transport offsite.

Involving government in these engagements may help to identify and assess regulatory barriers early in the conceptual analysis phase. While governments support local economic development opportunities, they also need to ensure public safety and consider the capacity of public infrastructure to accommodate new industrial activities. If a regulation prevents project development, then its foundation should be examined. Advancing initiatives in compliance with related rules and permits should be explored.

For example, waste management regulations can be perceived to create barriers to the transfer from and/or use of waste materials off the mine site, however it may be possible to adjust the assessment and monitoring of the material characteristics prior to transfer off-site, or to reclassify the waste as a product for a particular application. Other barriers respecting the transfer of liability or shipment of such materials may only require that designated protocols for its mode of transport and/or chain-of-custody be met.

Neither are different than might be done for the sale and shipping of traditional products in the sector but require an extra step or two to process.

Engaging with Downstream Buyers and Potential New Markets or Partners

Some large consumer-facing manufacturers and raw materials buyers would prefer to source materials from responsible producers. A mining organization that has explored the full list of resources at hand, including those currently treated as waste, will be in a better position to turn risk or waste in to value, and to improve their responsibility rating. There may even be synergies between downstream manufacturers and mining companies that allow for a new approach to extraction and processing materials.

To assess a lean and circular approach to business, miners can engage with adjacent sectors such as: local artisanal-scale and small-scale producers; industrial minerals and specialty minerals producers; energy companies; the cement and construction industries; and, value-add parts/equipment producers. Looking further downstream to the *customers of mining customers* there is a growing number of manufacturers who are exploring 3D printing opportunities and locked-in contracts for raw-material supplies, especially with companies who can verify responsible operations. With appropriate development agreements, specialty minerals producers and technology developers may offer, or design, modular units that can be added to existing extraction processing systems. Exploration of these shifts could create a new set of opportunities for raw materials producers – either in the creation of new products or changes to processes on both sides of buyer-seller agreements, allowing more flexibility in product quality – or simply through guaranteed supply contracts.

4.2.5 Applying Systems-based, Life Cycle Assessments

Economic analyses comparing new technologies to existing systems require systems-based, life cycle assessments. Higher capital costs for new technology and slightly higher operating expenses may be balanced by reducing the costs of managing emissions or discharges in other parts of the site ecosystem or reducing longer-term legacy and/or rehabilitation costs. A new technology may be built to last longer or to allow more flexibility in maintenance and upgrades through plug-and-play components, also reducing maintenance and/or replacement costs over time. The residual value of the components after on-site usefulness has passed also factors in.

When considering equipment sharing, or product-as-a-service models, all associated costs (including maintenance, ongoing refurbishment/replacement, and mobilization/shipment costs) are to be compared to full operating costs of the existing units (including the costs of management, maintenance, and parts replacement).

Processing the waste material of an existing mine site compared to the development costs of a greenfield property – to produce the same mineral constituents – can generate savings.

Reprocessing existing, older wastes can eliminate costly remediation by geochemically and geotechnically stabilizing residuals. This will reduce liabilities and associated final closure costs and may create marketable "green" products.

Further, the cost of extracting residual value from existing waste materials, rather than from raw resources, may be greater if the feed has already been crushed and ground. This may be the case when only the capital costs are compared, but not when systems-based, life cycle, full-cost accounting[82] is considered. Using old possibly hidden waste materials as feed eliminates real costs of exploration, permitting, site development, pit or underground excavation, hauling and stockpiling, and comminution associated with new resources. These savings can offset a slightly higher cost of re-mobilizing stored materials and re-processing the older wastes. Also, processing wastes reduces the costs of risk management and reclamation, offsetting the costs of shipping lower-value new products.

4.2.6 Investor Readiness

The mining sector is undergoing an interesting phase of change within the finance and investor community. More and more investors are introducing mandatory ESG standards and/or shifting to "impact investments" (see text box below).[83] At the same time, project financiers who fund the exploration phases of junior miners with a focus on rapid investment returns are still in the picture.

Impact investing is an exciting and rapidly growing industry
powered by investors who are determined to generate social and environmental impact as well as financial returns. This is taking place all over the world, and across all asset classes.

This situation has juniors and new smaller-scale developers caught between a challenge and an opportunity. Juniors typically look for project financing from short-term investors and focus on the available resource as a starting point. Needing to prove the reserves in order to sell, they may not have costed longer-term ESG risks or mitigation measures in their analysis.

Alternatively, juniors intending to proceed eventually with operations have a longer-term view for their properties and may have ideas for an optimized system, which will create value from multiple streams. However, many early-stage financiers are either unwilling to take the risk, or unable to fund the "fancy" additions to the project over a longer period, until there are economic returns on the initial investment. Short-term investors may not recognize the potential net gain made possible over the longer-term with an operation's reduced closure, risk and liability costs despite increased upfront capital spending (e.g., retrofits required for installation of improved performance measures).

As a result, when a mining organization is dependent on external funding sources, investors focused on short-term returns force decisions based on standard financial models of net present value. Majors can alter their financial models to support a longer-term outlook on investment but the more agile and smaller scale developers can be restricted by conventional short-term investment return demands.

In this situation, opportunity lies in imagining different funding sources. If traditional mining financiers are unwilling to take a longer-term approach to support proposed circular strategies, the focus could shift to impact investors and, more directly, manufacturers and material users who need guarantees on the ESG or sustainability claims from raw materials producers. The benefit of seeking investment from the downstream value chain is that it will result in more secure partnerships for supply volumes over a longer-term, consistency of quality demands and performance expectations and agreement on value of product. The challenge in seeking downstream engagement in resource extraction projects is overcoming the industrial/sectorial silos that persist.

5. CE and Minerals: Drivers, Demands and Market Opportunities for Mining Companies

Society needs more mined materials to build a clean energy future, so the mining sector needs to expand its efforts to implement more sustainable and responsible practices. To address this conundrum in a way that solves for ecological, economic and social needs - and industry's commercial needs - there is a growing recognition of an integrated CE approach to the mining and minerals sector. It has the potential to create economic value throughout the minerals supply network, while reducing risk and harm to communities and ecosystems. These trends are reflected in growing market and investment pressures to address a range of environmental and social concerns.

This section outlines key trends that are driving change in the mining sector, how minerals supply chain actors are responding, and how some of these pressures and opportunities may be addressed using CE and related strategies. It will focus on key questions:

- How will increasing demands for minerals affect environmental, social and economic needs and concerns over the coming decades? (Section 5.1)
- How do CE practices address carbon emissions reduction imperatives while meeting growing minerals demands associated with green energy technology infrastructure? (Section 5.2)
- How can companies address growing ESG concerns through the application of CE strategies? (Section 5.3)
- How can these issues contribute to the achievement of the SDGs as a global framework for sustainability? (Section 5.4)

5.1 Demand in Mineral Markets and Social, Economic and Environmental Impacts

The current trajectory of population and economic growth, with its associated materials consumption, is sobering in terms of potential environmental and social impacts. Global materials use is projected to more than double from 79 Giga tonnes (Gt) in 2017 to 167 Gt in 2060 (Figure 7). Growth in demand for motor vehicles and electronics is driving significant increases in demand for certain minerals. In addition to these consumer market trends, the minerals required for the expansion of renewable energy generation, transmission and storage will result in unprecedented demand for minerals.

Over time, despite projections of lower material intensity in production, the use of metals is forecast to increase 1.5 times in OECD countries, triple in large developing economies and 4-fold in all other countries.[84] The use of metals is projected to grow faster than any other consumable material.

Recycling rates for metallic minerals are projected to grow faster than the relative growth in primary mining activities.[85,86]

CE strategies aim to "decouple" economic growth from materials use by capturing and extending the value of materials throughout their life cycle. Some encouraging trends: between 1980 and 2009, relative decoupling started to occur across all G8 countries. Canada, Germany, Italy and Japan consumed less materials during this period. In *per capita* terms, consumption decreased or remained flat in all G8 countries with most decreases made in Japan, Germany, Italy and Canada, respectively. Apart from biomass for food, agriculture and fossil fuels, absolute decoupling has taken place in all material groups, with wood, metals and industrial minerals experiencing the strongest decoupling.[87]

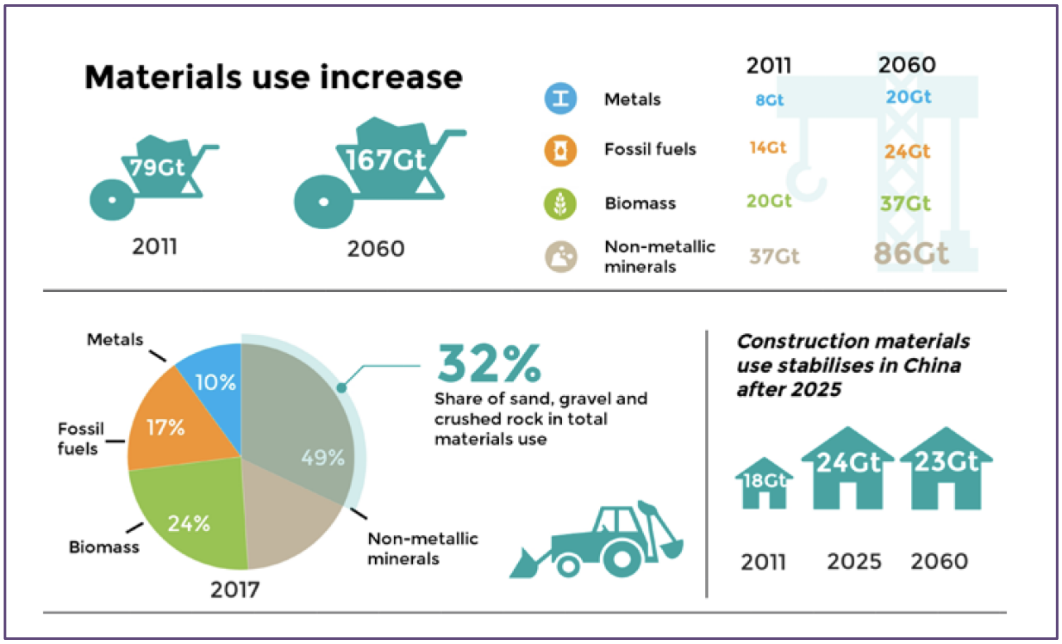


Figure 7: Materials Use Increase. Source: OECD (2019).[88]

These are encouraging trends, but more could be done to decrease consumption levels, address mounting pressures on planetary boundaries and achieve the economic potential inherent in CE systems.[89] Despite indicators of progress, between 2009 and 2017 Canada's material productivity (US dollars/kilogram total materials) lagged relative to other G8 countries, while its per capita consumption of materials is significantly greater. [90] [91]

Concurrent with increasing demand for minerals, a series of major tailings dam failures (including one in Canada), and conflicts concerning impacts on water, biodiversity and community health, have resulted in delays and cancellations of major projects around the world.[92] These issues, and limited economically feasible reserves for some essential minerals, lead to questions around stability of supply, and industry and government approaches to the social and ecological implications of this growth in minerals markets.

Figure 8 (based on Figure 2 but identifying more industrial activities) illustrates how mine life cycles present CE stewardship challenges and opportunities for both extraction-related *processes* and consumer-related *products*. While conventional extraction operations exert control over process stewardship, engagement with product stewardship strategies requires different kinds of partnerships and collaboration. Managed in an integrated way, these extra-mine site collaborations can increase returns, extend value and reduce liabilities throughout the full life cycle of mined materials.

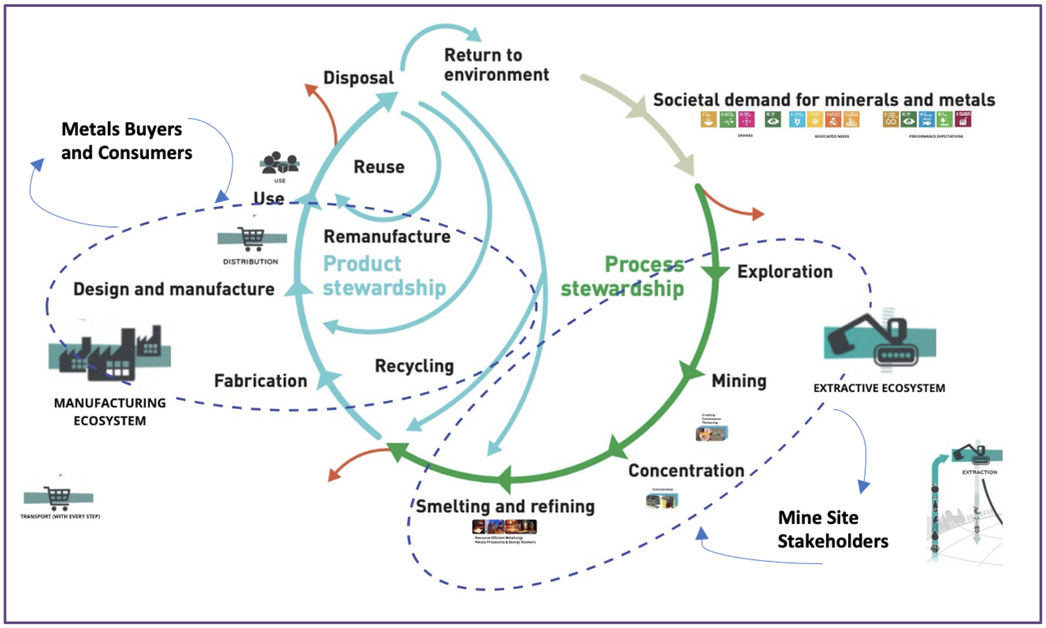


Figure 8: Main Life Cycle Stages for Minerals and Metals. Source: adapted from ICMM. (2006). Maximizing Value, Guidance on implementing materials stewardship in the minerals and metals value chain, p. 7 [93]

Measuring Progress towards a CE

The Circularity Gap Report: Launched in 2018, addressing the need for metrics to track trends towards CE objectives. The Global Circularity Gap Initiative has published annual reports on the materials flowing through and in (long-term) use by the economy. Metrics are based on rates of extraction, emissions, dispersal, waste and materials cycling. In 2020 the report found the global economy to be 8.9 percent circular, down from 9.1 percent in 2018. In addition to Global reports, a series of country and regional reports are now being undertaken including Quebec.

https://www.circularity-gap.world/global

5.2 CE Approaches and "Climate Smart" Carbon Reduction Imperatives for the Mining Sector

Addressing climate risk is a top priority for the mining industry. It is under pressure from governments, investors and consumers to develop strategies for carbon emissions reduction. According to McKinsey's Basic Materials Institute, many companies have set emissions-reduction goals, though below the broadly accepted objectives of nationally determined Paris Agreement goals. In theory, mines can fully decarbonize (excluding fugitive methane) through operational efficiency, electrification, and renewable-energy use.[94] They will do so in the context of increases in market demand for mineral commodities.

Mining is currently responsible for
4 to 7 percent of global GHG emissions. Scope 1 and Scope 2 CO_2 emissions from the sector (those incurred through mining operations and power consumption, respectively) amount to 1 percent, and fugitive-methane emissions from coal mining are estimated at 3 to 6 percent. A significant share of global emissions—28 percent—would be considered Scope 3 (indirect) emissions, including the combustion of coal.[95]

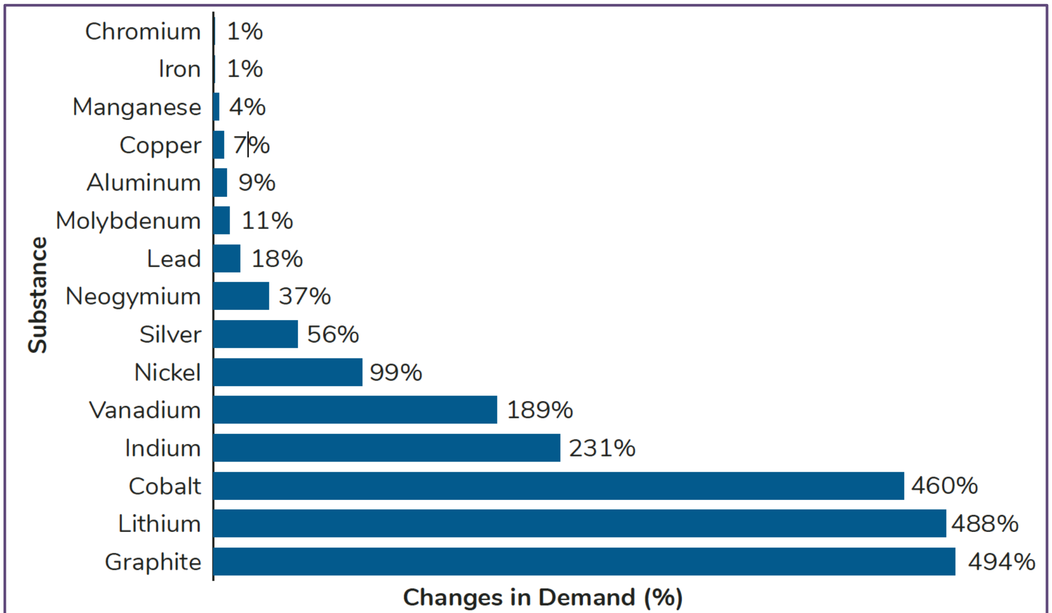
The World Bank's *Minerals for Climate Action: The Mineral Intensity of a Green Energy Transition* report concludes that the convergence of affordable, renewable energy systems, aggressive government commitments to carbon reduction targets and growing consumer demand will lead to a rapid and dramatic expansion of green energy generation, transmission and storage technology – and this will result in increased demand for minerals and metals.[96]

To highlight climate solutions, and to link these to mineral development, the World Bank has proposed a CE approach to address waste reduction, carbon emissions and socio-economic value generation.

5.2.1 The Need for More Minerals to Meet Green Energy Targets

Clean energy technologies, such as wind, solar and batteries, are *significantly more material intensive* than traditional fossil fuel-based energy systems.[97] In turn, production of minerals such as copper, lithium, cobalt, graphite, nickel and rare earth elements will need to keep pace if societies are to meet their renewable energy goals. The World Bank estimates that over 2.7 billion tonnes of minerals and metals will be needed by 2050 to deploy wind, solar, geothermal, and energy storage systems as required for achieving a below 2°C future. Figure 9 illustrates estimated growth in demand of various minerals.

Because unknown technologies may emerge (e.g., battery composition), demands on specific substances are uncertain and will vary over time. Minerals such as copper, chromium, and molybdenum are used in many clean energy generation and storage technologies so will not depend on a specific technology within the clean energy transition. Others, such as lithium and cobalt, are used for a limited number of technologies. Their future demand is less certain, being subject to technological disruption. Additionally, recycling to offset needs for primary metals demands could affect the projections for primary materials, as seen in Figure 10.[98]



Source: United States Geological Survey, 2019, and World Bank, 2020.

Figure 9: Changes in demand for minerals necessary for green energy transition 2018-2050
https://www.sciencedirect.com/science/article/abs/pii/S0048969719329869

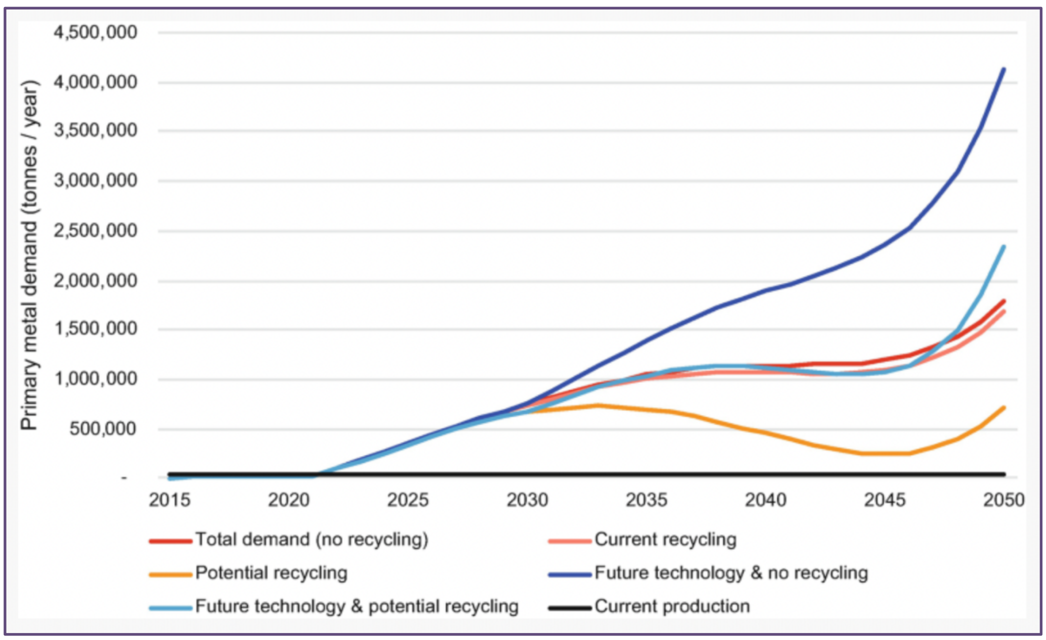


Figure 10: Annual primary demand from EVs and battery storage for Lithium. Source: https://link.springer.com/chapter/10.1007/978-3-030-05843-2_11#Fig8

Providing incentives for responsible, safe and efficient recycling, reuse, and refurbishment is a central part of the CE approach. However, even if 100 percent end-of-life product recycling is achieved, there still will be strong demand for primary minerals. It will be most difficult to offset primary source demands for materials like copper, lithium, silver and rare earths. Copper is widely used due to its high electrical conductivity and availability. Lithium, the key material in current battery technologies, only has limited recycling success from batteries that last ten or more years. Silver is used in 95 percent of PV panels and is not currently recycled due to the level of technical difficulty, though the industry is continuously increasing its materials use efficiency. Similarly, the rare earths, neodymium and dysprosium, are not currently recycled though R&D efforts are underway.[99] Substitution is possible but nearly all automobiles use these minerals. There are fewer challenges to reducing demand for primary metals in those commodities that have relatively high recycling rates globally (such as aluminum, cobalt and nickel) that can therefore more easily be substituted with other metals or technologies.

Technology and business model innovation in materials is growing as recovery and recycling are seen as economic and environmental priorities (see Section 6.2 Primary and Secondary Sources of CSM in Canada). Inherent technological challenges inform the projections of future metal demand from both primary and secondary sources.[100]

5.2.2 Demand for Clean Energy Minerals and Need for Responsibly Sourced Minerals

Civil society organizations recognize the imperative to build minerals-intensive low carbon energy systems of the future, and they have emphasized the need to deploy and integrate CE strategies, including recycling, to reduce both the total materials demand and the impacts of extraction.[101] They point to the opportunity and need to reduce overall materials demand by supporting and requiring greater mineral efficiency, through product and transportation system design, extended producer responsibility, and expanding re-use/re-purposing value networks. Regardless, this focus on efficiency and recycling cannot offset the growth of the need for primary metals to build clean energy systems.

Additionally, there is a call to government regulators, investors and downstream purchasers to prioritize the Critical and Strategic Minerals (CSM) extraction necessary for low carbon energy transitions over those that are not essential to meet carbon reduction goals (see Section 6.2).[102] Even for CSM, it is broadly recognized by industry and civil society that responsible sourcing will play a critical role in both protecting vital natural and social values, and improving the security of supplies of minerals critical to a renewable energy transition in both public and private sector supply networks.

As part of their *Climate Smart Mining* program, the World Bank outlined four key areas of innovation around carbon-specific mitigation and adaptation, impact reduction and market development (see Figure 11).[103] The Bank explicitly describes this integrated low carbon, zero waste model as reflecting the core principles of a CE strategy. These areas of innovation apply directly to mining operations with the potential to create savings – through efficiency and reduced liabilities and conflicts – and to generate new value through product development, expanded markets and investment access.[104]

The goal of Climate Smart Mining is

"the sustainable extraction, processing and recycling of minerals and metals… to secure supply for low carbon technologies by minimizing the climate and material footprints of these technologies throughout their value chain into an overall circular economy strategy for mining operations." [105]

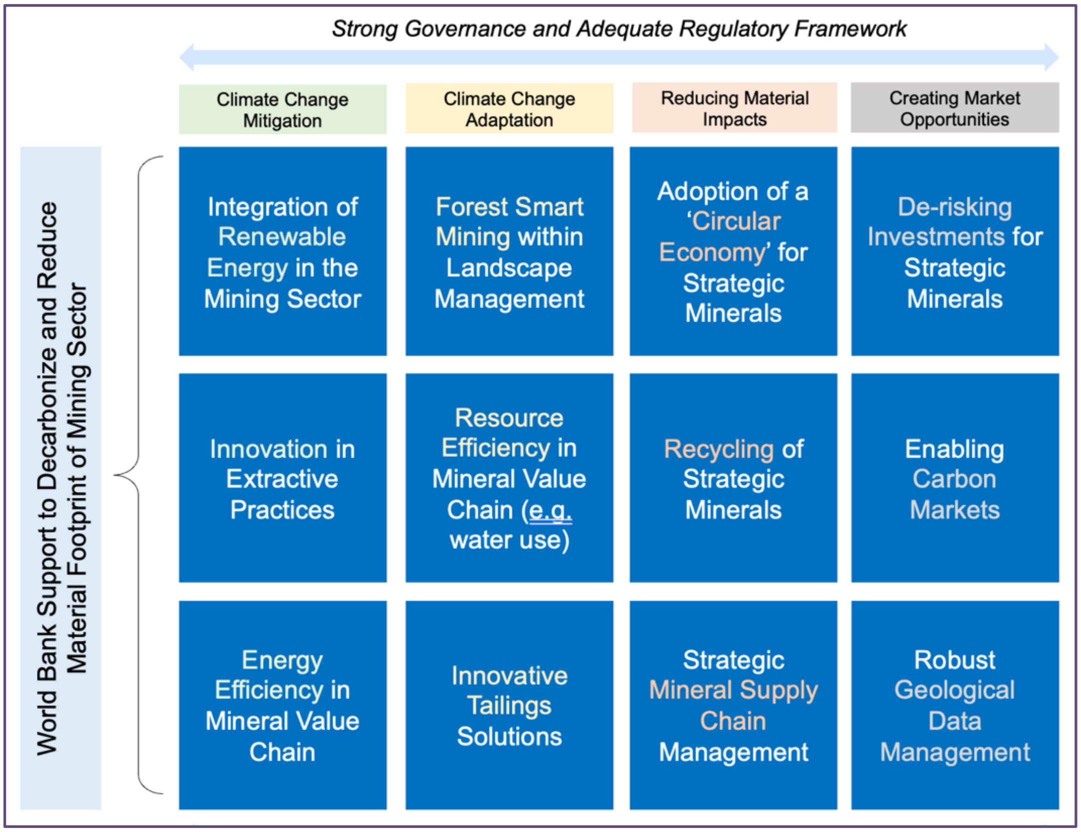


Figure 11: Building Blocks of Climate Smart Mining. Source: adapted from World Bank-IFC. 2020. Climate Smart Mining Initiative.

5.3 Link between Demand for Responsibly Sourced, Low Carbon Minerals and CE Mining Solutions

5.3.1 Market Pressures

Scrutiny around the environmental and social footprint of mining follows a trajectory that has been experienced by other sectors, including forestry, agriculture, fisheries and energy, wherein public criticism by Indigenous communities and civil society organizations is brought to the attention of extractive companies channeled through policymakers, consumer-facing companies and investors. Resulting market pressures then force, and ideally reward, leaders who adopt reforms to conventional industrial practices. These pressures for change have yielded gains in safety and resource efficiency and reductions in liability and project delays that benefit communities, ecosystem health and shareholders.[106]

Areas of concern, like carbon emission reductions, are causing market pressures for divestments and even the restructuring of companies in vulnerable commodity markets (e.g., thermal coal).[107] In early 2021, industry leaders stated, that:

> … intense pressure from environmental, social and governance (ESG) investors to meet climate targets will prompt imaginative efforts by big mining companies to dump, or greatly reduce, their exposure to their dirtiest, most carbon-intensive assets – mostly coal, oil and iron ore – commodities that are taking on pariah status after having powered two centuries of industrialization. [108]

5.3.2 Liability Concerns

Downstream market players and investors, along with civil society organizations and international agencies, have been engaging in dialogue and negotiations on improved performance as manifested in the Global Tailings Standard process.[109]

Several major institutional investors and pension funds are combining both mine waste and carbon liability concerns to assess investment risk in the mining sector. The Church of England Pension Fund, working with UNEP, Swedish National Pension Funds and a network of other investors on the implementation of the Global Industry Standards on Tailings Management, stated in March 2021 that they have "... *two strategic stewardship priorities, covering issues that will impact our members and the world they will retire into: climate change and extractive industries. These issues are inextricably linked and require systemic changes in the way companies operate, pension funds invest, and in how we steward our assets*." [110]

5.3.3 Responsible Sourcing

As consumer concerns about negative impacts from mining grow, possibly leading to stigmatizing certain products, there has been increasing interest in the idea of responsible sourcing of mineral products. Typically, these sourcing concerns are expressed through procurement policies that provide criteria and standards for suppliers to insure against specified impacts.[111] Responsible/ethical procurement strategies have been adopted by both public and private sector organizations and present opportunities for market differentiation for low impact operations.[112]

Early adopters seek to benefit from preferential access to emerging responsible sourcing markets and investment criteria, and to shape the nature of the dialogue around responsible practices in a CE for minerals. An illustration of industry response to applications of CE as a core business strategy is captured in the Quebec Mining Association's *Circular Economy Report 2020*.[113]

Changes in the way markets recognize and reward companies that can simultaneously solve for environmental and social concerns were projected in early 2021 by the iconic mine developer Robert Friedland. He foresees a longer-term shift in commodity pricing due to ESG and CE factors.

"What will be the impact?...

Cradle to grave, womb to tomb, or sperm to germ – the whole cycle is being analyzed. In a circular economy, mining has to reinvent itself as being part of that cycle and that means differential pricing and smarter markets… There will be no more one price for copper. There will be no more one-price for gold. Everything will be priced in relation to its ESG components..." [114]

5.3.4 Standards and Metrics

A key contributor to market pressures is the emergence of standards and metrics that allow companies to measure and report on progress towards reforms. There are no CE-specific standards for the extractives sectors yet but ESG standards of varying degrees of depth are integrated in a range of systems.

Mining-specific standards include the Initiative for Responsible Mining Assurance, MAC's "Towards Sustainable Mining" program, ResponsibleSteel, the Responsible Jewelry Council Certifications and many others (including those in the automotive and electronics sectors) which may focus on a particular commodity or issue of concern.[115]

The credibility and efficacy of the growing number of standards is being debated, but there is little doubt that ongoing scrutiny among buyers, investors and consumers will continue to drive industries, including the mining sector, to reduce waste, pollution, and carbon emissions and to improve performance on social issues in return for the associated expectation of preferential market and investment access.

An important issue for mining companies and downstream users of metals is to have standards that allow for efficient and effective reporting of verifiable performance metrics. Standards bodies are coordinating efforts to cross-reference and mutually recognize standards measurements to avoid duplication at the mine site and confusion in the marketplace.[116]

5.3.5 Minerals Supply Network Coordination and Value Retention

There is a convergence of concerns among downstream and civil society players related to mine waste, direct and indirect carbon emissions, and impacts on communities. CE framing presents potential advantages by addressing these concerns in a cost-effective, stable and efficient fashion with its focus on value creation, value retention and supplier partnerships. As the value of this systemic approach becomes better understood, more companies will brand their businesses as CE solutions.[117]

"Owing to buyers' sharper focus on sustainability,
miners will see demand increase for products that have been sustainably mined and that help customers reduce their emissions footprint. In a few cases, this might lead to a shift away from fossil resources and toward renewable materials, powerfully influencing how mining companies manage their mining and processing operations. This change also presents new opportunities—such as enabling miners to command increasingly large premiums... To better understand customers' sustainability needs, miners will need to engage with them in new ways, including in their marketing and sales approaches." [118]

5.3.6 From Mineral Extractor to "Materials Solutions Provider"

At a World Circular Economy Forum "Mining for Circularity" session event in October 2020, Mark Cutifani, the CEO of Anglo American, reflected on the business opportunity and industrial imperative represented by the CE:

> There is a strong rationale for us to engage with the circular economy that is strategic both from a planetary boundaries perspective and in order to support and accelerate our company's ambitions. Furthermore, our customers are demanding it ... If I look back over the years, we have characterized ourselves as a mining company, today we characterize ourselves as a metals and mining company, and tomorrow we could very well be categorizing ourselves as a materials solution company. [119]

Indicating momentum towards recognizing the value of a CE model for mining companies, even the venerable industry journal, *The Northern Miner,* has begun to explore the potential benefits of CE for minerals.[120]

In moving towards a future powered by "green metals", circular, closed-loop industrial models will become the norm. This shift invites the reimagining of the linear mineral extraction business as we know it. While raw extraction isn't going away any time soon, opportunities for new business models, including integrated materials companies, mineral solutions providers, and even closed-loop, metal-as-a-service offerings, will emerge. These are opportunities that mining companies are well-positioned to seize. Lose or acquire market share, disrupt ourselves, or be disrupted. The choice is ours.

5.4 CE and Sustainable Development Goals Relevant to Mining and Minerals

What are the SDGs*?*

In 2015, all United Nations Member States adopted The 2030 Agenda for Sustainable Development, which provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.

(source: https://sdgs.un.org/goals)

The minerals and metals industries contribute significantly to local and global economies and these materials are critical for achieving several of the SDGs. The connection between mining and the SDGs has been noted by the World Economic Forum, the Responsible Mining Foundation, and others. The ICMM analyzed the cross-cutting links between the SDGs and ICMM's *10 Principles for responsible practice*, which highlights the interrelationships between social, economic and environmental objectives.[121]

CE approaches align with the economic, social and environmental values objectives embodied in the SDGs. For example, achieving SDGs related to health and equality requires action on clean water and sanitation, affordable and clean energy, industry, innovation and infrastructure, and sustainable cities and communities. Implementing clean energy alternatives, water treatment and reuse/reduced use, regeneration of lands for growing food or ranching, and use of industrial minerals for building infrastructure, all contribute to achieving SDGs. However, these actions must also meet requirements of

SDGs for responsible consumption and production, climate action, terrestrial and aquatic life, and provide decent work and economic growth opportunities.

This complex interconnectivity of goals provides opportunities for socio-economic and environmental impacts, through choices in mine design and operations. See Table 3 for details on how circular strategies practiced in mining could impact the SDGs.

SDGs: DIRECT IMPACTS	LINKS TO MINING CIRCULARITY
SDG6: Clean water SDG14: Life below water	Mines reduce volume of withdrawals and impacts on clean-water resources and water bodies; treat and distribute clean water; protect and/or regenerate fish habitat
SDG7: Affordable & clean energy SDG13: Climate action	Mines reduce fossil fuel use and related emissions on site and in their supply chain activities; convert to renewable resources; partner with local remote communities to produce clean energy
SDG11: Sustainable cities & communities SDG12: Responsible consumption & production SDG15: Life on land	Material resources are conserved, wastes recovered and repurposed, excess materials are exchanged; systems-based solutions for long-term, shared, productive use of land, infrastructure, assets; regeneration of disturbed habitats
SDGs: INDIRECT IMPACTS	**LINKS TO MINING CIRCULARITY**
SDG1: End poverty SDG2: End hunger SDG3: Good health & well-being SDG9: Industry, innovation, infrastructure SDG16: Peace, justice, strong institutions SDG17: Partnerships	Preserving land access, addressing stakeholder concerns, inclusive planning and exploring synergies with agriculture, partnering to provide clean water or waste services, sharing infrastructure, keeping farmland pollution-free all support ending poverty and hunger, as well as good health and well-being, peace, justice, and strong institutions. Avoidance of environmental impacts and regenerative land-agriculture projects also facilitate good health and well-being, and local food provisioning.
SDG4: Quality education SDG5: Achieve gender equality SDG8: Decent work & economic growth SDG10: Reduced inequalities	Additional CE-related jobs, upskilling, reskilling, engagement of local businesses, leveraging local procurement/local value chains, creating collaboration clusters and horizontal linkages, and business development opportunities all facilitate local income and spending, reducing rates of poverty.

Table 3: SDGs and the Links to Mining Circularity

Lastly, and because circularity requires partnership and collaboration with others outside of the mining sector for maximum impact, positive impacts may be attributed to SDG17: Partnership for the goals.

Mining activities can impact many SDG outcomes because of the importance of the industry to the economy of many countries and the many ways and levels in which mining operations interact directly with people, land and water. There are opportunities to make a socio-economic and environmental difference through the choices made in mine design and operations (as measurable by the SDGs).[122]

The SDGs do not represent an additional set of requirements or norms for companies to follow. Rather, they provide a framework through which companies can demonstrate, via their integration and reporting activities, that they are managing the full range of mining-related economic and ESG issues in a responsible manner.[123]

The approach to sustainability through the SDG lens of "people, planet and prosperity" requires long-term thinking, partnerships, and strategic objectives that are integrated across the design, operation and supply network of the mine, consistent with CE principles and practices.

6. Government Policy and Regulatory Support for CE in the Mining Sector

Section 6 seeks to address a fundamental question within the context of mining and the CE and in this regard a question arises: what is the role of government? This question can be unpacked by examining current policies and identifying incremental steps that could advance CE.

Market and civil society forces continue to align around CE strategies while a number of governments are articulating policies that may help frame and support CE strategies for mining companies. Public sector initiatives can make important contributions to this transition by:

- Promoting and supporting research and innovation;
- Investing in infrastructure and market development;
- Convening and facilitating stakeholder collaboration and exchange; and,
- Coordinating trade policies (especially related to articulating effective outcome-based rules concerning the definition of waste versus resources).

Section 6.1 highlights policies and programs designed to help companies implement zero waste, low carbon CE strategies. It examines those that are linked with the political and economic context of the growing demand for responsibly sourced CSM associated with national renewable energy objectives.[124]

Section 6.2 touches on the status of primary and secondary production of CSM within Canada.

6.1 Existing CE Policies and Programs in Canada

As noted in the introductory section of this report, several regions have already made substantial investments and commitments in developing CE strategies to guide future economic pathways. The EU's comprehensive Circular Economy Action Plan,[125] the Nordic nations' regional CE collaboration,[126] China's extensive investments in CE policies and practices,[127] and the efforts of middle income (mining) nations like Chile[128] are all examples that Canada can draw upon to craft its own CE roadmap to serve its unique geographical, geological and demographic characteristics.

Canada is in the early stages of exploring the potential applications of CE strategies and has committed to hosting the World Circular Economy Forum in 2021.[129] There has been growing recognition of the value of a CE approach in forming an integrated economic and environmental strategy capable of simultaneously tackling inter-related challenges. This approach served as the basis for the Canada-wide Strategy on Zero Plastic Waste, released in November 2018 by the Canadian Council of Ministers of the Environment.[130,,131]

Elsewhere at the national level, key CE strategies are outlined in Environment and Climate Change Canada's pollution prevention plan (from design to materials substitution, waste recovery and upcycling).[132] These practices are not described formally as being part of a CE approach, but they are an example of an opportunity to weave existing policies into a coherent, integrated strategy that aims to optimize value from environmentally responsible practices.

In the mining and minerals sector, there are emerging opportunities associated with the need to link the green energy revolution with Canada's unique mining capacity and economy. This opportunity is captured as an element of the CMMP, with a significant emphasis, nationally and internationally, on expanding and securing supply chains for CSM.

At the provincial level, the Quebec government has taken the most aggressive approach to advancing a circular CSM development strategy[133] with an initial investment of $68M to build a business innovation hub for the rapidly expanding large-scale and EV battery market. This investment also supports advances in telecommunications, aerospace, renewable energy production, the medical sector and transportation electrification – all high-growth sectors in which the CSM supply is vital. Other mineral-rich provinces, like Newfoundland[134] and British Columbia,[135] are also working on developing green energy and mining development strategies that reflect core CE principles.

6.1.1 CE in the Canadian Minerals and Metals Plan (CMMP)

The CMMP has six strategic directions: 1) economic development and competitiveness; 2) science, technology and innovation; 3) advancing the participation of Indigenous peoples; 4) community; 5) environment; and 6) global leadership. Within the environment direction, the Plan advances several visions:

- Reduce the footprint of mining;
- Enhance closure and mine reclamation activities;
- Adapt the mining cycle to climate change; and,
- Introduce CE concepts to transform mining waste into useful products and reduce environmental liabilities.

While the fourth vision under the CMMP's environment direction concerns the MVFW initiative (see discussion next page), the CE concept (writ large) is presented in this report as an overarching, coherent and comprehensive framework that guides all efforts to improve the socio-environmental performance of the mining and minerals sector. More specific CE concepts, organized under technical and natural resources systems, are discussed in Sections 3.1 to 3.4.

The CMMP 2020 Action Plan *indicates that, as global demand for minerals and metals rises, so do expectations for minimizing footprints around industrial activities and their value chains. For Canada, this means translating the sector's innovation and expertise into solutions that allow Canadian operations to perform more efficiently and competitively around the globe.*
This requires fine-tuning our innovation ecosystem to better develop, demonstrate, adopt and export Canadian technologies, processes and services related to GHG and water reduction, energy efficiency, mining value from waste and site reclamation.[136]

A related area of program development has focused on extracting valuable elements from existing mine waste. The federal government established the MVFW initiative to advance the Canadian industry's ability to:

- Reduce mine waste environmental liability;
- Recover metal values from mine waste;
- Repurpose benign tailings residuals;

- Utilize mine waste as resources / by-products; and,
- Benefit from policy, tax and regulatory support.

An initial scoping and gap assessment were completed in 2019-20. CanmetMINING (NRCan) developed an implementation plan to address a range of variables including governance, policy and regulatory, research and technology, communications, and financial.[137] The MVFW initiative reflects the kinds of integrated strategies necessary to advance the CE objectives in the CMMP.

6.1.2 Critical and Strategic Minerals (CSM) in a Circular Minerals Economy

The need to advance and secure the mineral supply necessary for the renewable energy economy transition is closely tied to the growing international preoccupation with CSM. As noted in Section 5, there is increasing recognition that responsible mining is necessary to meet environmental, social and economic goals.[138,139] The opportunity presented by linking the interest in CSM with CE systems is that there is a focus on value-creation and supply chain efficiencies as an integral part of the commitment for environmentally and socially responsible mining. The explicit references to CE strategies by the World Bank's Climate Smart Mining Program, as outlined in Section 5.4.2, underscore the fundamental relationship of CSM and systemic CE approaches to their extraction and their management throughout associated supply networks.

Industry Perspectives on the Necessary Relationship between CSM and Responsible Mining

Without a sustainable and responsible critical mineral and metal manufacturing supply chain, Canada's competitiveness as a destination for advanced technology and manufacturing would be significantly diminished. Recent polling finds that almost 90 percent of those surveyed for MAC by Abacus Data like the idea of Canada being a preferred source for critical minerals and would like to see the government take steps to support this approach. (Source: Mining Association of Canada, re Critical Minerals)

Substances deemed "critical" and/or "strategic" vary from region to region, depending on government priorities. Criteria include substances that are essential for key sectors of the economy, that present a high supply risk, and that have no practical substitutes. "Strategic minerals" is a slightly broader category of material, deemed necessary for the implementation of key government policies. Focus for CSM has been around the EV and energy storage market, clean energy and renewable energy technologies, and defence technology.

National Focus on CSM Strategies

Domestically, CSM strategies and programs focus on geoscience and mineral exploration activities, research and development of mining technologies, and innovation and investment for minerals and metals processing and transformation. This taps into the growing international market for secure sources of critical and clean tech-enabling minerals and metals, while supporting and integrating Canada's growing clean technology and battery industries into global value chains.

Canada's List of Critical Minerals

The Government of Canada has developed a list of 31 minerals considered critical for the sustainable economic success of Canada and our allies and to position Canada as the leading mining nation, as set out in the CMMP.

(www.nrcan.gc.ca/our-natural-resources/minerals-mining/critical-minerals/23414)

According to the former Minister of Natural Resources Canada, Seamus O'Regan:

> Establishing the [CSM] list is an important step for Canada, especially as it can send a message about the country's intentions and priorities, especially reaching net zero emissions by 2050, to investors, and that its investment will ensure the country achieves its targets. "I think a huge part is signaling investors… it will only really happen sustainably and permanently and meaningfully if you harness the market, if you incent the market, if you incent investment. I think sending that signal is absolutely key. I know that there are a number of investors who have been waiting for that list and looking to it. (March 2021)[140]

Quebec has taken an ambitious and comprehensive approach to advancing a CE focused on CSM with their plan for the *Development of Critical and Strategic Minerals 2020-2025*.[141] Their strategy of supporting the transition to a lower-carbon economy seeks to deploy the province's value chains of CSM using the principles of sustainable development, social acceptability and wealth creation, including in local and Indigenous communities. In addition to geoscience and mining dimensions, the Quebec plan includes reclamation and recycling, and support for the CE projects applied to the CSM sectors.

Canada and the United States

Canada has been working with several nations on different aspects of CSM. In early 2021, CSM was featured in the Presidential/Prime Ministerial *Roadmap for a Renewed US-Canada Partnership*.[142] Notably, the two nations agreed to strengthen the Canada-U.S. Critical Minerals Action Plan which targets a net-zero industrial transformation, batteries for zero-emissions vehicles, and renewable energy storage, a primary objective of which is to build the necessary supply networks to make Canada and the United States global leaders in all aspects of battery development and production.

Canada and Other International Partners

Canada is working with the EU to advance the "Canada-European Union Comprehensive Economic and Trade Agreement Raw Minerals Dialogue" that seeks to reduce supply risks by promoting innovation and trade around critical raw materials, CSM, cleantech/clean growth, climate neutral economy, innovation, investment opportunities, and responsible (circular) business conduct.[143] In September 2020, the EU released an Action Plan on critical raw minerals looking at current and future challenges and proposed actions to reduce the EU's dependency on third party countries, diversifying supply from both primary and secondary sources, and improving efficiency *and circularity* while promoting responsible sourcing worldwide.[144]

Additionally, Canada and Japan are working to have critical minerals included in the Canada-Japan Energy Dialogue, and Canada is also cooperating with Australia on these issues to share best practices, set international standards and cooperate to support critical minerals supply and innovation leadership globally.

Global Battery Alliance

Other international initiatives in which Canada is participating include the Global Battery Alliance (GBA),[145] dedicated to developing a circular and sustainable battery value chain. Within the GBA, Canada is taking a leadership role in the Global Battery Passport that seeks to create a traceable value chain for EVs and batteries. The Passport will verify the origin of battery materials, disclose GHG footprints, work to extend battery life and promote recycling, all of which are consistent with an integrated CE approach. As part of this program, NRCan is working with Propulsion Québec (an industry cluster comprised of companies that are leaders in electric and intelligent land transport, research centres and groups, government departments and agencies, and industry networking partners) on a pilot project to test new technology capable of tracing minerals throughout a value chain.[146]

6.2 Primary and Secondary Sources of CSM in Canada

The attention by governments to CSM is heightened by Canada's unique, rich and diverse endowment of these minerals, which will be essential for the realization of carbon reduction targets and potential circular economies regionally, nationally and internationally. Canadian metals production currently draws on both primary and secondary (scrap and recycled) inputs. As interest and demand grows for resource efficient, zero waste, low carbon materials streams for various applications globally, Canada's capacity to expand and incorporate these secondary and primary materials streams in an environmentally responsible way will provide economic and environmental dividends.[147]

In terms of critical minerals for a green energy future, Canada already has a significant number of advanced projects, mines and processing facilities spread throughout the country.[148] The federal government recently commissioned a report on the status of primary CSM production in Canada, which includes an overview of the technical, policy and market challenges of bringing these materials into production.[149] The report highlights ways to support and accelerate production. Beyond the importance of having a well-defined and resourced "Critical Minerals Strategy," it will be important to have funding support for exploration programs, research and development, advancing the "circular use of critical minerals" (i.e., blending both primary and recycled sourcing), and boosting domestic refining and manufacturing capacities capable of drawing on domestic minerals supplies.

In terms of secondary sources, a P*reliminary Resource Recovery Report Card and Gap Assessment* was commissioned by NRCan in 2019 to estimate the recovery and recycling rates of selected materials and products, including metals, as part of an initial assessment of CE flows in Canada.[150] This report contained the following estimates:

- Canada produced 13.6 million tonnes of steel in 2018. About 4.8 million tonnes of purchased scrap were used in addition to 1.9 million tonnes of internally generated scrap for a total of 6.7 million tonnes of scrap steel. As with other commodities, the import and export of scrap steel is related to the location of facilities which use the scrap steel as feedstock. In some parts of the country, it is more cost efficient to import scrap steel from the US rather than transport it across Canada.

- From 2008 to 2018 the total amount of primary and secondary lead combined was between 250,000 to 270,000 tonnes/year. Of this, between 100,000 and 130,000 tonnes/year are from primary sources and 130,000 to 150,000 tonnes are from secondary sources.[151]
- For aluminum scrap, Canada exported 553,400 tonnes to the US and other countries in 2018. Over 100,000 tonnes of aluminum scrap were imported to Canada each year from 2016 to 2018. The amount of scrap aluminum which is collected and recycled domestically in Canada is not known and is a significant information gap.
- In 2018, Canada produced 304,000 tonnes of refined copper. Based on a recycled content rate of about 30 percent in the refined product, an estimated 101,000 tonnes of recycled copper were used by Canadian operations. Given that 109,720 tonnes of scrap copper were imported to Canada in 2018, at least this amount, and possibly an additional amount sourced domestically was used in copper production in that year. The total amount of scrap copper used from domestic sources is an information gap identified in the study research.
- The report estimates that 162,900 tonnes of zinc scrap were recycled in Canada in 2018.
- The estimated amount of nickel recycled in Canada in 2018 is 46,600 tonnes.

With population growth and market demand driving production and consumption of mineral-containing consumer goods, such as electronics, battery technologies, EVs and green energy technology, there will be a corresponding increase in the supply of end-of-life products. Arising from these increased material flows, there will be opportunities for the Canadian minerals industry to play a key role in the primary production and also in recovery, recycling and reuse through deployment of CE strategies nationally and internationally. Designing the most efficient and effective blend of private and public sector CE strategies represents a key challenge and opportunity for Canada. The NRCan 2019 report shows that there is already significant CE activity in Canada and large associated trade flows.

7. Building CE Capacity: Gaps and Recommended Next Steps

This report has provided an overview of market, policy and technology trends that are shaping the future of the mining industry. The convergence of growing carbon and industrial waste concerns with urgent demands for renewable energy systems and a call for more humane economic development (as outlined in the SDGs) has profound implications and provides opportunities for mining operations in Canada and around the world.

Progress has been made by mining companies and projects across Canada, and through programs such as the Canadian Mining Innovation Council, and Towards Sustainable Mining, but the application of best practices across the industry remains inconsistent and has not achieved the level of scale necessary to realize market benefits. This report has explored the potential value of scaling up common ESG and CE strategies in terms of the broader business case (Section 4.2) and market demand (Section 5.2).

Based on the review of current best practices and emerging business drivers, combined with interviews with mining and minerals sector leaders, there are three priority areas for support and capacity building that could advance the adoption of CE practices in Canada (Figure 12).

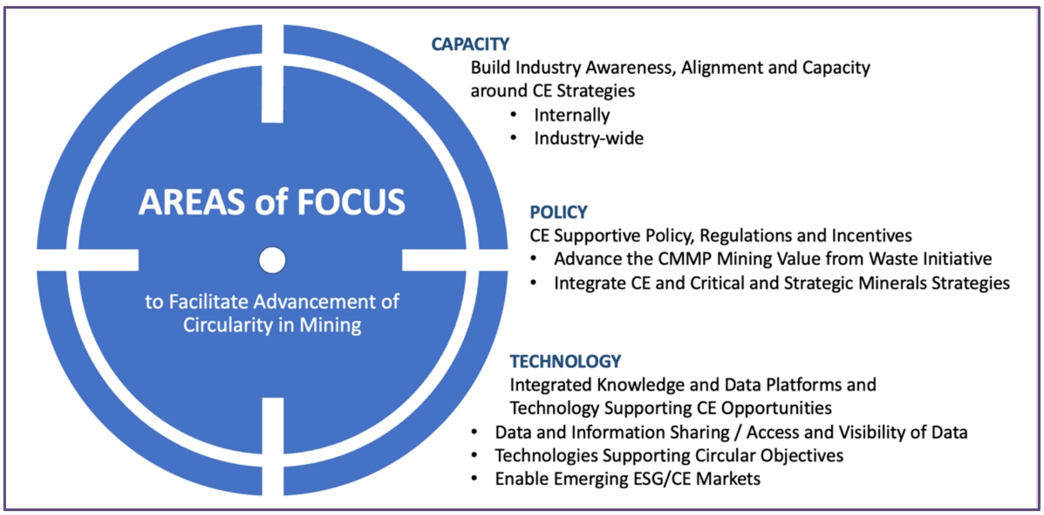


Figure 12: Three key areas where focused development will facilitate the advancement of circularity in mining. Source: MERG/Enviro Integration Strategies Inc.

7.1 Building Industry Awareness, Alignment and Capacity around CE Strategies

There are two big challenges in advancing the CE agenda within the mining sector. The first is to build awareness of the CE concept. How does it apply to the mining sector and what are its benefits? The second challenge is in changing the mindset and culture to meet new performance expectations, or even to operate under new business models.

This report has focused on highlighting what circularity in mining would mean, and ways in which the sector can participate in the CE. The information can help educate and engage industry and its workforce to identify and prioritize opportunities.

7.1.1 Internal Change

Organizational (or internal) change is key to advancing active exploration and implementation of CE strategies and tools. A number of related recommendations can be clustered into four broad areas, as follows:

Goals, Metrics and Incentives

- Decide on and formalize long- and short-term goals for circularity.
- Choose a point along the innovation ambition scale that the organization is ready for, and fully communicate those aspirations throughout the organization. Consider openly stating the aspirations, goals and/or specific objectives in a public capacity - on the company website, in sustainability reports, and in circularity forums. The more well known a company's intentions, the easier it becomes for others to connect and collaborate.
- Establish metrics that operators can use to guide thinking, to prioritize options, and to measure progress.[152]
- Link financial incentives to targets and apply them in such a way that all senior management, on-site managers and reporting employees can influence outcomes and realize incentives.

Awareness and Engagement

- Provide relevant CE educational materials to the workforce and help them see how they can make a positive impact. Mapping existing process flows and identifying potential sources of wastes can be valuable in this step.
- Engage and invite the workforce to use their imagination and generate relevant ideas within the scope of their own expertise. Bring multi-disciplinary groups together to "brainstorm" around a challenge. People often know exactly what can be adapted, and how easily, and the more that people feel ownership of changes selected for implementation, the greater the chances for success.

Resourcing and Evaluation Strategies

- Designate personnel to prioritize, investigate, and implement ideas, from small-scale, concepts to greater technological shifts. Organizational change does not happen if personnel are expected to work on such projects "off the side of their desk." Provide sufficient time to staff to support the establishment of connections within the CE network and to investigate opportunities.
- Undertake systems-based, LCAs to compare the new opportunities to existing strategies. Note also that dedicated financial resources for advancing such initiatives are necessary. Internal initiatives without sufficient funding will not advance.

Progress Tracking and Communications

- Highlight the progress of implementation, the potential for improvements shown by studies, and the benefits being realized by the organization from new CE strategies. Incremental steps add up. Celebrate successes and thank staff for their contributions to motivate by-standers or fence-sitters to join the effort.

7.1.2 Industry-wide Change

There are a few pre-competitive ideas that the mining industry should focus on to support and/or join the CE. These fall within the realms of resource evaluation, materials and assets classification, information sharing, and collaboration.

Resource Characterization and Evaluation for CE

With respect to resource evaluation, there is a tendency for miners and investors to recognize the value of a particular ore or commodity within a deposit, which then becomes the sole focus for assessing production and returns on investment. However, based on existing poly-metallic and poly-mineral operations, and waste evaluation studies showing valuable resources previously “left behind”, resource evaluations should be expanded to examine everything within the orebody. To quote Rio Tinto, "Understanding what is available at the beginning is crucial, which is something exploration in the past didn't look at. Once you understand what is in an orebody you can then tackle how to get it out.”[153]

Developers and investors should consider all the potential value within grasp, in feasibility studies or ongoing exploration, beyond the primary targeted commodity. This opportunity is of greatest significance for local partnerships and economic development around operations focused on internationally traded minerals, as discussed in Section 4.2.3. Given that lower-value industrial minerals always accompany metal mine operations, better characterization of the ore body early in the development process may help bring together large- and small-scale producers focused on diverse commodities. Doing so would maximize the benefit of every mine development to all producers involved, and to local constituents, including business owners, regional developers, and citizens.

Waste Classification and Inventory

With respect to formally recognizing mine wastes as resources, more work could be done to advance standardized schemes around materials and assets classification. There is a broad misunderstanding by the public, and in some cases within the mining sector, with respect to what mining “wastes” entail. A wide spectrum of types, characterizations and qualities of materials are handled within mining. Material designations include: concentrate, ore, low-grade stockpiles, mineralized waste; overburden and potentially acid-generating (PAG) or non-acid generating (NAG) waste rock; heap leach, rock and slag pads and piles; slurry, thickened and filtered tailings; backfill; sludge, slurries and solutions; in-process recyclables; anodes, cathodes, and bullion; process emissions and effluents; and others. This only covers the materials, not assets such as tools, parts, equipment, infrastructure, and lands.

For the purposes of maintaining safety in transport, proper containment and ultimate disposal, current waste classification guides focus mainly on identification of material source and type,[154] hazardousness[155] and/or level of radioactivity.[156] In addition, materials should be classified according to their mineralogy, geochemical and geotechnical characteristics (including safety risks such as chemical reactivity, e.g., potential for acid generation or metal leaching) and rheology (depending on its deposited state). Access to such information would allow others to identify potential uses for those materials. Similarly, assets that are no longer useful to an operator could be classified based on their life expectancy, age and current state of repair, record of maintenance, record of performance, etc. The metallic content of these assets can influence decisions regarding recyclability (e.g., nonferrous scrap is much more valuable than ferrous).

Establishing and applying consistent classification standards would allow for appropriate information sharing and for others to evaluate potential mineralogical value of residuals, to compare brownfield and greenfield opportunities, and to assess assets for their own investment, development or production circuits.

Mine Closure Objectives Guidance to Enable Future CE Strategies

For end-of-mine-life transitions or regenerative circular opportunities, it would help if there were a standard set of requirements, objectives and/or values established for different categories of land use. To date, there has been a lot of effort by organizations like MAC, ICMM and Landform Design Institute to create various closure-relevant support materials, including:

- Standardized closure frameworks;[157]
- Tools and guidance to engage and establish social transition and closure objectives;[158] and
- Engagement and integrated planning and design strategies[159] supporting the re-establishment of self-sustaining natural ecosystems.

These materials acknowledge a need for the identification of alternate land use opportunities, based on the influence of local communities, but they provide few examples of the objectives used. It would be beneficial to create guides, or to compile case studies that demonstrate how the objectives are used to advance social transition and different types of land use, such as has been suggested in a paper reviewing various uses for mining pit lakes.[160] A compilation guide would give organizations a starting point for imagination and dialogue.

Information and Lessons Sharing to Accelerate Learning

While not all companies will seek to pursue the potential opportunities and benefits associated with CE, among those that do there needs to be some alignment and recognition of the potential value of the CE and its place in the mining sector. If a broad understanding of CE can be established, then various actions can be undertaken such as information sharing, identification of opportunities, experimenting, pre-competitive technology development, co-development of mutually beneficial plans and the like.

Information sharing opens opportunities for synergy and collaboration. Several areas where increasing transparency can facilitate the industry moving forward include:

- Sharing successes with circular practices, strategies, and technologies. This can help others to see the value, validity, and proven paths to success and will encourage and facilitate others to move forward.
- Forming CE working groups for certain materials, or regional information exchanges to fast-track the identification of specific value opportunities and partners. This can be successful when members of the extended value and supply network, local communities and regional planners, and neighboring mines or non-mining operators are included.
- Encouraging active collaboration and integration wherever possible among CE mining initiatives across Canada and internationally. Groups focused on specific aspects of circularity within the mining sector, such as university-based research programs, technology development centres, and

industry focus groups, already exist. Mapping of and interaction with these initiatives should be actively facilitated.

- Exploring similar strategies applied in other industrial sectors (e.g., forestry, agriculture, cement and construction, wastewater management, petroleum, and nuclear sectors) can lead to valuable insights.

7.2 Towards CE Supportive Policy, Regulations and Incentives

There are reasons and ways for governments to accelerate the adoption of CE strategies and systems for mining operations. Public policy and regulations play a key role in enabling the potential value creation and liability reduction associated with applied CE practices. Government can assist by better understanding existing obstacles to innovation in mineral extraction processing, incentivizing investments in new technologies and practices, and encouraging CE through infrastructure support, network development, and procurement policies.

The inclusion of CE as an element of the CMMP represents an important opening that could be expanded beyond the current focus on tailings waste recovery and liability reduction. By employing an integrated CE framework more broadly, governments can leverage trends such as the growing concerns and interest around CSM and the increasing market interest in climate, environment and social performance measures.

7.2.1 Advancing Next Steps on the NRCan Mining Value from Waste (MVFW) Initiative

The first phase of NRCan's MVFW initiative revealed significant opportunities for recovering valuable minerals from existing tailings deposits. It also identified institutional and knowledge gaps and regulatory and financial barriers to realizing these potential benefits. As with other applications of CE strategies, effective implementation will require regulatory and policy, science and technology, economic and financial tools, and engagement and communications actions. A number of these steps were identified in the program's proposed implementation strategy as warranting further investment.

The establishment of a dedicated Circular Economy Secretariat with a multi-stakeholder technical committee would catalyze support for economically and environmentally beneficial activities at mine sites and could also provide a valuable integrated model for exploring and guiding other CE strategies for the mining sector. The MVFW initiative is a compelling example of a CE strategy that can expand economic returns for the mining sector, while reducing environmental risks for communities and ecosystems. At the same time, this kind of initiative can make a substantial contribution to national and international objectives to expand and secure supplies of CSM, which are often left behind as residual waste in conventional commodity extraction processes.

7.2.2 Greater Integration of CE and CSM Strategies

As noted in Section 6.1.2, Canada, the USA and other international partners have identified CSM as an urgent strategic priority in realizing a low carbon energy future.[161] It is recognized that access to CSM must be tied to meeting social and environmental objectives. This convergence of strategic needs and non-economic performance objectives suggests that an integrated CE approach to meeting CSM goals would make sense.

An important contribution to the Canada-U.S. Critical Minerals Action Plan will be to advance the MVFW initiative by: a) cataloging CSM stocks in mine waste; b) aligning regulatory conditions for safe extraction; c) addressing technological innovation needs; and d) supporting market development for the value of waste recovery resources.

Beyond the essential step of extracting CSM from existing mining wastes, there are unique challenges facing new CSM operations that could be better addressed with government support, as outlined in the following recommendations:

- Invest in geoscience to improve understanding of different deposits (including waste repositories) that contain high priority minerals.
- Support technological innovations (and associated value network partnerships) needed to commercially extract and refine the unique geological characteristics of CSM such as heavy rare earths, lithium and others.
- Use public funds to de-risk investments in new projects to attract a broader array of financiers to non-conventional mineral projects.
- Review and reform mining regulations to address existing barriers to operationalizing non-conventional extraction projects.
- Support better integration of primary and secondary source processing capacity and infrastructure to optimize the potential for producing CSM products for markets that combine both sources.

Quebec's integrated CSM supply chain strategy provides a good CE-oriented model for engaging public and private sector investors in these geoscience, technology innovation and green market issues. In addition to Quebec's ambitious CSM strategy, there are other CSM-targeted initiatives across government departments, both federal and provincial. An essential part of a successful strategy going forward will be breaking down silos between programs that seek to support green energy transitions, responsible market access, CSM supply chain security, and efficiency-oriented or clean technological innovation programs. A coherent, multi-factor, inter-departmental strategy that includes CE principles to solve these interrelated demands is needed. CE provides a strategically sound framework for accessing minerals for the future, as demonstrated by the range of CSM challenges and commitments.

7.2.3 Enabling Emerging Environmental, Social and Governance (ESG)/CE Markets

As discussed in Section 5.4, the convergence of metal buyers and investor demands for climate, environmental, social, and governance performance measures is framed by industry leaders through a CE lens, in part because of the value creation opportunities that are the focus of CE strategies.

To support industry's transition to a lower impact, higher value-creation/retention CE model, there are several things that governments can do to assist companies to adapt to and access these growing markets, which involve incentives, partnerships, policy integration and targets.[162]

Incentive Mechanisms

Incentives that can be deployed to encourage stakeholders to align their behaviours with a CE approach include:

- Green procurement policies;
- Targeted funding for CE products and services; and,

- Full cost accounting (re: externalities).

Partnerships and Collaboration

Partnership and collaboration between the private and public sector promote knowledge sharing, experimentation, and skills-building can advance CE via:

- Increased traceability and transparency of materials through CE supply chains;
- Pilot projects highlighting new relationships and technologies; and,
- Data platforms that:
  - consolidate CE information;
  - support technologies and participating stakeholders; and,
  - catalyze the exchange of materials and services throughout supply networks.

Fostering active CE networks will make CE more visible and contribute to relationship-building and creating communities focused on overcoming existing linear systems of exchange.

Aligning and Integrating CE into Mainstream Policies

Create new policies to guide CE actions and cross-reference existing mainstream economic, social and environmental policies to draw support from additional networks, expertise and budgets: these can encourage stakeholders to integrate relevant aspects of CE within their organizations and "connect the dots" (e.g., green energy, clean growth, climate action, and green mining).

Traceable Actions and Targets

To affect markets, CE policies should generate tangible results with traceable actions and hold stakeholders accountable for their progress towards agreed upon sector-specific objectives. Governments could ensure consistent monitoring of results and analysis of behavioural trends.

Having consistent and robust baseline data supports ongoing assessment of progress and the creation of near-term roadmaps and mechanisms to revise existing policies. This allows adjustments in response to the changing market, and thereby more effective implementation of CE policies, and informs long-term target planning for CE investment.

Work on CE metrics is in the early stages. Developing CE targets and indicators for the mining sector will be an important contribution to guiding investments and strategic priorities.

7.3 Integrated Knowledge and Data Platforms, and Technology Supporting CE Opportunities

The mining sector collects much data. A massive shift towards digitization of data to enable improved analysis of operational processes and decision-making in the "pit to product" value chain is underway. Organizations are also investigating the use of digital twins to assess and optimize design of future processing systems. These advances can serve to identify opportunities for reducing inefficiencies, optimizing re-circulation of resources, and reducing waste generation.

7.3.1 Information Sharing/Access and Visibility of Data

To enable exchanges of resources beyond the mine site, efforts should be made to collect and share information, with respect to available materials, infrastructure, assets and the demand or need for such resources. Posting such "buyer/seller" information to an integrated public domain would facilitate connections between owners and users of materials, including mining organizations, industrial mineral developers, specialty mineral producers, and other upstream supplier organizations, downstream value chain buyers, manufacturers, and regional planners.

Over the past couple of decades, there have been both national and regional efforts to compile and make data available in a digital format that can be manipulated. Data items include geographical, geological, land ownership, land use, habitat zones, environmental, information regarding exploration activities and operating and closed mine sites across Canada. For example, the Saskatchewan Mineral and Petroleum GeoAtlas site[163] utilizes ArcGIS software to allow users to view many combinations of datasets overlaying a map of the province. It is one of many tools that help developers assess the potential for developing mineral deposits. In addition, the National Orphaned and Abandoned Initiative (NOAMI) captures information to display the locations and closure risk states of inactive mine sites across most of Canada,[164] but information regarding the mineralogy, history of development or data to help determine potential for residual value at each property varies from site to site.

CanmetMINING has indicated there is an extensive consolidated database with significant tailings classification information but notes that there are data gaps on ownership, volume and tonnage. After this tailings inventory is updated, it will be used to identify priority sites for the MVFW initiative in collaboration with the provinces and territories. Investing in the expansion of this compiled dataset to include all mine wastes and tailings deposits in Canada, and information regarding other mine assets on each property, and then making it publicly available and searchable (with open-access for additional contributions by others) would enable several of the CE-related values described in Section 2.

7.3.2 Technologies Supporting Circular Objectives

To support networking and information sharing, it would be useful to include the following items in a consolidated database:

- Technology available to support CE processes (their capabilities and relevant applications, commercialized and proven at pilot scale);
- Technology in development;[165]
- Supporting research and researchers;
- Organizations interested and/or participating in CE strategies; and,
- Mapping of the ecosystem of stakeholders in CE, sortable by region, commodity, and service offering.[166]

In the absence of such information, operators could join innovation challenges, such as for lower-energy comminution or for tailings processing alternatives.[167] These challenges provide information and data to the public, paired with potential prize offerings, and an invitation to submit external proposals for new solutions to eliminate, reduce and/or stabilize wastes. Interestingly, if industry were to provide more information about the wastes and challenges they are managing, it might encourage technology developers to create solutions of their own accord and bring them to industry without major initiatives such as these.

Larger innovation consortia[168] are bringing together mining organizations, technology developers, researchers and solution providers to find solutions for "zero waste" or "zero carbon." In this collaborative ("pre-competitive") scenario, each participating company benefits by sharing the costs of research, development and commercialization of new technologies, while gaining insights and the advantages of multiple solution providers working together to solve a common problem.

7.4 A Summary of High Priority CE Solutions for the Mining Sector

This report has outlined a wide range of concepts and issues pertinent to CE for mining operations. Yet the path to CE can be embarked upon with just a few core principles and goals in mind.

- Break out of silo thinking on problem solving (carbon/water/tailings/wastes/social license) to explore and embrace a systems approach to solutions
    - This is key to unlocking new value generation.

- Catalyze new forms of collaboration among interested parties in the mineral supply ecosystem.
    - New value networks will be central to realizing the CE potential in the mining and minerals sector. These new relationships apply to both the industrial use of products and services for extraction, and the opportunity to feed new responsibly sourced materials into systems that are managing growth in demands. Some new value networks include:
        - new markets for waste products;
        - suppliers of products and services who can help monetize social and environmental objectives; and,
        - innovators who can re-design extraction and processing systems for critical minerals.

- Focus on using these tools and approaches to start to realize reductions in risks and impacts.
    - A fulsome suite of public policies and incentives will take some time to design and deploy. In the meantime, companies can re-examine conventional practices that generate waste and miss potential value, both on the mine site and with their upstream and downstream stakeholders.

Annex 1

The Evolution from Sustainable Development to the Circular Economy Concept and its Relevance to Mining

The main premise of circular economy (CE) and how it relates to associated concepts of sustainable development, resource efficiency and others has evolved in the last decade.[169,170]

Some of the initial ideas of CE emerged in the early 1960s with the environmental movement and concerns about pollution and waste and their impacts. The implications of these impacts on renewable and non-renewable resources were also important parts of the debate of this period and fed the development of new industrial and business frameworks that tried to translate concerns and theories into actions during the 1970s.

In the 1960s and 70s period, the concept of waste was framed in negative terms, focusing on ecological and social damages and associated costs. The emerging issues in these decades included the management of waste and the recovery of resources. Since solutions to deal effectively with waste and its impacts were not sufficiently embraced, this led to further developments during the 1980s and 90s, when waste as a resource started to receive serious consideration. At this time, new conservation-minded approaches began to be incorporated into a profitable (business) proposition. An example is the evolution of the concept of recycling from a charity and collection model in the 1960s and 70s to a business model, to subsequent decades in which recycled materials started to become a significant source of minerals. (See Section 5.2 for current rates of secondary (recycled) minerals in Canada.)

An important development in the 1980s was the emergence of the concept of Sustainable Development (SD) that tried to capture and address several disparate global environmental concerns from the 1960s and 70s. The concept of the triple bottom line, whereby strategic actions can simultaneously generate economic, environmental and social benefits, was one of the main advances that the SD concept delivered. Also, the idea of the interconnected relationship between different resources brought a new level of complexity to strategies to address global challenges. The SD concept framed those developments and related strategies in a new socio-economic model with a promise to allow both economic growth and a sustainable way of life.

The SD concept was translated into a formal international agenda in the early 1990s through the well-known United Nations *Agenda 21*[171] incorporating a broad range of political views globally but excluding any mention of the mining sector.[172]

Notwithstanding these lags in engaging the mining sector in SD discussions internationally, it is important to highlight the contributions of pioneering Canadian initiatives in translating mining-related principles into SD policies and practices. In the early 1990s, the multi-stakeholder Whitehorse Mining Initiative brought together a wide range of actors to negotiate a multi-faceted SD-related consensus *Accord*, which was the first of its kind globally.[173] Canada also played a leading role during the negotiations of the World Summit on Sustainable Development 2000-2002 which included the mining sector in its implementation paper.[174]

The mining sector was included in the implementation paper of Agenda 21
in 2002, almost a decade after its initial launch. This historical resistance to considering the mining sector as an economic sector contributor to SD resembles the situation today with the concept of CE in which the mining and minerals sector has received very limited attention relative to other sectors of the economy.

Unfortunately, evidence arising from the current state of environmental, social and economic considerations suggests that the ideas and approaches embodied in this first wave of SD were insufficient to arrest many of the core problems globally in a substantial way.[175,176] However, it has had the virtue of generating or causing the resurgence of multiple, parallel concepts such as zero waste and resource efficiency programs, extended producer responsibility, sustainable consumption and production movements, industrial ecology and green economy initiatives.

Where the mining sector is concerned, Canada has shown leadership in applying many of these concepts, and as early as 1996 was promoting both process and product life cycle analyses to encourage more holistic thinking about solutions.[177] These kinds of "green mining" innovations serve as a valuable platform for ongoing improvements. Individually and collectively, these tools and frameworks are important steps in the right direction. Nevertheless, there are two outstanding challenges: (a) they have not been consistently adopted across the sector, and (b) with a few notable exceptions, they tend to focus on efforts to increase the efficiency and reduce the harm associated with industrial processes within a predominantly linear economy. The result has been significant but fragmented and only partially has realized progress towards the goals of zero-waste, low carbon mining.

When it comes to the broader uptake and application of sustainable development and business ideas, there is still much work to be done.

As John Elkington, often credited with coining the term "Triple Bottom Line"
recently stated, "Clearly, the Triple Bottom Line has failed to bury the single bottom line paradigm." He suggested it be re-called for re-tuning as it failed to generate the kind of systems changes intended and needed.[178]

CE concepts have contributed to the maturation of SD strategies by focusing on integrated and systems solutions that address two needs: first, to move beyond the linear economic model; and second, to accelerate the decoupling of economic growth from materials use and environmental impacts. This ambitious and transformative approach requires markets, policies and technologies to undergo significant recalibration and strategic interconnection.

The term, "Circular Economy" was introduced in 1990 and gained traction in the mid-2000s as an umbrella concept capturing a range of tools under a unifying set of principles. The Ellen MacArthur Foundation played a central role in the development and promotion of the concept, in partnership with the World Economic Forum (WEF). Since that time, the term has been incorporated in national circular economic plans in Europe, China, and Latin America[179] and is a concept to be developed under the CMMP.

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