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PLANETARY BOUNDARIES, GLOBAL MATERIAL DEMAND AND THE EMERGING CIRCULAR ECONOMY: IMPLICATIONS FOR UPSTREAM RESOURCE PRODUCERS AND PRIMARY MATERIAL EXPORTERS

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Knowledge Synthesis Report:

Planetary Boundaries, Global Material Demand and the Emerging Circular Economy: Implications for upstream resource producers and primary material exporters

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Project Team

Principal Investigator: Geoff McCarney (University of Ottawa)
Co-Investigators: Manuele Margni (École Polytechnique de Montréal), Guillaume Majeau-Bettez (École Polytechnique de Montréal), Stephanie Cairns (Smart Prosperity Institute)
Graduate Research Assistants: Genevieve Donin (University of Ottawa), Geoffrey Lonca (École Polytechnique de Montréal), Nurul Hossain (University of Ottawa)
Contributors: Francois Saunier (International Reference Center for the Life Cycle of Products, Services and Systems (CIRAIG)), Shahid Hossaini (Smart Prosperity Institute), Sonia Patel (Smart Prosperity Institute)

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Executive Summary

Background: While in recent years climate change and biodiversity loss have been Canada's environmental policy priorities, globally these issues are increasingly seen as symptoms of a broader problem of overuse of resources (e.g. fossil fuels, biomass, construction materials, water, land and energy) and lack of attention to the impacts on the environment, such as pollution, this causes. The "Circular Economy" (CE) is a conceptual model that has begun to emerge in business, policy, and civil society discussions as a response to these challenges. At its ideal, the vision for a CE is one where the needs of an increasingly populous and wealthy global society can be met within the safe boundaries of key ecological systems and processes. CE thought leaders, such as the Ellen MacArthur Foundation, offer three core principles to enact this vision: i) waste and pollution are designed out the economy; ii) products and materials are kept in use; iii) natural systems are regenerated and enhanced.

Global government and business leaders (including the G7, G20, European Union (EU), Organisation for Economic Cooperation and Development (OECD), United Nations (UN), World Business Council for Sustainable Development (WBCSD) and World Economic Forum (WEF)) have all endorsed the vision for a more circular economy. For example, the European Commission adopted its first CE Action Plan in 2015 (and upgraded it in 2020) – including initiatives along the entire lifecycle of products promoting CE processes, fostering sustainable consumption, and ensuring that resources are kept within the EU for as long as possible. China (2008) and Japan (2013) also have active CE strategies and legislation, and new collaborations, such as one between China and the EU (announced in 2018) suggest a more comprehensive global vision.

While global research and policy interest in shifting to a CE are accordingly accelerating, early strategic thinking and policy development on the CE have been led by resource importing economies, and perhaps for this reason have a downstream focus on closing the loop for materials now flowing out of the economy as 'waste'. As a result, much of the international research focus has centred on the *consumption* side of CE, and popular visions of the CE increasingly focus on practices for reuse, repair, redistribution, refurbishment and remanufacture in downstream and product/consumer-markets. Primary resource sectors and producers have correspondingly been left on the periphery of CE research and policy discussions, as flows simply 'to be minimized'.

While reducing the flow and intensity of primary material inputs and waste generation in any given sector or region is indisputably a central tenant of an effective CE transition, the relevance of globally emerging CE policy discussions for economies with significant primary resource-producing sectors, such as Canada, but also many emerging economies in the Global South, is accordingly not well researched or understood. To date there has been little development of upstream CE visions or strategies for raw material producers or exporters, and little exploration of the implications of a future circular economy for the balance of supply and demand for key material resources and commodities.

Objectives: This project has sought to fill that gap, and to address increasing interest in knowledge and data generation around the implications for a shift towards more CE strategies in global markets for resource-producers. By reviewing both academic and grey (policy) literature, our knowledge synthesis attempts to initiate and inform a conversation about the role of primary natural resource-producing economies, and the mining, metals and minerals sector particularly, in an emerging global CE. In doing so, we hope to inform public discourse on the implications of global attention to the CE for Canada and enhance policy discussions to manage a Canadian CE transition amid the related challenges of growing global material demand, and the (likely significant) material demands of a low carbon economy, which will push the limits of resource production to remain with the Earth's carrying capacity.

Results: By reviewing and synthesizing both academic and grey literature on CE policies and approaches, as well as projections for global primary material demand, this project has attempted to focus on implications of emerging global CE frameworks for upstream natural resource producers – and particularly Canada. In doing so, our primary finding is that while CE policies may reduce demand for primary raw materials in some developed economies, a preponderance of evidence from international policy reports and projections, including from the World Bank (WB), United Nations Environment Programme (UNEP), the OECD, and other academic and policy literature suggests ongoing (and likely increasing) demand for primary metals and minerals over the coming decades, *even with increased circularity, and improved rates of material recovery, reuse, and recycling*. This understanding is driven by expectations of the material requirements for a low carbon transition, alongside projections of emerging economy material demands and realistic assessments of secondary material supply constraints in the near- to medium-term.

This finding opens a conversation about the role of primary natural resources in an emerging CE. By improving understanding of how a low carbon, circular transition may impact future primary material demand, this report begins the process of developing a better sense of the policies and practices that may be needed to support natural resource producing economies in an increasingly circular, materially intensive global economy. Indeed, a key finding of our review is that many industry players are already doing so – developing models of the mining and metals value chain to identify opportunities for CE interventions from the mine site all the way through to product end-of-life (EOL). However, this emerging understanding of the critical role to be played by primary material production in the global transition to a low carbon, circular economy is only an initial step. There is an urgent need for new research partnerships to develop a fuller picture of the real-world implications of a low carbon, circular economy transition for primary resource sectors and primary resource producing economies.

In particular, data availability and the development of analytical and modelling tools to support the kinds of analysis needed to transition to a CE in primary material production has been found to be a significant gap – limiting our current understanding of a CE transition in Canada. The issue of how to most effectively monitor progress towards CE is an emerging, and ongoing debate. As our findings illustrate, measuring the circularity of a system is challenging and there is no common agreement on how to capture the whole spectrum of CE strategies within one consistent assessment framework. However, in light of our review, we recommend considering the following aspects when measuring and tracking a Canadian CE transition: (1) keeping track of global Canadian material flows, (2) identifying the most strategic materials and sectors for the Canadian economy, and (3) designing circular scenarios to achieve optimal use of materials, including in primary production sectors, both in the extraction phase, all the way down the supply chain to product end of life.

Key messages: Without question, broad implementation of a CE will bring new and different challenges for Canada's economy – particularly our natural resource sectors. The findings of this initial exploration and knowledge synthesis of the implications of a CE for upstream resource producers and raw material exporters will be important to counter fears that raw material production has no place in the vision for a circular, resource efficient economy. A CE will favour durable, reusable, recyclable and/or compostable materials, and correspondingly will likely increase demand for strategic raw materials that better accommodate product designs to meet these requirements. Identifying policies and strategies to increase innovations for improved recycling, recovery, quality-assurance and traceability of primary resources will be necessary to take advantage of the opportunity presented by increasing demand for material resources for low carbon technologies, while ensuring the competitiveness of primary resource sectors in an increasingly circular value chain. A key recommendation of this work is the need for new research and partnerships to outline a Canadian, resource-based economy lens to contribute to emerging global thinking about a CE transition.

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Background & Objectives

The circular economy (CE) is a conceptual model that has begun to emerge in business, policy, and civil society discussions as a potential response to emerging global challenges of unsustainable resource use, and the environmental impacts (including emissions and other environmental degradation) that this causes. At its ideal, the vision for a CE is one where the needs of an increasingly populous and wealthy global society can be met within the safe boundaries of key ecological systems and processes (Rockström et al. 2009). Building on various schools of thought, including industrial ecology, life-cycle accounting, material footprint analysis, performance economy, biomimicry, and blue economy (Raufflet et al. 2019), the CE aims to close-the-loop on linear systems, minimize waste throughout the supply chain, and optimize material use (Lacy & Rutqvist 2015), offering a path forward into a world where economic growth and environmental degradation are decoupled (OECD 2018). CE thought leaders, such as the Ellen MacArthur Foundation, offer three core principles to enact this vision: i) waste and pollution are designed out the economy; ii) products and materials are kept in use; iii) natural systems are regenerated and enhanced (EMF 2017).

The circular economy's appeal lies in its broad value proposition, which promises benefits for the economy and business competitiveness, as well as new solutions for many of today's most challenging environmental concerns. For example, the communiqué from the 2017 G7 meeting in Bologna highlighted that there is strong evidence that the CE "can be a major driver to attain economic growth and employment and can bring about environmental and social benefits together with long-term economic competitiveness and prosperity" (G7 Environment Ministerial 2017). In this regard, it has been estimated that adoption of circular economy models could avoid the loss of up to US$4.5 trillion of global economic growth by 2030 and as much as US$25 trillion by 2050 (Lacy & Rutqvist 2015).

Recognizing these possibilities, international organizations, governments and business leaders including the G7 (2017), G20 (2017), European Commission (EC 2015), Organisation for Economic Cooperation and Development (OECD 2018), United Nations Environment Programme (UNEP 2011), World Business Council for Sustainable Development (WBCSD 2017), and World Economic Forum (WEF et al. 2014) have endorsed the vision for a more circular economy. Today, the CE is rapidly gaining traction and popularity in jurisdictions worldwide. For example, the European Commission adopted its first Circular Economy Action Plan in 2015, which was then upgraded to a newer and more ambitious plan in 2020 (EC 2020). The new plan announced initiatives along the entire lifecycle of products, promoting circular economy processes, fostering sustainable consumption, and ensuring that resources are kept in the European Union (EU) for as long as possible. Following suit, several member countries such as the Netherlands (2016), Finland (see SITRA 2016), Scotland (2016), and France (2017) have also created comprehensive CE roadmaps and strategies. See Table 1 for details.

The CE is also advancing in several Asian countries. Japan passed its Basic Act on Establishing a Circular Society in 2000, which guided the move away from mass production, mass consumption, and mass disposal; and led to the development of laws for individual waste and recycling (see Japan 2013). In order

Table 1: Summary of Selected National/Regional CE Roadmaps and Strategies

Jurisdiction	Description	Priority Sectors Identified
European Commission	"The Circular Economy Action Plan" was released in 2020. It aims at accelerating the transformational change required by the European Green Deal, while building on circular economy actions implemented since 2015. The plan presents a set of interrelated initiatives to establish a strong and coherent product policy framework to make sustainable products, services and business models the norm and transform consumption patterns so that no waste is produced in the first place.	• Electronics and ICT • Batteries and vehicles • Packaging • Plastics • Textiles • Construction and buildings • Food, water and nutrients
Netherlands	"A Circular Economy in the Netherlands by 2050" was released in 2016. With the aim of developing a circular economy in the Netherlands by 2050. The document outlines five instruments to meet these ambitions: fostering legislation and regulations; intelligent market incentives; financing; knowledge and innovation; and international cooperation. It also sets an (interim) objective of a 50% reduction in the use of primary raw materials (minerals, fossil, and metals) by 2030.	• Biomass and food • Plastics • Manufacturing industry • Construction sector • Consumer goods
Finland	"Finnish road map to a circular economy 2016–2025" was released in 2016 with the goal is to make Finland a global leader in the circular economy by 2025. The road map lists several targets spanning economic, environmental and social dimensions. It also outlines policy actions, key projects and pilots to promote these targets. In 2019, an updated roadmap was released with four strategic cross-sectoral goals: competitiveness and vitality; transfer to low-carbon energy; natural resources and guiding consumer decisions.	• Sustainable food system, • Forest-based loops • Technical loops • Transport and logistics • Joint national actions
Scotland	"Making Things Last - A Circular Economy Strategy" was released in 2016, building on the progress made on zero waste and resource efficiency agenda. The strategy outlines ambitions for waste prevention; encouraging eco-design; increasing product reuse, repair and remanufacturing; improving recycling rates; creating a unified framework for Expended Producer Responsibility; efficiently using biological resources; bring about behavior change, developing new skills; and improving measurement indicators.	• Food and drink, and the broader bioeconomy • Remanufacture • Construction and the built environment • Energy infrastructure
France	"The Roadmap for a Circular Economy" was released in 2018. The roadmap outlines 50 measures that ultimately aim to deliver better production, consumption and waste management. Amongst other goals, the roadmap aims to reduce natural resource use by 30% in relation to GDP between 2010 and 2030.	▪ Not specified
Japan	The "Circular Economy Vision 2020" was released in 2020 to encourage Japanese companies to exercise their strengths in mid to long-term industrial competitiveness. It aims to help Japan shift to new business models with higher circularity and resilient resource circulation.	▪ Not specified
China	China's "13th Five Year Plan" (2016) included CE strategies as part of an effort to promote efficient, intensive resource use. Specific CE targets included upgrading 75% of national and 50% of provincial industrial parks to promote circular operations and encouraging recycling of urban waste, resource management in industrial parks, and waste trading. China's "14th Five Year Plan" (2021) also includes emphasis on increased resource use efficiency through reduction and resource recovery; and accelerate building of systems for recycling old materials.	▪ Not specified

to keep this law relevant, the Plan for Establishing a Circular Society is reviewed and updated approximately every five years. In 2009, China's Circular Economy Promotion Law came into effect. This law aimed to achieve sustainable development by raising resource utilization rates and increasing resource recovery in production, circulation, and consumption (see Peoples' Republic of China 2008). China's 13th Five-Year Plan, released in 2016, re-emphasized this focus and included a goal to implement more circular development, encourage the circular use of resources between production and society, and accelerate efforts to recycle resources from refuse, while its recently announced 14th Five-Year plan (2021-2025) continues to outline a pathway towards green, low-carbon, and circular economic development (See Peoples' Republic of China 2016 & 2021, respectively).

Given these emerging efforts, initiatives are also underway to accelerate the adoption of CE practices on a global scale. In 2018, China and the EU signed a Memorandum of Understanding on Circular Economy Cooperation to align key mechanisms and work towards creating the building blocks for circular product standards and policies (EC 2018). Meanwhile, in academia, an international collaboration of researchers from the EU, China, and the US has recently called for new research and policy efforts to "globalize" the CE (Geng, Sarkis & Bleischwitz 2019), while studies are also beginning to investigate the international supply chain implications of the emerging CE policy frameworks summarized above (Nechifor et al. 2020). Several countries have also recently announced new national plastics pacts which aim to implement solutions towards a CE in plastics as part of an aligned response to plastic waste and pollution coordinated through the Ellen MacArthur Foundation's Plastics Pact Network.[1]

While global research and policy interest in shifting to a CE are accordingly accelerating, this review highlights that early strategic thinking and policy development on the CE have been led by resource importing economies, and perhaps for this reason have a downstream focus on closing the loop for materials now flowing out of the economy as 'waste'.[2] Thus, much of the international research and policy focus has centred on the *consumption* side of CE, including, for example: (i) how consumption-based measures of resource-use relate to issues of resource efficiency and productivity (e.g. Wiedmann et al. 2015; Bleischwitz 2010); and (ii) the drivers of resource demand and material productivity across nations (e.g. Steger & Bleischwitz 2011). Similarly, the EU's monitoring framework for a CE provides an example where the majority of indicators are focussed on policies, practices and outcomes for production and consumption, waste management, and secondary raw materials – as well as broader innovation and competitiveness outcomes in these sectors (Table 2). As a result, popular visions and conceptions of the CE increasingly focus on CE practices in downstream and product/consumer-markets. The CE's relevance or application to primary resource sectors, and primary resource producers, has largely been overlooked.

Without question, broad implementation of a CE will bring new and different challenges for resource-producing economies, including the Canadian and North American natural resource sectors, as well as primary resource producing economies in the Global South. Reducing the flow and intensity of primary material inputs and waste generation is indisputably a central tenant of an effective CE transition, and this

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[1] At the time of writing, countries which have joined the Plastics Pact Network included Canada, Chile, France, Netherlands, Poland, Portugal, South Africa, United Kingdom, and USA. The EU also has a regional plastics pact. For an updated list, see: https://www.ellenmacarthurfoundation.org/our-work/activities/new-plastics-economy/plastics-pact

[2] While CE roadmaps have recently begun to emerge from net resource exporting economies, including Chile (2020) and Australia (2021), these roadmaps maintain a primary downstream focus on reducing consumer and household wastes, innovating in design and manufacture, and improving recycling rates and secondary material use. Finland (see Table 1) may be the lone exception, including mention of forest-based loops, and including reference to minimization of environmental impacts from mining – although without specific details or targets.

Table 2: Classification of the EU CE Monitoring Framework Indicators

Classification	Focus	Indicators
Production & Consumption	EU Self-Sufficiency for Raw Materials	• Net Import Reliance (%)
	Green Public Procurement	• Share of public procurement measures above EU thresholds which include environmental elements
	Waste Generation	• Generation of municipal waste per capita (Kg per capita) • Generation of waste excluding major mineral waste per GDP unit (Kg per 1000 Euro) • Generation of waste excluding major mineral wastes per domestic material consumption (%)
	Food Waste	• Waste generated in the production, distribution, and consumption of food (million tonne)
Waste Management	Recycling Rates	▪ Recycling rate of municipal waste (%) ▪ Recycling rate of all waste excluding major mineral waste (%)
	Recycling/Recovery for Specific Waste Streams	▪ Recycling rate of (i) overall packaging, (ii) plastic packaging, (iii) wooden packaging, and (iv) e-waste (%) ▪ Recycling of biowaste (kg per capita) ▪ Recovery rate of construction and demolition waste (%)
Secondary Raw Materials	Contribution of Recycled Materials to Raw Materials Demand	▪ End-of-life recycling input rates (%) ▪ Circular material use rate (%)
	Trade in Recyclable Raw Materials	▪ Imports from non-EU countries (tonne) ▪ Exports to non-EU countries (tonne) ▪ Intra EU trade (tonne)
Competitiveness and Innovation	Private Investment, Jobs and Gross Value Added Related to Circular Economy Sectors	▪ Gross investment in tangible goods (% of GDP) ▪ Persons employed (% of total employment) ▪ Value added at factor cost (% of GDP)
	Number of Patents	▪ Number of patents related to recycling and secondary raw materials

Source: Adapted from Eurostat: Circular Economy Indicators (https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework)

is reflected in specific targets and objectives for resource efficiency, reuse, and virgin material reduction included in many of the CE roadmaps summarized in Table 1. China, for example, targets a reuse rate of 72% for industrial solid waste, while the Netherlands sets an (interim) objective of a 50% reduction in the use of primary raw materials (minerals, fossil, and metals) by 2030 and France aims to reduce natural resource use by 30% in relation to GDP between 2010 and 2030. Despite the clear implications for primary material markets suggested by these targets from major resource importers (including China and the EU), the relevance of globally emerging CE policy discussions for economies with significant primary resource-producing sectors is not well researched or understood. While to date there has been little development of an upstream circular economy vision or strategies for raw material producers or exporters, and little exploration of the implications of a future circular economy for the balance of supply and demand for key material resources and commodities, the potential impact could be significant, as reduced primary material demands interact with changing material commodity prices (e.g. see Nechifor et al. 2020).

As an initial contribution to begin filling this gap, this paper aims to provide a preliminary discussion on primary materials and resource producing economies in the emerging CE by investigating the implications for upstream resource producers and primary material exporters. The goals of this exploratory paper are threefold:

1. To link the role that primary material production plays in addressing material security into the emerging narrative and global vision of a CE.
2. To examine the potential implications of a future circular economy for market demand for key primary material resources and commodities.
3. To explore the role of circular economy strategies and practices in improving environmental and economic outcomes in primary material production sectors and prioritize next steps.

The review proceeds as follows: the first section will explore current models and representations of the CE, to try and develop an understanding of how primary resource sectors are currently reflected and integrated in CE frameworks and narratives. From there, we will examine recent projections of primary vs. secondary material demand in the coming decades, in an attempt to evaluate the feasibility of decoupling demand from primary resource use in an emerging CE. The third section will then explore models and frameworks for integrating primary resource extraction, and particularly the mining and metals sector, into existing CE models – to try and bridge the short- to medium-term resource demand gap that emerges in our review (even under assumptions with rapid scale-up of secondary material use). The fourth section will explore more specific options and examples to advance CE adoption in the mining and metals sector, while the fifth section will review existing indicators, modelling approaches, and tools needed to monitor and inform progress towards a CE. Finally, we will conclude with a summary and suggestions for next steps and research priorities.

Outcomes

Current Models of the Circular Economy (CE)

While the CE is a sufficiently broad concept that it offers the flexibility to be applied differently in different contexts and can accommodate a broad range of policy objectives, most of the early movement and strategic thinking on CE has come from net resource importing economies (see Tables 1 & 3). For example, while European industries consume more than 20% of the metals mined globally, European mines only produce a fraction of the global mineral supply (e.g. 1.5% of iron and aluminum and 6% of copper) (Vidal, Goffé & Arndt 2013). Moreover, of the 30 materials listed as critical raw materials for the EU, a majority are imported from non-EU countries.[3] Japan is also highly dependent on imports of critical raw materials. While Japan's material footprint in 2017 was 26 thousand kilograms per capita (not far from the OECD-

[3] European Commission: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

Table 3: Top Net Material Importers & Exporters (2017 Physical Trade Balance)

Largest Net Material Importers			Largest Net Material Exporters		
No.	Country	Net Imports (million tonnes)	No.	Country	Net Exports (million tonnes)
1	China	1,949	1	Australia	1,360
2	Europe	1,093	2	Russian Federation	707
3	Japan	634	3	Brazil	508
4	India	426	4	Indonesia	421
5	South Korea	417	5	Saudi Arabia	339
6	Germany	249	6	Canada	289
7	Singapore	156	7	Norway	171
8	Italy	145	8	UAE	160
9	United Kingdom	134	9	South Africa	146
10	Turkey	129	10	Kazakhstan	143
11	France	122	11	Qatar	138
12	Netherlands	98	12	Mozambique	117

Source: Author's Compilation. Data on physical trade balance obtained from UN Environment Programme, International Resources Panel. Global Materials Flow Database (https://www.resourcepanel.org/global-material-flows-database)

total of 24 thousand kg/capita), its domestic extraction used was only around 4 thousand kilograms per capita (much lower than the OECD-total of 14).[4]

Similarly, while China is the dominant global supplier of rare earth elements,[5] it is also on balance a net resource importer, and its approach to CE has been broadly focussed on material security and the environmental challenges created by rapid growth and industrialization (Peoples' Republic of China 2021). Specifically, this has included detailed coverage of specific downstream sectors, with CE measures meant to increase efficiency and secondary material usage in order to address concerns around waste and pollution outcomes in manufacturing (McDowall et al. 2017).

Given that the European Commission and countries such as China, Japan, and several EU-member states have taken the lead in adopting CE strategies and approaches, it is unsurprising that emerging global discussions around the CE have reflected these actors' specific interests and needs. As net resource importers, these countries have much to gain from increasing the number of times materials flow through their economic systems before final disposal. For instance, it is estimated that by following CE principles,

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[4] Organisation for Economic Cooperation and Development (OECD): https://stats.oecd.org/
[5] Natural Resources Canada (NRCan): https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/rare-earth-elements-facts/20522

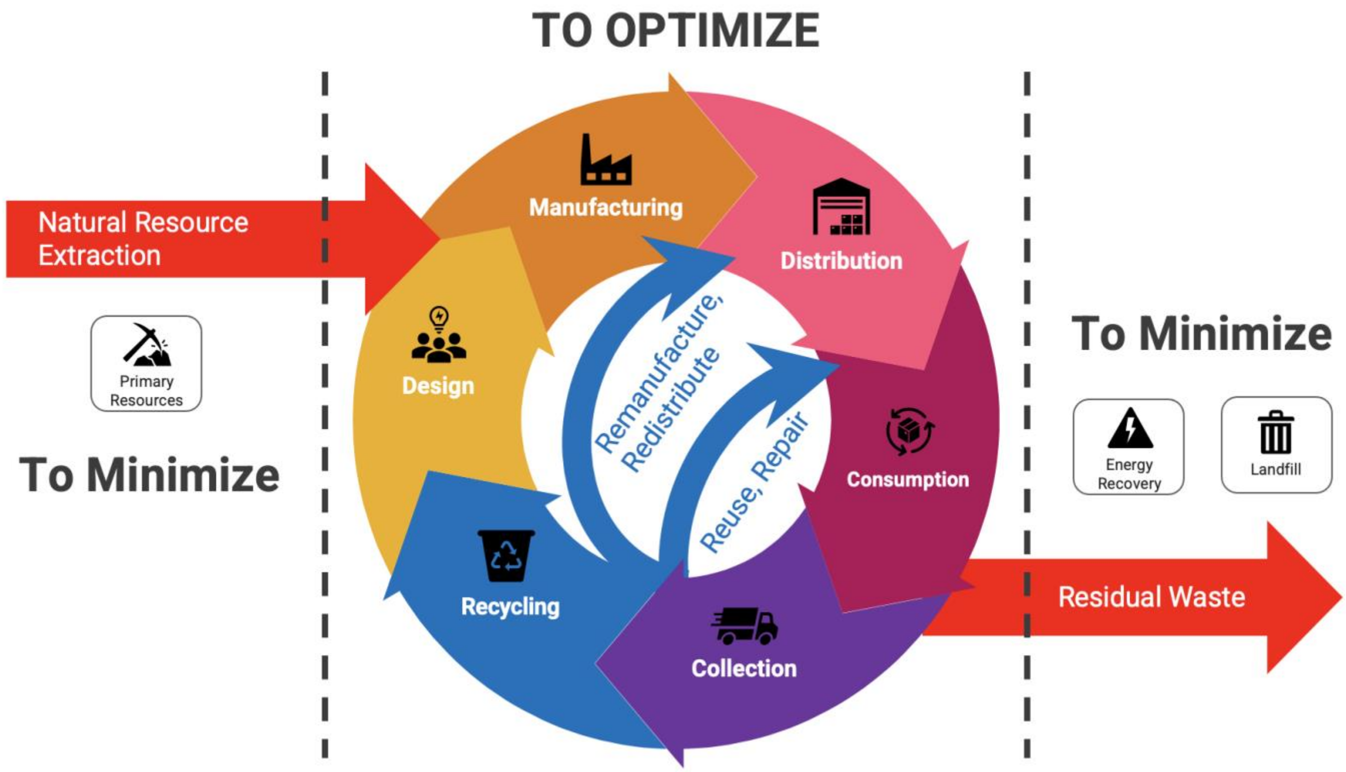

Figure 1: Stylized Version of Characteristic Circular Economy Model Focused on Manufacturing & Consumer Market 'Core' with Resource Producing 'Periphery'.

European manufacturers could save US$630 billion a year by 2025 (Scheel, Aguiñaga & Bello 2020). Secondary material production can also generate employment benefits (Bassi & Pallaske 2020), is often less emissions intensive than primary production (Nuss & Eckelman 2014, Hund et al. 2020) and can help secure supplies of critical metals and minerals, while reducing reliance on raw materials (e.g. Baars et al. 2021).

The consequent vision of the CE has unsurprisingly focused on downstream practices to reduce, remanufacture, or recycle products or materials in manufacturing, consumer product markets, and flowing out of the economy as waste – while emphasizing the need to reduce and/or minimize inputs of primary resources. The resulting conceptualizations and models of the CE published in the academic and grey/policy literature have primarily presented the CE as a circular flow of resources in production, manufacturing, and consumer product markets, situated within a linear system originating in primary raw materials, and ending at the landfill. Both the origination (raw material extraction) and termination (material waste/landfill) points of that system are then targeted as flows 'to be minimized' in a CE, with little additional detail and few linkages drawn between primary material inputs, circular processes or incentives in the broader economy and the kind of material waste outputs that result. Figure 1 presents a stylized version of this kind of CE framework, versions of which can be found published by a range of leading CE advocates.[6]

[6] See, for example: the EMF (February 2019) [Circular economy systems diagram](), the European Environmental Agency (November 2020) [Circular economy system diagram](), *or* the UN Environment Programme's International Resources Panel (UNEP 2020) report on [*Mineral Resource Governance in the 21st Century*]() *(Figure 4.6, pg. 127)*.

As a general feature of these models, the CE practices of reuse, repair, redistribute, refurbish, and remanufacture generally appear at the centre, whereas on the periphery are the extraction and import of natural resources, and outflows of waste materials. While they have helped to broaden overall awareness and understanding of the CE in both policy dialogues and broader research efforts, and to promote the necessary aim to reduce inputs of primary materials as much as possible, considerations of circular material flows, waste materials, or linkages rarely, if ever, extend from the centre to the periphery. As a result, primary raw material production is left outside of circular value chains, and potential linkages and interactions between circular products, processes, and innovations are separated from the activities, processes, and policy frameworks considered relevant for primary material producers and exporters. Accordingly, policies or assessments based on these traditional downstream, core-periphery style CE models may inadequately prepare the global economy for any continued requirements for primary material production, and the resulting interactions between primary and secondary material supply, during a low carbon, circular transition.

The implications of the limited upstream connections in these popular models can be seen in the broader literature. Echoing many of these models, the absence of linkages between policy and economic drivers in a circular 'core' and resource-producing periphery are apparent in many of the existing macro-economic modelling studies of a CE transition to date. For example, in a review of macroeconomic modelling efforts investigating the consequences of the transition to a CE, McCarthy et al. (2018) find that the implications of a CE transition for resource extracting and exporting economies are generally understudied – and that assumptions (or lack thereof) concerning future rates of productivity growth, material substitutability, and future consumption patterns are key determinants of model outcomes.

While all of the CE macroeconomic modelling efforts reviewed by McCarthy et al. highlight the potential for re-allocation effects of a CE between both sectors and regions, upstream linkages to primary extraction are primarily focussed on the impact that CE policies may have on resource extraction rates. In a context where CE is defined as "any process that enables the decoupling of economic output from virgin resource extraction" (McCarthy et al. 2018, pg. 16), this focus on assessing changes in resource extraction is understandable. However, it is also telling that while more detailed, single-region assessments of resource efficiency or other CE policies had been undertaken for many OECD countries (including Japan, Korea, Sweden, Germany, and France), at the time of their publication, no single-region assessments had been undertaken for countries with large extractive sectors (McCarthy et al. 2018).

Where primary resource producing countries or regions were included in multi-region models, all studies reviewed by McCarthy et al. found lower resource extraction rates through the implementation of CE policy instruments. However, it is important to clarify that these deviations are in relation to reference, or business-as-usual baseline scenarios of increasing resource demand, and that they generally assign primary resource flows to highly aggregated raw material categories due to data and processing constraints: e.g. metallic and non-metallic mining are often grouped into a single extractive sector. Evaluation of the resulting level of primary resource demand (as opposed to the change versus the baseline) and whether resulting deviations from the reference case presented increasing or decreasing demand of primary materials from current levels, or in reference to current reserves, is not generally studied. Nor, generally, are substitution between primary materials with differing environmental impacts or circularity potential, while issues of constraints on recyclability or supply of secondary material are generally overlooked (McCarthy et al. 2018).

Consequently, limited attention to detailed representation of resource-producing economies, and relatively limited assumptions regarding primary resource demand and a focus on marginalization of raw material production often drive macroeconomic results. For example, in a study of policy scenarios for a resource efficient economy, Meyer et al. (2016) model a global cooperation scenario in which world economic production (measured by GDP) continues to increase alongside improved material efficiency outcomes through 2050, suggesting overall (global) economic gains from a CE transition. However, individual country results broadly depend on relative positions in the international division of labour: countries that import materials are the winners (e.g. Germany increases its GDP by slightly more than 9% versus the reference scenario), while countries that export materials are the losers (Brazil and Canada see their output decrease by 16.5% and 7% versus the reference scenario, respectively). Key drivers of these outcomes are based on assumptions of (i) an ore-free renewable energy transition (energy is linked primarily to greenhouse gas emissions, not material requirements), (ii) a feasible 50% increase in the recycling rate for *all* metals, based on recent recycling rates for many major metals, and (iii) existing in-use material stocks plus increased recycling being sufficient to support global resource demand (with a smooth reduction to 5 tonnes of raw material demand per capita). It is implications of assumptions such as these that we turn next.

Projections for Primary vs. Secondary Material Demand: Prospects for CE and Decoupling

In both academic and grey literature, the CE's ultimate objective is commonly described using the concept of decoupling. UNEP (2011) has distinguished two types of decoupling: resource decoupling and impact decoupling. While impact decoupling aims to minimize resource extraction's overall environmental impacts, the focus of resource decoupling is to use fewer primary resources per unit of economic growth, thus delinking (to the extent possible) economic growth and natural resource depletion by minimizing resource extraction (UNEP 2011). Traditional CE models have accordingly approached primary resource sectors primarily from the perspective of encouraging resource decoupling – with a goal to minimize primary resource flows into the economy (Murrey et al. 2015). Once raw material extraction has been minimized, impact decoupling principles are then applied further down the supply chain, to minimize waste, reduce pollution, and recover materials and value in manufacturing and consumer product markets.

As the review in the previous section illustrates, prospects for resource decoupling in existing CE models are driven primarily by assumptions of future material demand, emerging (low carbon) energy technology material requirements, re-use and recyclability potential of materials in use, and substitutability of primary and secondary materials over time. While it is reasonable to expect CE policies, programmes and incentives will drive a degree of resource decoupling in the coming years by improving the efficiency of resource use per unit of economic activity relative to current rates, the potential for more absolute decoupling remains much less clear. The question then is one of degree, and whether a CE transition can drive sufficient resource efficiency improvements in coming years to not simply minimize, but reduce primary material demand in absolute terms, as CE models tend to suggest.

Primary Material Requirements, Growth, and Income Convergence: Unfortunately, most studies and projections of global raw material demand suggest serious challenges for absolute decoupling in the near- to medium-term (over the coming 40-60 years) – even with aggressive assumptions regarding circularity and resource efficiency improvements. Recent OECD projections of global material demand through 2060

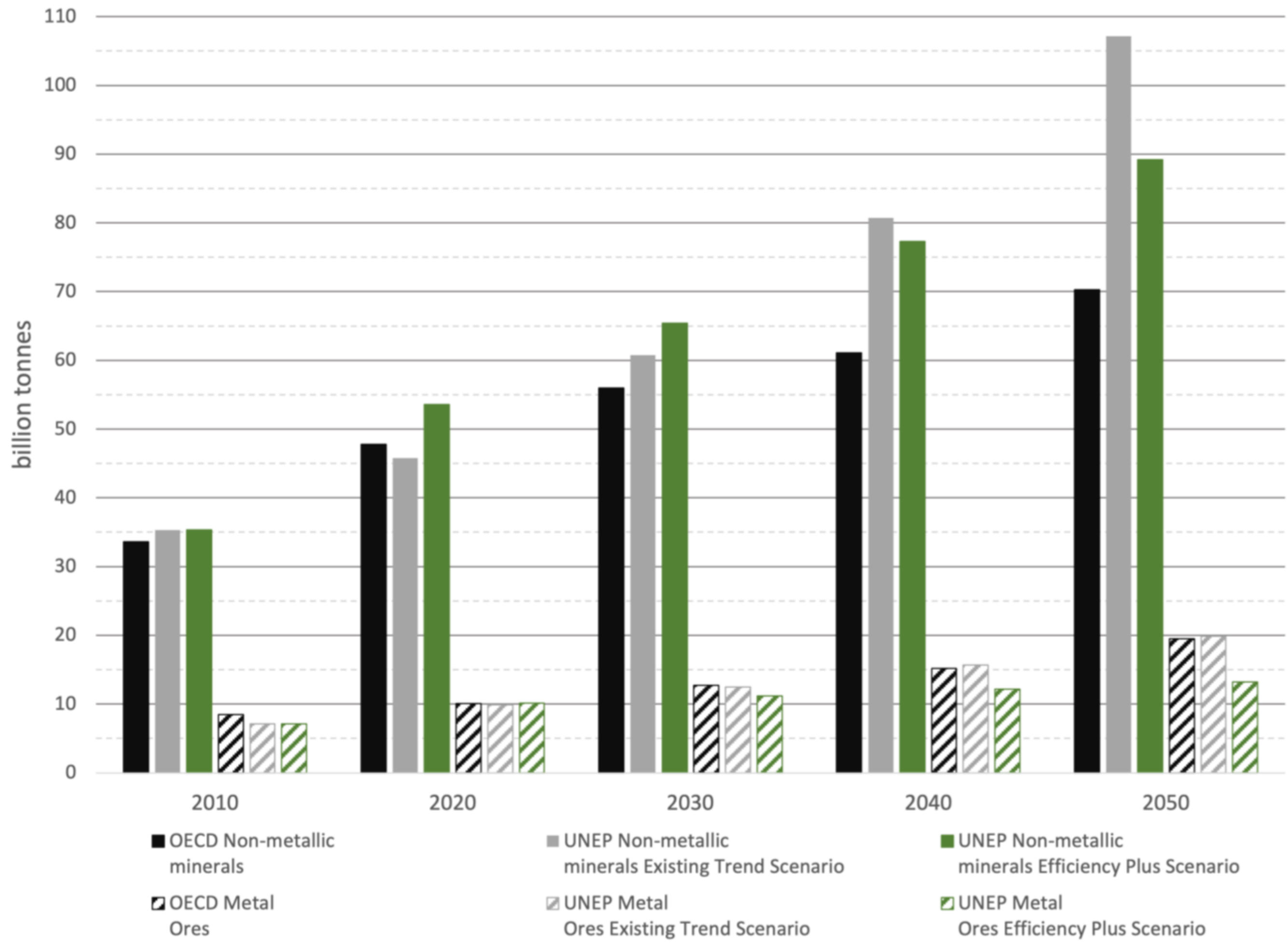

Figure 2: Projected Metal Ore & Non-Metallic Mineral Demand to 2050. Adapted from OECD (2019) and UN Environment Programme, International Resources Panel (IRP 2017)

indicate that primary material use will roughly double, from 89 Gt in 2017 to 167 Gt in 2060 – including growth in all major categories of materials, including 63% growth in fossil fuels, 73% in biomass, 97% in non-metallic minerals, and 126% in metals (OECD 2019: percentages indicate growth to 2060 from 2017 levels). Growth in metals demand particularly remains consistent even when broken down to the level of individual ore types, with projections of most metal ore usage levels approximately doubling, or more, to 2060 (OECD 2019, Figure 5.6). Even scenarios from the International Resources Panel (IRP) proposing an ambitious resource efficiency transition – via reduced resource intensity and slower growth in natural resource extraction -- only shave projected metals and mineral needs by approximately one quarter (IRP 2017). The World Economic Forum similarly projects that demand for commodities such as iron ore will continue to exceed recent levels through 2050, despite accounting for increasing regulation on material recycling and factoring in an expected slow-down and eventual decrease in China's steel consumption (WEF 2015).

Importantly, the OECD (2019) projections already account for relative decoupling, factoring in an average reduction of materials intensity for the global economy per year of 1.3% through 2060. However, this decoupling rate is not sufficient to match projections of increasing total material demand required to keep up with global population growth, continued convergence of living standards between developed economies and the rest of the world, and the shifting of global production to emerging economies with less efficient technology. Global populations are expected to jump to approximately 9 billion people by 2030 – including 3 billion new middle-class consumers (ICMM 2016) – and approximately 10 billion people by 2060.[7] If the growing middle class in emerging and developing countries follow a similar lifestyle as OECD countries, population growth and income convergence alone would drive demand for primary materials to more than triple from baseline (2017) levels, exceeding 300 Gt globally by 2060 (OECD 2019).[8] It is only by factoring in projections of structural change (including an increasing economic importance of service sectors) and an accelerated transformation towards more resource efficient production technologies that the OECD reduces its final projection to a doubling of global material demand by 2060 (167 Gt by 2060, instead of greater than 300 Gt).

These studies present a scenario of near- to medium-run growth in primary material demand, driven by population growth and a material-intensive process of infrastructure development in emerging economies. This has been happening in China, and – absent new policies and programs to further reduce demand and improve efficiency -- will correspondingly happen in many Asian and African countries in the coming decades (OECD 2019). Figure 2 provides a sense of the projected scale of change in raw material demand that is anticipated in this literature, combining projections of metal ore and non-metallic mineral demand through 2050 from both the OECD (2019) and UN Environment Programme's International Resources Panel (IRP 2017).

Material Requirements of a Low Carbon Economy: Note, however, that the projections cited above do not, in the main, account for the material requirements of a low carbon energy transition. For example, the central projections in the OECD (2019) study are based on the International Energy Agency (IEA)'s World Energy Outlook Current Policies Scenario (CPS) (IEA 2017). The CPS considers only those low carbon/climate change policies and measures in place or enacted by mid-2017, and specifically does not adjust for intended policies, or the policies that would be required to meet targets to limit global average temperature change to either 1.5 or 2 degrees. Nevertheless, with the recognition that a drastic reduction in fossil-fuels is necessary to reduce the risks of climate change, along with recent technological advances and innovation, low-carbon technologies are increasingly being adopted and achieving economies of scale (Clean Energy Canada 2017, Hund et al. 2020). The challenge is that the transition towards a low-carbon future will be very mineral intensive, with an increasing number of studies showing that low carbon energy technologies are more minerally intensive than fossil-fuel-based electricity generation (van der Voet, Kleijn & Mudd 2020, Watari et al. 2019, World Bank 2017, Hund et al. 2020). For example, a single solar photo-voltaic (PV) panel requires 19 minerals and metals. Of these, eight are designated as 'critical' in Canada, meaning that they are of high economic importance but face significant supply challenges (Clean Energy Canada 2017, Komnitsas 2020). Figure 3, adapted from the supplementary data tables provided by Watari et al (2019) and summarizing the relative estimated material intensity of different energy technologies, illustrates the scale of change in material requirements implied by a low carbon transition.

Studies projecting the implications of the increased material intensity of low carbon energy technologies for global material demand provide sobering results. According to the World Bank and its Climate-Smart Mining Group, limiting global average temperature increases to 2 degrees above pre-industrial levels will create a two- to four-fold increase (100 to 300 percent over baseline) in demand for metals required for renewable (wind and solar) energy technologies, with the spread determined by the assumed degree of

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[7] Source: Medium variant projection. United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. https://population.un.org/wpp/Download/Standard/Population/.

[8] Note: High-income countries consume 10 times more materials than low-income countries, on a per capita basis (IRP 2017).

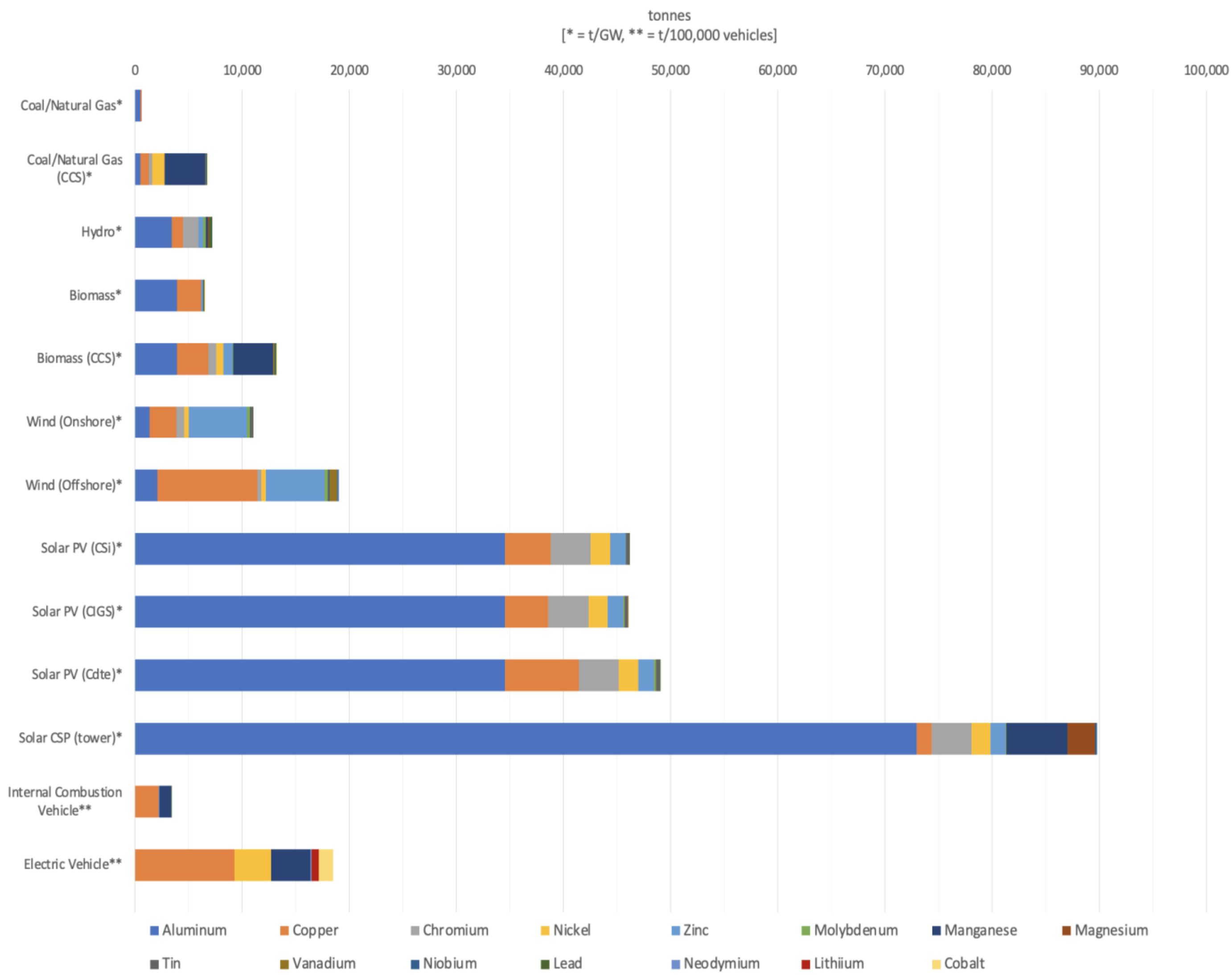

Figure 3: Material Requirements for Selected Energy and Transportation Technologies. Adapted from Watari et al. (2019) Supplementary Data Tables (S3-S13), who calculate material intensity by energy technology type by averaging estimates from previous literature (see Watari et al. 2019, Table 2, p.95 for the studies included). Values are provided in t/GW except for Internal Combustion and Electric Vehicles, which are in t/100,000 vehicles produced. Energy technology materials exclude steel, and vehicle materials exclude iron and aluminum used in vehicle body construction.

reliance on wind and solar technologies across competing scenarios (World Bank 2017, Hund et al. 2020). While these figures reference demand change relative to the base scenario in supplying electricity generation technologies only, the numbers are even more striking when viewed in reference to recent (2018) metal and mineral production levels. Hund et al. (2020) estimate that under the IEA 2 degree scenario (2DS), annual demand for battery minerals (graphite, lithium and cobalt) will increase by 450 to nearly 500 percent by mid-century versus 2018 production levels, and in excess of 500 percent in the 'Beyond 2 degree' scenario (B2DS). Meanwhile, demand for Indium (used in solar PV technology) is projected to grow by more than 200 percent, while Vanadium and Nickel (which are both used in energy storage) will approximately triple and double, respectively. See Figure 4

While increases for other major metals (such as aluminium and copper) are smaller in percentage terms – due to higher current production levels – they nevertheless also represent large absolute increases in

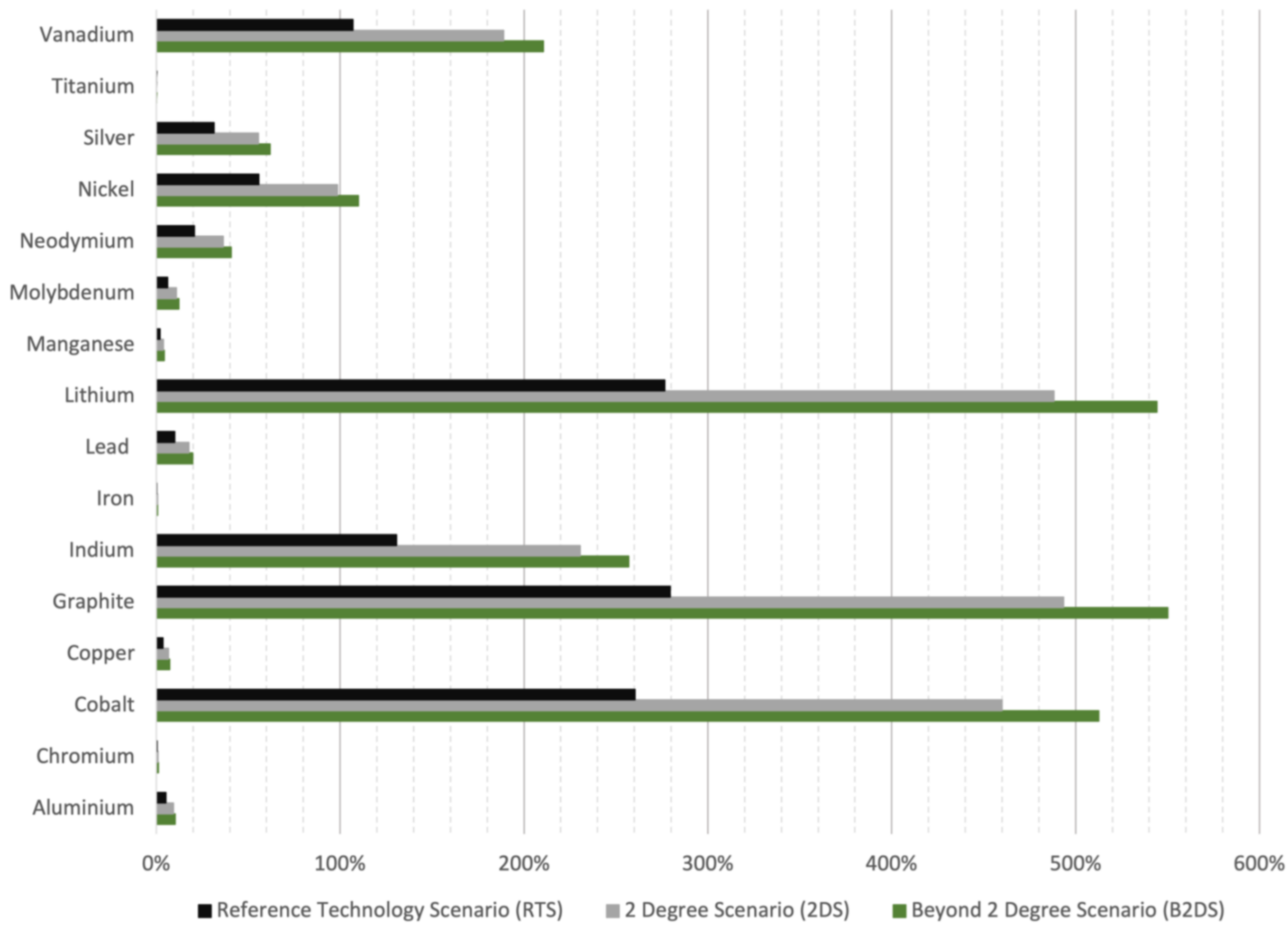

Figure 4: Projected Annual Demand from Energy Technologies in 2050 (% of 2018 Annual Production Levels). Adapted from Hund et al. (2020).

demand. A projected increase of annual aluminium demand for energy technologies of 9 percent of 2018 production levels represents an overall annual increase of 103 Mt by 2050 (Hund et al. 2020), part of an overall estimated eight-fold increase in total economic aluminium demand by mid-century (Lèbre et al. 2019). Copper demand for energy technologies is similarly estimated to increase by 29 Mt annually by 2050 (Hund et al. 2020), as part of an approximate doubling in total economic demand (Elshkaki et al. 2018). Importantly, the numbers for energy technology demand from the World Bank do not include infrastructure requirements that would go along with increased renewable energy generation, and so are likely under-estimated. Projections for different metals and minerals may also vary depending on the specific sub-technologies used across wind, solar, storage, and other renewable energy sources (Manberger & Stenqvist 2018, World Bank 2017) – a point which will be picked up on further below.

Factoring in these World Bank and other academic projections (i.e. Manberger & Stenqvist 2018, Lèbre et al. 2019, Elshkaki et al. 2018) regarding the material implications of a low carbon energy transition lends a robustness to projections of increased material use from the OECD and UNEP cited in the previous section, by adding another dimension of growth in material demand in the near- to medium-term. While the impacts of global population growth, material-intensive infrastructure development and income convergence in emerging economies could (at least partially) be addressed by behavioural changes or changing consumption habits (starting in developed countries), or by advances in recycling technologies for key materials, shortfalls in material availability for energy technologies could impact the speed of a potential low carbon transition (Hund et al. 2020), with a faster transition likely implying greater material use – given less time for innovative material-saving technologies to emerge. These primary material demand projections may be harder to bend down while also meeting essential climate change targets.

Substituting Primary for Secondary Material Supply: Moreover, while recycling initiatives are essential components of the CE, there is evidence that secondary materials alone cannot meet growing future materials demand. The primary material demand projections reviewed above include a range of estimated (as well as deliberately ambitious) projections of the availability of secondary materials to substitute for and offset primary material demand. The OECD (2019) study of material demand includes a recycling sector that is projected to more than triple in size by 2060 (increasing by a factor of 3.2), and a reprocessing sector that is projected to more than double (increasing by a factor of 2.4). While the OECD projections find that both the recycling and reprocessing sectors will grow more quickly than the mining sector to 2060, overall secondary material remains a small percentage of the global economy due to limited availability of secondary materials from in-use stocks as well as limited competitiveness of secondary versus primary extraction due to higher labour costs (OECD 2019).

Even assuming 100% end-of-life recycling rates, the World Bank projects that secondary aluminium will only meet 61% of estimated demand by 2050 (Hund et al. 2020). Similarly, with zinc, it is projected that in a growing economy with high dissipation rates and long product lifetimes, secondary supply from recycling will only be able to meet around 15% of the projected demand in 2050, while total demand for copper is also likely to exceed both primary and secondary supply by mid-century (Elshkaki et al. 2018; Figure 4). This pattern holds for many other metals as well, with the notable exception of lead. In case of lead, it is projected that secondary sources can meet a high fraction of future demand due to the relatively high recycling rate, low dissipative use, and short lifetime of its major end-use application (batteries) (Elshkaki et al. 2018). However, the Energy Sector Management Assistance Program (ESMAP), an initiative of the World Bank and 18 partners, argues that such high rates of material recovery, reuse and recyclability may not be available with the newer lithium-ion battery technologies that will be required to power a low carbon transition (ESMAP 2020).

There are several challenges to increasing the proportion of secondary materials available to meet future material demand projections. For one, not all materials are 100% recyclable at their end-of-life stage (UNEP 2011). While many of the base metals, such as copper, nickel, and zinc, currently have end-of-life recycling rates (EOL-RR) of just over 50%, there is a broad range of metals and metalloids with recycling rates below 1% (UNEP 2011; Haas et al., 2015). Furthermore, even though recycling rates are expected to rise in the future, there are other factors limiting the contribution of recycling to meet future material demand. These include, but are not limited to, dissipative material losses during the use phase of a product, product designs that impede recycling, and a lack of suitable collection and recycling infrastructure and technologies (UNEP 2013). The 'Minor Metals Challenge' (UNEP 2013) is an oft cited example – with minor metals such as palladium or indium embedded in small concentrations in million or billion units, in increasingly complex product designs, with new alloys and compounds that are difficult to disassemble (and may contain hazardous materials).

For specialty metals and rare earth elements (REEs) in particular, secondary production contributes only marginally (1% or less) to meeting current material demand (Jowitt et al. 2018). This low percentage can be attributed to the small amount of REE used in most end-products containing these elements, along with inefficient collection, technological difficulties of recovery and recycling, and lack of incentives (Binnemans et al. 2013; Jowitt et al. 2018).[9] While there is potential to increase the amount of REEs recycled, especially from major end-uses such as permanent magnets, fluorescent lamps, batteries, and catalysts, the methodologies to do this are still only at the nascent stages of research and development (Jowitt et al. 2018). The overall challenge for substituting primary for secondary demand is therefore similar to that described for many of the major metals listed above. In the case of two key REEs, neodymium and dysprosium, projections indicate that the gap between global demand and supply in 2050 cannot be closed by recycling alone, while in the long term (to 2100) secondary supply may only be able to meet 50% of projected demand (Habib & Wenzel 2014). Therefore, even with improved recycling of materials in the future CE, there may still be a gap between what the secondary market can supply, and the materials demanded by the economy (Elshkaki et al. 2018).

This literature implies that, at least for the foreseeable future, the global economy will continue to depend to a significant degree on the extraction of primary materials to meet material demands. Even with improved recovery, reuse, repurposing, or recycling of materials as CE policies and practices begin to come online, there is likely to remain a significant gap between what the secondary market can supply, and the materials demanded by a growing population (an increasing number of whom may aspire to middle class lifestyles and the infrastructure needed to support this), along with the urgent need to transition to low carbon energy technologies. As argued above, while it is therefore reasonable to expect CE policies, programmes, and incentives to drive a degree of resource decoupling in the near- to medium-term, these projected demand gaps suggest that absolute decoupling is not likely feasible -- absent more radical transformations in consumer preferences and energy requirements. The picture of the future that emerges is instead one in which increasing circularity will be essential to simply help offset significant increases in material demands through at least 2060 – so that both primary and secondary materials will be mobilized to meet the material requirements of global consumer demand (OECD 2019) and low carbon energy technologies (Hund et al. 2020) – with the least environmental impact possible.

This suggests a need to reconsider our conceptual models of a CE and the place of primary resource sectors particularly. Meeting projected material demands – even with ambitious secondary material substitution rates – will require refocussing on impact decoupling as a critical component of a CE across the entire value chain, from primary extraction to material or product end-of-life. The demand curves for primary materials surveyed here are an inconvenient truth for existing CE models. To bridge this demand gap in a sustainable way, it will be essential to integrate the extractive sectors and natural resource producing economies into our models of the CE – a fact which in no way undermines the importance of secondary material economies and the need to continue pursuing a dedicated approach to significantly reducing consumption levels.

[9] For example, a mobile phone contains more than 60 different metals, each in small proportions (UNEP 2013).

Implications for Policy, Practice & Research

The CE & Bridging the Demand Gap: Increasing the Focus Across the Value Chain

Thus far, this paper has outlined three important points. First, prominent conceptualizations and models of the CE have primarily presented the CE as a circular flow of resources in production, manufacturing and consumer product markets. Both the origination (raw material extraction) and termination (material waste/landfill) points of that system are generally portrayed on the periphery, as 'flows to be minimized' in a CE. Second, technological and demographic drivers are projected to significantly increase the demand for materials in the near- to medium-term (through at least 2060), across a wide range of metals and minerals required for infrastructure requirements and clean energy technologies. Third, increasing the production of secondary materials alone will not be sufficient to meet the projected growth in future material demand, and, as a result, production of both primary and secondary materials will likely need to increase for the foreseeable future.

Integrating Resource Extraction and Primary Resource Producers into CE Models: Taken together, these observations suggest we require a model of the CE that adequately considers the role of primary materials and upstream resource extraction sectors in addressing the material requirements inherent to a low carbon, circular economy transition. While there has been considerable focus on identifying policies and national CE roadmaps or pathways to improve the downstream circularity of materials and supporting efficiencies in secondary material production, discussions around the application of CE practices in upstream primary resource sectors have remained – by and large -- sidelined. By extending current CE models to include more direct integration of upstream natural resource sectors, including the integration

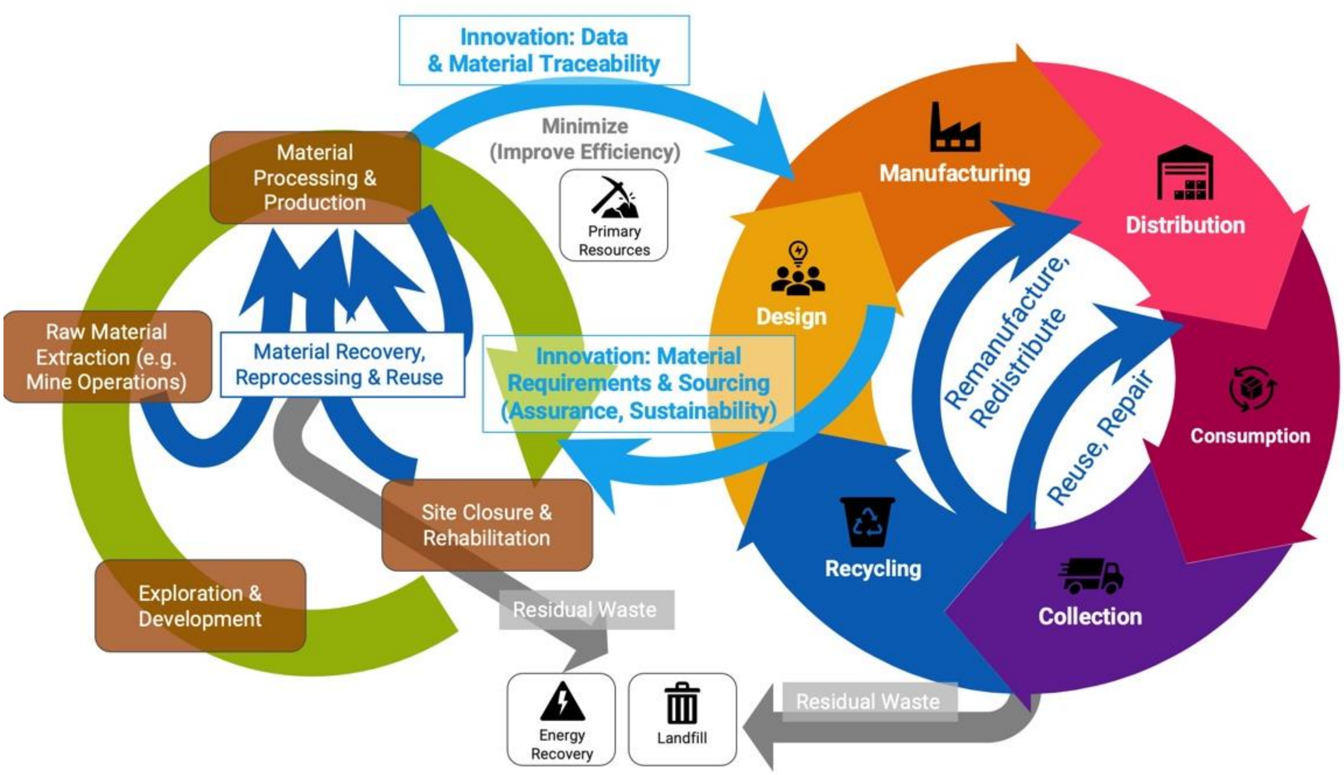

Figure 5: Updated Model of the Circular Economy, with Proposed Upstream/Downstream Linkages & Circular Practices Applied in the Upstream Primary Resource Sector

of primary resource producers and regions into circular value chains, the application of circular policies and practices to raw material extraction and processing stages, and the consideration of more direct linkages between emerging innovations in downstream consumer product markets and upstream economic actors, it should be possible to improve our understanding of the nature of primary resource production in an emerging CE, while helping to bridge the predicted secondary material demand gap.

Figure 5 attempts to update the stylized representation of current CE models (see Figure 1) with this kind of integrated upstream/downstream approach. It extends the core-periphery framework adopted in many current CE models to include the application of circularity to upstream primary material producers, as well as downstream manufacturing and consumer product markets. By extending the resource decoupling framework applied in most CE models to include a more detailed representation of possible CE applications to resource producers, circular site-level considerations, and possible linkages between innovations and incentives in circular product markets and upstream raw material investment and development, there is greater recognition around the role that primary resource production will continue to play in an emerging CE. While not intended to replace current CE models, which provided detailed insights into how CE practices can be developed and applied to downstream product markets (and for resource importing economies), the purpose of using this model is instead to investigate new opportunities for value creation and reduced environmental impact through the application of circular practices upstream.

In this sense, Figure 5 hints strongly towards a more focussed role for impact decoupling in upstream primary resource sectors, alongside improving linkages to better integrate strategic investments in upstream extraction with downstream innovations intended to improve efficiencies, enable new product designs, and improve overall material recovery, reuse and recyclability potential. The questions that emerge for upstream resource producers and exporters in this framework emphasize improving understanding of which primary materials will be demanded in an emerging CE, where are those materials located, and how can they be developed, extracted, and processed with minimal impact – and in accordance with CE principles of waste reduction, recovery, and reuse to reduce the environmental impact of upstream raw material extraction. More explicitly building these upstream linkages into existing CE frameworks will therefore help integrate projected requirements for continued primary material production into global CE narratives and roadmaps – by explicitly considering the likely incentives for primary producers in more circular supply chains, as well as the economic and strategic outcomes resulting from market interactions between primary and secondary material supply.

Applying CE Models Across the Mining Value Chain: Moreover, similar approaches are starting to emerge in the private sector. Figure 6 provides a closely related conception of the mining value chain, developed by Anglo American and Accenture (reproduced here with permission). It explores options to integrate CE practices to reduce (or eliminate) waste, improve resource (and value) recovery, integrate new sharing platforms, and develop new product-as-service models across the value chain – from the mine site through mining operations, processing, and then on through manufacturing to the more traditional CE consumer product cycle. The inclusion of considerations for CE approaches to upstream extraction and operations at the mine site, and through the life of mine cycle in this framework is critical. This inclusion reflects an established body of knowledge and practice around mining sustainability that has worked towards improving both resource and impact decoupling at the mine site level. Recognizing that primary materials will be needed for the foreseeable future to bridge the demand gap between secondary material supply and total resource demand, there are opportunities to integrate CE practices throughout exploration,

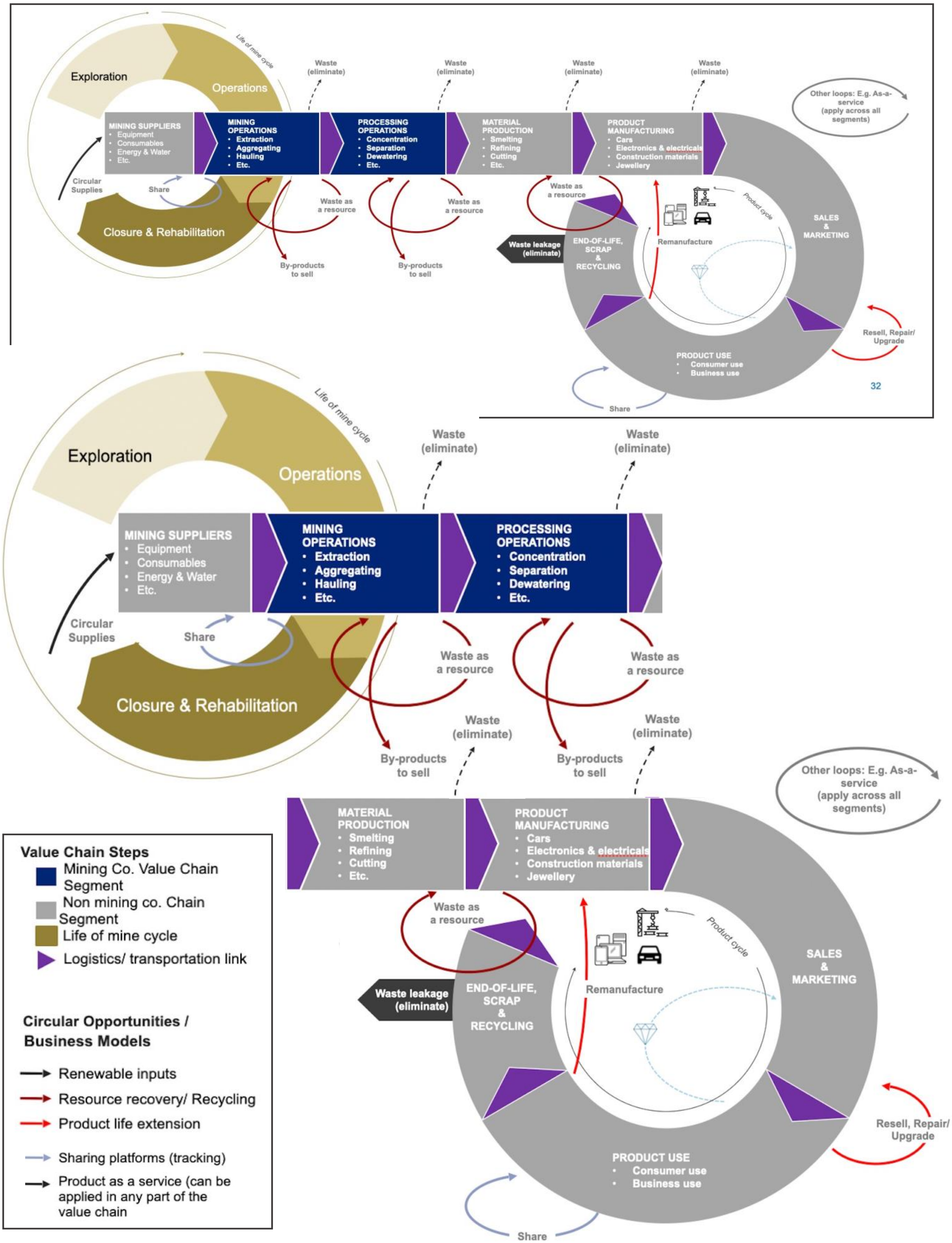

Figure 6: Circular Opportunities & Business Models in the Mining Value Chain. Figure produced by Accenture Strategies & Anglo American (copyright © 2019 Accenture). Reproduced with permission.

operations and closure/rehabilitation that are aligned with sustainability while creating new value and improving the competitiveness of mining operations within a more circular, integrated value chain.

The engagement of the private sector with this kind of CE model is not in itself surprising. Improvements in resource efficiency, waste/disposal reductions, and the creation of new value streams from resource recovery are all CE approaches that will help reduce costs, create markets, and improve overall sector competitiveness. CE approaches may also help to address emerging challenges in the mining and metals sector. For example, given the increasing demand for minerals and metals globally, the quality of known and easily accessible deposits is decreasing. As a result, mining operators will be required to increasingly pursue exploration and extraction deeper into the ground and in more remote locations, for lower grade ores (Vidal, Goffé, & Arndt 2013, Lusty & Gunn 2015, Ali et al. 2017). Unlocking these deeper deposits will undoubtedly be more costly and require new mining technology and innovations to reduce environmental risks and minimize impact (Meinert, Robinson, & Nassar 2016, Komnitsas 2020). Ensuring these innovations are consistent with CE principles, limit GHG emissions and appeal to customers and investors in increasingly circular downstream markets will be essential to mining operations' competitiveness.

Additionally, mining companies increasingly face a suite of challenges and costs linked with maintaining their social license to operate (SLO). SLO is an essential mechanism for ensuring the sector's viability and involves engaging relevant stakeholders throughout the project lifecycle to build and maintain trust (Owen & Kempt, 2013). Occurrences of mining projects being delayed or shut down due to public opposition are extensively documented and avoiding conflicts with local communities is paramount for project success (Owen & Kempt, 2013). Meeting future primary material demand may accordingly be hindered by the increased scrutiny faced by mining developments, especially given the rise of social media, which allows stakeholders to communicate and garner support for project oppositions more publicly (Elshkaki et al. 2018, Prior et al, 2016). In a market that determines investment based on short-term returns, this uncertainty may increase the risk of investing in projects based on long-term scarcity planning (Ali et al., 2017). Those companies that more effectively adopt, integrate, and demonstrate CE principles and practices may be better positioned in this increasingly scrutinized industry, and more effectively able to maintain their SLO, and their attractiveness for impact investors.

Linking the Role of Primary Material Production into CE Narratives: This kind of integrated, full-value chain CE model development can help identify key leverage points and opportunities to take advantage of sector-wide strategic opportunities to drive cleaner, more circular innovation outcomes. Figures 5 & 6 highlight that CE strategies and approaches can be extended upstream, to the mine site, mining operations and raw material processing levels – to reduce impacts and bring new value to the raw material extraction stage of product lifecycles. By focussing on these upstream operations and production cycles, approaches to improve the rate and efficiency with which target metals and minerals can be extracted and processed can be integrated into CE narratives. By doing so, opportunities to drive innovation in material extraction and competitiveness by branding companies or countries as producers of 'low embodied material' products, or to connect CE dialogues with ongoing sustainable mining, zero-waste mining, or responsible mining strategies – which are already working to reduce impacts and improve social and community-level outcomes – may be created.

Exploring the linkages between upstream operations and downstream manufacturing and product market cycles also provides opportunities to better understand which raw materials will continued to be demanded in a future low carbon, circular economy. In particular, as the world transitions to low-carbon energy sources, there is still an element of uncertainty regarding which energy technology pathways might

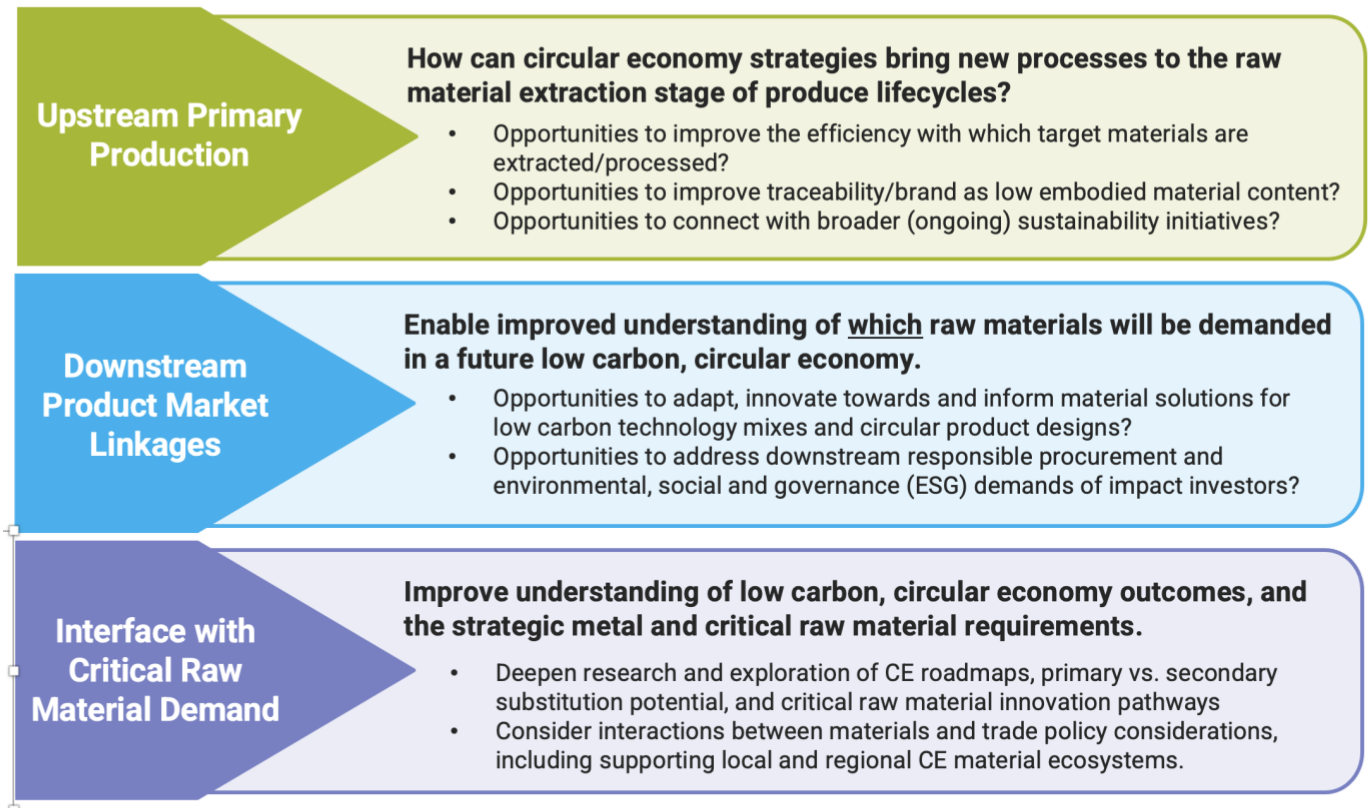

Figure 7: Key Take-Aways: Linking the Primary Resource Production into Circular Economy Narratives

eventually become dominant and the specific nature and quantity of materials that will be required to support them (van der Voet et al. 2017, Manberger & Stenqvist 2018, World Bank 2017). Variation in raw material requirements for energy technologies not only varies across energy generation types (e.g. wind, solar, or geothermal), but also across sub-technology types (such as direct drive versus gearbox driven wind turbines, or 1st, 2nd, or 3rd generation solar PV technologies) (Manberger & Stenqvist 2018, World Bank 2017). It is accordingly crucial to consider the implications of the various technologies being adopted, as they require different material inputs – materials which will have different upstream extractive impacts, embodied waste and GHG contents, recyclability potentials, and therefore criticality risks (Hund et al. 2020). Focussing exclusively on the downstream manufacturing and product market cycles – while assuming raw material inputs can be minimized – risks selecting for energy technologies that require metal and mineral material inputs that are more difficult to access, generate greater waste or higher emissions upon extraction, require processing or production operations which are themselves more material intensive, or which are located in remote or geopolitically risky regions.

Recognizing these upstream CE linkages accordingly creates opportunities for policymakers to incentivize strategic adaptations and to encourage and support innovation towards low carbon technologies and consumer product markets that optimize for circularity potential and material waste reduction along the value chain. Moreover, it also creates opportunities for end-users to signal consumer and public demands for more responsible products, and for upstream mining operators and raw material producers to address downstream responsible procurement and environmental, social and governance (ESG) demands in order to improve investment potential and market access. For example, BMW recently partnered with UAE's Emirates Global Aluminium to source low carbon, solar-made aluminium, while BMW, Daimler, Ford, and Microsoft (among other major purchasers) have all joined IRMA, signalling a desire to source materials responsibly -- and extending all the way back to the mine site.[10] Meanwhile, Australia has recently released a report of how its mineral resources can help responsibly meet Europe's battery metal requirements (Rutovitz et al. 2020). These developments suggest that it will be the producers and countries who not only can source the required metals and minerals, but who can do so while incentivizing, implementing, and tracking their material waste and environmental impact, and in accordance with the principles of a more circular value chain, who will be most competitive in meeting the material demands of a low carbon transition.

Overall, these observations suggest a key role for CE policies and approaches that not only minimize primary raw material demand from downstream consumer product markets, but which also drive improved competitiveness of strategic raw material production at the interface of emerging low carbon, circular technology markets. Doing so will require incentivizing and enabling upstream raw material extractive sectors to (i) levelize costs between primary and secondary material recovery, (ii) invest in measures to drive innovation, and (iii) incentivize improvements in material traceability, data on embodied waste and emissions, and product designs to improve ease of critical raw material tracking, recovery and recyclability. Figure 7 attempts to summarize many of the key opportunities and leverage points that thus emerge once primary material production is linked into CE narratives in this fashion.

Advancing CE Adoption in the Metals and Minerals Sector

Given the overview presented here, the inconvenient truth of continued short- to medium-term primary material demand alongside even aggressive assumptions for secondary material substitution potential suggests a need to define practical, strategic CE pathways for primary resource producing economies, and for sectors such as metals and mining. With international interest growing around the concept of CE and an increasing realisation among many actors of the material requirements of a low carbon energy transition, there is a near-term opportunity to lead in identifying and developing new policies and practices for integrating upstream natural resource sectors into emerging CE thinking globally. In doing so, the literature suggests it will be important to take a dynamic view of technology choice and material substitution potential – both across material types, and between primary and secondary sources (Manberger & Stenqvist 2018), while also moving beyond tax/subsidy approaches and "soft" consumer demand policies (such as eco-labels), to also consider strategic innovation and trade policies (OECD 2016).

To that end, this section attempts to deepen and focus shared understanding of key CE principles and issues for upstream resource producers, and to identify strategic priorities for action around the anticipated role of the mining and metals sector particularly in a circular, low carbon economy. It reports not only findings from a survey of the literature considering approaches and applications of CE principles in the metals and mining sector, but also summarizes the findings from a series of 14 interviews undertaken in February and March 2021 with CE leaders in the metals and minerals sector, including experts from industry and civil society (representing both Canadian, North American, and international

[10] Source: For the BMW and UAE Emirates Global Aluminum deal, see: https://www.bloomberg.com/news/articles/2021-02-02/metal-giant-to-supply-bmw-with-world-s-first-solar-made-aluminum. For the announcement of Ford Motor Company recently joining IRMA, see: https://media.ford.com/content/fordmedia/fna/us/en/news/2021/02/15/ford-initiative-promoting-responsible-mining.html.

perspectives). Among other priority issues for advancing CE approaches in the metals and mining sector, key messages and findings drawn in this study include the importance of:

1. *Improving understanding and data availability to inform CE practices at the mine site:* There is a need to invest in increasing recognition and understanding of CE practices and potential 'value from waste' at the mine site. Such activities could include developing common standards for recyclability and measures of critical materials in end-of-life products and waste. New sources of data and efforts to map out material flow for metals and minerals, develop scenarios, and inform prospective demand (to inform investments and R&D priorities) are similarly required.

2. *Developing a common understanding between CE and established sustainable mining initiatives:* A common language around CE as it relates to mining is required. This includes improving understanding of how CE principles and practices relate to established sustainable mining discussions, as well as more operational considerations: including the specific challenges and opportunities that arise at the local, national, or regional scale, and across value chains.

3. *Increasing focus on the link between CE and strategic (or climate action) metals and minerals and improving partnerships for upstream CE innovation:* The role of CE in advancing critical and strategic metal and mineral contributions to a low carbon energy transition needs to be prioritized. This includes new research, programs, and policy initiatives to advance the potential for circularity in specific, critical low carbon metal and mineral value chains, as well as to enable pre-competitive collaboration to accelerate innovation and de-risk CE investment in strategic 'climate action' metals and minerals.

These themes are discussed in greater detail below – highlighting how each focus area builds on the existing literature and addresses the emerging challenge of bridging the primary material demand gap.

CE Practices at the Mine Site: CE practices apply to various stages of mining operations, and the overall life cycle of the mine, and include approaches such as reducing waste, recovering maximal value from mine site operations, improving the efficiency of primary resource extraction, and ensuring effective mine site rehabilitation. However, while CE approaches may help create new value by reducing costs and driving improved efficiencies, integrating mining operations into a CE will require approaches that overcome challenges including long time horizons in building new mining infrastructure as well as operations in remote locations, and will require the creation of new data sources and partnerships to reduce mining impacts and waste streams. There is also a critical need to address knowledge and awareness gaps that exist in current understanding of problems and solutions for integrating the metals and mining sector into an emerging CE, while building broader awareness among private, public and civil society leaders of how the metals and mining sector fits within CE narratives.

Waste Minimization & Value Creation: Mining produces a significant amount of waste, representing a long-term liability for operators if managed improperly. Many different types of waste are produced on site, depending on the nature of the mine and its operations. Waste can include rocks, sludge, slag, tailings, and other by-products (NRCan 2019a). With a number of high-profile mining waste accidents occurring since the 1960s, the most recent example being the Brumadinho mine in Brazil, a central value of sustainable mining has emerged around the prevention, reduction, and safe containment of mining waste. As a result, a key theme in applying CE principles at the mine site is rethinking mine waste through the use of closed-loop systems to reduce waste outputs (Tayebi-Khorami et al. 2019). While waste prevention is the ultimate objective, where prevention is not possible the literature suggests that a waste reprocessing stage could help minimize waste and loss (Lèbre, Corder & Golev 2017).

According to conservative estimates, there is "10 billion in total metal value in Canadian gold mine waste alone" (NRCan 2019a). Reprocessing waste from the mine site to remove valuables, such as rare earth elements, gold, nickel and cobalt may also help reduce GHG emissions versus primary metal extraction since the initial extraction, crushing, and grinding has already taken place (NRCan 2019b). However, there exist significant challenges with reprocessing waste using conventional technologies. In the case of gold mine waste, tailings that consist of fine particles are agglomerated or massed together, making them challenging to reprocess. Unlocking the value in mineral waste will require new investment in developing the right technologies for mine waste reprocessing that reflect the variability in the types of waste and site conditions encountered across different mining operations (NRCan 2019a).

Examples of waste minimization in practice include Weir Minerals, a company that is helping its clients find more sustainable solutions for mine tailings by simulating what exists on-site and, from there, investigate new methods for tailings handling, reuse, and disposal.[11] Additionally, hydro-metallurgists with Canmet MINING Natural Resource Canada are working with 100-year-old tailings to try and determine the lowest possible temperature and acidity where all hazardous elements can be removed while recovering most of the gold (NRCan 2019a).

Resource Recovery & Efficient Extraction: One of the main challenges at all stages of mining is to improve resource efficiency (OECD 2020). Opportunities for efficiency improvements in mining operations have been highlighted at several stages in the sustainability literature. For one, mining operations often close temporarily or prematurely due to insufficient investment and/or material price fluctuations (Lèbre, Corder & Golev 2017; Laurence 2011). In one study which sampled 1,000 mines in Australia over a 30-year period, 75% were found to have closed prematurely, or to have chosen a high cut-off grade for material extraction – leaving lower grade materials behind (Laurence 2011).

Improving extraction efficiency in alignment with CE principles of reduced waste and resource recovery requires a more complete extraction of resources from existing mine sites. Such practices could include extending the life of mining operations and increasing the range of mineral recovery on-site to reduce the need to open new mines in green fields (Lèbre, Corder & Golev 2017). Not only is this beneficial for the environment, but it also has the opportunity to contribute to material security and critical material concerns. Many critical materials are currently produced as a by-product of other major industrial metals, such as copper, lead, zinc, and aluminum. For example, tellurium, a mineral used in photovoltaic solar cells, is recovered as a by-product from anode slimes during the electrolytic refinement of smelted copper. However, processing 500 t of copper ore produces less than 0.5 g of tellurium (Lusty & Gunn 2015). Therefore, although the price of tellurium is greater than that of copper, and demand is growing, there remains little economic incentive for producers to invest in the recovery of additional tellurium (Lusty & Gunn 2015).

Efficient extraction requires an investigation into the kinds of incentives that would convince or encourage producers to extract smaller deposits on site, such as tellurium, where they are not currently. In many ways, extending the life of mine sites to improve extraction efficiency is a novel application of CE principles to mining operations. Typically, when looking at CE from a downstream perspective, strategies to reduce

[11] Source: https://web.archive.org/web/20191127181359/https:/www.global.weir/newsroom/news-articles/alternative-uses-for-tailings/.

waste and extend in-use material lifetimes would be applied to the final product, such as a battery. However, when looking at circularity at the mine site, the site itself becomes the product. Therefore, this strategy revolves around extending the mine site's productive life, ensuring that maximal value is recovered before closure and rehabilitation. In this sense, CE approaches would ensure that the disruption that comes with establishing a mine site brings maximal value to society, even as economic margins become thinner. For example, Tomra Systems, a company delivering sensor-based ore sorting systems for dry material separation of various ores and minerals, is advancing CE at the mine site level by extending the lifetime of mining operations, the proactive management of mining waste dumps, and increasing the value derived from deposits (Casey 2020).

Mine Site Remediation & Rehabilitation: Historically, mine closures were an uncontrolled process with inadequate consideration for the social, economic, and environmental consequences of closure. Consequently, a number of legacy mine sites have become a major burden for governments, who are now responsible for remediating these sites. Furthermore, legacy sites' lasting damage has sewn distrust between communities and the mining industry worldwide. Governments have spent billions of dollars in attempts to remediate improperly closed or abandoned sites. Today, the consequences of improper closure or abandonment are well recognized. It is known that when mining companies do not adequately plan for reclamation and closure, deposits of mine waste may result in environmental and health impacts on local communities, vegetation may be slow to regrow, and biodiversity permanently reduced (APEC Mining Task Force 2018). The negative socio-economic impacts on neighbouring communities can last decades.

Remediation and rehabilitation is a critical phase of mining for the CE because it provides the opportunity to regenerate the site for future productive purposes. It is critical to begin planning for closure at the inception of the project. In Canada, unlike other jurisdictions, mine reclamation plans, including financial securities, are a condition of granting mine permits (NRCan 2019b). The Mining Association of Canada (MAC) has released its own Mine Closure Framework, which articulates a commitment to responsible mine closure and includes, amongst other things, developing mine closure plans in the design phase of the project, maintaining mine closure plans throughout the project lifecycle, developing reclamation objectives aligned with the Community of Interest's values, and establishing financial assurance for closure in accordance with applicable laws.[12]

Teck Resources Limited and Harmony Gold Mining Company Limited provide interesting applications of CE to mine site rehabilitation. Teck Resources Limited has recently purchased the SunMine solar energy facility from the city of Kimberley, British Columbia (BC). SunMine is located on the Teck's reclaimed former Sullivan Mine Site, and is the first grid-connected solar facility in BC, and the first build on a reclaimed mine site.[13] Harmony Gold Mining Company Limited meanwhile is using rehabilitated land to cultivate crops for renewable bio-energy, which will then be used to heat water in the elution process of the Harmony One plant (Harmony, 2017).

Specific Challenges to CE Adoption at the Mine Site: Despite the approaches reviewed above, many interview respondents noted that there nevertheless remains a cost differential between use of virgin and recycled metals and minerals, and that opportunities to realize value from recovered waste in mining operations are often low-margin activities even when profitable. These approaches are accordingly

[12] Source: https://mining.ca/wp-content/uploads/2019/02/TSM_Mine_Closure_Framework.pdf.
[13] Source: https://www.teck.com/news/news-releases/2020/teck-announces-purchase-of-sunmine-solar-energy-facility.

unlikely to be prioritized without additional incentives. In particular, limitations in adopting CE methods of waste recovery and reuse are often accentuated in remote regions or when operations must overcome greater distances for material transport between the mine site and potential end-users for waste resources. Material recovery and redirection of waste streams are also cited as unique business models, requiring new and innovative logistics systems and infrastructures from what current exists in many mining operations – and while the opportunity to realize value from new circular metals and minerals industrial ecosystems was often noted, distance and infrastructure requirements are considered a key challenge. Transporting waste materials from remote locations was also raised as risking new trade-offs between material recovery and GHG reduction objectives, among other factors.

Finally, data on material footprints of mining operations was highlighted as a key gap, which needs to be bridged to assess mining and metal sector resource efficiency outcomes. Efforts are needed to improve data access and sharing regarding measures of mining and metals sector circularity, and new approaches to (or standards for) definitions of what counts as 'waste' or 'resources' in financial and material accounting across the value chain are required to help identify opportunities for value-add assessment, understand waste material and value-recovery potential, and to inform potential investors.

Developing a Common Understanding between CE and Sustainable Mining Initiatives: Notwithstanding the above discussion, it is important to recognize that efforts to increase the mining and metals sector's sustainability already exist through a variety of industry- and 3rd-party-led initiatives. Over the past decade in particular, the rise of awareness and concern about the negative social and environmental impacts of raw material extraction in the mining sector has led to calls for greater accountability throughout the metals and minerals supply chain. However, a key theme from our interviews is that there is uncertainty about how CE links with broader initiatives around sustainable or responsible mining, including principles related to community sustainability or health and safety. There is therefore concern about whether and how emerging CE narratives will impact this broader focus. In particular, the growing range of 'buzzwords' around CE are perceived to increase the risk that it will be dismissed as another greenwashing initiative, and as distracting from other sustainable or responsible mining objectives that are already underway (and credibly established) in the sector.

The literature has so far generally understood sustainability and CE as coherent and interdependent disciplines (Sauvé, Bernard & Sloan 2016). At first glance, the difference between CE and sustainability is unclear, with few authors attempting to unpack their relationship (Geissdoerfer et al. 2017). However, while both concepts take a similar perspective of shared responsibility and coordination between actors and stakeholders – they are not one and the same (Geissdoerfer et al. 2017). In particular, several scholars in the circular economy literature have brought attention to the lack of consideration for "the social" dimension of sustainability in discussions on the circular economy (Geissdoerfer et al. 2017; Guisellini et al. 2016; Moreau et al. 2017; Padilla-Rivera et al. 2020.). That being said, given the finite nature of minerals and metals, and the environmentally damaging nature of resource extraction, unpacking a singular vision of sustainability for this sector has been a challenge (Laurence, 2011; Lèbre, Corder & Golev, 2017). As a result, sustainability itself also tends to capture a broad array of interventions (Geissdoerfer et al., 2017).

In practice, CE principles and indicators appear to tie into, support, and/or diverge from existing sustainability and responsible mining initiatives in the metals and minerals sector in a variety of ways. This includes industry- and 3rd party-led initiatives such as: the Initiative for Responsible Mining Assurance (IRMA)'s *Standard for Responsible Mining*, the Mining Association of Canada (MAC)'s *Towards Sustainable Mining* (TSM) program, and the International Council on Mining & Metals (ICMM) *Mining Principles*. Figure

MAC: Towards Sustainable Mining Protocols & Frameworks	IRMA: Standard for Responsible Mining Requirements	ICMM: Mining Principles
1. Biodiversity Management	1. Business Integrity • Legal Compliance • Community/Stake-holder Engagement • Human Rights & Due Diligence • Grievance Mechanisms & Access to Remedy • Transparency in Revenue Payments	1. Apply Ethical Business Practices
2. Crisis Management		2. Integrate Sustainable Development in Decision-Making
3. Climate Change	2. Planning for Positive Legacies • Environmental & Social Impact • Free, Prior, and Informed Consent • Community Support & Benefits • Resettlement • Emergency Preparedness • Reclamation & Closure	3. Respect Human Rights
4. Indigenous & Community Relationships		4. Implement Effective Risk Management Strategies
5. Prevention of Child & Forced Labour		5. Pursue Continual Improvement in Health & Safety
6. Safety & Health	3. Social Responsibility • Fair Labour • Occupational & Community Health & Safety • Conflict Affected & High-Risk Areas • Security Arrangements • Artisanal & Small-Scale Mining • Cultural Heritage	6. Pursue Continual Improvement in Environmental Performance
7. Tailings Management		7. Contribute to the Conservation of Biodiversity
8. Water Stewardship		8. Facilitate Responsible Production in Design, Use, Reuse, Recycling, Disposal
9. Mine Closure	4. Environmental Responsibility • Waste & Materials Management • Water Management • Air Quality • Noise & Vibration • GHG Emissions • Biodiversity & Ecosystem Services • Cyanide Management • Mercury Management	9. Pursue Continual Improvement in Social Performance
10. Responsible Sourcing		10. Engage Key Stakeholders in Sustainable Development Challenges

Figure 8: Select Industry- & 3rd-Party Led Sustainable and Responsible Mining Initiatives. Sourced and adapted from the Mining Association of Canada (MAC)'s Towards Sustainable Mining (TSM) program, the Initiative for Responsible Mining Assurance (IRMA)'s Standard for Responsible Mining, and the International Council on Mining & Metals (ICMM) Mining Principles.

8 summarizes the protocols, requirements and principles put forth for monitoring or evaluating sustainable/responsible mining practices from these respective frameworks. It is instructive to then compare these principles and standards to the EU's monitoring framework for a CE (summarized in Table 2). There is obvious and considerable overlap between the EU's proposed CE indicators and the various initiatives in Figure 8 – including around indicators focussed on responsible production and sourcing, waste management, water stewardship, climate change and GHG emissions, biodiversity and other environmental performance outcomes (including responsible mine closure).

However, there are also key points of differentiation, including emphasis across the initiatives in Figure 8 on respective human rights, health and safety, emergency preparedness, risk management and crisis management, social performance and community benefits, and fair labour which are outside the usual scope of CE indicators. There are also aspects of indigenous and community relationships, business integrity and ethical practices which are explicitly outlined in the initiatives in Figure 8, but usually implicitly assumed to flow from CE approaches and practices to a greater or lesser extent, and not explicitly targeted. Similar conclusions can be drawn in reference to other, recent CE indicator initiatives, including 'Circulytics' from the Ellen MacArthur Foundation (EMF 2020), the 'Circular Transition Indicators (CTI)' from the World Business Council on Sustainable Development (WBCSD 2021).[14] To the extent they focus beyond waste management and material flow (or material footprint) outcomes, broader community or social benefits in these frameworks are usually defined in an economic sense, and oriented towards innovation or job creation with CE applications.

Nevertheless, applying a CE lens at the mine site can provide tangible and practical guidance to decreasing the material and environmental footprint of raw material extraction and processing. It has also been noted that in some aspects CE "goes beyond traditional notions of sustainability by focusing on the positive restoration of the environment within the industry and achieving value from redesigning and remanufacturing systems, rather than simply improving resource utilization" (Sillanpää & Ncibi 2019, pg. 291). However, engaging fully with these opportunities at the site level requires an expanded CE model that acknowledges existing (established) approaches to sustainability. It is also important to note that some interview participants raised specific concerns about trade-offs between CE practices and community-level sustainability considerations: such as whether initiatives toward 'whole value mining' and more extensive waste recovery prior to remediation may unduly delay responsible mine closure, and the community benefits this often entails. There is also a need to ensure CE narratives draw lessons by looking at current understanding of the implications of existing sustainability and certification frameworks in the Global South (Hilson & Maconachie 2019; de Haan et al. 2020; Hirons 2019), to try and draw lessons of the likely impact of CE policies and practices for actors and stakeholders across the global mining value chain.

Innovation Challenges -- Strategic Materials and Upstream/Downstream Linkages: Different metals and minerals will be suited to different CE strategies and approaches. For example, some metals may face absolute demand constraints (e.g. for battery metals, such as lithium, or for some REEs used in renewable energy technologies), while other metals and minerals will be constrained by rising demand levels and significant ramp ups (or increases) vs current production levels (Manberger & Stenqvist 2018). In many such cases criticality and strategic economic importance will be key drivers of innovation, connecting upstream raw material supply, R&D investment, and downstream markets – particularly in renewable energy technologies. Criticality of metals and minerals generally changes over time based on the evolution of (i) supply risk, and (ii) economic importance (Coulomb et al. 2015), while recently the strategic importance of metals and minerals for a low carbon energy transition has been represented as the confluence of (i) a production-demand index, capturing the expected scale to which production must increase to meet energy technology demand, and (ii) a coverage-concentration index, capturing how cross-cutting or restricted a metal is in application across a range of alternative technology pathways (Hund et al. 2020). In both cases, there is a need to consider how research and circular innovation may interact with upstream production requirements and incentives for material recovery throughout the value chain. Recyclability potential, waste management capacity and primary-secondary material substitutability may therefore help to inform the strategic energy technology pathway selection, as well as regional or national priorities for research and innovation in circularity at different stages of critical metal and mineral value chains.

For other metals and minerals – both strategic and non-strategic -- a circular, low carbon economy is likely to require new policy, regulatory and business models to enable improved recovery and trade in material resources, and investments in innovative new technologies to improve material quality, traceability, and recyclability. A CE will favour durable, reusable, and recyclable/compostable materials (Cairns et al. 2018),

[14] For a recent overview of different CE indicator initiatives, see PACE (2021).

and correspondingly will likely increase demand for strategic raw materials and metals that better accommodate product designs to meet these requirements. Identifying policies and strategies to increase innovations for improved recycling, recovery, and quality-assurance/ traceability of mineral and metal resources will be necessary to take advantage of the opportunity presented by increasing demand for metal and mineral resources for low carbon technologies, while ensuring the competitiveness of the mining sector in an increasingly circular value chain.

In this regard specific regulatory, policy, and trade barriers to CE innovation in metals and mining were raised repeatedly and prioritized for attention throughout our interviews -- linking upstream incentives for more sustainable, circular primary material production with downstream drivers of circular material use and waste management throughout our society and economy. These include the need for common standards or taxonomies for recycled materials – particularly in trade rules and agreements (e.g. between the US and Canada, regarding new USMCA rules of origin). Prescriptive regulatory frameworks which prevent the use of certain recycled materials were also cited as an important barrier to circular innovation in the sector, with performance-based regulatory frameworks argued to provide stronger incentives for CE approaches in mining operations, and to enable increased use of secondary materials in infrastructure development and consumer products (including increased recycled or recovered content). Alternatively, the potential for government research labs to help demonstrate that new material sources from waste meet current product or safety standards – or to validate performance claims -- was also raised as a potential opportunity to advance CE approaches. Policies to help de-risk innovation and adoption of CE approaches were highlighted as a key priority – including potential tax incentive programs or other incentives for circular innovation, not only at the mine site, but also in waste reduction, recycling, and improved circularly and reduced material footprint across the value chain.

Finally, circular innovation may also be driven by the rise of awareness and concern about the negative social and environmental impacts of mining. These broader social concerns suggest wider, industry-level benefits of improving circularity, reducing waste, and improving accountability throughout the mining and metals sector. In this regard, there is a general agreement amongst the industry leaders and stakeholders we surveyed that there is broad scope for pre-competitive collaboration on innovation to advance CE practices, improve accountability, increase industrial efficiency in recycling and recovery, and gain value throughout different metals and minerals supply chains, integrating both primary and secondary materials. Moreover, while demand for metals and minerals is expected to increase in the near to mid-term, longer term increases in the quantity of secondary materials available for recovery suggest a need for collaborative approaches to provide broader material solutions, moving beyond a reliance on raw material extraction as market requirements and consumer preferences change.

Technical, policy and market conditions which may enable pre-competitive collaboration on innovation in CE approaches include a range of factors. Foremost, however, addressing the risks that might come from tailings failures or other risks from waste is fundamental to maintaining the mining industry's social licence, creating a strong motivator for collaboration to improve perceptions of the industry overall. Requirements for standardized reporting or transparency were also cited as important enabling factors, to help overcome proprietary data and evolving sensitivities around mining practices. Better accounting standards for the value of re-used or recycled materials – including new interpretations or approaches to financial accounting frameworks – were also mentioned again as enabling factors to help identify value-added opportunities for collaboration.

Data & Modelling Tools to Support a Circular Economy Transition

A key implication emerging from this review of priority actions for advancing CE approaches in the metals and minerals sector, and for integrating upstream natural resource sectors into emerging CE thinking generally, is the need to improve data availability, measurement and tracking for CE transitions in primary resource sectors. Improved data availability, data sharing for improved material traceability, and the development of analytical and modelling tools to support scenario development for improved material circularity from the extraction phase all the way down the supply chain to product end-of-life have been highlighted as core requirements – with data gaps limiting our current understanding of a CE transition in Canada and elsewhere. However, the issue of how to effectively monitor progress towards a CE is an emerging and ongoing debate. Measuring the circularity of a system is challenging and there is neither a single approach to defining and measuring material circularity, nor is there common agreement on how to capture the whole spectrum of CE strategies within one consistent assessment framework.

To supplement the discussion in previous sections on priority actions for a CE transition in metals and minerals, this section reviews existing CE assessment indicators and metrics and explores the relevant indicators and tools needed to monitor and inform progress towards a CE. In doing so, it will review indicators and tools mostly from the scientific literature and group them according to common characteristics related to the questions they are designed to answer. A key take-away from this review is that measurements of material circularity cannot simply sum up kilograms of materials -- there are different dimensions to consider depending on the diversity of substances to account for, the diversity of economic sectors, and the consequences for society on different timeframes. Modelling approaches, objectives, and data requirements are not independent, and the required data collection and analysis frameworks need to be chosen accordingly.

Table 4 summarizes the findings in this section by providing an overview of the different types of indicators that have been proposed in the literature to assess CE, the types of questions each indicator is designed to address, and the CE strategies they embody. As highlighted in Table 4, understanding potential future pathways for CE requires addressing three major questions: (1) how circular is the economy or sector of interest?; (2) how can material circularity be improved?; and (3) to what extent are CE approaches compatible with movement towards a more sustainable society?. In the remainder of this section, we review the types of indicators highlighted in Table 4 and address the questions they are most likely to help answer, in order to provide insights on the data, indicators and tools that will be required to inform a CE transition as it applies in primary materials (and other sectors).

How Circular is a Particular Economy or Sector of Interest? To initiate a step towards a CE at any scale (product, company, city, country), knowing the current state of "circularity" is essential to have a basis of comparison. Material accounting is therefore necessary to answer fundamental questions about material flows and to help policymakers assess the given state of circularity. As the CE mainly focuses on material resources, material accounting methods place material management on the forefront. Their goal is to indicate to what extent the system under assessment is material (and energy) consuming and how material (or energy) efficient it is.

Material Flow Analysis (MFA): The goal of MFA is to map and quantify the flows and stock of resources into and from (or within) a particular entity of human society (Decker et al., 2000). For instance, MFA might be used to describe a system such as a city or a country in terms of its input and output flows of materials in space and time (Rincón et al., 2013). An MFA starts by defining a system's boundaries and then

Table 4: Summary of CE Indicators Proposed in the Literature, the Questions they are Designed to Address and the Circular Strategies they Embody.

	How linear is an economy?		What can be done to improve material circularity country-wide?			To what extent is a CE a step towards a sustainable society?		Other relevant questions	What are the circular strategies illustrated?			
	How many materials does an economy consume?	How material/ resource efficient is an economy?	How well is an economy doing to facilitate CE?	How to monitor trade-offs?	What are the key strategic characteristics of materials and CE opportunities?	What are the environmental implications of a CE	What are the socio-economic implications of a CE?	How to consistently aggregate kg of materials?	Reduce resource consumption and preserve ecosystems	Give resources a new life by linking value chains	Extend the life of products and components	Intensify products use
EW-MFA indicators	X								X	X		
Material circularity indicators		X							X	X		
Normalization options		X							X	X	X	X
Decoupling indicators		X							X	X		X
Enabling parameters			X						X	X	X	X
Process parameters			X						X	X	X	X
Footprint indicators	X	X		X	X	X			X	X		
Criticality indicators					X	X		X	X			
Environmental impact indicators				X		X		X	Scenario modelling in a life cycle approach			

undertakes modelling of relevant processes and material flows within the system (Cencic & Rechberger 2008). Processes can be a transformation, transportation, or storage activity, and they are considered black boxes represented by inputs and outputs of the system (Cencic & Rechberger 2008). Processes are connected by material or energetic flows.

MFA has been used to study CE at the country, region, or city scale. Some researchers, for instance, have applied MFA to develop circularity indicators (Sassanelli et al. 2019), while others have assessed the circularity of the global economy, the EU, or a specific city (Haas et al. 2015; Mayer et al. 2019; Voskamp et al. 2017), using an Economy-Wide MFA (EW-MFA) framework. For example, a recent study assessing the circularity of European material flows (Mayer et al. 2019) has illustrated that the EU is still far away from achieving a CE -- with only a 9.6% recycling rate at the EU scale. MFA can also be adapted to account for costs rather than physical flows in so-called material flow cost analysis (MFCA) (Merli et al. 2018).

Scaling Indicators: Scaling indicators (also referred to as "throughput indicators") measure the amount of material and energy flows throughout a system. These indicators, derived from the MFA methodology, help set governmental or regional targets on reducing raw material extraction and/or material waste: such as the total amount of industrial solid waste for final disposal, the total amount of wastewater discharge, or total material consumption to identify unrecovered waste. These "throughput indicators" scale material flows throughout a system defined in space and time, with the aggregation level defined according to national accounting preferences, data availability and policies.

How Can Material Circularity be Improved? Barring a reduction in consumption levels, total material use can conceivably only be reduced through an increase in the efficiency of material use in an economy (i.e. a decoupling of material extraction from production and consumption activities). This section presents indicators relevant to the question of material efficiency.

Material Circularity Indicators: Circularity indicators are usually represented in the form of ratios, capturing efficiency measures such as the share of recycled materials in production or the proportion of unrecoverable to total waste. Examples of material circularity indicators include circularity gap indicators proposed by Aguilar-Hernandez et al. (2019), which compare non-recovered waste to waste generation and stock depletion. These types of indicators allow target-setting by tracking the share of recovered waste or by comparing non-recovered waste to domestic material consumption -- thus explicitly addressing the potential to reduce waste generation.

Normalized Indicators: Also identified as 'Intensive indicators', normalized indicators are designed to be independent of the size of the system under assessment. Normalized indicators often compare material flow indicators, either between each other or with other dimensions. A frequent application of normalized material accounts, for instance, is to compare obtained MFA values to another system of reference. In China, the National circular economy indicator system includes efficiency indicators such as energy consumption *per unit product* in key industrial sectors and water consumption *per unit product* in key industrial sectors. Other types of unidimensional indicators indicate the dependence of the physical economy on domestic raw material supply, expressed as the ratio of Domestic Material Consumption (DMC) to Domestic Extraction (DE), or illustrate trade intensity by measuring the import or export intensities of the physical economy (Krausmann et al. 2017). These indicators provide complementary information that help identify potential leakage, by measuring the displacement of raw material extraction abroad. Other normalization options include dividing material quantities by population or gross domestic product (GDP) giving, respectively, a demographic and an economic context to circularity comparisons across countries or regions.

Decoupling Indicators: Tracking GDP and material use such as DMC over time illustrates the decoupling process of a region. In a coupled pathway, the more the economy grows, the more it relies on raw material extraction. Decoupling implies a less material intensive economy, either by reducing material use or by introducing secondary materials back into the economy. Comparing material use or waste generation to population and tracking the evolution of population, GDP and material use (such as DMC) over time allows for measurement of the influence of specific explanatory variables on final material consumption and the possibility to calculate elasticities for these explanatory variables on material intensity.

Enabling Parameters: Unlike the material circularity, normalized, and decoupling indicators discussed above, enabling parameters do not quantify how well a particular region, country, or municipality is performing with regards to circularity. Instead, enabling parameters indicate how well a particular region or jurisdiction is doing to *facilitate* a CE through public policies or programs. For instance, Eurostat proposes to quantify gross investment in the recycling, repair and reuse sectors, as well as the number of patents related to recycling and secondary raw materials (see Table 2). Other potential enabling parameters include the number of circular businesses supported, investment in CE demonstration projects, legislative and normative incentives created, enterprises receiving financial support in connection with the CE, or the amount of financial aid granted to companies in connection with the CE.

Process Parameters: Process parameters attempt to make explicit what traditional MFA-derived indicators indirectly capture. Due to their black-box structure, MFA-derived indicators for macro scale systems (i.e. EW-MFA indicators) do not allow a sufficient level of detail to identify the contributions of alternative CE practices, and may allow for different interpretations of circularity outcomes. Process parameters, alternatively, attempt to track the implementation of specific CE strategies which ultimately may lead to reduced resource consumption. A typical illustration of process parameters deriving from the implementation of CE strategies was explored by Material Economics, in a recent report quantifying the potential for CE opportunities to reduce GHG emissions from heavy industry by 2050 in the EU (Material Economics 2018). For each material studied (steel, plastics, aluminum and cement) they identified circularity measures that reduce the need for primary materials, such as increased recycling, reduced waste in production, increased reuse of components, new business models (e.g. car sharing) or circular materials handling (e.g. increased reuse of building components). Thus, rather than a single indicator, approaches with process parameters illustrate CE as a combination of factors working together towards a reduction of material or energy use.

To What Extent are CE Approaches Compatible with a more Sustainable Society? This group of indicators connects other sustainable development dimensions with material use. While the concept of CE is often directly linked to strategies for reducing waste and saving material resources, it should also make explicit the connections of circular strategies to broader issues of sustainable development. For instance, recycling processes are sometimes energy intensive, so that connecting CE to other sustainability indicators is necessary to highlight potential trade-offs for CE strategies.

Footprint Indicators: A footprint represents the quantity of something to be measured (e.g. environmental impacts, material or energy consumption) required across the supply chain to service final demand. For instance, not all material inputs into the manufacturing process necessarily become part of the product. A country can, for instance, have a very high Domestic Material Consumption (DMC) because it has a large primary production sector for export or a very low DMC because it has outsourced most of the material intensive industrial process to other countries. Thus, a material footprint is an extension of standard material flow accounts that captures the amount of extracted material needed to produce a certain (set of) product(s), throughout the entire production chain, irrespective of whether material extraction took place domestically or in the rest of the world (Eurostat 2018). For example, Wiedmann et al. (2015) use footprint indicators to track countries' use of non-domestic resources throughout international supply chains.

Criticality Indicators: Criticality indicators refer to the geopolitical and strategic context of material use, usually capturing three primary dimensions of criticality: high geopolitical concentration of primary production, lack of available substitutes, and political instability in the extraction region (Graedel et al. 2015). Criticality indicators are highly relevant to make strategic decisions on the use of material in industrial supply chains – as they identify the vulnerability for industrial sustainability to various material-related supply constraints. For instance, Graedel et al. (2015) find that the criticality of metal supply tends to be particularly acute for those metals available largely or entirely as byproducts, used in small quantities for highly specialized applications, and possessing no effective substitutes.

Environmental Impact Indicators: While material flows are often viewed as a proxy for environmental damage in CE studies, linkages between material flows and specific environmental impacts should be further elaborated (Moriguchi 2007). Life Cycle Assessment (LCA) requires identifying and quantifying matter and energy flows throughout a product's life cycle, which consists of technological processes raw material extraction (the cradle) to the product's end of life processing (the grave). First steps in LCA usually consist in defining a functional unit, which quantifies the product's or service's function under assessment, and the definition of a life cycle's boundaries. Following this step, called the Life Cycle Inventory (LCI) phase, the Life Cycle Impact Assessment (LCIA) phase translates resources, waste and emissions into the resulting environmental impacts by building on scientifically-based cause-effect chains (Hellweg & i Canals 2014).

Life cycle methods have also been developed to evaluate the economic and social impacts of a product life cycle, called Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA), respectively (Fauzi et al. 2019). Those developments, along with others such as the inclusion of temporal and geographical dimensions, enable answering sustainability-related questions arising from increasingly complex production and consumption systems. LCA is accordingly one of the most widely applied methodologies to assess the environmental performance of CE strategies (Sassanelli et al. 2019). For example, Lonca et al. (2018) used it to identify potential environmental trade-offs between material versus environmental efficiency of circular strategies, while Laso et al. (2018) used LCC to evaluate the environmental and economic benefits of CE strategies. Outcomes from such LCA studies suggest that that circularity indicators based on MFA may in some cases be at odds with environmental indicators (Lonca et al. 2018; Walker et al. 2018).

Conclusion: Summary & Priorities for Next Steps

This report provides an initial attempt to consider the implications of emerging global CE frameworks for upstream natural resource producers. While reducing the flow and intensity of primary material inputs and waste generation in any given sector or region is indisputably a central tenant of an effective CE transition, the relevance of globally emerging CE policy discussions for economies with significant primary resource-producing sectors, such as Canada, but also the US and many emerging economies in the Global South, is not well researched or understood. To date there has been little development of an upstream circular economy vision or strategies for raw material producers or exporters, and little exploration of the implications of a future circular economy for the balance of supply and demand for key material resources and commodities.

The general picture that has emerged is that while CE policies may reduce demand for primary raw materials in some developed economies, the inconvenient truth is that a preponderance of evidence from the World Bank, UNEP's International Resources Panel, the OECD, and others suggests ongoing (and likely increasing) demand for primary metals and minerals over the coming decades, *even with increased rates of material recovery, reuse, and recycling*. This understanding is driven by expectations of the material requirements for a low carbon transition, alongside projections of emerging economy material demands and realistic assessments of secondary material supply constraints in the near- to medium-term.

Our findings are intended to open a conversation about the role of primary natural resources, and the mining, metals, and minerals sector particularly, in an emerging CE. By improving understanding of how a low carbon, circular transition may impact future primary material demand, we are gaining a better sense of the policies and practices that may be needed to support natural resource producing economies in an increasingly circular, materially intensive global economy. However, this emerging understanding of the critical role to be played by primary material production in the global transition to a low carbon, circular economy is only an initial step. Without undermining the importance of secondary materials economies and the need to take a very serious approach to significantly reducing the environmental impacts of overall consumption levels, there is an urgent need to develop a fuller picture of the real-world implications of a low carbon, circular economy transition for primary resource sectors, and the metals, minerals and mining sector particularly.

In that respect, further research in CE approaches, policies, and practice is needed in several critical areas. These include: improving recognition of the value of metals and minerals found in upstream waste materials and how to build new, vertically integrated regional CE ecosystems; developing or extending CE metrics and indicators to upstream resource producing sectors, and linking these with existing sustainable or responsible production initiatives; developing common standards for reprocessed and recycled materials, including clear rules for trade in secondary materials and secondary material content requirements; improved regulatory processes to enable innovation in material content and waste recovery, to help reduce risk and facilitate testing and adoption of new ideas; determining how innovation in new product designs can support critical metals and mineral recovery across the value chain; and development of scenarios linking upstream and downstream incentives for material demand, use, and recovery, and focussed on establishing the business case for increasing circularity in critical metals and minerals from extraction through to end-of-life (especially 'climate action' minerals and metals).

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