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METAL EXTRACTION IN A LOW CARBON ECONOMY: PROJECTED TRENDS IN METAL DEMAND AND POLICY OPTIONS FOR DEMAND REDUCTION

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Turning Down the Heat: Can We Mine our Way Out of the Climate Crisis?

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Preface

The following report takes the form of an annotated bibliography, and reviews recent literature on how low carbon energy technologies may drive changes in metals and mineral demand, and policy options that may be used to minimize resource extraction pressures and impacts on mining communities in Canada. It seeks to position metal extraction in Canada within broader discussions of climate change policy, for applications in best practice sharing and improved awareness of how the mining sector is implicated in visions of a low-carbon economy. Other benefits of synthesized evidence on this topic might arise in the form of improved coordination and effectiveness of future research funding.

The literature review is organized in four categories: *projected changes in metal extraction demand, policy tools for reducing metal extraction demand,* and *technological tools for reducing metal extraction demand.* These categories emerged based on research needs identified by MiningWatch Canada in discussion with the Smart Prosperity Institute. Acknowledging the interconnections among categories, categorization of specific adaptation methods can become difficult, as many analyzed sources provide information relevant to two or more subcategories. However, for ease-of-use and organizational purposes, sources and annotations are grouped according to the primary adaptation theme they address.

Each annotated bibliography category is preceded by a section summary and analysis which defines the scope of the investigation, outlines key relationships among sources, and identifies gaps in literature. Source annotations are highlighted by a bolded subject heading to facilitate quick reference, and in some cases a brief description of source content and any interesting conclusions.

Projected Changes in Metal Extraction Demand

"While the growing demand for minerals and metals provides economic opportunities for resource-rich developing countries and private sector entities alike, significant challenges will likely emerge if the climate-driven clean energy transition is not managed responsibly and sustainably." ~ (OECD, 2019)

Many studies have reported on projections of metal extraction demand in the context of growing renewable energy technology demand required to meet the climate crisis. While all studies maintain that metal extraction will increase, the magnitude of this increase, and distribution across different mineral resources is varied. Each piece of research holds a unique set of assumptions, shedding light on different aspects of the complexity of making such projections. These assumptions involve making decisions on future technology mix, resource intensity of energy production, and recycling rates.

Several studies explore the variability in extraction demand as a function of climate action, representing status quo and 2°C scenarios. The time period of projections is also varied among studies, ranging from 2050 to 2100. Most studies center metal demand projections around three technologies: wind power, solar photovoltaics, and lithium-ion batteries. Several studies point to the variation in demand projections according to future technology mix, not only between different renewable technologies such as solar and wind, but also within renewable energy technology categories (e.g. between different types of solar technologies).

Key Questions & Gaps in Research

- How might we evaluate demand model assumptions and reconcile differences in metal extraction demand projections.
- To what extent and to what ends will inter-technology and intra-technology choices impact increased metal demand pressures?
- To what extent can recycling and reducing metal intensity of renewable technologies influence demand reduction.
- In which metals is Canada most heavily invested in terms of current assets and exploration projects? (Available information is widely dispersed).

Brief on Metals in a Low-Carbon Economy

World Bank. (2019). “Climate-Smart Mining: Minerals for Climate Action”. [online] Available at: https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action

This web page contains a detailed infographic that summarizes challenges posed by metal demand projections, and a range of policy and technological solutions.

An Overview of Metal Demand in the Context of Renewable Growth

World Bank. (2017). The Growing Role of Minerals and Metals for a Low Carbon Future. Washington, DC, USA: World Bank Publications. http://documents.worldbank.org/curated/en/207371500386458722/pdf/117581-WP-P159838-PUBLIC-ClimateSmartMiningJuly.pdf

This report outlines metal demand projections for different climate policy scenarios, focusing specifically on pressures from growth in solar, wind, and energy storage technologies. It considers the varied metal demand according to choices between technologies (intertechnology, ie. solar vs. wind) and within a technology option (intratechnology, i.e. thin film solar vs. crystalline silicon solar). The research predicts that metal demand will roughly double by 2050 for those metals relevant to wind and solar, and increase tenfold for metals crucial to energy storage. The report does not incorporate metal recycling rates in its projections.

Placing Metal Demand in the Context of Broader Resource Projections

OECD. (2019). Global Material Resources Outlook to 2060: Economic drivers and environmental consequences. Paris, France: OECD Publishing. http://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf

This study provides a variety of clear infographics and figures relating to material use, resource demand projections, and economic growth. It predicts that while material demand is projected to increase, the material intensity of the economy will slowly decline, representing a relative decoupling of economic growth and resource use. Interestingly, Fig. 8 (pg.13) shows recycling outputs in 2060 to outpace primary metal extraction.

Summarizing the Challenges of Increased Metal Demand in a Low-Carbon Economy

Vidal, O., Goffé, B. and Arndt, N. (2013). Metals for a low-carbon society. *Nature Geoscience*, *6*(11), 894-896. http://doi:10.1038/ngeo1993

Projected metal demand is framed as a supply issue that “risks derailing the shift to renewable energy” (pg. 895). This source highlights the dependence of our energy future on metal extraction and challenges posed by supply constraints, yet it notes that metals often classed as critical, are not actually so, since they can be substituted by shifting technology preferences.

Decade-by-Decade Outlook on Metal Demand Projections

Boubault, A., & Maïzi, N. (2019). Devising Mineral Resource Supply Pathways to a Low-Carbon Electricity Generation by 2100. *Resources*, *8*(1), 33. https://www.mdpi.com/2079-9276/8/1/33/htm

This study makes metal demand projections by decade through 2100, with Fig. 3. It offers insight into the fluidity of shifts in technology mix, and how this might affect which metals experience the greatest growth in demand in a given decade. While focusing on the impacts of climate scenarios on metal demand, this research points to a lack of knowledge around how increased resource development might reciprocally constrain emissions reductions, if GHG emissions intensity of mining activities is not simultaneously improved.

Setting the Context: Current Market Situation for Metals Relevant to Renewable Transition

Buchholz, P. and Brandenburg, T. (2018). Demand, Supply, and Price Trends for Mineral Raw Materials Relevant to the Renewable Energy Transition Wind Energy, Solar Photovoltaic Energy, and Energy Storage. *Chemie Ingenieur Technik*, *90*(1-2),141-153 https://doi.org/10.1002/cite.201700098

On Proposing Guidelines for Policy-Making

Watari, T., McLellan, B., Ogata, S. and Tezuka, T. (2018). Analysis of Potential for Critical Metal Resource Constraints in the International Energy Agency's Long-Term Low-Carbon Energy Scenarios. *Minerals*, *8*(4), 156. https://www.mdpi.com/2075-163X/8/4/156/htm

This article considers metal demand projections, and the potential of recycling to limit primary demand, with the aim of informing policy-makers on critical metals and important points of intervention. It describes different models for mapping future metal demand, and how recycling effects are incorporated into these models.

Broadening the Scope to Other Renewable Energy Technologies

Tokimatsu, K., Höök, M., McLellan, B., Wachtmeister, H., Murakami, S., Yasuoka, R. and Nishio, M. (2018). Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2 °C target with 100 percent renewable energy. *Applied Energy*, *225*, 1158-1175. https://www.sciencedirect.com/science/article/pii/S0306261918307578?via%3Dihub

This article expands the scope of renewable energy shifts to include growth in energy production from geothermal, hydropower, wave power, tidal power, nuclear, and biomass, among others. It highlights the scale of metal demand growth by showing that projected energy sector demand requirements will surmount total production levels from the present day (Fig. 9).

Critical Metals by Renewable Technology: Inter-technology Variance

Grandell, L., Lehtilä, A., Kivinen, M., Koljonen, T., Kihlman, S., & Lauri, L. (2016). Role of critical metals in the future markets of clean energy technologies. *Renewable Energy*, *95*, 53-62. https://doi.org/10.1016/j.renene.2016.03.102

This article identifies critical metals for several key technologies implicated in a transition to renewable energy. It demonstrates the potential for the variance in metal demand with different inter-technology renewable choices. The following elemental breakdown by technology is adapted from Table 1 (pg. 42).

Solar: Silver, Indium, Gallium, Selenium, Cadmium, Tellurium, Silicon, Tin, Germanium, Molybdenum.
Wind: Copper, Rare Earths (Dysprosium, Neodymium, Praseodymium, Y, Terbium), Cobalt, Manganese, Chromium, Molybdenum, Nickel, Iron, Boron, Barium
Energy Storage: Lithium, Cobalt, Nickel, Carbon, Manganese (Lithium-ion Batteries); Vanadium, Zinc, Iron, Chromium (Vanadium Redox Batteries)
Electric Grids and Transmission: Aluminum, Copper, Germanium, Zinc, Tin, Steel (Iron-Carbon alloy)

Metal Use by Renewable Technology: Intra-technology Variance

Månberger, A. and Stenqvist, B. (2018). Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy*, *119*, 226-241. https://www.sciencedirect.com/science/article/pii/S0301421518302726

This article explains variations in metal demand according to intra-technology choices (ie. thin film versus crystalline silicon). For solar photovoltaic options, thin film uses less overall material, but contains more rare elements such as gallium, selenium, tellurium, cadmium, and indium. Among wind options, direct drive (permanent magnet) turbines are more efficient, but require more rare earth metals than gearbox (electromagnet) turbines. For energy storage, most battery technologies contain lithium, but varied amounts of other metals including nickel, cobalt, aluminum, manganese, and iron.

Further Reading

Elshkaki, A., Graedel, T., Ciacci, L. and Reck, B. (2018). Resource Demand Scenarios for the Major Metals. *Environmental Science & Technology*, *52*(5), 2491-2497. https://pubs.acs.org/doi/pdf/10.1021/acs.est.7b05154

Van der Voet, E., Van Oers, L., Verboon, M. and Kuipers, K. (2018). Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. *Journal of Industrial Ecology*, *23*(1), 141-155. https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12722 de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G. and Tukker, A. (2018). Metal supply constraints for a low-carbon economy? *Resources, Conservation and Recycling*, *129*, 202-208. https://www.sciencedirect.com/science/article/pii/S0921344917303762

Vidal, O., Rostom, F., François, C. and Giraud, G. (2017). Global Trends in Metal Consumption and Supply: The Raw Material–Energy Nexus. *Elements*, *13*(5), 319-324. https://doi.org/10.2138/gselements.13.5.319

Giurco, D., Dominish, E., Florin, N., Watari, T. and McLellan, B. (2019). Chapter 11: Requirements for Minerals and Metals for 100% Renewable Scenarios. In Teske, S. (Ed.) *Achieving the Paris Climate Agreement Goals*, 437-457. Cham, Switzerland: Springer International Publishing. https://link.springer.com/chapter/10.1007/978-3-030-05843-2_11

Specific Metals of Interest

Among Canada's largest economic mineral assets identified in *The Canadian Minerals and Metals Plan,* platinum group metals, cobalt, copper, iron, nickel, and aluminum, are notably implicated in projected demand increases associated with a low carbon transition. The extent to which certain metals are crucial to a low carbon economy will depend on a variety of factors, as outlined in the previous section. Rare earth metals, predicted by most sources to experience the largest growth in demand in coming decades, are not currently produced in Canada, but are the focus of numerous resource exploration projects. Several studies have focused specifically on projected demand trends for rare earths, platinum group metals, copper, and cobalt.

Rare Earth Metals

Goodenough, K., Wall, F. and Merriman, D. (2017). The Rare Earth Elements: Demand, Global Resources, and Challenges for Resourcing Future Generations. *Natural Resources Research*, *27*(2), 201-216. https://link.springer.com/article/10.1007/s11053-017-9336-5

Platinum Group Metals

Hao, H., Geng, Y., Tate, J., Liu, F., Sun, X., & Mu, Z. et al. (2019). Securing Platinum-Group Metals for Transport Low-Carbon Transition. *One Earth*, *1*(1), 117-125. https://www.sciencedirect.com/science/article/pii/S2590332219300181

Copper

Schipper, B., Lin, H., Meloni, M., Wansleeben, K., Heijungs, R. and van der Voet, E. (2018). Estimating global copper demand until 2100 with regression and stock dynamics. *Resources, Conservation and Recycling*, 132, 28-36. https://www.sciencedirect.com/science/article/pii/S0921344918300041

Cobalt

Alves Dias, P., Blagoeva, D., Pavel, C., & Arvanitidis, N. (2018). Cobalt: Demand-supply balances in the transition to electric mobility. Joint Research Centre of the European Commission. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112285/jrc112285_cobalt.pdf

Policy Tools for Reducing Metal Extraction Demand

The policy tools for reducing metal extraction demand range from regulatory measures that would involve significant government planning and intervention, to more decentralized market-based incentive and market stimulation programs. Many of such policies draw on principles that align with the concept of circular economy. Consequently, a survey of potential policy tools for ensuring metal extraction demand reductions are vaguely categorized according to circular economy strategies outlined in the SPI Circular Economy Policy Brief.

Most literature on policy tools for demand reduction is not specific to a certain metal, and could be applied to a wide range of metal supply chains. This research focuses on highlighting examples where demand reduction measures have been applied to the mining sector, but draws on selected other sources where no mining-specific literature is available. As there is limited research on extraction demand reduction policies specific to the Canadian mining industry, sources draw on experiences from various national and global contexts.

The way in which the policy options outlined below might align with current mining priorities in Canada can be understood within the context of *The Minerals and Metals Policy of the Government of Canada*, which identifies priorities in sustainable development, in addition to economic growth and job creation. There is no explicit reference to metal demand reduction as a strategy; reference to sustainability points toward a clean growth discourse.

Key Questions & Gaps in Research

- Where are the critical intervention points for metal demand reduction, specifically for metals produced in Canada, and by Canadian foreign mining assets?
- What is the role of government in implementing policy tools for reducing metal extraction demand?

Regulatory Programs - Extended Producer Responsibility

Extended producer responsibility (EPR) programs are a government regulatory tool that requires producers to assume responsibility for wastes, both in processing, and in the form of end-of-life products. EPR programs essentially internalize the externalities imposed by wastes produced along the supply chain, and incentivize firms to adopt more circular supply chains. Several EPR programs have been implemented in Canada, but none specific to primary resource extraction.

Perspectives on EPR and Circular Economy

Kunz, N., Mayers, K. and Van Wassenhove, L. (2018). Stakeholder Views on Extended Producer Responsibility and the Circular Economy. *California Management Review*, *60*(3), 45-70. https://doi.org/10.1177/0008125617752694

This article highlights existing instances and successes of EPR programs, predominantly in Europe, explains useful policy considerations, and explores challenges to implementation of EPR frameworks. The research points to need for further developing incentives within EPR to more effectively reduce primary resource extraction.

EPR and Metal Recycling in Action, Case Study: E-Waste in China

Cao, J., Lu, B., Chen, Y., Zhang, X., Zhai, G., Zhou, G., Jiang, B. and Schnoor, J. (2016). Extended producer responsibility system in China improves e-waste recycling: Government policies, enterprise, and public awareness. *Renewable and Sustainable Energy Reviews*, 62, 882-894. https://doi.org/10.1016/j.rser.2016.04.078

This study follows the implementation of an EPR program in China, and effectiveness from a government perspective. It highlights that the EPR measures contributed to increased e-waste recycling rates, improved waste treatment techniques, and reduced resource use (pg. 885).

Planning for Sector-based Transitions: Alternative Business Models

As indicated in several metal demand reduction models, recycling and resource efficiency improvements cannot wholly curb projected increases in metal extraction demand; alternative business models based on circularity will be essential. Planning for sector-based transition of the mining sector in Canada will be inherently political, with strong industry interests advocating for growth. Circular economy models are poised as a politically favorable approach to demand reduction, as they satisfy the apparent conflict between economic growth and a need for reduced primary resource extraction.

Shifting Business Models for a Circular Economy

Florin N., Madden B., Sharpe S., Benn S., Agarwal R., Perey R. and Giurco D. (2015). Shifting Business Models for a Circular Economy: Metals Management for Multi-Product-Use Cycles. Sydney, Australia: Institute for Sustainable Futures. http://wealthfromwaste.net/wp-content/uploads/2015/11/P3-FINAL-SHIFTING-BUSINESS-MODELS-FOR-CE-ONLINE.pdf

Developing Indicators for Progress in Circular Economy

Howard, M., Hopkinson, P. and Miemczyk, J. (2018). The regenerative supply chain: a framework for developing circular economy indicators. *International Journal of Production*

Research, 1366-588X [online] https://www.tandfonline.com/doi/full/10.1080/00207543.2018.1524166

With significant uncertainty around metal demand projections, setting targets for demand reduction and circularity is an arduous task, and represents a gap in both research and experience. Though not specific to the mining sector, this paper puts forth a framework for conceptualizing and developing these targets.

Product Service Systems: Producers Retaining Ownership Through Use

Kjaer, L., Pigosso, D., Niero, M., Bech, N. and McAloone, T. (2018). Product/Service-Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption?. *Journal of Industrial Ecology*, *23*(1), 22-35. https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12747

This study highlights the potential of alternative resource ownership models to capture the maximum value of resources. It proposes several methods for increasing circularity. Metal producers might offer additional services such as expertise alongside their products, or they might lease their products and retain ownership and the value of their end-of-life products.

Transition by Recycling and Responsible Sourcing

Dominish, E., Florin, N. and Teske, S., 2019, Responsible Minerals Sourcing for Renewable Energy. Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney. https://www.uts.edu.au/sites/default/files/2019-04/ISFEarthworks_Responsible%20minerals%20sourcing%20for%20renewable%20energy_Report.pdf

Designing Waste Out of the Process

Tayebi-Khorami, M., Edraki, M., Corder, G. and Golev, A. (2019). Re-Thinking Mining Waste through an Integrative Approach Led by Circular Economy Aspirations. *Minerals*, 9(5), p.286. https://www.mdpi.com/2075-163X/9/5/286/htm

Creating Markets for Secondary Products and Waste

Schreck, M. and Wagner, J. (2019). Incentivizing secondary raw material markets for sustainable waste management. *Waste Management, 67*, 354-359. https://doi.org/10.1016/j.wasman.2017.05.036

Creating Value from Mining Tailings

Kinnunen, P., & Kaksonen, A. (2019). Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. *Journal Of Cleaner Production*, *228*, 153-160. https://doi.org/10.1016/j.jclepro.2019.04.171

Planning for Sector-Based Transition, Case Study: Batteries

World Economic Forum. 2019. A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation. http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

This report incorporates concepts from circular economy, clean growth, and resource nexus thinking, and provides an interesting perspective on metal demand reduction by exploring a specific technology.

Market-Based Incentives: Taxes & Subsidies

Market-based incentives such as tax and subsidies have become the central policy choice for GHG emissions reduction but are not as commonly applied to resource extraction. In relation to mining, market-based incentives may take the form of a mining waste tax, recycling subsidy, or tax exemption for sustainable practices.

The Economics of Resource Market Failures, and Reasons for Demand Reduction Interventions

Aidt, T., Jia, L. and Low, H. (2017). Are prices enough? The economics of material demand reduction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *375*, 20160370. https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2016.0370

This report outlines the basic economics that informs resource market failures, and moves on to explain the economic reasoning for demand reduction interventions. It describes how a tax on use of inputs could be used to induce substitution toward other resources. In the case of mining, this might facilitate substitution away from more environmentally damaging extraction processes or supply constrained metals.

A Rare Earth Metal Extraction Tax, Case Study: China

Ge, J. and Lei, Y. (2018). Resource tax on rare earths in China: Policy evolution and market responses. *Resources Policy*, *59*, 291-297. https://doi.org/10.1016/j.resourpol.2018.07.016

This research investigates the implementation of a resource tax on rare earth metals to internalize extraction externalities, improve resource utilization efficiency, and limit excessive rare earth metal demand. The tax has resulted in a decrease in both rare earth production, and domestic demand.

A Survey of Market-Based Metal Recycling Policies

Söderholm, P. and Ekvall, T. (2019). Metal markets and recycling policies: impacts and challenges. *Mineral Economics* [online].

https://link.springer.com/article/10.1007/s13563-019-00184-5

This study explores the potential impacts of various market-based recycling policies, including virgin material taxes, recycling subsidies, and tradable recycling credits.

Metal Recycling and Mining Subsidies, Case Study: Sweden

Johansson, N., Krook, J. and Eklund, M. (2014). Institutional conditions for Swedish metal production: A comparison of subsidies to metal mining and metal recycling. *Resources Policy*, *41*, 72-82. https://doi.org/10.1016/j.resourpol.2014.04.001

Green Procurement & Sustainable Supply Chain Management

Responsible sourcing of metals can ensure metal supply chains are managed in a more efficient and sustainable way. Sustainable mining certification schemes based on principles of circular economy, could provide guidelines for responsible sourcing, and may allow firms to distinguish their resources, giving sustainably produced resources a competitive edge. Effective certification schemes must be well-defined and enforceable. They will be most effective if implemented in combination with government green procurement standards.

Canadian Green Procurement Policy

The way in which these policy options might be applied to a Canadian context can be understood Canada's policy on green procurement can be found through the following link. https://www.tbs-sct.gc.ca/pol/doc-eng.aspx?id=32573

Comparative Analysis of Sustainability Standards in the Mining Sector

Mori Junior, R., Franks, D.M. and Ali, S.H. (2015). Designing Sustainability Certification for Impact: Analysis of the design characteristics of 15 sustainability standards in the mining industry. Centre for Social Responsibility in Mining, University of Queensland. https://core.ac.uk/download/pdf/43375360.pdf

Framework for Effective Green Procurement

Xu, S., Chu, C., Ju, M. and Shao, C. (2016). System Establishment and Method Application for Quantitatively Evaluating the Green Degree of the Products in Green Public Procurement. *Sustainability*, *8(*9),941. https://www.mdpi.com/2071-1050/8/9/941/htm

Sustainability Accounting and Reporting in the Ming Sector

Lodhia, S. and Hess, N. (2014). Sustainability accounting and reporting in the mining industry: current literature and directions for future research. *Journal of Cleaner Production*, *84*, 43-50. https://doi.org/10.1016/j.jclepro.2014.08.094

Sustainable Supply Chain Management: Literature Review

Sauer, P. and Seuring, S. (2017). Sustainable supply chain management for minerals. *Journal of Cleaner Production*, *151*, 235-249. https://doi.org/10.1016/j.jclepro.2017.03.049

Sustainable Supply Chain Management: A Circular Economy Framework

Kazancoglu, Y., Kazancoglu, I. and Sagnak, M. (2018). A new holistic conceptual framework for green supply chain management performance assessment based on circular economy. *Journal of Cleaner Production*, *195*, 1282-1299. https://doi.org/10.1016/j.jclepro.2018.06.015

Sustainable Supply Chain Management, Case Study: Ghana

Peprah, J., Opoku-Fofie, I., and Nduro, K. Factors affecting green supply chain management in the mining sector in Ghana. *European Journal of Logistics, Purchasing and Supply Chain Management, 4*(1), 32-50. http://www.eajournals.org/wp-content/uploads/Factors-Influencing-Green-Supply-Chain-in-the-Mining-Sector-in-Ghana.pdf

Market Stimulation: Investment in Research & Development

Market stimulation through investment in research and development is a means for governments to support firms in adopting more environmentally sustainable practices, by making them more affordable, and allowing firms to remain competitive in global markets. If investment stimulates innovation in circular economy, then metal demand reduction can follow.

Impact of Green R&D Investment on of Market Value of Mining Firms

Ganda, F. (2017). Green research and development (R&D) investment and its impact on the market value of firms: evidence from South African mining firms. *Journal of Environmental Planning and Management*, *61*(3), 515-534.

Benefits of Green Credit Policy

He, L., Wu, C., Yang, X. and Liu, J. (2018). Corporate social responsibility, green credit, and corporate performance: an empirical analysis based on the mining, power, and steel industries of China. *Natural Hazards*, *95*(1-2),73-89.

Financing Innovation and Circular Economy

Goovaerts, L., Schempp, C., Busato, L., Smits, A., Žutelija, L. and Piechocki, R. (2018). Financing Innovation and Circular Economy. *Designing Sustainable Technologies, Products and Policies*, 427-432.

Technological Tools for Reducing Metal Extraction

Technological solutions to sustainability issues present exciting opportunities to reduce environmental impacts of metal extraction and processing, and support demand reduction though reducing metal intensity of renewable technology, facilitating increased product lifetimes, improving ease of refurbishment, and improving recycling or recovery strategies. These solutions might be incentivized by the various policy tools outlined in the previous section.

Key Questions & Gaps in Research

- What is the current state of metal recovery and recycling in Canada?
- What are the most significant opportunities to improve metal recovery, recycling, and resource efficiency in Canada through technology adoption?

Recovery

Metal Recovery, Case Study: Landfills

Wagner, T. and Raymond, T. (2015). Landfill mining: Case study of a successful metals recovery project. *Waste Management*, *45*, 448-457.

A Life-Cycle Analysis of Three Approaches to Metal Recovery

Li, Z., Diaz, L., Yang, Z., Jin, H., Lister, T., Vahidi, E. and Zhao, F. (2019). Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. *Resources, Conservation and Recycling*, *149*, 20-30. https://doi.org/10.1016/j.resconrec.2019.05.025

Recycling and Reuse

Overview of Metal Recycling Processes: Key Considerations

International Resource Panel. (2013). Metal Recycling: Opportunities, Limits, Infrastructure. http://wedocs.unep.org/bitstream/handle/20.500.11822/8850/Metal-recycling-opportunities-limited-infrastructure-Summary.pdf?sequence=1&isAllowed=y

The Current State of Knowledge on Metal Recycling Rates

Graedel, T., Allwood, J., Birat, J., Buchert, M., Hagelüken, C., Reck, B., Sibley, S. and Sonnemann, G. (2011). What Do We Know About Metal Recycling Rates?. *Journal of Industrial Ecology*, *15*(3), 355-366.

General Challenges in Metal Recycling

Reck, B. and Graedel, T. (2012). Challenges in Metal Recycling. *Science*, *337*(6095), 690-695. https://doi.org/10.1126/science.1217501

Challenges in Recycling Scarce Metals in Complex Matrices

Andersson, M., Ljunggren Söderman, M. and Sandén, B. (2019). Challenges of recycling multiple scarce metals: The case of Swedish ELV and WEEE recycling. *Resources Policy, 63,* 101403. https://www.sciencedirect.com/science/article/pii/S0301420719300625?via%3Dihub

Value Captured from Metal Recycling

Hatayama, H., Tahara, K. and Daigo, I. (2015). Worth of metal gleaning in mining and recycling for mineral conservation. *Minerals Engineering*, 76, pp.58-64. https://doi.org/10.1016/j.mineng.2014.12.012

Recovery and Recycling of Rare Earth Metals

Jowitt, S., Werner, T., Weng, Z., & Mudd, G. (2018). Recycling of the rare earth elements. *Current Opinion In Green And Sustainable Chemistry*, *13*, 1-7. https://doi.org/10.1016/j.cogsc.2018.02.008

Resource Efficiency

Improving Material Efficiency for Critical Metals

Ayres, R. and Peiró, L. (2013). Material efficiency: rare and critical metals. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*(1986), 20110563. https://royalsocietypublishing.org/doi/full/10.1098/rsta.2011.0563