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Circularity in Mineral and Renewable Energy Value Chains: Overview of Technology, Policy, and Finance Aspects

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EXECUTIVE SUMMARY

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The full report is available on CCSI's website at:
https://ccsi.columbia.edu/circular-economy-mining-energy.

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1. Introduction

The global transition to renewable energy systems will be mineral intensive and, under current conditions, will exacerbate mining's footprint on the planet. In addition, the material needs of a growing global population whose lives are increasingly digitized will further increase mineral demand. The success of the mining and metals sector in the coming decades will depend on its ability to meet those needs sustainably through a combination of responsible primary extraction and the adoption of circular economy approaches throughout the mineral and renewable energy value chains, ensuring that inherently durable materials never become waste.

The Columbia Center on Sustainable Investment (CCSI), supported by ICMM and the Enel Foundation, researched the conditions needed for mining companies to become stronger on **process circularity** and start embracing **product circularity** in their business models (Figure 1).

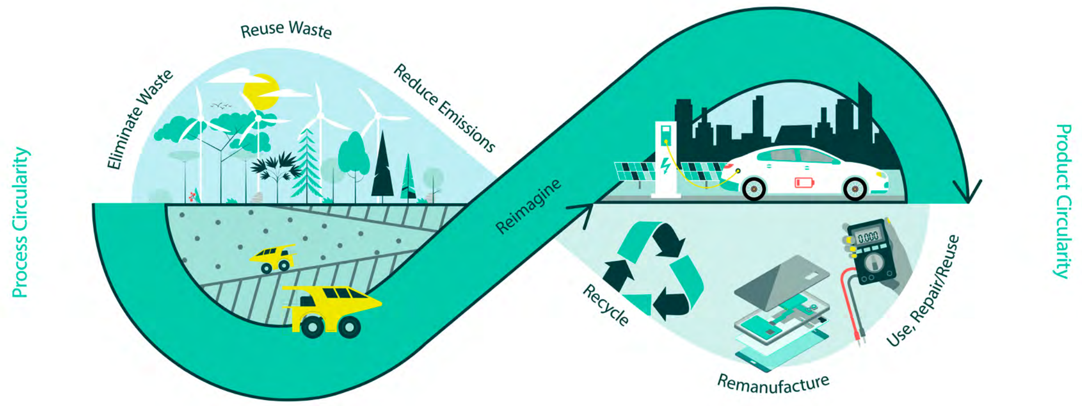

Figure 1. **Process and product circularity**
Source: ICMM 2023.[1]

Process circularity refers to reducing emissions and minimizing, reusing, and ultimately eliminating waste at mine sites and metal industries (Box 1), and **product circularity** refers to repairing, reusing, and remanufacturing equipment, and harvesting and recycling metals indefinitely through product design and collection processes.[2]

BOX 1. PROCESS CIRCULARITY AT LARGE

While process circularity covers all types of waste (minerals, energy, heat, rock, and land), this study focuses on mineral waste. Other studies authored or co-authored by CCSI focus on other aspects of process circularity:

- Renewable energy: *Net Zero Roadmap for Copper and Nickel,*[3] *The Renewable Power of the Mine*[4]
- Water: *Assessing Water-Related Risks in Mining and Framework for Shared-Use in Water*[5]
- Land: *Circular Economy: Mining Land Potential*[6]
- Implications of SDG 12 (Ensure sustainable consumption and production patterns) for the mining and metals sector: *Mapping Mining to the Sustainable Development Goals*[7]

The research focused on **process** and **product circularity** in the mineral value chains of solar photovoltaic (PV) panels and wind turbines (in short: solar and wind) and zeroed in on four key materials that are critical to solar and wind—aluminum, copper products, silicon, and steel. Many of the findings and conclusions are relevant and may be transferable to other material value chains of the energy transition.

Process circularity in mining activities and metals processing is critical to:

- Allowing mining and metals companies to reach net-zero emissions by 2050, in line with the Paris Agreement on climate change.
- Reducing the upstream scope 3 emissions of downstream players, including in the solar and wind value chains.
- Accessing existing tailings of immense value (Box 2), thereby providing a secondary source of minerals and other materials to limit a supply crunch.
- Securing export markets where due diligence requirements are becoming stricter (for example, the European Union (EU)'s proposed Corporate Sustainability Due Diligence Directive).[8]
- Ensuring the social license to operate for mining and metals companies by building up a legacy of long-lasting assets—namely, infrastructure assets that serve the reprocessing of mine sites' materials and minerals.
- Reducing Environmental, Social, and Governance (ESG) risks of downstream players, including along the solar and wind value chains, by minimizing negative social and environmental externalities of mining activities and metals processing.

BOX 2. COPPER VALUE IN TAILINGS

Approximately 46% of annual global mine tailings come from copper mines.[9] Concentrations of trace elements (including copper) in tailings are low, generally below 1%. In the last century, the copper content of some tailings was as high as 0.75%. Current deposits mostly contain 0.2%–0.8% copper.[10] For example, assuming the same concentration range, copper tailings produced in 2022 and amounting to 4,214 million metric tons (Mt) could be worth between USD 74 billion and USD 297 billion (using current primary metal price).[11]

In parallel, **product circularity** represents a business opportunity for the mining and metals companies, solar and wind manufacturers, and power utilities, because:

- Product circularity allows mining and metals companies to reduce their downstream scope 3 emissions.
- Solar and wind manufacturers and power utilities need the skills and understanding of the materials of the mining and metals sector to enable circular design and metal recoverability from products at end of life.
- Broad policy and societal support back the growth of the product circularity industry, particularly in the metal-intensive solar and wind value chains.
- Mining and metals companies need to put a product circularity strategy in place today to increase business resilience in the face of resource nationalism, which in turn limits the material supply risk for solar and wind manufacturers and power utilities.
- Product circularity strategies help prepare solar and wind value chains to access immense recoverable stocks and waste flows when products reach their end of life (Box 3). The mineral content in these stocks and flows is becoming of a higher grade than the grade of minerals and materials at mine sites, which is in constant decline,[12] particularly in copper, improving the business case of secondary recovery as compared to primary extraction.

BOX 3. ALUMINUM VALUE IN SOLAR WASTE AND STEEL VALUE IN WIND WASTE BY 2050

Approximately 212 million metric tons (Mt) of solar PV panel waste will be produced by 2050, including 39 Mt of waste of aluminum (approximately 22 years of production of aluminum in the United States (U.S.)[13]), worth USD 98 billion (at current metal prices[14]). Approximately 196 Mt of wind turbine waste will be produced by 2050, including 142 Mt of waste of steel (approximately 20 years of production of steel in the U.S.[15]) worth USD 121 billion (at current metal prices).[16]

CCSI's research first unpacks the technological and logistical hurdles for circularity in solar and wind value chains to understand the associated barriers that stronger policy and impact finance could lift (Section 2). Then it turns to exploring the necessary conditions to enable the mineral and metals sector to play a role in the circular economy of solar and wind value chains, in terms of both policy (Section 3) and finance (Section 4), also highlighting ICMM's ongoing work in identifying circular business models that mining and metals companies could prepare for under current conditions (Section 5). Finally, CCSI presents calls to action for mining and metals companies, solar and wind manufacturers and power utilities, and their industry associations (Section 6).

2. Roadmap of Technology Developments

CCSI's proposed roadmap of technology developments in the context of process circularity focuses on technologies minimizing or valorizing mining waste; in the context of product circularity, it focuses on recovery and recycling technologies in solar and wind value chains.

The overall picture of technological development for the commodities examined shows different levels of maturity and commerciality in process and product circularity across the mineral, solar, and wind value chains.

Process Circularity. To minimize or valorize mining waste, there already are commercially available technologies, such as in advanced geo-metallurgy or advanced sensing and sorting. Further technological development is expected to bring much more progress in precise mining and in-situ leaching (Figure 2).

Process circularity: Technology readiness Mining

 Technology requires innovation | no current cost competitive

 Some technologies ready, others close to market | some cost competitive or nearing competitive

 Technology close to market | costs nearing competitiveness

 Technology ready | cost competitive

Materials	*Technology Readiness*	*Details*
Advanced geo-metallurgy		These methods enable a holistic comprehension of the ore and tailings deposits, as well as the location and composition of waste rock. These methods are already cost-competitively available.
Advanced sensing and bulk ore sorting		These methods involve a penetrating sensor enabling the separation of unproductive material, diverting it away from further processing. Some tech is already available but some needs to be improved.
Thickening and dehydrating		Technologies to dewater the tailing dam exist but R&D is still happening to improve their cost-effectiveness.
Safe recovery of minerals from tailings		Traditional hydrometallurgical methods, such as solvent extraction and acid leaching are already used for the recovery of metals, but they can be costly and not environmentally safe. Bio-metallurgy is more promising, but its efficacy has room to grow.
Advanced particle sorting and preferential fracturing		Particle separators use sensor-based measurements to determine which rock fragments containing valuable metals should be recovered or rejected, enabling more targeted and controlled fracturing. Further tech development is expected to make it more cost-effective.
In situ leaching		The procedure of extracting desired minerals from an ore deposit by utilizing a chemically treated leaching solution is in still in R&D phase for the most part.

Figure 2. **Process circularity: technological readiness (mining)**
Sources: ICMM 2022,[17] IFC 2023,[18] Sarker et al. 2022,[19] Wang et al. 2022,[20] CCSI Analysis.

Product Circularity. Recovery and recycling technologies in solar and wind value chains vary depending on the material considered. Aluminum can commercially be recycled to solar grade, which is the same as the construction grade. The same is true for the steel used in wind turbine towers. Copper wires in wind turbines can also be commercially recycled to the required wind grade, which is not specific to wind turbines. To recycle solar silicon to solar grade and even to electronic grade, technology development is still expected to reduce costs, but R&D has already yielded good results, and so the recovery and recycling technology is nearly competitive. R&D still has big strides to make in the steel of the wind turbine generator, the composite materials of the wind turbine blades and some other components in solar panels, such as glass, Ethylene vinyl acetate (EVA) film, and back sheets. Throughout the design phase, hazardous substances need to be minimized with available technology for more accessible and healthier recycling (Figure 3).[21]

Product circularity: Technology readiness

Technology requires innovation | no current cost competitive

Some technologies ready, others close to market | some cost competitive or nearing competitive

Technology close to market | costs nearing competitiveness

Technology ready | cost competitive

	Materials	*Technology Readiness*	*Details*
Solar	Aluminum		Aluminum alloys in the 6000 series, especially grade 6063 aluminum, are the most common for solar panel frames. Recycling technology of 6000s is cost-effectively available.
Solar	Silicon		Some expensive technologies enable silicon-based solar cells to be reused or recycled to the same grade (in closed loops), but R&D is still needed for cost-effectiveness and minimizing downcycling.
Wind	Steel in the generator		NGO (non-grain oriented) electrical steel is hard to recycle, up to 10% can be recycled to produce a new unit of NGO electrical steel, which can only come from the BOF route.
Wind	Steel in the tower		The steel grades in wind turbine towers are similar to those used in construction. The structural grade steel can commercially be recycled or reused in construction.
Wind	Copper in the generator		Copper wire is used for the purpose of creating coil windings in the stator and rotor of the generator. Closed-loop and open-loop recycling options commercially exist for copper wires.

Figure 3. **Product circularity: technological readiness (solar and wind value chains)**
Sources: Aperam,[22] AZOM Material 2022,[23] Clean Energy Review 2022,[24] Composite World 2022,[25] Engineering 2020,[26] IFC 2023,[27] NREL 2021,[28] VSSES 2021,[29] CCSI Analysis.

Figure 4 presents the roadmap of technological development under current policy and finance conditions. The realization of enabling policy and finance conditions could considerably accelerate this timeline.

Circular economy technology roadmap to 2050

	Technology/Year	*2020s*	*2030s*	*2040s*	*2050s*
Mining	Advanced geo-metallurgy	Commercial			
	Advanced sensing and bulk ore sorting, tailings thickening, mineral recovery	R&D	Commercial		
	Advanced particle sorting and preferential fracturing	R&D		Commercial	
	In situ leaching	R&D		Commercial	
Solar	Aluminum	Commercial			
	Silicon	R&D	Commercial		
Wind	Steel in the generator	R&D			Commercial
	Steel in the tower	Commercial			
	Copper in the generator	Commercial			

Figure 4. **Roadmap to 2050 of focused mining process technologies and recovering and recycling technologies of the studied materials**
Source: CCSI Analysis.

The impact of R&D and technological development will occur initially mostly in closed loops, which enables the traceability of materials between buyers and purchasers (Box 4). On the contrary, in open loops and on the scrap market, other challenges compound the technological ones: challenges related to the collection infrastructure, logistics, the structure of the market, and cross-border trade (Figure 5).

BOX 4. CLOSED LOOPS VERSUS OPEN LOOPS

Closed loops occur when a material or product can be recovered and reused or recycled indefinitely for the same application for which it originally had, without a loss in quality and with zero waste.

Open loops mix materials of different sources and levels of quality, without traceability associated with the materials. As such, they are associated with the downgrading of material quality and the rejection of some materials for being of too low quality to be used.

Realizing open-loop circular economy in both ferrous and non-ferrous metals poses many challenges

Challenges identified in the value chains of steel, aluminum, and copper products.			
Collection & sourcing	***Scrap processing***	***Inventory & logistics***	***Trade policies***
• Different grade of scrap mix • Low integration between up- and downstream players • Collection rate is low from some sources (more for copper than for aluminum and steel that are bulkier in products) • Non-ferrous scrap may also end up in slags or remains in the form of impurities during other metal recycling process (e.g., copper, aluminum residues in steel scrap, steel residues in aluminum)	• Contamination with residues is common • Product design can make it more difficult to disassemble and separate • Recycling industry is fragmented which limits the scaling of recycling units and harmonized quality standards • Downgrading is frequent (e.g., aluminum scrap ends up in internal combustion engines)	• The fluctuation in prices between scrap and primary aluminum leads to difficult inven-tory management • Logistics cost limits the sales radius of recycling companies • Scrap supply & demand mismatch	• Lack of harmonized definitions of various types of materials, goods, and waste relevant to circularity • Tariff and non-tariff barriers to the free flow of scrap and finished products across borders

Figure 5. Challenges in realizing open-loop circularity in both ferrous and non-ferrous metals
Source: CCSI Analysis.

CCSI's in-depth analysis of current policy and financial conditions and hindrances reveals that increased policy and financial support are needed to lift the remaining technological and logistical barriers to process and product circularity along the mineral value chains of solar and wind.

3. Roadmap of Necessary Policy Conditions

CCSI analyzed circularity policies in nine countries or regions (Australia, Canada, Chile, China, the EU, India, Japan, South Korea, and the United States), selected based on the existence of relevant policies as well as their market share in the production of the minerals, metals, and products (solar PV panels and wind turbines) within the scope of CCSI's study. Based on this analysis, CCSI concludes the following:

- Few countries have dedicated policies for circularity in solar, wind, and metals. Even fewer countries consider linkages between raw material inputs and circular loops and roadmaps. Illegal trade and leakage of materials are high across all value chains, with some recent policy movement to address these issues.
- The regulatory framework should be further clarified in many countries, for various reasons: the complexity of the waste management regulations may encourage landfilling; laws may be contradictory; the re-processing of waste streams or tailings at mine sites is not normalized; sales of secondary products across industries are not authorized; or valuable co-products are qualified as waste.
- Ahead of regulatory clarifications, several states are unlocking R&D budgets to encourage innovation both in solar recycling technologies and in secondary minerals and metal recovery, when the metals and minerals are listed in the critical material lists.
- However, worldwide, the legal and policy framework should go beyond targeting reuse and recycling only, following the trend set by the EU, which is rolling out design requirements associated with digital passports in solar and wind energy value chains.
- The current expansion of Extended Producer Responsibility (EPR) (Box 5) to all solar PV panel value chains holds promise, if effectively designed. In wind, circularity policies remain limited to prolonging the life of turbines (given the difficulty of designing for recoverability and of recycling blades) and should be quickly developed further.
- There are good policies to be replicated or expanded worldwide, such as Australia's first public atlas of tailings and Japan's material efficiency policies in metal-making.
- Monitoring and enforcement systems are weak or absent and should be put in place in most studied jurisdictions.
- Post-mining land-use policies should be developed, moving beyond mine reclamation.

BOX 5. WHAT IS EXTENDED PRODUCER RESPONSIBILITY (EPR)?

The OECD defines EPR "as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. An EPR policy is characterized by:

- the shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities; and
- the provision of incentives to producers to take into account environmental considerations when designing their products. While other policy instruments tend to target a single point in the chain, EPR seeks to integrate signals related to the environmental characteristics of products and production processes throughout the product chain."[30]

To support the development of necessary conditions, CCSI proposes a policy toolkit (Figure 6) and roadmaps for policy deployment, distinguishing between process circularity policies (Figure 7) and product circularity policies (Figure 8). The ultimate goals are to incentivize design for material to be recovered forever, disincentivize waste creation, and enable recycling as a measure of last resort, according to the 9 "Rs" hierarchy (Figure 9).

The policies in CCSI's roadmaps aim at activating all the levers of circularity (rethink, reduce, reuse, and recycle, among others) by improving the policy landscape to shift business practices along the mineral value chains of solar and wind.

CCSI's suggested policies are inspired by recent policy developments (particularly in the EU), conversations with a wide range of experts, and CCSI's knowledge and expertise in related areas such as climate and industrialization policies.

While CCSI's suggested policies and roadmaps present various policies that can be used, the specific package of policies that a country or region may adopt will depend on the context. They will vary according to level of economic development, regulatory approaches, political feasibility, societal demand, and other factors.

Cross-cutting | Reduce | Rethink | Reuse/Recycle

Process and product circularity policy toolkit

Policy tools	*Type or topic*	*Policy measure*
Circularity roadmaps		• Develop a circularity roadmap for each industrial sector from resource extraction, leveraging the hierarchy of the 9Rs, promoting producer ownership as appropriate, harmonizing all laws related to each sector, and considering value chains
Regulatory and economic instruments	Design	• Harmonize accounting methods and require consideration of life-cycle emissions at the design stage
		• Require and incentivize designs that promote modular durability, taking into account the technological risk
		• Require and incentivize designs that enable reuse and recyclability (eg: no hazardous materials, easy disassembly)
		• Require and incentivize material efficiency in design
	Process	• Promote reduction of losses during manufacturing or mining (includes optimization of the extraction and operational process to minimize all wastes from energy to water to land to materials)
		• Require and incentivize land reclamation plans in early planning that include consideration for beneficial post-mining land uses
		• Promote industrial symbiosis, turning one industry's by-product into another industry's raw material
	Targets	• Set industry-specific material recovery targets with increasing levels of ambition
		• Set industry-specific collection rate targets with increasing levels of ambition
		• Set industry-specific minimum recycled content with increasing levels of ambition
	Standards	• Set quality standards for secondary minerals and metals and by-products and their reuse across industries
		• Set quality standards for recycling technologies
	Labels	• Require labeling and information on durability, recyclability and reparability of products within digital product passports
	Landfills and active/ legacy tailings	• Impose bans, restrictions and differentiated penalties to discourage landfilling of valuable materials
		• Streamline the permitting processes to reprocess waste streams and tailings
		• Incentivize the reprocessing of valuable waste above alternative treatment methods of waste, such as incineration
		• Eliminate regulatory uncertainty on what qualifies as waste
	Trade	• Progressively eliminate tariff and non-tariff barriers to trade in circular economy goods (second-hand goods, goods for refurbishment and remanufacturing, waste and scrap for recovery, secondary raw materials, and goods produced using circular processes) and services
		• Develop and harmonize definitions of remanufactured goods; used goods; hazardous and non-hazardous waste; scrap; second-hand goods; non-waste goods for reuse, repair, refurbishment, and remanufacturing; and goods produced using circular processes

Cross-cutting | Reduce | Rethink | Reuse/Recycle

Policy tools	Type or topic	Policy measure
Producer responsibility and ownership	Extended producer responsibility (EPR)	• Implement effective EPRs (institutional system to fight against leakage and free-riding, appropriate financing structure, allocation of responsibilities along the supply chain)
	From EPR to producer ownership	• Make producer ownership & product stewardship attractive by facilitating servitization or leasing models, where appropriate, and rewarding full circularity
Compliance promotion	Data availability and partnerships	• Set up publicly available material registries, including includes national/global tailings inventories
		• Actively facilitate cross-industrial partnerships for closing the loop on materials and land use
		• Increase data collection, stock and flow models, life-cycle assessment, and benchmarking of techniques (BAT)
Public information & awareness raising	Consumer and industry awareness	• Develop consumer-focused awareness campaign
		• Develop industry-focused awareness campaign
Public financing	R&D, infra-structure and procurement	• Finance R&D support
		• Develop de-risking financing structures to catalyze private funding
		• Finance collection, traceability, and recycling infrastructure
		• Require circularity in public procurement
Monitoring	Registration and monitoring metrics	• Require registration of products and their digital passports
		• Develop indicators to track the speed of innovation and demand growth of products to strike a balance between measures encouraging durability vs recyclability
Enforcement	System	• Develop a system of enforcement (dedicated mechanism, auditing mechanisms, penalty schemes)

Figure 6. Process and product circularity policy toolkit
Source: CCSI's policy and legal review.

Roadmap of policy conditions for process circularity

Now	*Short-term (5 years)*	*Medium-term (10 years)*
• Develop **circularity roadmap** and **awareness campaign** • **Remove legal barriers** and create standards for secondary markets • **Incentivize change in practice** (land repurposing, waste-free processing, and reprocessing) • **Impose landfill restrictions** • **Finance data, R&D, and infrastructure** • **Facilitate partnerships** • Set up **enforcement**	• **Move from incentivizing to requiring when possible; incentivize only when additional** (land repurposing, waste-free processing, and reprocessing) • **Require a life-cycle assessment** (LCA) for minerals and metals based on robust standards • **Set targets** for process circularity • **Leverage trade** for process circularity, distinguishing between circular and linear goods	• **Require digital passports** for minerals and metals, applicable to all producers, importers, and customers • **Foster industrial symbiosis** • **Review and adjust all policies**

Figure 7. Roadmap of policy conditions for process circularity
Source: CCSI's policy and legal review.

Roadmap of policy conditions for product circularity

Now	*Short-term (5 years)*	*Medium-term (10 years)*
• Develop **circularity roadmap** and **awareness campaign** • **Remove legal barriers and create standards for secondary markets** • **Incentivize change in practice** (circular product design, material efficiency and end-of-life waste reprocessing) • **Set dynamic targets** • **Impose landfill restrictions** • **Finance** data, R&D, and infrastructure • **De-risk** private investment when additional • **Facilitate partnerships** • **Set up enforcement**	• **Move from incentivizing to requiring when possible;** incentivize only when additional (product design and end-of-life waste reprocessing) • **Make extended producer responsibility (EPR) effective** • Require **digital passports** • Develop **economy-wide indicators balancing durability with recyclability** • Require circularity in **public procurement** • Address **trade issues** hindering product circularity	• Make **producer ownership / servitization / metals leasing** attractive for mining and metals value chains • **Review and adjust** all policies

Figure 8. **Roadmap of policy conditions for product circularity**
Source: CCSI's policy and legal review.

Full circularity entails following a hierarchy of principles

↑ *Increasing Circularity* ↑	Smarter product design, use and manufacture	R0 Refuse	Cap growth of demand for an end-product by seeking system efficiencies
		R1 Rethink	Change business models (e.g., shift to servitization) and critical infrastructure to achieve the same demand with fewer primary linear products
		R2 Reduce	Increase efficiency in product manufacture by seeking material efficiency
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of discarded product in a new product with the same function
		R7 Repurpose	Use discarded product or its parts in a new product with a different function
	Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
		R9 Recover	Incineration of material with energy recovery

Figure 9. **The 9 R hierarchy**
Source: Adapted from Julian Kirchherr, Denise Reike, and Marko Hekkert.[31]

4. Roadmap of Necessary Finance Conditions

Beyond venture capital and first-mover banks, private finance should support circular business models by integrating the linear risk analysis in valuation models. Circular business models are currently considered risky. Public finance, particularly from the EU, provides the only source of long-term low-cost capital for circular models, but it is growing and may play a catalytic effect on private finance. Mining and metals companies, solar and wind manufacturers, and power utilities should engage and develop business and governance models to ensure their inclusion in the EU taxonomy under the circular economy objective and become a beneficiary of sustainable finance.

To realize these conditions, CCSI proposes a roadmap to ensure that the financial institutions develop a financial engagement strategy and financial products tailored to support circularity (Figure 10).

Roadmap of finance conditions

Now	*Short-term (5 years)*	*Medium-term (10 years)*
• **Understand the linear risk** of current business models, • **Assess the business opportunities** associated with new business models, • **Support the development of circular metrics** beyond waste management and **strong taxonomy technical criteria for circularity** in mining value chains.	• Include circular economy in **engagement strategies**, • Engage in **public–private finance partnerships**; • **Start developing dedicated financial products to increase access to finance and reduce cost of capital.**	• **Measure results of the engagement and financing strategy and develop further dedicated financial products.**

Figure 10. **Roadmap of finance conditions**
Source: CCSI analysis.

To successfully implement the policy and finance roadmaps, stakeholders along the mineral value chains of solar and wind need to engage with policy makers, innovators, and financiers.

5. Circular Business Models

In parallel to following the roadmaps to put in place technology, policy, and finance conditions conducive to circularity, achieving circularity in the mineral value chains of solar and wind also depends on adopting circular business models throughout those value chains. While the success of the full transformation in business models depends on the necessary conditions, preparing for their deployment under current conditions is critical from a risk and opportunity strategy standpoint (Sections 2 and 6).

Although the development and adoption of these business models lie beyond the scope of this analysis, CCSI highlights the ongoing work undertaken by ICMM in examining six 'families' of circular business models that mining and metals companies could employ to test opportunities for operations, business units, and companies (Figure 11).

Companies throughout mineral value chains of solar and wind would need to examine the appropriate business models, in light of different policy, finance, and technological conditions, and ultimately deploy circular business models that are best suited to their placement along the cost curve.

Sustainable Mining Model	***Land-based Circular Model***	***Metal Solution Providers Model***	***Resource Solution Providers Model***	***Wastes Solution Provider Model***	***Carbon Solutior Provider Model***
Low position in the cost curve allows them to focus on improving their current mining business model	Change their focus from "extracting minerals/metals" to "maximizing value of land related business" - mining, renewable energy, battery management	Supply primary metals as part of a broader portfolio of products and services to support clients to transition	Similar to metals solutions providers but expanding to a broad range of materials/solutions - hydrogen, substitutes, etc.	Focus on turning waste into value not only for their operations but for others inside and outside of mining too	Waste solutions provider model but focused on carbon as waste flow

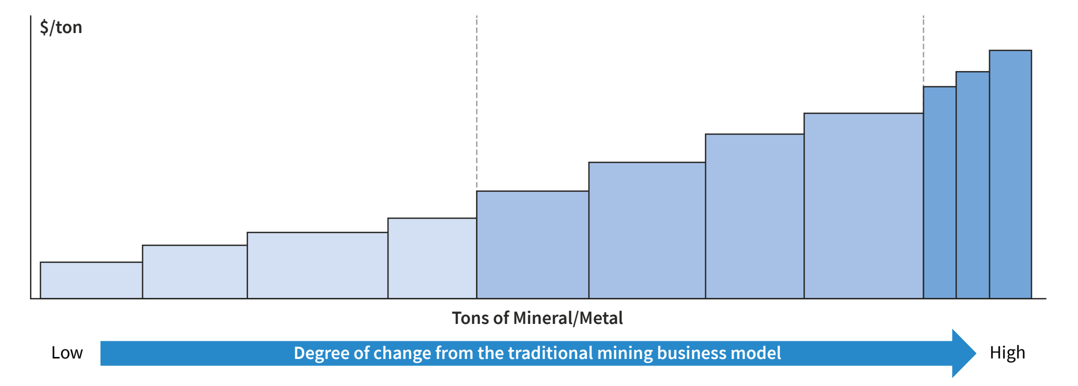

Figure 11. **ICMM six 'families' of circular mining business models**
Source: ICMM 2023 (forthcoming).

6. Conclusion and Recommendations: CCSI Calls to Action under Current (Sub-optimal) Conditions

Current technology, policy, and finance conditions are insufficient for the mining and renewable energy value chain to achieve full process and product circularity, which is necessary to achieve the Paris Agreement and the Sustainable Development Goals. We call on policy makers to quickly design and implement a comprehensive policy package to ensure full circularity and support the transformation of the economy.

Even pending the development of necessary technology, policy, and finance conditions, and for all the reasons provided in Section 2, mining and metals companies, solar and wind manufacturers, and power utilities can and should already take steps to accelerate circularity, by collaborating across the value chain and starting strategizing around the change in their business models. While this position is tested in this research in the context of mineral value chains of solar and wind, many of the findings can be expanded to other value chains relevant to the energy transition.

CCSI proposes the following calls to action for **policy makers, mining and metals companies, solar and wind manufacturers and power utilities, and industry associations of the mineral and renewable energy value chains.**

CALL TO ACTION FOR POLICY MAKERS

CALL TO ACTION: HOME COUNTRY GOVERNMENTS

1. **Adopt and continuously strengthen a comprehensive and nationally appropriate package of process and product circularity policies**, both broadly across sectors and specifically for mining and renewable energy value chains, comprising policy tools, such as those indicated in the Process and Product Circularity Policy Toolkit, expanding from a focus on waste management to a focus on design for durability and recoverability.

2. **Engage in international cooperation and negotiations** with other governments, including in the Global South, to tackle trade aspects, just transition issues, and other cross-border challenges in achieving a global circular economy.

3. **Welcome input from all stakeholders**—from private sector actors to research institutions—in developing and adopting policies for a circular economy.

CALL TO ACTION: HOST (AND DEVELOPING) COUNTRY GOVERNMENTS

1. **Instigate a public–private dialogue with the mining and metals sector** to identify linkages between circular economy and inclusive growth drivers (local employment, skills, and infrastructure).

2. Require **process circularity** in mining engineering design and feasibility studies.

3. **Facilitate a dialogue across industries** and in particular between smelters, on the one hand, and the solar PV panel and wind turbine industries, on the other.

4. Require **the analysis of beneficial post-mining land use opportunities** in mining engineering design and in the closure and reclamations plans.

5. **Leverage trade partners in the Global North** to secure public funding and technology and regulatory collaboration for the formal circular economy to take hold in the Global South too.

CALL TO ACTION FOR MINING AND METALS COMPANIES

1. Create a **Chief Circularity Officer** or adopt **a network governance model**, bringing together expertise across the company and clearly assigning the responsibility to develop a **circularity strategy** and take the following steps.

2. Conduct a **process circularity** assessment and internally disseminate its results.

   a. Explore **what is already being done on process circularity** across company operations and departments and **what revenues, net cost savings, and improvements to the social license to operate** can be associated with it.

   b. Assess **whether pushing process circularity further could yield more benefits**.

3. Conduct a **product circularity assessment** and internally disseminate its results.

   a. Document when the mineral is an enabler of **durability in intermediary and final products in solar and wind value chains**.

   b. Explore **new market opportunities at the nexus of minerals and metals, on the one hand, and solar and wind energy, on the other**.

   c. Document new, changing, and requested **partnerships and opportunities for collaboration** with solar and wind value chains around circularity.

4. **Implement the circularity strategy** and **continually monitor its implications**.

   a. Start to explore **circular business models** in the material-energy nexus that are most appropriate for the company's position on the cost curve (as explained in Section 5).

   b. Examine the **implications of circularity for strategies and operations of various departments** within the company.

CALL TO ACTION FOR SOLAR AND WIND MANUFACTURERS AND POWER UTILITIES

1. Create a **Chief Circularity Officer** or adopt **a network governance model**, bringing together expertise across the company and clearly assigning the responsibility to develop a **circularity strategy** and take the following steps.
2. Assess how **process circularity at mine sites could lower the greenhouse gas emissions as well as other ESG risks** of the mineral value chains of solar and wind and support the mining and metals sector in accelerating process circularity.
3. **Assess how the collaboration with the mining and metals companies could look like** for them to leverage their expertise and contribute to product circularity of solar PV panels and wind turbines.
    - For example, explore collaborations along mineral value chains of solar and wind to **develop digital passports for relevant minerals and materials, which will facilitate circular procurement on the part of the solar and wind manufacturers and utilities.**

CALL TO ACTION FOR INDUSTRY ASSOCIATIONS OF THE MINERAL AND RENEWABLE ENERGY VALUE CHAINS

1. Develop a **shared understanding** among value chain stakeholders about what process circularity and product circularity entail.
2. Establish a **circular economy baseline considering process and product circularity** across critical value chains.
3. **Map where the most valuable stocks are** and understand **what technology, policy, and finance conditions are needed** to make them easy to recover.
4. **Better understand the value of different circular business models** under various scenarios of changes in policy, finance, and technological conditions.
5. Stay attuned to the **emerging circularity policy** and **ESG finance agenda** (e.g., initiatives under IRENA,[32] UNEP,[33] the UN initiative on zero waste,[34] and World Business Council for Sustainable Development (WBCSD)'s CEO Guide to the Circular Economy[35]).
6. **Engage with policymakers, financiers, and technology providers** to ensure that enabling conditions are in place for mining and metals companies to play a role in the circular economy of solar and wind value chains, ensuring their long-term sustainability.

Endnotes

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