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Perspective

The role of design in circular economy solutions for critical materials

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SUMMARY

The accelerating pace of resource consumption threatens long-term availability of critical materials: those resources that play an essential role in modern society but are vulnerable to supply chain disruptions. Established resource management strategies have struggled to reduce the risks of metal criticality, and the demand for these materials continues to grow. Circular economy offers a new paradigm for addressing metal criticality through solutions that enable material and product reuse, remanufacturing, and recycling. However, products containing critical materials are rarely designed to be upgraded, reused, or disassembled at end of life to access the valuable materials contained within. Here, we explore the potential for design interventions across the technology life cycle that can enable circular economy solutions and minimize risks of material criticality.

INTRODUCTION

Technological innovation has a key role to play in achieving sustainable development goals such as clean and affordable energy, clean water and sanitation, and sustainable cities and communities.[1] However, new technologies may also lead to unforeseen sustainability challenges. For example, widespread adoption of automotive catalysts in response to air pollution regulations, such as the 1970 US Clean Air Act,[2] was followed by a tripling in consumption of platinum group metals.[3] These metals, including platinum, palladium, and rhodium, face declining reserves, require significant energy and expense to mine,[4] and have no viable material substitutes that offer comparable performance.[5] Although the emergence of electric vehicles may diminish the need to treat combustion engine exhausts, it also comes with new material risks. The lithium-ion batteries that power electric vehicles rely on cobalt,[6] which has a geographically concentrated supply chain[7] in which resource extraction contributes to environmental, human health, and sociopolitical impacts.[8,9]

These examples embody the problems of technology development under the current paradigm of a "linear economy." This model, often described as "take, make, and waste," sees high-quality resources extracted from the natural environment, converted into products with a finite lifetime, and then dispersed back into the environment in a degraded form, with minimal resource or value recovery.[10] Although the linear economy contributed to rapid economic growth and global development for many years, it is now pushing against the biophysical limits of what the planet can support.[11,12] A growing concern is whether continued technological innovation can be sustained with a shrinking pool of accessible natural resources.

This concern is particularly evident for the resources known as critical materials. In 2008, a committee of the US National Academies published an analysis that sought to determine which nonfuel minerals might be "critical" to the national economy.[13] This study devised a two-axis system (Figure 1) to make this determination based on "supply risk" and "impact of supply disruption." The idea was that if a country, a region, or the world were unable to procure a specific material that was needed for an important technology or application, the inadequacy could hamper industrial progress. The first axis of this rating system was intended to capture the likelihood of supply disruptions, which may be caused either by real physical scarcity of a resource or by short-term shortages due to rapid-demand growth, natural disasters, trade policies, or geopolitical unrest and instability.[14,15] The second axis was designed to evaluate the degree to which that supply-demand imbalance would cause disruption in essential infrastructure and industrial activities, particularly in the defense[16] and clean energy[17] sectors. Variations of this basic concept underlie all subsequent evaluations of criticality.

Over the years since the concept of criticality was formalized, a number of evaluations of critical material risks have occurred. Recent approaches have also demonstrated that the environmental impacts of obtaining a material[18] and the availability of comparably functioning material substitutes[19] should be considered in determining criticality. Despite differences in approach and in local resource availability, the lists of critical materials for countries and regions around the world have turned out to be largely similar. This consistency is shown in Figure 2 for criticality assessments for the United States[20] and the European Union (EU).[21] Now, well over half of all elements that are not noble gases or highly radioactive are so identified. As a consequence, the issue of material criticality is not an occasional

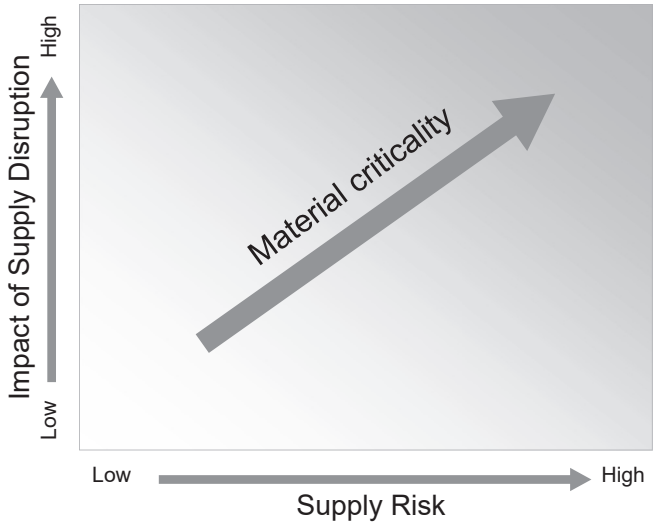

Figure 1. Determination of material criticality based on the criticality matrix

This approach assesses the risk of a supply restriction or disruption occurring (horizontal axis) and the potential impact of that supply disruption on the economic sectors in which the material is used (vertical axis).[13] Criticality risk increases as one moves from the lower-left to the upper-right quadrant of the matrix.

finding of interest but a universal concern for considerations involving resource availability and sustainable development.

These trends are unlikely to change in the future if critical material extraction and use continue in a business-as-usual manner. In fact, supply chain risks are likely to worsen going forward, potentially leading to additional materials being deemed critical.[22] Disruptive events like the COVID-19 pandemic demonstrate vulnerabilities in critical material supply.[4,23,24] But these are only a precursor to the supply chain impacts anticipated in the future, including disruptions due to natural disasters and climate change,[25] increased demand for clean energy technologies that mitigate climate impacts,[26] and growing trends of nationalism, extremism, and geopolitical conflict.[27]

THE CHALLENGES OF CRITICALITY AND DESIGN

Despite the growing body of literature that has established the concerns surrounding material criticality,[22,28] demand for these metals and minerals continues to grow. For example, the global demand for rare earth elements (REEs), deemed critical by the United States and the EU, has more than doubled since 1995, with a nearly 60% production increase in the last decade alone (Figure 3). In the case of metals like cobalt and lithium, which find applications in all major sectors—aerospace, defense, energy, transportation, electronics, and telecommunication—the demand has grown more than 300%.[20,29] A similar case is observed for indium, a geologically scarce metal that is a key raw material in flat panel displays and solar photovoltaics (PVs). The annual global demand for indium has increased to over 750 metric tons in recent years, a 125% increase since 2000.[30]

While studies project that the annual demand for most of these critical metals will continue to maintain rapid growth into the future,[31] there has been limited success in supplementing the supply of some of these materials through recycling. Many critical materials, especially gallium, indium, and the REEs that are used in renewable energy technologies and other high-tech applications, are mostly obtained from primary metal mining and refining. Even with major policy and technology efforts to support recycling in the EU, only about 20% of platinum and cobalt is obtained from secondary (recycled) sources; this rate is 5% or less for most other critical materials.[29]

The continued demand for critical materials and reliance on primary mineral sources can be traced back through the technology and product design process. Scientists and engineers have taken full advantage of the periodic table of elements in creating truly revolutionary materials and products. Unfortunately, scant attention has been paid to redeploying those materials and products following initial use. The result has been very low product reuse, remanufacturing,[32] and recycling.[33] Design for material recovery is not a routine priority for the product designer, whose role has historically been to create products that are functional, desirable, and easy to understand and operate.[34] The design process typically incorporates factors such as a real or anticipated market need, a firm's business strategy, technical and economic specifications, and scientific advancements and innovation,[35] with environmental dimensions included only if they align with broader business needs.

Material criticality is also rarely a factor that influences the material choice in product designs for a technology. Material selection typically focuses on narrowing down a broad suite of candidate materials on the basis of their characteristic properties, such as strength, hardness, reactivity, conductivity, or electrical resistance, and their match to the fabrication and service requirements of the intended application.[36] Whereas cost continues to be one of the most important decision points, parallel consideration of a material's environmental attributes is only recently becoming more common.[37] In the past few years, there has been a rapid expansion of sustainable design tools and methods intended to support these decisions, but uptake of these practices by designers is still limited and inconsistent.[38]

Further, many of the design decisions that directly influence critical material use happen well before the product realization phase, typically occurring during fundamental scientific research or technology development.[39] At this early stage, the focus is on materials that provide the greatest performance in an application. By the time the technology comes to market, downstream engineering and product designers may not even realize that they are specifying a component with criticality risk, particularly if the materials are present in low concentrations, as is the case for critical metals found in aluminum alloys.[40] However, even without full control over material selection, product designers still have the ability to influence a product's durability, lifespan, and potential for end-of-life reuse or recycling to displace demand for future critical material extraction.

Take, for example, the case of consumer electronics, which are estimated to contain more than 60 elements[41] that originate from over 50 countries. Over half of these elements[42] are in the critical material list shown in Figure 2. Most are embedded within composite materials and complex components, such as tin-based solder, germanium in semiconductors, cobalt-rich cathodes in lithium-ion batteries, and neodymium in hard drives

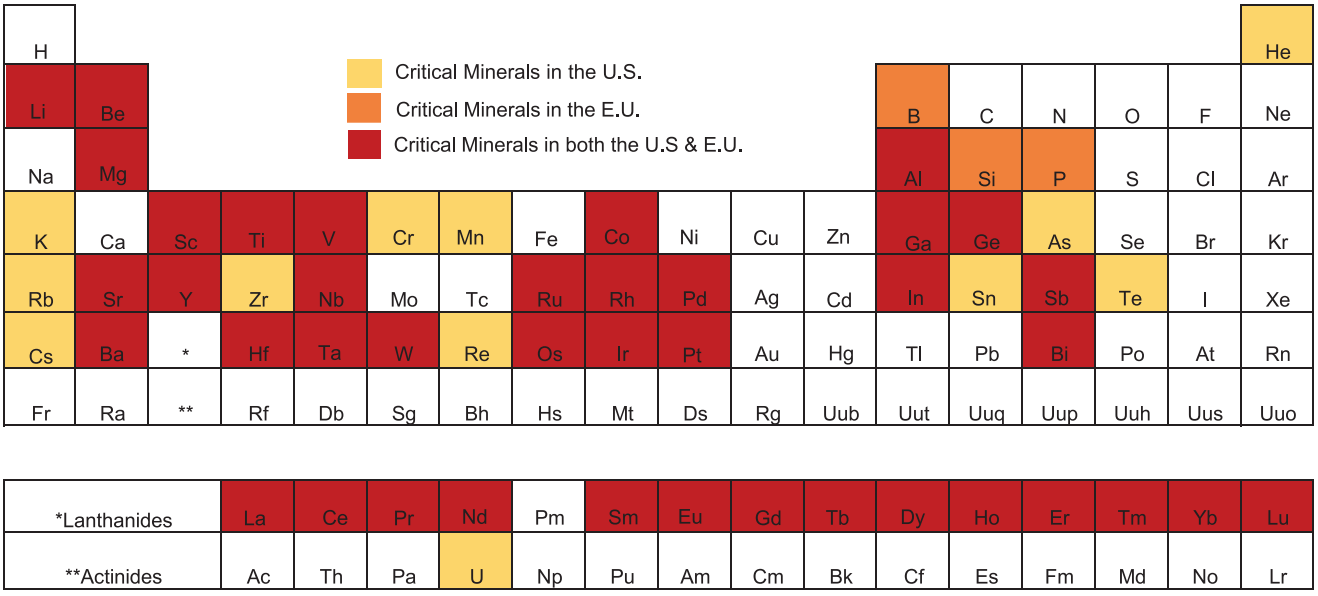

Figure 2. Elements designated as critical materials by the United States and the European Union

and headphones.[6,43,44] Very few of these resources are currently obtained from secondary sources or recycled when electronics reach their end of life.[45] Whereas part of the problem is a lack of recycling technology to carry out chemical separation and recovery, a greater challenge stems from the underlying product design. Figure 4 illustrates the design barriers to material recovery for a typical smartphone, a high-tech product that has both wide adoption and multiple critical material dependencies.

Another facet of the design challenge is the overall complexity, low elemental concentration, and poor separability of components and composites that contain critical materials. Products rarely bear labels or compositional profiles that could be used to identify the presence of critical materials during recovery processes.[46] Without such information, or knowledge of initial material formulation, it is likely to be more difficult to recover critical materials through recycling than to extract them from a primary ore.[47] Further, the design phase typically fails to consider material dissipation during product manufacturing and use. Take, for example, the case of germanium and antimony used in manufacturing polyethylene terephthalate (PET) and acrylonitrile butadiene styrene (ABS) plastics. Some 25% of the germanium used in the United States is used as a polymerizing catalyst for PET;[48] the germanium remains in the plastic once manufacturing is completed, and PET discarded in the United States is primarily landfilled. Even if the PET were recycled, there is no technology for germanium recovery. A similar situation holds for ABS, in which antimony is used as a flame retardant.[49]

A second example is that of modern high-strength low-alloy steels, which see increasing use in automotive technologies, industrial equipment, farm and construction machinery, and energy transmission infrastructure. In current practice, niobium, vanadium, and other critical materials are used in low percentages to enhance the properties of those alloys.[50,51] Although the minor element quantities are small from the alloy perspective, their use constitutes around half of all flows into use for those critical materials. Moreover, in current industrial practice, those trace metals are generally lost to larger alloy streams during recycling.[52,53] As a consequence, the failure to consider recovery and recycling during alloy design and use unintentionally results in the loss of the minor metals.

CIRCULARITY AS A SOLUTION FOR CRITICALITY

The unique sustainability challenges presented by critical materials require new approaches to maximize benefits in emerging technologies while minimizing production and consumption impacts. The emerging circular economy paradigm offers a portfolio of solutions that may help minimize criticality risks and improve the overall sustainability of critical material extraction, use, and end-of-life management. The circular economy—in contrast to the current linear model—aims to foster continued innovation and economic development but decouple growth from extractive and wasteful use of natural resources. This approach is achieved through the three interconnected approaches of narrowing, slowing, and closing resource loops.[54,55]

Narrowing resource loops refers to resource-efficient processes that fulfill societal needs but reduce the net amount of materials used per unit of economic activity.[56,57] Potential strategies include substituting renewable for non-renewable resources,[58] dematerializing products through technological progress and multifunctionality,[59] substituting digital alternatives for physical goods,[60] and sharing or leasing products and services rather than individually owning goods.[61,62] The common goal across these strategies is to reduce the net amount of resources extracted from nature, which, in turn, can reduce the waste that is ultimately generated. The success of such approaches often hinges on behavioral response. For example, efficiency gains resulting from technological innovation may reduce marginal costs, which in some cases leads to lower prices and increased demand,[63,64] potentially creating a rebound effect.[65]

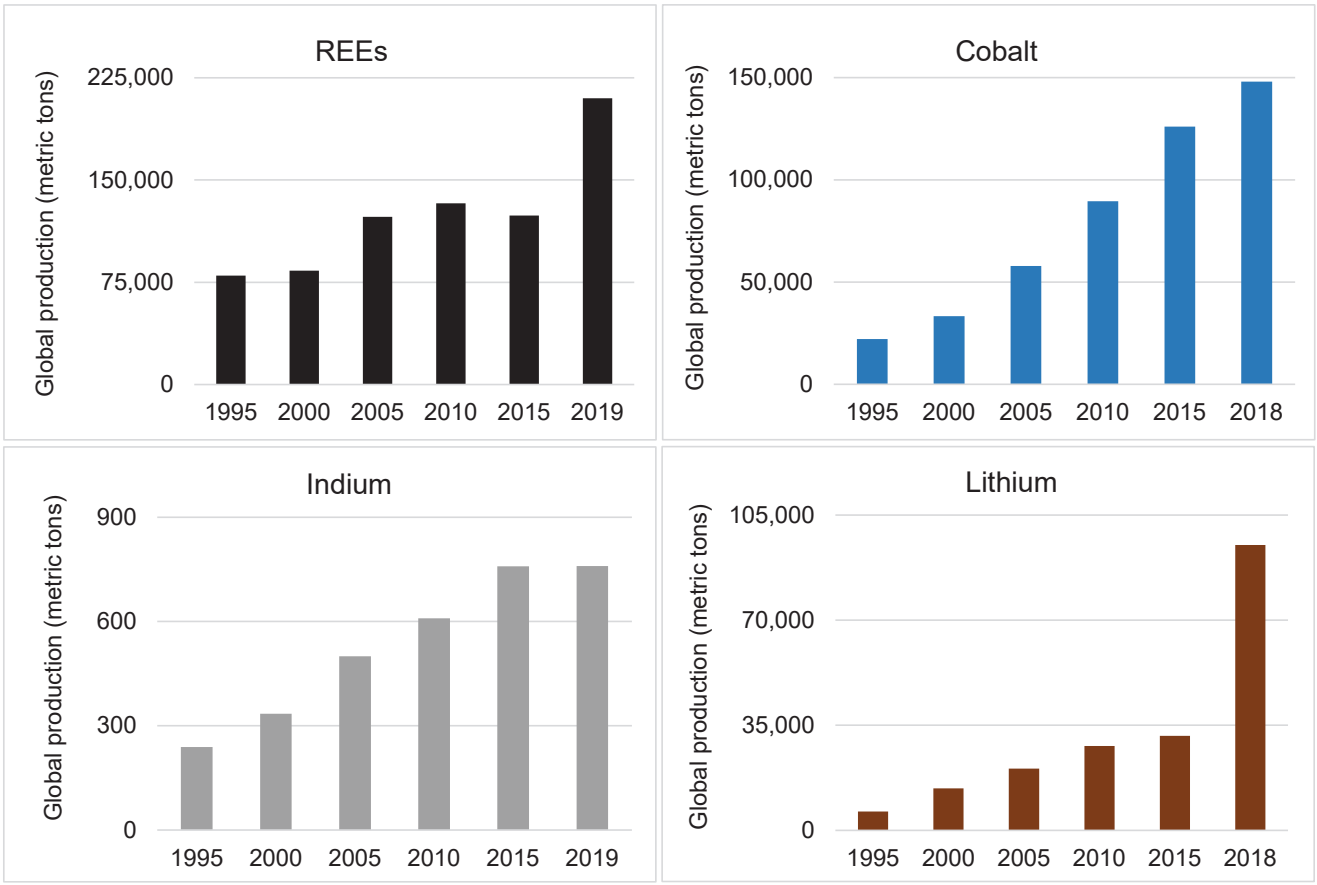

Figure 3. Global production of critical materials: Rare earth elements, cobalt, indium, and lithium
REEs represent rare earth oxide production, cobalt and lithium represent mine production, and indium represents refinery production. Data extend through 2018 or 2019 based on the most recent estimates available.[30]

Slowing resource loops refers to methods used to retain the use and value of a material or product for as long as possible. This approach includes designing products that are durable and retain both their function[66] and their appeal to users[67] over an extended lifespan. A complementary strategy is creating products that are more easily disassembled and upgraded,[68] both to allow the initial user to carry out maintenance and repair that extend the initial service life and to facilitate access to components requiring repair or replacement so that the critical material value can be extended over multiple life cycles.[69] Remanufacturing follows a standardized process of testing, cleaning, and restoring components or products to "as-new condition and performance or better,"[32] theoretically allowing for a complete substitution for a new product and avoiding upstream material extraction and manufacturing processes. The success of these strategies depends on manufacturers seeing a business case for value-retaining designs and systems[70] as well as consumers being willing to alter their behavior.[71] For example, consumers have historically expressed resistance toward remanufactured goods due to negative misperceptions about their quality and performance.[72]

Closing resource loops refers to the processes used to recover a resource, once its full useful life is complete, and return it to productive use, i.e., on a cradle-to-cradle basis. This model of closed-loop material flows takes inspiration from organisms in natural ecosystems that continually cycle nutrients and energy.[73,74] Circular economy envisions industrial ecosystems that mimic their biological analogs, whereby waste from one process becomes the "food" for another. This approach entails an interconnected suite of activities beginning with collection of manufacturing scrap or end-of-life products, followed by transportation and consolidation of similar components or materials, and finally the use of physical, chemical, and thermal technologies to separate and purify individual elements or compounds. Recycling is the concept most commonly associated with circular economy studies,[75] likely because of the full circle it evokes, wherein recirculation of materials would prevent future extraction of raw materials from nature. In practice, material recovery is imperfect, due to dispersion of elements during processing and loss of their functional quality.[76] However, recirculation is a needed final step in the circular economy cascade, as it retains the resource, economic value, and embodied energy[77] of materials after lifespan extension and reuse pathways are exhausted.[78]

ENABLING CRITICAL MATERIAL CIRCULARITY THROUGH DESIGN

Circular economy strategies offer the potential to reduce material criticality risks, particularly if implemented proactively.[79]

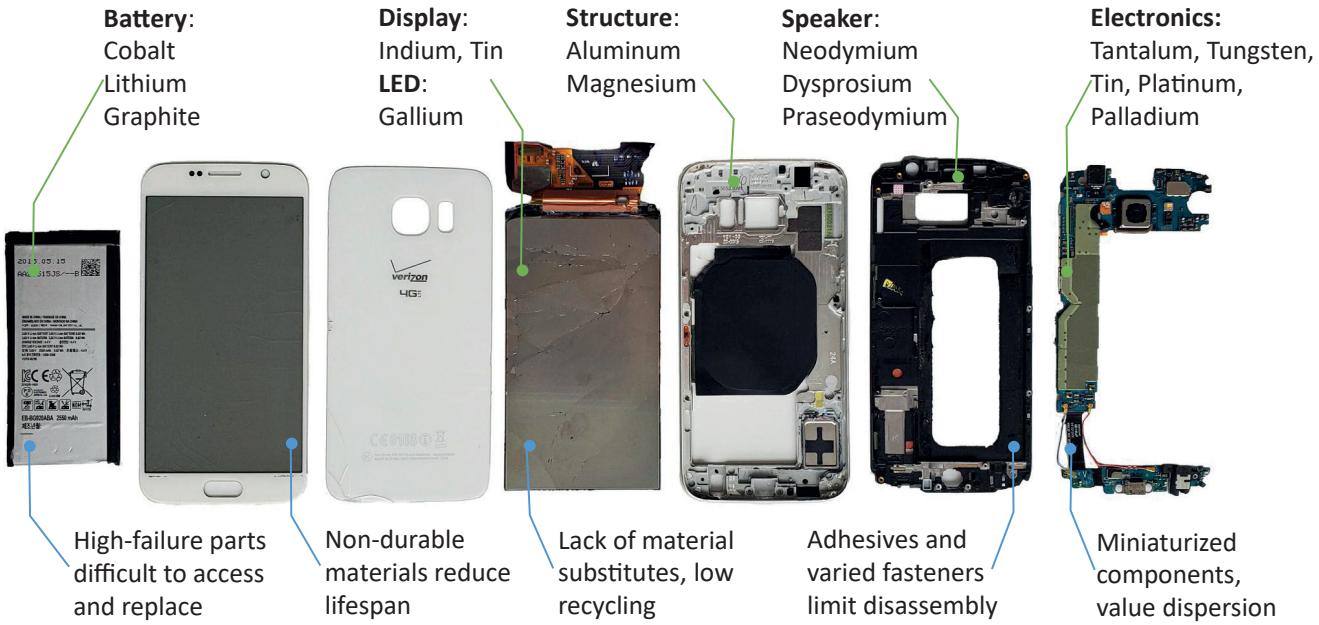

Figure 4. Illustration of critical material use in a smartphone and the design challenges that limit circular economy strategies that may slow and close resource loops for these materials

The design stage is one of the first leverage points at which these strategies can be enacted. However, many traditional approaches to sustainable design have not explicitly focused on critical materials or are not well aligned with challenges specific to their extraction, use, and recovery.[39] Thus, there is both a pressing need and a compelling research opportunity to explore new design approaches that will enable circular economy solutions for critical materials. This section explores potential design avenues and the enabling innovations and systems that may help facilitate their broader adoption.

Design solutions are discussed here in the context of the critical material life cycle: resource extraction, raw material processing, component and product manufacturing, distribution, use, and end-of-life value retention and material recovery (Figure 5). This life-cycle perspective recognizes that critical material use does not happen in isolation, but rather comes about as a result of numerous upstream processes and may influence environmental impacts in downstream processes or interacting systems.[80] The material life cycle exists in a broader technological innovation cycle, which spans fundamental research and development that studies the properties, uses, and performance of critical materials; technology and product design that specifies and tests these materials in specific applications; and the ultimate scale-up and widespread adoption of products containing these materials.

The earliest point at which circular economy interventions might minimize critical material risk is at the onset of technology research and development. Unfortunately, potential risks are difficult to anticipate this early, because sufficient data about a technology's use do not yet exist; but, paradoxically, changes are increasingly difficult to enact once a technology is widely adopted and such data become available.[81] This dilemma motivates the need for prospective[82] or *ex ante*[83] environmental assessment methods to simulate future impacts of early-stage technologies. In critical material research, scenario-driven material flow analyses have modeled potential material demand and recycling needs due to technology adoption in the clean energy sector.[7,84,85] However, due to data availability, such forecasts typically model technologies that are at or near commercial scale. For example, a forecast of indium demand due to future solar panel adoption[86] may base estimates on known PV systems. Ideally, such impact forecasts would be incorporated even earlier, during the lab-scale design of next-generation solar cells.[87,88]

As technology development progresses, the next opportunity for narrowing resource loops is through material selection. Take, for example, the case of lithium-ion batteries used in electric vehicle applications. These batteries contain the eponymous lithium, as well as varying amounts of cobalt, aluminum, nickel, and manganese in the cathode and graphite in the anode.[46] Shifting toward battery designs with lower cobalt concentrations can reduce criticality risk and the social, environmental, and economic impacts of the cobalt supply chain.[89,90] However, material substitutions are not without trade-offs, as low-cobalt battery chemistries are likely to increase demand for nickel,[91] which is often jointly mined with cobalt,[7] and decrease the economic potential of battery recycling.[92] A similar perspective might inform the consideration of silicon-based anode materials that substitute for critical natural graphite in the lithium-ion battery anode,[93] but which introduce trade-offs in terms of battery performance and upstream energy for manufacturing.[94] These examples highlight the importance of proactively evaluating design choices through a life-cycle perspective.

For many critical materials, however, substitution is difficult if not impossible, due to the unique properties that these elements provide in high-tech applications. Many elements listed as critical have no functionally comparable substitutes, including rhenium used in superalloys for jet engines and turbines,

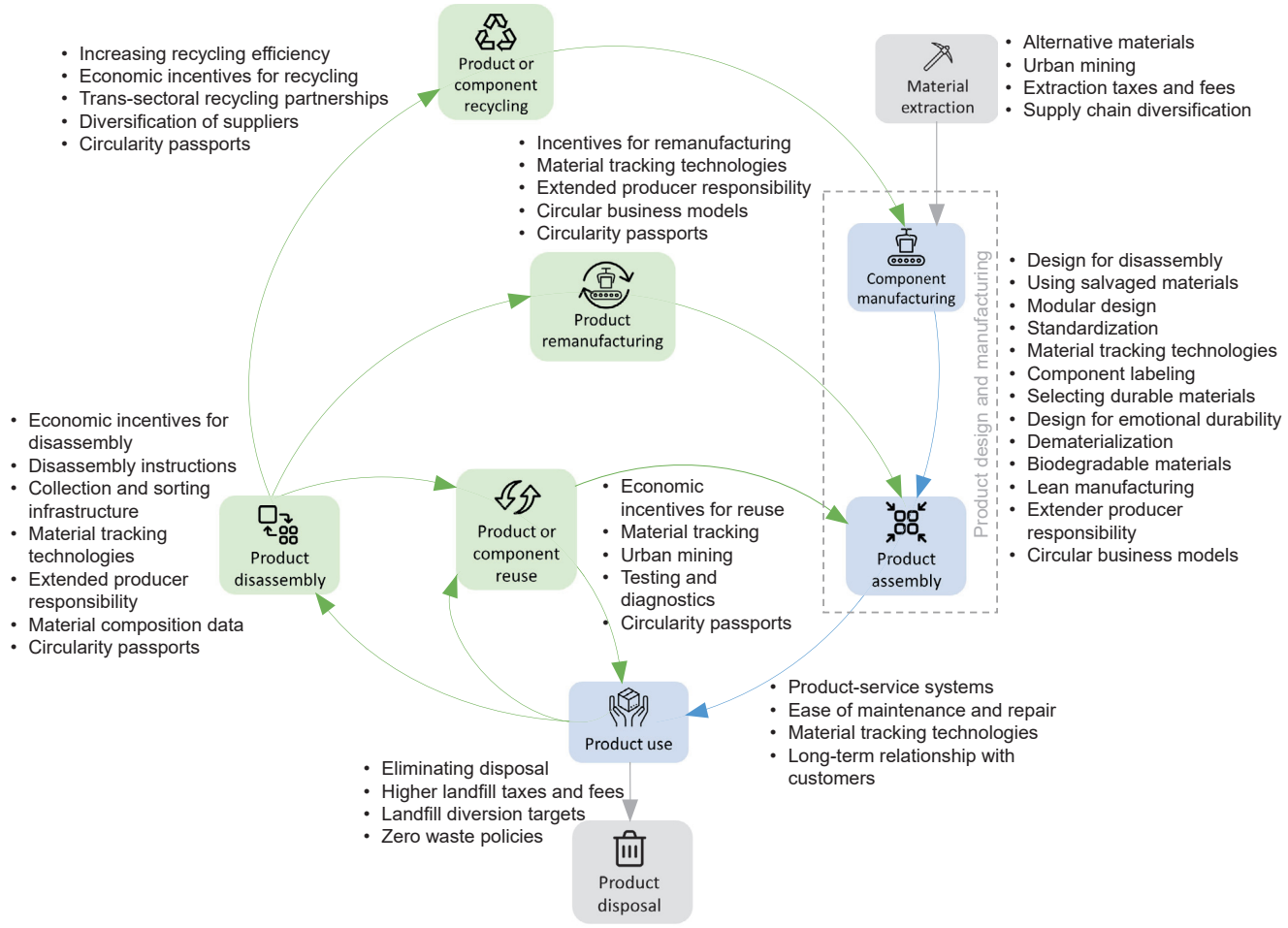

Figure 5. Circular economy enablers over the technology life cycle

The life-cycle phases in gray would be drastically reduced or eliminated in an ideal circular economy. The life-cycle phases in blue are common to both linear and circular economies; and those in green represent extended life-cycle phases that are key to a circular economy for critical materials.

rhodium used in industrial catalysts, and several REEs used in phosphors, magnets, and other industrial applications.[19] Because many known substitutes are also designated as critical materials, as is the case for platinum group metals, material ranking systems used in parallel with technical design constraints can help prioritize which material presents the lowest criticality risk for a given application.[95,96]

When substitution is not possible, another early-stage intervention is design of a resilient supply chain to minimize the likelihood or severity of a supply disruption occurring. In principle, a diversified supply chain that could obtain needed materials from multiple suppliers who mine and refine metals in many different countries would minimize risks in the same way that a financial portfolio is diversified to reduce the risk of poor portfolio performance due to large loss in value by a single stock. Supply chain diversification strategies include expanding the geographic mix of countries from which a critical material is mined and refined,[14] increasing the number of material and component suppliers,[97] implementing lean manufacturing,[79] and stockpiling critical material resources to buffer against future shortages.[25] The supply chain can also be diversified through increased use of secondary material sources. Here, a promising research avenue is urban mining, that is, the process of recovering resources from the existing stocks of products, materials, buildings, and infrastructure dispersed in urban systems that would otherwise end up in a landfill.[98,99]

In situations where the use of a critical material cannot be completely avoided or minimized, product design, policy, technology, and business models—in concert—can improve circular economy prospects and reduce criticality risks over a product's life cycle (Figure 5). Keeping products, components, and materials in circulation *by design* through reuse, remanufacturing, and recycling will require thoughtful and proactive consideration. For example, the PV panel manufacturer would consider assembly with an eye toward eventual disassembly and material recovery. Bold strategies are needed in all life-cycle stages.

In product design and manufacturing phases, design opportunities center on component manufacturing and product assembly (see Figure 5, blue life-cycle stages). Today's increasing complexity and heterogeneity of parts and composites leads to mixing of materials that are later difficult to recover or reuse.[100] In contrast, design strategies that enable a more circular

economy include modular design, design for disassembly (DfD), the use of components with standard dimensions, and appropriate material combinations.[101] For example, Dell has introduced computer designs with modular components that can be easily disassembled for repair, remanufacture, or reuse.[102] The theory and practice of DfD[103] predates circular economy[104] and has been a core tenet of the broader eco-design field. Although its application to critical materials has not been fully explored, DfD may help overcome barriers for recovery of critical materials. A recent study on PV module decommissioning concluded that applying DfD strategies to PV systems can increase overall recovery and recyclability of their materials and should be a priority for solar deployment in OECD countries.[105]

In addition to DfD and modular design, other circular economy design strategies include dematerialization (designing with as few materials and components as possible) and design for durability. At a physical level, durability reflects a product's ability to withstand wear, fatigue, and degradation over time,[106] a goal that can be addressed through the use of high-quality parts and robust assembled components. Theoretically, a durable good will slow demand for new critical materials entering the economy without decreasing value, particularly if the higher-quality durable good is reflected by higher prices.[107] However, durability goes beyond physical properties: design for emotional durability[67] can be used to create products that are loved and trusted for longer.[54] This strategy is understudied, but potentially offers the most promise in extending the lifespan of products whose working lifetime is directly influenced by consumer behaviors.[108] For example, emotional attachment to a laptop or smartphone, which would typically be discarded before its full useful life is complete, could spur a user to invest in its maintenance and repair and delay replacement with a new device.[109]

Complementary design enablers will be required to support these strategies and overcome some of the economic barriers to design for reuse and recycling. For example, recovery of PV panels, which may contain gallium, indium, and tellurium, is complicated by the geographical dispersion of the modules, the low value of materials in small quantities, and lower costs of ore extraction.[79,110] Material tracking technologies and geographic information systems can be used to identify economically viable points to localize dispersed recoverable metals and enable urban mining at larger scales.[98,103,111,112] Another innovation is using material tracking technologies to bring the recovery plant to the material. A successful case study is HydroWEEE, a highly automated mobile recycling plant developed to extract critical metals at the point where wastes are collected, which avoids the need to invest in expensive centralized facilities or haul materials over long distances.[113]

Upstream design strategies will require both a policy "push" and a market "pull." Potential policy mechanisms include extended producer responsibility, economic incentives and taxes,[15] requirements for supply chain disclosures and transparency,[114] and eco-labeling and procurement standards that credit recovered material use.[115] The relative ability of such mechanisms to alleviate criticality risks has yet to be fully evaluated. Scaling up design approaches will be in the context of circular business models that promote long-term relationships with customers during the product-use phase, while providing timely maintenance services and take-back programs.[54] Circular business models have shown economic potential in the PV industry,[116] and leasing solar panels is a common option for many manufacturers, who retain the ownership of the modules and provide repair and maintenance as needed. Committed maintenance and repair in turn can avoid premature obsolescence of products and components and extend the product life cycle to enable future reuse, remanufacturing, and recycling. Advancing circular economy business models will require ongoing experimentation to verify their environmental and economic outcomes,[117] demonstration projects to build trust in participating firms,[118] and incubators to foster early-stage network development and funding for entrepreneurial efforts.[119]

An example of design strategies that enable products or components to be reused either in the same application or across different sectors is the reuse of lithium-ion batteries from electrical vehicles as backup storage for grid-scale PV installations.[120] This strategy requires the design of a durable battery pack that can ultimately be disassembled, tested, diagnosed, repaired, and reconfigured between the first and the second life cycle.[78] Second-life users may, however, be wary of product quality, as they do not typically have access to data that characterizes first-life use and wear. Two emerging types of technology offer the promise to promote trust across the supply chain: quality testing and diagnostic technologies for secondary products, components, and materials, and the innovative technology of circularity passports. Circularity passports, or material passports, combine material tracking technology with blockchains and the Internet of Things to create and store reliable circular economy-relevant data over a product's life cycle.[121,122] The information provided by circularity passports can then support stakeholder decisions on whether goods should be reused, remanufactured, or recycled.

CONCLUSIONS AND FUTURE RESEARCH OUTLOOK

The ability to sustain technological progress hinges on the continued availability of the natural resources that power society's most important products and infrastructures. Critical materials present a complex sustainability challenge, as they are vulnerable to supply disruptions but also crucial to many essential products and industries. But critical materials also present an opportunity for innovations to spur circular economy research and ongoing development of new business models. Design is the touchstone between these challenges and opportunities: current design practices hinder reduction, reuse, and recycling of critical materials, but circular design solutions have the potential to transform this system and provide global social, economic, and environmental benefits.

Achieving circular economy goals will require innovation that spans every scale of a product, from atoms and molecules to the built environment. Disassembly and reuse can occur at a molecular level from early-stage technology design to loop-closing chemical recycling;[123] reuse and remanufacturing can be applied at a product or component level; and each phase of a product's life cycle requires and interacts with urban and industrial infrastructure. In a truly circular system, the facilities and infrastructure needed to design, manufacture, sell, collect, disassemble, and recycle goods are also designed for circularity. Although the circular design strategies discussed herein are

specific to technologies and products that contain critical materials, they can be extended more broadly to transform the buildings and infrastructure in which these products are made, used, transported, and recovered.[103,124,125] Hence, circular economy demands a convergence of disciplines and knowledge, together with the ability to rapidly scale solutions from circular materials to circular societies.

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