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Perspective

Bolstering supplies of critical raw materials for low-carbon technologies through circular economy strategies

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ABSTRACT

Global scenarios in line with Paris Agreement climate goals would increase deployment of low-carbon technologies that contain significant amounts of critical raw materials (CRMs). However, most climate policies and decarbonization pathways typically do not identify the role CRM supply could play in slowing or limiting the scale-up of low-carbon technologies. Circular economy strategies can help secure the supply chain for many CRMs. While it is technically possible to recover all CRMs, current recovery is limited by the lack of a strong economic driver or policy that could provide economic incentives, support a cost-competitive secondary material market, and encourage the use of recycled materials. In this perspective, we investigate the potential of two circular-economy strategies, end-of-life collection and recycling. Our results show that enhanced collection and recycling could enable secondary materials to meet 37%–91% of demand for CRMs in low-carbon technologies in 2050, depending on the technology type and characteristics (e.g., shorter lifetime of battery energy storage systems). However, progress is required in building robust collection frameworks, developing cost-competitive and highly efficient recycling technologies, and designing recycling-friendly products.

1. Introduction

A transition to low-carbon energy systems—including but not limited to renewable energy technologies, electric vehicles (EVs), and battery energy storage systems (BESS)—is already underway. Under the Paris Agreement, 195 countries pledged to limit global warming to well below 2.0 °C. In the United States (U.S.), solar and wind installed capacity is forecasted to rise from 180 gigawatts (GW) (about 14% of installed power generation capacity) today to 1329 GW (about 56% of installed capacity) by 2050, and the Biden Administration plans to make the power sector carbon free by 2035 [1,2]. EV sales are expected to accelerate so, by 2040, battery-electric and plug-in hybrid electric vehicles will account for most new cars sold and 42% of U.S. cars on the road [1]. The European Union (EU) has a more aggressive goal of at least 30 million EVs on the region's roads by 2030 [3]. EU wind and solar installed capacities are expected to double by 2025 and 2030, respectively, compared to 2020 [4]. China, which accounts for almost 30% of

today's global greenhouse gas (GHG) emissions, has pledged to reach carbon neutrality by 2060 [5].

This global energy transition could drive one of the most substantial increases in critical raw material (CRM) demand in history. CRMs are defined as raw materials that are economically and strategically important to an economy but carry high risk associated with their supply due to various factors such as insufficient production capacity, geopolitical concerns, and market price dynamics [6]. The list of CRMs can differ between countries. For example, some minerals not critical to EU can be critical in the U.S., such as manganese [7,8]. Low-carbon technologies typically have high and diverse mineral resource requirements compared to conventional counterparts. For example, the International Energy Agency (IEA) reports that EVs require about five times more CRMs than conventional vehicles [9]. Similarly, building offshore wind turbines requires well over 10 times more copper than building coal and natural gas power plants for similar capacities [9]. According to a World Bank report (2020), meeting Paris Agreement targets will require 3

Abbreviations: BESS, battery energy storage systems; CdTe, cadmium telluride; CIGS, copper indium gallium (di)selenide; CRM, critical raw material; c-Si, crystalline silicon; EOL, end of life; EU, European Union; EV, electric vehicle; GaAs, gallium arsenic; GHG, greenhouse gas; GW, gigawatt(s); IEA, International Energy Agency; kt, thousand metric tons; LFP, lithium iron phosphate; LIB, lithium-ion battery; NCA, lithium nickel cobalt aluminum oxide; NCM, lithium nickel cobalt manganese oxide; PMG, permanent magnet generator; PV, photovoltaic; REE, rare earth element; SDS, Sustainable Development Scenario; STEP, Stated Policies Scenario; USGS, U.S. Geological Survey.

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billion metric tons of materials worldwide for low-carbon technology, representing more than 1000% growth in demand for key CRMs by 2050 [10].

However, the ability of CRM supply to keep up with demand is uncertain. Table 1 shows that expected CRM demand from low-carbon technologies in 2040 significantly exceeds current supply for many materials. We limit the discussion in this paper to cobalt, lithium, manganese, nickel, natural graphite, rare earth elements (REEs—neodymium, dysprosium, and praseodymium), cadmium, indium, gallium, selenium, silver, and tellurium. We also consider copper, which is an important base metal required in larger amounts in low-carbon technologies than in conventional technologies and used in more applications, in addition to clean energy, than any other CRM. These materials are essential to producing the low-carbon technologies—such as EVs, BESS, photovoltaic (PV) panels, and wind turbines—that are expected to proliferate and help mitigate GHG emissions [11]. Although reserves of some materials are more than adequate to supply industries around the world for decades (as seen in Table 1) and mining of these materials is expected to increase over the next decade, the scale and speed of the required increase are cause for concern [12]. Opening a new mine typically can take 10–20 years and require significant capital investment [13–15]. Demand for required materials might outpace the addition of new mining capacity. In addition, some known reserves may not be technically or economically extractable, and, with ore grades declining, mining requires increasing amounts of energy and water [14,16,17]. Some materials are available in only small quantities, are not geographically distributed in high concentrations, and have low substitutability. Some CRMs can only be produced in combination with more common metals to justify investments in mining [18,19].¹

Geopolitics is another main reason why some of these materials appear on the CRM list. Mining mostly occurs in a few countries, and ore refining is concentrated in even fewer countries [42]. As shown in Fig. 1, production of most CRMs used for low-carbon technologies tends to be concentrated in particular (typically one dominant) countries. DR Congo, Indonesia, Australia, South Africa, and China have large shares of the production of key CRMs used in LIBs. For example, 70% of cobalt, 35% of nickel, 52% of lithium, 30% of manganese, and 65% of graphite come from DR Congo, Indonesia, Australia, South Africa, and China, respectively. Although cobalt is mined primarily in DR Congo, 80%–90% of the worldwide refining takes place in China, and Chinese companies control more than 40% of DR Congo's cobalt-mining capacity [43]. China also controls almost half of global lithium production, particularly in South American countries.² Most lithium from Australia is shipped to China for processing [22]. Although production of silver and copper is more distributed worldwide, REEs and other metals used in thin-film PV technologies such as gallium, indium, and tellurium are also produced heavily in China. In 2010, China imposed export restrictions on all 17 REEs to Japan, owing to a political dispute [44]. However, China's attempt to use REEs as a political weapon inspired some importing countries to look for other sources and increase domestic production. China currently accounts for 58% of global REE production (compared to 98% in 2010) (Fig. 2A). Similarly, Indonesia banned exports of nickel-containing ores in an effort to develop a domestic value chain from nickel mining through nickel refining [13].

With growing worldwide demand for CRMs, the risk, frequency, and

¹ Most cobalt is mined as a byproduct of copper (44% of cobalt production in 2019 was a byproduct of copper) or nickel (50% of cobalt production in 2019 was a byproduct of nickel) [28]. Tellurium is from large-tonnage, low-grade ores from copper and copper-gold porphyry-type deposits, as a byproduct of copper refining [29]. Indium is produced almost solely as a byproduct of zinc smelting and refining [30].

² According to Reuters.com, China has invested \$4.2 billion in South America in the past 2 years, surpassing the value of similar deals by Japanese and South Korean companies [46].

Table 1

CRM production and theoretical reserves in 2020 compared with projected demand from low-carbon technologies in 2020 and 2040, in thousand metric tons (kt).

	2020 production	2020 reserves	2020 demand from low-carbon technologies	2040 expected demand from low-carbon technologies
Cobalt (for EVs and BESS)	140	7100 (~57% in DR Congo)	21	136–455
Nickel (for EVs, BESS, and wind)	2500	94,000 (~25% in Indonesia)	196	1272–3804
Manganese (for EVs, BESS, and wind)	18,500	1,330,000 (~45% in South Africa)	82	245–664
Lithium (for EVs and BESS)	82	21,000 (~45% in Chile)	22	276–904
Natural graphite (for EVs and BESS)	1100	320,000 (~28% in Turkey)	156	1204–3849
Neodymium (for EVs and PMG wind)		120,000 — a		
Dysprosium (for EVs and PMG wind)	240 — a	total for all 17 REEs	6.36	22–47
Praseodymium (for EVs and PMG wind)	17 REEs	(~37% in China)		
Silver (PV)	25	500 (~18% in Peru)	1.98	2.30–2.67
Gallium (PV)	0.3	Not Available	0.0042	2.11–2.77
Indium (PV)	0.90	Not Available	0.0155	0.06–0.07
Tellurium (PV)	0.49	31 ^a	0.21	0.29–0.33
Selenium (PV)	2.9	100 ^a	0.04	0.05–0.07
Cadmium (PV)	23	Not Available	0.20	0.31
Copper (EVs, wind, and PV)	20,000	870,000	740	2373–5078

Notes: (1) PMG stands for 'Permanent Magnet Generators'. Currently, around 20% of wind turbines are equipped with PMGs, which has implications for REEs used in PMGs, specifically neodymium, dysprosium, and praseodymium [20]. These materials are also used in nearly all EV motors and most efficient consumer electronics such as air conditioner systems with inverter drives [21]. Non-PMG wind turbines do not have permanent magnets; thus, they do not require REEs. (2) Lithium-ion batteries (LIBs) (represented in EV and BESS in the table) are based on all types of commercial batteries currently in the market and expected to be in the market in the next 5–10 years. Commonly used LIB cathode chemistries include lithium nickel cobalt manganese oxide (NCM), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP) [22]. Currently, NCM and NCA batteries constitute about 70% of the market, although battery technology is evolving quickly, and new and improved chemistries such as lithium-sulfur (Li-S) and lithium-air batteries (Li-Air) likely will have larger shares in the future [22–24]. (3) Two main types of PV panels are used today: crystalline silicon (c-Si) and thin film. C-Si technology accounts for more than 90% of the global market share [21–25]. Thin-film technologies—including copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe)—make up the remainder of the market, and they are used in more specialized applications. Additionally, a recent IEA report suggests that higher-efficiency GaAs (gallium arsenic) based solar cells may gain about 5% market share by 2040 owing to new developments that are reducing costs [6]. (4) The minerals listed in the table are based on "critical" designations in the U.S., EU, and Japan [12,26,27]. Some minerals not critical to the U.S. are critical in the EU and/or Japan. We try to be as comprehensive as possible with CRMs discussed in this paper for low-carbon technologies.

Source: Production and reserve data from the U.S. Geological Survey (USGS) [28–41]. Demand estimates from IEA, representing its Stated Policies (STEP) and Sustainable Development (SD) scenario results as a range for 2040 [9].

^a Estimations of United States Geological Survey (USGS).

material, except copper has a 37% import rate.

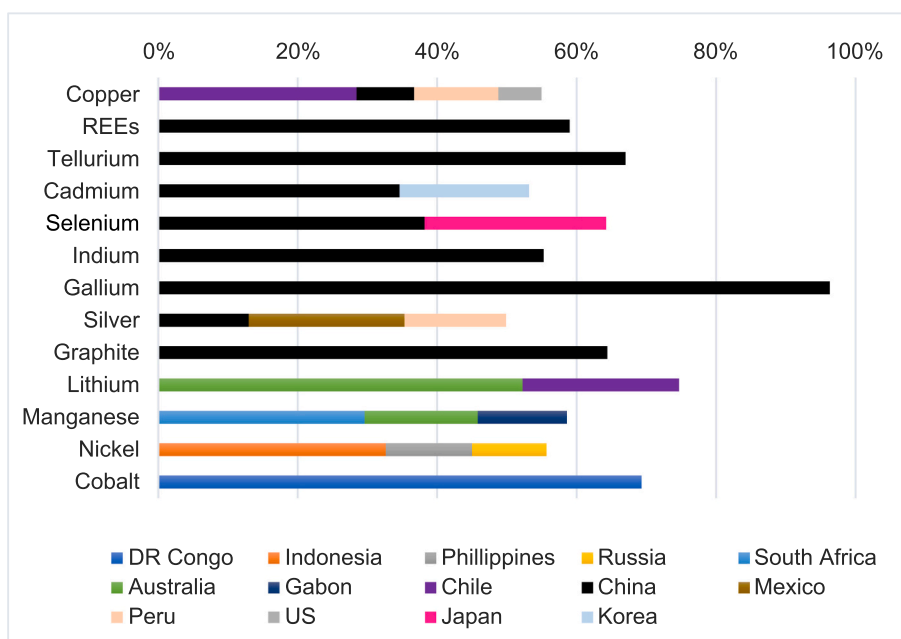


Fig. 1. Mine production shares of CRMs discussed in this paper, 2020
Source: USGS [28,29,30,31,32,33,34,35,36,37,38,39,40,-41].

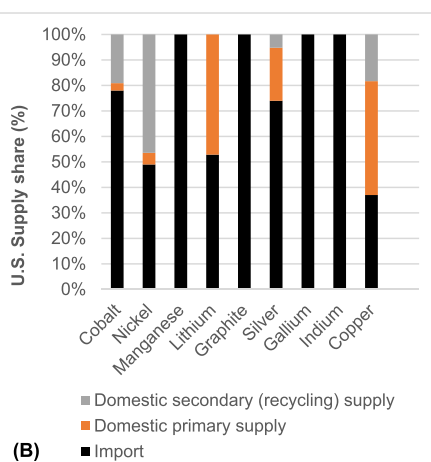
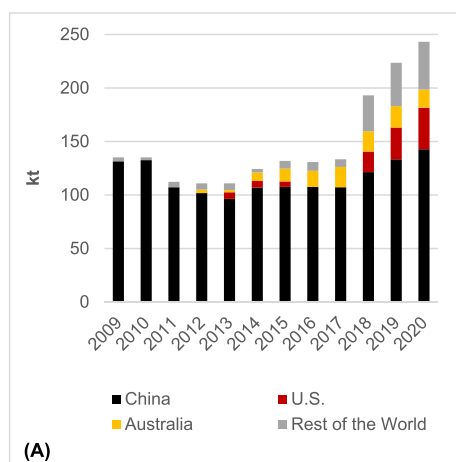


Fig. 2. Historical CRM trends
(A) Global production of REEs between 2009 and 2020.
Notes: Mount Weld Mine in Australia and Mountain Pass Mine in California together now account for nearly a quarter of global REE supply.
Source: USGS [31].
(B) U.S. dependence on imports for select CRMs in 2020
Notes: The United States is a net exporter of REE mineral sources, but 100% of REEs are refined and processed to REE compounds and metals in China.
Source: USGS [28–41].

magnitude of geopolitical conflicts can increase. In February 2021, in recognition of such a possibility, U.S. President Biden signed an executive order to increase the resilience and reliability of critical supply chains, including CRMs along with LIBs and semiconductors [45]. Fig. 2B displays U.S. import dependence for select CRMs, compared to domestic primary and secondary material production (recycling). Import dependence ranges from 50% to 100% depending on the

Along with expanding sustainable and responsible mining,³ lowering material intensity, and employing material substitution (wherever possible),⁴ circular economy strategies can help secure the supply chain for many CRMs used in low-carbon technologies while reducing dependence on mining activities. The circular economy is defined as a continuous development cycle that meets human needs while

³ Sustainable and responsible mining is commonly defined as mining that includes and respects all stakeholders in the value chain, minimizes and takes account of its entire environmental impact, and support sustainable development goals (SDGs) by protecting workers rights, eliminating child labor, preventing any forms of discrimination against workers, and excelling in worker health and safety while also prioritizing a fair division of economic and financial benefits [54].

⁴ In many cases, material substitution is impossible or merely shifts the bottleneck from one CRM to another [13,14].

conserving and enriching natural capital, optimizing resource utilization, and reducing or eliminating environmental degradation by managing finite stocks and renewable flows [47]. A circular economy aims to decouple economic growth from the consumption of resources and its impact on environment and human well-being (such as exposure to toxic chemicals, damage to biodiversity, and release of GHG emissions) through circularity practices. Promoting better use of products and materials (e.g., sharing, leasing, reusing, repairing, refurbishing, recycling, and increasing process efficiency), use of renewable energy, and elimination or substitution of toxic chemicals as much as possible at all phases of product life cycles are some of the key circular economy practices.

Many CRMs have high recycling potential, but end-of-life (EOL) recovery of CRMs from low-carbon technologies is generally low, often because of technological challenges, collection issues, and economic barriers [48–51].

While the criticality of key raw materials for low-carbon technologies is discussed widely in recent literature, a foundation for systematized scenario-based advice for closing the resource loop is lacking. We believe circular economy strategies must play a role in reducing the stress on CRM primary supply chains. In this perspective, we focus on collection and recycling of EOL low-carbon technologies—two main circular economy strategies—because of their larger potential to scale up compared with other strategies. We focus our suggestions primarily on five circular economy scenarios to investigate the high-level impact of various collection and recycling rates on recovery of CRMs from EOL low-carbon technologies as secondary raw material supply options. However, knowledge of the impact of collection and recycling on CRM supply for low-carbon technologies is not enough to spur action. Hence, before presenting our results, we review current practices and barriers for collection and recycling and offer potential pathways that could help enable a more circular low-carbon energy system.

2. Current practices, barriers, and pathways related to end-of-life CRM collection and recycling

For many CRMs, sorting and recycling technologies are not competitive with the low prices of virgin (primary) CRMs. If virgin CRM prices increase, the economics could change. For example, cobalt recycling became economically attractive owing to increasing cobalt prices following supply constraints [52]. Other metals could follow similar trends driven by increased demand from large-scale penetration of low-carbon technologies. For example, neodymium and dysprosium prices peaked in 2011 after China reduced quotas and PMG demand rapidly increased [53].

Metals related to LIB recycling have been most thoroughly examined in the literature [55–62]. Most recycling processes prioritize recovery of cobalt and nickel, because of their high virgin material prices, while less valuable metals including lithium and manganese are not usually recovered (Table 2) [28,56,63]. Although lithium, manganese, and copper are technically nearly 100% recyclable, because of current

battery designs they are hard to separate from other metals without using expensive organic reagents for solvent extraction [21,62]. Efforts such as the U.S. Department of Energy Critical Material Institute's LIB recycling projects aim to recover lithium from EOL equipment [64]. In addition, some major lithium mining companies are partnering with automotive equipment manufacturers on lithium recycling [65].

PV panels are recycled in existing recycling plants, mostly for glass and scrap metal (e.g., aluminum) [66]. Although technically they are 100% recyclable, recovering the small amounts of valuable (e.g., silver, copper), scarce (e.g., indium), or most hazardous (e.g., selenium) materials requires additional thermal treatment or use of expensive organic solvents [67]. Tellurium and cadmium are exceptions, with recycling efficiencies above 65% [68]. For example, almost no recycling of silver from PV panels occurs even though silver has an overall current recycling rate of 30%–50% and represents nearly 50% of material value in PV panels [63]. However, First Solar, a CdTe PV manufacturer, recovers cadmium and tellurium from CdTe panels at around 70%–90% efficiency via its recycling program [69].

Recycling of copper used in wind turbines is well established, with high recycling rates [70]. There is currently no recycling of dysprosium or neodymium from PMGs used in wind turbines, mainly owing to the low cost of virgin materials (Table 2) [28].

Design for recycling (or design for sustainability) efforts could make CRM recycling from low-carbon technologies more viable. However, it can be challenging to design a product for recycling without changing the product's functionality or increasing its cost [71]. In addition, there is often a lack of information about the concentration of CRMs used in the EOL technologies, making it difficult for recyclers to perform material recovery efficiently and economically.

Because recycling of EOL products would be economically viable only for large volumes of materials, high collection rates are needed, yet the long lifetimes of some low-carbon technologies slow the return of materials to the recycling stream [72]. For example, EOL PV panel volumes are generally too low for recycling to be economically favorable today owing to the long life expectancy of most panels (about 30 years) and the fact that PV deployment has only recently increased sharply. However, with increasing CRM stocks in many EOL low-carbon technologies, the flow of materials into recycling likely will increase. Currently, there is not much literature discussing the volume of EOL products required to make recycling cost-competitive. In their analysis, D'Adamo et al. [73] show that low quantities of EOL PV products (~ 2 kt of waste crystalline Si PV modules) cause economic losses for the recovery of valuable materials/metals and point out that larger capacity recycling is necessary to reduce the cost of recycling.

Collection volumes of EOL EV LIBs are likely to be higher, because the collection channels (auto dealerships) already exist, and battery lifetimes are relatively short (10–15 years). Battery collection is required by a new European regulation, and in jurisdictions where regulations do not apply, some manufacturers already offer cash rebates to incentivize battery takeback [74]. A newly proposed EU regulation aims to establish requirements and targets for collection, treatment, recycling, and repurposing of EOL batteries [75]. PV recycling schemes are in place in some jurisdictions. For example, in the United States, PV panels are considered universal waste in California. In 2017, the State of Washington passed a bill that requires PV panel manufacturers to pay for a takeback and recycling program. In the EU, PV panel waste is treated under the general e-waste directive, requiring 85% collection at EOL [76]. Implementation of the EU PV waste directive, however, has been limited owing to a lack of enforcement and compliance [77]. Recovery efforts can be encouraged by establishing e-waste directives specific to low-carbon technologies, using policy mechanisms such as standards that mandate the content of recycled material in new products, and implementing regulations that enforce collection and recycling targets. Regulations can also incentivize design for recycling to reduce recycling costs and increase the efficiency and economic competitiveness of secondary material markets. In addition, effective monitoring of

Table 2
Current recycling efficiency rates based on literature.

Technology	Cu	Co	Ni	Li/ Mn/C	REEs	Ag/Ga/In/Se/Cd/Te
BESS	45%	74%	65%	0%		
EVs	45%	74%	65%	0%	0%	
PV panels	34%					67% for Te and Cd; 0% for the rest
Wind turbines	90%		68%		0%	

Notes: Cu = copper; Co = cobalt; Ni = nickel; C = natural graphite; Ag = silver; Ga gallium; In for indium; Se for selenium; Cd for = cadmium; Te = tellurium; Li = lithium; Mn = manganese.

Source: [10,68,70].

compliance would increase the effectiveness of regulations and ensure CRMs are cycled at their highest utilization in the circular low-carbon energy system.

At the same time, collection of EOL products is usually a logistical challenge. There is no established reverse logistical chain for most low-carbon technologies, so the routing, timing, quantity, and nature of EOL equipment are often uncertain. For example, recycling wind turbines requires transporting bulky equipment from remote areas to recyclers. Using digital technologies to trace and track the products would increase collection efficiency and volumes, support compliance efforts, and help optimize the logistical chain and collection points. Digital technologies such as blockchain and other artificial intelligence technologies can also record manufacturing data such as material content and concentration, making it easily accessible to recyclers. Establishing a manufacturers consortium could bring together all actors in the logistical chain and create a circular ecosystem.

The current approach of collecting EOL products mixed together hinders the sorting process and leads to contamination because some metals end up in the wrong recycling stream (mostly mixed with base metals). A dedicated collection scheme for each product type would help ensure materials are recycled to their highest potential.

Table 3 summarizes the barriers to EOL low carbon technology collection and recycling as well as some potential solutions that we discuss in this section. “Likely Time Frame” indicates how quickly a solution can be deployed. While some of these solutions can individually help for increased levels of collection and recycling, achieving a robust and self-sustaining circular low-carbon energy system requires simultaneous progress on many of these fronts.

3. Scaling the impact of CRM collection and recycling

To understand the impact of CRM recovery from EOL low-carbon technologies on reducing primary CRM demand, we present a high-level analysis of EOL product collection and recycling. Other researchers have discussed or predicted EOL material volumes for CRMs from some key low-carbon technologies [10,13,21,22]. Bosch et al. [13] found that metals from recycling EVs would not account for a significant share of total metal demand until 2040 in the Netherlands. Hund et al. [10] found that—with 100% recovery (60% for lithium)—secondary raw materials can meet 39% to 59% of demand for aluminum, copper, cobalt, nickel, and lithium from select low-carbon technologies in 2050. Xu et al. [22] showed that EV battery recycling could reduce 20%–45% of cumulative material demand through 2050, depending on LIB type. Similarly, Dominish et al. [21] discussed that recycling can meet about 30%–50% of cumulative material demand from LIBs through 2050. However, all these analyses are based on maximum theoretical recovery of EOL materials, and they do not explore the impact of circular economy strategies focusing on different collection rates and recycling efficiency levels.

Both Hund et al. [10] and Xu et al. [22] project EOL material volumes according to IEA low-carbon technology scenarios, while Dominish et al. [21] use One Earth Climate Model’s long-term energy scenarios. We follow a similar approach. To estimate EOL material volume for CRMs in 2040 and 2050, we use the material demand estimated in IEA’s SDS scenario for each low-carbon technology in 2030 and 2040 (see Fig. 3 and Table 1) [9]. We apply a logistics curve to calculate the failure probability of the technologies in stock to obtain the annual EOL volume. See the appendix for methods, logistic curves, and parameter assumptions.

Fig. 3 shows our estimates of EOL CRM volumes in 2040 and 2050 along with current recovered material volumes compared to demand from the literature. EOL material could supply approximately 37% of total material demand from EVs in 2040 (58% in 2050) as well as about 45% of total material demands from BESS and wind turbines by 2040 (81% for BESS and 96% for wind turbines in 2050). Because of the longer life of PV panels, only 3% of material demands could be supplied

Table 3
Barriers and solutions to EOL CRM collection and recycling.

Barriers	Solutions	Likely Time Frame
Market	Incentivizing recovery efforts—collection, recycling, design for recycling—can help establishing a cost-competitive secondary material market.	
Economics: Low prices of some virgin CRMs	Prices can increase with growing demand and associated stress in supply chains, e.g., virgin cobalt prices increased significantly over the last decade owing to supply constraints, making recycling attractive.	Can correlate with the rate of increase in demand
Technology Design: Complex product designs	Design for recycling, design for sustainability	Long term
Recycling/sorting technology: Lack of sorting and recycling technologies on a commercial scale	Innovation, R&D	Medium to long term
Lack of data recording on CRM content and concentration	Disclosure of bill of materials	Short term
Collection		Once the enough EOL stock of low-carbon technologies (depending on the technology) are available, this will not be a barrier.
Delay: Long lifetime of some low-carbon technologies		
Infrastructure: Lack of established collection infrastructure	Organizing a manufacturers consortium to increase collaboration and communication Forming reverse logistical chains and optimum collection points	Short to medium term Short to medium term
Contamination: Mixed approach to collection	Designing product-specific collection schemes	Short to medium term
Regulations	Designing a special e-waste product category for each low-carbon technology to avoid low-carbon technologies that contain CRMs mixed with other metal scrap	Short to medium term
Waste directives: Lack of EOL waste directives/regulations for low-carbon technologies	Executing legislative action (e.g., subsidy programs and enforcing collection and recycling target rates) that incentivize collection and recycling efforts Tracking collection and recycling activities, designing penalty and reward mechanisms for collection volumes and product recycled material content	Short to medium term
Compliance: Lack of compliance and enforcement		Short to medium term
CRM standards: Absence of standards such as recycled material content and display of bill of materials	Designing legislation to cover such standards	Short to medium-term

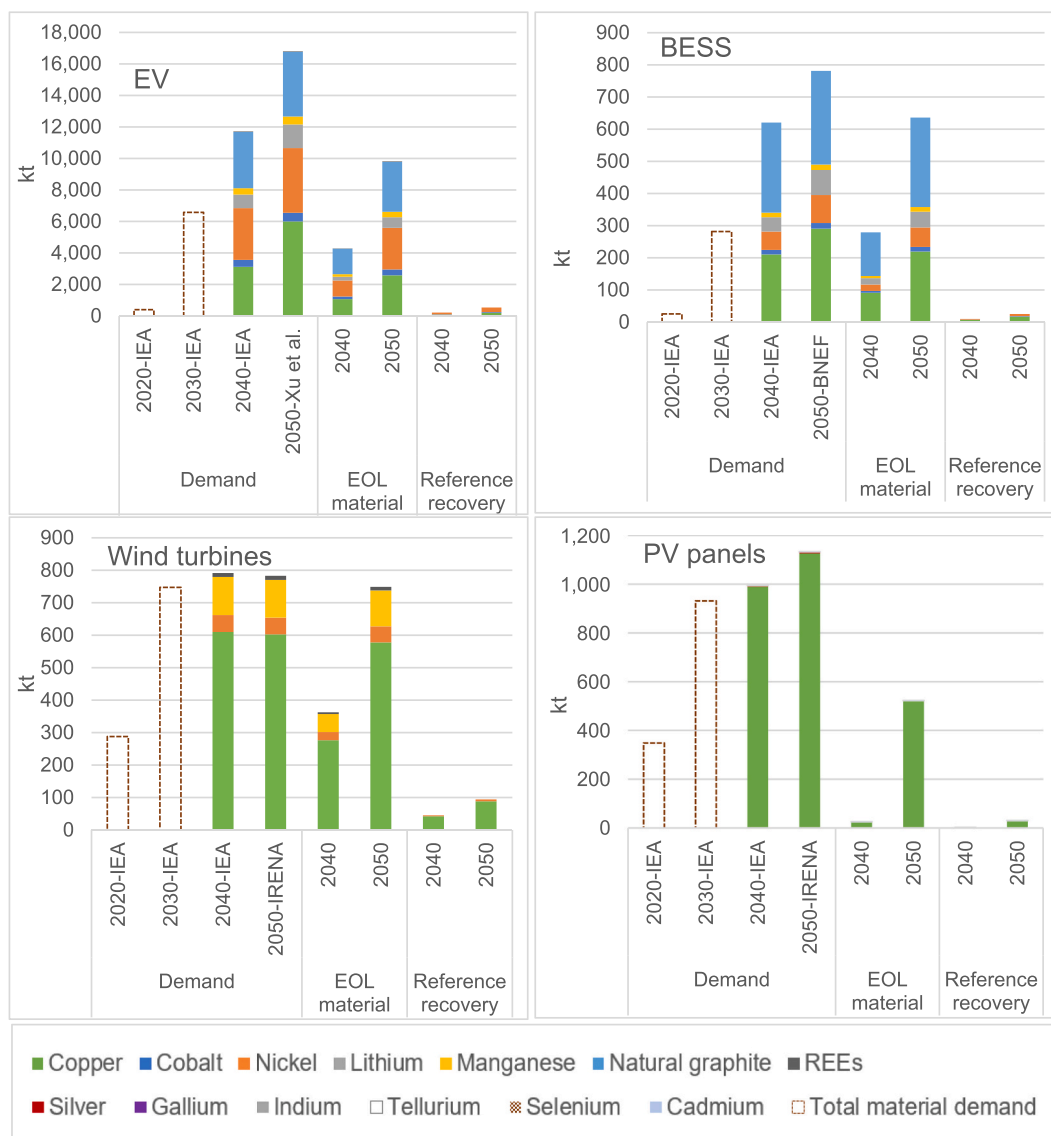


Fig. 3. Material demands and EOL material volumes in 2040 and 2050 for EVs, PV panels, wind turbines, and BESS
 Note: Scales differ on the y-axes. Reference recovery represents the recovery of EOL materials when current collection and recycling rates are applied.
 Source: Demand values are based on IEA, IRENA, Xu et al., and BloombergNef (BNEF) [9,20,22,79].

by EOL equipment in 2040; the rate increases to 46% in 2050 as the first large-scale installed capacities reach EOL. Our results agree with the estimates of Hund et al. [10] and Dominish et al. [21] for 100% EOL material recovery for LIB materials, even though our method is different; both analyses assume technology reaches EOL once the average lifetime is achieved, while we use a survival function. In our method, the technologies in the stock can fail and reach EOL before the average lifetime is achieved.

To obtain a high-level estimate of material recovery from EOL materials, we use the current average collection efficiency of electronic and electrical waste (e-waste) worldwide (i.e., 17% based on Forti et al. [78]) and current technology- and material-specific recycling rates from the literature. See Table 2 for current technology- and material-specific recycling rates. We assume current collection and recycling rates will be constant through the analysis period (our ‘Reference recovery’ scenario for EOL materials). Under this scenario, only 0.4%–7% and 7.3%–14.7% of the total material demand in 2040 and 2050 could come from EOL materials as secondary material supply, respectively, depending on the technology and the material.

We compare the Reference recovery scenario results with five

alternative scenarios with increasingly ambitious collection and recycling rate targets (Table 4). Maximum possible recycling rates are assumed to be 95% for all CRMs based on technically achievable recycling rates from the literature. Literature on maximum recycling efficiency of all CRMs discussed in this paper shows rates between 95% and 100% [21,62,63,67,69–71]. On the other hand, there is no information about the technical limitations of collection in the literature. Achieving

Table 4
 Scenarios used in this analysis.

Scenarios	Collection Rate	Recycling Rate
Reference recovery	Current (17%)	Current
CES 1	Current (17%)	Maximum possible
CES 2a	50%	Current
CES 2b	50%	Maximum possible
CES 3a	100%	Current
CES 3b	100%	Maximum possible

Note: See Table 2 in Section 2 for the current recycling rates. The current collection rate is based on Forti et al. [78]. The maximum possible recycling rate is assumed to be 95% [21,62,63,67,69–71].

high collection rates can depend on various factors including policy mechanisms, incentives, and establishing robust reverse logistic chains as discussed in the previous section. In the scenarios, we aim to show the impact of 50% and 100% collection of EOL equipment, compared to 17% in the Reference recovery scenario. Although our scenario assumptions entail uncertainties, we believe our results are still indicative of CRM potential from increased collection and recycling from low-carbon technologies.

Fig. 4 summarizes the impact of our collection and recycling scenarios on total primary CRM demand in 2040 and 2050. Scenarios that increase collection rates while keeping current recycling rates constant (CES2a and CES3a) are less effective in reducing primary material demand. The CES2a scenario increases the secondary material supply potential by 8%–35% in 2050, depending on the technology, while the CES3a scenario yields a 16%–71% increase. Wind turbines have established recycling routes for nickel and copper, about 80% of total CRM demand is from copper (Fig. 3), and copper is recovered at a 90% rate when collection occurs. Thus, increases in secondary material supply with increasing collection rates are highest for wind turbines.

Scenarios that assume new recovery technologies with improved recycling rates (CES1, CES2b, and CES3b) reduce primary material

demand significantly with increasing collection rates. The CES1 scenario explores the impact of higher recycling rates and current collection rates; its reduction in primary material demand is similar to the reduction in the CES2a scenario (except for wind turbines). The CES2b and CES3b scenarios yield 19%–45% and 37%–91% reductions in 2050, respectively. For EVs and BESS, cobalt and nickel already have relatively high recovery rates of around 70%, so most of the increase in the CES3b scenario for the secondary material supply comes from lithium, manganese, natural graphite, and copper. As mentioned in the previous section, the current recovery rates for these materials are almost zero, except for copper at about 45%. The secondary material supply share increases from 19% to 56% for EVs and from 19% to 77% for BESS in 2050 when comparing the CES3a and CES3b scenarios. This highlights the importance of advancing the recycling of battery materials in an economically attractive way. For wind turbines, the impact of improved recycling increases the recovery rate from 71% in the CES3a scenario to 91% in the CES3b scenario. This highlights the importance of improving the collection of EOL wind turbines. PV panels use copper heavily, with a much lower recycling efficiency of about 34%. Secondary material supply can increase from 16% in the CES3a scenario to 37% in the CES3b scenario with high recycling efficiency. This share could be even

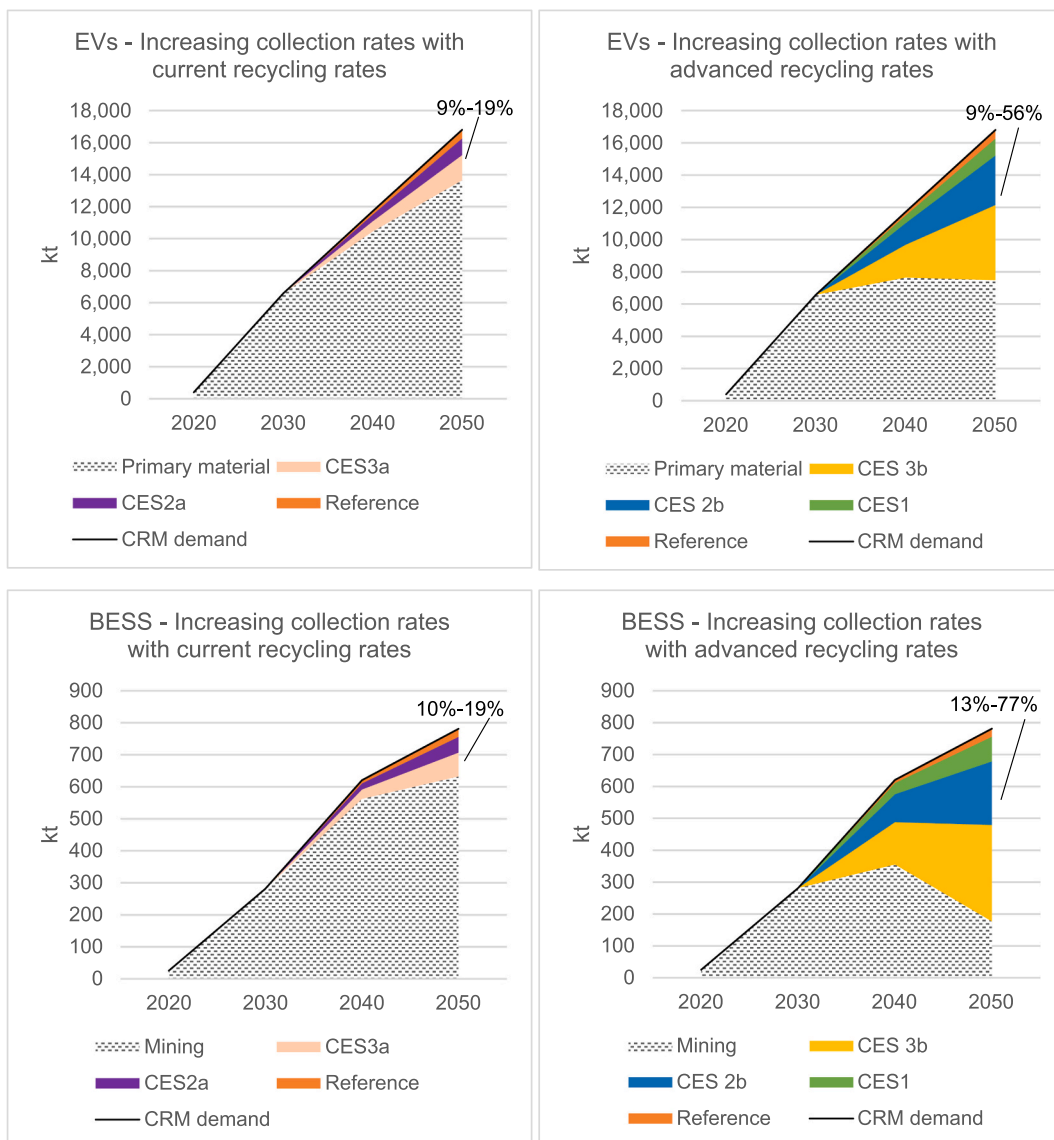


Fig. 4. Primary and secondary material supply shares in collection and recycling scenarios.



Fig. 4. (continued).

higher in the periods after 2050 with increasing volumes of EOL PV panels.

Additionally, Table 5 provides details of the secondary material supply potential of CRMs in the scenarios. The table presents the aggregated material volumes for each CRM. Please see Appendix Tables A1-A4 for results providing details on the individual technologies discussed. The results show that the CES1, CES2b, and CES3b scenarios could provide approximately 10%, 30%, and 55% of the combined CRM demand from the four low-carbon technologies. Specifically, these scenarios could make up about 13%, 39%, and 78% of REE demand from EVs and PMG wind turbines in 2050. Similarly, 7%, 22%, and 44% of lithium demand from EVs and BESS in 2050 could come from the CES1, CES2b, and CES3b scenarios, respectively. As previously noted, there is currently no recovery of lithium and REE from low-carbon technologies. However, there is increasing research and effort to reverse this trend as insufficient supply, geopolitical conflicts, and economic competition are expected to corner the lithium and REE market. Our results show a benchmark for the effectiveness of circular economy strategies in providing an alternative supply route.

Although quantifying the life cycle impact of recycling against virgin CRM production is beyond the scope of this paper, we acknowledge that

the energy required and the emissions and hazardous pollutants generated during recycling would vary depending on a variety of factors, including but not limited to metal's properties, scrap quality, product design, recycling process used, and renewable content of electricity used [80–84]. In general, mechanical recycling (i.e., direct melting) of metals is less energy-intensive, while chemical recycling processes (e.g., hydrometallurgy, pyrometallurgy, organic solvents, or electrochemical extraction), which most CRMs currently are recycled, can require energy-intensive reactions and high temperatures compared to primary metal production [85]. For example, Usapein and Tongcumpou [86] show that direct melting can significantly reduce the total emissions associated with production (i.e. mining, transportation, and refining) of silver. On the other hand, Jiang et al. [87] and Golroudbary et al. [88] discuss that metallurgical recycling of LiB batteries leads to GHG increase, due to the intense energy demand. However, some other researchers contradict, arguing that batteries manufactured with secondary materials from metallurgical recovery technologies can reduce the GHG emissions when the share of renewable energy in the grid is high enough [89–91].

Table 5
CRM demand and secondary material supply in collection and recycling scenarios (kt).

	2040						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	4928.8	132.5	236.0	389.6	694.0	779.2	1388.0
Cobalt	455.1	22.0	28.2	64.6	83.0	129.3	166.0
Nickel	3396.1	117.6	171.7	345.9	505.0	691.8	1010.1
Lithium	903.8	–	41.0	–	120.7	–	241.4
Manganese	535.5	–	36.5	–	107.3	–	214.7
Natural graphite	3848.7	–	282.6	–	831.3	–	1662.6
REEs	46.6	–	3.3	–	9.8	–	19.6
Silver	2.3	–	0.020	–	0.059	–	0.117
Gallium	2.8	–	0.000	–	0.001	–	0.002
Indium	0.1	–	0.000	–	0.000	–	0.001
Tellurium	0.3	0.001	0.002	0.004	0.006	0.008	0.012
Selenium	0.1	–	0.000	–	0.001	–	0.002
Cadmium	0.3	0.001	0.002	0.004	0.006	0.008	0.011

	2050						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	8019.3	332.7	629.5	978.4	1851.3	1956.8	3702.7
Cobalt	568.9	48.6	62.4	143.0	183.5	285.9	367.1
Nickel	4247.2	304.3	444.4	895.1	1307.1	1790.1	2614.1
Lithium	1576.4	–	116.9	–	343.8	–	687.6
Manganese	637.8	–	75.9	–	223.2	–	446.4
Natural graphite	4391.2	–	556.5	–	1636.7	–	3273.5
REEs	50.6	–	6.7	–	19.7	–	39.4
Silver	2.9	–	0.4	–	1.1	–	2.2
Gallium	3.1	–	0.01	–	0.03	–	0.06
Indium	0.1	–	0.00	–	0.01	–	0.02
Tellurium	0.4	0.03	0.04	0.08	0.11	0.16	0.22
Selenium	0.1	–	0.01	–	0.02	–	0.04
Cadmium	0.3	0.03	0.04	0.07	0.11	0.15	0.21

4. Conclusions and recommendations

The demand for most CRMs used in low-carbon technologies will increase exponentially, stressing primary material supply chains through geopolitics, market dynamics, and limits on reserves, production capacity, and infrastructure. To keep global warming well below 2 °C, global climate policy must make manufacturing of low-carbon technologies and sourcing of CRMs an essential part of the decarbonization approach. Energy transition and green recovery policies and projects—following the COVID-19 pandemic—are already increasing rapidly, placing significant pressure on CRM supply chains. While it is important to diversify material sourcing from sustainable and responsible mining activities as much as possible and to reduce material intensities, these measures alone will not be sufficient to meet growing demand and reduce supply disruptions. Scaling up CRM mining and processing requires long time frames and large capital investments, which can delay production of materials needed for decarbonization. For instance, more than 200 copper mines are expected to run out of ore before 2035, without enough new mines in the pipeline to take their place, leading to a supply shortfall of more than 15 million metric tons by 2035 [92].

Our high-level analysis of collection and recycling of low-carbon technologies shows that, with current global practices, less than 15% of select CRMs could come from EOL recovery in 2050. However, the most ambitious strategy—resembling closed-loop circularity practices with 100% collection and a maximum potential recycling efficiency—can meet 37%–91% of CRM demand in 2050, varying by low-carbon technology type. Although significant barriers, such as building robust collection frameworks and developing cost-competitive and highly efficient recycling technologies, must be addressed to fully realize

the potential, our analysis suggests that comprehensive collection and recycling of EOL low-carbon technologies can mitigate the likelihood or severity of supply disruptions.

Recycling of low-carbon technologies potentially can provide economic value and employment opportunities as well. For example, recoverable materials from decommissioned PV panels could be worth up to \$15 billion by 2050 [93]. Our results also show that increasing collection without advances in recycling or vice versa can have different impacts on different technology recovery pathways. Boosting EOL material collection rates without progress in recycling rates is least effective for EVs, BESS, and PV panels. However, when high-throughput recycling and sorting technologies are available, increased collection has a large impact on recovery of CRMs from these products—showing the need for advances in sorting and recycling, including development of technologies that recover lithium and REEs. In contrast, recycling of wind turbines can already achieve high rates. Thus, promoting advances in recycling technologies without increasing collection is not as impactful for wind turbines, demonstrating the need for enhanced turbine collection practices.

A transition that integrates a circular economy with a low-carbon trajectory would not only minimize disruptions of CRM supplies—and therefore indirectly accelerate decarbonization—but also drastically reduce resource depletion through reduction in primary material demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

We estimate EOL material volumes in 2040 and 2050 based on scrappage of stock, considering the median equipment lifetime and a growth parameter that determines how fast low-carbon technologies are retired around the median lifetime. We calculate survival rates through a logistic curve as follows:

$$survival_t = 1 - 1 / (1 + e^{-\beta(t-t_0)}) \tag{1}$$

where t_0 is the median lifetime of the equipment, t is the age in a given year, and β is a growth parameter that determines how fast the equipment is retired around t_0 . Median lifetimes and the value for β for EVs, BESS, wind turbines, and PV panels are calibrated by comparing survival rates from Xu et al., BNEF, Mauritzen, and Carrara et al. [22,79,94,95]. Fig. A1 shows the survival curves we use for EVs, BESS, wind turbines, and PV panels.

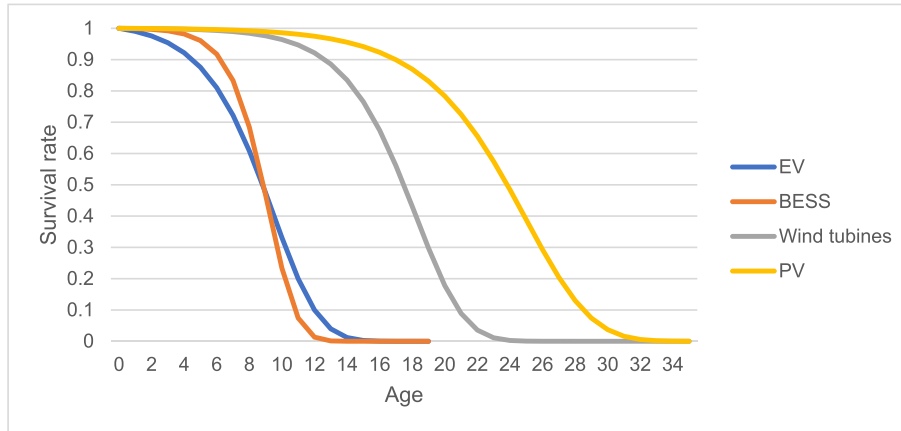


Fig. A1. Technology-specific survival curves used in this analysis. Note: Median lifetimes are assumed to be 15, 10, 20, and 30 years for EVs, BESS, wind turbines, and PV panels, respectively. The β parameter is calibrated as 0.65, 0.65, 0.5, and 0.4 for EVs, BESS, wind turbines, and PV panels, respectively.

Technology stock, St_t , in a year is the sum of new sales in year t and prior-year sales that are still in service, as follows:

$$St_t = S_t + \sum_{u=1}^{t-1} S_u * survival_{t,u} \tag{2}$$

where S_t is the new sale in year t . The new sales of low-carbon technologies at year t (for the period 2020–2050) are based on IEA, IRENA, Xu et al., and BNEF [9,20,22,79].

Material volume in new sales is formulated based on a parameter defining the specific material amount used in an equipment.

$$M_{i,t} = S_t * \alpha_i \tag{3}$$

where α_i is per unit amount of material i in the equipment in terms of weight. $M_{i,t}$ are the total weight of material i used in the new sales at year t . We use the annual material demand from IEA and Xu et al., to calibrate α_i (Fig. A2) [9,22].

Annual EOL volume of material i , $EOL_{i,t}$, is the material discarded in the scrapped stock of the technology in year t :

$$EOL_{i,t} = \sum_{u=1}^t M_{i,u} * (1 - survival_{t,u}) \tag{4}$$

Annual recovery volume of material i from EOL equipment in year t , $R_{i,t}$, is then calculated as a factor of technology specific collection (cl_i) and technology and material specific recycling rate (rc_i):

$$R_{i,t} = EOL_{i,t} * cl_i * rc_i \tag{5}$$

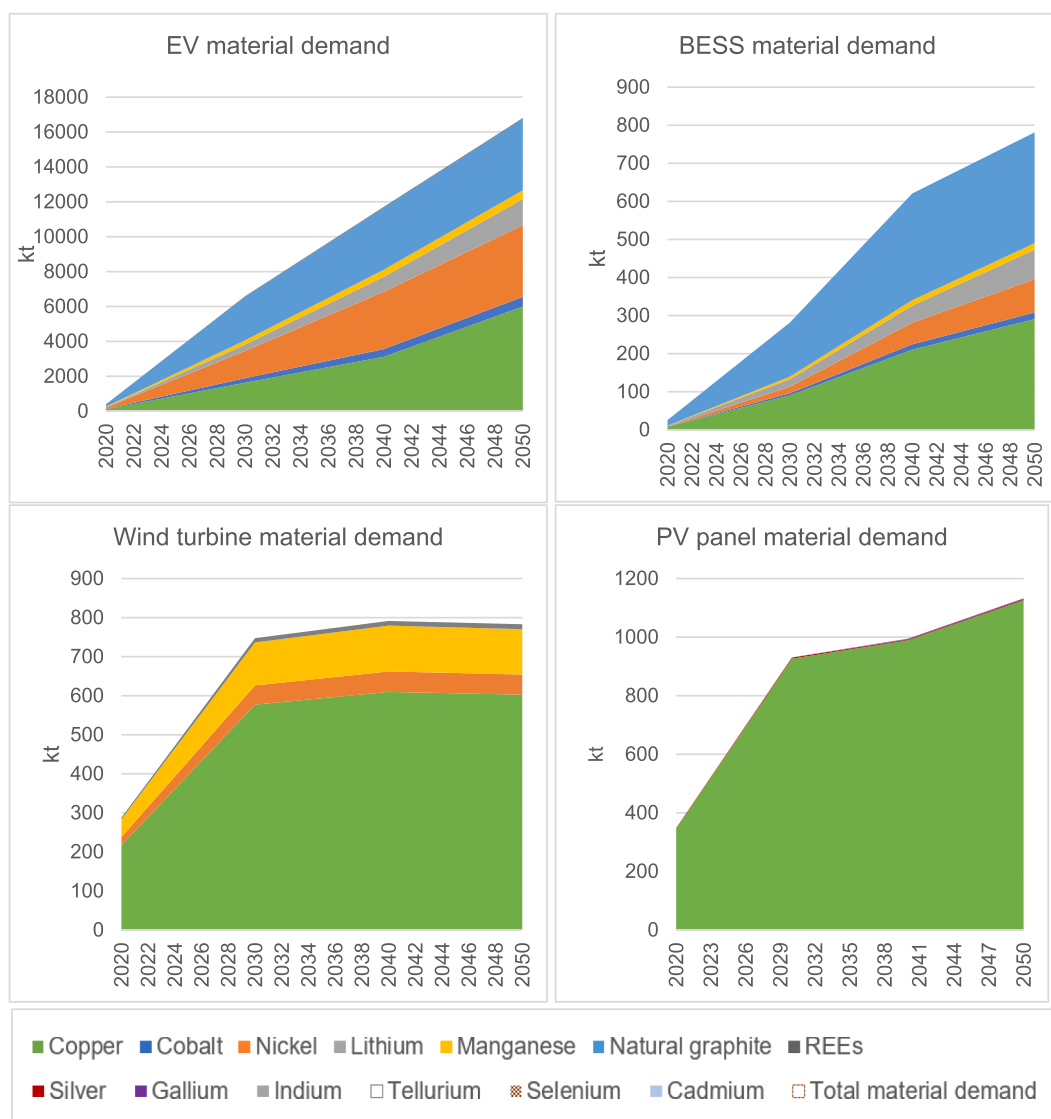


Fig. A2. Annual material demand for EVs, BESS, wind turbines, and PV panels between 2020 and 2050.

Note: Scales differ on y-axes.

Source: Demand values at 2020, 2030, 2040, and 2050 are obtained from IEA, IRENA, Xu et al., and BNEF [9,20,22,79]. Demand values in between years are based on linear interpolations by the authors.

Table A1

CRM demand and secondary material supply in 2040 and 2050 from EVs in the scenarios (in kt).

	2040						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	3119.3	81.7	172.5	240.4	507.4	480.7	1014.8
Cobalt	441.1	21.3	27.3	62.5	80.2	125.0	160.5
Nickel	3286.7	112.5	164.4	330.9	483.6	661.8	967.2
Lithium	859.3	-	37.8	-	111.3	-	222.6
Manganese	403.8	-	26.5	-	77.8	-	155.7
Natural graphite	3568.5	-	260.7	-	766.8	-	1533.6
REEs	34.7	-	2.5	-	7.3	-	14.5
2050							
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	6000.0	197.4	416.7	580.6	1225.7	1161.2	2451.4

(continued on next page)

Table A1 (continued)

	2050						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Cobalt	551.4	46.8	60.1	137.7	176.8	275.4	353.5
Nickel	4108.4	291.9	426.6	858.6	1254.8	1717.1	2509.6
Lithium	1498.7	–	109.0	–	320.6	–	641.1
Manganese	504.7	–	55.7	–	163.8	–	327.7
Natural graphite	4100.0	–	511.6	–	1504.7	–	3009.3
REEs	37.8	–	4.9	–	14.4	–	28.8

Table A2

CRM demand and secondary material supply in 2040 and 2050 from BESS in the scenarios (in kt).

	2040						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	210.6	7.0	14.7	20.5	43.4	41.1	86.8
Cobalt	14.0	0.7	0.9	2.1	2.7	4.3	5.5
Nickel	57.1	2.2	3.2	6.5	9.5	12.9	18.9
Lithium	44.5	–	3.2	–	9.4	–	18.8
Manganese	14.3	–	1.1	–	3.2	–	6.3
Natural graphite	280.2	–	21.9	–	64.5	–	128.9
	2050						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	290.8	16.8	35.5	49.4	104.3	98.8	208.6
Cobalt	17.5	1.8	2.3	5.3	6.8	10.6	13.6
Nickel	87.1	6.7	9.8	19.7	28.8	39.4	57.6
Lithium	77.7	–	7.9	–	23.3	–	46.5
Manganese	17.0	–	2.3	–	6.9	–	13.8
Natural graphite	291.2	–	44.9	–	132.1	–	264.2

Table A3

CRM demand and secondary material supply in 2040 and 2050 from wind turbines in the scenarios (in kt).

	2040						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	609.8	42.3	44.7	124.4	131.4	248.9	262.7
Nickel	52.3	2.9	4.1	8.6	12.0	17.1	23.9
Manganese	117.4	–	9.0	–	26.3	–	52.7
REEs	11.9	–	0.9	–	2.5	–	5.1
	2050						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	602.5	88.4	93.3	260.1	274.5	520.1	549.0
Nickel	51.7	5.7	8.0	16.8	23.5	33.6	46.9
Manganese	116.0	–	17.8	–	52.5	–	104.9
REEs	12.8	–	1.8	–	5.3	–	10.6

Table A4
CRM demand and secondary material supply in 2040 and 2050 from solar PV in the scenarios (in kt).

	2040						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	989.1	1.4	4.0	4.2	11.8	8.5	23.7
Silver	2.3	–	0.020	–	0.059	–	0.117
Gallium	2.8	–	0.000	–	0.001	–	0.002
Indium	0.1	–	0.000	–	0.000	–	0.001
Tellurium	0.3	0.001	0.002	0.004	0.006	0.008	0.012
Selenium	0.1	–	0.000	–	0.001	–	0.002
Cadmium	0.3	0.001	0.002	0.004	0.006	0.008	0.011
	2050						
	Demand	Secondary Material Supply					
		Reference	CES1	CES 2a	CES 2b	CES 3a	CES 3b
Copper	1126.1	30.0	83.9	88.3	246.8	176.7	493.7
Silver	2.9	–	0.4	–	1.1	–	2.2
Gallium	3.1	–	0.01	–	0.03	–	0.06
Indium	0.1	–	0.00	–	0.01	–	0.02
Tellurium	0.4	0.03	0.04	0.08	0.11	0.16	0.22
Selenium	0.1	–	0.01	–	0.02	–	0.04
Cadmium	0.3	0.03	0.04	0.07	0.11	0.15	0.21

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