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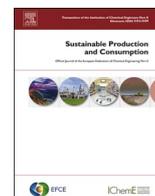
Slowing, narrowing, and closing material flows: Impacts on metal demands in wind and solar power

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Slowing, narrowing, and closing material flows: Impacts on metal demands in wind and solar power

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ABSTRACT

Ambitious electrification and decarbonization targets will increase demand for metals used in renewable electricity technologies. Circular economy strategies have been proposed to curb this demand, but the combined impacts of longer design lifespans, material-intensity reductions, substitution, and recycling—strategies that slow, narrow, and close material flows—remain unquantified. Here we estimate the quantities of germanium, gallium, neodymium, praseodymium, dysprosium, and terbium required for a large-scale deployment of wind and solar power in Sweden through 2050. We then assess how these strategies affect material demand. We find that across metals, their combined implementation can reduce cumulative primary metal demand by 52–60% for wind and 55–72% for solar power, substantially lowering dependence on primary production. Strategies that narrow material flows demonstrate the greatest reduction potential. Nevertheless, primary demand persists for most metals through 2050, indicating that additional primary or other secondary supplies will still be necessary. The impact of circular economy strategies is metal-, technology-, market-share- and time-dependent. Therefore, no single strategy fits all contexts, instead tailored portfolios are needed to reduce metal demand. A trade-off emerges within the transition period to 2050: a combination of strategies that most reduce gross metal demand can increase primary demand. This trade-off requires industrial and policy decision-makers to choose between minimizing the total material throughput or the reliance on primary supply. Ultimately, tailored portfolios of strategies that slow, narrow, and close material flows are essential to reduce metal demand and support the transition to a renewable electricity system.

1. Introduction

The expansion of renewable energy technologies, particularly wind turbines and solar photovoltaic systems, is among the main options considered for decarbonizing the power sector (IPCC, 2011). However, the large-scale deployment of renewable technologies demands a significant increase in the production and processing of several minor metals, of which gallium, germanium, neodymium, praseodymium, dysprosium, and terbium, all listed as both critical and strategic raw materials under the European Commission's Critical Raw Material Act (CRMA) (European Commission, 2024). The growing dependence on these metals may pose substantial challenges to the large-scale adoption of wind and solar technologies.

The supply chains of these metals—particularly rare earth elements (REE) [neodymium, dysprosium, praseodymium, and terbium]—face challenges in scaling up as projected demand rises well above current

production levels (Deetman et al., 2021; Kalt et al., 2022; Lee et al., 2024; Yu et al., 2023). Geographic concentration of REE (Ilankoon et al., 2022; Golev et al., 2014), gallium and germanium (Wesselkaemper et al., 2025) supply chains increases vulnerability to interruptions and geopolitical tensions. Additionally, local social and environmental impacts associated with their extraction, processing, and waste (Zapp et al., 2022; Talan and Huang, 2022; Ali, 2014; Lèbre, 2020; Luo et al., 2025; Yandem and Jabłońska-Czapla, 2024) complicate supply expansion, highlighting the need for research focused on strategies to reduce material demand.

In this context, Circular Economy (CE) strategies are presented as key solutions to reduce the demand (Lee et al., 2024; Lallana et al., 2024; Wang et al., 2024a; Li and Adachi, 2019; Elshkaki and Shen, 2019; Månberger and Stenqvist, 2018) and therefore, mitigate the supply risks and social and environmental impacts associated with the large-scale adoption of low-carbon technologies (Creutzig et al., 2024). CE

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strategies can affect material flows in different ways. Bocken et al (Bocken et al., 2016). introduced the Slow-Narrow-Close framework of material loops for strategies to move from a linear to a CE. *Slow*, as the name suggests, is about slowing down the flow of materials through the prolonged use and reuse of products over time. This can be achieved through the design of long-lasting products and strategies for product lifespan extension (for instance through repair and remanufacturing). *Narrow* is about reducing material use per unit of product produced. *Close* refers to the closing of the material loop between the end-of-life (EoL) and production stages of a product's lifecycle, thereby creating a circular flow of materials. This is achieved through recycling.

The total demand for a material (i.e. *gross demand*) can be met by *primary demand*—the quantity supplied through new extraction and processing—and/or *secondary supply*, which refers to the quantity supplied from nonprimary sources i.e. recycling. Currently, recycling capacities for gallium, germanium, neodymium, praseodymium, dysprosium, and terbium remain negligible (European Commission, n. d.). Therefore, reducing gross demand currently equates to reducing primary demand. However, as recycling efforts accelerate—aligned with the European Commission's target to meet 25% of the EU's strategic material demand through recycling by 2030 (European Commission, 2024)—this dynamic will likely change. Reducing gross demand is likely to remain a key focus, especially given the urgency and scale required to decarbonize the energy system. At the same time, primary demand is generally associated with higher supply-chain environmental impacts compared to secondary supply (Maani et al., 2020; Jouini et al., 2022; Tawalbeh et al., 2021; Komoto et al., 2018; Chowdhury et al., 2021; Wang et al., 2025). These impacts are often disproportionately placed on low-income or Indigenous communities (Luckeneder et al., 2021; Owen et al., 2022). Therefore, increasing the share of secondary supply to satisfy the gross demand is widely considered a promising strategy to close material loops and reduce reliance on primary extraction.

A few previous studies have focused on the impacts of CE strategies on the material requirements of renewable energy generation technologies in low-carbon transition pathways. A study on decarbonization scenarios for the Dutch electricity system (Van Oorschot et al., 2022) shows that implementing material intensity (MI) reduction can reduce the annual gross demand of neodymium by 81% by 2050, compared to a reference case. A global study conducting dynamic material flow analysis, showed that the combined effect of MI reduction, substitution, reuse and recycling can reduce cumulative REE primary demand from wind turbines, electric vehicles and other sectors by 59 to 67% among metals over a 30-year period (Wang et al., 2024b). The same study also shows that MI reduction and substitution can limit cumulative primary demand for REE more than reuse and recycling. A study on material requirements in the US wind and solar power generation shows that closed-loop recycling, MI reduction, and changing market shares of sub-technologies can reduce primary material requirements by up to 40% on average (Lee et al., 2024). A recent study by the authors (Savvidou et al., 2026) investigating metals in wind and solar photovoltaic power, shows that the combination of longer design lifespan, MI reduction, and substitution result in total cumulative gross metal demand reductions in the range of 45–80% among metals by 2050.

Existing literature investigated the impacts of one or several CE strategies. However, to the authors' knowledge, the combined effects of longer design life, material intensity reduction, substitution and recycling—which together span the Slow-Narrow-Close framework—have not yet been studied. Additionally, while some studies focus on either primary or gross demand and others cover both, no study has examined the dynamic interactions between gross and primary demand following the implementation of Slow-Narrow-Close CE strategies. Our previous study (Savvidou et al., 2026) demonstrated that combining slow and narrow CE strategies produces trade-offs between reducing gross material demand and increasing secondary supply, which in turn affects primary demand. Given the absence of the close strategy, it was not

possible to quantify these interactions between gross and primary demand. To the authors' knowledge, no study has yet quantified these trade-offs for the combined Slow-Narrow-Close strategy set.

In this study, we therefore address the following research questions: *How do the CE strategies longer design lifespan, material intensity reduction, substitution and recycling across the Slow-Narrow-Close framework affect gross and primary demand of metals during large-scale deployment of wind and solar technologies? Additionally, do trade-offs arise from implementing these strategies together?* We develop explorative scenarios, that serve as useful tools for understanding the implications of alternative future pathways, thereby informing strategic decision-making (Börjeson et al., 2006). We include in total six minor metals: gallium and germanium in solar panels, and neodymium, dysprosium, praseodymium and terbium in wind turbines. Among the various minor metals used in these technologies, these six are identified as critical and strategic raw materials under the CRMA. We use Sweden as a case study. To place these estimates in a metal supply capacity context, the future primary demands are compared with Sweden's shares in the current global primary production levels of the respective metals, based on a per-capita allocation.

2. Methodology

2.1. System boundaries

This section defines the system boundaries of our analysis across temporal, technological, and material dimensions.

Temporally, scenarios cover 2022–2050, with 2021 as the base year. Since estimating the fraction of older wind and solar photovoltaic capacity still in operation requires historical commissioning data (see Fig. 1), our dataset extends back to 1996. Given the end year of our scenarios and the long lifespans of wind and solar technologies, the full lifecycle of technologies introduced later in the scenario period is not fully captured (Fig. 1). This limits our ability to show the full contributions of longer design lifespan and recycling strategies within the temporal boundaries of our analysis, as these effects are expected to continue having an impact beyond 2050.

For the material dimension of our analysis, we focus on six metals in wind and solar technologies that are listed as both critical and strategic raw materials under EU's CRMA: gallium, germanium, neodymium, praseodymium, dysprosium, and terbium. These metals define the technology boundaries of our study, summarized in Table 1. Specifically, onshore and offshore wind turbines have two main turbine configurations: direct-drive and gearbox, both employing REE in permanent magnets (PM) but with different material intensities (Andersen et al., 2016). For solar technologies, commercially available options include first-generation crystalline silicon and second-generation thin films—amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). Our analysis covers a-Si panels containing germanium and CIGS panels containing gallium.

In our scenario analysis, we investigate substitution—the replacement of certain metals in wind and solar technologies with alternative metals, components, or different sub-technologies—to reduce reliance on critical and strategic metals. Further details on the assumed alternatives are provided in Section 2.3.

2.2. Modelling framework

The material dynamics are modeled using the dynamic material flow analysis (MFA) model developed in our earlier research (Savvidou et al., 2026). Here, the model is further expanded to account for equal-per-capita allocation analysis and for recycling, thereby allowing to distinguish between gross and primary demand.

Our modelling framework is illustrated in Fig. 2. Calculations are carried out in five sequential steps, indicated in the numbered purple boxes. First, based on installed wind and solar capacity, the stock-driven MFA (step 1) generates new capacity demand *inflows*. These inflows are

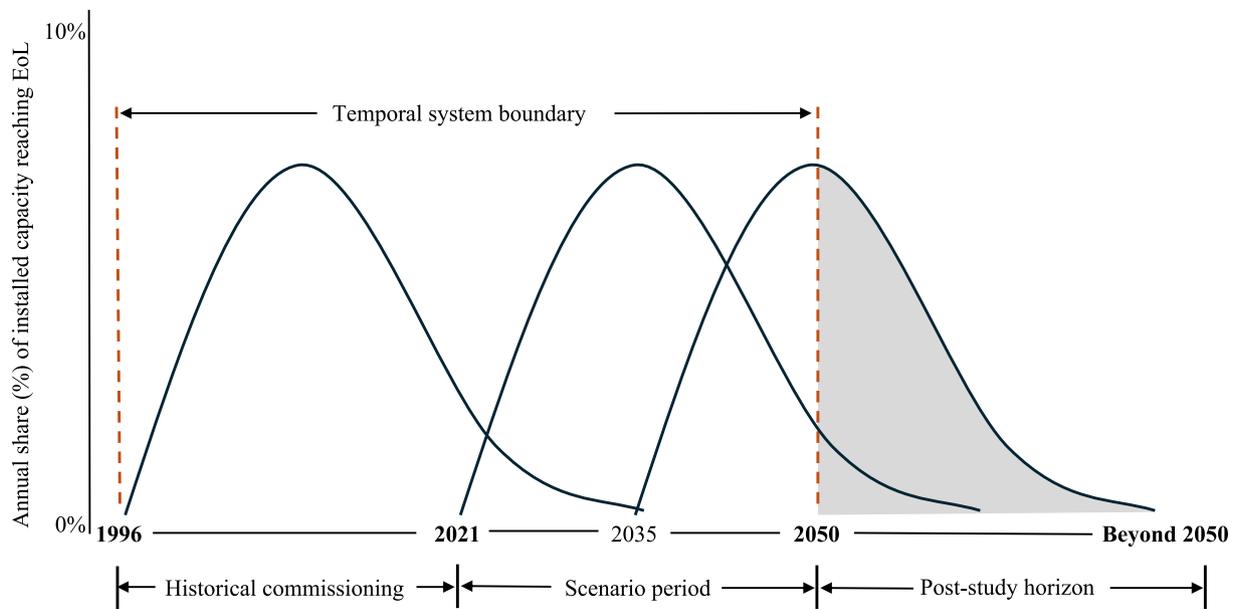


Fig. 1. Temporal system boundary (1996–2050) and a conceptual representation of the lifespans of technologies commissioned in different years within this boundary. The figure shows three technology lifespan distributions—expressed as the annual share (%) of installed capacity reaching EoL—for technologies commissioned in 1996, 2021 (the base year), and 2035. While a lifespan distribution exists for every year within the system boundary, only these three are shown for illustration. The graph illustrates that the majority of technologies commissioned in 1996 are decommissioned before 2021, although a small share continues beyond that year into the scenario period. Similarly, most technologies commissioned in 2021 are decommissioned within the scenario period, but some extend into the post-study horizon, indicated by grey shading. For technologies commissioned later in the scenario period (e.g., 2035), a large portion reaches EoL during the post-study horizon.

Table 1

Technology, sub-technology, component, and material layers of wind and solar technologies.

| | | |
|----------------|---|---|
| Technology | Wind turbines (onshore & offshore) | Solar panels (distributed & centralized grid-connected) |
| Sub-technology | Direct-drive permanent magnet synchronous generators (DD-PMSG) Gearbox permanent magnet synchronous generators (GB-PMSG) | Amorphous silicon (a-Si) Copper indium gallium diselenide (CIGS) |
| Component | Rare earth element (REE) permanent magnets (PM) Neodymium (DD-PMSG & GB-PMSG) Praseodymium (DD-PMSG & GB-PMSG) | Solar cells |
| Material | Dysprosium (DD-PMSG & GB-PMSG) Terbium (DD-PMSG & GB-PMSG) | Germanium (a-Si) Gallium (CIGS) |

converted to material inflows (gross demand) using sub-technology market-shares and material intensity coefficients (step 2). Note that endogenous feedback on sub-technology market-shares (e.g., changes due to reduced metal scarcity following increased endogenous secondary supply) is not modeled. The material inflows feed into a dynamic inflow-driven MFA (step 3), resulting in material outflows. Outflows are then converted to secondary supply by applying old scrap collection rates for wind and solar technologies and metal-specific recycling process efficiency rates (step 4). Primary demand is calculated as gross demand minus secondary supply. Finally, the equal-per-capita allocation analysis results in the primary demand shares of each metal relative to current global annual production (step 5).

The CE strategies considered are longer design lifespan, MI reduction, substitution, and recycling. Longer design lifespan involves enhancing technology designs to increase the operational service life of

products. MI reduction focuses on minimizing the quantity of materials required by improving the design of technologies. Substitution entails replacing certain metals in final applications with alternative metals, components, or different sub-technologies to reduce reliance on critical materials. Recycling involves the recovery of metals from EoL technologies that have reached waste treatment facilities, enabling these materials to be further used in new applications.

Main calculations regarding steps 1–3 as developed in our earlier work (Savvidou et al., 2026) are provided in Supplementary section 1. Below the recycling and equal-per-capita allocation analyses (steps 4 and 5) are described.

2.2.1. Recycling analysis

To investigate the potential impacts of recycling on the primary demand of metals, old scrap collection rates (hereafter called *collection rates*) and recycling process efficiency rates (hereafter called *recycling rates*) are applied to the material outflows, and primary demand was calculated as follows:

$$SS_m(t) = outflow_m(t) \times collection_k(t) \times recycling_m(t)$$

$$PD_m(t) = inflow_m(t) - SS_m(t)$$

where $SS_m(t)$ is the secondary supply of metal m at time t recovered through the recycling process, $collection_k(t)$ is the collection rate of EoL sub-technology k (wind and solar sub-technologies) at time t , and $recycling_m(t)$ is the recycling rate of metal m at time t . $PD_m(t)$ is primary demand of metal m at time t , which is a result of the gross demand ($inflow_m(t)$) minus the $SS_m(t)$.

Collection rate represents the rate at which a wind or solar sub-technology that has reached its EoL arrives at a waste treatment facility. In the EU, solar panels fall under category VII of waste electrical and electronic equipment (WEEE). The European WEEE Directive (2012/19/EU) establishes a minimum collection target of 65% of the average weight of electrical and electronic equipment (EEE) placed on the market during the previous three years, effective from 2019. This

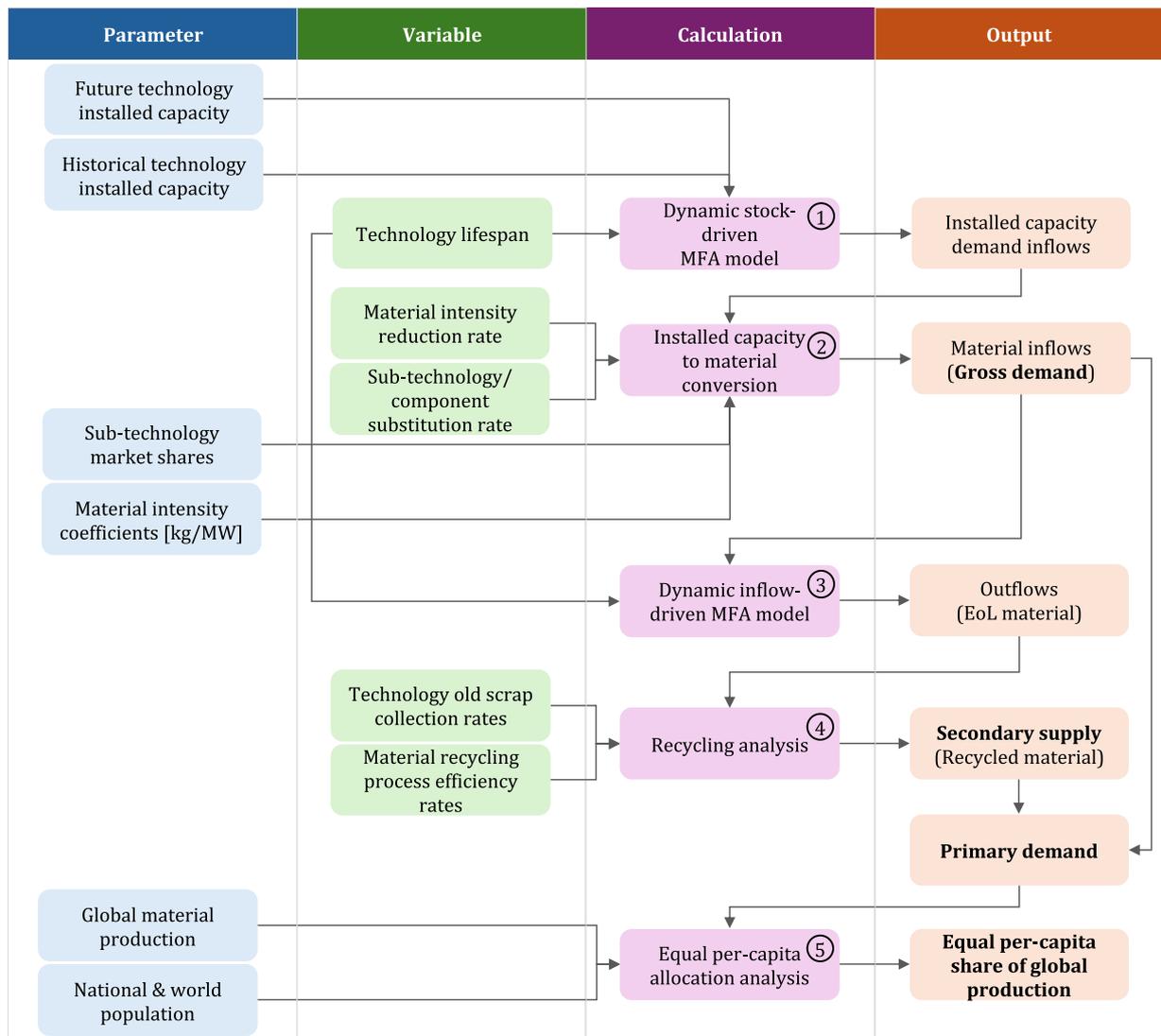


Fig. 2. Graphical representation of the modelling framework. Outputs presented directly in the manuscript are highlighted in bold.

directive implements the Extended Producer Responsibility principle, requiring producers to cover the costs of WEEE management. Additionally, the legislation plans to raise the collection target from 65% to 85% once the European Commission develops a methodology for estimating WEEE generation.

The recycling rate represents the rate at which the secondary raw materials contained in EoL technologies that have reached an official waste treatment facility are recovered. The process of recovering the same metal from different technologies may necessitate specific methods. Each technology's design, the form in which the metal is used, and its combination with other materials can greatly affect the specificity and complexity of the recovery process. Therefore, for the collection of data, the recycling rate of metals associated with specific technologies is important. Data for the recycling rate were gathered, which measures the proportion of a material in the waste flows that is recycled for wind and solar power technologies.

Supplementary section 2 provides further details for the main assumptions made for the collection and recycling rates, along with data sources.

2.2.2. Equal-per-capita share of primary production

To put our results into context, we provide the equal-per-capita share of each metal's current global production as a benchmark against annual primary metal demands. This comparison assumes that the metals are

used exclusively for wind and solar technologies, whereas in reality, other sectors—such as electric vehicles, which require REE—also demand these metals and are expected to grow. The purpose of this comparison is to indicate the current capacity of extraction and refining industries to supply the metals under study, rather than to propose a normative or realistic allocation of these metals.

Germanium and gallium are exclusively produced as byproducts and therefore their worldwide annual production is measured as processed/refined production. REE are economically extracted as primary raw materials and therefore their global production is measured as primary production.

Sweden's equal-per-capita shares, PP_S , of worldwide annual primary or processed production, PP_W , for each metal considered are estimated as follows:

$$PP_S = PP_W \frac{P_S}{P_W}$$

Where P_S is Sweden's population and P_W is the world population in the base year. Swedish population data are based on Statistics Sweden's (Statistics Sweden, 2022) and global population data are based on the United Nation's Department of Economic and Social Affairs Population Division (United Nations, 2024). The worldwide primary and/or processed production of each metal in 2021 are from the EU Raw Materials

Information System (European Commission, n.d.). Values for the worldwide production of each metal and the allocated share for Sweden are provided in Supplementary Table S3.

2.3. Scenario setting

Fig. 3 provides an overview of the CE strategies and developed scenarios, along with their effect on material flows. Table 2 summarizes the main assumptions and input data for the analysed CE strategies and the scenarios. Additional details on the assumptions and data sources for longer design lifespan, MI reduction, and substitution can be found in our earlier work (Savvidou et al., 2026), while information on recycling assumptions and references is provided in Supplementary section 2 and Supplementary Tables S1 and S2.

In total, three scenarios are investigated: a Baseline scenario, assuming no CE strategy is implemented, a Narrow-Close scenario in which MI reduction, substitution and recycling are implemented, and a Slow-Narrow-Close scenario in which all CE strategies are implemented (see Fig. 3 and Table 2). The impact of CE strategies if implemented in isolation is also calculated.

To describe projected trajectories of wind and solar installed capacity, we adopt the Swedish transmission system operator's Renewable Electrification (RE) scenario as model input (Fig. 4). This scenario shows a sharp increase in electricity demand—more than doubling between the base year and 2050—driven by electrification of industry and transportation, supported by large-scale deployment of wind and solar power. Onshore wind already accounted for 21% of electricity generation in 2021 and remains a major source, reaching 26% of installed capacity by 2050. Offshore wind and solar currently have minimal shares but are projected to grow substantially, reaching 33% and 22% of installed capacity, respectively. By 2050, electricity generation is dominated by offshore wind, onshore wind, and solar power. While electricity systems and decarbonization strategies vary across countries, they commonly involve significant investments in renewable energy and transportation electrification. The RE scenario represents a high-electrification, high-renewables pathway typical of ambitious decarbonization efforts. Although alternative demand trajectories—more conservative or aggressive—are not explored here, our results remain relevant to countries undergoing rapid renewable expansion alongside increased electrification of their energy systems beyond Sweden.

The high sensitivity of results to market shares of wind and solar sub-technologies—each with unique material intensities—have been

demonstrated in the literature (Lee et al., 2024; Nassar et al., 2016). Examining market-share pathways during renewable expansion thus reveals when and which sub-technologies drive significant, pathway-dependent changes in metal demand, providing valuable insights for decision makers. Given this sensitivity, we present our results in three pathways with varying market-shares of the sub-technologies: a 'central' pathway, together with two market-share pathways with a diminishing and expanding use of REE-containing PM wind and thin-film solar sub-technologies. For this, we use three pathways developed by the European Commission's Joint Research Center (Carrara et al., 2020): low market-share (LMS), medium market-share (MMS) and high market-share (HMS). In 2018, permanent magnet turbines (DD PMSG & GB PMSG) accounted for approximately 30% of the market-share in the EU onshore wind fleet. They increase to 52%, 59% and 65% by 2050 under the LMS, MMS and HMS pathways, respectively. Offshore wind is already dominated by permanent magnets; the HMS preserves this dominance (95% in 2050), while the MMS and LMS drop to 68% and 44% respectively. In 2018, first-generation solar panels held about 95% of the market, while a-Si and CIGS panels accounted for approximately 0.3% and 1.9%, respectively. By 2050, under the LMS, thin-films nearly vanish (a-Si: 0%, CIGS: 1%), the MMS yields modest growth (a-Si: 1%, CIGS: 4.5%), and the HMS sees strong thin-film uptake (a-Si: 3%, CIGS: 10%).

3. Results

3.1. Future primary demand reduction potentials

Fig. 5 compares the annual primary metal demands (given in metric tonnes, hereafter called tons) for the different CE strategies with the Baseline scenario, both if implemented in isolation and if CE strategies are combined in the Narrow-Close and Slow-Narrow-Close scenarios for the period of 2022–2050. This is shown for the three market-share pathways. For comparison, each panel also shows the equal-per-capita share of the metals' current annual global production (horizontal black lines).

As can be seen, primary demand under the different CE strategies (indicated with green lines) differs by metal, market-share pathway, and over time. For solar sub-technologies (Fig. 5a–f), MI reduction produces by far the largest primary demand reductions throughout most of the scenario period. The only exception is germanium in the LMS pathway, in which the market-share of a-Si diminishes by 2050: recycling drives

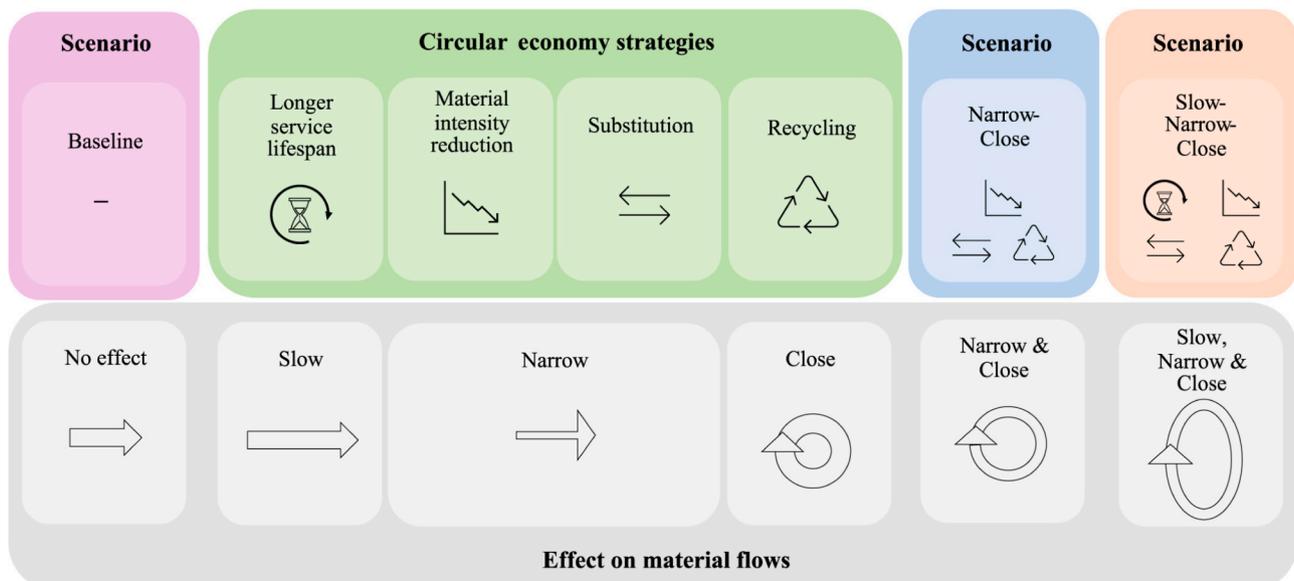


Fig. 3. Circular economy (CE) strategies included in our analysis and the developed scenarios, along with their effects on material flows.

Table 2

Main assumptions and input data for the analysed CE strategies together with the three scenarios. The table summarizes the key assumptions and input data for each CE strategy across the base year, and baseline, Narrow-Close, and Slow-Narrow-Close scenarios. Data sources for each CE strategy are provided. Additional details on assumptions for longer design lifespan, MI reduction, and substitution are provided in Savvidou et al (Savvidou et al., 2026), while recycling assumptions are available in Supplementary section 2.

| CE Strategy | Base year (2021) | Baseline scenario | Narrow-Close scenario | Slow-Narrow-Close scenario | References |
|-------------------------------|---|---|------------------------------------|--|---|
| Longer design lifespan (Slow) | Mean lifespan values: Onshore wind: 21.7 years Offshore wind: 23.6 years Solar: 26.3 years | Base year mean lifespan values: constant* | Same as Baseline scenario | Mean lifespan values in end year (2050): Onshore wind: 30 years Offshore wind: 35 years Solar: 40 years. Values linearly interpolated between base year and end year* | (Carrara et al., 2020; Liang et al., 2022) |
| MI reduction (Narrow) | Material intensities (kg/MW): DD-PMSG: Neodymium: 176.6 Praseodymium: 35.3 Dysprosium: 26.6 Terbium: 5.7 GB-PMSG: Neodymium: 34.5 Praseodymium: 6.8 Dysprosium: 5.1 Terbium: 1.3 a-Si: Germanium: 45.3 CIGS: Gallium: 6.8 | Base year MI reduction rate: constant at zero | Same as Slow-Narrow-Close scenario | Compound annual growth rates (% per year): 2021–2050: Neodymium, Praseodymium: –1.2 Dysprosium, Terbium: –2.4 2021–2030: Germanium: –4.8 Gallium: –9 2030–2050: Germanium: –3.3 Gallium: –4.9 | (Elshkaki and Shen, 2019; Månberger and Stenqvist, 2018; Carrara et al., 2020; Zhou et al., 2020; Valero et al., 2018; Watari et al., 2019; Imholte et al., 2018; Li et al., 2020; Kumari et al., 2018; Hoenderdaal et al., 2013; Pavel et al., 2017) |
| Substitution (Narrow) | Substitution rate: 0% | Base year substitution rate: constant | Same as Slow-Narrow-Close scenario | Substitution rates in end year: Wind: 50% Solar: 20%. Values linearly interpolated between base year and end year. Substitution options: perovskite solar panels, REE-free PM, and high-temperature superconductors. Collection rates in end year: Wind: 95% Solar: 85%. | (Wang et al., 2024a; Carrara et al., 2020; Arvidsson and Sandén, 2017; IEA, 2022) |
| Recycling (Close) | Collection rates: Wind: 80% Solar: 65% Recycling rates: neodymium, praseodymium, dysprosium, terbium, germanium, gallium: 0% | Base year collection rates: constant Base year recycling rates: constant | Same as Slow-Narrow-Close scenario | Values linearly interpolated between base and end year. Recycling rates in end year: neodymium, praseodymium, dysprosium, terbium, gallium: 90% Germanium: 80%. Logistic curve was applied between base and end year. | (Lee et al., 2024; Lallana et al., 2024; Wang et al., 2024a; Gregoir and van Acker, 2022; Schulze and Buchert, 2016; Dominish et al., 2019; ESA, 2022; Charpentier Poncelet et al., 2022; Domínguez and Geyer, 2019; Roelofs, 2020; Habib and Wenzel, 2014) |

* Age-dependent lifespan probability function is modeled using a Weibull distribution with mean lifespans as indicated in the table and a standard deviation of 5 years.

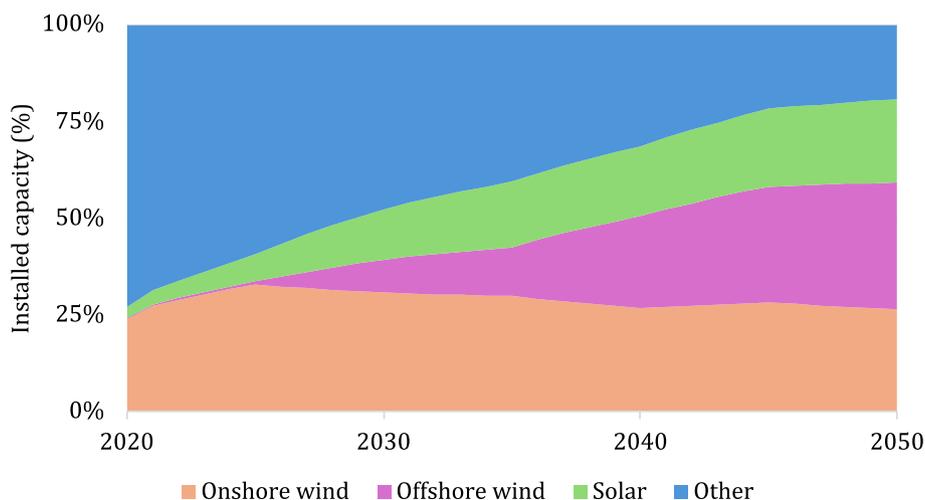


Fig. 4. Installed capacity shares in the Swedish electricity system by source—onshore wind, offshore wind, solar, and other—in the Renewable Electrification (RE) pathway. Source: Authors based on Svenska Kraftnät (Svenska Kraftnät, 2021). Note: Data are given every five years; intermediate values are linearly interpolated.

net negative primary demand from 2037 onward (i.e. secondary supply exceed gross demand). Substitution is generally the strategy that provides the next largest reductions in primary demand, although its rank relative to recycling changes over time as EoL capacity outflows increase

in the later stage of the transition, and recycling rates are modeled to experience rapid increase post-2035 to 2040 (see Supplementary Fig. S1). Specifically for germanium, substitution is the second largest reducer until 2036, 2040 and 2048 for the LMS, MMS and HMS

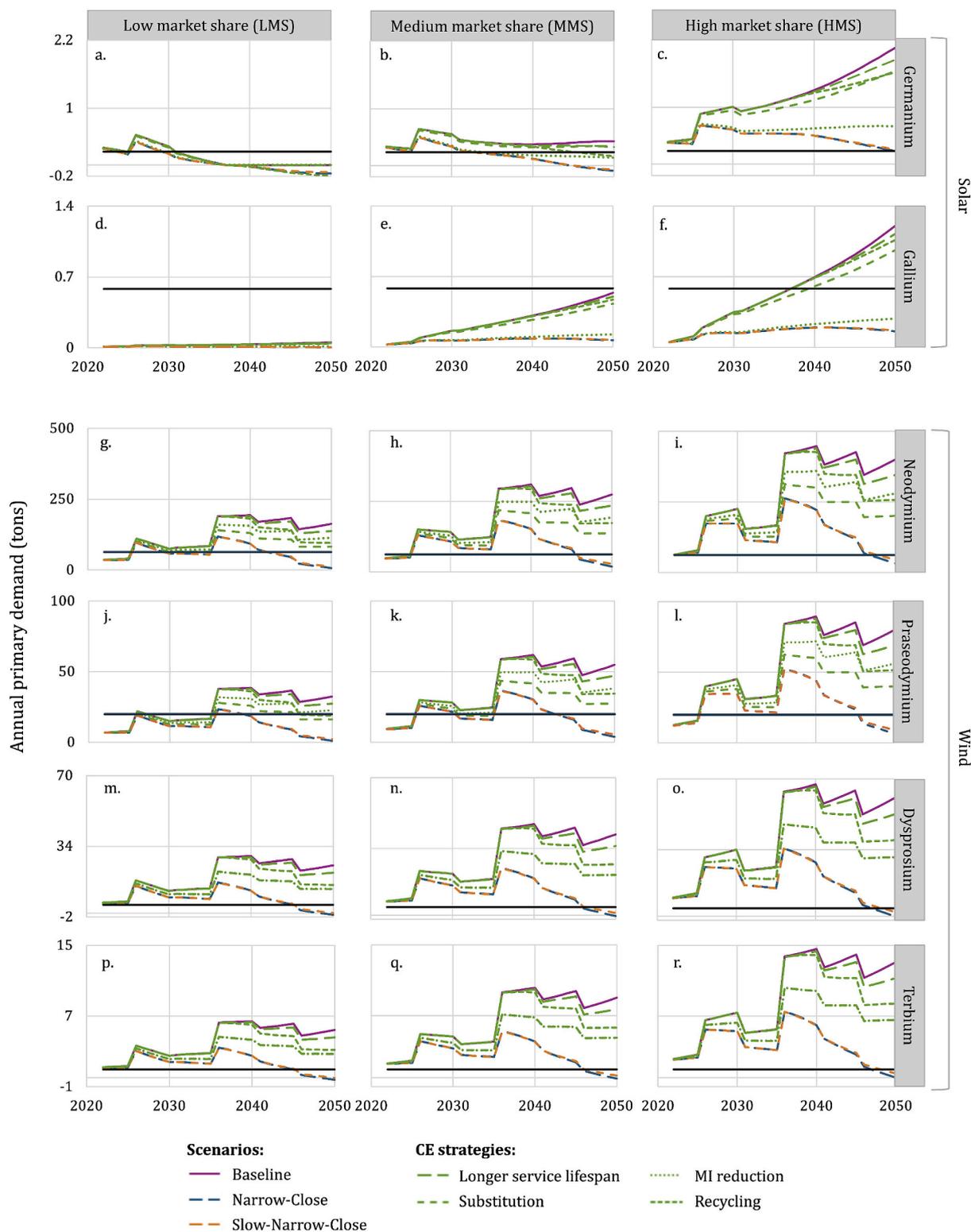


Fig. 5. Annual primary demand for the metals germanium (a–c), gallium (d–f), neodymium (g–i), praseodymium (j–l), dysprosium (m–o), and terbium (p–r) under three market-share pathways: LMS (a, d, g, j, m, p), MMS (b, e, h, k, n, q) and HMS (c, f, i, l, o, r). Baseline scenario is shown with solid purple line; Narrow-Close and Slow-Narrow-Close scenarios are shown with dashed blue and dashed orange lines; individual CE strategies are shown with green lines (different dash patterns). For comparison, each panel also shows the equal-per-capita share of the metals' annual global production (horizontal black line). All quantities are shown in tons. Note: Gallium equal-per-capita share exceeds the plotted range (see Supplementary Table S3). LMS and MMS pathways germanium and gallium series are shown in higher resolution in Supplementary Fig. S2. The shape of time series is driven by installed capacity data. Observed discontinuities correspond to historical step changes in capacities, and the five-year intervals used in the prospective capacity data. For dysprosium and terbium, substitution and MI reduction yield equal reductions across all market-share pathways.

pathways, respectively, after which recycling has higher reduction potential. In the MMS pathway, the primary demand in the longer design lifespan yields lower primary demand than substitution from 2048 onward. For gallium, substitution remains the second most effective strategy throughout the MMS and HMS pathways; in the LMS pathway it ranks second until 2046, after which recycling yields greater reductions. Longer design lifespan is generally the least effective strategy.

For wind power (Fig. 5g-r), substitution yields the largest reductions in primary demand, followed by the MI reduction; for dysprosium and terbium, substitution and MI reduction provide the same reductions across market-share pathways. For neodymium and praseodymium (Fig. 5g-l), recycling reduces primary demand to a lesser extent than MI reduction for most of the scenario period. Yet, its reduction grows towards the end of the scenario period and reverses the ranking from 2046 onwards as outflows from technologies reaching their EoL increase towards the end of the scenario period along with the increasing recycling rates reaching high values by 2050. Longer design lifespan has the lowest reduction throughout the scenario period and across market-share pathways. Although longer design lifespan has generally the lowest reduction for both wind and solar technologies during the scenario period, its contribution would continue to grow beyond the scenario end-year because of the long lifespans of these technologies—particularly offshore wind and solar, which are introduced or expanded later in the studied period (see Fig. 4).

Overall, our results show that if the MI reductions (narrow strategy) are achieved, by 2050, 19–66% (depending on metal and market-share pathway) of cumulative primary demand could be avoided. For example, for germanium, in HDS pathway, MI reduction alone reduces cumulative primary demand from 34 to 18 tons. For the second narrow strategy (substitution), the reduction varies between 4 and 38% across metals and market-share pathways. The slow strategy (longer design lifespan) achieves lower reductions, in the order of 0.2–5%. In the absence of slow and narrow CE strategies, the close strategy (recycling) results show that if high collection and recycling rates are achieved by 2050 for wind and solar EoL management, depending on market-share pathway 11–13% of the primary REEs used in wind power, 7–37% for germanium and 4–8% for gallium used in solar could be avoided.

Looking at the combined impacts of all CE strategies in the Slow-Narrow-Close scenario in 2050, compared to the Baseline scenario, the annual reduction is in the range of 89%–100% and 86%–117% (depending on metals and market-share pathway) in wind and solar, respectively. Annual primary metal demands are eliminated for germanium in 2037 and 2046 in the LMS and MMS pathways respectively, and for dysprosium and terbium in 2050 in the LMS pathway. Cumulatively, compared with the baseline scenario, 52–60% and

production capacity. Indeed, historically, global production of these metals has expanded in response to demand and prices, though often with socio-environmental consequences.

With the exception of gallium, an equal-per-capita share of annual global production is not sufficient to meet primary demand during the entire scenario period for any metal under any CE strategy. Gallium primary demand, as the only exception, stays below the equal-per-capita share across all CE strategies under the LMS and MMS pathways (Fig. 5d-e). In the HMS pathway (Fig. 5f), MI reduction keeps gallium primary demand below the equal-per-capita share; the other strategies exceed that threshold in 2038 (longer design lifespan and recycling) and 2040 (substitution). Germanium (Fig. 5a-c) shows large differences across market-share pathways. In the LMS pathway (Fig. 5a), all strategies remain consistently below the equal-per-capita share from 2031 onward. In the MMS pathway, longer design lifespan and substitution keep germanium primary demand above the equal-per-capita share for the entire scenario; MI reduction and recycling reduce demand below that share by 2035 and 2046, respectively. In HMS pathway, no strategy achieves primary demand below the equal-per-capita share at any time. Dysprosium and terbium primary demand remain well above the equal-per-capita share under all strategies and market-share pathways for the entire scenario period (Fig. 5m-r). Neodymium (Fig. 5g-i) likewise stays above the equal-per-capita share from 2025 onward in all market-share pathways. Praseodymium (Fig. 5j-l) exhibits pathway dependent behaviour: in the HMS pathway it remains above the equal-per-capita share throughout; in the MMS pathway it remains above from 2026 onward except for substitution, which remains above only from 2036 onward; in the LMS pathway it remains above the equal-per-capita share from 2036 onward. Considering the collective impacts of all CE strategies in the Slow-Narrow-Close scenario, primary demand for all metals is reduced below the equal-per-capita share of their annual global production at different times before the end of the period (with the exception of germanium in the HMS pathway).

As can be seen in Fig. 5, towards the end of the scenario period, primary demand under the Narrow-Close scenario, which combines the MI reduction, substitution and recycling, becomes lower than that of the Slow-Narrow-Close scenario, which includes in addition the longer design lifespan. In fact, the primary demand does not follow a consistent trend throughout the scenario period, but this is hardly visible in Fig. 5 because the differences are relatively small. Fig. 6 shows the difference ($\Delta_{\text{Primary demand}}$) in primary demand between Slow-Narrow-Close and Narrow-Close scenarios over the scenario period, which is calculated as follows:

$$\Delta_{\text{Primary demand}} = \text{Primary demand}_{\text{Slow-Narrow-Close}} - \text{Primary demand}_{\text{Narrow-Close}}$$

55–72% of metals in wind and solar power respectively could be exempt from demand, significantly lowering the need for extraction. Overall, the combined impacts of all strategies exhibit strong reductions of annual primary metal demands and even eliminate it for some metals. At the same time, while the CE strategies can significantly reduce primary metal demand—particularly for metals like germanium and at the end of the scenario period dysprosium, and terbium—primary demand for most metals persist throughout the scenario period.

To contextualize our findings, we compare annual primary metal demands with an equal-per-capita share of each metal's global production, shown as horizontal black lines in Fig. 5. This comparison indicates the current capacity of extraction and refining industries to supply the metals studied and highlights the scale of expansion needed in primary and/or secondary supply, rather than setting a limit on material

Fig. 6 shows the values for the MMS pathway, but a similar pattern is observed in all three pathways, albeit at different scales. Negative values indicate that the primary demand of the Slow-Narrow-Close scenario is lower than that of Narrow-Close scenario and positive values indicate the opposite. As can be seen, for the first part of the scenario period, primary demand of the Slow-Narrow-Close scenario is slightly lower than that of Narrow-Close scenario but then, as EoL capacity outflows increase and recycling rates are increasing in the later stage of the transition, this reverses and becomes comparatively much higher. Cumulatively this results in having higher primary demand in the Slow-Narrow-Close scenario for the scenario period as a whole, which involved high electrification and increased penetration of renewable technologies. Overall, this indicates that, if the goal is solely to reduce total primary demand during the scenario period, prioritizing the

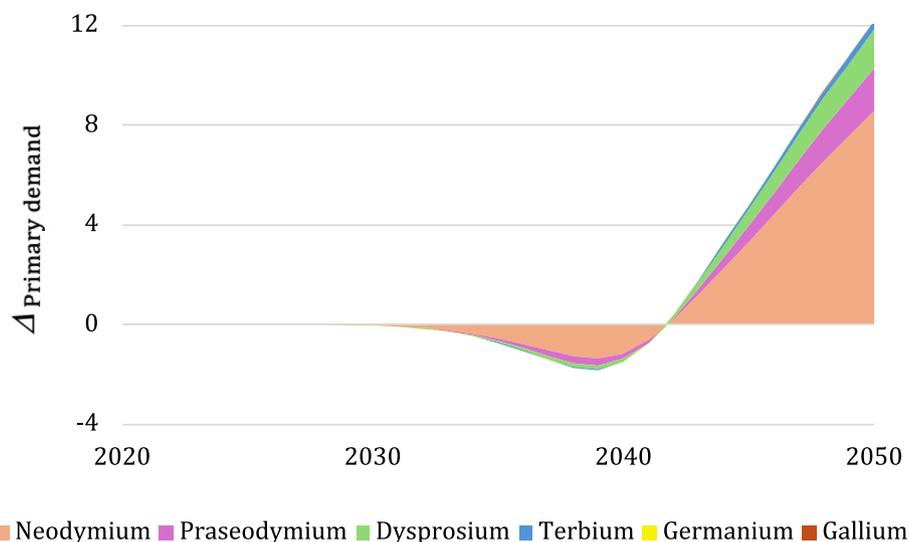


Fig. 6. Difference (Δ) in primary demand between Slow-Narrow-Close and Narrow-Close scenarios over the scenario period within the MMS pathway. The figure shows that primary demand is lower in the Slow-Narrow-Close scenario until around 2042, after which the trend reverses. Note: Time series for germanium and gallium follow the same pattern as neodymium, praseodymium, dysprosium, and terbium but are not visible due to their smaller scale. Although presented for the MMS pathway, similar trends occur across all three pathways.

narrow and close strategies without implementing the slow strategies may be preferred.

3.2. Gross and primary demand

In this section, we analyse the Narrow-Close and the Slow-Narrow-Close scenarios further, by examining the dynamics between primary and gross demand and secondary supply.

Fig. 7 shows the gross demand, primary demand, and secondary supply in tons per metal for the period of 2022–2050, under the two scenarios and the three market-share pathways. Unlike primary demand, gross demand, as indicated by the solid lines, in the Slow-Narrow-Close scenario is consistently lower than the gross demand in the Narrow-Close scenario over the scenario period. Therefore, the Slow-Narrow-Close scenario yields lower gross demand than in the Narrow-Close scenario. But this reduction in gross demand is fulfilled by a higher cumulative primary demand as shown in Fig. 6 (and lower secondary supply).

This dynamic is due to how different CE strategies affect material flows. Longer lifespans (the slow strategy) delay technology decommissioning, which postpones both the installation of new technologies—and thus metal inflows—and the generation of scrap metals (outflows) available for recycling. Narrow strategies reduce the material intensity of new technologies, leading to an immediate reduction in inflows required for new installations and a gradual reduction in outflows, as technologies with lower material intensity reach EoL. The combination of slow and narrow strategies reduces both inflows and outflows compared to narrow strategies alone; however, outflows are reduced to a greater extent than inflows. This occurs because, in any given year, outflows depend on the capacity and material intensity of technologies installed at the start of their lifespans, while inflows (gross demand) are based on the capacity and improved, lower material intensities of newer technologies. Secondary supply results from outflows multiplied by collection and recycling rates, which start at zero but increase rapidly after 2035, becoming significant towards the late 2030s (Supplementary Fig. S1). Since gross demand equals primary demand plus secondary supply, and secondary supply decreases more sharply than gross demand, primary demand must increase slightly to compensate, resulting in greater reliance on primary production.

Therefore, during the scenario period, using the slow strategy (longer design lifespan) in combination with the narrow and close strategies

creates a trade-off between the objective of reducing gross demand on the one hand, and reducing the primary demand on the other hand. Gross demand reduction addresses the urgent, system-scale need to deploy renewable technologies quickly to meet decarbonization targets, whereas primary demand reduction avoids larger supply-chain environmental and social impacts—often borne disproportionately by low-income or Indigenous communities (Luckeneder et al., 2021; Owen et al., 2022). Thus, the trade-off reflects a tension between speed and scale of deployment and the equity and environmental harms of primary sourcing. We observe this trade-off during the transition period with large-scale deployment of renewable technologies. Beyond the scenario period, the impacts of both longer design lifespan and recycling are expected to increase, and at the same time, the deployment of renewable technologies may slow down, following the achievement of decarbonization target. This would have an impact on the trade-off observed.

Despite this trade-off, it is important to understand the potential of secondary supply to satisfy gross demand and therefore reduce primary demand in the Slow-Narrow-Close scenario. In the scenario, the secondary supply, indicated by the orange dotted lines, is an insignificant source of metals for both wind and solar power until the late 2030s. This indicates that primary demand, or secondary supply from other sources, is required for the majority of the scenario period. For germanium, which shows the highest potential, gross demand is eliminated by 2037 in the LMS pathway (Fig. 7a). That means that all secondary supply produced from 2038 could be used to meet demand of germanium in other applications. In the MMS pathway (Fig. 7b), germanium secondary supply exceeds gross demand in 2046 and by 2050 it meets 187% of gross demand. This means that the recycled germanium from the solar technologies reaching their EoL from 2046 onward is sufficient to meet the entire gross demand with remaining supply for other applications. In the HMS pathway (Fig. 7c), secondary supply of germanium fulfils 46% of gross demand by 2050, reducing therefore the primary demand accordingly. For gallium, the secondary supply has a substantially lower potential, reaching 58%, 22%, and 20% of the gross metal demands in the LMS, MMS, and HMS pathways respectively in 2050. For neodymium and praseodymium (Fig. 7g-l), 76%, 66%, and 63% of gross demand can be fulfilled by secondary supply in LMS, MMS and HMS pathways respectively by 2050. For dysprosium and terbium (Fig. 7m-r), secondary supply meets over 50% of gross demand by 2046 across the market-share pathways. By 2050, it fulfils 101%, 87%, and 83% of gross demand in LMS, MMS, and HMS pathways respectively.

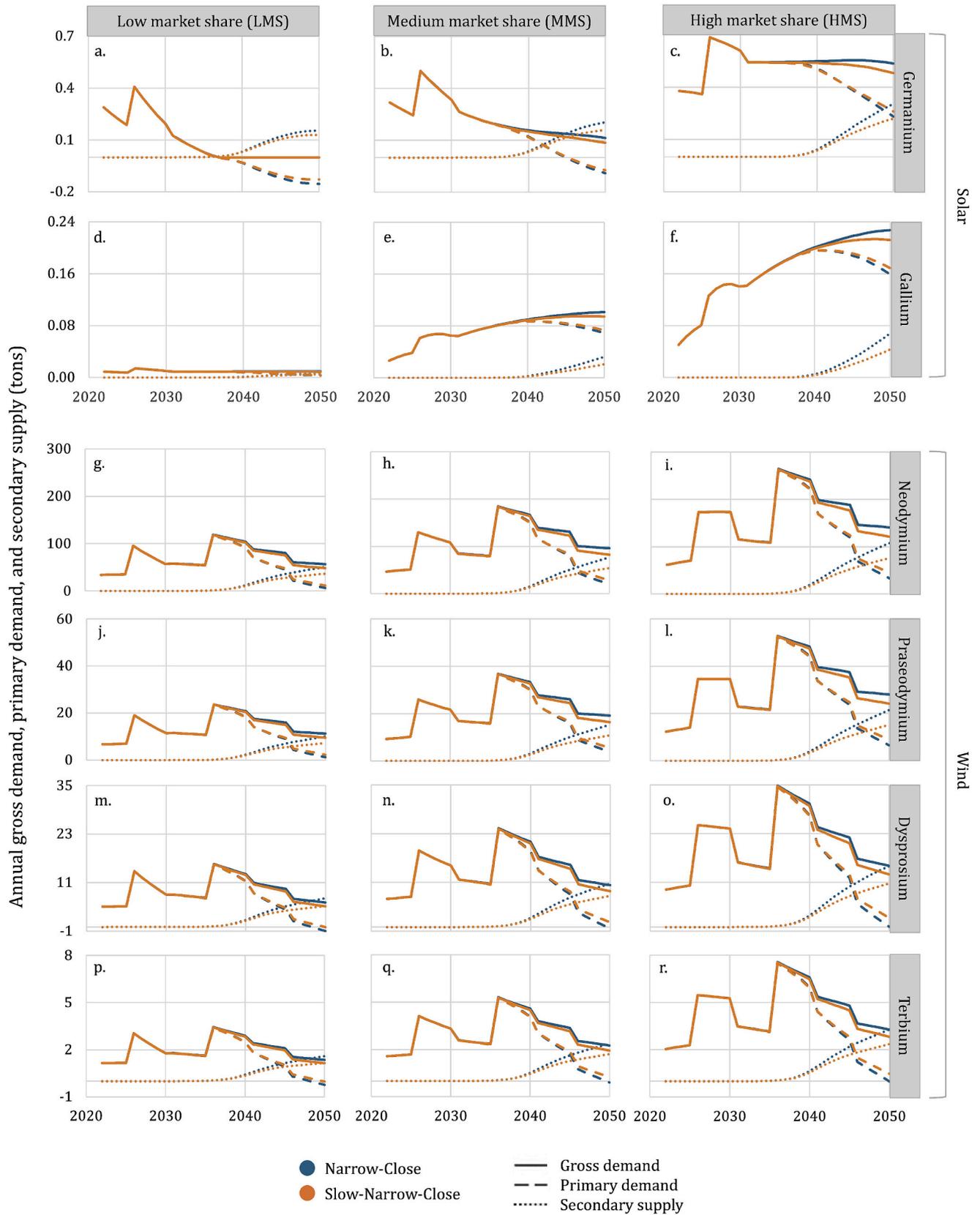


Fig. 7. Annual gross demand (solid), primary demand (dashed) and secondary supply (dotted) in tons for germanium (a–c), gallium (d–f), neodymium (g–i), praseodymium (j–l), dysprosium (m–o), and terbium (p–r) under three market-share pathways: LMS (a, d, g, j, m, p), MMS (b, e, h, k, n, q) and HMS (c, f, i, l, o, r). Narrow-Close scenario is shown in blue and Slow-Narrow-Close scenario is shown in orange. All quantities are in tons per year. Note: LMS pathway gallium series is shown in higher resolution in Supplementary Fig. S3.

Overall, secondary supply does not have potential for supplying metals until the late 2030s given that recycling is not introduced until mid-2030s. However, as recycling rates accelerate during 2040s, CE strategies combined as shown in the Slow-Narrow-Close scenario can substantially increase the secondary supply potential towards the end of the scenario period. The secondary supply potential to satisfy gross demand depends largely on the market-share pathway and varies over time and among metals. For solar (Fig. 7a-f) there are large differences among the sub-technologies. For wind power (Fig. 7g-r), the Slow-Narrow-Close scenario exhibits a strong potential to increase the secondary metal supply, with potentials in the range of 63%–101% depending on metals and market-share pathway.

4. Discussion

4.1. Impact of individual CE strategies on primary demand

Examining individual CE strategies, our study reveals large variation in their impact depending on the metal, technology, market-share pathway and timing. Nevertheless, some trends emerge; for solar power, *MI reduction* shows the strongest potential to lower primary metal demand, consistent with previous studies (Savvidou et al., 2026; Davidsson and Höök, 2017; Gervais et al., 2021). For wind power, *substitution* is the strategy with the strongest potential, followed by *MI reduction*. Overall, strategies that narrow material flows demonstrate the greatest reduction in metal demands for both wind and solar power during the transition to a more electrified and decarbonised energy system with widespread deployment of these technologies.

Our findings on *recycling*, which closes material flows, align with previous research (Li and Adachi, 2019; Habib and Wenzel, 2014; Månberger, 2023; Lundaev et al., 2023), indicating limited impact in the early transition stages. Recycling initially achieves only small reductions because EoL outflows are limited and recycling capacity for these metals is currently lacking and will require time to develop. However, post 2040, secondary supply increases substantially, covering over half of gross demand for most metals and market-share pathways by 2050. For germanium, dysprosium and terbium, secondary supply has the highest potential and can, under certain market-share pathways, fully meet gross demand—eliminating primary demand and its associated supply chain impacts, while leaving surplus supply for other applications. This underscores the importance of initiating and scaling recycling efforts, especially for these metals, to reduce reliance on primary sources (Gregoir and van Acker, 2022). It is important to note that our MFA model is application-specific and does not track cross-sector flows; thus, competition for secondary materials across sectors is not accounted for. As part of assessing the need to scale primary production and recycling for this sector, it would be valuable for future studies to investigate the supply and demand dynamics of secondary materials in other sectors.

Longer design lifespan, which slows material flows, is the strategy with the weakest potential during the scenario period. Future research could extend the timeframe beyond 2050 to capture the full lifecycle of wind and solar technologies deployed during the transition as illustrated in Fig. 1. This would allow a more comprehensive assessment of longer design lifespan and recycling, and the potential of CE strategies in a renewable-energy-saturated electricity system, assuming renewable expansion slows after decarbonization targets are met. However, new technologies and substitutes may emerge by then, potentially requiring different metal demands.

4.2. Combined impact of CE strategies on primary demand

Regarding the Slow-Narrow-Close scenario, our analysis demonstrates strong potential to reduce annual primary metal demand—and even eliminate it for some metals—during the energy transition with large-scale wind and solar deployment. Between 2022 and 2050, cumulative primary demands decrease by 52–60% for wind and 55–72%

for solar power compared to the Baseline scenario. Thus, implementing CE strategies within the Slow-Narrow-Close framework can reduce cumulative primary metal demands by more than half. Furthermore, consistent with earlier research (Lee et al., 2024; Månberger and Stenqvist, 2018; Van Oorschot et al., 2022; Nassar et al., 2016; Davidsson and Höök, 2017), we find that adopting less material-intensive sub-technologies substantially lowers metal demand, as reflected in the marked differences across the three market-share pathways.

Except for germanium in the LMS and MMS pathways, our results show that primary demand remains necessary for all metals throughout the scenario period, despite reductions from combined CE strategies. This indicates that meeting increased electrification and decarbonization targets with large-scale wind and solar deployment will require expanding metal production or other secondary supply sources. It underscores the need for parallel measures ensuring just, responsible, and transparent sourcing to complement CE strategies.

4.3. Primary demand and equal-per-capita allocation

For solar power, primary demand for germanium and gallium remains below an equal-per-capita share of global production throughout or for most of the scenario period in the Slow-Narrow-Close scenario, except for germanium under the HMS pathway. For REE used in wind turbines, this only occurs after 2040 across metals and pathways. Therefore, our results indicate that the current production levels of the extraction industry to supply the required metals for wind power need to increase more compared to solar power. Germanium and gallium are by-product metals, which can be selectively extracted and refined at various stages of host metal production. Since many refineries currently lack by-product recovery technologies, implementing these could boost by-product metal output without increasing host metal extraction (Fizaine, 2013; Frenzel et al., 2017). Quantifying these potential increases through future research can better inform future scenario analyses of primary extraction levels. For wind power, dysprosium and terbium show greater potential to reduce and eventually eliminate primary demand by 2050 compared to neodymium and praseodymium. However, dysprosium and terbium show a lower potential than neodymium and praseodymium to reduce primary demand below equal-per-capita global shares. This aligns with earlier research (Wang et al., 2024b), indicating that dysprosium and terbium pose greater resource constraints on decarbonization targets due to limited in-ground and in-use stocks.

The equal-per-capita allocation used in our analysis does not predict actual national access—for example, Sweden's—because it excludes factors like trade dynamics, contracts, and political considerations. Rather, it functions as a supply capacity benchmark and not as a normative or predictive allocation scheme.

4.4. Trade-off from the combined implementation of slow, narrow, and close strategies

Strategies to slow material flows have received much less attention than narrow and close strategies (Watari et al., 2020). By examining the slow strategy alongside the others, our results reveal a trade-off that, to the best of our knowledge, has not been discussed before: combining the *slow* strategy with *narrow* and *close* reduces gross demand but increases primary demand compared to *narrow* and *close* strategies alone. Thus, from a material quantity perspective, the preferred scenario depends on policy priorities: Slow-Narrow-Close scenario if minimizing gross demand is prioritized, or Narrow-Close scenario if minimizing primary demand is the focus. Further research on the social and environmental impacts of these scenarios could add valuable information to the priorities involved. Importantly, this trade-off is time horizon dependent—while the Slow-Narrow-Close scenario results in higher cumulative primary demand through 2050, extending the analysis beyond 2050 would likely reduce this difference and may even reverse it, if renewable

capacity expansion plateaus after 2050, the effects of longer design lifespans and recycling accumulate over time, and the interplay of narrow strategies and recycling become more evident as material intensities are reduced resulting in less metal outflows for secondary supply. Therefore, understanding the interactions between the slow, narrow and close strategies—and their impacts on gross and primary demand beyond the scenario period—is crucial, as longer design lifespans and recycling effects grow, while renewable capacity expansion may slow after decarbonization targets are met. These temporal dynamics raise questions about whether and when the observed trade-off could disappear or reverse, and under what conditions, providing important guidance for policy and supply chain actors on which strategies to prioritize and when. However, such decisions require this material-focused research to be complemented by social and environmental impact analyses, as well as costs.

4.5. Implications for industry and policy

Our findings are relevant to stakeholders across wind and solar power supply chains — including primary extraction and processing, component and sub-technology manufacturing, recycling, and electricity producers— as well as policy makers governing these chains.

We demonstrate that CE strategies can reduce reliance on primary resources by more than half, emphasizing the importance of applying CE across the Slow-Narrow-Close framework in energy and resource policies. However, meeting metal demand will still require scaling up primary production and/or expanding secondary supplies. Therefore, our findings highlight the urgent need for policymakers and industry to secure reliable, more sustainable metal supplies to meet decarbonization targets amid large-scale integration of wind and solar growth. Additionally, our results indicate that the current production levels of the extraction industry will need to grow more for wind power than for solar power sub-technologies to supply the required metals. If reliance on primary extraction continues, it is crucial to implement parallel measures that ensure responsible, transparent, and equitable sourcing alongside CE strategies. This integrated approach is especially important given the rising demand for these metals driven by the wider adoption of other low-carbon technologies, such as electric vehicles.

Moreover, we show that the effectiveness of CE strategies in reducing primary demand varies substantially by metal, technology, market-share pathway, and over time. Consequently, no single solution fits all contexts. Policymakers and industry could prioritize strategy portfolios tailored to metal-specific opportunities and temporal windows. For example, they could develop collection and recycling capacity early to capture large secondary supplies for metals such as germanium, dysprosium and terbium. At the same time, they could invest in strategies that deliver faster, larger impacts in the shorter term such as MI reduction for germanium and gallium, and substitution for REE. Current EU policies, including the CRMA and the European Sustainable Products Regulation, provide a strong foundation for supply security and CE principles. Further integration of CE strategies—especially incentives for MI reduction and substitution—alongside the existing priorities on recycling and primary production would be highly beneficial. Specifically, incentives for MI reduction could include eco-design requirements limiting magnet mass per installed capacity; substitution could be supported by promoting development of high-performance REE-free magnets. Recycling efforts could focus on dedicated REE, gallium, and germanium recycling plants and integrating these metal flows within the WEEE directive. Longer design lifespans could be encouraged through programs aimed at extending turbine and solar panel durability with clear safety and performance standards.

Our research draws attention to a trade-off when CE across the Slow-Narrow-Close framework are jointly implemented during the transition, as detailed previously. Understanding how this trade-off evolves over time, will equip stakeholders across the renewable technology supply chain with the insights needed to prioritize strategies appropriately at

different transition stages.

4.6. Limitations

Our analysis relies on several assumptions regarding future technological developments and market trends, such as market-shares, material intensities, and recycling rates, which introduce inherent uncertainties. We assess the sensitivity of our results to varying market-shares, through presenting our results in three different market-share pathways. Still, these are stylized pathways and market-shares may in reality be lower or higher than the LMS and HMS respectively. Anticipated MI reductions, as shown in our earlier study (Savvidou et al., 2026), have a substantial impact on projected metal demand, particularly towards the end of the scenario period. Future research can assess the results' sensitivity to varying degrees of material intensity reduction achieved through improved technology design.

Limitations regarding assumptions on longer service lifespan, MI reduction and substitution are elaborated in our earlier research (Savvidou et al., 2026). For recycling, our model assumes collection and recycling rates will increase to high levels by 2050. Currently, the EU lacks recycling capacity for the metals included in our analysis (European Commission, n.d.), though this is expected to change in the future. Several EU Member States are advancing industrial pathways for recovering REE from EoL permanent magnets, waste electrical equipment and industrial residues, supported by the European Commission's CRMA. Notable, in 2025, eight out of the 47 strategic projects under CRMA in the EU were approved for the metals in our study, two of which are specifically on recycling. Collectively, these initiatives highlight a growing European landscape of specialized extraction, processing, substitution and recycling efforts for critical and strategic materials essential to renewable energy technologies.

Reflecting these developments, we model recycling rates using logistic functions: rates remain low until infrastructure is established, then increase rapidly before slowing as recycling market approaches saturation. According to our assumptions, recycling rates expand rapidly after 2035–2040, somewhat lagging behind the European Commission's 2030 target of meeting 25% of strategic material demand through recycling. Future studies could explore the sensitivity of results to earlier or later recycling uptake. Furthermore, while we ensured that the recycling rate values collected from the literature focus on recycling efficiencies at the EoL of wind and solar sub-technologies (recycling process efficiency rate based on functional recycling efficiency i.e. the process whereby the metals in decommissioned technologies are separated and sorted to obtain secondary materials that are returned to raw material production processes), we could not always confirm whether these values refer to a theoretical, thermodynamic or technical performance. Future research could assess the impacts of recycling based on different rates, including theoretically maximum potentials and data from current pilot projects.

5. Conclusions

A material flow analysis is carried out to investigate how Circular economy (CE) strategies across the Slow-Narrow-Close framework for material flows—longer design lifespan, material intensity reduction, substitution, and recycling—affect primary and gross demand for minor metals in wind and solar power technologies. Sweden is used as a case study during a large-scale deployment of these technologies towards ambitious electrification and decarbonization targets.

The combination of slow, narrow, and close CE strategies can cut cumulative primary metal demands by more than half and eliminate annual primary demand for germanium well before the end of the scenario period, with dysprosium and terbium falling to zero by 2050. Overall, the combined implementation of these CE strategies substantially reduces dependence on primary production. Still, aside from germanium, primary demand persists through the end of the scenario period for all metals, so the CE strategies alone cannot satisfy increasing

demand. Consequently, primary and/or other secondary supplies will remain necessary. This underscores the need for concurrent measures that ensure equitable, responsible, and transparent supply alongside CE strategies.

The effectiveness of CE strategies in reducing primary demand varies substantially by metal, technology, market-share pathway, and over time. Therefore, no single solution fits all contexts; policymakers and industry could tailor strategy portfolios to specific metals and timing, such as building early recycling capacity for certain metals while prioritizing rapid-impact strategies like material intensity reduction and substitution for others.

Studying the slow strategy alongside the narrow and close strategies reveals a trade-off: combining slow, narrow, and close strategies reduces gross demand compared to narrow and close strategies alone, but this reduction is achieved at the expense of higher primary demand. Which scenario is preferable therefore depends on policy priorities—whether to minimize total material throughput or to minimize reliance on primary supply.

Examining metals dynamics in the electricity transition reveals insights that can shape energy, climate and natural-resource policy and inform government and industry decision-making as the shift to low-carbon, circular economy proceeds. Our findings underscore the need to integrate policy on CE strategies across the Slow-Narrow-Close framework for material flows with energy policy and highlight the synergies and trade-offs that emerge when these strategies are implemented together during the transition.

Data Statement

The data that supports the findings of this study are available in the supplementary information of this article.

CRediT authorship contribution statement

Georgia Savvidou: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Ljunggren:** Writing – review & editing, Supervision. **Filip Johnsson:** Writing – review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

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