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RESEARCH

Circular technology design and its potential influence on minor metals demand in wind and solar expansion

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Abstract

The rising global demand for metals used in renewable energy generation technologies poses supply risks and socio-environmental impacts, threatening a sustainable energy transition. While the role of circular economy in reducing their demand has gained attention, its potentials related to advances in technology design remains underexplored. Here, we use explorative scenarios to assess circular technology design potentials for 11 minor metals through longer design lifespan, metal intensity reduction, and substitution, during large-scale deployment of wind and solar power in energy transition to 2050. Using Sweden as a case study we show that these strategies collectively may reduce cumulative demands for minor metals by 42–80%, depending on the metal. While all strategies reduce demand for metals in new technologies, their combination slightly increases the gap between this demand and the quantities in decommissioned ones. For wind power, no individual strategy results in metals available for recovery in quantities sufficient to satisfy new demand before 2050, although their combination achieves this for dysprosium and terbium. For solar power, reducing metal intensity alone substantially reduces demand across metals and enables silver and germanium available for recovery to meet new demand before 2050. However, for most metals, the availability for recovery remains insufficient throughout most of the scenario period, highlighting the need for continued additional primary or secondary supply. To fully explore the potential benefits of these circular design strategies, opportunities across all stages of the wind and solar supply chains must be examined—assuming the anticipated technological developments materialize.

Keywords "Industrial ecology" · "Material flow analysis" · "Renewable electricity" · "Circular economy" · "Wind" · "Solar"

1 Introduction

Low-carbon technologies such as wind and solar photovoltaics (PV) are critical for mitigating climate change (IPCC, 2011). However, global demand for the minerals required for these and other energy transition technologies is expected to increase substantially (Deetman et al., 2021; Kalt et al., 2022; Yu et al., 2023). Concentrated metal supply chains pose risks of short-term disruptions and geopolitical tension (Sattich et al., 2021; Troll & Arndt, 2022). As deployment of wind and solar PV technologies accelerates, understanding the associated metal dynamics becomes increasingly important.

Ensuring a fairer energy transition requires strategies that secure metal supply chains and reduce the associated impacts. Circular Economy (CE) strategies—alongside demand-side strategies—offer key pathways to mitigate material impacts from renewable energy expansion. Most prior studies that have explored prospective minor metal demand focus on recycling as a CE strategy, see Table 1. The ability to reduce the need for primary metals through recycling is limited in the short-term (Habib & Wenzel, 2014; W. Li & Adachi, 2019; Månberger, 2023), due to the currently negligible EoL recycling capacities for many minor metals (Supplementary Information SI1 Table S1.1), long technology lifespans, and the rapidly increasing demand.

CE strategies targeting technology design improvements—such as material intensity (MI) reduction, substitution, and longer design lifespan—have received less

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attention despite their potential impact. To our knowledge, only five studies consider substitution in wind or solar contexts, as shown in Table 1. In these, emerging options—such as high-temperature superconductors (HTS), ferrite-based permanent magnets, perovskite solar cells, and silver-free silicon panels—are considered early-stage and not yet thoroughly examined. However, recent industrial announcements suggest such technologies are approaching commercialization (Adamas Foehringer Merchant, 2024; Fraunhofer, 2022; Intelligence, 2023; Snieckus, 2019). Further, longer service lifespan is especially relevant for onshore wind power, where rapid growth since the early 2000 s means much capacity will soon reach its EoL. Despite recent deployments of wind turbines with projected lifespans of 30 years (S. Fogelström, Swedish Wind Centre, personal communication, May 3, 2023) [Supplementary Information SI1 Table S1.3], most scenarios still assume lifespans of 25 years or less (Liang et al., 2022). Table S1.3 in Supplementary Information SI1 provides further context and examples on recent innovations in circular technology design strategies on MI reduction, substitution and longer design lifespan. Finally, aside from Li and Adachi's (2019) work, which focused specifically on one metal (silver) and on MI reduction in crystalline-silicon PV, no study has assessed the combined potential of longer design lifespan, MI reduction, and substitution in reducing metal demands. Given their substantial potential demonstrated individually, investigating them in combination—including substitution via novel technologies—can provide valuable insights into alleviating metal supply challenges.

Building on the above studies, our study explores: *What is the potential impact of circular technology design strategies—including longer design lifespan, MI reduction and substitution—on minor metal demand, and to what extent can new demand be met by metals available for recovery from decommissioned technologies amid the rapid expansion of wind and solar technologies to 2050?* We develop explorative scenarios, which serve as useful tools for understanding the implications of alternative futures to support decision-making (Börjeson et al., 2006). We use a dynamic, technology-specific material flow analysis of 11 minor metals (neodymium, praseodymium, dysprosium, terbium, silver, germanium, cadmium, tellurium, indium, gallium, selenium) in wind turbines with rare-earth permanent magnets and four solar technologies. Sweden is used as a case study. Our analysis relies on data and assumptions for the future that are inherent to uncertainty. Therefore, the goal is not to produce predictive figures, but rather to generate estimates of the potential for different circular technology design strategies to reduce demand during the rapid upscaling of a renewable electricity system.

2 Methodology

2.1 Scope and system definition

We conducted retrospective (1996–2021) and prospective (2022–2050) analyses to estimate demand for new infrastructure and decommissioning capacity over time.

In terms of technologies, we analyze onshore and offshore wind (see Supplemetary Information S1 Figure S1.1 for historical installed capacities) considering two turbine configurations: direct-drive and gearbox. We include turbine designs that employ rare-earth elements (REE) in permanent magnets (PM), which exist in both configurations (Andersen et al., 2016). Therefore, we include direct-drive permanent magnet synchronous generators (DD-PMSG) and gearbox permanent magnet synchronous generators (GB-PMSG) for both onshore and offshore applications. For solar (see Supplementary Information SI1 Figure S1.2), we include distributed and centralized grid-connected applications and exclude off-grid solar capacity. Four sub-technologies are considered: wafer-based crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS).

We model two light REE (LREE), neodymium (Nd) and praseodymium (Pr), and two heavy REE (HREE), dysprosium (Dy) and terbium (Tb)—all used in DD-PMSG and GB-PMSG generators at different intensities (Supplementary Information SI1 Sects. 5 & 7). For solar sub-technologies we model silver (Ag) used in c-Si, germanium (Ge) used in a-Si, cadmium (Cd) and tellurium (Te) used in CdTe, and indium (In), gallium (Ga), and selenium (Se) used in CIGS. Of the 11 metals included, Ga, Ge, Nd, Pr, Dy, and Tb are listed on the EU's Critical Raw Materials Act (European Commission, 2024). Except for Ag and the REE, which can be economically extracted as primary raw materials, these minor metals are produced exclusively as byproducts (Nassar et al., 2016).

2.2 MFA modeling framework

Figure 1 summarizes the Material Flow Analysis (MFA) modelling framework, including main calculation steps, model input data, variables and output data. The main model calculations are performed in three steps.

First (Step 1, Fig. 1), the annual inflows to the wind and solar power generating capacities (stock) are quantified by means of a dynamic, stock-driven MFA model:

$$inflow_k(t) = stock_k(t) - stock_k(t-1) + outflow_k(t) \tag{1}$$

$$outflow_k(t) = \sum_{\tau=t_0}^{t-1} inflow_k(\tau) \times (1 - L(t-\tau)) \tag{2}$$

Table 1 Dynamic material flow studies that have evaluated the future demands for minor metals (among other materials) from energy technologies, including circular economy strategies and their key characteristics

Study	Region	Scenario final year	Circular economy strategies included	Materials Included
(Lallana et al., 2024)	Spain	2050	**Recycling, MI reduction, Longer design lifespan**	Al, Cu, Co, Li, Mn, Ni, Au, Ag, Pt, Pd, Dy, Nd
(Lee et al., 2024)	US	2050	Recycling, MI reduction, Substitution	Cr, Zn, Ga, Se, Mo, Ag, Cd, In, Sn, Te, Pr, Nd, Tb, Dy, Pb
(Wang et al., 2023)	Global	2050	Recycling	Al, cement, Cu, fiberglass, glass, Mn, Mi, Si, steel, Cd, Dy, Ga, In, Nd, Se, Ag, Te
(Van Oorschot et al., 2022)	The Netherlands	2050	MI reduction	Steel, Al, Cu, Ag, Cd, Ga, In, Ge, Si, Nd, Dy, Tb, Li, Co
(Elshkaki and Shen, 2019)	China	2050	**Recycling, MI reduction, Longer design lifespan**	Ag, Te, In, Ge, Se, Ga, Cd, Nd, Dy, Pr, Tb, Pb, Cu, Ni, Al, Fe, Cr, Zn
(Watari et al., 2019)	Global	2060	Recycling, MI reduction	In, Ga, Se, Te, Cd, Ag, Dy, Nd, Li, Co, Ni, Pt, Fe, Al, Cu
(Månberger and Stenqvist, 2018)	Global	2060	Recycling, MI reduction, Substitution	Ag, Nd, Dy, Co, Pt, In, Te, Cu, Ga, Li, Ni, Se
(Valero et al., 2018b)	Global	2050	Recycling	Nd, Dy, In, Ga, Se, Te, Cd, Ge, Ag, Mo, Cu, Cr, Ni, V, Pb, Sn, Al, Fe, Si, Ti, Zn, Ar, Mg,Mn, K, P
(Valero et al., 2018a)	Global	2050	Recycling	Nd, Dy, Pr, La, Ce, Gd, In, Ga, Se, Te, Cd, Ge, Ag, Mo, Cu, Cr, Ni, V, Sn, Al, Fe, Ti, Zn, Mg, Mn, Li, Pd, Pt, Ta
(Tokimatsu et al., 2018)	Global	2100	**Recycling, MI reduction, Longer design lifespan**	Nd, Dy, In, Ga, Se, Te, Cd, Ag, Mo, Mn, Mg, Cu, Cr, Al, Ni, Fe, Li, Co, Va, Zr, Pt, Pd, La, Y, Hf, Ti, B, W, Nb
(McLellan et al., 2016)	Global	2050	Recycling	In, Te, Se, Cu, Dy, Nd, Y, Pt
(Grandell et al., 2016)	Global	2050	Recycling, Longer design lifespan	Ag, Nd, Pr, Dy, Tb, Y, La, Ce, Eu, Co, Pt, Ru, In, Te
(Nassar et al., 2016)	USA	2040	Recycling, MI reduction	Ag, Cd, Te, In, Ga, Se, Ge, Nd, Pr, Dy, Tb
(Wang et al., 2024)	Global	2050	**Recycling, MI reduction, Substitution, Reuse**	Nd, Dy, Pr, Tb
(Deng and Ge, 2020)	Global	2040	Recycling	Nd, Pr
(Cao et al., 2019)	Denmark	2050	MI reduction, Longer design lifespan	Nd, Dy, steel, cast iron, nonferrous metals, polymer materials, fiberglass, concrete
(Fishman and Graedel, 2019)	US	2050	MI reduction	Nd
(Habib and Wenzel, 2014)	Global	2100	Recycling	Dy, Nd
(Gervais et al., 2021)	Global	2050	MI reduction, Substitution	Al, Si, Cu, As, Sn, Bi, Ga, Ag, Pb, In, Se, Zn, Ni, Cd
(Zhou et al., 2020)	Global	2050	MI reduction	Ge, Cd, Te, In, Ga, Se
(Li and Adachi, 2019)	Global	2050	**Recycling, MI reduction, Longer design lifespan, Substitution**	Ag
(Davidsson and Höök, 2017)	Global	2070	Recycling, MI reduction	Si, Ag, In, Ga, Se, Te, Cd

Several of the studies include other technologies in addition to wind and solar PV. The green shading indicates studies that include both wind and solar PV technologies, orange shading indicates studies that have included wind but not solar PV technologies, and blue shading indicates studies of solar PV, but not wind technologies

$$t = [1996, \ldots, 2050] k = \left[Distributed\ solar\ PV, Centralized\ solar\ PV, Onshore\ wind, Off\ shore\ wind\right]$$

where $inflow_k(t)$ is the newly installed capacity (MW) of technology k in year t, $stock_k(t)$ is the capacity stock of solar, onshore and offshore wind power at t, $outflow_k(t)$ is decommissioned capacity at t, and $L(t)$ is the age-dependent lifespan probability function. $L(t)$ determines the proportion of each past inflow remaining in the stock (declining from 100 to 0%) and is modelled with a two-parameter Weibull distribution (for details of mean lifespans and standard deviations, see Supplementary Information SI1 Sect. 6).

We then applied market shares (MS), specific per subtechnology l and year t, and metal intensities (MI), specific per metal m and year t, to each technology $inflow_k(t)$ (Step 2, Fig. 1). The metal inflow ($inflow_m(t)$) calculations can be summarized as follows:

$$inflow_m(t) = \sum_k [inflow_k(t) \times \sum_l MS_l(t) \times MI_m(t)] \tag{3}$$

$$l = [\textbf{DistributedsolarPV} : cSi, aSi, CdTe, CIGS\ \textbf{CentralizedsolarPV} : cSi, aSi, CdTe, CIGS\ \textbf{Onshorewind} : DDPMSG, GBPMSG\ \textbf{Offshorewind} : DDPMSG, GBPMSG]$$

$$\mathrm{m} = [\textbf{DistributedsolarPV}\text{: Ag, Cd, Te, Ge, In, Ga, Se } \textbf{CentralizedsolarPV}\text{: Ag, Cd, Te, Ge, In, Ga, Se } \textbf{Onshorewind}\text{: Nd, Pr, Dy, Tb } \textbf{Offshorewind}\text{: Nd, Pr, Dy, Tb]}$$

Metal inflows are passed to a second inflow-driven MFA (Step 3, Fig. 1), to calculate metal stock accumulation and the metal outflows from technologies reaching their EoL:

$$outflow_m(t) = \sum_{\tau=t_0}^{t-1} inflow_m(t) \times (1 - L(t - \tau)) \tag{4}$$

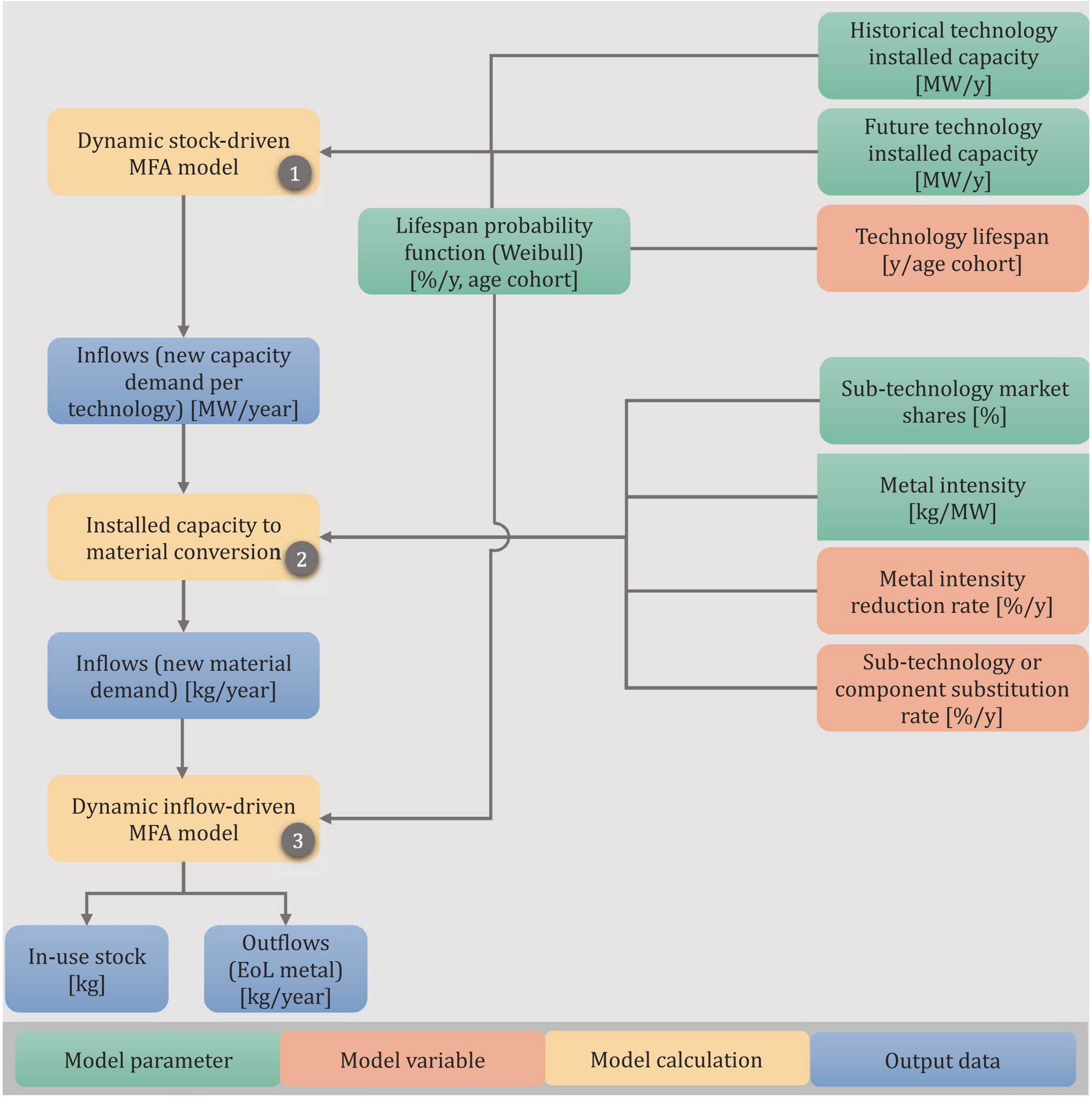

Fig. 1 Graphical representation of the model structure, including the input and output data, model variables, and main calculations. Indicated in orange are the model variables, through which the circular economy strategies are explored

$$stock_m(t) = stock_m\left(t_0\right) + \sum_{\tau=t_0}^{t} inflow_m(\tau) - outflow_m(t) \quad (5)$$

where $outflow_m(t)$ denotes the outflow of metal m in year t, $stock_m(t)$ the in-use stock of metal m at t and $stock_m\left(t_0\right)$ is the initial in-use stock of metal m.

The analysis uses a Python-based MFA model, based on ODYM framework (Pauliuk & Heeren, 2020). Key parameters and variables such as historical and future installed capacities, sub-technology MS, and MI are detailed in Supplementary Information SI1 Sects. 1, 5, 7.

2.3 Scenario setting

In line with the scenario typology proposed by Börjeson et al. (2006), this study adopts an explorative scenario approach, for limiting minor metal demand during expansion of wind and solar technologies for the energy transition period up to 2050 under the implementation of different CE strategies. In total, three circular technology design strategies that impact metal demand are investigated: longer design lifespan, MI reduction and substitution. Based on these, we develop five scenarios, as described in Table 2: a Baseline scenario (in which none of the strategies are applied), a Longer design lifespan scenario, an MI Reduction scenario, a Substitution scenario, and a Composite scenario that combines all three strategies. All scenarios make use of the Renewable Electrification (RE) pathway from the Swedish transmission system operator (Svenska Kraftnät) for describing the expansion of solar and wind power installed generating capacities over time (Fig. 2).

For Longer design lifespan, the Weibull distribution's lifespan is changed to reflect the longer lifespans. For the MI reduction and Substitution strategies, Eq. (6) is expanded to include the reduction and substitution rates in the calculation of metal inflows as follows (Step 2, Fig. 1):

$$inflow_m(t) = \sum_k \left[inflow_k(t) \times \sum_l MS_l(t) \times MI_m(t) \times \left(1 - reduction_m(t)\right) \times \left(1 - substitution_m(t)\right)\right] \tag{6}$$

where $reduction_m(t)$ is the reduction rate of the metal's m intensity as a result of the MI reduction strategy in time t and sub-technology l. $substitution_m(t)$ is the rate at which the wind and solar sub-technologies are replaced with novel applications. The substitution options that are either theoretically possible or commercially available and associated assumptions were obtained from literature and are included in Table 2 together with the key references (further details are provided in the Supplementary Information SI1 Sect. 8).

In addition to these five scenarios, we develop two alternative scenarios to assess the sensitivity of our results on two key uncertainty factors: MS and MI. The sensitivity analysis tests the impacts of varying the MS of more critical material-intensive sub-technologies (those including Ga, Ge, Nd, Pr, Dy, and Tb that are listed on the EU's latest critical raw materials list) and of varying MI of the metals in our analysis. In total, we develop two scenarios: a scenario with reduced MS of thin-film solar and REE-containing PM wind sub-technologies alongside lower MI (scenario SI), and another with increased shares of these sub-technologies and higher MI (Scenario SII). For the MI ranges, given the significant variance shown in Supplementary Information SI1 Figures S1.5 and S1.6, we assume a 10% increase and decrease in SI and SII respectively. The range used for the MS is based on the JRC's Low Demand Scenario (LDS) and High Demand Scenario (HDS). [see Supplementary Information SI1 Sect. 10 for more details].

2.4 Metal demand–supply balance

In addition to assessing the impact of CE scenarios on metal demand in wind and solar power, we also investigate their effect on the 'metal demand–supply balance'. The balance is defined as the difference between the annual inflows and outflows of metals, i.e., the difference between the demand for metals for new technologies and the quantity of metals that are available for recovery in technologies reaching their EoL. A negative metal demand–supply balance means that more metals are exiting the system than are needed to meet current demand. In other words, the metals that are available for recovery from decommissioned technologies exceed the quantity needed to support a continued capacity expansion. For example, if the metals in old wind turbines that are being decommissioned surpass what is needed to build new turbines, this would result in a negative balance—signalling strong potential for metal recycling. Conversely, a positive metal balance means that metal inflows (demand) are greater than the outflows (materials available for recovery). This would occur, for example, when the industry is still expanding rapidly and new installations require more metals than can be recovered from retiring systems, thus necessitating input from either primary or other secondary resources. The metal demand–supply balance therefore reflects the trends in metal flows during the deployment of wind and solar. Furthermore, it signals if there is a potential for recycling to reduce the need for primary or secondary resources. A negative demand–supply balance means that a high recycling chain efficiency would enable a large share of the metals to be supplied within the system itself. A positive demand–supply balance means that irrespective of the recycling chain efficiency, the system would require resources, either primary or secondary to be added from other applications.

3 Results

3.1 Metal demand

Table 3 summarizes the projected cumulative metal demands (inflows) for the period of 2022–2050 in metric tonnes (henceforth referred to as 'tons'), broken down by scenario and sub-technology. Table 3 also shows the reduction potentials (indicated with colours) for the four CE scenarios compared to the Baseline scenario. The annual metal demands for the same period per scenario for wind and solar technologies are portrayed in Fig. 3.

The impacts of the scenarios vary across the wind and PV technologies. For wind, the scenario that yields the most substantial reduction is the Substitution scenario for LREE (Nd and Pr), whereas for HREE (Dy and Tb) the Substitution and MI reduction scenarios have equal contributions (Table 3, Fig. 3). On a cumulative basis (Table 3), the Longer design lifespan, MI reduction, and Substitution scenarios

Table 2 Scenario description

Scenario	Baseline	Longer design lifespan	Metal intensity reduction	Substitution	Composite
Scenario description	The RE pathway from Svenska Kraftnät	Longer service lifespan through improved technology designs	Reduced MI through improved technology designs	Replaced metals in final applications through substitution with alternative metals, components, or sub-technologies	Assumptions in Longer design lifespan, MI reduction, and Substitution scenarios combined
Wind and solar PV installed capacities	Capacities of solar PV, onshore and offshore wind power reach 22.9, 28.2, and 35 GW, respectively by 2050 (see Fig. 2 for trend over time)	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Baseline scenario
Longer design lifespan assumption	No longer design lifespan assumed. Baseline lifespans of 26.3, 21.7, and 23.6 years for solar PV, onshore and offshore wind power kept constant throughout the scenario period	Linear increase from base year 2021 lifespan values (26.3, 21.7, and 23.6 years) to 40, 30 and 35 years for solar PV, onshore wind and offshore wind, respectively by 2050	Same as in Baseline scenario	Same as in Baseline scenario	Same as in Longer design lifespan scenario
MI reduction rate assumption	No MI reduction assumed. MI reduction rate kept maintained at zero throughout the scenario period	Same as in Baseline scenario	Compound annual growth rates (ranging between −0.1% and −16%) per metal based on averages taken from the literature for 2050 and/or 2030	Same as in Baseline scenario	Same as in MI reduction scenario
Substitution rate assumption	No metal substitution rate assumed. Metal substitution rate maintained at zero throughout the scenario period	Same as in Baseline scenario	Same as in Baseline scenario	Linear increase to 20% and 50% substitution rates for solar PV (current sub-technologies are assumed to be substituted by perovskite solar PV/Silver intensity replaced by copper in c-Si panels) and wind (REE-containing PM are substituted by the REE-free PM/PM-containing technology replaced by HTS technology), respectively, by 2050	Same as in Substitution scenario

Table 2 (continued)

Scenario	Baseline	Longer design lifespan	Metal intensity reduction	Substitution	Composite
References	(Liang et al., 2022), (Carrara et al., 2020), (W. Li & Adachi, 2019), (Elshkaki & Shen, 2019), (Watari et al., 2019), (Valero et al., 2018a, 2018b), (Zhou et al., 2020), (Månberger & Stenqvist, 2018), (P. Wang et al., 2019), (Imholte et al., 2018), (J. Li et al., 2020), (Kumari et al., 2018), (Hoenderdaal et al., 2013), (Pavel et al., 2017), (Leader et al., 2019)	(Liang et al., 2022), (Carrara et al., 2020)	(Elshkaki & Shen, 2019), (Carrara et al., 2020), (Zhou et al., 2020), Fishman and Graedel (2019), Wang et al. (2024), Gregoir and van Acker (2022), (JRC, 2016), (Schulze & Buchert, 2016)	(P. Wang et al., 2024), (Carrara et al., 2020), (Fraunhofer, 2022), (Arvidsson & Sandén, 2017), (IEA, 2022)	

For further details, refer to Supplementary Information SI1 Sects. 5–8

achieve demand reductions for REE of 4%, 20%, and 31% of all the metals, respectively. MI reduction and Substitution scenarios show slightly higher reduction potentials for offshore compared to onshore wind turbines. In contrast, the Longer design lifespan scenario shows the opposite trend, which is explained by the later introduction of offshore wind power capacity (after 2025) in the scenario (Table 3). For the solar sub-technologies, MI reduction is by far the scenario with the largest potential for decreasing annual and cumulative demands. Thereafter follow the Substitution and Longer design lifespan scenarios. On an annual basis, this order is preserved throughout the period with the exception of Ge, for which the inflows in the Longer design lifespan scenario becomes lower than in the Substitution scenario from 2048 onwards. Cumulatively, the Longer design lifespan, MI reduction, and Substitution scenarios result in total metal reductions of 4%, 74%, and 12%, respectively. Although the Longer design lifespan scenario shows the weakest potential for both wind and solar technologies during most of the scenario period, its impact is expected to increase beyond 2050. This is due to the long operational lifespans of these technologies. This is especially the case for offshore wind and solar, which compared to onshore wind, are introduced later in the studied period (Fig. 2).

For some metals in solar power, strategies lower annual demands under base year (2021) demand levels, despite the large increase in the solar installed capacity. MI reduction alone results in lower-than-base year demand levels for Ag and Ge well before the end of the period. Under this single scenario, demand stays below the 2021 levels for most of the scenario period, leading to reductions of 80% for Ag and 56% for Ge by 2050 (Fig. 3). In the Composite scenario, Ag and Ge achieve an 86% and 73% reduction in demand compared to 2021. While no single strategy is sufficient to attain lower that base year demand level for Cd throughout the scenario period, the Composite scenario achieves that toward the end of the scenario period reaching 10% reduction compared to base year levels by 2050. For the remaining four metals (used for the CdTe and CIGS sub-technologies), lower than base year level demands are not achieved under any single strategy or the Composite scenario throughout the scenario period. Overall, our results show that by implementing the MI reduction scenario, Ag has a stronger potential for reducing annual demand than any other minor metal for the solar sub-technologies. For wind power (Fig. 3), no single strategy is sufficient to attain a demand lower than base year levels throughout the scenario period. Supplementary Information SI1 Figures S1.7 and S1.8 provide the results disaggregated for onshore and offshore wind power as well as per sub-technology.

Overall, the Composite scenario shows that between 2022 and 2050, the CE strategies combined can cut the required cumulative demands for Dy, Tb, Ge, Nd, and Pr by

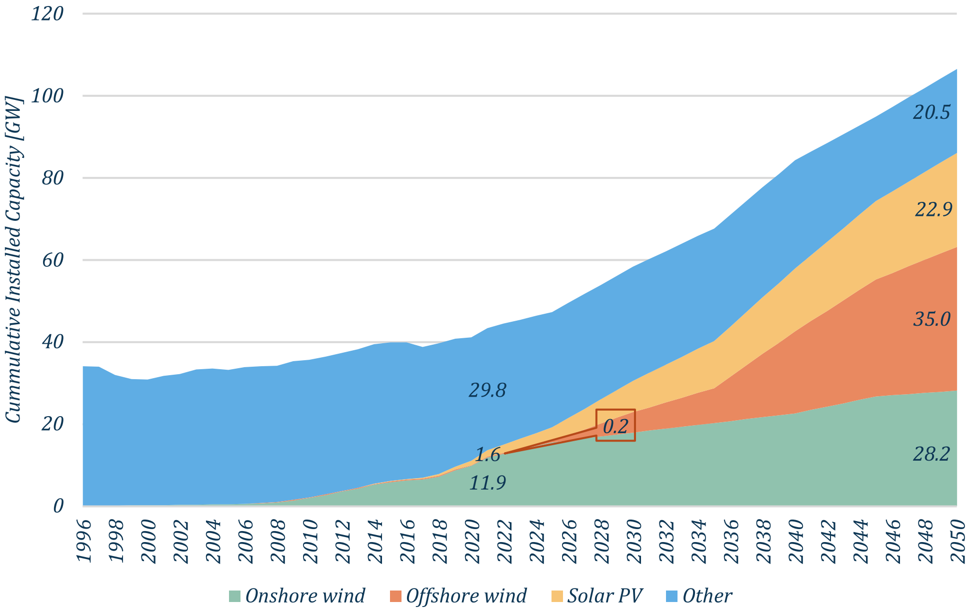

Fig. 2 Onshore wind, offshore wind, solar PV and remaining electricity sources installed capacities in the historical period (1996–2021) and the scenario period (2022–2050) period for the Renewable Electrification (RE) pathway. The values for 2021 and 2050 are highlighted. Note: As the data from Svenska Kraftnät are provided on a 5-year basis, the values between the 5-year intervals are linearly interpolated. Source: (Svenska Kraftnät, 2021). Underlying data for this figure are available in Supplementary Information SI2

about half as compared to the Baseline scenario (between 45 and 53%) [Table 3]. Ag, Cd, Ga, Te, Se, and In show higher cumulative reduction potentials, with the first three achieving reductions of more than 70%, and Ag, in particular, reaching 80%. On an annual basis (Fig. 3), between the Baseline and Composite scenarios, LREE and HREE achieve a 70% and 79% reduction, respectively in 2050, and for solar metals the reduction is in the range of 72 to 94%. Therefore, the combination of strategies based on circular technology design development (longer design lifespan, MI reduction and substitution) exhibits strong potential to reduce both the annual and cumulative demand for metals of the energy transition period with large-scale deployment of renewable power.

Tables S1.21 and S1.22 in Supplementary Information SI1 Sect. 10 show the results of the sensitivity scenarios SI and SII respectively. Scenario SI models an ambitious reduction in the MS of more critical metal-intensive sub-technologies and a reduction of MI. For wind, this results in lower metal demands, with reductions ranging from 35 to 43% across different metals (Nd, Pr, Dy, Tb) and scenarios as higher shares of GB-PMSG turbines—which use smaller amounts of permanent magnets (PM)—and non-PM-containing turbines are deployed. For solar, metal demands are significantly lower for all metals except Ag used in c-Si. Ag metal demand is not significantly reduced because the decrease in thin-film solar results in greater c-Si deployment. The material demands of metals used in thin-film solar (Cd, Te, Ge, In, Ga and Se), are greatly reduced in this scenario, with reductions ranging between 53 and 90%. For Ge and Ga, the two metals used in thin films and included in the EU's latest critical raw materials list, the reduction is ranging from 75 to 87% and 86% to 89%, respectively, across scenarios. Overall, the scenario shows that major reductions in the demand for minor metals and especially critical raw materials are possible if less material-intensive sub-technologies are adopted and material intensity reductions are realized. Scenario SII that models substantial increase in the MS of more critical metal-intensive sub-technologies and an increase of their MI results in substantially higher metal demands, in the range of 34–58% for wind sub-technologies and 86–215% for solar. This scenario demonstrates that if more material-intensive sub-technologies are deployed along with higher MI of metals, a significant growth in metals, and especially critical raw materials, requirements can be expected.

3.2 Metal demand–supply balance

As shown above, the combination of Longer design lifespan scenario and MI reduction and Substitution scenarios reduces metal demand (inflows). However, when considering both inflows and outflows, new patterns emerge. Longer design lifespan alone shifts inflows and outflows in time, and therefore reduces them at the same rate, resulting in the same demand–supply balance as the Baseline scenario. Therefore, longer design lifespan alone as a strategy reduces demand but does not affect the demand–supply balance. Secondly, Longer design lifespan scenario together with MI reduction and Substitution scenarios reduce the demand–supply balance at a lower rate than MI reduction and Substitution scenarios alone. This occurs because longer lifespans together with MI reduction and Substitution strategies influence the metal demand for replacing decommissioned technologies by both shifting it in time and reducing it, given the improvement in the technology's material intensity over

Table 3 Cumulative demands (inflows) for minor metals (in tons) for the period 2022-2050 and the percentage reductions in the CE scenarios compared to the Baseline scenario

Technology	Sub-technology	Minor metal	Cumulative (2022-2050) demands (inflows) in scenarios [tons]					Reduction in cumulative demands compared with the Baseline scenario [%]			
			Baseline	Longer design lifespan	MI reduction	Substitution	Composite	Longer design lifespan	MI reduction	Substitution	Composite
Wind onshore	DD-PMSG	Nd	1268	1210	1046	897	730	5%	18%	29%	42%
		Pr	254	242	209	179	146	5%	18%	29%	42%
		Dy	191	182	135	135	96	5%	29%	29%	49%
		Tb	41	39	29	29	21	5%	29%	29%	49%
	GB- PMSG	Nd	493	471	406	348	283	5%	18%	29%	43%
		Pr	97	92	80	68	55	5%	18%	29%	43%
		Dy	73	69	51	51	37	5%	29%	29%	50%
		Tb	19	18	13	13	9	5%	29%	29%	50%
Wind offshore	DD-PMSG	Nd	3808	3660	3071	2580	2050	4%	19%	32%	46%
		Pr	762	732	614	516	410	4%	19%	32%	46%
		Dy	573	550	388	388	263	4%	32%	32%	54%
		Tb	123	118	83	83	57	4%	32%	32%	54%
	GB-PMSG	Nd	159	154	128	108	86	4%	19%	32%	46%
		Pr	31	30	25	21	17	4%	19%	32%	46%
		Dy	23	23	16	16	11	4%	32%	32%	54%
		Tb	6	6	4	4	3	4%	32%	32%	54%
Wind total (onshore & offshore)	**DD-PMSG & GB-PMSG**	**Nd**	**5729**	**5494**	**4651**	**3933**	**3148**	**4%**	**19%**	**31%**	**45%**
		Pr	**1143**	**1096**	**928**	**785**	**628**	**4%**	**19%**	**31%**	**45%**
		Dy	**859**	**824**	**590**	**590**	**407**	**4%**	**31%**	**31%**	**53%**
		Tb	**188**	**181**	**129**	**129**	**89**	**4%**	**31%**	**31%**	**53%**
Solar PV (decentralized & distributed)	**c-Si**	**Ag**	**857**	**822**	**185**	**757**	**168**	**4%**	**78%**	**12%**	**80%**
	a-Si	**Ge**	**12**	**12**	**7**	**11**	**6**	**5%**	**42%**	**10%**	**49%**
	CdTe	**Cd**	**100**	**96**	**32**	**87**	**28**	**3%**	**67%**	**13%**	**71%**
		Te	**77**	**75**	**34**	**68**	**30**	**3%**	**56%**	**13%**	**62%**
	CIGS	**In**	**20**	**19**	**10**	**17**	**8**	**2%**	**51%**	**14%**	**58%**
		Ga	**7**	**7**	**3**	**6**	**2**	**2%**	**66%**	**14%**	**71%**
		Se	**46**	**44**	**20**	**39**	**17**	**2%**	**55%**	**14%**	**62%**

The reduction potentials are classified as follows: up to 20% (dark-orange); between 20% and 40% (light-orange); between 40% and 60% (yellow); between 60% and 80% (light-green); and between 80% and 100% (dark-green). For wind power, the data are provided first by location (onshore & offshore) and sub-technology (DD-PMSG & GB-PMSG), followed by the total wind category in bolt, which combines both location and sub-technology

time. Outflows, however, only shift in time under the combined influence of these strategies. Therefore, at any given year the combination of longer design lifespan, MI reduction and substitution strategies reduces both inflows and outflows compared to MI reduction and substitution strategies alone. However, inflows are reduced at a slower rate than outflows. As a result, their difference (demand–supply balance) becomes larger, reducing their potential for recycling.

To showcase these patterns, Fig. 4 portrays the demand–supply balance for all scenarios as well as a scenario combining the MI reduction and Substitution strategies alone (Material intensity reduction & Substitution scenario). The difference between the reduction potential of all three strategies combined as shown in the Composite scenario, and the MI reduction and Substitution strategies alone as shown in the Material intensity reduction & Substitution scenario is small (Fig. 4). By 2050—the year when the difference between the two scenarios is largest for all metals compared to other years in the scenario period—this difference still remains small. Specifically, the difference is around 5% for solar (except for Ge, which is slightly higher) and 9% for wind sub-technologies.

A negative demand–supply balance is reached for Ag, Ge, Dy, and Tb, albeit in different years during the scenario period. Ag reaches a negative demand–supply balances in 2040 under three scenarios: MI reduction, Composite, and MI reduction & Substitution. While the demand–supply balance reduction potential of the MI reduction scenario is lower than the Composite scenario in 2040, this trend is reversed in 2043 as the material intensity of crystalline silicon sub-technologies continues to decrease. The MI reduction & Substitution scenario maintains the highest reduction potential throughout the scenario period, just as in every other metal. Ge attains a negative demand–supply potential in 2044 under the MI reduction & Substitution scenario, and in the following year under the MI reduction and Composite scenarios. Furthermore, Substitution scenario alone attains a negative demand–supply balance for Ge in 2048. For wind,


Wind power - metal demands
Neodymium [Nd] - ton/year
400
300
200
100
0
2020
2030
2040
2050
Praseodymium [Pr] - ton/year
80
60
40
20
0
2020
2030
2040
2050
Dysprosium [Dy] - ton/year
60
40
20
0
2020
2030
2040
2050
Terbium [Tb] - ton/year
15
10
5
0
2020
2030
2040
2050
Solar PV power – metal demands
c-Si - Silver [Ag] - ton/year
50
40
30
20
10
0
2020
2030
2040
2050
a-Si - Germanium [Ge] - ton/year
1
0.5
0
2020
2030
2040
2050
CdTe - Cadmium [Cd] - ton/year
8
6
4
2
0
2020
2030
2040
2050
CdTe - Tellurium [Te] - ton/year
6
4
2
0
2020
2030
2040
2050
CIGS - Gallium [Ga] - ton/year
0.75
0.5
0.25
0
2020
2030
2040
2050
CIGS - Indium [In] - ton/year
2
1.5
1
0.5
0
2020
2030
2040
2050
CIGS - Selenium [Se] - ton/year
4
3
2
1
0
2020
2030
2040
2050
Baseline
Lifespan expansion
Metal intensity reduction
Substitution
Composite

◂**Fig. 3** Annual metal demands (inflows) in tons per year for each metal and scenario for the wind (onshore and offshore, DD-PMSG and GB-PMSG) and solar PV (centralized and distributed) technologies. Note: Supplementary Information SI1 Sect. 9 provides the disaggregated wind results per location and sub-technology, given the different market shares and metal intensities. Underlying data for this figure are available in Supplementary Information SI2

while no single strategy achieves a negative demand–supply balance, the MI reduction & Substitution and Composite scenarios achieve that in 2048 and 2050 respectively (for the wind power results per location and sub-technology, see Supplementary Information SI1 Sect. 9). Although the demand–supply balance decreases substantially, it remains positive throughout the period for Nd, Pr, Te, In, Ga, Se and Cd. This means that, regardless of the recycling chain efficiency, additional primary or other secondary resources would be needed throughout the period. Among these, In, Ga, Se, and Te, in particular, show the lowest potential in achieving negative demand–supply balance.

Overall, for Ag and Ge, MI reduction alone achieves a negative demand–supply balance well before the end of the scenario period. This means that given a high recycling chain efficiency, a large share of the metals could be supplied within the system with potentially remaining supplies that can be used in other applications. For Dy and Tb, the combined implementation of all CE strategies (Composite scenario) is essential to ultimately achieve a negative balance. For all remaining metals, additional primary or secondary metal supplies are needed.

4 Discussion

Our research investigates the dynamics of minor metals in scenarios driven by large-scale wind and solar deployment to achieve climate mitigation targets. It provides insights into the potential for reducing metal demands through strategies that focus on circular technology design improvements (i.e., longer design lifespan, MI reduction, substitution).

For solar, our study showcases the strong potential of MI reduction to lower minor metal demand, consistent with earlier research (Davidsson & Höök, 2017; Gervais et al., 2021). Furthermore, it shows this strategy's high potential to achieve negative demand–supply balances for Ag and Ge. Overall, we show that sub-technology choices for solar are key determinants of demand reduction, as supported by previous studies (Davidsson & Höök, 2017; Månberger & Stenqvist, 2018; Van Oorschot et al., 2022). For wind power, results show higher potential to reduce demand and achieve negative demand–supply balance for HREE compared with LREE. Wang et al. (2024) highlight that, from a resource availability perspective (including both in-ground and in-use stocks), HREE are more likely to constrain decarbonization targets than LREE.

Our analysis identifies In, Ga, Se and Te as metals with the lowest potential to achieve negative demand–supply balances throughout the scenario period. These metals are also highlighted by Gervais et al. (2021) and Watari et al. (2018), who additionally note Ag requires special measures due to its increasing demand, high depletion potential, and the environmental impacts associated with its production.

Although some metals achieve negative demand–supply balances by 2040, for most metals, this is not reached at all during the scenario period. In line with the findings of Wang et al. (2023) and Lee et al. (2024), our results indicate a need to expand metal production to meet decarbonization targets, under large-scale wind and solar expansion. This underscores a key policy insight: while circular technology design strategies can significantly reduce metal demand—particularly for metals like Ag and Ge—they are insufficient on their own to fully satisfy new demand (given high recycling efficiencies) for most metals. As such, substantial primary or secondary metal supplies will still be required throughout the energy transition. This highlights the importance of parallel strategies to ensure responsible, transparent, and sustainable sourcing to complement CE strategies. Coordinated international frameworks could facilitate transparent reserve management and equitable access, enhancing supply chain resilience and buffering against market volatility, supply disruptions, and geopolitical risks (Månberger & Johansson, 2019; P. Wang et al., 2024). Existing EU policies such as the Critical Raw Materials Act and the European Sustainable Products Regulation address aspects of supply security and circularity, providing a strong foundation for further action. Integrating CE strategies with primary supply policies remains essential. For example, regulations encouraging product design for recyclability could be paired with support for expand recycling infrastructure—particularly for metals with negligible EoL recovery capacities. Simultaneously, fostering innovation in substitution technologies may reduce dependence on constrained metals. Long-term policy roadmaps could balance immediate primary supply needs with gradual transitions toward circularity. This requires dynamic monitoring of material flows, market developments, and technological progress. Multi-stakeholder collaboration—including governments, industry, researchers, and civil society—is critical to implement these integrated strategies effectively. By addressing primary supply security and circularity within a cohesive policy framework, decision-makers can better support the sustainable scaling of low-carbon energy technologies while mitigating economic, environmental, and social risks associated with metal demand.

Our results on demand–supply balance indicate that, although the availability for recovery varies across metals


Wind power – demand-supply balance
Neodymium [Nd] - ton/year
300
200
100
0
2020
2030
2040
2050
Praseodymium [Pr] - ton/year
60
40
20
0
Dysprosium [Dy] - ton/year
50
40
30
20
10
0
-10
Terbium [Tb] - ton/year
10
8
6
4
2
0
-2
Solar PV – demand-supply balance
c-Si - Silver [Ag] - ton/year
40
30
20
10
0
-10
a-Si - Germanium [Ge] - ton/year
0.9
0.6
0.3
0
-0.3
CdTe - Cadmium [Cd] - ton/year
5
4
3
2
1
0
CdTe - Tellurium [Te] - ton/year
4
3
2
1
0
CIGS - Gallium [Ga] - ton/year
0.5
0.4
0.3
0.2
0.1
0
CIGS - Indium [In] - ton/year
1.5
1
0.5
0
CIGS - Selenium [Se] - ton/year
3
2
1
0
Baseline
Lifespan expansion
Metal intensity reduction
Substitution
Composite
Metal intensity reduction & Substitution

◂**Fig. 4** Minor metal demand–supply balance (the difference between yearly inflows and outflows) in tons per year for each metal and scenario for the total wind (onshore and offshore, DD-PMSG and GB-PMSG) and total solar PV (centralized and distributed) technologies. Underlying data for this figure are available in Supplementary Information SI2

and time, most metals' demand will continue to rely on primary or other secondary supplies throughout the energy transition period regardless of recycling efforts. This aligns with studies highlighting recycling's limited short-term capacity to reduce primary metal demand (Helander & Ljunggren, 2023; W. Li & Adachi, 2019; Lundaev et al., 2023). For metals achieving negative demand–supply balance (Ag, Ge, Dy, Te), initiating and scaling recycling capacities is important as previously noted (Gregoir & van Acker, 2022), especially since their current EoL recycling capacities are negligible (see Supplementary Information SI1 Table S1.1).

Despite the absence of established recycling systems, these metals demonstrate high theoretical recycling efficiencies—around 80% or higher (Domínguez & Geyer, 2019; Dominish et al., 2019; ESA, 2022). In Europe, initiatives like Norway's Resitec (recycling leftover wafers) and France's Veolia (recovering Si and Ag from EoL solar panels) demonstrate progress (Gregoir & van Acker, 2022). However, separation and purification require large-scale testing, and economic challenges remain, with feasibility dependent on EoL volume (Klimenko et al., 2021). Fishman and Graedel (2019) suggest stockpiling EoL PM until recycling becomes economic viable.

Implementing CE strategies requires coordinated technological, policy, and infrastructure efforts to overcome barriers such as technological maturity, market acceptance, regulatory support, and economic viability (Wang et al., 2022). Many substitution technologies are still in early development or commercialization, posing challenges for rapid scaling. Market dynamics influence CE adoption, with businesses often undervaluing strategies due to short-term costs or lack of incentives. Kirchherr et al. (2018) identify cultural barriers—limited consumer awareness and cautious corporate attitudes—as primary obstacles, compounded by insufficient government coordination.

Despite these challenges, signs of large-scale implementation exist. For example, Smith and Eggert (2018) noted a 30% in REE after the 2011 REE price spike, and like Vestas invest in repairable, longer-lasting designs (Vestas, 2022). Emerging substitution technologies such as high-temperature superconductors for wind turbines and perovskite solar cells show commercial potential within a decade (Adamas Foehringer Merchant, 2024; Fraunhofer, 2022; Intelligence, 2023; Snieckus, 2019). Gervais et al. (2021) and Wang et al. (2024) include such design improvements in their technological pathways.

Advancing CE requires monitoring developments and enacting policies that foster innovation and investment. International collaborations like the EU's Global Alliance on Circular Economy and Resource Efficiency can support this through regulations and funding for early-stage circular design in low-carbon energy technologies (P. Wang et al., 2022), reducing market uncertainties and creating stable demand for circular products.

Our analysis relies on several assumptions regarding future technological developments and market trends, which introduce inherent uncertainties. For example, anticipated reductions in material intensity per installed capacity—drawn from the literature and detailed in Supplementary Information SI1 Tables S1.4-S1.19 and Figures S1.5 and S1.6—have a substantial impact on projected metal demand, particularly toward the end of the scenario period. Furthermore, in our analysis, we use the JRC's MDS scenario for the market shares of sub-technologies. This scenario maintains the dominance of crystalline silicon (c-Si) and accommodates a higher market share of generators with REE-containing PM in offshore wind and, to a lesser extent, in onshore wind. Some studies have investigated higher or lower market shares of thin-film and REE-containing PM in wind turbine sub-technologies (Lee et al., 2024; Nassar et al., 2016; Valero et al., 2018a, 2018b). While such assumptions are necessary for long-term assessments, they carry a high degree of uncertainty (Nassar et al., 2016). We emphasize that our findings should be interpreted within the context of these assumptions, as an *explorative* study aimed at investigating what can happen under certain conditions, rather than predicting the expected pace or scale of future developments. Further, we test the sensitivity of our results to these two key uncertainty factors by conducting a sensitivity analysis. The results of our sensitivity analysis are consistent with those from comparable studies on wind and solar material requirements (Lee et al., 2024; Nassar et al., 2016). For example, Lee et al. (2024) finds a 91% reduction in cumulative Ga demand in 2050 in a scenario with shrinking MS of thin-film solar alongside rapid technology improvement. The Composite scenario modelled in the sensitivity analysis of our study calculates a 86% reduction, consistent with the results of Lee et al. (2024). The key takeaway from our sensitivity analysis is that substantial decreases in the need for minor materials, and in particular critical raw materials can be achieved through the adoption of less material-intensive sub-technologies and the realization of material intensity reductions.

Furthermore, in our analysis, the metals with the lowest potential for achieving demand–supply balance throughout the scenario period are all associated with thin film sub-technologies—even under a scenario that maintains the dominance of c-Si. At the same time Ag used in c-Si has the highest potential for negative balance from all metals studied, indicating that, a continued dominance of crystalline silicon (c-Si) is preferred assuming the availability of an adequate recycling capacity for Ag.

Substitution in wind power includes component-level (REE-free ferrite PM replacing REE-based PMs) and sub-technology-level changes (HTS replacing PM-based systems). In solar, we assume substitution of current technologies with perovskite and Ag-free crystalline silicon panels. While these technologies eliminate the minor metals in current wind and solar applications, they introduce new metals that may be associated with new trade-offs. HTS generators, which can achieve higher efficiencies than REE-based PM wind turbines, utilize yttrium-barium-copper oxide magnets (Liang et al., 2022). Yttrium, baryte (one of the most common minerals of barium) and copper are included in the EU's critical raw materials list and copper is also included in the EU's strategic raw materials list (European Commission, 2024). Ferrite-based PM offer a cost-effective and readily available alternative to rare earth magnets, albeit at the expense of reduced magnetic strength, increased size and weight, and potential limitations as to performance. The perovskite solar technology, which has achieved considerable efficiency improvements in laboratory settings, comprises lead iodide and methylammonium iodide (Pastuszak & Węgierek, 2022). As it contains lead, it poses significant environmental and health risks (UNEP, 2020). At the same time, substitutes present promising solutions for lead-free perovskites (Kour et al., 2019). Overall, the choice between current and novel technologies involves balancing the trade-offs involved. Research studies can investigate the potential trade-offs of these substitution options in terms of the technology performance, supply risk, and social, environmental and economic impacts.

As our analysis runs only until 2050, it does not fully capture the long-term impact of extended design lifespans. Exploring lifespan effects over a longer horizon is a key area for future research. Future research could explore the combined potential and possible trade-offs of incorporating CE strategies from other technology lifecycle stages, such as operation and maintenance, as well as end-of-use stages—including component reuse, refurbishment, and recycling.

5 Conclusions

We developed five scenarios to investigate how CE strategies related to technology design advancements—longer design lifespan, metal intensity reduction, and substitution—can reduce the demand for minor metals and support demand–supply balance amid large-scale deployment of variable renewable electricity generation technologies achieving climate mitigation targets.

Using Sweden as a case, our findings indicate that circular technology design development can substantially reduce minor metal demand during the transition to a decarbonized electricity system by 2050. For wind power, cumulative reductions range between 45 and 53% compared to the Baseline scenario. For solar power, most metals have cumulative reductions exceeding 60%. On an annual basis, reductions reach 70–79% for wind power and 72–94% for solar power. These finding highlight the the importance of understanding the dynamics and critical role of design-based CE strategies in reducing minor metal demand. Not only do such reductions reduce demand, but also the social and environmental impacts associated with their extraction as well as geopolitical risks, supply security and pressure on reserves.

In wind power, no single strategy achieves a negative demand–supply balance before 2050, but the combination of CE strategies does so for Dy and Tb towards the end of the scenario period. For solar, metal intensity reduction alone leads to negative demand–supply balances for Ag and Ge well before 2050. However, positive demand–supply balances persist for In, Se, Ga, Te, Cd, Nd, and Pr across all scenarios, indicating continued reliance on primary or other secondary supplies throughout the energy transition period, irrespective of their recycling. Overall, our results underscore the opportunity to expand recycling of certain metals while expanding production of others are crucial if the decarbonization target is to be met through large-scale variable renewable deployment. Our analysis shows that combining the Longer design lifespan with MI reduction and Substitution lowers the potential for recycling. Future research could incorporate recycling rates to assess outcomes in terms of primary metal demand and secondary supply availability.

The results of our study are relevant for actors along the supply chains of wind and solar technologies—from primary metal extraction to component and technology manufacturing, recycling, and the electricity sector. They highlight the importance of incorporating circular economy strategies focused on technology design into energy policy and emphasize the synergies and trade-offs of their combined implementation during the transition. Circular technology design can substantially reduce reliance on primary resources, even without efficient recycling systems and other circular strategies such as reuse, repair and remanufacturing. Continued monitoring of these and other CE strategies combined with proactive policy interventions across all stages of the supply chain is essential to translate this potential into practice.

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Data availability The data that supports the findings of this study are available in the supporting information of this article.

Declarations

Conflict of interest The authors declare no competing interests.

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