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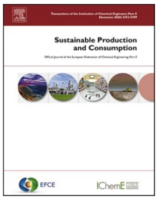

Material Requirements, Circularity Potential and Embodied Emissions Associated with Wind Energy

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ABSTRACT

Wind energy, which is often posited as a key decarbonisation option, represents one of the fastest-growing energy sources globally in recent years. Research on the material requirements for transitioning to a low-carbon electricity system at national levels, as well as research exploring the potential of the electricity system to serve as a source of secondary materials remains underexplored. We address these gaps in the knowledge by analysing the stocks and flows in a wind power system towards 2050 using Sweden as a case study, including the demands for bulk (concrete and steel) and critical materials (neodymium and dysprosium), through a dynamic material flow analysis based on policy-relevant scenarios. We demonstrate that some of the investigated scenarios generate substantial increases in the stocks and flows of bulk and critical materials. We show that, after 2045, the year by which Sweden has committed to reducing greenhouse gas emissions to net-zero, the inflows show a decreasing trend while the outflows show an increasing trend, suggesting the beginning of the closing of the material loops, provided untapped circularity potentials transform into actual capacities. For wind power to comply with emissions targets, the steel and concrete production processes will need to be decarbonised at a rate in line with the climate targets. We show that the adoption of mitigation measures to decarbonise the concrete and steel industries aligned with Sweden's climate change mitigation agenda, has the potential to reduce embodied carbon emissions for wind power infrastructure in 2045 from corresponding to around 4 % of current total national emissions in the absence of measures to practically negligible levels. National policies need to focus on promoting the implementation of circularity strategies and decarbonising the entire value chain of the involved materials.

1. Introduction

April 22, 2016 marked the day when the European Union (EU) and 174 countries across the globe signed the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC, 2016). In doing so, they agreed to enhance their efforts to address the threat of climate change by developing climate plans, known as Nationally Determined Contributions (NDCs) specifying their actions to decrease global anthropogenic greenhouse gas (GHG) emissions. However, even if all unconditional NDCs are implemented, the world will still be on track to 2.6 °C temperature rise at the end of the 21st century, far beyond the goals of the Paris Agreement (UNEP, 2022). This emphasizes the need for nations to accelerate their decarbonization efforts beyond current plans (UNEP, 2022).

Wind energy is a key technology in the global collective effort towards decarbonisation (IPCC, 2011; Rogelj et al., 2018). Policy supports, together with rapidly falling costs for wind power have led to strong expansion of wind power in recent years (Fig. 1) (a trend also seen for solar power). Despite the potential role of low-energy-demand scenarios (Grubler et al., 2018) or degrowth (Keyßer and Lenzen, 2021), the diffusion of clean energy technologies, such as wind power, will need to be greatly expanded to handle both decarbonisation of the existing electricity system (Araújo, 2022) and electrification of the industry and transport sectors. In the EU, wind power is expected to be the largest electricity generation source as early as 2027 (European Commission, 2021). In Sweden, the country with the fourth-largest wind capacity in Europe as of 2021 (12.1 GW) (Eurostat, 2023) and used as case study in this work, wind power already plays an important role. In the same year, wind power contributed around 16 % (27.1 GWh) of total electricity generation (Statistics Sweden, 2023). The electrification of the Swedish industry and transport sectors, including the first projects involving steel production using hydrogen, will increase Sweden's electricity demand. This demand is estimated to more than double by 2045 (Svenska Kraftnät, 2021), making a strong case for additional renewables,

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especially wind power (although nuclear power may also become a major contributor (Swedish Energy Agency, 2023)).

The rapid expansion of wind energy has implications for different material supply chains. The material consumption of the wind power sector is of special interest because it involves a nexus of interconnected energy, environmental, social, geopolitical (Månberger and Johansson, 2019), and economic trade-offs. The spectrum of raw materials needed for wind turbines can be divided into two broad categories: critical and bulk materials. Regarding the critical materials, one of the most-concerning aspects is the risk related to the supply of the rare earth elements (REEs) for the permanent magnets (PMs) in generators for wind turbines. The EU relies 100 % on imports from highly localized supplies for the dysprosium, neodymium, and praseodymium used in the PM generators of wind turbines; this means that these materials have high supply risk value in the EU's 2020 critical raw material list (European Commission, 2020a). This supply risk is further exacerbated by the concurrent growth in demand for REEs in other key decarbonisation technologies, such as the synchronous electric motors in electric vehicles. There are also concerns regarding dependence upon a single source market, given that China has a near-monopoly on both the production of REEs and the manufacturing of PMs. Finally, recycling levels are either zero or extremely low (Carrara et al., 2020; Ciacci et al., 2019; Gregoir and van Acker, 2022).

The quantitative assessment of bulk materials is motivated by reasons other than supply risk concerns. The concrete and steel industries together supply two of the main bulk materials for wind turbines and account for about one-eighth of global greenhouse gas (GHG) emissions (Ritchie et al., 2020). The steel and cement (used in concrete) production sectors are considered hard-to-abate (Davis et al., 2018; Rissman et al., 2020), making demand-side measures highly relevant. According to Kalt et al. (2022), if measures to reduce GHG emissions are not applied in the processing industries, the GHG emissions associated with bulk materials (mainly iron/steel and aluminium) could make up 10 % of the remaining carbon budget for a 50 % chance of limiting global warming to 1.5 °C. In Sweden, the cement and steel industries combined currently account for about 15 % of national emissions (the cement industry accounts for 4 % and the steel industry for >10 %) (Cementa, 2018; Jernkontoret, 2018). While Swedish and European industries are investing in decarbonising both steel and cement production, the transition will take time and will require the use of emerging technologies (Gerres et al., 2019; Karlsson et al., 2020; Löfgren and Rootzén, 2021).

Relevant to both the critical and non-critical materials composing the wind power infrastructure are the associated environmental and social impacts. These include issues such as waste generation, land, air and water pollution, biodiversity loss, and human rights violations, including workers' rights, land rights and indigenous peoples' rights (Gregoir and van Acker, 2022; Miller et al., 2018; Sauer and Seuring, 2019; Sovacool et al., 2021).

To address the aforementioned concerns the EU established ambitious targets to shift towards a circular economy (European Commission, 2020b). An important aspect of circular economy is the recovery of materials from anthropogenic stocks. An example of such a stock is the wind power system. In the context of this study, circularity potential of wind power represents the quantity of required new materials for wind turbines that could theoretically be mitigated through secondary material supply from wind turbines reaching their end-of-life (EoL). Examining the circularity potential of wind power can offer valuable insights on the potential of closing the material loops, provided that circularity strategies are in place either within the wind power sector or across sectors. Another important aspect of circular economy, is the focus not only on production but on transforming consumption by moving towards resource use that is responsible, reduced and demand-driven (Velenturf and Purnell, 2021). Given the projected increase in electricity demand, to become sustainable, the generation of electricity (e.g., by wind turbines) should not only focus on reducing emissions but also on becoming more efficient with regards to resource use. Exploring multiple scenarios that are all aligned with emission targets but have varying wind penetration and therefore resource use for wind, can offer valuable insights to this respect.

The Swedish transmission system operator Svenska Kraftnät (SvK) has published a report that describes the potential for the electricity transition in Sweden and formulates a pathway towards >55 GW (about 200 TWh of electricity generation) of combined offshore and on-land wind power by 2045, in its most ambitious scenario. However, aspects related to the material requirements of the scenarios, such as natural resource consumption, material intensity, supply chains and circularity of EoL turbines have been largely overlooked in the literature on the situation in Sweden. The importance of these issues is recognized by the EU (European Commission, 2020b) and Sweden (Conde et al., 2022).

The dynamics of material requirements for low-carbon transition pathways have been explored extensively at the global level (Chen et al., 2023; Deetman et al., 2021; Deng and Ge, 2020; Elshkaki and Graedel, 2013; Farina and Anctil, 2022; Grandell et al., 2016; Kalt et al., 2022; Moreau et al., 2019; Schlichenmaier and Naegler, 2022; Sovacool et al., 2020; Tokimatsu et al., 2017, 2018; Watari et al., 2019, 2020) and to a lesser extent at the European level (Berrill et al., 2016; Carrara et al., 2020; Ciacci et al., 2019; Gregoir and van Acker, 2022; Lehtveer et al., 2021). This research indicates a steep increase in the demand for most of

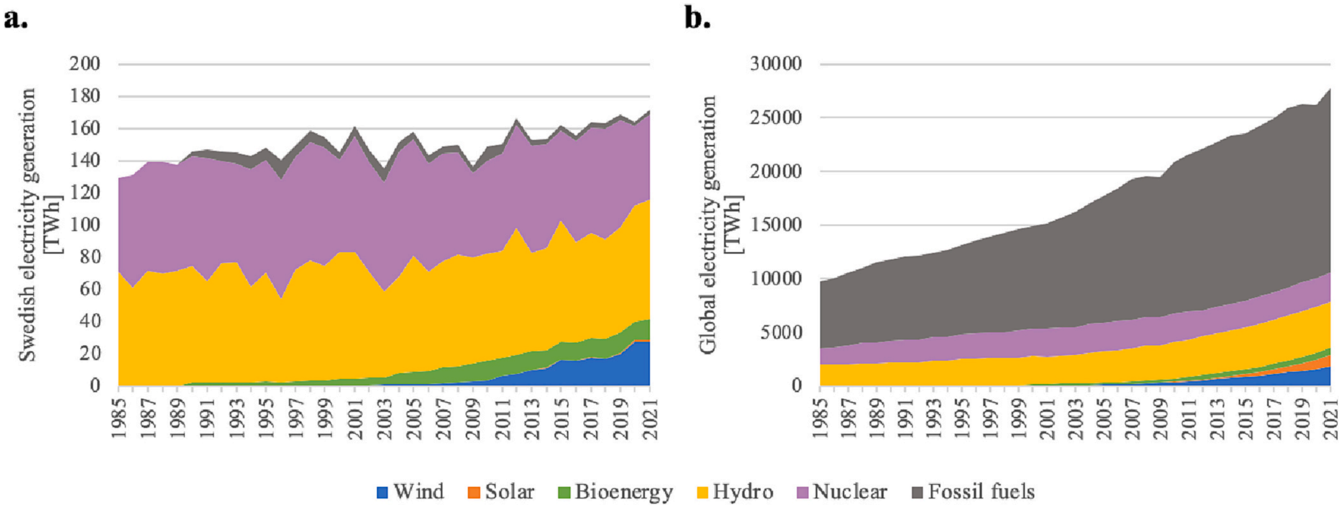

Fig. 1. Electricity generation by source in **a.** Sweden and **b.** World. Wind power is portrayed in blue between 1985 and 2021. Source: Our World In Data (Ritchie et al., 2022).

the materials used in the low-carbon transition due to the growth in electricity demand and a move towards renewable energy technologies, which have higher material intensities and require expansion of the electricity storage capacity and the transmission infrastructure.

However, according to Liang et al. (2022), research on the national level is still lacking. Among the few national-level studies, those exploring the material requirements for wind energy have focused exclusively on bulk materials (Li et al., 2020), while others have been concerned with critical metals only (Fishman and Graedel, 2019; Imholte et al., 2018; Nassar et al., 2016), some have dealt with both (Cao et al., 2019; Farina and Anctil, 2022; Ren et al., 2021; van Oorschot et al., 2022; Zimmermann et al., 2013), and some have concentrated on one specific metal (Fishman and Graedel, 2019). In terms of the type of wind power, some studies have focused on offshore wind turbines alone (Fishman and Graedel, 2019) and some on onshore wind turbines alone (Wilburn, 2011), while the majority have covered both land-based and offshore wind power (Cao et al., 2019; Farina and Anctil, 2022; Imholte et al., 2018; Li et al., 2020; Nassar et al., 2016; Ren et al., 2021; van Oorschot et al., 2022; Zimmermann et al., 2013). In doing so, an important element is a clear distinction between onshore and offshore wind when presenting the demands for materials (Ren et al., 2021). This is important since offshore wind turbines generally require more materials than their onshore counterparts (see Supplementary Material Section 1). The almost non-existent offshore wind capacity in Sweden, along with the strong potential for offshore wind power considering Sweden's long coastline, make Sweden an interesting case for studying the differences in material dynamics between onshore and offshore wind.

Furthermore, discussions on the energy transition often focus on how to supply emission-free electricity, while the embodied emissions in the demand for infrastructure are frequently overlooked in the literature (Kalt et al., 2022). Transitioning to an emissions-free electricity system necessitates consideration of the emissions associated with the production of the materials, such as steel and concrete, along with the operational emissions.

Finally, there is increasing interest in assessing the potential to repurpose metal outflows from the electricity system (Cao et al., 2019; Deetman et al., 2021; Elshkaki and Shen, 2019; Kalt et al., 2021; Li et al., 2020; van Oorschot et al., 2022). Indeed, given that currently the deployment of wind power technologies does not appear to have any coordinated and long-term approach towards life-cycle extraction, use and recovery of materials (Jensen et al., 2020), waste materials will be generated at higher rates as the electricity demand and renewable electricity generation technologies grow. However, given that wind power expansion in Sweden gained momentum only in the early 2000s, while in other European countries such as Denmark and Germany such developments happened earlier, discussions related to the re-use and recycling of wind turbines in Sweden have not occurred to the same extent as in Denmark and Germany (Swedish Energy Agency, 2016). The dismantling of wind turbines on a larger scale in Sweden, however, will occur in the decade post-2025, making this topic highly timely (Swedish Energy Agency, 2016).

This study examines the relationships between recent scenarios for the development of electricity generation presented by the Swedish transmission system operator SvK and the materials stocks dynamics. However, as the system is in transition, it is uncertain to what degree the materials exiting the system after the wind turbines reach their EoL will match the newly required materials. In this study, by employing a material flow analysis (MFA), we analyse the stock dynamics of two bulk materials (steel, concrete) and two critical materials (neodymium and dysprosium). We differentiate between onshore and offshore wind turbines. We consider the need to replace aging turbines and anticipate improvements in material intensities. We determine the material requirements for the future wind system, and also assess the specific share of the stock that becomes available for recovery after the use phase, which could contribute to resource circularity and reduce the need for primary mining. Finally, we quantify the embodied emissions for the wind infrastructure in the absence of GHG mitigation measures in the steel and concrete industries and compare them with the potential reductions in case mitigation measures are implemented, as well as with the operational emissions of the scenarios. To the best of our knowledge, this is the first national level study that quantifies for the material dynamics as well as the embodied emissions of clean energy technologies, contributing therefore to the energy-climate-material nexus. By basing our work on policy-relevant scenarios, it is possible to examine the connections between the circular economy and the energy and climate policy objectives, towards making relevant policy recommendations.

This study examines the relationships between recent scenarios for the development of electricity generation presented by the Swedish transmission system operator (SvK) and the materials stocks dynamic with the aim to address the following research questions:

1. What quantity of materials would be required for wind power in the SvK-scenarios?
2. What is the potential availability of secondary materials from future wind power infrastructure in Sweden?
3. How much embodied emissions are associated with the steel and concrete requirements for future wind power infrastructure in Sweden?

By employing a material flow analysis (MFA), we analyse the stock dynamics of the steel and concrete and two critical materials (neodymium and dysprosium) found in wind turbine components and foundations. The MFA covers the period from 1995 to 2050.

2. Materials and Method

2.1. Methodological Approach

In the MFA, resource flows and stocks are accounted for within space and time-defined system boundaries, such that a balance of inflows and outflows of resources is established based on the conservation of matter principle (Brunner and Rechberger, 2016). Mathematically, at time t, the stock is a function of the vintaged inflow cohorts that materialised until time t with a model memory of their compositions and relative shares in the stock. This model memory is a prerequisite for having age-dependent survival rates for each age cohort and the associated outflows. Based on the assumption that all inflows depreciate in a similar manner over time, the resource stock can be expressed as a convolution, according to Eq. (1):

$$stock = \sum_{\tau=t_0}^{t} inflow(\tau)^{*}survival(t-\tau) \tag{1}$$

The stock at a given time t is the sum of the shares from past inflow vintages (from the beginning of the model at time-step t_0 to the present model time t) that have not yet reached their EoL. The proportion of each past inflow vintage that is still part of the stock is determined using a survival curve for the lifetime $survival(t)$, which shows the share of the vintage that has not yet been removed from the stock (i.e., it decreases over time, starting at 100 % and eventually reaching 0 %).

As mentioned above, the time-defined boundary of this MFA is the period between 1995 and 2050. The system boundary includes the wind turbines and foundations. It does not include the electrical grid system (internal cables, transformers and external cables). The calculations and flow of data are performed in five steps, as shown in Fig. 2. The first step (see 1 in Fig. 2) is a dynamic MFA model variation of Eq. (1) for calculating inflows to the wind-power generating capacity. Retrospective and prospective stock-driven MFAs are used to estimate the inflows in the historical and future periods. The stock-driven MFA is conceptually similar to the framework proposed by Müller (2006). In Step 2 (Fig. 2), the capacity inflows are differentiated according to capacity

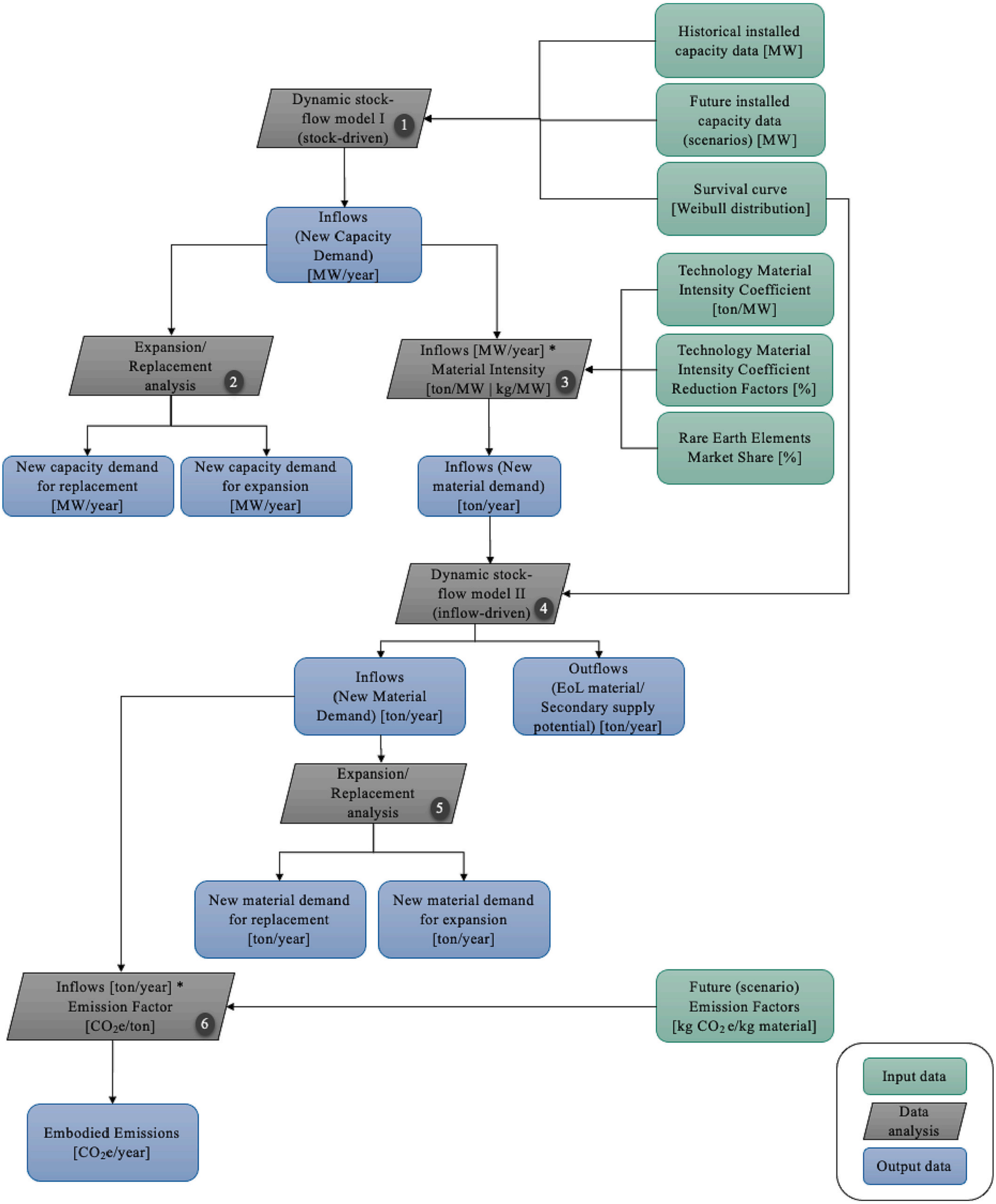

Fig. 2. Graphic representation of the model presenting the input data, data analysis steps and output data.

demand for replacement and expansion. For Step 3, the material inflows are estimated considering the material intensity coefficients, their reduction on the scenario period and the market shares of REEs. These results are then fed into an inflow-driven dynamic MFA model (Step 4), which is developed to estimate the material stocks, inflows, and outflows. The inflow-driven MFA is similar to that proposed by van der Voet et al. (2002). The fifth step differentiates the inflow of materials into replacement and expansion material demands. Finally (Step 6 in Fig. 2), the embodied emissions for the bulk materials are estimated considering the emissions factors for the steel and concrete industries from the supply-chain perspective. The data and calculations involved in each step are detailed in the following sections.

2.2. Stock-driven Modelling of Wind Installed Capacities

Historical data on commissioned turbines and the retrospective MFA analysis are essential to estimate the share of past wind turbines that are still in use today. The data used for the historical and future stocks are described in Section 2.5.1. A stock-driven MFA model estimates the corresponding inflows and outflows in each time-step. The future flows of newly installed generating capacities of wind power are driven by the development of the stock and the assumed lifetime based on Eq. (2):

$$inflow_{MW}(t) = stock_{MW}(t) - \sum_{\tau=t_0}^{t-1} inflow_{MW}(\tau)^{*}survival(t-\tau) \tag{2}$$

which is a step-wise recursive function derived from Eq. (1), in which the initial stock is $stock_{MW}(t_0) = inflow_{MW}(t_0)$. The generating capacity inflows are then (Step 2) divided into the demand for expansion of wind capacity and the demand for replacement of existing capacity that is reaching its EoL, using Eqs. (3) and (4), respectively. If an increase in wind power capacity occurred in period *t*, the share of inflow capacity meant for expansion is the incremental increase in capacity *ΔstockMW (t)*, and the remainder of the inflow is for replacement purposes. If no increase in wind installed capacity occurred, all of the inflow is for replacement of the EoL capacity.

$$expansion_{MW}(t) = \begin{cases} \Delta stock_{MW}(t), & \Delta stock_{MW}(t) > 0 \\ 0, & \Delta stock_{MW}(t) \le 0 \end{cases} \tag{3}$$

$$replacement_{MW}(t) = \begin{cases} inflow_{MW}(t) - expansion_{MW}(t), & \Delta stock_{MW}(t) > 0 \\ inflow_{MW}(t), & \Delta stock_{MW}(t) \le 0 \end{cases} \tag{4}$$

2.3. Inflow-driven Modelling for Wind System Material Requirements

In Step 3, $inflow_{MW}(t)$ is converted to demand for materials using the material intensity coefficients for the bulk materials (steel and concrete) and the critical materials (neodymium and dysprosium) in our model. For bulk materials, we consider improvements to their material intensities upon material demand. For critical materials, in addition to material intensity improvements, we consider a fixed and static market share of wind turbine technologies that use permanent magnet generators.

The inflow of materials (in mass) represents a conversion of the demand for capacity from the first step, $inflow_{MW}(t)$, multiplied by the material coefficient of the period, $Coef(mat, t)$, which indicates the specific mass of each material per unit of installed capacity [Eq. (5)]. A range of values for $Coef(mat, t)$ for each material was collected from the recent literature. The differences in the amounts of materials required for onshore and offshore wind power are documented in the academic literature, as shown in Tables S1-S4 in the Supplementary Material. In general, offshore wind power requires more materials than onshore wind power.

$$inflow_{ton}(mat, t) = inflow_{MW}(t)^{*}Coef(mat, t) \tag{5}$$

We set $Coef(mat, t)$ to the average of the collected values for 2020, and set target decreases of 30 % and 10 % in material intensity in 2050 for the REEs and bulk materials, respectively. Thereafter, we linearly interpolated the values for the intermediate periods. This reduction aims to capture future improvements in permanent magnet and bulk material efficiencies, as well as other techno-economic developments.

Demand for materials is then fed into a second dynamic MFA model to estimate the accumulation of stocks of materials in onshore and offshore wind capacity and the accompanying outflows of materials from the EoL capacity per period (Step 4 in Fig. 2). The materials embedded in a wind turbine are assumed to be replaced during the turbine's lifetime. We, therefore, use the same lifetime survival curve ***survival(t)*** to model the accumulation of material stock in the installed generating capacity, using a second 'inflow-driven' dynamic MFA model:

$$stock_{ton}(mat, t) = \sum_{\tau=t_0}^{t} inflow_{ton}(mat, t)^{*}survival(t-\tau) \tag{6}$$

The outflows are estimated using the mass balance, so that the outflow is equal to the inflow minus the addition to the stock:

$$outflow_{ton}(mat, t) = inflow_{ton}(mat, t) - \Delta stock_{ton}(mat, t) \tag{7}$$

The outflows are assumed to become either discarded outflows or potential secondary sources of materials.

The material inflow is further divided into to the expansion and replacement demands (Step 5 in Fig. 2). If an expansion of generating capacity occurs during period *t*, the share of inflow meant for expansion is the incremental increase in capacity $\Delta stock_{MW}(t)$ from Step 1, and the remainder of the material inflow is for replacement purposes. If no expansion occurs, all the inflow is for replacement of the EoL capacity:

$$expansion_{ton}(mat, t) = \begin{cases} \Delta stock_{MW}(t)^{*}Coef(mat, t), & \Delta stock_{MW}(t) > 0 \\ 0, & \Delta stock_{MW}(t) \le 0 \end{cases} \tag{8}$$

$$replacement_{MW}(t) = \begin{cases} inflow_{ton}(mat, t) - expansion_{ton}(mat, t), & \Delta stock_{MW}(t) > 0 \\ inflow_{ton}(mat, t), & \Delta stock_{MW}(t) \le 0 \end{cases} \tag{9}$$

We thereby obtain the annual and cumulative material requirements and material outflows for the period of 2021–2050. To place our results into a broader perspective, we relate the material inflows in the scenario period to the literature estimates for current overall material use in Sweden. We then estimate the proportion of material from the decommissioned stock that could potentially be recovered.

2.4. Embodied Emissions

In Step 6 of the analysis, we estimate the embodied emissions related to the bulk material requirements (cement and steel) for the wind turbines in our study and compare those to the operational emissions of the total electricity generation in the scenarios in focus.

The embodied emissions in wind turbines are calculated using Eq. (10):

$$EmbodiedEmissions(mat, t) = inflow_{ton}(mat, t)^{*}EF(mat, t) \tag{10}$$

where $EmbodiedEmissions(mat, t)$ is the total embodied CO_2e emissions for both onshore and offshore wind turbines at year *t*, and material *mat*. $EF(mat, t)$ is the emissions factor at year *t* and for material *mat*.

2.5. Scenarios, Data, and Assumptions

2.5.1. Scenarios for Wind Power Installations and Lifetimes

The historical wind turbine stock development data required for the approach used in this paper are obtained from the Swedish Wind Turbine Registry (Lansstyrelsen, 2022) for the period of 1995–2020.

Data on wind onshore and offshore wind capacities from the SvK scenarios up to 2050 are considered the stocks for the future. To assess the material stocks and flow developments related to Swedish wind electricity generation in the future, we adopted three scenarios from SvK: Decentralised Renewable (DR), Dispatchable Electrification (DE), and Renewable Electrification (RE) (Svenska Kraftnät, 2021). The levels of electricity demand in the scenarios vary depending on: the amount of hydrogen produced using electricity; energy efficiency; digitisation; import dependency versus degree of self-sufficiency; and the extent to which biofuels are part of the electricity mix. SvK provides the simulation results, which were obtained in a collaboration with stakeholders from the industry, with the intention of identifying future needs and challenges for the power system. In all the scenarios, the national climate targets are met, albeit through different means. A common element in all the scenarios is a strong increase in electricity generation and a heavy reliance on wind energy. Yet, the scenarios show large differences in terms of the balance between onshore and offshore wind capacities, given the wide range of offshore wind power capacities across the scenarios. This range is especially interesting to consider because the very existence of a future Swedish offshore wind power sector is still unclear.

In 2020, onshore and offshore wind power installed capacities were roughly 9.5 GW and 0.2 GW, respectively. Table 1 shows the onshore and offshore wind capacities in 2050 for the three SvK scenarios, each reflecting different assumptions regarding electrification and renewable energy shares. The DR scenario prioritises resource conservation, energy efficiency, and decentralised energy systems, resulting in lower wind capacities compared to the other scenarios (22.6 GW and 1.5 GW for onshore and offshore power, respectively). In the DE scenario, the electricity demand increases significantly, and onshore and offshore wind capacities reach 25.1 GW and 12 GW accordingly. The RE scenario sees the sharpest increase in electricity demand, with land-based wind power in the north and offshore wind power dominating along the coasts, reaching total installed capacities of 28.2 GW and 35 GW, respectively. A more detailed description of the scenarios can be found in the Supplementary Material Section 2.

To determine the lifetime distribution of the wind turbines and the corresponding survival function, we assume that these follow a Weibull distribution. This assumption stems from a study of the wind turbine stock in Denmark (Cao et al., 2019), which investigated real-life operating lifespans, including certain amounts of wind turbines installed as pilot projects with a shorter lifetime as well as wind turbines operating beyond their intended lifespans, resulting in a Weibull fit. The parameters used in the Weibull distribution assume mean lifetimes of 20 years for the historical period up to 2020 and 25 years for the period between 2021 and 2050. In both cases, a standard deviation of 5 years is assumed. For future periods, both longer (Carrara et al., 2020) and shorter (Cao et al., 2019) lifetimes have been suggested in the literature. Therefore, we assess the impacts of lifespan extension or shortening through a sensitivity analysis of the results with two alternative curves for the scenario period 2021–2050 (see Supplementary Material Fig. 1), changing the mean lifetimes of the turbines. The cumulative distribution function of the Weibull distribution and the standard deviation of 5 years are maintained. The first alternative involves a reduced lifetime of 20 years (used in many studies) and the second applies an extended turbine lifetime of 30 years, as suggested by Carrara et al. (2020).

Table 1
Installed capacities in 2050 in the SvK scenarios.

SvK scenario	Abbreviation	Wind type	2050 Installed capacity [GW]	Total electricity demand [TWh]
Decentralised renewable (*Småskaligt förnybart*)	DR	Onshore Offshore	22.6 1.5	184
Dispatchable electrification (*Elektrifiering planerbart*)	DE	Onshore Offshore	25.1 12.0	282
Renewable electrification (*Elektrifiering förnybart*)	RE	Onshore Offshore	28.2 35.0	298

2.5.2. *Wind Power Material Requirements*

To capture future improvements in REEs and bulk material efficiencies and other techno-economic developments, we assume reductions in their material intensities. With regards to REEs, a 30 % reduction is applied. Smith and Eggert (2018) recognized past reductions of this magnitude in response to the 2011 REE price spike. For the bulk materials, a 30 % reduction was deemed to be very ambitious. Farina and Anctil (2022) found that the bulk material intensity in wind turbines remained almost constant between 1990 and 2014. However, material efficiency will most likely improve in the future, with a consequent reduction in material intensity. A moderate reduction in the order of 10 % compared to the current values is assumed by 2050, in line with the Carrara et al. (2020) medium demand scenario for structural materials in wind power installations. Although some studies have included such dynamics (Fishman and Graedel, 2019; van Oorschot et al., 2022), others have assumed constant values for material intensities for wind power in their future scenarios (Imholte et al., 2018; Watari et al., 2018; Wilburn, 2011). This assumption is tested in a sensitivity analysis.

We assume that all turbines up to 2050 will be installed with the same bulk materials. Various studies directed towards the use of more-lightweight materials are ongoing and could change the material usage patterns in the future. For offshore wind turbines, different types of foundations can result in different material intensities. For example, it can be assumed that there is no concrete used for certain foundation types, such as floating wind turbines (Kalt et al., 2022). However, the potential market share of floating offshore wind turbines is uncertain. Other alternatives to structural materials, such as wood (Landqvist and Lind, 2023) or the use of concrete as an alternative to steel for offshore wind turbine foundations (Mathern et al., 2021), are beyond the scope of the present study because these technologies are yet to be implemented beyond the laboratory-scale or pilot-scale. In addition, many aspects, such as their material intensities, potential market penetration rates and the time horizons for their introduction, remain to be elucidated.

REEs are essential for turbine designs that employ permanent magnets. Thus, the use of REEs is dependent upon the shares of permanent magnet technologies in the wind power industry. Even though permanent magnets are expensive and metal-intensive, most of the alternatives have lower efficiency and performance levels (Rabe et al., 2017). Direct-drive permanent magnet generators eliminate the failure-prone gearbox, enabling a reduction in size and thereby reducing the turbine's overall weight (Carrara et al., 2020). Compared to the gearbox, permanent magnet generators are associated with higher levels of reliability and lower maintenance needs (Nassar et al., 2016). This increases their attractiveness, especially in offshore applications (Giurco et al., 2019; Pavel et al., 2017; Rabe et al., 2017; World Bank, 2017), and justifies their continued use in all the scenarios considered. Data on the market shares of permanent magnets are not available for the Swedish wind turbine stock. Therefore, the market share of permanent magnets in the EU (Carrara et al., 2020) is assumed also for Sweden: with 30 % applied from 2021 and up to 2050 for onshore wind turbines. The European offshore wind turbine market is currently dominated by permanent magnets. Here, we assume that the entire stock until 2050 will be installed with permanent magnets. Offshore turbines with capacities >5 MW are unlikely to have gearboxes and are, therefore, likely to require permanent magnets. Alternatives to neodymium-based magnets, such as samarium- and cobalt-based magnets or generators that do not require permanent magnets, such as super-conducting generators, are beyond the scope of this study, not least because these technologies are yet to be implemented at industrial scale (Carrara et al., 2020; Pavel et al., 2017) and several key aspects remain unknown.

2.5.3. Embodied Emissions

For the emissions factors, we use the Karlsson et al. (2020) study, which describes pathways for the decarbonisation of the concrete and steel industries following a supply chain perspective. We develop two cases using two different sets of emissions factors. In the first, which we call the *no change* case, currently used processes (blast furnaces for reducing iron from ore and conventional fossil fuel-reliant processes for cement clinker production) are assumed to remain in place. Both processes produce emissions due to the chemical reactions involved, so the average process emissions remain constant. In the second case, which we call the *transformative change* case, a reduction in process emissions is assumed to be achieved by adopting technological innovations that are currently under development [i.e., hydrogen-based direct reduction for steel production, and alternative fuels (derived from wastes and biofuels) combined with carbon capture and storage in the cement industry]. Changing the energy mixes is also considered in this case, such that both changes in energy-related GHG intensities and technological progress towards low-carbon technologies for process emissions are considered. Steel compositions that include primary and secondary (recycled) materials represent another important factor affecting GHG emissions. For structural steel and other steel products that are currently produced from primary steel, Karlsson et al. (2020) have assumed that 30 % of the steel in these products will be produced from secondary steel by 2050. For the emissions factors in the retrospective analysis (1995–2020), we assume constant 2020 values. Historically, emission factors were likely higher than in 2020, although no historic emission factors were available.

To place the embodied emissions in perspective, a comparison with emissions from electricity generation is conducted. For this, we use projected electricity generation emissions factors for Sweden, as derived from Karlsson et al. (2020), and we multiply these by the electricity generation values of the SvK scenarios. The emissions factors used are listed in Tables S6-S8 in the Supplementary Material. The results for emissions are presented up to 2045, which is the last year for which Karlsson et al. (2020) provide emissions factors and the year by which Sweden has committed to reducing GHG emissions to the net-zero level.

3. Results

3.1. New and Decommissioned Wind Power Capacities

Fig. 3 shows the estimated newly installed capacities grouped in 5-year periods for onshore, offshore, and total wind turbine capacity under the three SvK scenarios of Decentralised Renewable (DR), Dispatchable Electrification (DE) and Renewable Electrification (RE). The five-year installed capacity is divided into expansion and replacement demands in the upper graphs, while the lower graphs show the growth and depreciation dynamics of the newly installed generating capacity by age cohorts (5-year periods) over time. The five-year installed capacity differs substantially among the scenarios. For example, the estimated peak five-year installed capacity appears in different time periods in each scenario. Moreover, looking at the composition of the demand for new wind capacity, there are considerable changes in the needs for expansion and replacement among the scenarios.

Considering onshore wind turbines (Fig. 3a), during the historical period and up to the first scenario period (2021–2025), expansion is the main driver of the demand. However, post-2025, the demand for replacing wind turbines that are reaching their EoL becomes increasingly larger, and in all the scenarios, it becomes the main driver of newly installed capacity well before 2050. In fact, for DR, replacement becomes the main driver as early as the period of 2026–2030, and remains so until 2050. In the DE scenario, replacement becomes the main driver post-2030 and remains so until the end of the scenario period. In the RE scenario, replacement also becomes the main driver post-2030 and remains so for a decade, followed by a period (2041–2045) that is characterized by more expansion than replacement. Replacement once again becomes the main driver at the end of the period (2046–2050). In all three scenarios, at the end of the scenario period (2045–2050), replacement accounts for about 75 % of the demand for new onshore capacity.

For onshore wind power, 2025 is an inflection point in all the scenarios, when the increasing trend of the total demand for new capacity (for expansion and replacement) is disrupted and this is followed by a substantial decrease during the period of 2026–2030. As a result of the high demands in the short term for wind capacity in combination with a relatively low level of currently installed capacity, all the scenarios indicate that onshore annual installed capacities will rapidly increase up to 2025, mostly due to expansion. According to the Swedish Wind Energy Association, Sweden has by the end of 2022 a wind power installed capacity of around 14.6 GW (with a yearly production level of around 30 TWh). This capacity is expected to reach around 18.3 GW (roughly 50 TWh) by 2025, based on the onshore wind power plants that have all the permits and for which there are investment decisions (Swedish Wind Energy Association, 2022). However, looking at the total onshore demand, this trend of decreasing growth rates during the period of 2026–2030 ends when the increase in the number of retired wind turbine kicks in post-2030. Despite this, the overall onshore five-year demand for 2021–2025 is only exceeded during the period of 2041–2045 in the RE scenario.

For offshore wind turbines (Fig. 3b), there is a large difference in the amounts of newly installed capacity between the scenarios (cf. Table 1), where the SvK scenarios reflect higher uncertainty in terms of future investments in offshore wind power. Thus, the compositions of the capacity additions for offshore wind turbines follow a different path than the onshore wind capacities. Given the negligible investments made in offshore wind capacity to date, nearly all the demand up to 2050 is for the expansion of generating capacity. Consequently, the need for replacement of wind capacity that is reaching its EoL does not become apparent until the very end of the scenario period. In the RE scenario, in 2050, the demand for replacement is about a quarter of the total demand for new additions. Given that the majority of investments for the expansion of wind power are introduced around 2030 and onwards, and the assumed lifetime is 25 years, the need to replace obsolete wind turbines post-2050 is expected to become more dominant. The lifetimes of the wind turbines will obviously strongly influence these results. Some studies have suggested longer lifetimes, and we test the sensitivity of the results to this parameter in the Supplementary Material Section 4.

Overall, considering the total wind capacity (Fig. 3c), the composition of the demand for wind capacity additions varies between the scenarios. In the DR scenario, after 2025, the replacement of obsolete wind power capacity is the main driver for new wind installations. However, in the RE scenario, expansion of wind turbines is the main driver of new wind installations throughout the scenario period, largely promoted by the expansion needs of offshore wind power. The DR scenario is the only scenario in which the total capacity additions during the first scenario period are never exceeded during the remainder of the scenario period. Historically and up to 2021, the largest newly installed capacity of wind was in 2021 with 2.1 GW (Lansstyrelsen, 2022). The maximum newly installed capacity under the RE scenario, the scenario with the highest demand for newly installed capacity, is reached in the period of 2036–2040 with 17 GW. This equates to an average annual installed capacity of 3.4 GW, which is equivalent to a 63 % increase compared to the 2021 newly installed capacity. The maximum newly installed capacity in the DR scenario is 6.4 GW for the period of 2021–2025, corresponding to an average annual addition of 1.3 GW of wind capacity, which is lower than the 2021 newly installed capacity. For the DE scenario, the maximum newly installed capacity is reached in

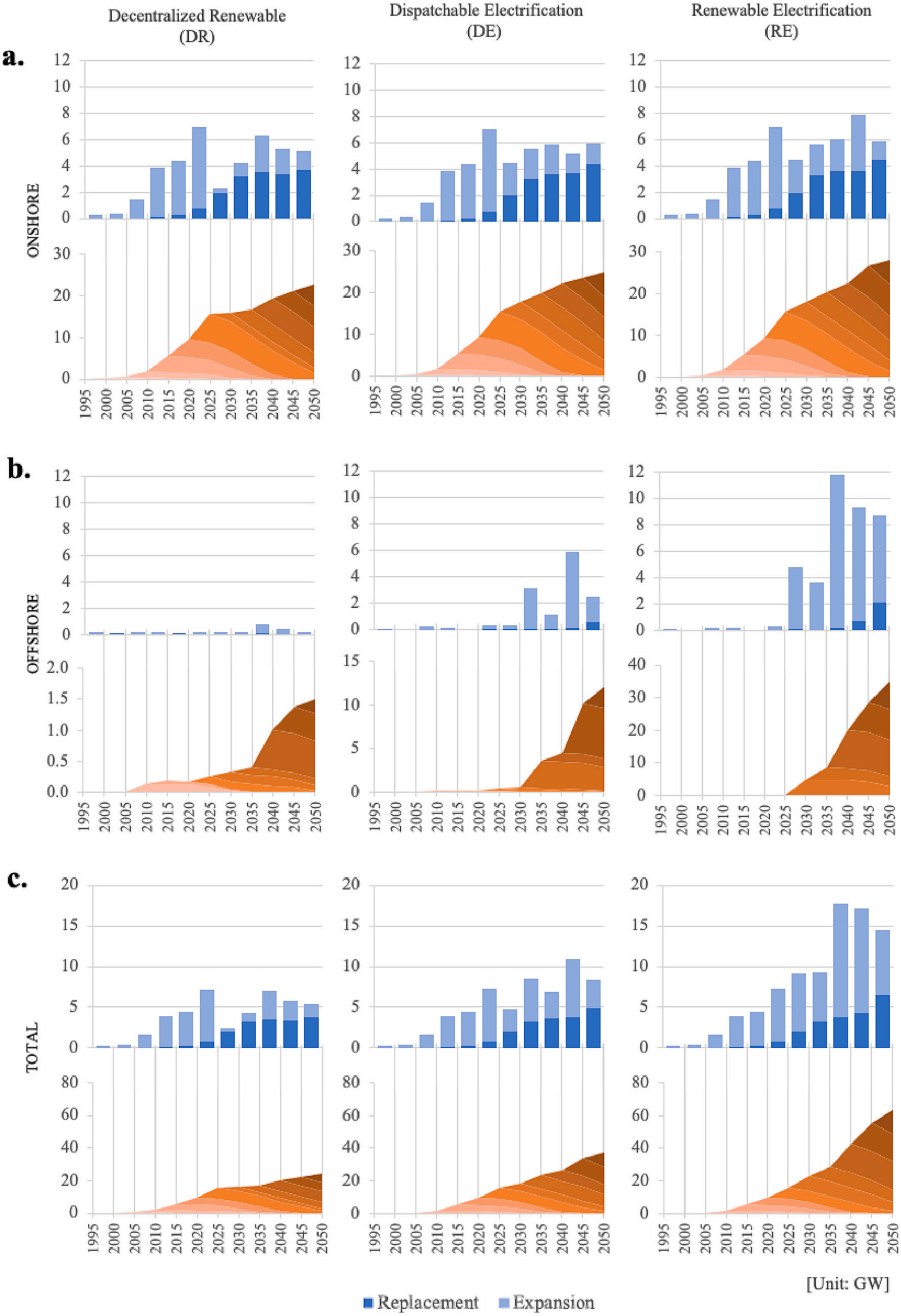

Fig. 3. Newly installed capacity of wind power over time. Quinquennial (5-year) newly installed generating capacity (in GW) for the period 1995–2050 for the purposes of replacement and expansion, and the corresponding growth and depreciation dynamics of the capacity over time, with age cohorts (5-year) indicated with different shades of orange for the Decentralised Renewable (DR), Dispatchable Electrification (DE), and Renewable Electrification (RE) scenarios and for: **a.** onshore wind turbines; **b.** offshore wind turbines; and **c.** total wind turbines. Note the different scales on the ordinate axis between the graphs.

the period 2041–2045, with an annual average of 2.1 GW (10.4 GW in total), i.e., the same as the 2021 capacity additions.

3.2. Material Requirements and Potential Secondary Materials Supply

Substantial increases in material requirements are needed for some of the estimated wind power scenarios in Section 3.1. Fig. 4 shows the results for the material requirements (inflows) and potential secondary

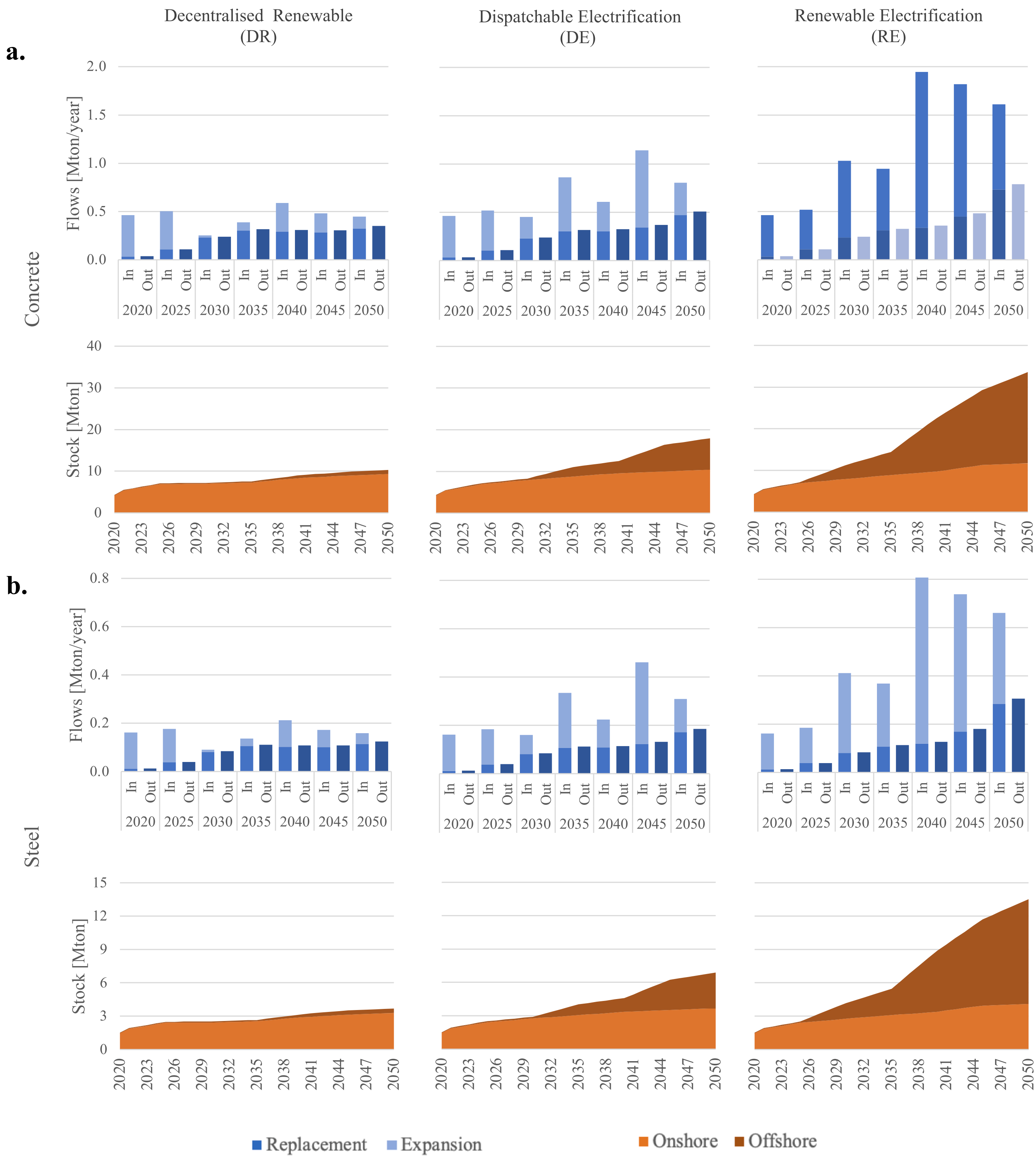

Fig. 4. Material flows and in-use stocks of concrete and steel. Material requirements (inflows) for newly installed capacity for replacement and expansion and for potential secondary material supply (outflows) from decommissioned capacity for Years 2020, 2025, 2030, 2035, 2040, 2045 and 2050, and the corresponding material stock development from 2020 to 2050 for the Decentralised Renewable (DR), Dispatchable Electrification (DE), and Renewable Electrification (RE) scenarios for bulk materials **a.** concrete and **b.** steel.

materials supplies (outflows) for concrete and steel, along with the total in-use stock of the studied materials in the scenario period for the three scenarios.

In 2020, the estimated in-use stocks of bulk materials for concrete and steel are 4.3 and 1.5 Mt., respectively. By 2050, the stock of concrete reaches roughly 10.3 Mt. in the DR scenario (roughly, an increase by a factor of 2.4), and it reaches 33.6 Mt. (an increase by about a factor of 7.8) in the RE scenario due to the extensive implementation of onshore and offshore wind technologies. The steel in-use stock in 2050 is in the range of 3.7–13.5 Mt., thus increasing by a factor of 2.5 (DR scenario) to

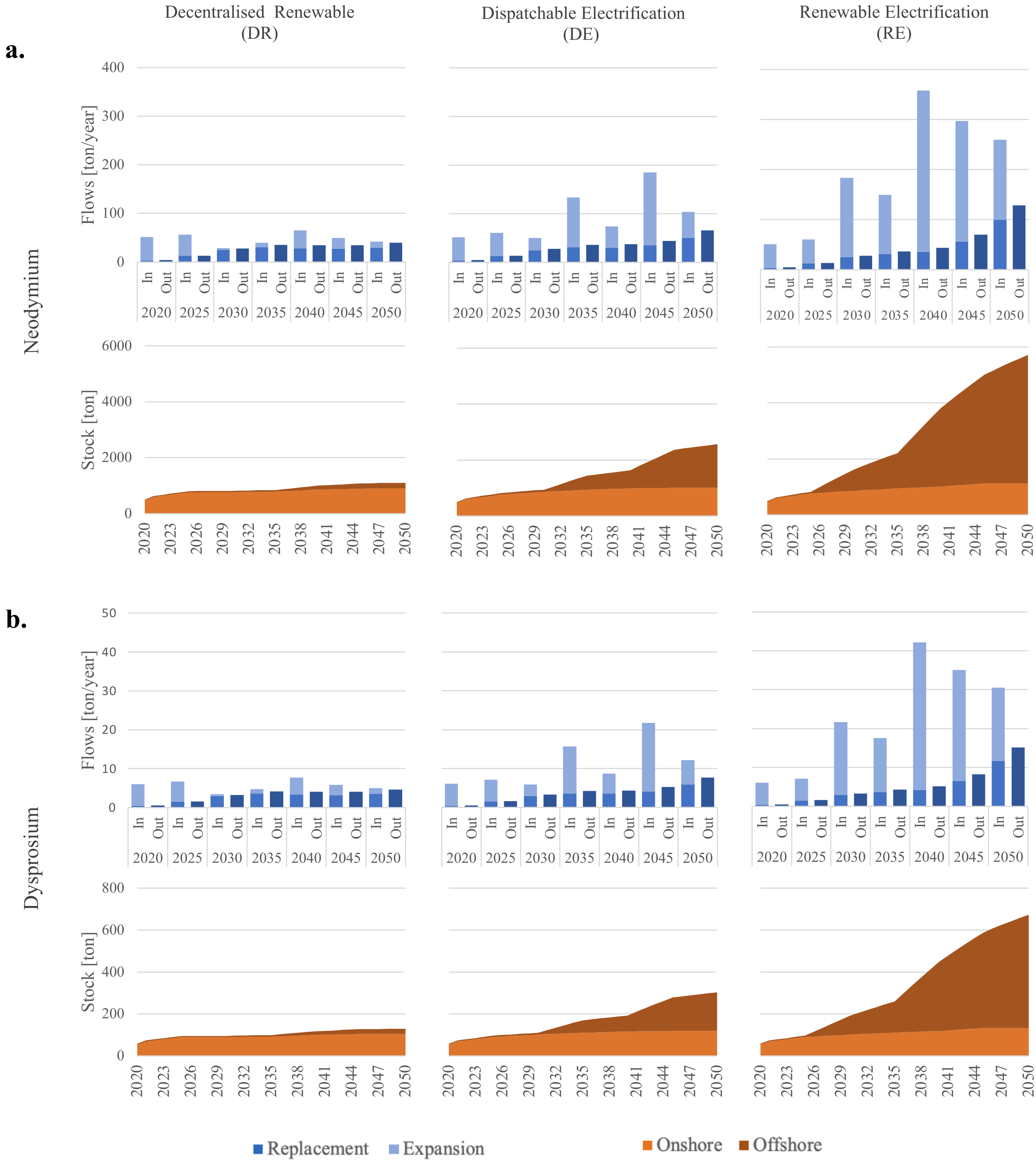

Fig. 5. Material flows and in-use stocks of neodymium and dysprosium. Shown are the material requirements (inflows) for newly installed capacity for replacement and expansion purposes, and the potential secondary material supply (outflows) from decommissioned capacity for Years 2020, 2025, 2030, 2035, 2040, 2045 and 2050, together with the corresponding material stock developments for the period of 2020–2050 for the Decentralised Renewable (DR), Dispatchable Electrification (DE), and Renewable Electrification (RE) scenarios for: **a.** neodymium; and **b.** dysprosium.

9.0 (RE scenario). Offshore wind turbines require larger amounts of concrete and steel per installed capacity than onshore wind turbines. In the RE scenario, the only scenario that has higher offshore than onshore wind capacity towards the end of the scenario period, the installed capacity of offshore wind exceeds that of onshore in 2044. However, the in-use stocks of concrete and steel in offshore wind turbines in the scenario exceed those of onshore wind turbines earlier than 2044 (in 2038 and 2037 for concrete and steel, respectively).

Of the years presented, the estimated annual concrete demands in Scenarios DR, DE and RE reach their highest values of 0.6, 1.2 and 1.9 Mt. in 2040, 2045 and 2040, respectively (Fig. 4a). Compared to the concrete demand for new wind power construction in 2020, this constitutes increases in demand by roughly factors of 1.2, 2.0 and 4.0, respectively. The total amount of cement used in Sweden in 2019 was about 2.8 Mt. (Wadell, 2022). Assuming a 14 % share of cement in concrete (Colangelo et al., 2018), this means that Sweden used around 20 Mt. of concrete in 2019. Therefore, the annual concrete demand for wind power during the scenario years with the highest demands would be between 3 % and 10 % of the 2019 concrete use level in Sweden.

As shown in Fig. 4b, the annual inflows of steel in the electricity system increase roughly by the following factors: 1.3 in the DR scenario in 2040; 3.0 in the DE scenario in 2045; and 5.0 in the RE scenario in 2040, as compared to 2020 inflows (from about 0.16 Mt./year to 0.21–0.81 Mt./year). In 2020, the estimated demand for steel for wind turbines is 0.16 Mt., which is roughly 5 % of the 2020 apparent steel use (deliveries – exports + imports) in Sweden (3.1 Mt) (Jernkontoret, 2020). In the scenario with the highest wind power growth (RE), the annual steel requirement for wind turbines in the year with the highest demand (2040) is expected to be up to 26 % of the current total level of steel use in Sweden.

While remaining lower than the inflows, the outflows of concrete and steel from decommissioned turbines increase from low levels in 2020 to substantial levels by 2050. From roughly 0.036 Mt. in 2020, the annual concrete outflows are estimated to be 10–22 times larger (0.35–0.79 Mt) in 2050 compared to 2020 in all the scenarios. This is equivalent to 2 %–4 % of the concrete used in Sweden in 2019. In 2050, the steel annual outflow increases to between 0.12 and 0.3 Mt. compared to 0.013 Mt. in 2020. This is equivalent to 4 %–10 % of the apparent steel use in Sweden in 2020. Throughout the scenario period, outflows are consistently higher than the demand for replacement, since the decommissioned older turbines are replaced with new turbines with improved technologies that require less materials per installed capacity.

The estimated in-use stocks of neodymium, and dysprosium, in 2020 were 500 and 60 t, respectively (Fig. 5). The neodymium stocks grow to about 1.1, 2.6 and 5.7 thousand tonnes (increasing by factors of 2, 5 and 11) in the DR, DE and RE scenarios, respectively in 2050. The dysprosium stock experiences the same magnitude of change. The increases in the neodymium and dysprosium in-use stocks in the RE scenario are substantially larger than the increases in the stocks of bulk materials, despite the higher material efficiencies assumed for the REEs (30 % reduction in material intensities by the end of the scenario period), as compared to the bulk materials (10 % reduction in material intensities by the end of the scenario period). This is driven by the demand for offshore wind turbines, as, according to our assumptions, 100 % of the offshore fleet is installed with permanent magnets that require REEs.

From about 51 t in 2020, annual neodymium inflows are estimated to increase roughly by a factor of 1.2 in the DR scenario in 2040, by a factor of 4 in the DE scenario in 2045, and by a factor of 7 in the RE scenario in 2040 (Fig. 5a). The dysprosium annual inflow is between 8 and 42 t in the years with the highest annual inflows, as compared to 6 t in 2020, following a similar trend as the neodymium annual inflows (Fig. 5b). In similarity to the bulk materials, throughout the scenario period, the outflows are consistently higher in REEs than the demand for replacement but lower that the total new demand. However, given the higher efficiency potential of REEs, the difference between outflows and replacement demand is more prominent in the case of REEs.

Data on the total current use of neodymium and dysprosium are not available because these materials are often embedded in products that are imported into Sweden, which means that tracking their use is complicated. To place the REEs demands in the scenarios into perspective, we compare their use in the scenarios with the quantity of REEs needed in electric vehicles. Our results show that under our scenario assumptions, roughly 6550 t of neodymium would be required between 2021 and 2050 to achieve the wind infrastructure designated by the RE scenario. This corresponds approximately to what is required for 9 million electric cars [which require on average 0.73 kg of neodymium per vehicle with the current technology (Fishman et al., 2018)]. This is almost double the current personal vehicle fleet in Sweden, which is approximately 4.9 million vehicles (Transport Analysis, 2022). For dysprosium, it is estimated that 771 t would be required in the RE scenario between 2021 and 2050, which could meet the needs for dysprosium in about 23 million electric vehicle motors [requiring an average of 0.034 kg of dysprosium per vehicle (Fishman et al., 2018)].

Table 2 shows the shares of the outflows compared to inflows on an annual basis for selected years, as well as for the entire scenario period. This indicates the potential for circularity, or in other words, the quantity of required new materials that could potentially be mitigated through secondary material supply (outflows). For REEs, which face supply risks, we show that roughly 20 %–59 % of their total demand between 2021 and 2050 in Sweden could be met by domestic secondary supply if currently untapped circularity potentials were transformed into actual capacity. Notably, at the end of the scenario period (Year 2050) in the DR scenario, the REEs show an almost full circularity potential (94 %). For bulk materials, the results indicate that 28 %–56 % of the concrete demand and 25 %–56 % of the steel demand could be met by outflows from wind turbines that are reaching their EoL between 2021 and 2025. Just as with the REEs, bulk materials attain their highest circularity potentials in the DR scenario, with roughly 80 % in Year 2050. While steel enjoys a high recycling rate, concrete recycling is currently at low levels in Sweden, as well as in other regions (Marsh et al., 2022; Mineral Products Association, 2022).

The circularity potentials of the bulk and critical materials are, however, consistently reduced when there is stronger growth of wind power (RE, which has the strongest growth of wind power, shows the lowest circularity potential). This is because the in-use stocks in the DR scenario either remain stable or increase only slightly, while the stocks that are being decommissioned gradually increase. Still, there is a 20 %–28 % recycling potential. In addition, Figs. 4 and 5 show that the outflows exhibit mainly an increasing trend through the years, whereas the inflows exhibit a decreasing trend towards the end of the scenario period. This implies a trend towards higher circularity potential towards the end of the scenario period.

3.3. Embodied Greenhouse Gas Emissions

Fig. 6 shows the cumulative embodied CO_2e emissions in the wind infrastructure for steel (Fig. 6a) and concrete (Fig. 6b) for the period of 1995–2045. In the *no change* case, which assumes that current emissions factors will stay the same throughout the scenario period, the cumulative emissions of steel increase roughly by factors of 4 (scenario DR) to 9 (scenario RE) by 2045, as compared to 2020 cumulative emissions (from about 3 Mt.CO_2e to 12–30 Mt.CO_2e). For concrete, the *no change* case results in cumulative embodied emissions increasing by a factor of 4 in the DR scenario and by a factor of 8 in the RE scenario (from 0.7 Mt.CO_2e to 2.6–5.8 Mt.CO_2e). However, in the *transformative change* case, which assumes reductions in process emissions from the steel and concrete industries through the adoption of hydrogen-based direct reduction in steel production, and through the adoption of alternative fuels (derived from wastes and biofuels) combined with carbon capture and storage in cement production, the increase in embodied emissions is substantially smaller. The cumulative emissions from steel increase roughly by factors of 2.0 and 4.0 in the DR and RE scenarios, respectively, by 2045

Table 2
Circularity potentials (shares of outflows compared to inflows across the materials and scenarios for Years 2020, 2025, 2030, 2035, 2040, 2045, and 2050, as well as for the period 2021–2050.

Scenario	Material	2020	2025	2030	2035	2040	2045	2050	2021–2050
DR	Concrete	8 %	22 %	94 %	82 %	54 %	65 %	79 %	56 %
	Steel	8 %	22 %	93 %	82 %	53 %	64 %	78 %	56 %
	Neodymium	9 %	24 %	96 %	89 %	53 %	70 %	94 %	59 %
	Dysprosium	9 %	24 %	96 %	89 %	53 %	70 %	94 %	59 %
DE	Concrete	8 %	21 %	53 %	41 %	56 %	37 %	66 %	41 %
	Steel	8 %	21 %	53 %	37 %	54 %	33 %	63 %	38 %
	Neodymium	9 %	22 %	55 %	27 %	50 %	24 %	63 %	32 %
	Dysprosium	9 %	22 %	55 %	27 %	50 %	24 %	63 %	32 %
RE	Concrete	8 %	21 %	27 %	38 %	22 %	29 %	52 %	28 %
	Steel	8 %	21 %	23 %	34 %	18 %	27 %	49 %	25 %
	Neodymium	9 %	22 %	15 %	25 %	12 %	24 %	49 %	20 %
	Dysprosium	9 %	22 %	15 %	25 %	12 %	24 %	49 %	20 %

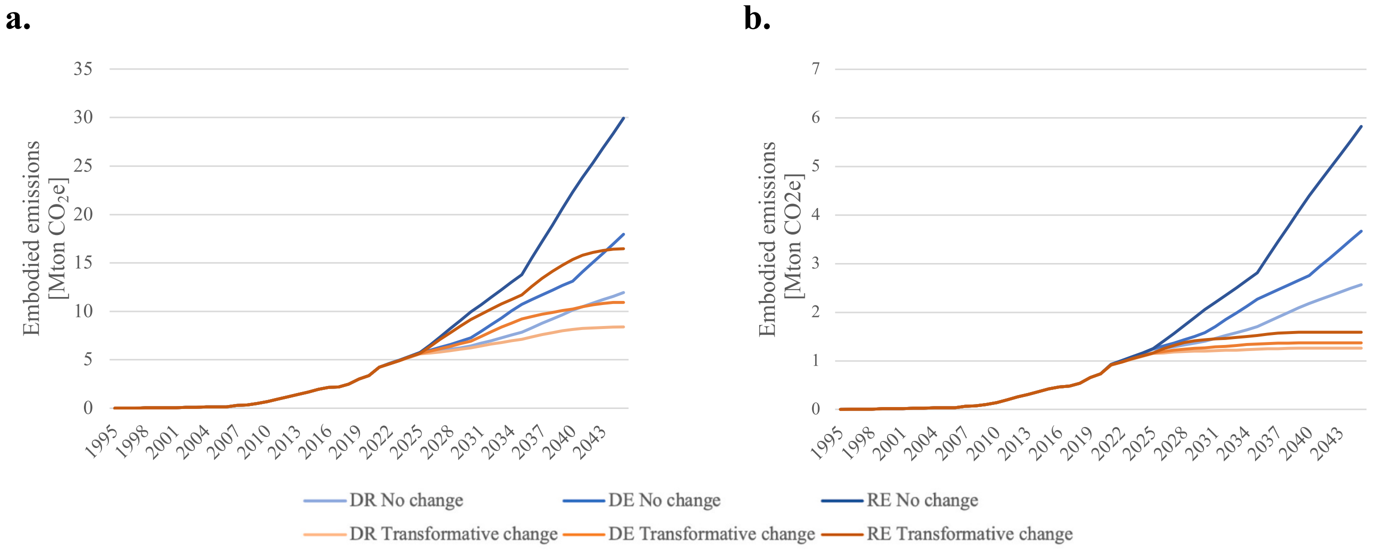

Fig. 6. Cumulative embodied emissions up to 2045 for the **a**. Steel and **b.** Concrete requirements for wind power infrastructure in the Decentralised Renewable (DR), Dispatchable Electrification (DE), and Renewable Electrification (RE) scenarios.

compared to 2020 (8.5 to 15.1 Mt.CO_2e). For concrete, there are increases by factors of 1.7 and 2.2 (1.3 and 1.6 Mt.CO_2e) in the DR and RE scenarios, respectively. Compared to steel, the changes in emissions related to concrete happen faster. This is because the emissions factor used for concrete assumes the decarbonisation of the cement industry in Sweden, as concrete is mainly produced domestically. In contrast, the emissions factor for steel, which is traded on a larger international market, considers the transition at the European level, which is proceeding more slowly compared to the Swedish steel decarbonisation timeline. In addition, cumulative emissions from concrete do not increase from 2040 onwards, underlining that the industry is expected to be net-zero by 2040. For the cumulative emissions from steel, while a small increase occurs post-2040, the increase weakens substantially thereafter. Fig. 6 shows that the main differences in embodied emissions levels between the scenarios occur post-2025.

Fig. 7 visualises the annual embodied emissions related to the steel and concrete requirements of wind turbines, along with the expected total electricity operational emissions and the total electricity generation in each scenario and for the two cases for the period of 2025–2045. The emissions factors for the operational emissions of electricity generation include emissions from the Swedish electricity generation mix, taking into account electricity imports and exports (Karlsson et al., 2020). Across the scenarios and cases, in 2025, the embodied emissions account for roughly 9 % of the total emissions (the sum of the embodied and operational emissions). Of that, 7 % is related to steel and 2 % is related to concrete. However, by 2045, the share of embodied emissions varies substantially among the scenarios and cases. The shares of embodied emissions in the total emissions (the sum of the embodied and operational emissions) by 2045 increase to 43 %, 57 % and 66 % in DR, DE and RE scenarios, respectively. In the RE scenario, from the 66 %, 55 % is related to steel, with the remaining 11 % being related to concrete. In 2045, steel-embodied emissions for the development of wind power alone account for higher emissions than the total electricity operational emissions. However, in the *transformative change* case (Fig. 7b), which reflects the transformation already in planning and under development in the steel and concrete industries, embodied emissions for wind turbines' bulk material requirements in 2045 account for merely 1 %–3 % of the total operational emissions in the DR and RE scenarios, respectively, all of which is attributed to steel since concrete is assumed to have net-zero emissions by 2040. In 2045, the wind power embodied emissions of concrete and steel in the *no change* case are in the range of 0.4–1.9 Mt. CO_2e in the scenarios, which is equivalent to 1 %–4 % of the total national emissions for Sweden in 2020, which was 49.7 Mt.CO_2e (Statistics Sweden, 2021). In the *transformative change* case, the embodied emissions are only 0.01 % to 0.03 %, which is a practically negligible level.

In summary, the results presented in Figs. 6 and 7 show that it is critical that the entire value chain of any energy infrastructure is decarbonised (the *transformative change* case) if climate targets are to be met.

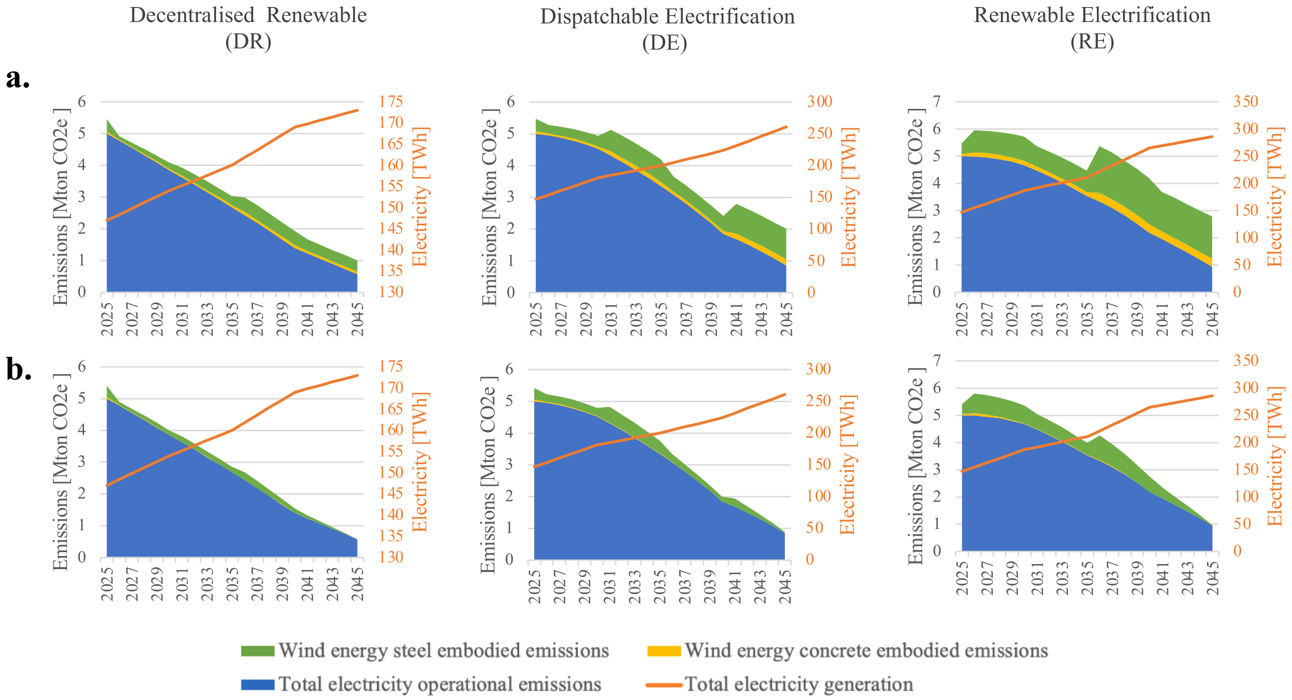

Fig. 7. Embodied (steel and concrete) emissions of the Swedish wind power infrastructure, with the operational emissions of the total electricity generation (primary axis) and electricity generation (secondary axis) in the Decentralised Renewable (DR), Dispatchable Electrification (DE), and Renewable Electrification (RE) scenarios for: **a.** the 'no change' case; and **b.** the 'transformative change' case. Note that the same emissions factors for operational emissions were used across the three scenarios and the two cases.

3.4. *Sensitivity Analysis*

Changes to the lifetime of the survival curve do not influence the material demands for expansion. Compared to our original scenario assumptions, shorter or longer mean lifetimes change the demand for replacement and the availability of outflows. In the case of longer mean lifetimes (30 years instead of the original assumption of 25 years), the total material demands for the period of 2021–2050 decrease by 3 %–9 % for the different materials (concrete, steel, neodymium, dysprosium) and scenarios (DR, DE, RE). For example, increasing the lifetime to 30 years means that the steel demand decreases from 4.8, 8.3 and 15.5 Mt. over the scenario period to 4.4, 7.7 and 14.7 Mt. in the DR, DE and RE scenarios, respectively (decrease of 10 %, 7 % and 6 %, respectively). The amount of steel that becomes available from turbines that are reaching their EoL also decreases when there is an extended lifetime, albeit at a higher level compared to the rate of replacement demands. The decrease in outflows varies between 18 % and 31 % (for all the results, see the Supplementary Material Tables S9-S11). Given that the material outflows scale down at a higher rate than replacement when the average lifetime is extended, the ratio of outflows to inflows decreases from 21 %–60 % among the scenarios and materials in the original scenario assumptions (see Table 2) to 15 %–53 %. This suggests that longer lifetimes diminish the potential supply bottlenecks (given the lower demand for replacement). An extended lifetime also reduces the circularity potential or the need for recycling of secondary supplies (given the reduction in the outflows to inflows ratio). The opposite happens in the case of shorter mean lifetimes (20 years). The ratio of outflows to inflows increases to 29 %–64 %, indicating an increase in the secondary supply of materials.

In our scenario settings, the material intensities are assumed to decrease by 10 % and 30 % at the end of the scenario period for the bulk materials and REEs, respectively. Many studies have assumed a fixed material intensity throughout their study periods, and we compare our results to such a case (Supplementary Material Table S12). Applying a fixed material intensity indeed shows, as expected, increases in the demand for both expansion and replacement. For bulk materials, the demand in 2021–2050 increases by 6 %–7 % in all three scenarios, while for REEs the increase varies between 21 % (in the DR scenario) and 26 % (in the RE scenario). The outflows show a lower increase than the inflows, given that the majority of the outflows even towards the end of the scenario period are from wind turbines installed earlier in the scenario period, during which there are less-prominent differences between the original scenarios and the scenarios without any changes in material intensity. The outflows become equal to the demand for replacement, since no technology improvement is assumed. Finally, there is a slight decrease in the ratio of outflows to inflows, indicating a reduction in the potential for secondary material supplies.

4. Discussion

Material demands, circularity potential and embodied emissions for wind power developments are explored by applying a material flow analysis based upon energy transition scenarios using Sweden as a case study. Our findings highlight the need for planning for the large-scale replacement of onshore wind turbines. For offshore wind turbines, the need for replacement is expected to predominate post-2050. Considering the total (onshore and offshore combined) growth rates for wind capacity addition, the scenario with the largest increase in wind turbine installations results in a 63 % increase in the installation rate, as compared to current installation rates.

From the material point of view, our results confirm the well-established notion that a substantial and rapidly increasing quantity of materials is present in technologies needed for the energy transition (Deetman et al., 2021; Kalt et al., 2022; van Oorschot et al., 2022). Moreover, even with the ambitious RE scenario, SvK recognizes that given the rapid development of the demand for electricity over the past years, for example with regards to the electrification of industry, it is possible that the need for electricity will be even greater than what is assumed in the SvK scenarios investigated in this work. Given that the demand for these materials extends beyond the wind infrastructure and encompasses the broader decarbonisation of the electricity sector and the reduction of carbon emissions and replacement of fossil fuels in other industries [e.g., transportation, which will require greater metal usage due to electrification (Fishman et al., 2018)], our findings underline the importance of including these materials in plans for the circular economy. Extending the boundaries of this study to include a scenario analysis of the material requirements for the electricity system transition as a whole, including other electricity generation technologies, storage and transmission technologies, could help to identify opportunities to increase self-sufficiency in terms of the material supply through circular activities.

Although our results show an increasing circularity potential at the end of the scenario period (with the inflows decreasing from 2040 or 2045 onwards, depending on the scenario, and the outflows mostly increasing from 2020 onwards across all the scenarios), the strong demand for a supply of primary materials is expected to persist throughout the transition period. During this period, it is imperative to adopt responsible mining practices (Sovacool et al., 2020; Sprecher and Kleijn, 2021; Watari et al., 2021). After this period (post-2050), however, materials from the outflows could be used instead.

Currently, the production of REEs and the manufacturing of PMs is almost fully concentrated to China. This has caused a widespread concern on the international community with policy makers outside China being encouraged to implement actions aimed at preventing a potential disruption in supply chains (Sattich et al., 2021; Smith Stegen, 2015; Troll and Arndt, 2022). Regarding EU-China relations, while in the past, the utilization of renewable energy fostered stronger cooperation between the regions, the current trend of relying more on national priorities when making policy decisions poses challenges to advancing further collaboration (Sattich et al., 2021). Given the current dependency of EU on foreign supplies, this poses a challenge for EU's REEs material resilience and by extension the possibility of meeting the climate goals under the Paris Agreement. As a response, the European Raw Materials Alliance (ERMA) finalised in 2021 an investment pipeline for supplying 20 % of Europe's REEs magnet-related needs by 2030, and developed strategies to create a circular economy for critical raw materials (Gauß et al., 2021). A recent announcement by the Swedish government shows that Sweden has the capacity to mine REEs through the so called Per Geijer deposit in Kiruna which has been stated to be the largest deposit of REEs in Europe (LKAB, 2023). LKAB, the state owned Swedish mining company, has announced that their production potential could satisfy up to 30 % of Europe's need of REEs (LKAB, 2021). Therefore, the Swedish government is positioning mining in Sweden as a potential key contributor to the EU internalization of a big share of the entire supply and production chain, supporting the ERMA's goal of a domestic REE magnet manufacturing and contributing to increased self-reliance of REEs for EU and its member states (Euractiv, 2023). At the same time, while Swedish mining is frequently portrayed as aligning well with sustainability efforts, it is also linked with negative impacts to the livelihood of indigenous Sami people and with local conflicts (De Leeuw, 2023). This emphasizes the role of circularity in just energy transition and in overcoming potential bottlenecks for enhancing domestic material supply. Given China's dominant position, it remains uncertain whether Europe will be successful in achieving a domestic value chain. Yet, the European Commission has recognized the importance of establishing resilient and sustainable supply chains and the development of European value chains in strategic industries with the aim to promote industrial autonomy.

To allow materials from the wind power outflows to be circulated back to the system, it is imperative that appropriate collection, sorting, re-use, and recycling practices are put in place. The metal recycling industry is advancing rapidly (IEA, 2021), and wind turbines have been identified as a source of neodymium with good recyclability potential in Europe (van Nielen et al., 2023). Our work shows that in the scenario with the smallest difference between the inflows and outflows, neodymium and dysprosium reach a circularity potential of about 94 %. While those are encouraging signs for the future, policies related to minimum recycling content, tradeable recycling credits, and virgin material taxes may be needed to encourage such developments (Söderholm and Ekvall, 2020). Moreover, a study on circular economy examining a metric to determine sustainable resource use found that, the amount of neodymium needed for a wind turbine in many countries including Sweden, is not justified by the electrical energy it produces (Sherwood et al., 2022) pointing to the need to advancing the development of low or rare earth-free magnets (Cui et al., 2018). Overall, implementing strategies aligned with the principles for a sustainable circular economy (Velenturf and Purnell, 2021) such as increasing the collection, recovery and recycling rates, accelerating the development of low or rare earth-free magnets, prioritizing design for recycling (Omodara et al., 2019), increasing the lifetime of wind turbines, should be an important policy priority.

As a country with ambitious climate change mitigation targets for steel and cement industries (Cementa, 2018; Jernkontoret, 2018), Sweden has the possibility to make its electricity infrastructure emissions-free in terms of embodied GHG emissions. Our study shows that implementing carbon reduction strategies in these sectors, could decrease the carbon emissions associated with wind power infrastructure from currently about 4 % of the country's total national emissions to almost negligible levels by 2045. Success in this endeavour, however, depends on the timely implementation of technologies for creating climate-neutral concrete and steel. This in turn necessitates the establishment of markets for these materials through measures such as procurement requirements and emissions reporting (Löfgren and Rootzén, 2021). Properly designed and strictly enforced procurement requirements can lower technological and market barriers by creating a demand for low-carbon products.

Further research could enhance our understanding of those aspects that remain uncertain. For example, we have limited knowledge regarding the potential to reduce the material intensity in wind turbines and regarding the market share of wind technologies with different design aspects, such as technologies that require permanent magnets or technologies that have different foundation types (for example, floating offshore wind turbines) (Carrara et al., 2020; Farina and Anctil, 2022; Kalt et al., 2022). Our analysis shows that increased material efficiencies can reduce the demand for new materials. In the case of REEs, this is the case despite the higher market shares of REEs that are assumed. While we make certain assumptions with respect to the market shares of technologies that require permanent magnets and, therefore, with respect to the use of REEs, we did not conduct a sensitivity analysis on this topic, given the vast range of possible market shares. However, further research could shed light on the extent of the impacts of material efficiency and market shares on closing the material loops.

As we move towards a just energy transition, it is important to consider where the materials in our energy infrastructure are coming from, how they are extracted and produced, and what this means for global environmental justice. This includes examining the global dimensions of material supply, notably relating to North-South relations and global inequalities (Clancy et al., 2020; Sovacool, 2021; Sovacool et al., 2021), as well as gaining experiences of material source communities (Sovacool, 2021). Furthermore, both critical and non-critical materials used in wind power infrastructure have complex and vulnerable supply chains. The most effective and equitable paths forward for material production in the energy transition need to be explored further, whether this can be through reduced reliance on such materials, reshoring of material extraction, the development of material recycling technologies and practices, extension of lifespans of technologies or more socially and environmentally responsible forms of material mining.

5. Conclusions

Using Sweden as an example, we present a material flow analysis model that assesses the material demands and secondary supply potentials of wind energy developments. We have analysed three energy transition scenarios up to 2050, covering different potential penetration levels of wind power and have examined the stocks and flows of four materials: two bulk materials (concrete and steel) and two rare earth elements (neodymium and dysprosium). In addition, we have investigated the embodied emissions associated with steel and concrete production processes.

Our findings indicate that the replacement of aging onshore wind turbines is expected to become increasingly important from 2025 onwards. Towards the end of the scenario period (2045–2050), across all the scenarios studied, replacement accounts for 75 % of the demand for new onshore capacity. Regarding offshore wind power, the potential build-up of offshore wind infrastructure, which until now has struggled to take off, is associated with higher material demands compared to the onshore wind infrastructure.

The shift towards greater wind energy penetration in Sweden, driven by its goal to achieve net-zero emissions, could face growing challenges with respect to the supply and end-of-life management of bulk and critical materials in the coming decades. Scenarios with higher wind energy capacities exhibit a substantial increase in material demand (roughly 400 % increase for concrete, 500 % increase for steel, and 700 % increase for neodymium and dysprosium in the scenario and year with the highest wind capacity), revealing a possible conflict between policies aimed at combating climate change and those promoting sustainable resource use.

Outflows of material from wind turbines that are reaching their end-of-life also experience substantial increases. Even though the outflows of materials remain lower than the inflows during the period across all the scenarios, there is a trend towards a reduction of the difference between the inflows and outflows towards the end of the period. In the scenario with the smallest difference between the inflows and outflows, the bulk materials reach a circularity potential of about 80 %, while the rare earth elements attain an even higher potential of 94 %. While in the other scenarios the circularity potential is lower, the increase in the circularity potential during the last 5 years of the scenario period across all the scenarios shows that following the transitioning period, closing the material cycle and, thereby, eliminating primary resource mining, could be possible if untapped recycling potentials are transformed into actual capacity. Therefore, establishing effective and sustainable circular strategies is important. Until that time, it is imperative to invest in demand measures and ensure responsible mining practices. Overall, while the increasing demand for materials for a low-carbon electricity system may be justifiable, it is important to investigate ways to reduce the need for primary resources and to increase the re-use of existing materials through circularity measures.

We show that if technological innovations to decarbonise the cement and steel industries are not adopted, the embodied emissions related to the wind power concrete and steel requirements could account for up to 66 % of the total (embodied and total electricity operational) emissions. Therefore, these materials warrant greater attention in terms of strategies aimed at mitigating climate change and sustainable resource use.

As demonstrated in this study, unlocking the interconnections between material and energy dynamics can provide insights into the synergies and trade-offs between energy, climate, and natural resource strategies. Such insights can guide governmental and industrial decision-making in the transition to a low-carbon and circular economy. Investigations of the energy and material dynamics, including the circularity potentials of other electricity-generating technologies, as well as the electricity storage capacity and transmission infrastructure will provide important directions for future research.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.07.012.

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