Environmental assessment and guidance for the future offshore wind energy development

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Chapter 2

Future material requirements for global sustainable offshore wind energy development

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Abstract

Offshore wind energy (OWE) is a cornerstone of future clean energy development. Yet, research into global OWE material demand has generally been limited to few materials and/or low technological resolution. In this study, we assess the primary raw material demand and secondary material supply of global OWE. It includes a wide assortment of materials, including bulk materials, rare earth elements, key metals, and other materials for manufacturing offshore wind turbines and foundations. Our OWE development scenarios consider important drivers such as growing wind turbine size, introducing new technologies, moving further to deep waters, and wind turbine lifetime extension. We show that the exploitation of OWE will require large quantities of raw materials from 2020 to 2040: 129-235 million tonnes (Mt) of steel, 8.2-14.6 Mt of iron, 3.8-25.9 Mt of concrete, 0.5-1.0 Mt of copper and 0.3-0.5 Mt of aluminium. Substantial amounts of rare earth elements will be required towards 2040, with up to 16, 13, 31 and 20 fold expansions in the current Neodymium (Nd), Dysprosium (Dy), Praseodymium (Pr) and Terbium (Tb) demand, respectively. Closed-loop recycling of end-of-life wind turbines could supply a maximum 3% and 12% of total material demand for OWE from 2020 to 2030, and 2030 to 2040, respectively. Moreover, a potential lifetime extension of wind turbines from 20 to 25 years would help to reduce material requirements by 7-10%. This study provides a basis for better understanding future OWE material requirements and, therefore, for optimizing future OWE developments in the ongoing energy transition.

Highlights

- Scenarios were developed for OWE technology development
- Bulk materials, key metals, REEs, and other materials were assessed under IEA scenarios
- The exploitation of OWE will require large quantities of raw materials
- Closed-loop recycling could supply 6-12% of material demand by secondary materials from 2030
- Technology development will increase usage of REEs but reduce key metal demand

Keywords: Offshore wind energy (OWE); wind turbine; foundation; material demand; rare earth elements (REEs); recycling; material flow analysis (MFA); circular design (CD)

2.1 Introduction

In recent years, the global share of renewable energy (RE) has risen sharply, largely driven by the need to achieve environmental and climate targets [1]. Offshore wind energy (OWE) is a compelling and rapidly maturing RE technology that is poised to make a major difference in the energy transition [2]. According to the offshore wind energy outlook of the International Energy Agency (IEA) [3], in 2019 offshore wind had a total capacity of 23 GW and accounted for 0.3% of global power generation. The IEA foresees strong growth in installed OWE capacity, with a likely doubling by 2025, and a total of 342-560 GW by 2040 [3]. This large-scale technological transition has the potential to reduce humanity's greenhouse gas emissions. However, in order to fully evaluate its viability, the physical material requirements of potential future OWE installations must be assessed in the context of technological development, including the provisioning of primary and secondary materials [4], and the waste generated by the disrupting technologies [5].

Various studies have performed material flow analyses (MFAs) of OWE. Global OWE material requirements in the context of the global energy transition have been calculated, but have ignored technological variations and evolution [6,7]. Other studies have been mainly done at state or regional levels. For instance, bulk material demand was investigated for the Danish [8], German [9], UK [10], Chinese [11], and EU [12] OWE industry. Rare earth element (REE) requirement was assessed for the Danish [8], German [9], US [13,14], and EU [12] market. Several studies have considered different component technologies, e.g. direct drive (DD) based nacelles [9], permanent magnet (PM) based nacelles [8,9,13,14], and fix-bottom based foundations [9,10].

The previous efforts are valuable in analysing future material demands of the OWE sector. For instance, studies have shown that offshore wind turbines have continuously been increasing in size [8–11]. They have also indicated that lifetime extension [8,9,11,14] and material efficiency improvements [12,14] can reduce future OWE material requirements. However, particularly at global level, these studies calculate material demand in an aggregated way that does not capture the heterogeneity of turbine component technology and associated material compositions and recycling potential. Furthermore, earlier studies often have been performed with limited material coverage, mainly focusing on bulk materials and REEs without considering other materials [6,12,13]. Assessments of the recycling and circularity potential of offshore wind turbine materials are also lacking [15].

In view of the aforementioned limitations, we performed a dynamic material flow analysis (dMFA) for OWE with the following objectives:

- To explore OWE capacity and technology development scenarios. This study showcases three technology development scenarios, which were modelled within the framework of two capacity scenarios from the IEA offshore wind outlook report [3]. The scenarios specifically include the growth of wind turbine size, the introduction of emerging technologies (e.g. new generators, new blade fibre, and floating foundations), the changes of technological market shares, lifetime extensions, and the potential secondary material recycling.
- To estimate corresponding flows of materials and stocks of bulk materials, key metals, REEs, and other materials used in future global OWE. This includes calculating the potential future raw material demand and secondary material supply until 2040.

This study applies a high-resolution dMFA framework to assess future material demand from the global OWE sector. The dMFA considers detailed technology development for various turbine components and material circularity under different global scenarios. The combination of these various aspects within the dMFA framework allows for assessing the role of circular design in reducing material demand.

2.2 Data and methods

2.2.1 Model overview

This study assessed the material demand for the nacelle, rotor, tower, and foundation (**Figure 2.1**). The nacelle consists of key electrical and mechanical components including the main shaft, control system, and generator. Seven nacelle technologies with different generator types were evaluated, i.e., squirrel cage induction generator with full converter (SCIG), doubly-fed induction generator (DFIG), electrically excited synchronous generator (EESG), permanent magnet synchronous generator gearbox based, median speed or high speed, (PMSG-GB), permanent magnet synchronous generator direct-drive (PMSG-DD), pseudo direct-drive (PDD), and superconducting direct-drive (SDD). The rotor comprises blades (mainly made of fibre and resin), a hub and a blade pitch system. Three types of blade compositions were considered, i.e., glass fibre (Glass), carbon fibre (Carbon), and biological fibre (Biological). The tower is often made of large tubular steel sections attached to an anchor component and erected on a foundation [16,17]. Steel tower technologies, including tubular steel towers, lattice towers, and combined tubular and lattice towers, and hybrid tower technologies (combined steel and concrete) were modelled. Foundation technologies modelled include five fixed-bottom foundation technologies, i.e., gravity-base (G-B), monopile (MP), suction bucket & tripod (SB&T), high-rise pile cap (HPC) and Jacket, and three floating foundation technologies, i.e., semi-submersible (S-S), Spar, and tension leg platform (TLP). Different component technologies follow varying development paths and associated materials distributed in the nacelle, rotor, tower, and foundation are built and recycled in different routes. Materials embedded in each component of the wind turbine were therefore classified into bulk materials, i.e., high-alloy steel (Fe_H), low-alloy steel (Fe_L), iron, concrete, electrics and electronics (EE), glass fibre (F_G), carbon fibre (F_C), bio fibre (F_B), resin, and polymers; key metals, i.e., Copper (Cu), Aluminium (Al), Chromium (Cr), Manganese (Mn), Zinc (Zn), Molybdenum (Mo), and Nickel (Ni); rare earth elements (REEs), i.e., Neodymium (Nd), Dysprosium (Dy), Praseodymium (Pr), Terbium (Tb), Yttrium (Y); and other materials, i.e., Boron (B), (**Figure 2.1**). The equipment for electricity transmission, e.g. cables and transformers in the power grid interface, is excluded. The OWE transmission becomes complicated when integrating into power grid due to the complexities of submarine cable layout and routing, and further additions of controllers and transformers. All combinations of technologies are assumed to be possible in the scenarios in this paper. In summary, this study addressed 23 materials embedded in 20 technologies within 4 components.

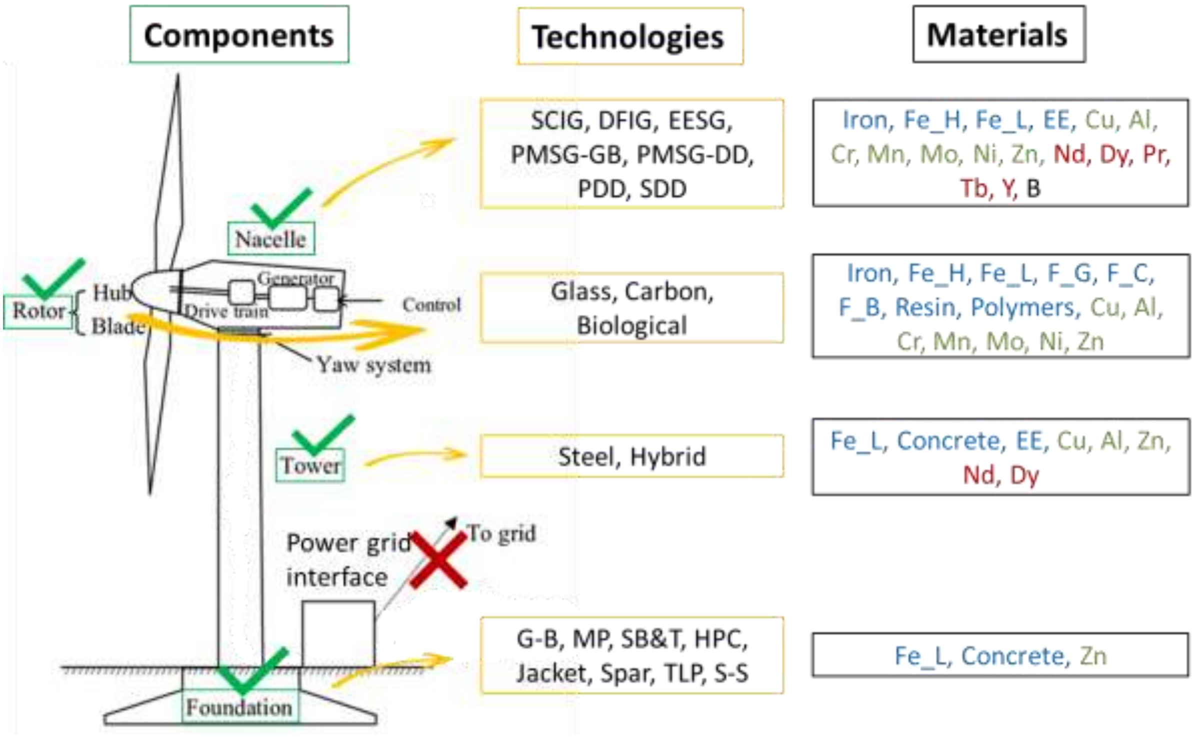

Fig 2.1: Research boundary (the turbine figure source: [18]): components (in green boxes), technologies (in yellow boxes) and materials (in black boxes). Bulk materials, key metals, REEs and other metals are marked in blue, green, red, and black, respectively.

2.2.2 Material flow model

Material flow analyses (MFAs) can be performed at different levels of aggregation. Initially, MFA was mainly used to calculate material requirements of countries as a whole [19]. Over time, MFA became more and more applied to quantify the input and output flows, and stocks of materials related to the supply of specific products or services [20]. MFA has been used, amongst others, to describe the material requirements, stock development, and expected end of life waste flows related to sustainable technology transitions, for e.g. solar power [21], onshore wind energy [22], electric vehicle batteries [23,24], and technologies for direct air capture of CO2 [25]. A three-level (i.e., capacity, technology, and material level) dynamic material flow model (dMFA) was developed to calculate material demand **(Figure 2.2).** The newly commissioned (inflow) and decommissioned (outflow) offshore wind capacities were calculated from the assumed development of in-use capacities (stock) and lifetime distribution, according to:

$$\mathrm{I}_t = \mathrm{S}_t - \mathrm{S}_{t-1} + \mathrm{O}_t \tag{1}$$

$$\mathrm{O}_t = \sum_{T=t_0}^{t-1} \times (1 - L_{t-T}) \tag{2}$$

where $\boldsymbol{I}_t$ and $\boldsymbol{O}_t$ indicate the newly commissioned and decommissioned offshore wind capacities (C), technologies (T) or materials (M) in the year of *t*, respectively; $\boldsymbol{S}_t$ and $\boldsymbol{S}_{t-1}$ indicates the stock of offshore wind capacities (C), technologies (T) or materials (M) in the year of *t* and *t-1*, respectively; t_0 refers to the time offshore wind turbine, technologies or materials starts to use*;* and $\boldsymbol{L}_{t-T}$ refers to the lifetime distribution of offshore wind turbines, which shows the probability of reaching EoL after ***t-T*** years. As most of the offshore wind turbines have yet to reach their end-of-life (EoL), historical data on actual lifetime of offshore wind turbines is not statistically significant to determine future lifetimes [26]. Current studies often assume wind turbine lifetimes follow a normal distribution with a mean of approximately 20 years [8,12,27]. Other studies, however, have suggested a Weibull distribution around a 20 year life time [9,28]. However, these distributions were based on data sets that include information about onshore wind farms, which may not represent fully translate to offshore systems. Offshore wind turbines are expected to have longer lifetimes of 25 to 30 years [29]. Therefore, this study assumed offshore wind turbine average lifetimes with a 20-year mean in 2020 that increases to a 25-year mean in 2040, and a 5-year standard deviation Normal distribution. A linear dynamic yearly increase was assumed for lifetimes from 2020 to 2040 (**Figure S2.1)**. Closed-loop recycling of EoL offshore wind turbines can limit the need for primary resource use for OWE expansion. In this paper, we assumed that materials from decommissioned offshore wind turbines ($\boldsymbol{O}_{(M)}$) would be used in new installed capacity.

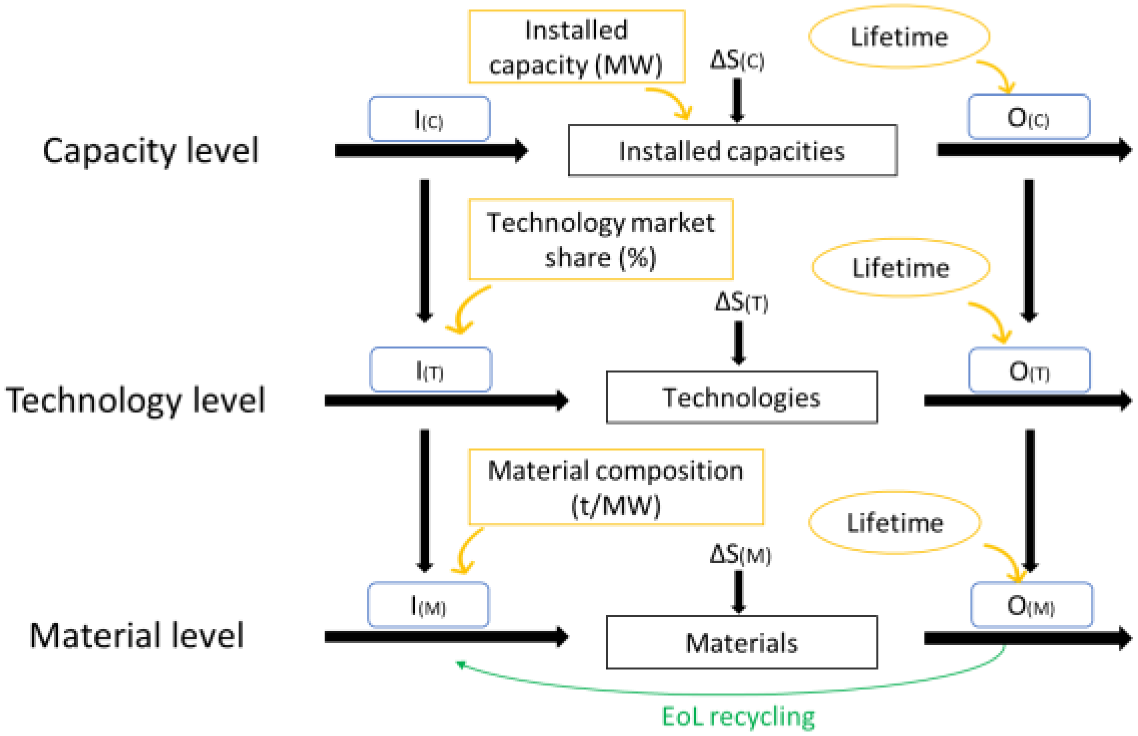

Fig 2.2: The diagram of the three-level dMFA model. I, S and O indicate the newly commissioned (Input), in-use (Stock) and decommissioned (Output), respectively. C, T and M indicate offshore wind capacities, technologies and materials, respectively.

2.2.3 Installed capacity development

In 2019, the IEA presented two OWE installed capacity scenarios [3], namely the State Policy (SP) and Sustainable Development (SD) scenarios (shown in **Figure 2.3**). Based on current and proposed policies, global offshore wind power capacity in the SP Scenario is set to increase 15-fold over the next two decades, growing at 13% per year. In the SD Scenario, offshore wind becomes the leading source of electricity globally, with a 25-fold from 2020 to 2040, rising to 560 GW by 2040 (65% more than the SP scenario). The annual new installed capacities continuously increase in the SD scenario and approximately double those of the SP scenario.

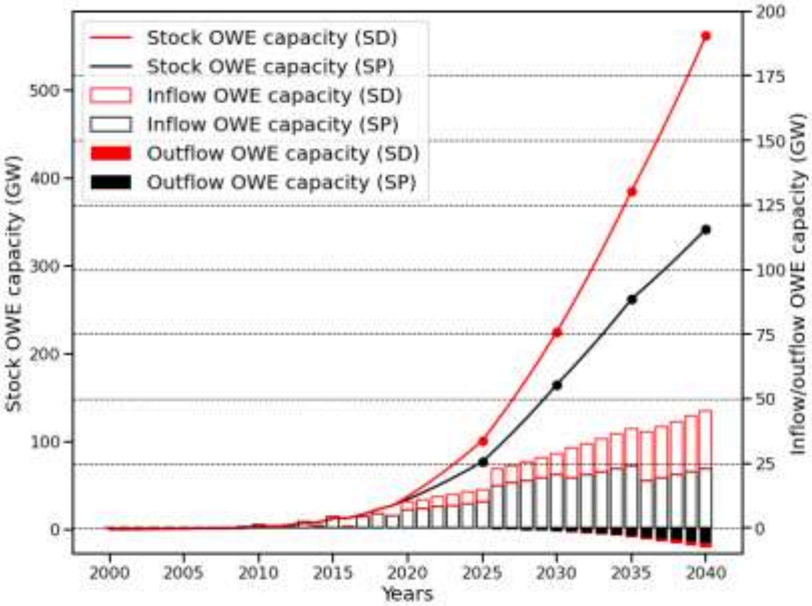

Fig 2.3: Installed capacity development. The red and black circle points indicate the stock (commissioned) capacity in 2025, 2030, 2035, and 2040, under SD and SP scenarios provided by IEA [3], respectively. The red and black lines show the stock (commissioned) capacity for other years (by using regression), under SD and SP scenarios, respectively. Positive and negative bars represent inflow (newly installed) and outflow (decommissioned) capacity (based on dMFA), respectively.

2.2.4 Technology development

2.2.4.1 Turbine size development

Technology development has promoted increasing turbine size and capacity (unit capacity), rotor diameter, and hub height. In this study, turbine size data from 165 offshore wind projects, including those fully commissioned and in the pipeline from the 4C offshore company, were selected for assessment [30]. The rotor diameter was determined from the turbine capacity based on a power law (curve fitting and extrapolation). The hub height was determined from the square of rotor diameter base on a power law, as from a geometrical standpoint, the hub height cannot be smaller than half the rotor diameter [31]. Linear regressions were used to model the future average turbine capacity, the relationship between turbine capacity and rotor diameter, and the relationship between square of rotor diameter and hub height **(Figure S2.2)**. Average turbine capacity is likely to reach 15 MW in 2040, compared with less than 2 MW in 2000 and over 6 MW in 2020, respectively. Rotor diameter is expected to increase twofold by 2040, from 150 m in 2020 to approximately 300 meters in 2040. Hub height is likely to expand from approximately 100 meters in 2020 to 150 meters in 2040.

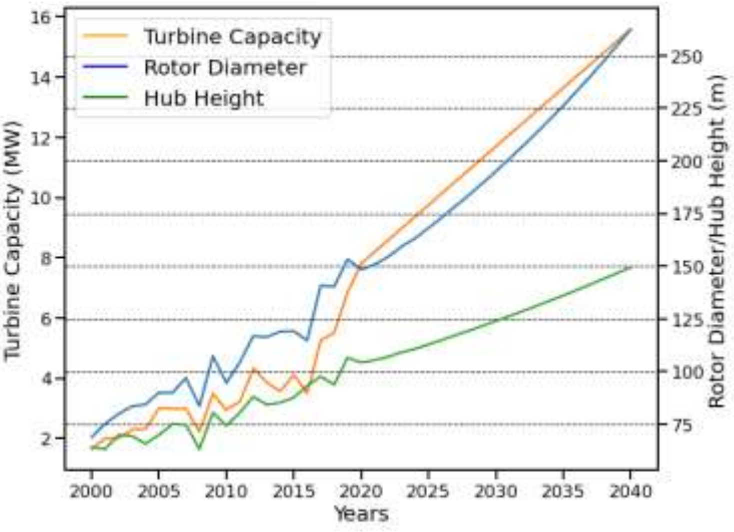

Fig 2.4: Offshore wind turbine size development. Turbine capacity development was modelled based on projects from 4C offshore [3]. Linear regressions were used to model the future average turbine capacity, the relationship between turbine capacity and rotor diameter, and the relationship between square of rotor diameter and hub height.

2.2.4.2 Development of market shares

This study considered both state-of-the-art and emerging technologies in the nacelle, rotor, tower and foundation. The current market share of these technologies was based on various sources [26,32,33]. For generator technologies in the nacelle, generators with gearbox (DFIG, SCIG and PMSG-GB) currently dominate the market, accounting for 54%, 27% and 12% of total installed capacities, respectively. Generators with DD systems (PMSG-DD and EESG) make up the rest, with 5% and 2% of total installed capacities, respectively. We developed a roadmap for technologies for each of the four main OWE components from 2020 to 2030 (section **S2.2.4.2** of the chapter 7**)**. For this period, we assumed that the offshore wind turbine manufacturers will gradually replace generators with gearbox using DD systems. Besides, PM-based generators technologies, e.g., PMSG-GB and PMSG-DD will take a higher share. Blades were assumed to be mainly made of glass fibres, followed by carbon fibres. Steel is the main material currently used for towers. For the foundation, most offshore wind farms currently use a monopile foundation, while Suction Bucket & Tripod, High-Rise Pile Cap and Jacket foundations are used less often. As of 2030, we expect that the technology development will bring in advanced and new technologies in all four components. Therefore, three technology scenarios, i.e., conventional technology (CT), advanced technology (AT) and new technology (NT), have been used to depict different roadmaps of OWE technology development as of 2030. These scenarios portray different future technology market shares in the four main OWE components. The CT assumed that the OWE technology evolution follows a conventional roadmap from 2020 to 2030; the AT assumed further development of advanced technologies (e.g., PM-based generators, carbon fibres, hybrid towers, and floating foundations); and the NT assumed a massive development of advanced technologies, as well as the introduction of new technologies (e.g., PDD and SDD generators, biological fibres and multiply types of floating foundations). **Table 2.2** and **section S2.2.4.2** of the chapter 7 present a general introduction of three technology scenarios.

2.2.5 Relative material composition

The relative material composition (RMC) (% of total technology mass) of the state-of-the-art technologies was collected from literature (shown in **Table 2.1**) and the RMC of advanced and new technologies was derived based on specific assumptions for each component.

2.2.5.1 Nacelle

The RMC of the PMSG-GB was obtained by the mean value of the PMSG-HS and PMSG-MS, and the market share of the PMSG-HS was assumed to be identical to the PMSG-MS. The PMSG-HS and PMSG-MS have a higher rotational speed, so the total weight of the generator is much smaller compared to that of EESG-DD -DD and PMSG. Nevertheless, the PMSG-DD is also smaller than EESG-DD because of less cooling requirement and the permanent magnet. The copper RMC of the PMSG-HS was used as a proxy for the PMSG-DD. In terms of other metals, the RMC of the EESG-DD was used as a proxy for the PMSG-DD [34]. The material breakdown of PDD and SDD was assumed identical to the PMSG-DD since PDD and SDD are direct-drive and contain fewer copper windings [28].

2.2.5.2 Rotor

The rotor comprises blades (consisting of a combination of fibres and polymer), a hub and a blade pitch system. Typically, the blades fraction is 60% [28,35]. Carbon fibres require less resin RMC than glass fibres [35]. Biological fibres (e.g. sisal, flax, hemp and jute) have the potential to reduce costs and environmental burden [36]. Shah and colleagues [37] further demonstrated the possibility of bamboo in wind turbine blades. However, large-scale biological fibre blades has not been deployed. Due to insufficient data, the RMC of biological fibres was assumed to be similar to that of carbon fibres. Note that the term polymer in this analysis includes thermoset and thermoplastic resins.

2.2.5.3 Tower

The RMC of hybrid towers combining concrete (~87.7%) with low alloyed steel (~11.3%) was assumed to be stable over time.

2.2.5.4 Foundation

The RMC of floating foundations was calculated based on previous data [38]. TLP was assumed 100% made of low alloyed steel. Semi-submersible and spar foundations have small proportions of concrete (~5.8% and ~7.1%) within their total weights, respectively.

2.2.6 Material requirements

2.2.6.1 Calculation of total mass

The mass of the nacelle, rotor, and tower was scaled according to the rotor diameter and hub height relation, while the mass of the foundation was determined by total wind turbine mass (sum of nacelle, rotor and tower mass) and foundation-to-turbine ratio, which was based on the turbine capacity. We applied a power scaling law following previous studies such as the Wind Power database [39] and other scientific literature [40,41]. The scaling formula is as follows:

$$M_i = a_i \times \boldsymbol{F}(C, D, H)^{b_i} \tag{3}$$

where $\boldsymbol{M_i}$ indicates the mass of technology i; $\boldsymbol{F}$ is the function of turbine capacity, rotor diameter and hub height; and a_i and b_i are the constant factor and scaling factor for technology i, respectively. This analysis applied constants and scaling factors from various references [9,42,43], and used previously established foundation-to-turbine ratio data [38,44]. More detailed information is provided in **S2.2.6.1** in chapter 7.

2.2.6.2 Calculation of material mass

Absolute material compositions (AMC) (material content per capacity unit) for individual technologies can be calculated by multiplying the RMC with technology mass (M), and then divided by turbine capacity (C), as shown below:

$$AMC_{ijt} = \frac{M_{it} \times RMC_{ijt}}{C_t} \tag{4}$$

Where $\boldsymbol{AMC}_{ijt}$ and $\boldsymbol{RMC}_j$ indicates the absolute and relative composition for material *j* and technology *i*, at time *t*, respectively.

Due to their relatively small quantities, the AMCs of REEs, Epoxy resin, fibres and Boren (B) were directly collected from literature and reports (shown in **Table 2.1**). REEs (Nd, Dy, Pr, and Tb) were mainly embedded in PM-based generator technologies, i.e., EESG, PMSG-GB, PMSG-DD, PDD, and SDD. Notably, the tower also contains a small amount of REEs, which we keep constant in time [14]. REE requirements were calculated based on the weight of PMs and the REE content of wind turbine generators. The following published breakdown information was applied in the present study: Nd accounts for about 29% of magnet weight and Dy for 4% [14]. PDD contains 1350t REEs per GW [45] and demand for SDD was assumed to be similar with EESG [14]. SDD requires extra Y for superconducting wires, with 0.3t per GW [14]. Taking into account future improvements of wind generators, AMC of REEs in generators were assumed to decrease over time. Following previous findings [45–47], a share of 25% Nd of magnet weight in 2025 and 20% in 2040 were assumed in future generators. The material reduction for other REE metals (Dy, Pr and Tb) follows the same trend of Nd. B is only found in PMSG-GB, PMSG-DD and PDD, with 1t, 6t and 12.5t per GW, respectively [14]. Due to unavailable material composition data, cumulative values were applied for polymers and Zn, and their material demand is practically identical across different turbine types. High alloyed steel is made of Cr, Mo, Mn and Ni and their compositions are distinguished by different nacelle types.

Finally, material demand was calculated by summing values obtained by multiplying material composition with the volume of newly installed OWEs by market share:

$$MD_{jt} = \sum_{i=1}^{n}(AMC_{ijt} \times MS_{it} \times I_t) \tag{5}$$

where $\boldsymbol{MD}_{jt}$ is the material demand for material *j* at year *t*; $\boldsymbol{MS}_{it}$ is the market share of technology *i* at year t; $\boldsymbol{I}_t$ is the input of OWE installation (new installation) at year *t*.

2.2.7 Recycling scenarios

Material outflows are the result of EoL OWE demolition, thus the cumulative material demand for OWE installation is expected to generate large amounts of waste when offshore wind turbines reach their end-of-life. Here, we calculated results for three recycling scenarios, namely EoL 100% recycling (EoL100), EoL optimistic recycling (EoL_O), and EoL conservative recycling (EoL_C) to show material specific recycling rates (**Table 2.3, Table S2.1)**. The EoL100 scenario assumed all materials are fully collected and recovered, making it a hypothetical scenario to estimate the upper bound of secondary material recovery. Two more realistic scenarios, i.e., EoL_O and EoL_C, were used to represent optimistic and conservative recycling capabilities, respectively. In these two scenarios, bulk materials used for foundations, such as concrete and Fe_L, were assumed to be left in situ. Therefore, recycling of concrete and Fe_L was not considered in this study. According to a status report on recycling rates of metals from International Resources Panel (IRP), the United Nations Environment Programme (UNEP)[48], at a global level only a limited number of key metals are found to be recycled at a substantial scale. 52% and 99% of Fe_H, 42% and 53% of Cu, 42% and 70% of Al, 87% and 93% of Cr, 53% and 53% of Mn, 30% and 30% of Mo, 57% and 63% of Ni, and 19% and 60% of Zn are assumed as EoL_C and EoL_O recycling rates in this study, respectively [48,49]. REEs in wind turbines can be easily dismantled and physically concentrated. However, efficient metallurgical separation and refining processes are still at the research and development stage [50]. There have no technologies been identified as mature technologies for EoL PMs recycling and the associated REEs recovery in wind turbines. Therefore, 1% recycling rates were reported in [48] were assumed in the EoL_C. In the EoL_O scenario, REEs presumably bear a higher recycling potential in next decades and were assumed to achieve 21% recycling rates [51]. There are an increasing number of studies on blade recycling methods, e.g. mechanical, thermal, and chemical methods [51].

However, they are still subject to limitations, such as degradation during recycling [52]. Composite materials (Polymer and resin) used for blades is considered unrecyclable in this paper.

Table 2.3: Three recycling scenarios with their general descriptions. The detailed recycling rates can be found in **Table S2.1**.

Scenario	**Recyclable materials**	**Unrecyclable materials**	**Description**
EoL100	All	-	All materials from outflow are 100% recycled
EoL_O	Fe_H, Cu, Al, Cr, Mn, Mo, Ni, Zn, B, REEs	Fe_L, Iron, Concrete, fibres (polymer and resin)	Key metals are recycled with high recycling rates; REEs are considered recyclable; bulk materials like Fe_L, concrete and polymer are assumed not recyclable.
EoL_C	Fe_H, Cu, Al, Cr, Mn, Mo, Ni, Zn	Fe_L, Iron, Concrete, fibres (polymer and resin), REEs	Key metals with low recycling rates are considered recycled; REEs and bulk materials like Fe_L, concrete and polymer are assumed not recyclable.

2.2.8 Sensitivity analysis

We performed a sensitivity analysis by varying four main parameters in our model: life time of wind turbines, technology market shares, material intensities, and recycling rates.

2.2.8.1 Changes of lifetime

Increasing wind turbine lifetimes will reduce material requirements. As mentioned, this study assumed a dynamic lifetime that is growing from a 20-year mean in 2020 to a 25-year mean in 2040, with a 5-year standard deviation normal distribution. To discuss the material requirements changes due to the effect of lifetime, a comparison analysis with four other alternative lifetimes was performed. Current offshore wind farms, including near-shore and experimental sites, that have been decommissioned are limited to eight wind farms (see **S2.8.1** in chapter 7). Based on these decommissioned projects, a lifetime with 11.4-year mean and 7.2 standard deviation normal distribution was obtained. Other parameter variations include: lifetimes with 20-year mean and 5-year standard deviation, 20-year mean and 7.2 standard deviation normal distribution, and a dynamic lifetime with a 20-year scale in 2020 increasing to a 25-year scale in 2040. Three Weibull distributions were further calculated for comparison purposes.

2.2.8.2 Changes of technology market shares

For simplicity, a 50% change (increase or decrease) of market shares was assumed under the SD-AT scenario for the following technologies: Nacelle: EESG, PMSG-DD, PDD, SDD; rotor: F_C; tower: Hybrid; foundation: MP and S-S. An adjustment of the market shares of the remaining technologies was made to maintain the same ratios.

2.2.8.3 Changes of material intensity

Material intensity refers to materials use per MW. In this study, we varied material intensity of technologies by 20%, both as increase and decrease, for Iron, Cu, Al, resin, Nd, Dy, Ni and Zn, under the SD-AT scenario.

2.2.8.4 Changes of recycling rates

For simplicity, a 50% increase of recycling rates was assumed for polymer, resin, and REEs (Nd, Dy, Pr, and Tb), under the SD-AT scenario and EoL_O recycling scenario.

Table 2.1: 23 Material relative and absolute compositions of the considered technologies and components. Materials marked in Italic, star, bold are bulk materials, key metals (Cr, Mn, Mo and Ni are key metals that made of high alloyed steel, and REEs; Zinc (Zn) (marked in underscore) is a key metal for coating, due to a lack of data, it was considered as a cumulative way; the unit of absolute compositions: ton/GW

	Nacelle (Generator type)							**Rotor (Blades fibre)**			**Tower**		**Foundation**							
Materials	SCIG [9,14,54]	DFIG [9,14]	EESG [9,14,54]	PMSG-GB[9,14]	PMSG-DD[9,14]	PDD [9,14,45]	SDD [5,9,14]	Glass [9,28,35]	Carbon [9,28,55]	Biological [9,28,55]	Steel [9,14]	Hybrid [9,14]	G-B [56]	MP [9]	SB&T [9]	HPC [54]	Jacket [9]	Spar [38]	TLP [38]	S-S [38]
Iron	35.6%	35.6%	52.6%	41.5%	52.6%	52.6%	52.6%	25.8%	25.8%	25.8%										
Fe_H	41.1%	36.1%	29.8%	39.3%	29.8%	29.8%	29.8%	9.4%	9.4%	9.4%										
Fe_L	12.5%	20.7%	8.9%	10.3%	8.9%	8.9%	8.9%	9.8%	9.8%	9.8%	97.1%	11.3%		100%	67.7%	40.2%	85.8%	92.9%	100%	94.2%
Concrete												87.7%	100%		32.3%	59.8%	14.2%	7.1%		5.8%
Cu*	3.2%	2.1%	7.7%	2.2%	2.2%	2.2%	2.2%	0.1%	0.1%	0.1%	0.9%									
Al*	1.0%	1.1%	0.9%	0.9%	0.9%	0.9%	0.9%	0.1%	0.1%	0.1%	1.0%									
EE	0.6%	0.3%	0.1%	0.4%	0.1%	0.1%	0.1%				1.0%	1.0%								
F_G								37.3%												
F_C									41.7%											
F_K										41.7%										
Resin								17.5%	13.7%	13.7%										
Nd			16	39	168	348.9	16				12	12								
Dy			4	4	15	31.2	10				2	2								
Pr			9	4	35	72.7	2													
Tb			1	4	7	14.5	1													
Y							0.3													
B				1	6	12.5														
Polymer								4600	4600	4600										
Cr*	470	470	525	580	525	525	470													
Mn*	780	780	790	800	790	790	780													
Mo*	99	99	109	119	109	109	99													
Ni*	430	430	340	440	240	340	430													
Zn*										5500										

Table 2.2: Three technology scenarios (i.e., CT, AT and NT) for the four main components (i.e., nacelle, rotor, tower and foundation) of OWE.

Technology scenarios	**Component**			
	Nacelle	**Rotor**	**Tower**	**Foundation**
Conventional Technology (CT)	DFIG and SCIG will still dominate the market and advanced and new types are not expected.	Both glass and carbon fibres will be used.	Only steel towers will be used	Fixed-bottom based foundations (mostly monopile) will dominate the market, as floating foundations are still being tested.
Advanced Technology (AT)	Market share of PM-based generator technologies is rising, followed by conventional generator types.	More carbon fibres will be used, followed by glass fibres.	Only steel towers will be used	Floating foundations (mainly semi-submersible) will enter the market, but fixed-bottom based foundations will dominate.
New Technology (NT)	New types PDD and SDD will come into use, but PMSG-GB and PMSG-DD still hold large market shares	Biological fibres will reduce the dominance of glass and carbon fibres.	Hybrid towers combining steel and concrete will be used	Large-scale floating foundations will be used with semi-submersible floating foundations being amongst the most widely used.

2.3 Results and discussion

2.3.1 Mass and material intensity developments

Mass intensity, that is the mass per unit of OWE capacity, will increase from 365.2 t/MW in 2020 to 559.6 t/MW in 2040 (53.2% increase) (**Figure 2.5-a**). This is mainly due to two factors. **1)** offshore wind turbines with higher capacity (larger size) will lead to a more than average increase in the weight of the foundation. Our results show that the market is expected to experience a slightly faster increase in turbine capacity than rotor diameters and hub height from 2020 to 2040 (see **Figure 2.4**) due to technological limitations, e.g. blades cannot be folded once constructed. Nevertheless, the exponential increases in mass resulting from the growing turbine sizes will proceed at an even faster pace (see **S2.6.1**). **2)** New technologies increase the mass intensity of the nacelle by up to 80% compared to conventional technologies. For instance, the market is expected to shift from nacelles with a gearbox to DD designs (nacelles without a gearbox). Since DD designs are heavier, this increases generator total mass. With regard to towers, the introduction of hybrid towers requires more concrete, which also increases the mass intensity.

The specific material intensities are also set to increase for the four largest bulk materials from 2020 to 2040, especially for low alloyed steel and concrete (**Figure 2.5-b)**. Furthermore, since PM-based generator technologies are replacing PM-free nacelles, the REE intensity will grow roughly twofold from 2030 to 2040 (**Figure 2.5-c).**

Despite of the increase of mass and material intensity, larger turbines have higher capacity factors (CFs) than smaller ones, which means larger turbines are more efficient in converting wind power into electricity [57]. Larger turbines have more chances of using DD nacelles technologies with less operation and maintenance (O&M) costs [58]). Moreover, material efficiency in the near future will likely improve as a result of advanced engineering innovations and manufacturing methods [59]. Several components of wind turbines may be made with lighter designs (e.g. lattice towers than tubular towers) and lighter materials (e.g., lighter fibres in the blades) in an attempt to reduce costs while achieving structural fatigue requirements and maintaining strength.

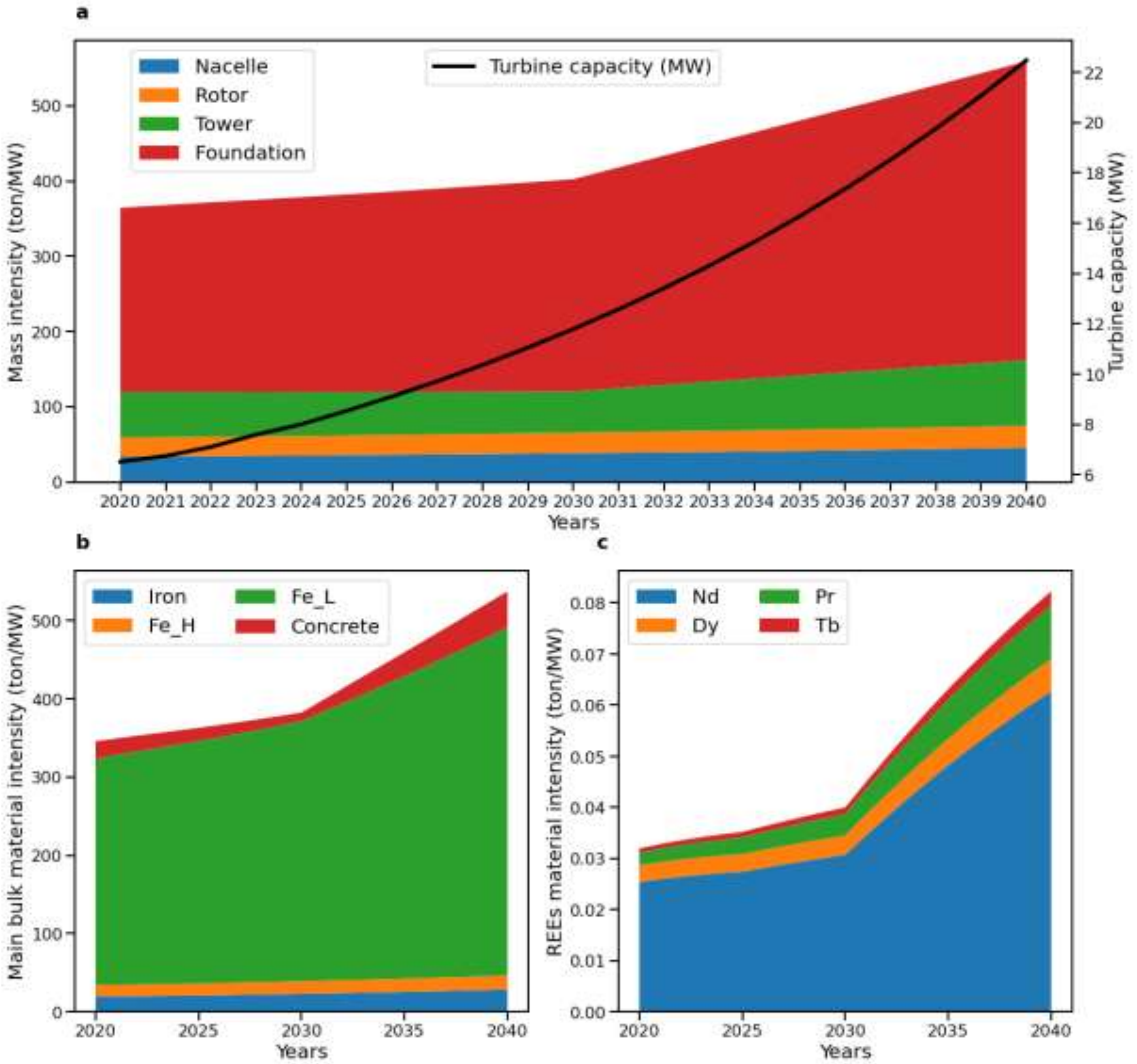

Fig 2.5: Mass and material intensity changes (based on AD scenario). **a**: Mass intensity changes for four components; **b**: Bulk materials intensity changes from 2020 to 2040; **c:** REEs intensity changes from 2020 to 2040. Mass and material intensity changes for CT and NT scenarios can be found in **Figure S2.4**.

2.3.2 Material demand

2.3.2.1 Material demand based on Sustainable Development – Advanced Technology (SD-AT) scenario

As wind turbines become larger and move farther away from shore into deeper waters, more bulk materials (mostly low alloyed steel) are required to build the support structures, i.e., the tower and the foundation. In the SD-AT scenario, the OWE sector will cumulatively require approximately 192.9 Mt of low-alloyed steel, 8.8 Mt of high-alloyed steel, 12.9 Mt of iron, and 13.4 Mt of concrete in the period between 2020 and 2040. These trends imply a 55, 49, 55 and 50-fold expansion by 2040 compared to current demands, respectively. Meanwhile, cumulative demand for key metals (Cu, Al, Cr, Mn, Mo, Ni and Zn) will grow from about 2 Mt in 2020-2030 to about 3.7 Mt in 2030-2040, reflecting an increase of about 85%. The large-scale deployment of PM based generator technologies by 2040 will cumulatively require over 25 kt of Nd, 2.8 kt of Dy, 3.8 kt of Pr and 1.1kt of Tb, which corresponds to 38%, 24%, 24% and 26% of the production volumes in 2020, respectively.

Table 2.4 shows annual material demand in 2030 and 2040, and their ratios to current demand and production. Bulk material and key metals demand will increase by two orders of magnitude from 2020 to 2030, and see an over twofold expansion from 2030 to 2040. 267.5 and 478.8 kt total demand for key metals (Cu, Al, Cr, Mn, Mo, Ni and Zn) are required in 2030 and 2040, which is less than 1% and 2% of the production volumes in 2020, respectively. The total demand for REEs (consisting of ~76% of Nd, ~9% of Dy, ~11% of Pr, and ~2% of Tb) for OWE in 2030 and 2040 will increase by two and three orders of magnitude from 2020 values, which is 3% and 11% of the REE supply in 2020, respectively. While this value is hence low compared to current REE production, strong competition for REEs may develop from other sectors with fast growing REE demand, such as e.g., EVs [60], onshore wind power [61], electronics, and industrial robots [62].

2.3.2.2 Material demand comparison

As described in section **S2.3,** the SD scenario has higher OWE installed capacities than the SP scenario. The blue and red bar in **Figure 2.6 a-d** show the cumulative material demand between 2020 and 2040 under SP and SD capacity scenarios, respectively. Approximately 95 Mt more bulk materials, 3.2 Mt more key metals and 17.0 kt more REEs are cumulatively required under the SD scenario between 2020 and 2040, compared to the SP scenario (also see **Table S2.3**).

The Cu, Al and steel demand decreases in the AT scenario and declines even further in the NT scenario when compared to the baseline CT scenario. The CT scenario assumes no permanent magnets will be used, and hence has low REE requirements. On the contrary, 8.9 and 17.7kt more REEs will be required up to 2040 for the AT and NT scenarios, respectively. This is due to the anticipated large-scale use of PM-based generators technologies in the AT scenario and further introduction of new generator types (i.e., PDD and SDD) in the NT scenario. In terms of bulk materials, the AT and NT scenarios require approximately 160% and 331% more concrete but 4% and 7% less steel than the baseline (CT). This is partially because of the growing market shares of hybrid tower concepts, as hybrid designs make use of concrete. Also, the reduction of monopile foundations (made from low-alloyed steel) in the AT and NT scenarios lead to a market share growth of other types of foundations (consisting of steel and concrete). However, there is a decreasing trend for Cu and Al demand under the AT and NT scenarios. Furthermore, the AT and NT scenarios reduce the copper demand by 7% and 9% and the aluminum demand by 2% and 6% respectively compared to the baseline (CT) scenario. This reduction stems predominantly from the elimination of traditional generators, i.e., SCIG, DFIG and EESG.

Table 2.4: Annual material demand in 2030 and 2040, and their ratios to current material demand and production under SD-AT scenario; Materials marked in Italic, star, bold are bulk materials, key metals and REEs, respectively; The percentage of material demand for OWE to total production is marginal so current production of bulk materials is not provided

Materials	**Production in 2019 (kt)**	**Annual material demand (kt)**			**Ratio to current demand (%)**		**Ratio to current production**[63] **(%)**		
		2020	2030	2040	2030	2040	2020	2030	2040
Iron	/	234.3	619.3	1436.3	264.3	613.0	/	/	/
Fe_H	/	179.3	430.5	911.7	240.1	508.5	/	/	/
Fe_L	/	3496.2	8883.8	22344.2	254.1	639.1	/	/	/
Concrete	/	265.4	289.3	2316.7	109.0	872.9	/	/	/
EE	/	8.8	17.7	49.3	201.1	560.3	/	/	/
Polymer	/	55.6	123.1	231.4	221.4	416.2	/	/	/
Resin	/	53.0	123.6	232.5	233.3	438.7	/	/	/
F_G	/	108.9	225.1	296.6	206.7	272.4	/	/	/
F_C	/	5.1	52.3	275.6	1025.1	5403.2	/	/	/
F_B	/	/	/	/	/	/	/	/	/
Nd	65.1	0.3	0.8	3.2	267.9	1027.3	0.5	1.3	7.6
Dy	11.5	0.0	0.1	0.3	252.9	797.9	0.2	0.9	4.5
Pr	15.8	0.0	0.1	0.5	384.4	1810.5	0.3	0.7	5.7
Tb	4.20	0.0	0.0	0.1	336.0	1350.9	0.0	0.8	4.9
Y	12	/	/	/	/	/	/	/	/
Cu*	20000	17.2	46.8	69.9	272.3	406.5	0.1	0.2	0.5
Al*	64000	11.9	25.5	42.8	214.7	359.3	0.0	0.0	0.1
Cr*	44000	5.9	13.5	26.5	228.6	448.7	0.0	0.0	0.1
Mn*	19000	9.5	21.1	39.9	222.2	420.0	0.0	0.1	0.2
Mo*	290	1.2	2.7	5.3	227.7	444.4	0.4	1.0	1.9
Ni*	2700	5.1	10.9	18.0	213.0	353.9	0.2	0.4	0.8
Zn*	13000	66.4	147.0	276.4	221.4	416.2	0.5	1.1	2.1
B	/	0.0	0.0	0.1	421.7	2675.9	/	/	/

2.3.2.3 Material demand distribution

Bulk materials represent the main mass demand of future OWE technologies. Altogether, about 320 Mt of material will need to be installed in the OWE sector between 2020 and 2040. These are mainly comprised of steel (~82%), followed by cast iron (~5%), concrete (~5%), fibres (~2%), resin (~1%) and other materials (~5%). The foundation requires most of the low-alloyed steel and accounts for 84%-85% cumulative requirements from 2020 to 2040, followed by the tower (13%-14%). Most of the iron and high-alloyed steel is used in the nacelle, followed by the rotor. Also most of the copper and aluminium is used in the nacelle. However, this trend is declining as a result of the predicted introduction of more advanced generator types. The requirements for REEs largely originate from the nacelle and this increases over time with rising market shares of PM-based generator technologies.

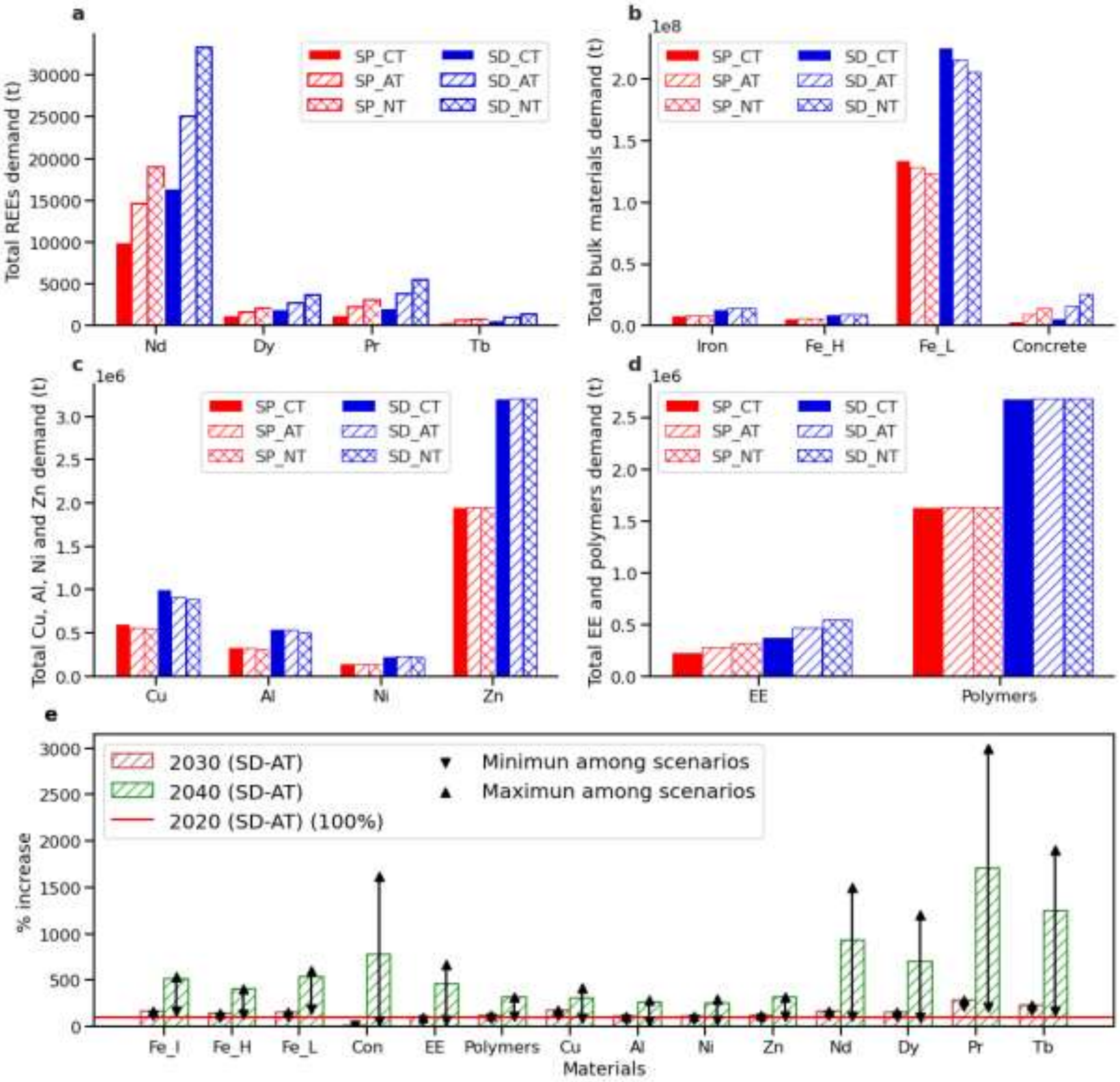

Fig 2.6: Material demand analysis. **a-d**: Cumulative material demand from 2020 to 2040 under SP and SD capacity scenarios and CT, AT and NT technology scenarios; **e**: Material demand in 2030 and 2040 in comparison to 2020.

2.3.2.4 Closed-loop second-use material demand

Closed-loop recycling can supply secondary materials and mitigate material criticality [64]. Under the EoL 100 recycling scenario, which assumes all obsolete materials from decommissioned OWE can be re-used, approximately 3% and 12% of material requirements for OWE can be obtained via closed-loop recycling between 2020 and 2030, and between 2030 and 2040, respectively. The proportion of materials suitable for new uses can increase approximately four times between 2030 and 2040 with respect to the period from 2020 to 2030 as more offshore wind turbines reach the end of their lifetime. A larger proportion of materials is expected to be supplied by second-use materials after 2040. Although the vast expansion of the OWE sector implies the inevitable use and dominance of primary materials, such secondary materials could still represent a substantial source to supply large-scale OWE development. Moreover, based on the EoL_C and EoL_O recycling scenarios, lower material quantities can be recycled when offshore wind turbines reach their end-of-life. In the EoL_O, 3%-10% of Fe_H, 2%-6% of Cu, 2%-8% of Al, 2%-7% of Ni, 2%-7% of Zn, 1%-2% of Nd, Dy, Pr and Tb can be supplied by secondary materials between 2020 and 2030, and between 2030 and 2040, respectively. In the EoL_C, only a few key metals are recycled and almost all REEs are supplied by primary sources.

Wind turbines are on average 85% recyclable according to the Vestas Sustainability Report [17]. In theory, 100% of the materials from OWE can be collected and recovered. However, there is currently a lack of well-defined circular design (CD) approaches that helps to maximize the potential for recycling and re-use [65]. Iron and key metals can eventually be recycled or even reused as spare components with low losses [26]. Foundations however in most cases are left on site and the Fe_L and concrete used in them are not disposed of elsewhere [64].

REEs are of high economic importance with high recycling potential [66]. However, few projects have reached desirable scales of REEs recycling due to technical challenges [67]. Overall, less than 1% recycling rates have been reported [49] in the literature. Nevertheless, the industry has strengthened the interest in recovering REEs from OWE facilities and 21% recycling rates are expected [51]. Greater PM sizes and thus material contents, would facilitate the recovery of such magnets and their REEs at the product's end-of-life stage. REE outflows from decommissioned wind turbines will remain small when compared to the rapidly growing global REE demand.

Wind turbine rotors (mainly blades) consist of composite materials that are challenging to recycle due to their material compositions [67,68]. The majority of the fibre composite materials are currently landfilled as they are difficult isolate and recover. Although research is ongoing on fibre composite recycling, the use of recycled fibre composites in structural applications is still limited and usually consists of downcycling into other applications [52]. For instance, current recycling techniques, including mechanical, thermal, and chemical methods have various limitations, for instance the reduction of material quality, high energy consumption, and long cycle times [52]. Future studies should look to improve the recyclability of turbine rotors, with the goal of increasing the recycling rates of EoL composite materials.

There are many recycling chains from product to recycled materials for the OWE sector. These recycling chains may create a complex system and several procedures need to be understood by system actors and policymakers. Four are outlined here: **1)** The economic value of recycled materials. Understanding this is critical for collection activities, incentives for disposal and, eventual recycling or reuse; **2)** A better understanding of the physical separation and linked metallurgical processing; **3)** The identification of the concurrent materials requirements and manufacturing process selection; **4)** The design and optimization tools and techniques used to incorporate the decommissioning processes and manufacturing solutions. This is needed to expand the use of recycled materials.

2.3.3 Sensitivity analysis results

2.3.3.1 Changes in lifetime

Cumulative material demand from 2020 to 2040 under various assumptions with regard to lifetimes and life time distributions are shown in **Table S2.3.** Material demand decreases significantly when lifetime expands from 20 years to 25 years. Cumulative Iron, steel, concrete, Cu, Al and REEs requirements declined by approximately 7%, 7%, 8%, 6%, 6% and 7%, respectively, under the SD-AT scenario. For a normal distribution, increasing lifetime mean significantly decreases material requirements. A concomitant increase in lifetime standard deviation slightly diminishes the scale-down of the material demand. The comparison between two dynamic lifetime assumptions shows that there is no significant difference between a normal distribution and a Weibull distribution. It is noteworthy that most wind turbines will not have reached their lifetimes in the horizon year 2040 even with an unrealistically low 11.4-year average lifetime (average lifetime based on decommissioned projects). More materials are expected to be saved with a 25-year lifetime than a 20-year lifetime towards 2050 and beyond.

2.3.3.2 Changes in technology market shares

Table S2.4 illustrates these results of the sensitivity analysis of technology market share changes. The market exhibits a significant potential to further increase PM-based generator technologies in the next two decades. With market shares of other (non-drivetrain) technologies unchanged, an increasing market share of the PMSG-DD, PDD and SDD generator technology by 50% would bring in approximately 2, 3, and 4-fold expansions of cumulative Nd demand, respectively. On the contrary, ~161% of Nd would be saved if PMSG-DD loses 50% of its market share. As offshore wind farms keep on being deployed farther offshore towards deeper waters, floating foundation technologies are expected to grow significantly. The increasing market share of semi-submersible floating foundations by 50% would increase cumulative low-alloyed steel demand by ~39%; while the decreasing market share of the monopile fixed-bottom based foundation by 50% would also decrease cumulative low-alloyed steel demand by ~42%.

2.3.3.3 Changes in material intensity

In parallel to the growth in OWE mass intensity, materials intensity is projected to increase. **Table S2.4** shows the sensitivity analysis of material intensity changes. Overall, OWE material intensity is expected to increase in time. In the event that the iron, copper, aluminum, nickel and zinc intensity increases by 20%, there would be an approximately 11%, 13%, 13%, 13% and 13% reduction of cumulative material demand, respectively. The same trend can be found for REEs. Approximately 9% and 10% reduction of Nd and Dy requirements are followed by a 20% material intensity increase. The market is expected to have more PM-based nacelle technologies in the next two decades according to the AT and NT scenarios and the REEs intensity is expected to grow for the OWE sector. However, foreseeable technologies aiming to reduce REEs in PMs and improve REE efficiency are currently under development. Specific amounts of REEs necessary to produce PM-based nacelle technologies of similar strength could decrease in the near future. Nonetheless, cumulative material demand can dramatically increase if material intensity decreases by 20%. The material reduction is almost threefold when compared to a material intensity increase of 20%.

2.3.3.4 Changes in recycling rates

Table S2.4 shows the results of the sensitivity analysis of recycling rate changes. REEs and composite materials (polymer and resin) are currently difficult to recycle leading to the low recycling rates assumed in this paper. In the event that Nd, Dy, Pr, and Tb recycling rate increases by 50%, there would be an approximately 7%, 6%, 8%, and 7% reduction of cumulative material demand, respectively. Approximately 4% reduction of polymer and resin requirements can be achieved with a 50% recycling rate increase.

2.4 Conclusions

This study showcases an in-depth analysis on global material demand for the OWE sector by considering detailed technology development and material circularity under different scenarios. Bulk materials, rare earth elements (REEs), key metals, and other materials for manufacturing offshore wind turbines nacelles, rotors, towers and foundations were considered. OWE development scenarios were proposed to discuss important drivers such as growing wind turbine size, introducing new technologies, moving further to deep waters, and wind turbine lifetime extension. We found that:

- The trend of installing larger offshore wind turbines will lead to higher material requirements per MW than in the past
- The anticipated development of the OWE sector will require substantial amounts of bulk materials, key metals, and REEs. The large deployment of OWE has low resilience to supply bottlenecks for key metals and may trigger REEs supply problems
- Closed-loop secondary material supply can attenuate the high material demand only to a minor degree due to the expected fast growth of the OWE sector. Larger proportion of materials is expected to be supplied by second-use materials as more turbines reach their lifetime after 2040
- Extending lifetimes and technology developments can help reduce the material demand of future OWE deployments

So, to reduce material demand, OWE innovations should focus on extending the lifetime of turbines, improvement of material efficiency, as well as the enhancement and introduction of new technologies in the four key components of OWE turbines studied here. Although EoL recycling can only replace a relatively small fraction of primary materials due to the fast development of newly projected OWE capacities, the development of a EoL recycling is still important to enable a circular OWE system in the future. Application of the circular strategies based on material EoL recycling is expected to improve the availability of recycled materials and to better fit the increasing decommissioned material volumes. Cross-sectoral collaboration (open loop recycling and cross-sectoral recycling) should be performed to have incentive policies that ensure the solid integration of material supply chain and the profits of other stakeholders. Furthermore, in order to keep the pace or even accelerate the clean energy transition, the findings of the present study can help to identify green opportunities in the supply chains of the OWE sector and could facilitate the optimization of the portfolio of wind power technology development.

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