Environmental assessment and guidance for the future offshore wind energy development

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Chapter 1

General introduction

1.1 Background

Global warming has a grip on the planet. Energy use is currently at the heart of climate challenge and alternatives are key to the solutions. Energy-related greenhouse gas (GHG) emissions form the main contributor to the global warming problem [1] and continued to grow. In 2022, the growth was 321 Mt (+0.9%), leading to a new high of over 36.8 Gt CO2-eq as global GHG emission total [1]. Despite the rapid diffusion of renewable energy systems, fossil fuels, such as coal, oil and gas, are still the backbone of the energy system and contribute to two third of today's global electricity generation [2]. This accounts for over 75 percent of global GHG emissions [3]. Driven by the environme ntal and climate targets that 90-95% of net emissions are needed to be reduced by 2040 [4], it becomes ever more crucial to accelerate the energy transition.

Renewable energy sources, such as wind, solar, geothermal, biomass, and hydro, can make important contributions to a global strategy to phase out fossil fuels for reducing GHG emissions. According to the International Renewable Energy Agency [5], 90 percent of the world's electricity can and should be produced from renewable energy by 2050. Wind energy continues to be the main renewable technology, generating 1870 TWh of electricity in 2021, almost as much as all other non-hydro renewable energy sources combined [6]. Offshore wind energy (OWE) involves the utilization of wind turbines specifically designed and installed in the marine environments to harness the energy from the force of the wind and convert it into electricity. While OWE has so far less installed capacities than onshore wind energy installations, it has significant potential advantages in comparison to onshore wind energy because of the higher turbine size, enormous deployment potential, use of areas with consistently strong winds, and lower problems in terms of spatial planning and interference with humans. According to Global Wind Energy Council [7], OWE has the biggest growth potential among any of the renewable energy sources. Unlocking the full global potential could even meet the world's total electricity demand in 2040 11 times over [2]. This could make a major difference in the energy transition. Over the past few decades, the levelized cost of energy of OWE has continuously declined. The OWE industry has been rapidly expanding and maturing that is poised to become one of the most important custodians of the world's coastal waters. The global installed capacities are projected to increase 15-24 fold from 23 GW in 2018 to 342-562 GW by 2040 [2]. Such large-scale developments will green the electricity system and are crucial to tackle the climate problem.

1.2 Sustainability challenges and opportunities of offshore wind energy development

1.2.1 Offshore wind energy development

Since the commissioning of the first offshore wind farm (OWFs) in Denmark in 1991, OWE sector has been experiencing continuous technological innovation. Recent developments with regard to OWE include the significant upscaling of both capacities per turbine and wind farms [8]. The average nominal capacity of commercial turbines increased from approximately 3 MW in 2010 to 6 MW in 2020, and the OWE industry is targeting 15-20 MW turbines in 2030 [2]. Turbine size, including rotor diameter and hub height, went through an exponential growth [9]. The OWE turbines and other components are foreseen to have enlarged operational lifetimes. Several component technology innovations are being developed. For example, permanent magnet based and direct drive generator technology allows wind turbines to operate at lower speeds with lower failure rates [10]. Development of advanced technologies, like superconducting generators [11], new fibre technologies [12] in blades, and hybrid tower concepts [13], will enable turbines to have higher efficiencies and thus have higher energy yields. Furthermore, innovations such as spar and tension leg platform floating foundations [14] allow more turbines moving further from shore in deep waters to harvest better wind resources. This will massively unlock new OWE development possibilities. This movement necessitates next to the advancement of floating foundation technologies, also the development of more sophisticated logistical vessels for installation, operation, and maintenance purposes. Overall, these factors affect the OWE-relevant environmental impacts and bring in sustainability challenges and opportunities.

1.2.2 Offshore wind energy associated environmental footprint

Large-scale OWE development has the potential to reduce humanity's GHG emissions drastically. However, realizing these large-scale OWE developments will require substantial quantities of materials and will be associated with climate, biodiversity, and other impacts on the environment. Primary and secondary materials will be required for manufacturing offshore wind turbines, foundations and transmission components [15]. In the end of life stage, the waste generated by OWE infrastructure will pose a challenge in terms of re-use, recycling and treatment [16]. The large-scale OWE deployment will also lead to environmental impacts associated with supply chains during the manufacturing, installation, operation and maintenance, and decommissioning and end-of-life (EoL) recycling of wind turbines, foundations, and transmission equipment. Furthermore, the OWF operation can be associated with negative or positive impacts on marine ecosystems. For example, offshore wind turbines can cause seabird and bat collisions [17]. OWF operation causes noise and vibration that may affect fish and marine mammal communication and navigation [18]. Submarine cables generate electromagnetic fields that may disturb foraging, orientation, and migration of fish species [19]. Submarine cables and mooring cables may also increase the risk of entanglement [20]. On the other hand, OWE foundations and scour protections will form artificial reefs that attract species for food or refuge. The long-term cumulative impacts of these changes on marine biodiversity remain largely unexplored. Overall, the above-mentioned OWE-related environmental concerns require further a spatial analysis, since different marine areas may have different geographical site characteristics, such as wind speed, water depth, and distance from shore. Those geographical factors affect the OWE site development and associated mitigation strategies of environmental impacts.

1.3 Research gaps

Given the expected development of the OWE sectors and the potential environmental concerns highlighted above, there are several important gaps in knowledge.

- Research into global OWE material demand has generally been limited to few materials and has been based on a low technological resolution. Literature in general calculates material demand in an aggregated way that does not capture the heterogeneity of turbine component technology and associated material compositions and recycling potential. Moreover, previous studies have been conducted with limited material coverage, primarily concentrating on bulk materials and rare earth elements (REEs) while neglecting other essential materials [21, 22]. Furthermore, there is a lack of assessments regarding the recycling and circularity potential of materials used in offshore wind turbines [23].

- Although life cycle assessment (LCA) has been commonly used to assess the cradle-to-the-grave environmental impacts of OWE projects, important limitations in insight remain. There is a high level of uncertainty in such impacts per MWh electricity generation given changes in the turbine size, lifetime, the increasing distance from shore, as well as due to recent changes and developments in component technologies [24]. Further, previous studies have not adequately addressed potentially significant life cycle phases, such as installation, maintenance, and end-of-life (EoL) recycling. As indicated, there is a rapid expansion of OWE installed capacity at a global scale. At this moment there is insufficient insight into the cumulative life cycle impacts of supply chains, and biodiversity impacts at locations where large OWE farms are build, also in view of the above-mentioned future technological developments.

- Biodiversity change by the OWE development was theoretically analyzed in several previous studies [25, 26] but quantitative assessments (and monitoring) of the actual impact of OWE development on marine life were limited to short periods of time in only a few sites. Given the potential long-term cumulative impacts of large-scale projected OWFs on marine biodiversity, an important limitation is that life cycle impact assessment (LCIA) methods to assess effects on marine biodiversity are still at an early stage of development, much less mature than LCIA methods for terrestrial and freshwater biodiversity [27]. Characterization factors (CFs) used for LCIA that consider multiple relevant impacts related to OWFs in a consistent manner, including also positive impacts (e.g., artificial reef effect) and potential indirect impacts (e.g. trawling avoidance), are still missing.

- OWE spatial planning is often based on criteria such as economic, technical and social viability [28], leading to a constrained scope that primarily targets at a few specific regions. For OWE, there are hardly assessments that include in an integrated manner the potential spatial tradeoffs between e.g. material demand, impacts on the environment (e.g. in terms of life cycle GHG emissions of OWE operations and biodiversity), next to low-carbon energy generation potential. Further, site-specific/geographical factors, such as water depth, wind speed, and distance from shore, exert a notable influence on such environmental impacts. But there are limited studies how expected technical development of OWE may reduce such impacts. Overall, insights lack how OWE spatial planning in relation to expected future technical developments may reduce the OWE-related footprints.

1.4 Research questions and relevant methods

This thesis uses dynamic material flow (dMFA) analysis, prospective LCA, LCIA on biodiversity, and marine spatial analysis to address the above-mentioned research gaps. The main research question (RQ) and relevant sub-research questions are articulated as follows:

The main RQ is: **what are the environmental impacts of the offshore wind energy development?**

In view of the research gaps identified above, to answer the main RQ this thesis addresses the following sub-research questions:

RQ1: What is the future material demand for global OWE development?

RQ2: What are the cradle-to-the-grave environmental impacts of global OWE development?

RQ3: What are the impacts of OWE development on marine biodiversity?

RQ4: How can the environmental footprint of OWE development be reduced by optimal spatial planning in combination with technical innovation, illustrated by the case of the North Sea?

To answer the research questions, this thesis uses the following methods.

- **Dynamic material flow analysis (dMFA):** dMFA is a well-known method to quantify the input and output flows, and stocks of materials related to the supply of specific products or services [29]. dMFA, among other methodologies, has been applied to characterize various aspects of sustainable energy infrastructure development. For example, it has been utilized to describe annual material requirements, stock evolution, and projected annual EoL waste flows associated with the establishment of solar power [30], onshore wind energy [31], electric vehicle batteries [32], and technologies for direct air capture of CO_2 [33]. It is hence a proven research method to address RQ1. dMFA can be combined with scenario analysis to estimate corresponding flows of materials and stocks of bulk materials, key metals, REEs, and other materials used in future OWE development.

- **Prospective life cycle assessment (LCA):** LCA is an approach to assess the environmental impacts of a product or service throughout its life cycle [34]. To evaluate the future environmental impacts, prospective LCA has been developed by considering the future performance of foreground (e.g. how to extrapolate the life cycle inventory from current to future situation) and background systems (e.g. how to model the electricity mix change in the future) [35]. The prospective LCA model can be further dynamic (time-dependent) at the level of inventory analysis or impact assessment [36]. Combining prospective LCA with a time perspective allows comprehensively quantifying current and future environmental impacts of OWE development. This method is very well suited to determine the cradle-to-the-grave impacts of a functional unit (e.g. MWh electricity output) of an individual wind turbine under different current and future foreground and background technology scenarios. In combination with projection of the future OWE installed capacity (see RQ1), this gives insight into the cradle-to-the-grave impacts for future global OWE development (RQ2).

- **Life cycle impact assessment (LCIA) on marine biodiversity:** LCIA characterization factors (CFs) that quantify impacts on biodiversity have been developed mainly based on the potential disappeared or affected fraction of species [37]. For OWE, one method considers the alteration in seabed type and the duration of this change [38]. Additionally, another LCIA method allows for the evaluation of the effects of noise pollution on cetaceans [39]. Both are relevant to OWE development, but they are based on different taxa and different reference states. They also do not comprehensively cover all types of biodiversity impacts that may be related to OWE development. Developing a LCIA method enables to better understand marine biodiversity change caused by OWE interventions, including seabed occupation, artificial reefs, and trawling avoidance. Such a LCIA method related to impacts on marine biodiversity in combination with scenarios for OWE deployment can answer RQ3.

- **Integrating GIS, dMFA and and prospective LCA for spatially optimized OWE siting:** We translate the characteristics of specific geographic sites into information that can be utilised to understand the life cycle environmental impacts of developments, such as e.g. OWE, in that area by combining dMFA and prospective LCA and location characteristics in a spatially explicit way [40]. This approach allows for an integrated, and spatial assessment for an area like the North Sea how an optimal siting of OWE turbines can be realised in view of their material requirements and life cycle impacts on climate change, biodiversity, etc., considering factors like wind resources, water depth, and distance from shore, and technological development, including turbine size, lifetime enlargement, and component technology advancement (RQ4).

1.5 Guide to this thesis

This thesis consists of 6 chapters (**Figure 1.1**). The **chapter 1** describes the background, research questions, relevant methods, and the structure of the thesis.

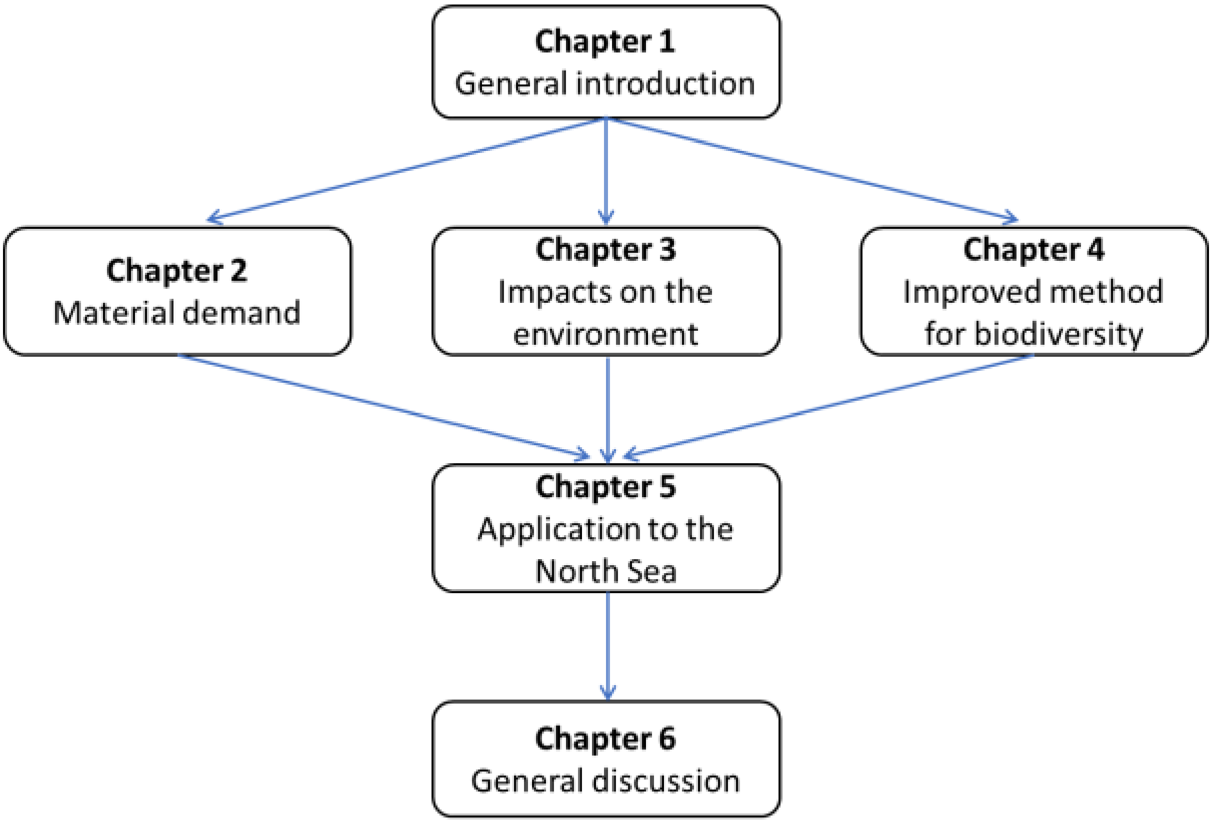

Figure 1.1: Outline of the thesis.

Chapter 2 addresses the RQ1. We assess the primary raw material demand and secondary material supply for the global development of OWE. Our analysis encompasses a broad range of materials, including bulk materials, rare earth elements, key metals, and other materials that are crucial for manufacturing offshore wind turbines and foundations. We account for potential OWE technology advancements, such as increasing wind turbine size, implementing new technologies, expanding farther from shore into deeper waters, and extending the operational lifetime of wind turbines. Sensitivity analyses with regard to lifetime, technology market shares, material intensity, and recycling rates are conducted.

Chapter 3 addresses the RQ2. We undertake a prospective LCA to comprehensively quantify current and future environmental impacts of OWE development on a global scale. To do so, we build dynamic parameterized life cycle inventories by incorporating high technology resolution supply chains, particularly emphasizing on installation, operation and maintenance, decommissioning, and EoL recycling. These LCIs are tailored to account for specific factors that evolve over time, such as the expansion of turbine size, the transition to more distant offshore locations, advancements in technology, and developments in EoL recycling practices. Further, we use futurized background LCI data for e.g. energy production that aligns with underlying technological trends and advancements in the OWE sector. The chapter presents a sensitivity analysis of results, and discusses limitations and an outlook.

Chapter 4 addresses the RQ3. It integrates the long-term cumulative impacts of OWE interventions, i.e. artificial reefs, seabed occupation and trawling avoidance, on marine biodiversity into CFs for LCIA, thereby capturing the broader environmental consequences of OWE development. We assess changes in benthic biodiversity on both hard substrates and soft sediment across various effect distances and then quantified and translated into characterization factors. The benthic biodiversity changes on hard substrates and soft sediment in different effect distances are estimated and translated into CFs. We analyze marine biodiversity gains and losses during offshore wind farm operation based on the results, using OWFs in the North Sea as a case. The interpretation of the developed method, effect of geography and range, interventions in other life cycle stages and technologies are discussed.

Chapter 5 addresses RQ4. We assess for each siting location of wind turbines in the North Sea, the potential environmental footprints per MWh electricity produced including material demand, embodied GHG emissions and several other life cycle impact categories across the full turbine life cycle, including EoL. We also assess the impacts on biodiversity by screening the potential overlap of OWE installations with protected areas. We analyse these footprints both for the current (2020) and future (2040) OWE technology, which is expected to have larger including turbine size and lifetime, and improved component technology. The assessment considers multiple geographical factors, including wind speed, water depth, distance from shore. We detect not only the major hotspots in environmental impacts for North Sea OWE, but also the least-impactful locations for the wind farms.

Chapter 6 presents a synthesis of the answers to the research questions, followed by a general discussion and recommendations for future research.

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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.

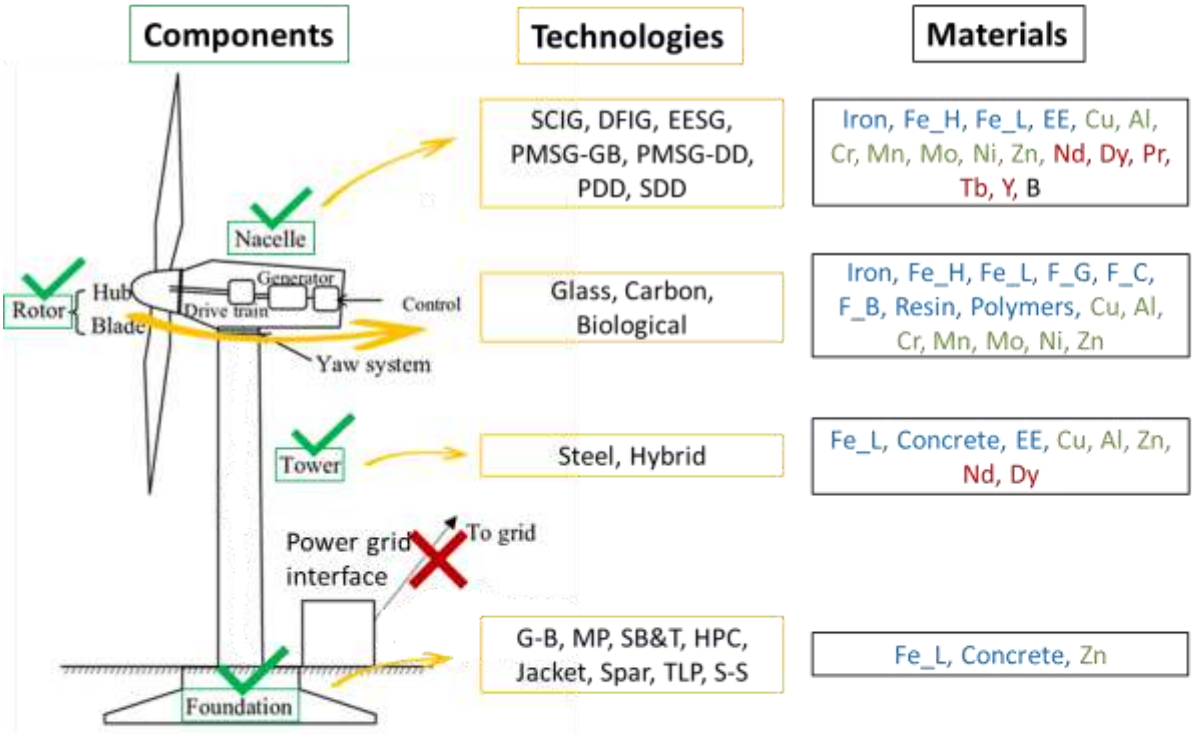

Fig 2.1: Research boundary (the turbine figure source: [18]): components (in green boxes), technologies (in yellow boxes) and materials (in black boxes). Bulk materials, key metals, REEs and other metals are marked in blue, green, red, and black, respectively.

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:

$$\mathrm{I}_t = \mathrm{S}_t - \mathrm{S}_{t-1} + \mathrm{O}_t \quad (1)$$

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

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.

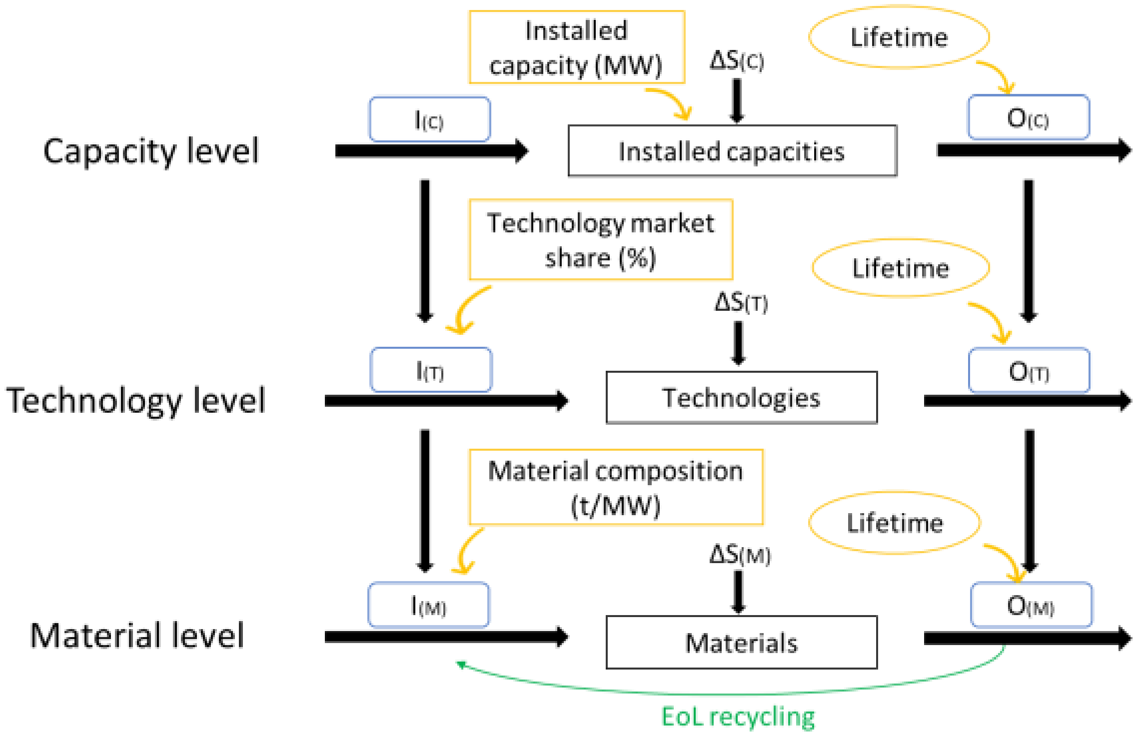

Fig 2.2: The diagram of the three-level dMFA model. I, S and O indicate the newly commissioned (Input), in-use (Stock) and decommissioned (Output), respectively. C, T and M indicate offshore wind capacities, technologies and materials, respectively.

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.

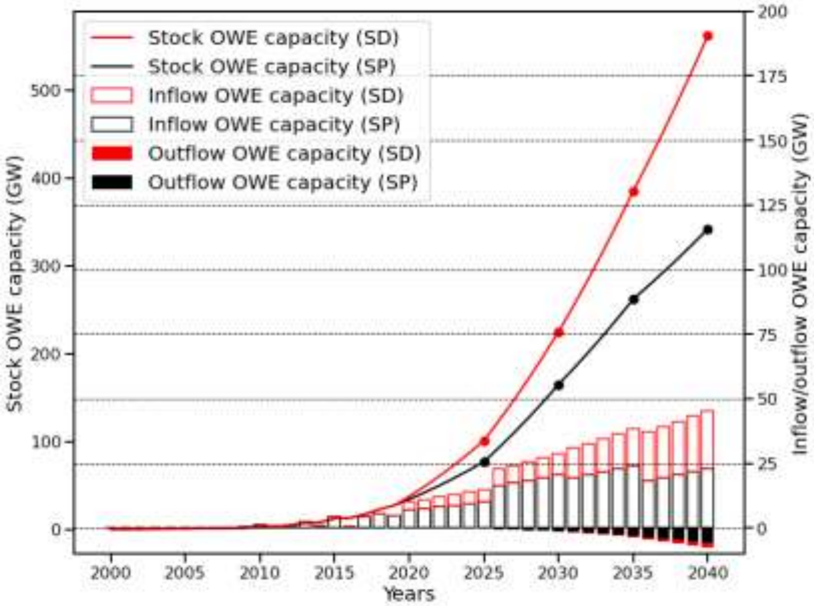

Fig 2.3: Installed capacity development. The red and black circle points indicate the stock (commissioned) capacity in 2025, 2030, 2035, and 2040, under SD and SP scenarios provided by IEA [3], respectively. The red and black lines show the stock (commissioned) capacity for other years (by using regression), 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.

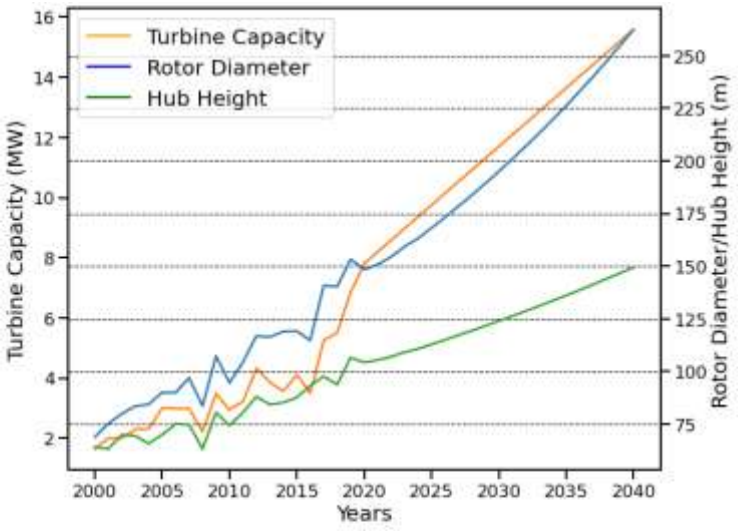

Fig 2.4: Offshore wind turbine size development. Turbine capacity development was modelled based on projects from 4C offshore [3]. Linear regressions were used to model the future average turbine capacity, the relationship between turbine capacity and rotor diameter, and the relationship between square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

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

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:

$$AMC_{ijt} = \frac{M_{it} \times RMC_{ijt}}{C_t} \qquad (4)$$

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:

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

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 [9,14,5 4]	PMSG - GB[9, 14]	PMSG - DD[9, 14]	PDD [9,14,4 5]	SDD [5,9,14]	Glass [9,28,3 5]	Carbon [9,28,5 5]	Biolog ical [9,28, 55]	Steel [9,14]	Hybri d [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.

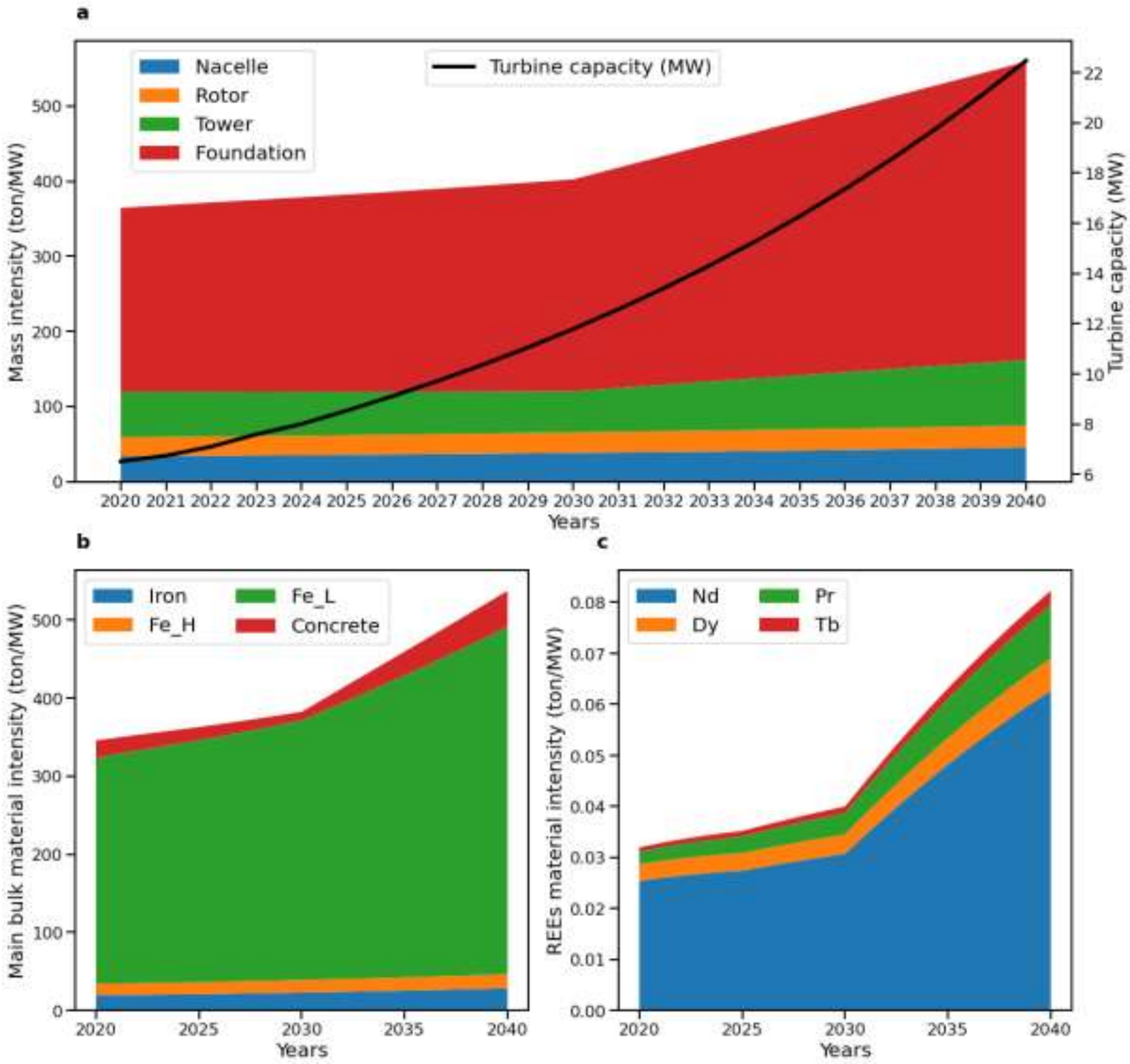

Fig 2.5: Mass and material intensity changes (based on AD scenario). **a**: Mass intensity changes for four components; **b**: Bulk materials intensity changes from 2020 to 2040; **c:** REEs intensity changes from 2020 to 2040. Mass and material intensity changes for CT and NT scenarios can be found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

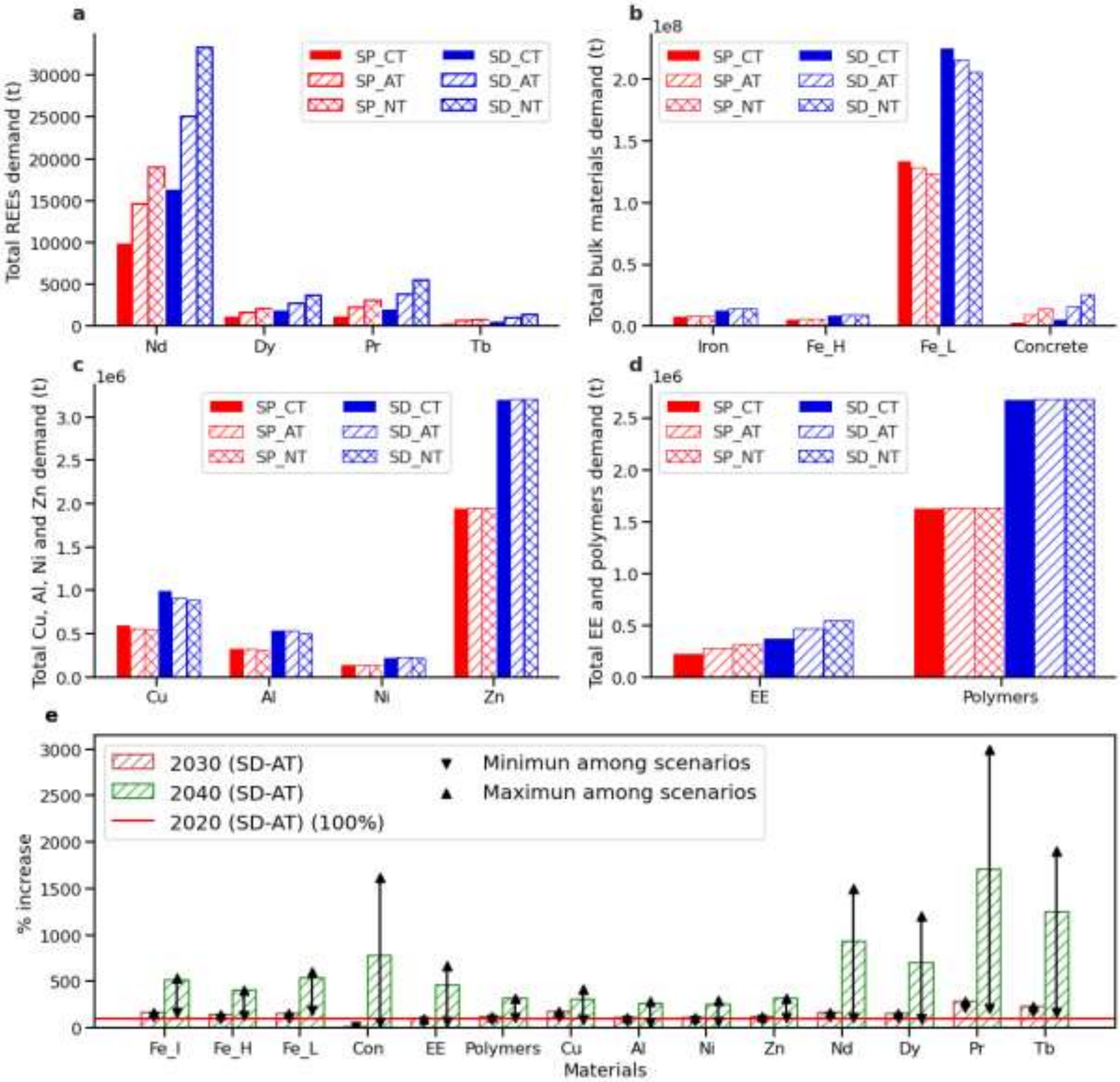

Fig 2.6: Material demand analysis. **a-d**: Cumulative material demand from 2020 to 2040 under SP and SD capacity scenarios and CT, AT and NT technology scenarios; **e**: Material demand in 2030 and 2040 in comparison to 2020.

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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Chapter 3

Environmental impacts of global offshore wind energy development until 2040

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Abstract

The continuing reduction in levelized cost of energy is driving the rapid development of offshore wind energy (OWE). It is thus important to evaluate, from an environmental perspective, the implications of expanding OWE capacity on a global scale. Nevertheless, this assessment must take into account various scenarios for the growth of different OWE technologies in the near future. To evaluate the environmental impacts of future OWE development, this paper conducts a prospective life cycle assessment (LCA) including parameterized supply chains with high technology resolution. Results show that OWE related environmental impacts, including climate change, marine ecotoxicity, marine eutrophication, and metal depletion, are reduced by ~20% per MWh from 2020 to 2040 due to various development including size expanding, lifetime extension, and technology innovation. At the global scale, 2.6-3.6 Gt CO2-eq of greenhouse gas emissions are emitted cumulatively due to OWE deployment from 2020 to 2040. The manufacturing of primary raw materials, such as steel and fibers, is the dominant contributor to impacts. 6-9% of the cumulative OWE related environmental impacts could be reduced by end of life (EoL) recycling and the substitution of raw materials.

Synopsis: OWE development will reduce electricity related environmental impacts, and EoL recycling would alleviate raw material requirements and further reduce those impacts.

Key words: Offshore wind energy; electricity production; prospective life cycle assessment; circularity; scenario analysis

3.1 Introduction

The installed capacity of global offshore wind energy (OWE) has increased by ~30% per year from 2000 to 2018. It is furthermore projected to increase 15-24 fold from 23 GW in 2018 to 342-562 GW by 2040 [1]. A key reason for this rapid development is the continuing reduction in the levelized cost of energy [2]. While OWE development is an effective way to reduce energy-related greenhouse gas (GHG) emissions [3], it will incur in environmental impacts related to the manufacturing, installation, operation and maintenance (O&M), and decommissioning and end-of-life (EoL) recycling of wind turbines, foundations, and transmission equipment. These impacts remain largely uncertain with the turbine size, the distance from shore both increasing, as well as with recent changes in component technology development [4].

Life cycle assessment (LCA) studies have shown the significance of lifetime and capacity factors (CFs) for environmental impacts of electricity generation by the OWE [5–8]. Region/site specific studies have been conducted for specific sizes (e.g. ecoinvent 1-3 MW [7,9–12], 3-5 MW [5,13–20], 8 MW [21], and 10 MW [22]), specific generator technologies (e.g. gearbox based (GB) [7,11–16,19,23], and direct drive (DD) [22,24]), and specific foundation technologies (e.g. Monopile [7,9,14,17,19,20,23], gravity-based [7,13,19], Jacket [16,19], and semi-submersible floating [15,18,22,25]). Yet, there is a lack of LCA research quantifying OWE environmental impacts on a global scale that considers future technological developments such as increased turbine sizes and novel component technologies. The evolution of turbine size and market share of technologies have so far not been well considered in the prior studies. Exponential growth of turbine size has promoted increasing CFs in the past years [26,27,28]. The average nominal capacity (NC) of commercial turbines increased from approximately 3 MW in 2010 to 6 MW in 2020, and the industry is targeting 15-20 MW turbines in 2030 [1]. Permanent magnet (PM) based generator technology allows wind turbines to operate at lower speeds and thus have higher efficiencies and energy yields [29]. Moreover, there are few environmental assessments for emerging technologies, like superconducting generators [30], new fibre technologies [31] in blades, hybrid tower concepts [32], and spar and TLP floating foundations [33]. Further, potentially important life cycle phases such as the installation, maintenance, and EoL recycling, are not well captured in the typical reference life cycle inventory (LCI) data sets (e.g. ecoinvent 1-3 MW, and National Renewable Energy Laboratory (NREL) 5 MW [34]). Background system changes, such as the energy transition, are also not commonly considered [5,7,25,9,13–15,17,19,20,23] or not sufficiently and transparently described in the literature [12,16,18].

This paper develops a prospective LCA model to comprehensively quantify current and future environmental impacts of OWE development on a global scale until 2040. Dynamic parameterized LCIs were built by including high technology resolution supply chains notably by focusing on installation, O&M, decommissioning, and EoL recycling, that were often neglected in existing literature. LCIs for a given year (from 2020 to 2040) were adjusted by underlying dynamic trends, including turbine size expanding, moving further from shore, technology and EoL recycling development. LCA results were furthermore based on futurized background LCI data derived by combining ecoinvent 3.7.1 database [35] and information from SSP2 scenarios from the IMAGE integrated assessment model [36]. Such an in-depth analysis on global environmental assessment of the OWE sector allows for a better understanding of the implications of OWE research and development strategies, and circular design.

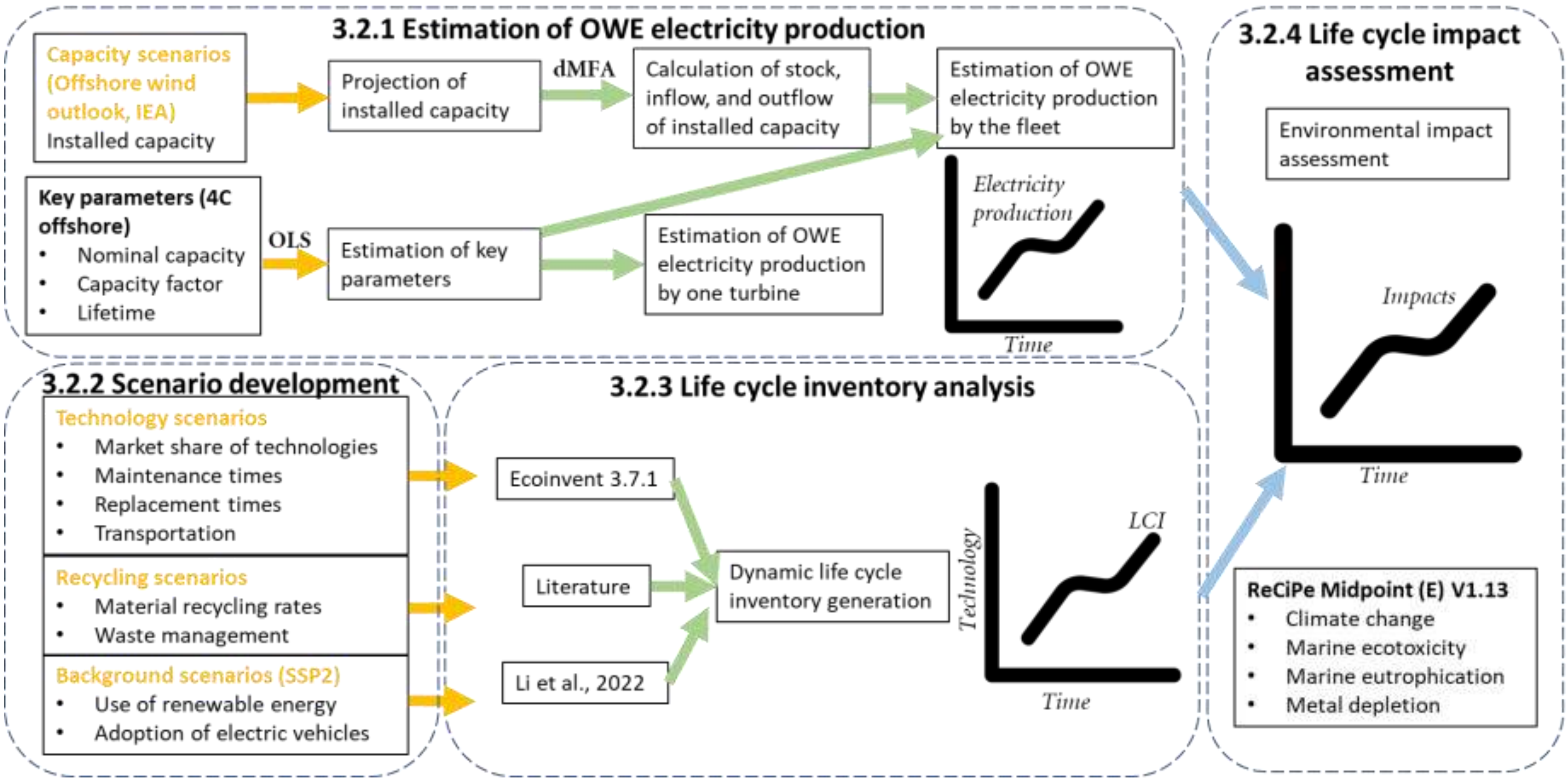

Figure 3.1: The environmental impact calculation overview.

3.2 Methods and data

Environmental impacts were calculated both per MWh and per fleet, spanning from cradle to grave. It thus includes the full life cycle: manufacturing, installation, operation and maintenance (O&M), decommissioning, and EoL recycling. The calculation of environmental impacts is performed via the steps in the subsections below (**Figure 3.1**)

3.2.1 Estimation of OWE electricity production

The electricity production (EP) over the full life cycle of a single wind turbine installed at year t ($EP_t^{Turbine}$) was calculated based on three key parameters, i.e. capacity factor (CF), lifetime, and nominal capacity (NC) (shown in eq. (1)). The estimation of these three parameters from 2020 to 2040 is introduced in **S2.1** in **Supporting Information I**.

$$EP_t^{Turbine} = CF_t \times Lifetime_t \times NC_t \tag{1}$$

The EP at fleet level at year t EP_t^{Fleet} was calculated based on CF, lifetime, and installed capacity (Stock) (shown in eq. (2)). The inflow (I), stock (S), and outflow (O) capacity from 2020 to 2040 were calculated based on a dynamic material flow analysis (dMFA) [37] in line with two IEA OWE capacity scenarios, i.e. Stated Policy (SP) and Sustainable Development (SD) [1] .

$$EP_t^{Fleet} = CF_t \times Lifetime_t \times S_t \tag{2}$$

3.2.2 Scenario development

3.2.2.1 Technology scenarios

Three technology scenarios, i.e. conventional technology (CT), advanced technology (AT), and new technology (NT), were developed to show technological roadmaps (market shares of technologies in the nacelle, rotor, tower, and foundation) [37] and applied in this paper. These scenarios were extended by adding maintenance times, replacement rates, and transportation strategies. An overview of the scenarios is presented in **Table 3.1**.

3.2.2.2 Recycling/EoL scenarios

Moreover, three EoL scenarios, i.e. hypothetical EoL scenarios (EoL_H), optimistic EoL (EoL_O), and EoL conservative EoL (EoL_C), were included in this paper to discuss the environmental performance of EoL second material use and waste material treatment. These scenarios were extended by adding waste management processes, e.g. landfilling or incineration. An overview those three EoL scenarios is shown in **Table 3.2**.

3.2.2.3 Background scenarios

Background scenarios are derived from a combination of ecoinvent 3.7.1 data with scenario data of IMAGE. The latter models global future scenarios based on shared socio-economic pathways (SSPs) [38] and representative concentration pathways (RCPs). Two ‘’Middle-of-the-Road’’ SSP scenarios, SSP2-base and SSP2-RCP2.6 [39] were derived using the *premise* framework [40] and implemented in this study. SSP2-base and SSP2-RCP2.6 showcase the future socio-economic developments for the year 2020, 2025, 2030, 2035, and 2040, under global warming of 3.5 °C and 2 °C frameworks, respectively [41]. We applied linear regression to adapt to each year from 2020 to 2040.

3.2.3 Life cycle inventory analysis

Dynamic parameterized LCIs were generated by including detailed supply chains for state-of-the-art and perspective component technologies in four OWE components, i.e. the nacelle, rotor, tower, and foundation. This was conducted by using material flows and stock from a previous paper [37] and collecting inventories from literature [7,13,14,36–38]. LCIs for a given year (from 2020 to 2040) were adjusted by adapting to parameter change (underlying dynamic trends), including turbine size expanding, moving further from shore, component technology and EoL recycling development. All endpoint supply chains were modeled through the use of ecoinvent 3.7.1 (allocation, cut-off by classification) [35]. Lastly, we use the modified LCIs in conjunction with outcomes of the IMAGE for the SSP2-base and SSP2-RCP2.6 background scenarios (**3.2.2.3**). The last step leads to a superstructure database that is modelled in Activity Browser [45]. All parameters embedded in the processes are shown in **Table S3.9**. An overview of all processes in each life cycle stage is shown in subsections and a full table that summarizes all processes and corresponding flow values is provided in **LCI** in **Supporting Information II**.

3.2.3.1 Manufacturing

Manufacturing includes processes ranging from material mining, material manufacture, and component fabrication as well as assembly of turbines (including the nacelle, rotor, and tower), foundations, and transmission infrastructures (including cables and transformers). Material requirements from 2020 to 2040 for manufacturing turbine and foundation (an introduction provided in **3.2.3.1.1** in **Supporting Information I**) were calculated based on a dynamic material flow analysis (dMFA) from our previous work [37]. Energy use for material processing, miscellaneous collection, and assembly was taken from ecoinvent [35] and adjusted by nominal capacity development. The materials used for manufacturing transmission infrastructure were derived from [13,43] and adjusted by the distance from shore (details can be found in **S3.2.3.1.2** in **Supporting Information I**).

3.2.3.2 Installation

Installation processes consist of towing the foundations and turbines out to the site, laying the cabling, and assembling the final units [42,44]. Installation processes are primarily related to marine vessel operation, in which impacts were calculated based on vessel work time and fuel consumption [14,47]. Foundation installation processes vary among foundation types with different work times [47]. Eight foundations [37] were classified into four types by their installation processes, i.e. foundation type I: Gravity-Base and High-Rise Pile Cap; type II: Monopile; type III: tripot and Jacket; Type IV: floating foundations (Semi-Submersible, Spar and TLP). For type I and II foundations, sour protection is needed before installation setup. Type II and III foundations need driving piles into the seabed. While type IV relies on mooring systems. Processes related to foundations installation were adapted from [48], see also **3.2.3.2.1** in **Supporting Information I**. Methods and procedures to install turbines (discussion in **3.2.3.2.2** in **Supporting Information I**) were already well managed and only marginally different among turbine types [49]. This paper adopted turbine installation processes from [14] and used them for all turbine types. Installation of transmission includes installation of transformer substations and cables (discussion in **3.2.3.2.3** in **Supporting Information I**), which was modeled based on [50].

3.2.3.3 Operations and maintenance (O&M)

This paper classified O&M processes into two categories, i.e. preventative (scheduled) maintenance, and corrective (unscheduled) maintenance (see also **3.2.3.3** in **Supporting Information I**). We assumed 1−2 times of preventative maintenance and 1−4 times of corrective maintenance per year per turbine, in line with literature [13,51]. In addition, the replacement of large parts (the generator, gearbox if applicable, and blades) and small parts (0.5 t low-alloy steel) were included in this paper. The annual replacement rate of the generator was assumed as 2.5% (DD nacelle technologies) and 5% (gearbox-based nacelle technologies) per turbine, respectively. Dynamic change of replacement rates was assumed in line with the market share of DD nacelle technologies. The annual replacement rate of the blades was assumed to be 5% per turbine. The annual replacement rate of small components was assumed as 36.2% per turbine [13]. These replacement rate values are in line with literature [7,13].

3.2.3.4 Decommissioning

Decommissioning was considered to be the opposite process of installation (detailed processes are provided in **3.2.3.4** in **Supporting Information I**) [52]. The time taken for decommissioning processes was assumed 50% less than installation [53]. This paper assumed that the removal of turbines and foundations is only included after wind farms reaching their lifetimes. Transmission infrastructures, e.g. transformers and cables were assumed to be left in situ.

3.2.3.5 End of life (EoL) recycling

EoL recycling and waste treatment were modeled separately from the decommissioning. Recycled materials were assumed to be indefinitely supplied as raw materials for the OWE sector (closed-loop recycling) and non-recycled materials were assumed to be either landfilled or incinerated. EoL recycling of OWE materials were discussed in line with three recycling scenarios (**Table 3.2**). The energy use for EoL recycling was excluded due to lack of data. Up to 10% of the recyclate for this sector has been reported [54] but the energy use for recycling is largely uncertain and may widely vary over for different recycling routes. For instance, the energy use of EoL blade recycling technologies (e.g. mechanical, fluidised-bed, and pyrolysis recycling) were reviewed in the literature and varied over one order of magnitude (0.27-30 MJ/kg) [54,55]. These energy requirements vary due to recycling technology readiness level and waste treatment capacity and policies (e.g. landfill capacity and policies) [56]. Several lab-scale technologies to improve recycling rates have been developed, but they have not reached cost parity with landfilling [54]. Detailed processes related to secondary materials from EoL recycling and waste treatment (e.g. landfill and incineration) are shown in **LCI_EoL** in **Supporting Information II**.

Table 3.1: Overview of preventative (scheduled) and corrective (unscheduled) maintenance times, replacement rates and transportation strategy in conventional technology (CT), advanced technology (AT), and new technology (NT) scenarios.

Technology scenario	**Technology development**	**Maintenance times (per turbine and year)**	**Replacement rates** [1]	**Transportation means (in addition to workboats being used in near-shore sites)**
CT	Technology evolution follows a conventional roadmap	2 times unscheduled maintenance 4 times scheduled maintenance (conventional nacelle technologies with high failure rates still dominate the market)	High annual replacement rates (~5%) were assumed as most nacelles are likely to be gearbox based.	No additional
AT	Further development of advanced technologies (e.g., PM-based generators, carbon fibres, hybrid towers, and floating foundations)	2 times unscheduled maintenance 2 times scheduled maintenance (The market brings in more DD nacelle technologies with low failure rates)	Moderate replacement rates (from ~5% in 2020 to ~3.8% in 2040) were assumed as more DD nacelle technologies with less failure rates comes to the market.	20% of wind turbines were assumed to be supported by helicopters for sites further from shore with deep waters.
NT	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)	1 times unscheduled maintenance 1 times scheduled maintenance (more DD nacelle technologies with low failure rates are deployed)	Low replacement rates (from ~5% in 2020 to ~3.3% in 2040) were assumed as much more DD nacelle technologies with less failure rates are introducing.	50% of wind turbines were assumed to be supported by helicopters for sites further from shore with deep waters.

Table 3.2: Hypothetical end-of-life (EoL) scenarios (EoL_H), optimistic EoL (EoL_O), and EoL conservative EoL (EoL_C) EoL scenarios. The detailed EoL recycling rates can be found in **Table S1** in [37]. Waste treatment processes are introduced in **S2.2.2.4** in chapter 7. **Materials**: Fe_L: Low-alloyed steel; Fe_H: High-alloyed steel; REEs: Rare earth elements.

Scenario	Recyclable materials	Unrecyclable materials	EoL recycling rates	Waste treatment
Hypothetical scenario (EoL_H)	All	-	All materials from outflow are 100% recycled	No waste materials in this scenario
Optimistic scenario (EoL_O)	Fe_L, Iron, Concrete, Fe_H, Cu, Al, Cr, Mn, Mo, Ni, Zn, B, REEs	Polymer (fibres, resin)	Bulk materials and key metals were assumed to be recycled with high recycling rates; REEs were considered recyclable; polymer in blades was assumed not recyclable.	Most of the waste materials are incinerated; the rest are landfilled
Conservative scenario (EoL_C)	Fe_L, Iron, Concrete, Fe_H, Cu, Al, Cr, Mn, Mo, Ni, Zn	REEs, Polymer (fibres, resin)	Bulk materials and key metals with low recycling rates were considered recycled; REEs and polymer were assumed not recyclable.	Most of the waste materials are landfilled; the rest are incinerated

3.2.4 Life cycle impact assessment

The life cycle impact assessment was conducted using the Activity Browser [57] according to ReCiPe Midpoint (H) V1.13 [58] impact categories (a full list shown in **Table S3.8**). Climate change, marine ecotoxicity, marine eutrophication, and metal depletion, were considered as the most relevant impact categories to electricity production by the OWE (discussion can be found in **3.2.4** in **Supporting Information I**). The environmental impacts (EIs) of one turbine were calculated as the ratio of its life cycle impacts and its electricity production (EP), where life cycle environmental impacts (LCEIs) were calculated as the sum of the impacts over the lifetime. The EI per MWh in year t EI_t^{MWh} was normalized to one MWh by EI per turbine divided by nominal capacity (NC) (shown in eq. (3)).

$$EI_t^{MWh} = \frac{\mathrm{LCEI}_t}{\mathrm{EP}_t} \times \frac{1}{NC_t} \tag{3}$$

Fleet level EI in year *t* (EI_t^{Fleet}) was calculated as the sum of the life cycle impact of the wind turbine capacities being part of the fleet and divided by the sum of their EP, where the EI of manufacturing and installation was calculated based on the inflow (I) capacities. The EI of O&M and decommissioning (including EoL recycling) was calculated based on stock (S) and outflow (O) capacities, respectively [37].

$$EI_t^{Fleet} = \frac{1}{\mathrm{EP}_t} \times \frac{1}{NC_t} \times (LCEI_t^{Manufacturing} \times I_t + LCEI_t^{Installtion} \times I_t + LCEI_t^{OM} \times S_t + LCEI_t^{Decommissioning} \times O_t) \tag{4}$$

3.2.5 Sensitivity analysis

We performed a sensitivity analysis by modifying parameters by possible ranges, i.e. 20-25 years of lifetime, 50-60% of CF, 5-20 MW of nominal capacity, 155-315 m of rotor diameter, and 10-100 km of distance from shore, to investigate the variances of environmental impacts per MWh based on the AT technology scenario, EoL_O recycling scenario and SSP2-base background scenario in terms of impact categories considered in this paper. A further sensitivity analysis was performed by altering 20% of several parameters embedded in scenarios, i.e. technology market shares, maintenance time, replacement rates, transportation strategy, recycling rates, and waste treatment.

3.3 Results and discussion

3.3.1 Environmental impact intensity

The GHG intensity (per MWh) in the CT scenario declines from 20.1 kg CO2-eq for 2020-2025 to 15.8 kg CO2-eq for 2035-2040 (~21% drop). Similar reductions are found for marine ecotoxicity (~25% drop), marine eutrophication (~22% drop), and metal depletion (~16% drop) (the impact intensity for all evaluated impact categories are shown in **Intensity_ReCipe** in **Supporting Information II**). Impact intensities based on AT and NT scenarios are ~14% and ~25% lower than in the CT scenario, respectively (**Figure 3.2**). This is due to the higher development and market share of advanced technologies in the AT scenario, as well as the introduction of new technologies in the NT scenario. The continuous reduction in environmental impact intensities is expected due to various factors including lifetime extension, size expanding, and technology innovation (**3.3.4**, further discussion provided in **3.3.1** in **Supporting Information I**).

The environmental impact intensities calculated using the ecoinvent database and NREL 5 MW model result in ~13.5 kg and ~15.0 kg CO2-eq per MWh, which are ~12% and ~2% lower than that of the average value (2020-2040) under our baseline scenario AT, respectively. On average, GHG intensities of earlier studies show a much larger variation (7.8-49.4 kg CO2-eq per MWh) [7,10,61,12,14,17–20,59,60]. The variability in these results reflects the differing assumptions, system boundaries, LCI data and impact assessment methods. In general, our modelled environmental impact intensities are higher than those in [12,17,19,56,58]. This may be due to the fact that we included detailed data for installation, O&M, and decommissioning in the life cycle. Further, earlier studies are often constrained by not accounting for underlying dynamic trends, such as changes in turbine size, lifetime, component technology and recycling development.

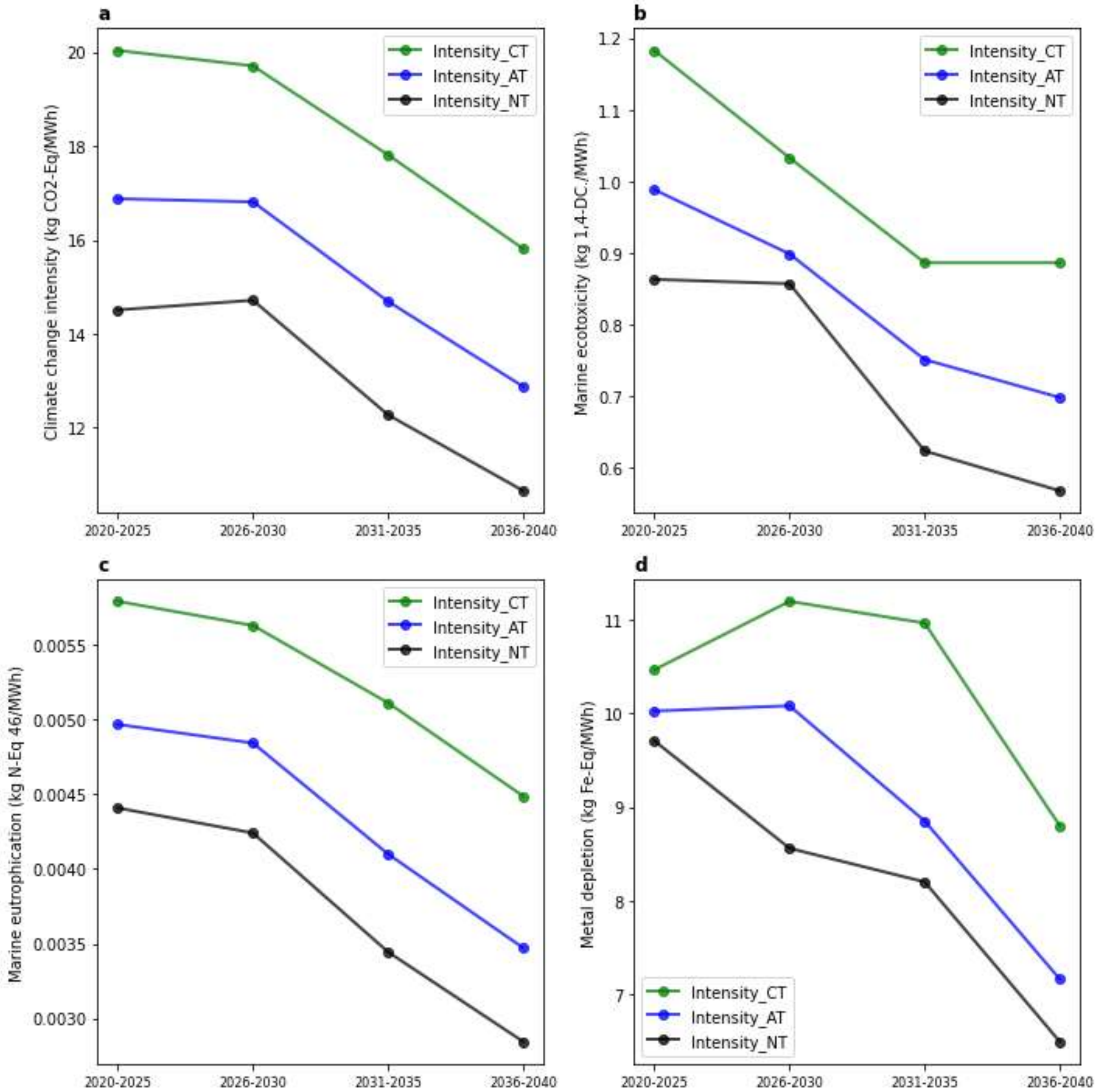

Figure 3.2: Environmental impacts per MWh, 5-year average, based on conventional technology (CT), advanced technology (AT), and new technology (NT) scenarios, under EoL_O recycling scenario, and SSP2-base background scenario.

3.3.2 Fleet environmental impact

At the fleet (total installed capacity) scale, the deployment of OWE will cumulatively (2020-2040) result in a contribution of 2.6-3.6 Gt CO_2-eq to climate change. However, this compares to 124-207 Gt CO_2-eq emissions (48-58 times more) that would be generated when producing the same quantity of electricity with the global electricity mix of 2020. The impacts under SP scenario are ~42% lower than that of SD because less installed capacities are assumed in the SP scenario (**Figure 3.3**). The deployment of OWE will cumulatively (2020-2040) result in 171 and 242 Mt 1,4-DC to marine ecotoxicity, 0.7 and 1.0 Mt N-eq to marine eutrophication, and 0.8 and 1.1 Gt Fe-eq to metal depletion, under SP and SD capacity scenarios, respectively (**Figure 3.3**). Fleet impacts on other impact categories are shown in **Results_Fleet_Impact** in **Supporting Information II.**

The yearly fleet impacts will increase from 2020 to 2040 as more installed capacities are projected over time. Under the SD capacity scenario, ~81 Mt CO2-eq climate change relevant GHG will be emitted from 2020 to 2025. It will increase to ~168 Mt CO2-eq (~107% increase) in 2025-2030, ~216 Mt CO2-eq (~167% increase) in 2030-2035, and ~264 Mt CO2-eq (~226% increase) in 2035-2040 (**Figure S9**). Such impacts will further increase after 2040 since a substantial new OWE capacity will be installed globally over time.

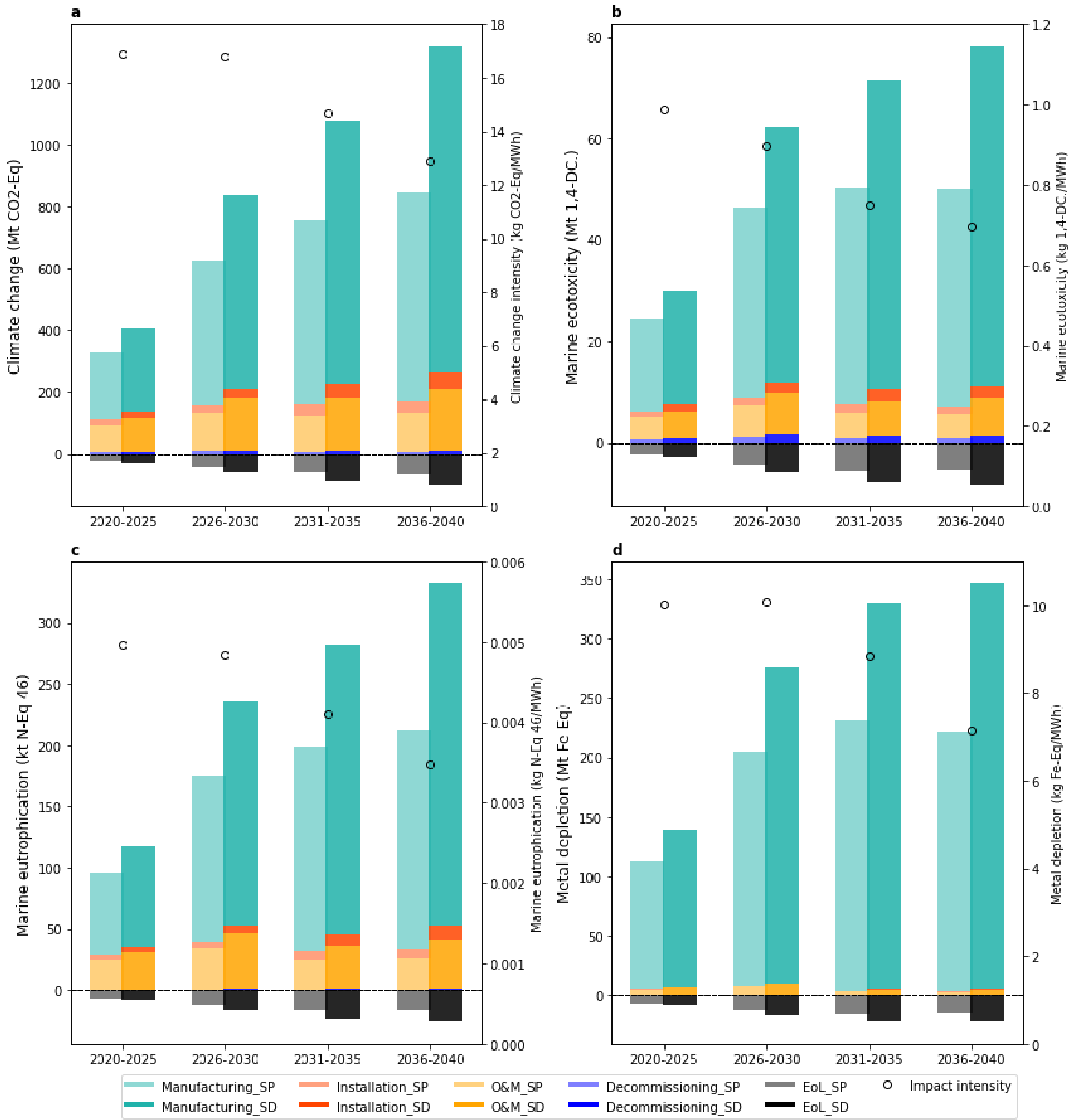

Figure 3.3: 5-year cumulative fleet environmental impacts contribution analysis by life cycle stage, for the stated policy (SP) and sustainable development (SD) capacity scenarios. 5-year average fleet environmental impact intensity (per MWh) for the AD technology scenario, EoL_O recycling scenario, and SSP2-base background scenario.

Renewable energy sources, especially wind and solar power, generated 23.2% of world's electricity in 2020 (a 7% increase from 2019) [62]. The increasing deployment of renewable energy systems will result in a large reduction of environmental impacts of electricity production. According to our analysis (**Figure S3.8**), the average (from 2020 to 2040) GHG intensities (per MWh) based on SSP2_base and SSP2-RCP2.6 scenarios are 0.3 (~2%) and 1.7 (~10%) kg CO2-eq lower than that of 2020 values, respectively. More importantly, such decarbonisation of the electricity system by the OWE has the potential to play an important role by replacing or displacing 408-584 GW of fossil fuels (60.9 % of fossil based electricity [62]), which would cumulatively (2020-2040) reduce GHG emissions by 124-207 Gt CO2-eq; additional inputs of (essential) metals by 2-3 Gt 1,4-DC; chemical nutrients emissions by 15-21 Mt N-eq; and minerals by 28-34 Gt Fe-Eq.

3.3.3 Contribution analysis

At the component level, turbine-related processes (including the nacelle, rotor, and tower) together have the largest cumulative (2020-2040) impacts, i.e. ~2.0 Gt CO2-eq (~56%) to climate change, ~155 Mt 1,4-DC (~64%) to marine ecotoxicity, ~0.6 Mt N-eq (~57%) to marine eutrophication, and ~0.8 Gt (~77%) Fe-Eq to metal depletion. The foundation-relevant impacts are ~27%-~75% lower than the turbine-relevant impacts (**Figure 3.4** and **Table S3.10**). The transmission-relevant processes account for <5% of impacts.

At the process level for each of life cycle stage, manufacturing contributes to the largest portion (i.e. ~75%-~98%), of cumulative (2020-2040) environmental impacts, with this contribution increasing from 2020 to 2040 (**Figure 3.3** and **Figure S3.10**). This is mainly due to certain raw materials, such as steel (reinforcing steel and low-alloyed steel combined), fibers (carbon fibers and glass fibers combined), copper, and zinc, which are required along with the rapidly growing turbine size and technology development (**Figure 3.4**). Steel (reinforcing and low-alloyed combined) has the largest cumulative (2020-2040) contribution among all processes, e.g. ~1.6 Gt CO2-eq (~45%) to climate change, ~104 Mt 1,4-DC (~43%) to marine ecotoxicity, ~0.4 Mt N-eq (~41%) to marine eutrophication (**Figure 3.4**). It is not surprising since a substantial number of supporting structure (e.g. foundations and towers), are made from steel. Fiber in the blade has significant impacts, with ~17%, ~7%, and ~23% on climate change, marine ecotoxicity, and marine eutrophication, respectively (**Figure 3.4** and **Table S3.10**).

Installation contributes ~5% to climate change, ~3% to marine ecotoxicity, and ~4% to marine eutrophication, but has a negligible effect on metal depletion (<1%) (**Figure 3.3 and Table S3.10**). The contributions of decommissioning are minor (<2% to all impact categories) as only small portions of turbines (40.1-48.6 GW including turbines installed before 2020 and in the 2020-2040) will be decommissioned between 2020 to 2040. Although installation and decommissioning together account for only small portions of environmental impacts, several processes may cause severe damage to the marine ecosystem [63,64]. For instance, installation with type II and III foundations (**Table S3.2**) may damage the seabed ecosystem due to pile driving. Removal of foundations is furthermore likely to affect the local hard-substrate habitat [64]. These impacts could likely increase due to more complex installations with wind turbines moving farther from shore into deeper waters. Installation disruptions on the seabed could also be greatly reduced in the near future through the development of the combined turbine-foundation installation technologies [65]. This innovation will likely reduce installation- and decommission-relevant environmental impacts [66].

The contributions of O&M to impacts are significant (e.g. ~0.7 Gt CO2-eq (~19%) for climate change, ~19 Mt 1,4-DC (~8%) for marine ecotoxicity, and ~0.2 Mt N-eq (~17%) for marine eutrophication (**Figure 3.4** and **Table S3.10**)), but they do decrease from 2020 to 2040 (**Figure 3.3**). This continuous reduction trend is mainly due to the increasing contribution of manufacturing to impacts, the deployment of DD nacelles with fewer failure rates, and optimization of marine transportation. O&M impacts are to a large extent underestimated by previous studies (accounts for 1-6% of total global warming potential reported from [5,9,11]). Our results show that O&M has a relatively high contribution, which are in line with literature [13,18,59]. Replacement- and transportation-relevant fuel consumption (diesel and heavy fuel oil) account for the majority of impacts in O&M (**Figure 3.4** and **Table S3.10**). These impacts will likely increase due to the higher failure rates related to turbine size enlarging [68,69] and moving into deeper waters with harsher marine environments [70].

EoL recycling can alleviate raw material requirements and reduce environmental impacts. Although the vast expansion of the OWE sector implies the inevitable use primary materials, secondary materials could still represent a substantial source to supply large-scale OWE development. ~7%, ~11%, ~7%, and ~6% of climate change, marine ecotoxicity, marine eutrophication, and metal depletion can be reduced by EoL recycling, from 2020 to 2040, respectively (**Figure 3.3**). Impact reductions by EoL recycling under our hypothetical EoL_H scenario are, based on a 2020-2040 average, around 70% higher than that of under EoL_O scenarios (**Figure S3.11**). The contribution of EoL recycling to impact reduction will likely increase as more offshore wind farms reach their EoL after 2030. However, recycling rates are pretty low currently for certain materials, (e.g. fibers and REEs). Impact reductions under EoL_C scenario (non-recyclable blades and <1% of REE recycling rates were assumed) is on average (from 2020 to 2040) ~25% lower than that of under EoL_O scenarios, in terms of impact categories considered in this paper (**Figure S3.11**). Fiber in blades is currently difficult to recycle, however, and its contribution to manufacturing environmental impact is relatively high, e.g. ~22%, ~7%, and ~29% of climate change, marine ecotoxicity, and marine eutrophication, respectively (**Figure 3.4** and **Table S3.10**). Current methods to address blade waste (e.g. landfilling in pieces and incineration) [71], are gradually becoming banned due to costly mechanism and the resulting pollution [55,56]. According to the European Composites Industry Associate (EUCIA), co-processing of fiber in a cement kiln is a viable recycling method for these materials. Mechanical processing of fiber is under development with a high upscaling potential [72], with methods under development to improve process efficiency, lifetime, and viable recycling pathways for blades. Further, new technologies have been developed by the OWE industry to enable recyclable blades with organic materials. For instance, Siemens Gamesa has launched fully recyclable offshore wind turbine blades [73] and Vestas also aims to make fully recyclable blades by 2030 [42].

REEs are of high economic importance but their production induces high environmental impacts. Less than 1% recycling rates have been reported and few projects have reached desirable scales of REEs recycling due to technical challenges [37]. The industry has strengthened the interest in recovering REEs from OWE facilities and 21% recycling rates are expected [74]. 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 [71]. However, meeting sustainability targets will require engagement and collaboration among turbine and blade manufacturers, and the cautious consideration of other ethical and environmental impacts.

Although this study assumes that transmission infrastructures will be left in situ, they may one day also be removed. The contribution of transmission infrastructures to impacts is insignificant (<5% for all impact categories, **Figure 3.4**) but materials contained in transmission cables (e.g. Cu and Al) have high recycling rates. Steel foundations were assumed to undergo high recycling rates. All in all, ~3% of climate change relevant GHG could be reduced by foundation EoL recycling, which accounts for ~41% of total impacts by EoL recycling (**Table S3.10**). However, the removal of foundations is generating controversial due to extreme costs and potential impacts to the ecosystem [57,58]. The decommissioning of foundations is likely to leave about a meter of material in the seabed, as opposed to complete removal.

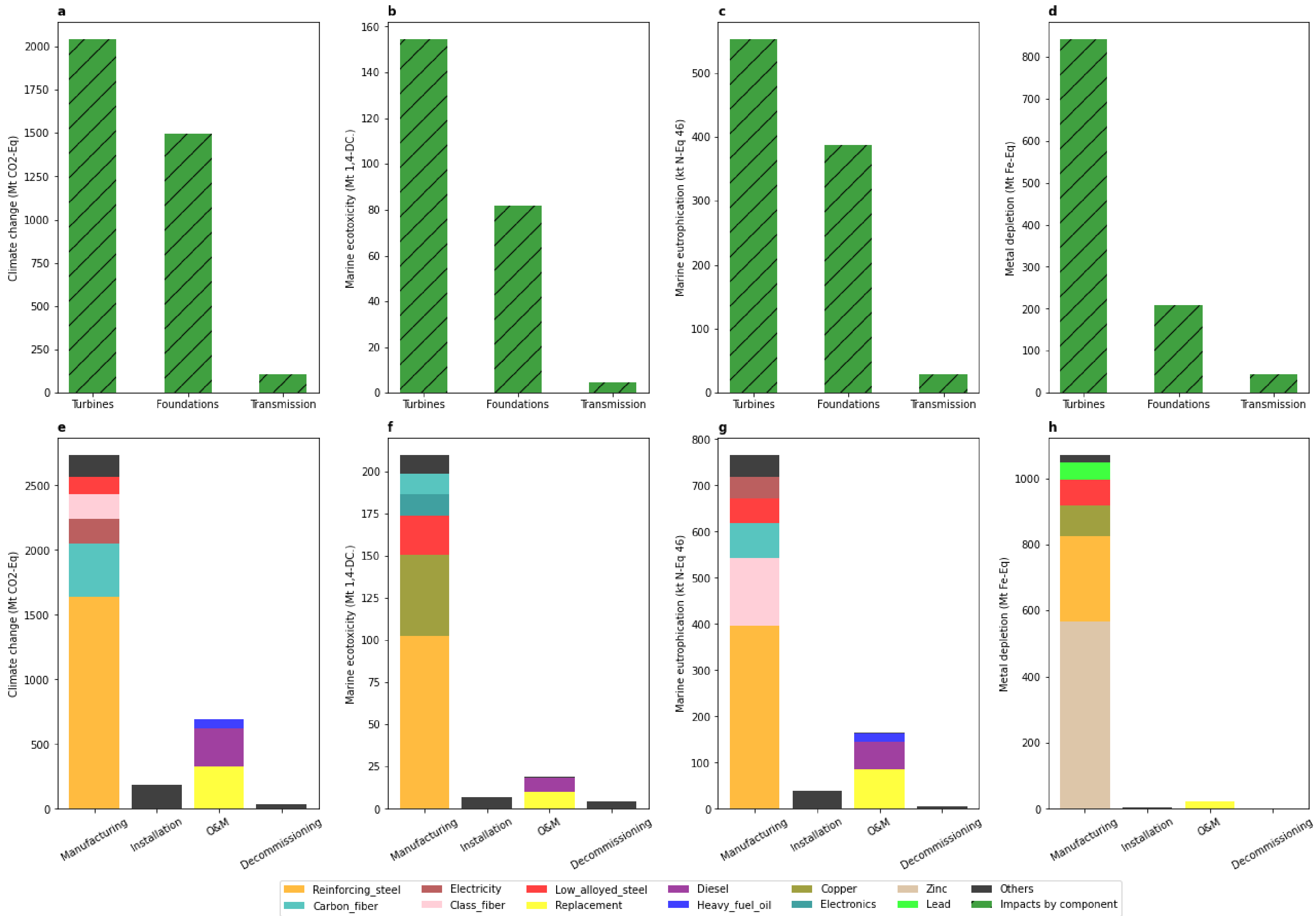

Figure 3.4: a-d: Contribution analysis by component; **e-h:** Contribution analysis by major processes in each of life cycle stage. All contribution analysis was conducted for cumulated (2020-2040) impacts, under SD capacity scenario, AD technology scenario, EoL_O recycling scenario, and SSP2-base background scenario.

3.3.4 Sensitivity analysis

The largest variations of impact intensity are related to turbine size. GHG intensity is doubled (~225%) and halved (~58%) when nominal capacity changes from the proposed ones (**3.2.1** in **Supporting Information I**) to 5 MW and 20 MW, respectively. The GHG intensity will decrease by ~11% if the proposed lifetime (from 20-years in 2020 to 25-years in 2040, linear change) alters to 25-years (and increase by ~11% when the proposed lifetime alters to 20-years). GHG intensity variations of +9% and -9% are observed when the CF is adjusted to 50% and 60%, respectively. Distance from shore variations (which indicates equipment transportation distance and cable length) had an insignificant effect on the environmental impacts (**Figures S3.12-S3.15**).

Changes in technology market shares result in a relatively higher level of variability in all impacts than other embedded parameters discussed in this paper. For instance, cumulative GHG emissions from 2020 to 2040 change by approximately +3% (-2%), +4% (-4%), and -9% (+3%) when the market shares of PM-based nacelles, DD-based nacelles and floating foundation technologies increase (or decrease) by 20%, respectively. Increasing recycling rates and reducing landfill processes by 20% could reduce ~4% and ~2% the environmental impacts. Maintenance times, replacement rates and transportation strategy have negligible affects environmental performance. <2% of variations are seen for all impact categories considered in this paper (**Table S3.11**).

3.3.5 Limitations and outlook

This study evaluated the environmental impacts for global OWE development in using a prospective LCA model with various scenarios for technology and EoL recycling development. This LCA model is dynamic at the level of inventory analysis, yet we have not included time-dependent characterization factors as developed, e.g. by Lan and Yao [76] for greenhouse gases. The Activity Browser software did not allow for a dynamic impact assessment. Furthermore, dynamic characterization factors were not available for all impact categories considered. Although the LCIs and results presented here provide new insights at the global level, more specific data and scientific understanding would be still required to adapt the system to regional/local cases. This could be achieved by using GIS-based datasets with higher geographical resolution for site-specific parameters (e.g. wind speed and water depth). Furthermore, ecoinvent processes may underestimate the EI, which could be improved with LCI databases that better represent downstream supply chain process. For example, small processes are hard to quantify, some important processes are outside of the defined system boundary, and some processes might have high impacts but are even not included in ecoinvent (e.g. production of dysprosium, terbium, and yttrium, and the availability of new materials and specialized vessels).

This study used prospective LCI databases derived from a coupling of the ecoinvent database with data from IMAGE. However, IMAGE is conservative on renewable energy development, (e.g. ~3.7% and ~5.3% annual average (from 2020 to 2040) growth of wind energy based on SSP2-base and SSP2-RCP2.6, respectively [38]). It may lead to a relatively small overestimation of impacts as the background production of materials and supply of electricity do not profit from rapid OWE development. This limitation could be improved by implementing foreground OWE scenarios in IMAGE in order to assure full consistency between the models. Further, the upscaling of OWE requires larger and more specialized background infrastructure (e.g. uploading and transportation equipment), that is not well modeled (or even unavailable) in the current LCI database, e.g. ecoinvent, (more discussion in **S3.3.5** in chapter 7). This study did not include these background infrastructure changes due to a lack of data. Future studies are warranted to consider these background changes and associated impacts. Such improvement would be beneficial to understand (marginal) cause–effects and feedback mechanisms of OWE technology development by using consequential LCA models.

In addition, research is just beginning to unravel the impacts of the OWE on marine ecosystems (e.g. sea bed destruction, acoustic disturbance produced by turbine operation and vessel transportation [77], creation of hard-bottom habitat [78], and electromagnetic fields enhancement by underwater transmission cables [79]). Further research is needed to integrate these impacts into an cumulative framework that includes the impact categories considered in this paper. Further uncertainty analyses based on global sensitivity approaches (e.g. Monte Carlo simulation and resampling methods), could be applied in the future to globally assess uncertainties and provide more extensive recommendations.

3.4 References

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Chapter 4

Offshore wind energy and marine biodiversity in the North Sea: life cycle impact assessment for benthic communities

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Abstract

Large-scale offshore wind energy developments represent a major player in the energy transition but are likely to have (negative or positive) impacts on marine biodiversity. Wind turbine foundations and scour protection often replace soft sediment with hard substrates, creating artificial reefs for sessile dwellers. Offshore wind farm (OWF) furthermore leads to a decrease in (and even a cessation of) bottom trawling, as this activity is prohibited in many OWFs. The long-term cumulative impacts of these changes on marine biodiversity remain largely unknown. This study integrates such impacts into characterization factors for life cycle assessment based on the North Sea and illustrates its application. Our results suggest that there are no net adverse impacts during OWF operation on benthic communities inhabiting the original sand bottom within OWFs. Artificial reefs could lead to a doubling of species richness and a two order-of-magnitude increase of species abundance. Seabed occupation will also incur in minor biodiversity losses in the soft sediment. Our results were not conclusive concerning the trawling avoidance benefits. The developed characterization factors quantifying biodiversity-related impacts from OWF operation provide a stepping stone towards a better representation of biodiversity in life cycle assessment.

Keywords: Offshore wind farms; marine ecosystems; characterization factors; species richness; species abundance; seabed occupation; artificial reef; trawling avoidance

Synopsis: This study develops a marine biodiversity impact assessment method for life cycle assessment and shows no net adverse impacts on benthic biodiversity during offshore wind energy operation.

4.1 Introduction

The North Sea holds approximately two thirds (~19 GW) of the globally installed offshore wind energy (OWE) capacity [1]. The OWE industry is expected to progressively expand in the North Sea by 2050, with a target of 300 GW set by the European Commission [2]. Such large-scale development would be a pillar for the energy transition and greenhouse gas emission mitigation, but could have a substantial impact on marine biodiversity. Offshore wind turbines can cause collisions and a change in the migratory paths of seabirds and bats [3]. Noise and vibration during offshore wind farm (OWF) installation and operation may affect fish and marine mammal communication and navigation [4]. Electromagnetic fields generated by submarine cables may disturb foraging, orientation and migration of fish species [5–7]. Contrastingly, OWE infrastructure can also attract species for food or refuge (e.g. larger gulls [8], demersal and bentho-pelagic fish [9]). Since foundations occupy the seabed, they could have impacts on benthos [10]. Foundations and scour protections are quickly colonized by hard substrate benthic species [10,11]. Such artificial reefs can provide habitat and food for benthic communities. Further, bottom trawling in OWFs is typically not permitted, and the OWE development will therefore lead to bottom trawling free zones with effects that are potentially similar to fishery restrictions or conservation areas [10]. These effects may have significant impacts on local ecosystems, yet the long-term cumulative impacts of large-scale projected OWFs on marine biodiversity remain largely unknown. In order to avoid shifting the burdens of from greenhouse gas emission mitigation to marine biodiversity, there is a need to understand the local and cumulative impacts of OWE development on marine biodiversity.

Declines in marine biodiversity driven by human activities have been documented on a global scale [12,13]. The environmental impact assessment framework has been used to discuss regulatory needs to prevent marine biodiversity loss from OWFs [7,14,15]. Other studies have theoretically analyzed how OWE relevant impacts can be assessed, including habitat change [5,9,16–19], electromagnetic fields [5,9,16–18,20], noise [5,9,16–18,20], artificial reefs [9,10,18], and fishery avoidance [9,17,18]. However, quantitative assessments (and monitoring) of the impact of OWE development on marine life have been limited to only a few areas (the southern North Sea [21], Dutch North Sea [21–23], Belgian part of the North Sea [21], and the UK [24,25]), and specific impacts (artificial reefs [21,24], bottom-trawling avoidance [25], and noise [22]). To better quantify the impacts on marine biodiversity, a more comprehensive assessment method is required, that takes into account long-term cumulative effects of different stressors on marine communities instead of individual species [9].

Life cycle assessment (LCA) is a method to quantify environmental impacts over the life cycle of products. It has been used to assess the environmental impacts of electricity production from OWE on a global scale, focusing on impact categories such as climate change, marine ecotoxicity, and marine eutrophication [26]. However, life cycle impact assessment (LCIA) methods to assess effects on marine biodiversity are still at an early stage of development, and much less mature than LCIA methods for terrestrial and freshwater biodiversity [27]. Nonetheless, LCIA methods that quantify seabed disturbance impacts on ecosystem quality have been developed. One method takes into account the change in seabed type, and how long this change lasts [28]. Another LCIA method enables assessing the impacts of noise pollution on cetaceans [29]. Both are relevant to OWE development, but they are based on different taxa and different reference states, which do not allow for a comprehensive assessment on their own. Other LCIA methods with a focus on marine biodiversity, such as for ocean acidification [30] or plastic debris entanglement [31], do not cover impact categories that are at the core of the impacts expected from OWE development, such as habitat change. Further, prior studies have mainly used hypothetical frameworks due to incomplete knowledge of the environmental mechanisms (e.g. theoretical benthic response and recovery times) and a lack of empirical data. Characterization factors (CFs) within LCIA that consider multiple relevant impacts in a consistent manner, including also positive impacts (e.g., artificial reef effect) and potential indirect impacts (e.g. trawling avoidance), are still missing.

This study aims to assess the macrobenthic (infaunal and epifaunal benthic organisms > 1mm, living within or on the seabed, respectively) biodiversity changes from artificial reefs, seabed occupation and trawling avoidance caused by the OWF operation. The macrobenthos plays an essential role in marine ecosystem functioning by degrading organic matter and transferring energy to higher levels in the marine food web [32], acting as a food source for demersal fish species and crustaceans [33,34]. The benthic biodiversity changes on hard substrates and soft sediment in different effect distances were estimated and translated into CFs. These OWE-specific CFs were derived and integrated into the LCIA framework to assess the OWE development impacts in the North Sea. This study provides a stepping stone towards a better understanding of marine biodiversity change caused by OWE development and a new perspective on sustainable OWF management.

4.2 Materials and methods

4.2.1 Scope and study area

This paper develops CFs to calculate the impacts on biodiversity changes per turbine, per MW, and per total installed capacity (fleet) across the assumed 25 years of OWF operation [26]. Biodiversity was represented by the commonly used indicators species richness and abundance. The impacts from installation and decommissioning were excluded as they are likely temporary (several months or years) and localized when compared to impacts from operation [35]. Due to data scarcity, other communities were out of the scope of this study. We used both sediment infauna and hard substrate epifauna data from OWFs and their control sites in Denmark, Germany, the Netherlands, and Belgium (**Figure 4.1**). Samples from one research platform (i.e. BeoFino), which was placed in German waters to study impacts before any OWF had been installed, were also used (**Table 4.1**). Sample data in other countries with OWE development were either not found or inaccessible (e.g. the UK). The studied OWFs, control sites, and the research platform have similar environmental conditions as they are located in the North Sea ecoregion with similar habitat types, i.e. offshore circalittoral sand or muddy patches. All wind farms have fix-bottom-based foundations (Monopile, Jacket or gravity-based) and are located in shallow waters (<50 m water depth).

4.2.2 Sample pre-processing

Samples were taken both on hard substrates by divers scraping fauna from the OWF/research platform foundations and from the scour protection rocks, or by collecting smaller rocks as a whole, and from soft sediment by using box cores, and Van Veen grabs. Note that soft sediment data was only available in two wind farms (C-Power and Princes Amalia). For more information on the sampling method, we refer to Coolen et al. [21,42]. Organisms were identified to the species level. Sample coordinates, sample date, sample type (hard substrate or soft sediment), and sample size were registered for each OWF/research platform (**Table 4.1**). Installation age was calculated based on the time since installation and rounded to the nearest calendar year. We did not take into account that wind turbines were constructed gradually over time in a wind farm. Temporal distribution of the samples and basic information of OWFs, e.g. status of OWFs and number of turbines, are shown in **Table S4.1**. Samples collected before installation were excluded since insufficient data was available from the different datasets.

4.2.3 Sample geo-processing

To distinguish different OWE interventions (i.e. seabed occupation, artificial reefs, and trawling avoidance), samples were categorized into two substrate types (STs), i.e. **Hard** (hard substrate) and **Soft** (soft sediment). Samples were further classified into three effect locations (ELs) by distance, i.e. **Outside** (distance to the nearest wind farm >500 m), **Near** (distance to the nearest wind farm <=500 m & distance to the nearest turbine >=250 m), and **Immediate** (distance to the nearest turbine <250 m) (**Figure 4.1**). The distances to the nearest farm and the nearest turbine were calculated by ArcGIS Pro toolbox "Geoprocessing" – "Near". We used wind turbine coordinates from the global OWF database

[36]. We defined a convex hull of each OWF, i.e. the smallest convex polygon that contains all wind turbines of a farm, and added a buffer (500 m) by using ArcGIS Pro to delineate a 500-m security zone around a farm, within which bottom trawling is generally prohibited [37]. We assumed that seabed occupation and artificial reefs impact macrobenthos within 250 m diameter of the wind turbine foundation [38]. In summary, our dataset covers between 39 and 923 samples for each combination of substrate type and effect location (**Table 4.1**).

4.2.4 Biodiversity model fit and estimation

Sample data (covering up to 11 years of turbine life) was used to fit a generalized linear mixed model (GLMM) and then estimate the biodiversity values from 12 to 25 years after installation.

$$B \sim Age + ST + EL + r(WF) + o(ln(Sample_{area})) \quad (1)$$

where biodiversity (B) is represented by species richness and abundance. A Poisson distribution with an ln link was used in the GLMM. Installation age (Age), substrate type (ST), and effect location (EL) were considered key parameters for biodiversity and included as fixed effects in the model. We added the wind farm (WF) to the model as a random effect, i.e. $r(WF)$, as samples taken in the same year, substrate type, or effect location could be affected by wind farm variation in environmental conditions. The offset term $o(ln(Sample_{area}))$ was used to adjust the richness for different spatial extent within sampled surface area, since the richness and sampled area relation is non-linear [39]. Abundance was directly standardized to a sampled area of 1 m^2. The assumptions of homogeneity of variance, normality, and variable collinearity were checked and a diagnosis report can be found in **S4.2.4** in chapter 7. Additionally, a model validation was conducted and prediction error-based indicators were reported in in **S4.2.4** in chapter 7. R version 4.0.1 [40] and RStudio version 2022.2.1.461 [41] were used for the data analysis.

Species diversity from five oil and gas platforms (**Outside-Hard**) (**Table S4.3**), operated by ENGIE Exploration & Production Nederland B.V. (ENGIE), was calculated as a sanity check for richness and abundance in **Immediate-Hard**. The oil and gas industry has a long history of offshore development in the North Sea and implements a similar foundation structure as offshore wind farms. Although with considerable uncertainty in quantification and with annual fluctuation, the evolution of biodiversity from 12 to 25 years after OWF installation was assumed to be similar to observed old oil and gas platforms. The average values of richness and abundance from the installation of these platforms (in the period 1972-1999) to 2014-2015 were calculated. The biodiversity values from the GLMM were cut-off and corrected if they went beyond the range of those in the oil and gas platforms.

4.2.5 Characterization factor (CF) development

We developed CFs based on the difference in biodiversity (B) between the OWE intervention (seabed occupation, artificial reefs, or trawling avoidance) and the associated reference state (RS), which is a state represents today's state but without such intervention. The average biodiversity values (richness and abundance) in different ELs and STs from installation to 25 years of operation were used to reflect the benthic response to an intervention.

$$CF = 1 - \frac{B_{OWE}}{B_{RS}} \quad (2)$$

The proposed CFs express the potentially disappeared fraction of species (PDF) or abundance (PDF_A). Therefore, positive CF (ranges from 0 to 1) reflects a relative loss of species or decrease in abundance. Negative CF (any negative number) represents a relative gain of species or increase in abundance. Different ELs and STs result in three CFs in line with three interventions, i.e. artificial reefs (CF_{AR}), seabed occupation (CF_{SO}) and trawling avoidance (CF_{TA}). Artificial reefs and seabed occupation are relatively local (**Immediate**). Trawling avoidance impacts larger areas (both **Immediate** and **Near**). More specifically, CF_{AR}, CF_{SO}, and CF_{TA} were quantified based on **Immediate-Hard**, **Immediate-Soft**, and **Near-Soft**, respectively. CF_{TA} excluded **Immediate-Soft** as seabed occupation also affects the **Immediate-Soft**. The RS for CF_{AR} and CF_{SO} was set to **Near-Soft** to isolate their effects, as trawling avoidance affects both the **Immediate** and **Near** effect locations. The RS for CF_{TA} was set to **Outside-Soft**, which represents the natural variation of biodiversity.

4.2.6 Inventory analysis and impact assessment

To assess the impacts (biodiversity changes) of each intervention and discuss the cumulative impacts, our CFs were further combined with associated affected areas along the OWF operation time in line with three functional units (per turbine, per MW, and fleet). Artificial reefs and seabed occupation have the same size of impact areas (i.e. **Immediate,** 0.0625 km^2 per turbine), although they impact different ST (i.e. **Hard** and **Soft**, respectively). Trawling avoidance has a larger impact area (i.e. **Near**), and its impact area per turbine was calculated based on the size of the wind farm with a 500 m buffer divided by the wind turbine count. The size of each wind farm with the buffer was calculated by ArcGIS Pro toolbox "Geoprocessing" – "Calculate Geometry Attributes". The impact assessment results per turbine were further converted to per MW and per fleet. Lifetime extension and turbine size growth are expected in the future, which control the affected time and area, respectively. The average individual turbine capacity is likely to reach 20 MW (compared to ~6 MW in 2020) and lifetime will increase to 30 years in 2050 [26]. The impacts per MW were calculated based on impacts per turbine divided by average individual turbine capacity. A linear regression was used to model the turbine capacity projection to 2040 [26] and extended to 2050 (**Table S4.4**). The area affected by artificial reef and seabed occupation effects is assumed to be proportional to the foundation size. The area subjected to trawling avoidance depends on the OWF size (further details in **S4.2.6** in chapter 7). In terms of fleet impacts, 300 GW of installed OWE capacity is targeted in the North Sea by 2050 [2]. Considering the turbine size development, the North Sea will require 15,000-50,000 wind turbines by 2050.

4.2.7 Sensitivity analysis

Impact areas may change depending on the ecological context and reference state [42]. To carefully address different spatial scales in the evaluation of three interventions, we conducted a sensitivity analysis by altering the thresholds used for the EL categorization by 50%, i.e. ±50% of 500 m buffer around the wind farm and ±50% of 250 m distance from the turbine. An additional sensitivity analysis was conducted by comparing results of only considering the observations (average biodiversity values through 11), and max yearly average within the data range (observed at age 11) to the whole time series (with estimation until age 25). Further, results of randomly leaving out 20% of samples were compared to those with all samples.

Table 4.1: Sample data overview, with columns for the country offshore wind farm belongs to (Country), offshore wind farm name (Wind farm), maximal installation age (Age max), samples in different effect locations and substrate types (Immediate-Hard, Near-Hard, Immediate-Soft, Near-Soft, and Outside-Soft), and data source.

Country	Wind farm	Age max	**Immediate-Hard**	**Near-Hard**	**Immediate-Soft**	**Near-Soft**	**Outside-Soft**	Data source
Belgium	Belwind	10	64	0	0	0	0	[43–45]
Belgium	C-power	11	21	124	14	193	152	[43,46–48]
Denmark	Horn Rev 1	3	289	504	0	0	0	[43,49,50]
Germany	Alpha Ventus	4	216	0	0	0	0	[43,51,52]
Germany	BeoFino	5	218	0	0	0	0	[43,53–55]
Germany	DanTysk	6	36	0	0	0	0	[43,50]
The Netherlands	Prinses Amalia	7	79	0	25	72	109	[23,43,56,57]
Total			923	628	39	265	261	

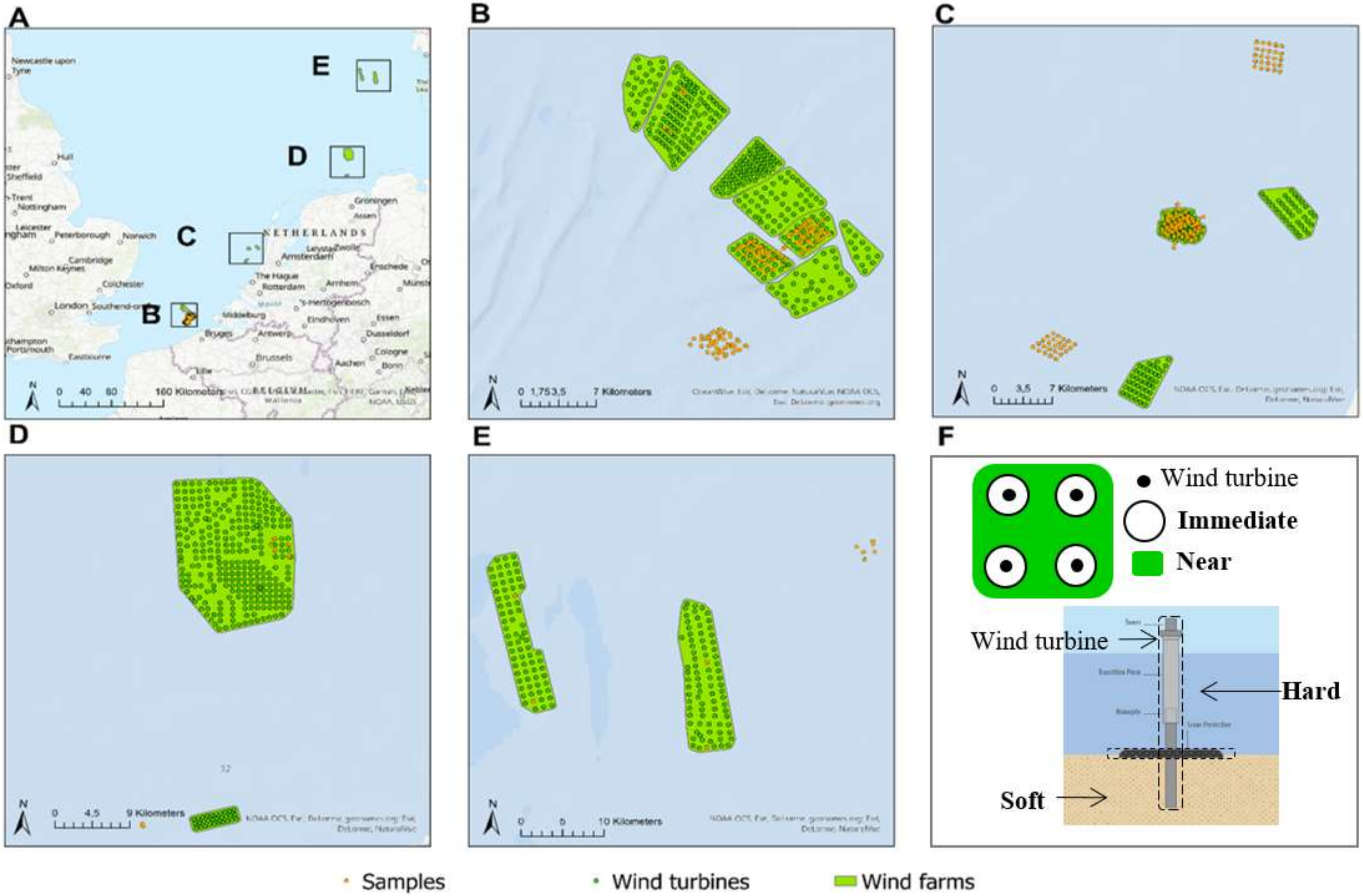

Figure 4.1: Overview of studied offshore wind farms (green areas) with turbine foundations (green dots) and sample locations (orange dots). **A**: the North Sea; **B**: Belgium; **C**: the Netherlands; **D**: Germany; **E**: Denmark; **F**: an illustration figure of effect locations (**Immediate** and **Near**) and substrate type (**Hard** and **Soft**). The maps were drawn using ArcGIS Pro, and the base map is the World Topographic Map from Esri (http://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f).

4.3 Results

4.3.1 Biodiversity evolution in different effect locations (ELs) and substrate types (STs)

Species richness and abundance on hard substrates are greatly higher than on soft sediment and will increase over time since OWF construction (**Table S4.6**, **Figures 4.2** and **4.3**). Species richness in **Immediate-Hard** will increase from ~17 species per 0.01 m^2 one year after installation to ~23 species per 0.01 m^2 at the end of the OWE turbine lifetime (**Figure 4.2**). Abundance in **Immediate-Hard** at the end of turbine lifetime is expected to quadruple compared to one year after installation (**Figure 4.3**) as the community structure gradually changes after the switch from soft to hard substrate. Sanity check results (**Table S4.3**) show that the species richness and abundance values in **Immediate-Hard** are within the range of that oil and gas platforms (**Outside-Hard**).

Species richness in all **Soft** categories is below 13 per 0.01 m^2 along the turbine lifetime (**Figure 4.2**). Species richness in the **Immediate-Soft** is slightly lower than in the **Near-Soft** and much lower than in the **Outside-Soft** (**Figure 4.2** and **Table S4.6**). Spatially, species richness decreases toward wind turbines. Species abundance in the **Immediate-Soft** is higher and slightly higher than that in the **Near-Soft** and **Outside-Soft**, respectively (**Figure 4.3** and **Table S4.6**).

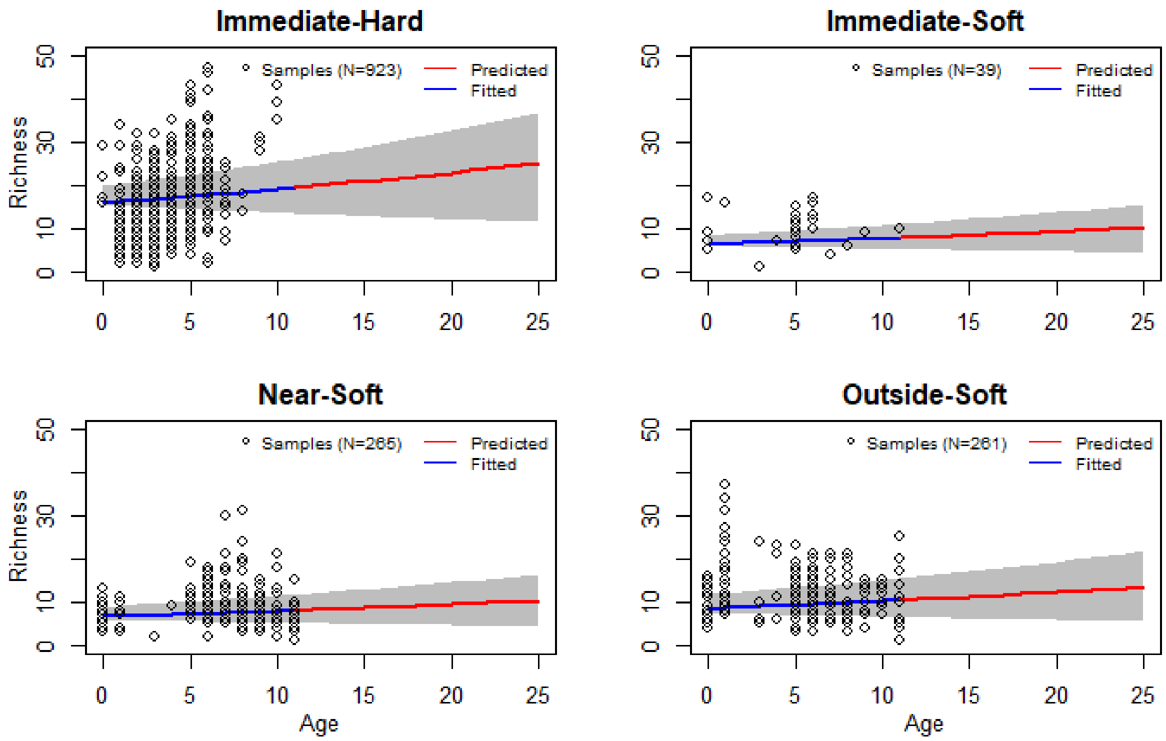

Figure 4.2: Species richness evolution from installation to 25 years afterwards. The grey shaded area shows the 95% confidence interval.

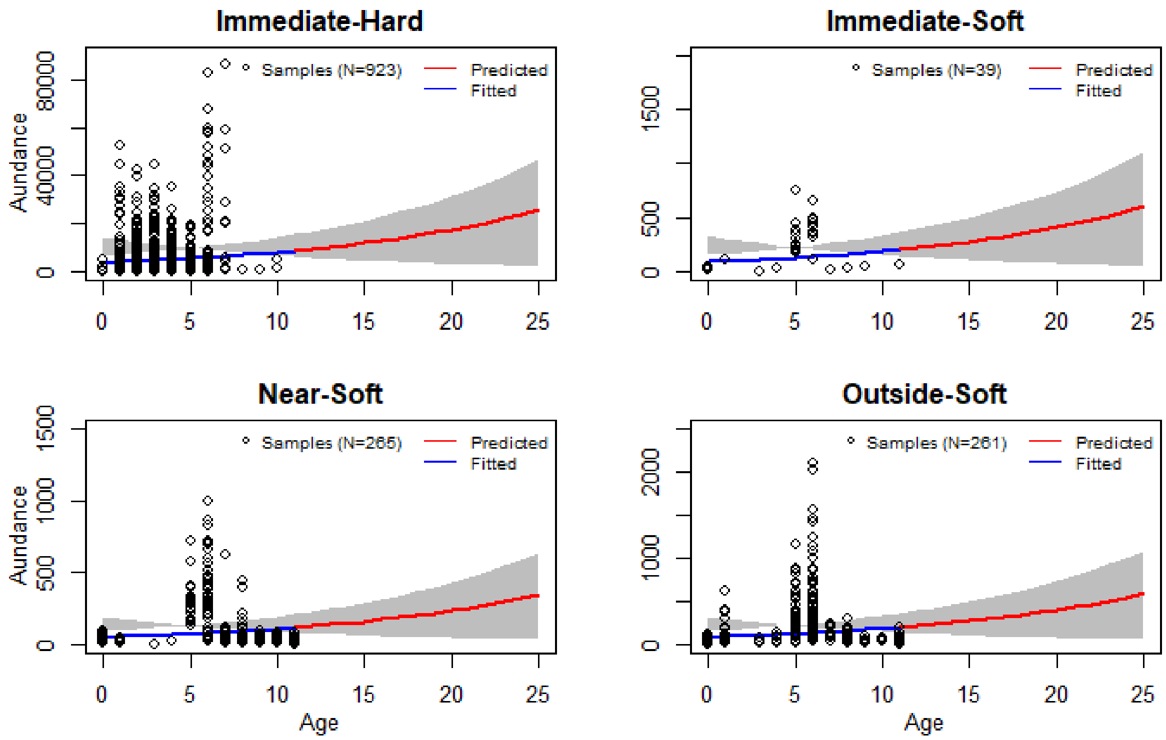

Figure 4.3: Species abundance (individuals/m^2) evolution from installation to 25 years afterwards. The grey shaded area shows the 95% confidence interval. Note that the subplots are not directly comparable because the y-axis limits differ.

4.3.2 Characterization factors

We apply the developed CFs to biodiversity changes associated with three OWE interventions (i.e. artificial reefs, seabed occupation and trawling avoidance) in characterisation perspectives:

1) Artificial reef: Marine benthic biodiversity on hard substrates will significantly increase due to the artificial reefs. CFs for artificial reefs (CF_{AR}) show -0.88 PDF and -42.87 PDF_A (**Table S4.6**, **Figures 4.4** and **4.5**), which indicates a doubling of species richness and an increase by 2 orders of magnitude for abundance on hard substrates.
2) Seabed occupation: CFs for seabed occupation CF_{SO} range from -0.41 to 0.39 PDF and from -2.14 to 0.05 PDF_A (**Table S4.6**, **Figures 4.4** and **4.5**). So, for the effect locations and substrate types for which we assume seabed occupation effects, both positive and negative impacts can occur.
3) Trawling avoidance: Our results do not reflect the trawling avoidance benefits from the OWF. Nonetheless, we apply the average of negative values as the CF results for trawling avoidance, i.e. -0.10-0.00 PDF and -0.01-0.00 PDF_A (**Table S4.6**, **Figures 4.4** and **4.5**).

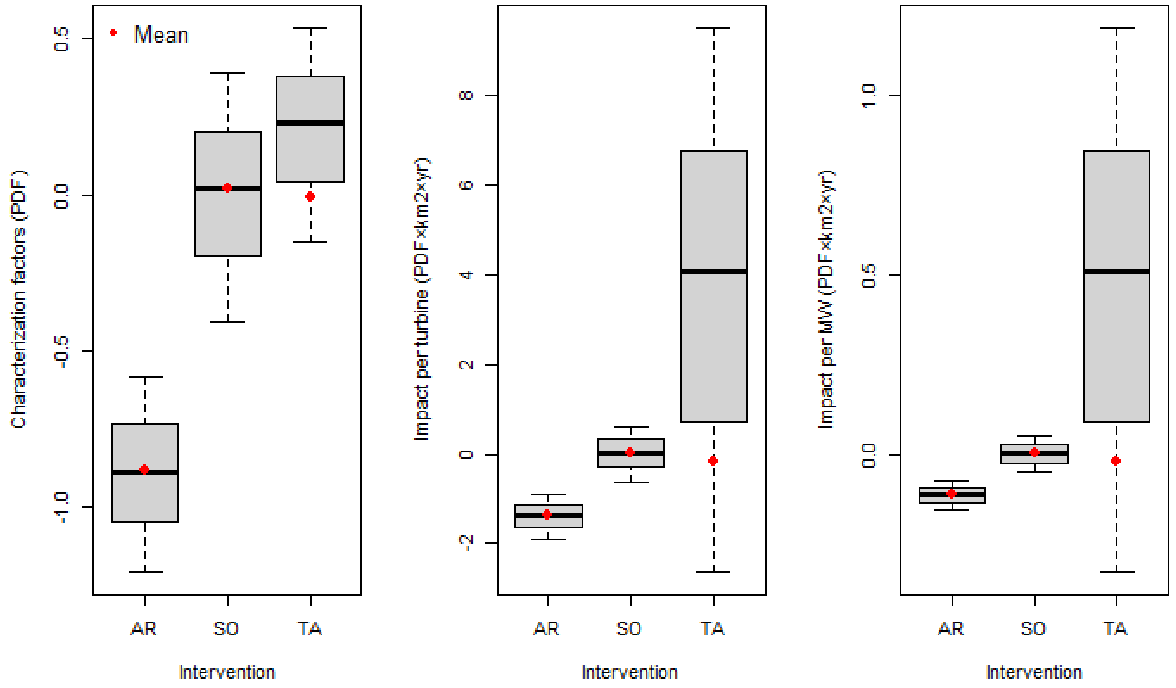

Figure 4.4: Characterization factors and impact assessment results for species richness. AR: artificial reefs, SO: seabed occupation, and TA: trawling avoidance. The average values (red points) are used for CFs and impact assessment results in this study. Note that the average of negative values are applied for TA.

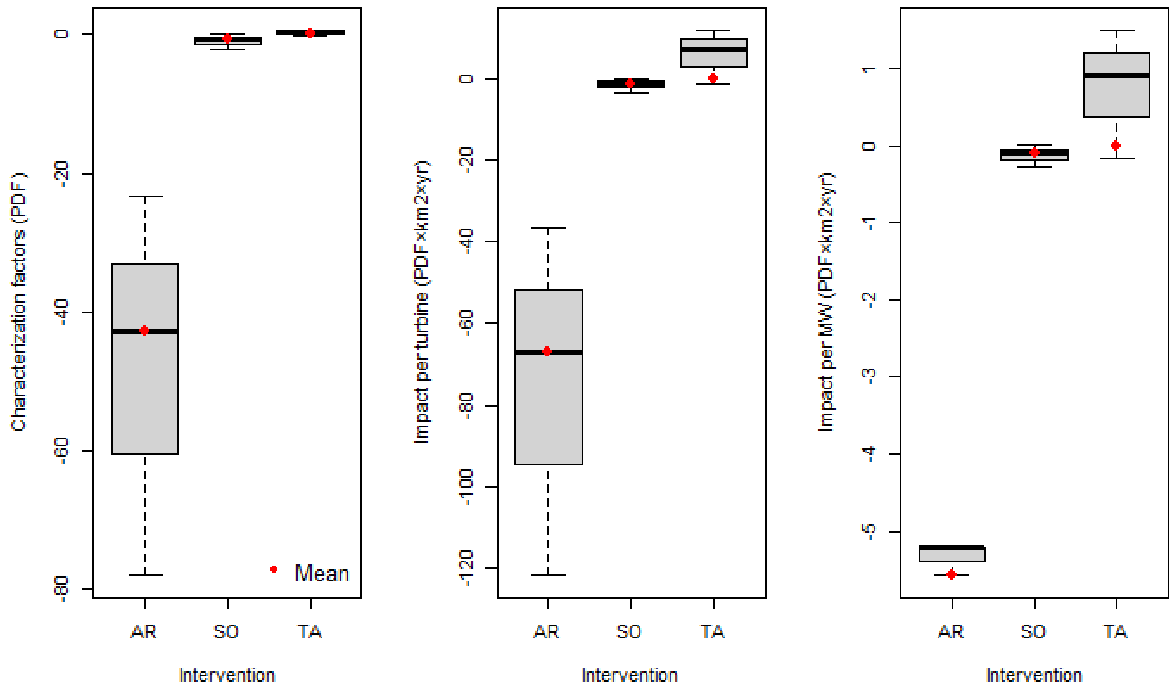

Figure 4.5: Characterization factors and impact assessment results for species abundance. AR: artificial reefs, SO: seabed occupation, and TA: trawling avoidance. The average values (red points) of CF and impact assessment results are used in this study. Note that the average of negative values are applied for TA.

4.3.3 Inventory analysis and impact assessment

The impact area for artificial reef and seabed occupation effects is 0.06 km^2 per turbine. 0.71 km^2 of area per turbine is supposed to be affected by trawling avoidance based on the studied OWFs. Impacts of artificial reefs on species richness and abundance are -1.38 PDF $km^2\times yr$ and -66.99 $PDF_A\times km^2\times yr$, respectively. Impacts of seabed occupation are approximately 1.35 (98%) PDF×$km^2\times yr$ and 65.86 (98%) $PDF_A\times km^2\times yr$ lower than the absolute values of artificial reef effect, respectively. Trawling avoidance effects range from -1.89 to 9.31 PDF×$km^2\times yr$ and from -1.41 to 11.98 $PDF_A\times km^2\times yr$ (**Figures 4.4** and **4.5**). In summary, one turbine has net biodiversity gains for benthic species (based on the average of negative values of CF_{TA}), i.e. -1.34 PDF×$km^2\times yr$ and -65.64 $PDF_A\times km^2\times yr$.

As wind turbine sizes grow, artificial reef and seabed occupation effects could slightly decrease per MW since large turbines have smaller affected areas per MW than smaller turbines. However, the trawling avoidance affected areas per MW could greatly increase when turbine size and thus distance between foundations expands (**Table S4.4**). Wind turbine lifetime extension will increase all impacts discussed in this study. Impact assessment results per fleet show that impacts from -1.01×10^5 to -5.71×10^4 PDF×$km^2\times yr$ and from -3.72×10^6 to -2.61×10^6 $PDF_A\times km^2\times yr$ are expected in the North Sea from 2020 to 2050.

4.3.4 Sensitivity analysis

Our results demonstrate that ±50% of 500 m buffer is responsible for only slight changes in CFs. However, ±50% of 250 m will considerably affect the CF results. There is no substantial difference between CF results when considering estimated values and without considering estimated values (average values through age 11 or max yearly average within the data range). The species richness and abundance in all categories increase over time, which shows the robustness of CF results. Randomly leaving out 20% of samples hardly affects the CF results (**Table S4.7**).

4.4 Discussion

Knowledge impacts of OWE development on marine biodiversity are still limited. To our knowledge, this is one of the first studies to explore patterns of change in marine biodiversity in different ELs and STs. This study takes one step further by extrapolating marine biodiversity in time/area, and integrating this knowledge into a broader perspective by developing empirical CFs that can be used in LCA studies. Three developed CFs enable to separately assess three interventions by the OWE development, i.e. artificial reefs, seabed occupation, and trawling avoidance. Although the interventions considered in this study act simultaneously during OWF operation, they affect different ELs and STs with different benthic communities. Adopting separate CFs broadens the application of CFs and each CF could be used for similar interventions by other marine activities (e.g. CF_{SO} is also relevant to cable laying). The developed CFs provide a stepping stone towards a better representation of biodiversity in LCA studies. Although the simulation goes beyond observed data, our sensitivity analysis verifies the feasibility of considering the 25-year operation time (**Table S4.7**). Scenarios will be developed to show different trajectories of future biodiversity evolution. Future research should extend such monitoring time series and consider more site conditions. For instance, site monitoring should happen more before the OWF construction and continue throughout the OWE lifetime. Monitoring should also include (future) sites outside the current developed areas. Moreover, more monitoring efforts should be done in soft sediment, which enables us to better understand specific interactions with the local marine environment and take steps to avoid or minimize negative impacts. This could be achieved by parameterizing our CFs by considering more site-specific environmental parameters (e.g. more detailed substrate types, water depth, water temperature, and seasonal patterns). Collaborative efforts from industry, academia and government are needed to leverage more knowledge, data, and resources [58].

4.4.1 Interpretation and limitations of CFs

The enhancement of forage base and piscivorous predators by the artificial reefs could explain the increase in biodiversity on hard substrates [59]. However, artificial reefs will also attract new species (non-indigenous species). The positive CF results for seabed occupation might be explained by a substantially higher mortality/migration of certain native benthic species within immediate zone than in surrounding areas, but the impact is short-term (1 year), especially in sandy sediments that are poor in infauna diversity [35]. The increased biodiversity in the nearby hard substrates can partly spill over to the soft sediments, as deposition in the form of faecal pellets expelled by filtering epifauna leads to an increase in organic matter [60]. This could also be considered an effect of artificial reefs, although the CFs for the artificial reefs in our study refer to that on hard substrate. Consequently, the biodiversity of the original soft sediment fauna decreases slightly, but new (other) species come into the area, so the species richness and abundances increase [46].

A limitation of our work is that, in line with the current LCIA methods for biodiversity, we took into account species richness and abundance only. Future research is required to understand the ecological effects [44] of biodiversity change. This could be done by expanding the analysis to community level, looking into the potential modification of community structure. The slight decreases in species richness and an increase of abundance in the immediate soft sediment might lead to a less healthy community in certain directions around a wind turbine [61]. The introduction of artificial reefs might trigger an increase in the opportunistic species density [62]. We acknowledge that in general, this statement might be true for areas hosting rare species, such as gravel beds. For the Belgian and Dutch OWFs, the original community consisted of opportunistic species. Macrobenthos in the species-poor sandbanks recovered quickly after OWF construction and no rare species were lost [62].

It is difficult to demonstrate a trawling avoidance effect since our soft sediment data was only collected in two OWFs (C-Power and Princes Amalia) in relatively short time frames. Another issue is that there are currently no good control sites. Natural spatial variability complicates the detection of a trawling avoidance effect. The biodiversity values in the reference area outside of Belgian wind farms were already higher than within the wind farms before OWF installation [35]. The locations studied were geographically separated, and future research needs to include natural reefs. A larger sample size through more wind farm studies in a longer temporal range is also required to properly test this effect. OWFs are currently closed to trawl fisheries in the North Sea [63]. In Germany, the OWE development is assigned high priority to sea use and adheres to strict safety regulations [64]. Bottom-disturbing activities, like anchoring or dragging of fishing gear, are forbidden within the Dutch and Belgian OWF safety zones [65]. However, the trawling avoidance by the OWFs may cause more intensity of trawling in areas outside OWFs. When wind turbines become bigger with larger spacing between turbines, ships would be allowed to pass through OWFs [65], although trawling is still forbidden. The trawling free zones within OWFs have been considered multi-use options to better use ocean space for energy generation [66,67]. For example, integration floating photovoltaics into OWFs will increase power conversion efficiency and seem to have insignificant effects on fish populations, although long-term environmental impacts, e.g. shading effects, remain unexplored [68].

4.4.2 Effect of geography and range

The results presented in this study may not be suitable to be applied in other ecoregions as different habitat types may have different patterns of change in benthic communities. Results based on three years of sample data from the Block Island wind farm in the US [69] (**Table S4.8**) show major differences in species richness and abundance compared to the North Sea. Further onsite sampling efforts for OWFs in other ecoregions will benefit a better understanding of biodiversity change on a larger scale. However, the proposed CFs could still be applied in other ecoregions as similar effects might be expected to occur elsewhere. In addition, at the regional scale, this study focuses on the North Sea, which is one of the OWE hotspots.

Artificial reefs and seabed occupation can have larger effect areas than we considered in this study. However, to what extent the effects will impact benthic communities outside the diameter of the wind turbine, in soft sediment, or even the pelagic compartment remains unknown. It is also challenging to separate anthropogenic impacts and natural variability in the OWE developed areas [70]. Long-lasting monitoring in **Immediate** and **Near**, at the surface and near the bottom of the wind turbine are required to gain a better understanding of how effects radiate outward from the wind turbine and how far. More samples in control/reference sites also allow for better sampling designs. Further, monitoring efforts should move towards information-rich data collection (e.g. distilling site-specific and ecological responses across areas and species), thus allowing a broader scale of interpretation of OWE interventions [7]. Monitoring methods like environmental DNA (eDNA) metabarcoding with a higher chance of detecting species could be an alternative to the current time-consuming and costly routine biomonitoring [71].

4.4.3 Interventions in other life cycle stages

The macrobenthic biodiversity can be affected and/or modified by OWF installation and decommissioning [9], although these effects are likely to be more localized and shorter when compared to that of OWF operation. Processes during installation, e.g. pile driving, dredging and smoothing, create noise and vibration that impact seabed habitats [10]. This study did not take into account that wind turbines were constructed gradually over time in a wind farm, and construction may continue after the first turbines already start operation. The OWF installation time is highly uncertain and depends on, for instance, OWF size, foundation type, site condition, and equipment availability [72]. ~20% of samples were collected at an installation age of 0 or 1, which might affect our results as some impacts might come specifically from installation. Effects from decommissioning are still poorly known as only a limited number of OWE projects have been decommissioned. The complete removal would be the opposite process of installation [18], but it is controversial due to potential impacts on the ecosystem. Proposals for alternative uses of hard substrates from the OWE infrastructure, e.g. renewables-to-reefs [73], are expected. Partial removal (cutting part of the foundation and leaving the rest in situ) will create lesser disruptions to the colonizing benthic communities around the foundations [74]. There are also social and engineering aspects to be considered in removing a foundation. Future studies should consider more interventions along the OWF life cycle and assess the cumulative effects. Some lessons could be learned from the oil and gas industry [37].

4.4.4 Technology

Different OWE foundation technologies will create different artificial reefs in terms of size and materials [75], which affect the success and degree of habitat creation and use [76]. Foundation technologies also determine the installation and decommissioning processes [77], which result in varied stressors on the seabed with different impacts on benthic communities (**Table S4.9**). Future work is needed to include more foundation types, especially floating foundations, which are assembled on land and then connected to mooring cables. Although anchor installation may involve pile driving and mooring cables that produce noise during operation, the floating foundations are expected to cause less vibration and noise than fix-bottom-based foundations. Turbine (i.e. nacelle, rotor, and tower) and transmission (e.g. cables, transformers and substations) technologies are expected to have minor impacts with slight variations on benthic species.

4.5 References

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Chapter 5

Optimal technology and choice of location can halve the North Sea's offshore wind energy environmental footprint

This chapter has been prepared to submit to Nature Sustainability

Abstract

Offshore wind energy (OWE) is expected to play a key role in the energy transition. While being a renewable energy technology, offshore wind farms (OWFs) can have considerable environmental footprints. It concerns their substantial material demand next to greenhouse gas (GHG) emissions in their supply chains. These concerns require further analysis of potential mitigation strategies. This study spatially assesses the material, carbon and biodiversity footprint of potential OWF locations in the North Sea, next to their low-carbon energy generation potential, taking into account future technological developments. We find that the northern North sea, particularly near shore areas, seems the best location to site the envisaged future 180 GW OWE capacity. Using current technology, a capacity at that location only requires only 8.1 Mt embodied GHG emissions per annum, while annually 312 Mt GHG emissions are avoided if produced with the current continental European electricity mix. Conversely, the central North Sea has drawbacks such as large copper and aluminum requirements and related embodied GHG emissions due to large distances to shore, next to high overlap with biodiversity protected areas. Developing OWFs in the optimal locations with cleaner technological development, mainly turbine size enlargement, has the potential to halve all current environmental footprints.

5.1 Main

Offshore wind energy (OWE) development is increasingly implemented in many coastal regions. There is a growing need to accurately pinpoint and understand the environmental footprint related to OWE deployment. It is particularly important to understanding how the location of offshore wind farms (OWFs) may create a trade-off between electricity production on the one hand and material, biodiversity and greenhouse gas (GHG) footprints of their development on the other hand [1]. The North Sea is an attractive sea basin for OWE development, due to rather strong and continuous winds, relatively shallow water [2] and proximity to extensive energy and electricity markets [3]. Consequently, the North Sea is globally at the forefront of OWE development. Since 2011, the overall installed capacity in the North Sea has tripled to around 19 GW by 2020, reaching two thirds of the global installed OWE capacity [4]. In a continuous push to harvest OWE, plans for the North Sea region now aim at 180 GW of installed capacity by 2050 [5], roughly a 10-fold increase from contemporary values, to supply 800 TWh of electricity per year [6]. These large-scale OWFs will cover roughly ¼ of the total surface of the North Sea (Figure 1). They also will need substantial quantities of bulk and critical raw materials, for manufacturing offshore wind turbines, foundations, and transmission components. Furthermore, the manufacturing, installation, and operation of OWFs have additional direct and indirect impacts on the environment such as GHG emissions and marine biodiversity due to, among others, energy use in material manufacturing, seabed occupation, material and personnel transport.

To ensure the greenest possible OWE deployment, a balancing of various factors and trends needs to be taken into account: 1) better wind resources are often encountered farther offshore in deeper waters, 2) greater turbine efficiency and capacity depends on enlarging the turbine size, requiring an increase in rotor diameter, hub height and, consequently, the larger size of support (e.g. foundation) structures [7], 3) rapidly advancing technologies change the material composition and type of components (e.g. generator, rotor, and blades) [7, 8], 4) wind turbine lifetimes are increasing with time.

Here, we analyse the implications of spatial/geographical siting choices and technological improvements of OWFs in the North Sea on the environmental footprint per MWh electricity produced across the full OWE turbine life cycle including end of life, such as material demand, impacts on biodiversity, and impacts on global warming. We analyse this footprint per MWh of electricity produced by the OWE on specific locations by considering multiple geographical factors, including wind speed, water depth, and distance from shore. We compare present day (2020) technologies and estimates of a future (2040) emergent technology mix, characterised by e.g. enlarged turbine sizes, longer lifetimes, and improved component technologies (see more details in the Method). We estimate material demand for the nacelle, rotor (including blades), and tower using a dynamic material flow analysis [7]. We add the material use for the foundation and transmission infrastructure by considering the water depth and distance from shore, respectively. Using such site-specific material demands per MWh electricity production we calculate the life cycle GHG impacts by using a prospective life cycle assessment model as described in earlier work [8]. Our model does include life cycle impacts related to these materials for climate change (GHG emissions; in this paper expressed in GWP100 CO2-Eq), marine ecotoxicity, marine eutrophication, and metal depletion (expressed as METPinf kg 1,4-DC-Eq, MEP kg N-Eq, MDP kg Fe-Eq respectively; see **Figure S5.3** and [8]). We further calculate the requirement for finished materials, including steel and copper, and show how these compare to current global demand, since this is more intuitive that using one of the life cycle impact assessment scarcity indicators. We investigate the impacts on biodiversity by screening overlap with protected areas of potential OWE locations. This comprehensive analysis can be used by government for the OWE strategic planning that not only allows to detect the major hotspots in environmental impacts for North Sea OWE, but also the least-impactful locations for OWFs per MWh of electricity produced.

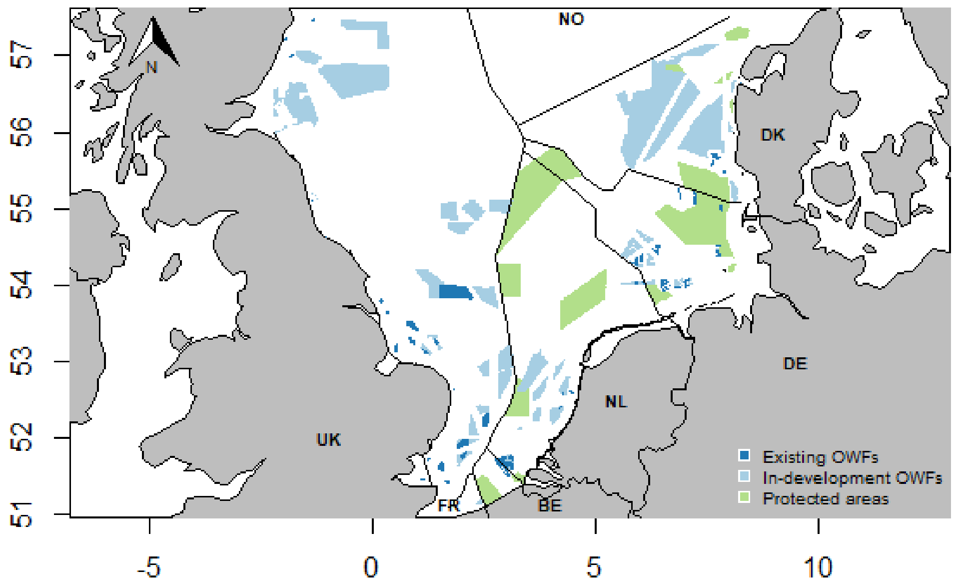

Figure 5.1: Overview of the North Sea, including the Norwegian (NO), Danish (DK), Germen (DE), Dutch (NL), Belgian (BE), French (FR) and the United Kingdom (UK) Exclusive Economic Zones (EEZs); existing and in-development (including under construction, approved, and planned) offshore wind farms (OWFs), and protected areas.

5.2 Results

OWE locations and environmental footprint

Figure 5.2 and **Figure S5.1-S5.3** show maps with basic characteristics per location (wind speed, water depth, distance from shore, and capacity factor (**Figure S5.1**)), material requirements per MWh electricity produced (**Figure 5.2** and **S5.2**), and , and Life cycle impacts per MWh electricity produced (**Figure 5.2** and **S5.3**). These figures show the following.

The northeastern and western nearshore areas exhibit favorable wind resources in combination with low water depth (**Figure S5.1**). This implies a low steel need for foundations and low copper and aluminum need for transmission. Overall, this leads to the lowest material demand and life cycle environmental impacts per MWh electricity produced (**Figures 5.2, S5.2** and **S5.3**) compared to other regions.

OWFs located further offshore regions require a higher demand for copper and aluminum (**Figures 5.2** and **S5.2**), as they require more transmission infrastructure, such as cables. OWFs in offshore regions also have more transport and other impacts related to operations and maintenance (which may contribute about one-fifth to overall GHG emissions across the full turbine life cycle [8]). These factors imply OWE placed in the central North Sea incur higher embodied GHG emissions and other environmental impacts per MWh electricity produced throughout the full turbine life cycle, despite the favorable wind resources in the region (see **Figure S5.3**). Further, the development of OWE in the central North Sea foresees a large overlap with protected areas (**Figure 5.1**). In particular, OWE development in the Dogger Bank located in the central North Sea needs to carefully address ecological concerns [9]. Future installations in central areas of the North Sea should focus on efficient O&M practices (e.g. detailed vessel routing planning) and component technological advancements (e.g. more usage of direct drive nacelles with fewer failure rates [8]).

Table 5.1: The average environmental footprints (material demand and life cycle impacts) per MWh electricity production of existing and in-development (In-dev), including under construction, approved, and planned OWFs (see **Figure 5.1**) by EEZ in the North Sea, based on the current (2020) OWE technology mix.

Exclusive economic zone (EEZ)	Material demand						Life cycle impact categories							
	Steel (g)		Copper (g)		Aluminium (g)		Climate change (kg CO_2-Eq)		Marine ecotoxicity (kg 1,4-DC.)		Marine eutrophication (kg N-Eq)		Metal depletion (kg Fe-Eq)	
	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev
Belgian	579.51	-	18.73	-	2.47	-	10.31	-	882.12	-	3.61	-	10.09	-
Danish	338.00	774.76	17.82	27.31	2.40	3.13	7.68	9.93	679.80	665.69	2.74	3.07	7.81	7.33
Dutch	605.96	584.84	19.28	21.47	2.51	2.68	10.07	10.51	850.67	823.83	3.50	3.51	9.71	9.31
French	-	-	-	-	-	-	-	-	-	-	-	-	-	-
German	624.99	769.55	22.73	27.94	2.78	3.18	9.83	11.44	749.28	762.54	3.24	3.53	8.43	8.39
Norwegian	-	-	-	-	-	-	-	-	-	-	-	-	-	-
United Kingdom	638.29	1017.94	23.84	27.14	2.87	3.12	11.08	11.77	792.67	728.37	3.54	3.34	8.83	8.03
The North Sea	607.53	817.61	21.07	26.97	2.70	3.10	9.94	10.48	799.82	728.66	3.50	3.28	8.81	7.79

Table 5.2: The average environmental footprints (material demand and life cycle impacts) per MWh electricity production of developing OWFs in each EEZ in the North Sea, based on current (2020) and future (2040) OWE technology mix. [1] High: more overlaps with protected areas; Low: less overlaps with protected areas.

Exclusive economic zone (EEZ)	Material demand						Life cycle impact categories								Biodiversity loss[1]
	Steel (g)		Copper (g)		Aluminium (g)		Climate change (kg CO_2-Eq)		Marine ecotoxicity (kg 1,4-DC.)		Marine eutrophication (kg N-Eq)		Metal depletion (kg Fe-Eq)		
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	
Belgian	612.91	366.35	18.63	12.50	2.46	2.13	10.61	5.66	880.17	473.44	3.65	1.90	10.03	4.99	High
Danish	841.27	491.91	28.63	22.50	3.24	2.90	10.79	4.88	682.21	353.55	3.24	1.52	7.43	3.65	High
Dutch	732.64	434.73	27.42	21.28	3.14	2.81	12.33	5.60	788.22	409.49	3.72	1.76	8.60	4.22	High
French	640.65	380.32	17.66	11.52	2.39	2.06	10.25	5.61	886.18	478.92	3.60	1.90	10.15	5.06	Low
German	733.47	434.95	27.51	21.37	3.15	2.82	11.77	5.36	755.57	392.43	3.57	1.69	8.25	4.05	High
Norwegian	1279.22	719.99	24.50	18.37	2.92	2.58	8.78	4.24	621.92	327.82	2.79	1.37	6.91	3.41	Low
United Kingdom	1141.84	649.54	27.12	20.99	3.12	2.79	11.35	5.25	744.51	388.91	3.47	1.66	8.16	4.01	Low
The North Sea	909.36	529.81	25.57	19.43	2.92	2.58	10.05	5.03	765.54	403.51	3.43	1.69	8.50	4.20	-

Such improvements however also will reduce embodied impacts of OWE on other locations, implying the relative drawbacks of OWE developments in the Dogger Bank will persist.

Apart from the nearshore areas discussed before, the northern North Sea is characterized by deep waters that require a higher level of steel-based supporting infrastructure, mainly foundations. OWFs in the northern regions of the North Sea require approximately 2 times more low-alloyed steel (steel) than in the southern locations (**Figure 5.2**). Manufacturing of steel could contribute ~45% to the overall GHG emissions among all processes along turbine full life cycle [8]. However, the northern North Sea benefits from favorable wind resources (60% higher capacity factors than the south) (**Figure S5.1**), resulting in similar GHG emissions per MWh produced electricity along the turbine full life cycle to the southern North Sea (**Figure 5.2**). Further, the greater wind resources in the northern North Sea result in lower environmental impacts per MWh produced electricity for other life cycle impacts, such as marine ecotoxicity (**Table S5.3**).

So, the northern North Sea, particularly its nearshore areas, seems a favorable location for OWFs. Innovations such as floating foundation technologies could overcome the drawback of the deep waters in this area, substantially reducing the amount of required foundation materials and simplifying installation and decommissioning. Conversely, OWE development in the south North Sea would result in high marine ecotoxicity and metal depletion impacts per MWh produced electricity due to its less favorable wind resources, despite the short distance to the electricity markets (surrounded by the UK, Belgium and the Netherlands).

Our results further indicate that existing OWFs (~19 GW in total) occupy locations with some of the lowest energy production to material demand or life cycle impact ratios (**Table 5.1**). OWF locations in development, including those under construction, approved, and planned (see **Figure 5.1**), show higher environmental footprints per MWh electricity produced than those of existing OWF locations, since they are located further from shore and towards deeper waters. Future OWE installations will likely move even further from shore and into much deeper waters, ultimately covering ¼ of the total surface of the North Sea. They may thus demand more materials and result in higher GHG emissions per MWh of electricity produced throughout the turbine lifespan than those of existing installations (**Table 5.1**), unless they are placed in areas with higher wind speeds. Our results reveal that all 180 GW OWE installations could be placed in the northern North Sea where wind resources can be harvested at high capacity factors. Our calculations show that despite higher absolute material use and life cycle GHG emissions per wind turbine produced, placing OWE in this reason leads to the lowest GHG emissions per MWh of electricity produced throughout the turbine lifespan (see **Figure S5.4**). When we zoom in on other impact indicators, conclusions can differ. Locating future OWFs in nearshore regions along the North Sea coastlines will minimize copper use. South, western nearshore and central (mainly the Dogger Bank) regions of the North Sea are the optimal locations for OWE development in terms of steel requirement (**Figure S5.4**). But as Figure 1 shows, many of these central regions are protected areas and hence likely have drawbacks from a biodiversity perspective.

Since the GHG emissions per MWh produced include the GHG for steel, copper and aluminum production, we would cautiously argue that the northern North Sea could be the best place to site the envisaged 180 GW capacity, also since there is no overlap with protected areas. It is desirable to conduct a more in-depth multi-criteria study for OWF siting considering multiple environmental footprints simultaneously, which is out of the scope of this study.

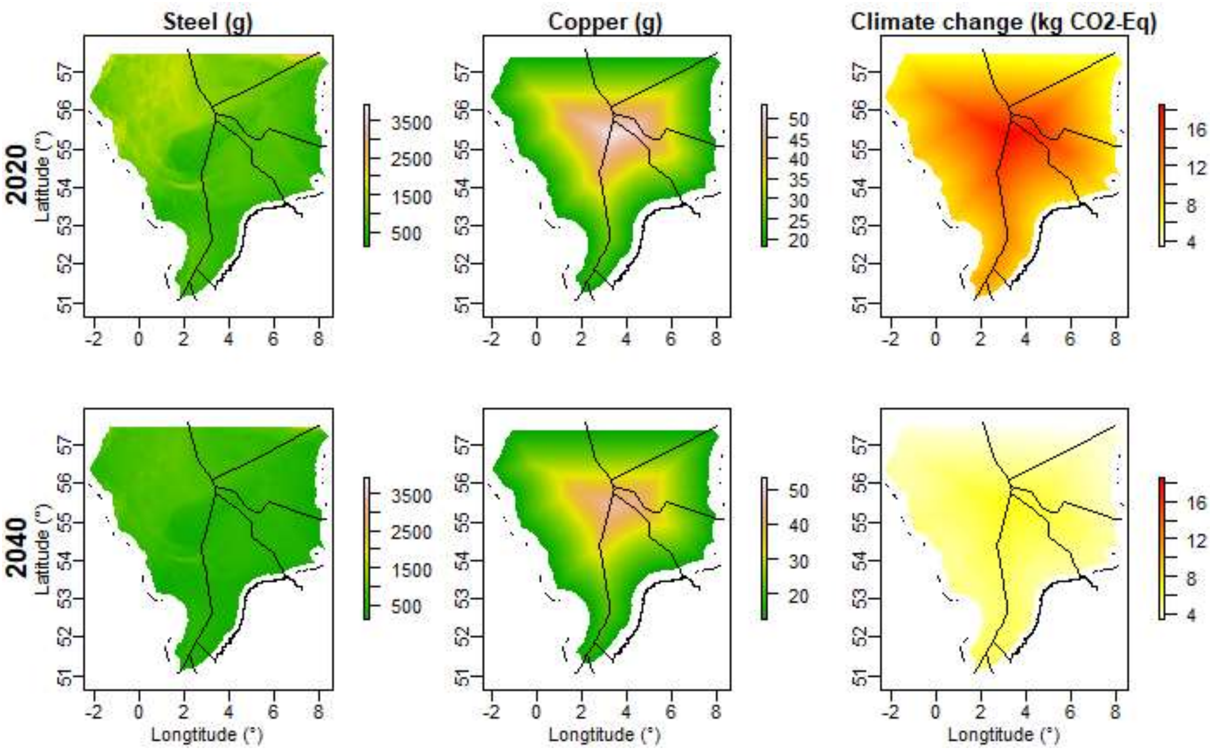

Figure 5.2: Demand for low-alloyed steel (steel) and copper per MWh electricity production and embodied GHG emissions per MWh electricity production across OWE full life cycle in the North Sea, based on current (2020) and future (2040) technology mix.

Trade-offs across OWE locations and improvement potential using an improved technology mix

Deploying 180 GW OWE capacity in the North Sea capable of generating ~800 TWh of electricity per year, with contemporary technologies, will require on average once off ~727 Mt of steel and ~20 Mt of copper. In this calculation we use the average wind speed, water depth and distance from shore of the North Sea for each pixel in our GIS map. The embodied GHG emissions for this OWE capacity is on average ~8.5 Mt of GHG emissions per year throughout the full 20-year turbine life cycle, mainly (~75%) derived from the manufacturing of turbines and foundations [8]. These limited GHG emissions have to be compared with the 312 Mt GHG emissions (~38 times more) that are currently produced annually for generating the same amount of electricity with the continental European electricity mix of 2020.

The spatially optimal locations in terms of GHG emission, i.e. the Northern North sea could lead to on average ~8.1 Mt (~5% drop) of GHG emissions per year at the same electricity output throughout the full turbine life cycle, but would require ~1066 Mt of steel and ~20 Mt of copper (see **Table S5.3**). Although this demand accounts for ~60% and ~83% of the global steel and copper consumption in 2020 (see **Table S5.3**), respectively, considering 180 GW OWFs will be installed between 2020 and 2050, on average, the annual demand for steel and copper only accounts for ~2% and ~3% of the global steel and copper consumption in 2020, respectively.

If siting of 180 GW OWE is spatially optimized in terms of steel and copper requirements respectively (see **Figure S5.4**), this leads to demand in steel of ~569 Mt (~22% drop) and copper of ~18 Mt (~10% drop). These locations are however not spatially optimal for GHG emissions – the locations with lowest steel requirements lead to ~10.9 Mt, and the locations with the lowest copper requirements lead to ~8.8 Mt of GHG emissions per year for 180 GW installed capacity.

A future improved technology mix as described in our earlier work [8], which includes turbine size enlargement, lifetime extension, component technological innovation (see **Table S5.2**), and improved background energy systems till 2040, has the potential to lead to an overall ~320 Mt (~44%) and ~5 Mt (~25%) decrease in demand for steel and copper, respectively, for installing 180 GW of OWE capacity, based on the average wind speed, water depth and distance from shore of the North Sea (see **Figure 5.2** and **Table 5.2**). It is associated with on average ~4.7 Mt (~45%) GHG emissions per year (but over a 25 years life span, see **Table S5.2**) throughout the full turbine life cycle. Other environmental impacts undergo a reduction with an updated technology mix as well, including marine ecotoxicity, marine eutrophication, and metal depletion (**Figures S5.2** and **S5.3**). Further, developing OWFs in the optimal locations for respectively steel use, copper use and GHG emissions (**Figure S5.4**) with this future technology would lead to the following reductions: steel demand to ~381 Mt (~52%), copper demand to ~7 Mt (~35%), and GHG emissions to ~4.3 Mt (~51%) per year along the turbine lifetime.

We discussed the drivers of such decreasing footprints in earlier work [8]. Enlarging turbine size contributes most to reductions, since this leads to an increased capacity factor and a higher harvesting of wind resources. Turbine lifetime extensions of 20 to 25 years could cut down GHG emissions across the full turbine life cycle per MWh electricity produced with ~11% [8]. When coupled to circular design such as closed-loop recycling, can supply secondary materials, mitigate material criticality, a further reduction of 6-9% life time GHG emissions per MWh electricity produced is possible [8]. Larger turbines also lead to biodiversity benefits. Although they require increased spacing and lead to larger affected seabed areas, the impacts per MW installed capacity on marine biodiversity will be substantially lower [11]. Further, wind turbines with longer blades have slower spinning rates to avoid erosion [10], which consequently reduces collisions with birds and bats [12].

Additional further technology improvements we did not quantify here include the following. Further turbine size enlargement may be pursued, which is currently limited by engineering constraints, such as installation, logistics, and grid connection. In addition, component technology advancement, such as floating foundations [13], presents a promising solution in deep waters to substantially decrease demand for steel. Several components of wind turbines can be made with lighter designs and materials in an attempt to reduce environmental impacts while achieving structural fatigue requirements and maintaining strength. Furthermore, a faster decarbonization of the background energy system as we counted with will lead to a further lowering of embodied GHG emissions of OWFs.

Achieving low impact OWE in individual Exclusive Economic Zones (EEZs)

The OWE technical potentials and geographic characteristics (**Table S5.1**), associated material demand, and the impacts on climate and biodiversity per MWh electricity generated vary across different Exclusive Economic Zones (EEZs). The Norwegian North Sea, northern UK North Sea, and western Danish North Sea exhibit high steel demand, moderate associated GHG emissions but low impacts on marine ecotoxicity and metal depletion per MWh electricity output across the full turbine life cycle (**Figure 5.2**). These regions currently lack operational OWFs, but have massive potential for OWE development due to favorable wind resources (**Figure S5.1**). Although harvesting the region's OWE relies on installing OWF in fairly deep waters, floating foundation technologies are maturing to offer possibilities to unlock potentials. The Norwegian North Sea, amongst others, shows the least life cycle impacts per MWh electricity production (**Table 5.2**). The Norwegian government has set an ambition to develop 4.5 GW OWFs with a specific focus on floating wind farms [14]. As the largest OWE market in Europe, the UK has a more ambitious mission to achieve up to 50 GW of OWE by 2030, including 5 GW from innovative floating OWFs [15]. There are no planned OWFs in the Belgian and French North Sea areas due to limited space (**Table 5.1**). The Belgian, Danish, Dutch, and German EEZs partially overlap with protected biodiversity areas, indicating high levels of biodiversity loss (**Figure 5.1** and **Table 5.2**). The Dutch and German EEZs exhibit moderate levels of material demand and life cycle impacts per MWh electricity production. The Dutch government has presented the Offshore Wind Energy Road Map determining locations and timeline of the new OWFs [16]. This provides clarity to stakeholders and ensures certainty for OWE developers. German government has developed the Site Development Plan as the steering planning instrument for the use of OWE with the associated cross-border power lines and areas for other forms of energy generation [17].

Overall, there is a lack of macro-level collaboration between countries concerning spatial planning for OWE in the North Sea. To achieve minimal impacts, cross-border spatial planning in the North Sea and collaboration between various countries is crucial, which requires aligning various policies and targets. For example, the Strategic Environmental Assessment North Sea Energy [18] was carried out to assess the cumulative impacts of large-scale wind farms, involving cross-border maritime spatial planning among authorities Netherlands, Germany, France, Scotland, and Denmark. Further, it is important to examine the conflicts with marine activities, such as navigation routes, underwater pipelines, fisheries, sand mining areas, military training zones, tourism and the preservation of underwater cultural heritage, including archaeological investigations. As the future OWFs are likely to occupy ¼ of the seabed space, the possibilities of multifunctional use of these areas should be carefully considered. This requires new regulations and technical innovations allowing for multifunctional use of areas in the North Sea. Such innovations include the construction of oyster beds [19], floating solar farms [20], mussel farms or seaweed cultivation [21] between wind turbines' supporting structures, co-existence with fishing activities [22], and artificial energy islands [23].

Conclusions and policy implications

A sound spatial planning of the 180 GW OWFs envisaged by 2050 in the North Sea is crucial. Different siting locations have trade-offs in terms of biodiversity impacts, material use, and life cycle GHG emissions per MWh electricity produced given wind speeds, seabed depth, distance from shore, and other locations. Comprehensive studies in which such spatial trade-offs are optimized lack. Due to lack of this information and a lack of macro-level collaboration across countries responsible for the different EEZ's this can lead to sub-optimal siting decisions in an infrastructure development that ultimately will cover 25% of the North Sea surface.

Our study is one of the first in showing site-specific advantages and disadvantages of OWF placement, considering the current situation and expected future improvements in wind turbine technology. We show the implications of siting decisions and technology are significant. Siting optimized for minimal steel use leads to embodied GHG emissions for 180 GW OWE capacity of 10.9 Mt/year. Siting optimized for embodied GHG emissions reduces this to 8.1 Mt/year. Using improved technologies reduces this further to 4.3 Mt/year.

Our current conclusion is that the envisaged 180 GW OWFs seem best placed at the (nearshore) northern North Sea regions. These regions have favourable wind resources and the lowest life cycle impacts GHG emissions per MWh electricity produced. These locations also have limited overlap with protected areas from a biodiversity perspective. A drawback are the relatively deep waters and hence relatively high steel use (see **Table S5.3**). New technologies such as floating foundations, not considered in this paper, could overcome this drawback. We also suggest that development of OWF in the central North Sea should be minimized due to the long distance to shore, which results in high demand for copper and associated GHG emissions, and other environmental impacts across the full turbine life cycle.

More in-depth follow-up research that looks better to such siting choices via multi-criteria analysis is desired. To further mitigate footprints that are not reliant on the optimal spatial siting of OWFs, it is crucial to make substantial investments in technological advancement of OWE, such as turbine size enlargement, lifetime extension and component technological innovations.

5.3 Methods

We use the Epifauna habitat map as the base map for the North Sea in our GIS based system [24]. We add EEZ boundaries, existing and in-developing (including under construction, approved, planned) OWFs (until 2018), and protected areas [25] to the base map (**Figure 5.1**). The environmental footprints per MWh of electricity produced by the OWE, including once off finish material demand, and impacts on carbon (GHG emissions) and climate throughout the full turbine life cycle, are calculated as the ratio of the footprint and electricity output cross a turbine's full life cycle, and normalized to one MWh. We calculate the average footprint for each existing and in-development OWF by EEZ by considering geographical factors, including wind speed, water depth, and distance from shore, based on the current (2020) technology mix. We also calculate the average footprint for each EEZ by comparing the current and future (2040) OWE technology mix. All analyses are performed using the R Statistical Software v4.2.0 [26].

Calculation of electricity output

The electricity output by one turbine is calculated based on a turbine's nominal capacity, lifetime, and capacity factor (the ratio of electricity produced by a turbine in a given period to its nominal capacity). Future nominal capacity and lifetime are projected by a linear regression based on historical data [7]. We normalize the footprint to one MWh by dividing a turbine's nominal capacity. The capacity factor is calculated based on site-specific wind speed [27] (see more details in supplementary materials). We use mean annual wind speed (m/s) from NEWA [28] at height 200 m as this height is close to wind turbine average hub height. Wind speed distributions in time and space are assumed static in the studied period (2020-2040).

Calculation of material demand

We include one bulk material (steel) and two other major metals (copper and aluminium) as their demand varies in locations. We use material demand results for the nacelle, rotor (including blades), and tower from a dynamic material flow analysis [7]. OWE foundations are made from steel and we calculate the steel demand for the foundation by considering site-specific water depth. We add the material requirement for transmission infrastructure. Demand for steel, copper, and aluminium from export transmission cables is calculated based on distance from shore and associated material intensity [29] (see details in supplementary materials).

Calculation of life cycle environmental impacts

We calculate life cycle impact categories, including climate change, marine ecotoxicity, marine eutrophication, and metal depletion from ReCiPe 2016 Midpoint (H) V1.13 [30] by using a prospective life cycle assessment model based on self-consistent advanced technology foreground scenario [8] and SSP2-RCP2.6 background scenario [30]. We use life cycle inventory results from [8] and classify processes into water depth-orientated, distance from shore-orientated, and the rest processes. Water depth-orientated processes, namely foundation-relevant processes, are converted to impacts per meter and adapted to water depth. For distance from shore-relevant processes, processes related to export cables are updated by multiplying export cable material demand per km with the distance from shore. Processes related to installation, O&M, and decommissioning are converted to impacts per km, and adapted to the distance from shore (see source data).

Calculation of impacts on marine biodiversity

Due to a lack of spatial information on marine species habitats, we assess OWE impacts on marine biodiversity by screening the overlaps of potential OWE installations with protected areas.

Modelling of geographical factors (spatial perspective)

We use Bathymetry (water depth) data from ETOPO [31]. For each pixel, we calculate the shortest distance to shore by using distance function from the Terra package v1.5-21 [32] for R.

Modelling of technology mix (technological perspective)

We model the technology mix based on multiple OWE technological factors, including turbine size and lifetime, market share of technologies in the nacelle, rotor, and tower, maintenance times, replacement rates, and transportation strategies. The current technology mix is based on OWE technological development in 2020 [7, 8]. We use the projected values of turbine size and lifetime in 2040 [7], estimates of market share of technologies in the nacelle, rotor, and tower, and maintenance times, replacement rates, and transportation strategies in 2040 based on the advanced technology scenario as the future, emergent technology mix [7, 8]. For 2040, we did take into account any improvement of the background energy mix for producing turbine components. We refer to the summary in **Table S5.2** and detailed data provided in our previous studies [7,8].

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Chapter 6

General discussion

This thesis asked as main research question: **what are the environmental impacts of the offshore wind energy development?** The thesis therefore aims to address offshore wind energy (OWE) associated environmental footprint, including material requirement, embedded climate, biodiversity, and other impacts on the environment. **Table 6.1** summarizes the research questions (RQs) presented in the introduction, the associated methods, and the answers to questions. RQs 1-4 correspond to Chapters 2-5.

Table 6.1: Summary of research questions (RQs), the associated methods, and answers to RQs.

Questions	Methods	Answers
RQ1: What is the future material demand for global OWE development (**Chapter 2**)?	➢ Dynamic material flow analysis (dMFA) ➢ Scenarios on OWE installed capacity, technology and closed-loop end of life (EoL) recycling ➢ 4 OWE components, 20 technologies, and 23 materials	➢ Mass intensity (the mass per unit of OWE capacity) will increase over time ➢ Substantial amounts of raw material is required ➢ Closed-loop recycling and lifetime extension will reduce material demand
RQ2: What are the cradle-to-the-grave environmental impacts of global OWE development (**Chapter 3**)?	➢ Prospective life cycle assessment (LCA) ➢ Dynamic life cycle inventories (LCIs) ➢ 4 impact categories: climate change, marine ecotoxicity, marine eutrophication, and metal depletion	➢ OWE related environmental impacts per MWh will be reduced from 2020 to 2040 ➢ The manufacturing of primary raw materials dominates the impacts ➢ Impacts related to operation and maintenance (O&M) are significant
RQ3: What are the OWE development impacts on the marine biodiversity (**Chapter 4**)?	➢ Develop characterization factors (CFs) to quantify the impacts on biodiversity changes ➢ 3 main interventions: seabed occupation, artificial reefs, and trawling avoidance	➢ Marine biodiversity in hard substrates are greatly higher than on soft sediment and will increase over time since offshore wind farm (OWF) construction ➢ No net adverse impacts during OWF operation on benthic communities
RQ4: How to lower the North Sea's OWE environmental footprint (**Chapter 5**)?	➢ Spatially analyze the environmental footprint by considering multiple geographical site factors ➢ Assess the impacts throughout the whole life cycle by comparing present day (2020) technologies and estimates for future technology mix for the year 2040	➢ Optimal locations and cleaner technological development, mainly turbine size enlargement, has the potential to halve all the current environmental footprint ➢ Future OWFs seem best placed at the (nearshore) northern North Sea regions ➢ The deployment of OWFs in the central North Sea should be minimized

6.1 Answers to research questions

RQ1: What is the future material demand for global offshore wind energy development?

We calculate the demand for 23 different materials for manufacturing OWE turbines (including the nacelle, rotor, and tower) and the foundation. Those materials are categorized into bulk materials, key metals, rare earth elements (REEs), and other materials in 20 state-of-the-art and emerging technologies in four OWE components, i.e. the nacelle, rotor, tower and foundation. We develop a comprehensive three-level (i.e., capacity, technology, and material level) dMFA model to quantify the annual newly commissioned (inflow), in-use (stock) and decommissioned (outflow) OWE capacities, technologies, and materials until 2040 based on the assumed development of capacities, technologies, and materials and their associated lifetime distribution, respectively. We use two OWE installed capacity scenarios, i.e. the State Policy (SP) and Sustainable Development (SD) scenarios from IEA [1]. We develop three technology scenarios, i.e. conventional technology (CT), advanced technology (AT), and new technology (NT) to show the future market shares of component technologies in the nacelle, rotor, tower, and foundation. Further, we develop three EoL recycling scenarios, i.e. EoL 100% recycling, EoL optimistic recycling, and EoL conservative recycling to discuss the material closed-loop EoL recycling rates.

We found that **mass intensity (e.g. kg per MW) will increase over time:** Under the AT scenario, the mass intensity is expected to rise significantly from 365.2 t/MW in 2020 to 559.6 t/MW in 2040, representing a 53.2% increase. This upward trend can be attributed to two factors. 1) the adoption of offshore wind turbines with higher capacities and larger sizes will result in a more than average increase in the weight of the foundation; 2) the incorporation of new technologies will raise the mass intensity of the nacelle by up to 80% compared to conventional technologies.

Substantial amounts of raw material requirements: More bulk materials (mostly low alloyed steel) are required to build the support structures, mainly foundations. Under the SD-AT scenario, the OWE sector's cumulative demand for low-alloyed steel from 2020 to 2040 is estimated to be 192.9 Mt, representing a 50-fold expansion compared to current demands. Meanwhile, there will be an increase in the cumulative demand for key metals (e.g. Cu, Al, Cr, Mn, Mo, Ni, and Zn). From 2020 to 2030, the cumulative demand for key metals will be ~2 Mt, which will increase to ~3.7 Mt from 2030 to 2040, reflecting an overall increase of ~85%. The significant deployment of permanent magnet (PM) based generator technologies will lead to increased demand for specific REEs. Cumulatively, by 2040, the OWE development will require over 25 kt of Nd (neodymium), 2.8 kt of Dy (dysprosium), 3.8 kt of Pr (praseodymium), and 1.1 kt of Tb (terbium). These quantities correspond to 38%, 24%, 24%, and 26% of the production volumes in 2020, respectively.

Closed-loop EoL recycling and lifetime extension will reduce material demand: In the EoL 100 recycling scenario, closed-loop EoL recycling is expected to play a significant role in meeting material requirements for the OWE sector. Between 2020 and 2030, approximately 3% of the material needs for OWE can be fulfilled through closed-loop EoL recycling. This proportion is projected to increase to approximately 12% between 2030 and 2040 as the recycling infrastructure and practices improve over time.

RQ2: What are the cradle-to-the-grave environmental impacts of global offshore wind energy development?

We build a prospective LCA model to quantify current and future environmental impacts of OWE development across full turbine lifetime on a global scale until 2040. Our model incorporates dynamic parameterized LCIs that include high-resolution supply chains, notably focusing on installation, O&M, decommissioning, and EoL recycling processes. These LCI data are from material flows and stock data in Chapter 2 and collected from relevant literature [2, 3]. We adjust the LCIs for each year between 2020 and 2040 to account for changing parameters, such as turbine size enlargement, growth of capacity factors, increase of distance from shore, component technology advancements, and EoL recycling developments. We further adjust LCI data in conjunction with outcomes of background system change, such as energy transition. We apply three technology scenarios (i.e. CT, AT, and NT) from Chapter 2 and extend them by adding adjustments of maintenance times, replacement rates, and transportation strategies over time. We calculate life cycle impact assessment results for global warming, marine ecotoxicology, marine eutrophication and metal depletion.

We found that **OWE related environmental impacts per MWh will be reduced from 2020 to 2040:** In the CT scenario, the GHG intensity (per MWh) decreases from 20.1 kg CO2-eq for 2020-2025 to 15.8 kg CO2-eq for 2035-2040, representing a significant drop of approximately 21%. Similar reductions are observed for marine ecotoxicity (~25% drop), marine eutrophication (~22% drop), and metal depletion (~16% drop). These continuous reductions in environmental impact intensities can be attributed to various factors, including lifetime extension, the expansion of turbine size, and technological innovations.

The manufacturing of primary raw materials contributes the largest to the impacts, followed by the O&M: The life cycle stage of raw materials production has the largest contribution (i.e. ~75%-~98%), of cumulative (2020-2040) life cycle environmental impacts, with this contribution increasing from 2020 to 2040 along with rapidly growing turbine size. The substantial contribution of manufacturing to impacts is primarily driven by specific materials, such as steel in foundations, fibers in blades, copper in generators, and zinc for coating. Our results further showcase that the O&M will make a relatively high (up to ~19%) contribution to environmental impacts, and these impacts will likely increase due to the higher failure rates related to turbine size enlarging and moving into deeper waters with harsher marine environments.

The largest variations of impact intensity are related to turbine size: Various technological factors significantly influence the environmental impacts of OWE development. Notably, turbine size plays a crucial role in determining the environmental impacts. Our results show that GHG intensity is highly sensitive to turbine size changes, doubling (∼225% increase) when nominal turbine capacity shifts from the proposed values to 5 MW and halving (∼58% decrease) when nominal capacity changes to 20 MW. Adjusting the turbine lifetime (from 20 years to 25 years) can lead to a ∼11% decrease in GHG intensity. The distance from shore is in comparison to the former factors relatively unimportant, since our assumption on distance from shore is based on existing nearshore OWFs. However, the longer transportation and export cable routes could lead to higher impacts related to O&M and copper and aluminum use when OWFs moving further from shore.

RQ3: What are the OWE development impacts on the marine biodiversity?

We assess the North Sea's OWE long-term cumulative impacts on marine biodiversity. We quantify three main interventions from OWF operations on marine biodiversity (macrobenthic communities), i.e. seabed occupation, artificial reefs, and trawling avoidance. To do so, we use both sediment infauna and hard substrate epifauna samples from OWFs and their control sites, and research platforms in Denmark, Germany, the Netherlands, and Belgium. We categorize samples into two substrate types, namely **Hard** (hard substrate) and **Soft** (soft sediment), to assess biodiversity using species richness and abundance. The samples are further classified into three effect locations based on distance: **Outside** (>500 m from the nearest wind farm), **Near** (<=500 m from the nearest wind farm and >=250 m from the nearest turbine), and **Immediate** (<250 m from the nearest turbine). The sample data, spanning up to 11 years of turbine life, is used to fit a generalized linear mixed model, which enables the estimation of biodiversity values from 12 to 25 years after OWF installation. The developed CFs enable to quantify the difference in marine biodiversity between the OWE intervention (seabed occupation, artificial reefs, or trawling avoidance) and the associated reference state.

We found that **species richness and abundance on hard substrates are greatly higher than on soft sediment and will increase over time since OWF construction**: One year after installation, the species richness in the **Immediate-Hard** is approximately 17 species per 0.01 m2. It is projected to be around 23 species per 0.01 m2 by the end of the OWE turbine lifetime. The abundance in the **Immediate-Hard** is expected to quadruple compared to one year after installation due to gradual changes in the community structure following the switch from soft to hard substrate. Throughout the turbine lifetime, species richness in all **Soft** categories remains below 13 per 0.01 m2. Spatially, species richness declines closer to wind turbines. As for species abundance, the **Immediate-Soft** has higher abundance levels than the **Near-Soft** and slightly higher abundance levels than the **Outside-Soft**.

No net adverse impacts during OWF operation on benthic communities: Seabed occupation may result in minor biodiversity losses in soft sediments. However, the implementation of artificial reefs has the potential to significantly enhance marine benthic biodiversity. The CFs for artificial reefs show -0.88 for species richness and -42.87 for species abundance on hard substrates, indicating that the establishment of artificial reefs could double the number of species and result in a substantial increase in species abundance by two orders of magnitude. Our results are not conclusive concerning the trawling avoidance benefits. Overall, there are no net adverse impacts during OWF operation on benthic communities inhabiting the original sand bottom within OWFs.

RQ4: How to lower the environmental impacts of OWE development in the North Sea?

To support OWE siting choices, we do a spatially explicit analysis of the environmental footprint of OWE in the North Sea. We base the analysis on data gathered in particularly chapter 2 and 3. We calculate the site-specific demand of materials for turbine construction, MWh electricity output, O&M, etc. by considering multiple geographical site factors, such as water depth, wind speed, and distance from shore. This allows then for site-specific assessment of demand of finished materials like steel and copper, impacts on climate, and biodiversity, and other environmental impacts, per MWh electricity produced. We assess the footprint throughout the full life cycle, including the end-of-life, and compare results for present day (2020) technologies and estimates for future technology mix for the year 2040.

We found that **locations makes a difference to environmental footprint.** There are distinct spatial variations in material requirements and associated environmental impacts per MWh electricity produced across turbine full life cycle. The nearshore regions of the northern North Sea have higher wind speeds and related electricity generation, and in turn, present lower the material demand and associate lice cycle environmental impacts per MWh electricity produced. The central regions of the North Sea have a higher demand for copper, since they are situated farther from the shore, requiring a more extensive transmission infrastructure, especially cables. Although these regions have substantial advantages of great wind resources, the length of submarine electricity transport cables and the effects of transportation-intensive installation, and notably O&M incur higher embodied GHG emissions per MWh electricity produced throughout the full turbine life cycle. Furthermore, the deployment of OWE in the central North Sea foresees a large overlap with protected areas. The northern North Sea is characterized by deep waters that require a higher level of steel-based supporting infrastructure, mainly foundations. However, the northern North Sea benefits from favorable wind resources, resulting in even slightly better GHG emissions per MWh produced electricity along the turbine full life cycle to the southern North Sea.

Cleaner technological development and optimal locations will halve all current environmental footprint of the North Sea's OWE: Based on the average wind speed, water depth, and distance from shore of the North Sea, the deployment of 180 GW offshore wind energy will necessitate approximately 727 Mt of steel and around 20 Mt of copper, and result in ~8.5 Mt of GHG emissions per year throughout the full turbine life cycle. This capacity will avoid 312 Mt of GHG emissions if the same electricity output would be produced with the average continental European production mix of 2020. If siting of 180 GW OWE is spatially optimized in terms of steel and copper requirements respectively, it leads to demand in steel of ~569 Mt (~22% drop) and copper of ~18 Mt (~10% drop). These locations are however far from optimal from the point of view of life cycle GHG emissions (10.9 and 8.8 Mt/year respectively). The Northern North Sea, being the spatially optimal location in terms of GHG emissions, has the potential to lead to an average reduction of approximately 8.1 Mt (around 5% decrease) of GHG emissions per year when compared to the same electricity output over the entire turbine life cycle. Deployment of improved technologies such as larger turbines and enhanced life times shows a promising potential to reduce the associated environmental footprint. There could be approximately a 44% decrease in demand for low-alloyed steel, a 25% decrease in demand for copper, and a substantial 45% reduction in GHG emissions. The enlargement of turbine size emerges as a key driver in achieving these reductions and minimizing the overall environmental impacts. Turbine lifetime extension and component technological innovation can further lower the environmental footprint. Overall, developing OWFs in the optimal locations including the use of such improved technologies could reduce steel and copper use to ~381 Mt (~52%) and ~7 Mt (~35%) respectively, and reduce GHG emissions per year along the turbine life times to ~4.3 Mt per year (~51%).

Different exclusive economic zones (EEZs) have different strategies to achieve low environmental footprint: The Norwegian North Sea, northern UK North Sea and western Danish North Sea currently lack operational OWFs, but these areas have massive potential for OWE development due to favorable wind resources. Although the region's deep waters might require a substantial demand for steel, floating foundation technologies could substantially reduce the amount of required foundation materials. These regions also exhibit low impacts on biodiversity. Conversely, the Belgian and French EEZs show comparatively low material demands but high values in climate change, marine ecotoxicity and metal depletion impacts due to lower wind resources, implying impacts per MWh electricity output are relatively high. There are no planned OWFs in the French and Belgian North Sea areas due to limited space. Dutch and German EEZs show moderate level of material demand and GHG emissions per MWh electricity produced across the full turbine life cycle.

6.2 Answer to the main research question – key results related to impacts of OWEs

On the basis of the answers to research questions as given before, we now can synthesise an answer to the overall research question: **what are the environmental impacts of the offshore wind energy development?**

Since chapter 5 did a case study for the North Sea where we integrated already results of the dMFA, ex-ante LCA, and other information in a spatially explicit way, this chapter already answers much of the overall research question. Some key take away messages stand out.

Our dMFA results in chapter 2 show that mass intensity (e.g. kg steel per MW) will increase over time. Substantial amount of raw materials are required along with the OWE installed capacity growth. Closed-loop second-use materials could only supply 3% of material demand from 2020 to 2030 but have the potential to meet up to 12% of material requirement from 2030 to 2040. This implies that for the foreseeable future OWE development will have to rely largely on primary materials. To ensure closed-loop materials use on the longer term, ensuring circular design of OWE installed now is crucial.

Our prospective LCA in chapter 3 found that the manufacturing of primary raw materials, such as steel for foundations and fibres for blades, contributes the largest to the impacts. Impacts of O&M is not ignorable and will likely increase in the future. Expected technical improvements such as larger rotors and life time extension will reduce life cycle environmental impacts of OWE installations (e.g. global warming potential per MWh) with around 60% from 2020 to 2040. Such technical improvements hence should be further stimulated, next to optimized O&M. Future OWE development should enhance the deployment of direct drive generators, and efficient O&M practices (e.g. optimization of marine transportation).

Our analysis of impacts of OWE on marine biodiversity in chapter 4 shows that the combination of seabed occupation, artificial reefs, and trawling avoidance will lead to enhanced species richness and abundance mostly due to OWE artificial reef effects. No net adverse impacts are detected during

OWF operation on benthic communities. Further refinement of the life cycle impact assessment method is however desirable.

Finally, the spatial analysis of siting choices of OWE in the North Sea in chapter 5 shows the following. Siting choices do have impacts. But for instance a change from siting 180 GW capacity of OWE in an ‘average’ North Sea to optimal locations for GHG emissions per MWh electricity produced only leads to a reduction of 9.5 to 9.1 Mt GHG emissions per year. As shown in chapter 3 the impact of technical improvement is much more relevant and in combination with optimal siting can lower emissions to 4.3 Mt GHG per year. Note that an important factor in impact reduction is the expected decarbonization of energy used in the production stages for OWE, so decarbonizing the energy system quicker as we counted with can further reduce life cycle GHG emissions of OWE deployment.

The North Sea case also allows to put the impacts of such a massive infrastructure development in a broader perspective. With a 20 (current) to 25 (future) life span of OWE, creating 180 GW OWE capacity in the North Sea would result in the range of 100 to 225 Mt GHG emissions. This is just about one year of the current Dutch GHG emissions. The once-off steel and copper requirements using current technology would require 727 Mt and 20 Mt respectively 41% and 83% of the current global production, and hence be small taking into account this OWE will be installed in a period of about 20 years. As indicated this capacity will avoid 312 Mt of GHG emissions if the same electricity output would be produced with the average EU production mix of 2020. All this indicates OWE is a very promising and feasible technology for future carbon-neutral electricity generation.

6.3 Methodological innovations

Improved technological resolution data within a dMFA framework (chapter 2): Previous MFA studies calculated OWE material demand in a generalized manner with insufficient material coverage, neglecting the diversity in turbine component technology, material compositions, and recycling capabilities. We address the data gap by covering almost all materials, including bulk materials, rare earth elements, key metals, and other materials that contain in OWE turbines and foundations. Further, we consider the variations and evolution of OWE component technologies by considering the growth of wind turbine size, the changes of component technological market shares, turbine lifetime extensions, and the potential secondary material recycling.

Improved LCI data of installation, O&M and EoL stages in a dynamic and prospective LCA model (chapter 3): Prior LCA studies have not adequately considered the evolution of turbine size and market share of component technologies, leading to a lack of global-scale LCIs research documenting OWE environmental impacts, particularly with regards to installation, O&M and EoL stages. We contribute the literature by building dynamic parameterized LCIs that includes detailed supply chains for perspective and state-of-the-art component technologies in the nacelle, rotor (including blades), tower and foundation. LCIs are converted to yearly dynamic by adapting OWE technological development, including turbine size growth, lifetime enlargement, development of component technologies and EoL recycling.

New characterisation factors for assessing long-term cumulative impacts of OWE on marine biodiversity (chapter 4): LCIA methods to quantify effects on marine biodiversity are still in early stages of development. There are no LCIA methods yet to quantify marine biodiversity change caused by key interventions specific for OWE, such as seabed occupation, artificial reefs, and trawling avoidance. We address this gap by developing empirical CFs for LCA by extrapolating marine biodiversity in time and area. We explore patterns of change in marine biodiversity in different effect locations and substrate types. The developed CFs enables us to assess long-term cumulative impacts on marine biodiversity, and separately quantify the biodiversity impacts from OWE interventions, which provides a stepping stone towards a better representation of biodiversity in LCA.

Integration of GIS maps and OWE-related environmental footprints, to a spatial analysis (chapter 5): OWE site development results in environmental footprints, including finished material demand and life cycle impacts on the climate, biodiversity and other impacts on the environment. OWE siting decisions are often made without those insights. We take the first step to combine existing models, such as GIS, dMFA, and prospective LCA, so that spatially explicit assessment of footprints, taking into account future technology development, becomes possible. We consider our study as one of the initial demonstrations of site-specific benefits and drawbacks associated with OWF deployment, taking into account both the current state and anticipated future advancements of OWE technologies. Further elaboration of our approach, particularly a better assessment of trade-offs of different aspects such as material use and other environmental impacts, is desirable.

6.4 Limitations and outlook

Chapter 2 showed that requirements for REEs, such as neodymium and dysprosium, do require a significant scaling up of mining of these metals, along with the increasing market shares of PM-based turbines. Our study used existing recycling rates (i.e. less than 1% recycling [4]) due to a lack of solid lab data. With the high economic importance and potential supply problems related to REEs, there is an increasing need to enhance the recovery of REEs. Greater PM sizes and thus material contents, would facilitate the recovery of such PMs and their REEs at the wind turbine's end-of-life stage. The OWE industry has strengthened the interest in recovering REEs from wind turbines and 21% recycling rates are expected by 2040 [5].

Chapter 3 showed that manufacturing of fibers has significant impacts on climate change, marine ecotoxicity, and marine eutrophication. We only considered current end-of life approaches (e.g. landfilling in pieces and incineration) to address blade waste but these waste treatment methods are gradually becoming banned. There is a need for further research and ongoing efforts in recyclable blades with organic materials and fiber composite recycling. The blades recycling rates are currently fairly low and existing recycling techniques, such as mechanical, thermal, and chemical methods, have their limitations, such as reducing material quality, consuming high amounts of energy, and having long recycling pathways [6]. Overall, future research should focus on enhancing the recyclability of turbine blades, aiming to increase the recycling rates of end-of-life composite materials.

Another limitation is that our study did not include the OWE-related onshore infrastructure, such as onshore substations, land cables, and electricity storage. Their material demand and associated environmental impacts, however, could be significant. Short-term grid storage, in particular, plays a crucial role in OWE power system due to the nature of OWE's intermittency. Certain critical elements (e.g. cobalt and lithium) and REEs (e.g. terbium and dysprosium) are required for manufacturing the batteries for OWE electricity storage. Future works should extend the research scope by considering such onshore infrastructure to gain a broader insight of environmental impacts of the total OWE power system.

While our LCIs in chapter 3 have offered valuable insights at the global level, more specific data (e.g. more accurately represent downstream supply chain processes) are necessary to adapt the system to regional and local contexts. Further, future studies should consider more background LCI data changes – where our work just focused on changes in carbon intensity of energy use, there may be adjustments in mining and refining processes of metals, etc.

In Chapter 4, we only consider species richness and abundance to represent biodiversity. To gain a more comprehensive understanding of the ecological effects of biodiversity change, future research needs to extend the analysis to the community level and use more indicators [7]. Long-term monitoring efforts are required to gain better insights, including both the surface and near the bottom of the wind turbine, to understand how effects propagate outward and their spatial scope.

Additionally, monitoring efforts should capture more site-specific and ecological responses across various areas and species [8]. Innovative monitoring methods, like environmental DNA (eDNA) metabarcoding, may enable to detect species with higher efficiency compared to traditional, time-consuming, and costly routine biomonitoring [9]. Future research should include a larger sample size by encompassing more wind farms over an extended temporal range. Incorporating natural reefs into the study would contribute to a more comprehensive understanding.

Chapter 5 shows that different locations in the North Sea present trade-offs concerning biodiversity impacts, material usage, and life cycle GHG emissions. We show the optimal locations in terms of each of those factors. Additional comprehensive research is needed to improve the selection of OWF siting choices through multi-criteria analysis. Ideally, OWE generation is reasonably in line with daily and seasonal changes in demand, despite variety in wind patterns. A more dispersed distribution of OWE over the North Sea may lead to less variability in electricity generation as concentrating OWE in a specific area. This perspective is not included in Chapter 5.

In general, there is a notable absence of macro-level collaboration among countries regarding spatial planning for OWE in the North Sea. To achieve minimal environmental impacts and optimize the utilization of resources, it is essential to establish cross-border spatial planning and foster collaboration among the various countries involved.

6.5 Final remarks

To minimize material demand, innovations in OWE technological development should prioritize extending the turbine lifetime, enhancing material efficiency, and introducing new technologies in the four key components of OWE turbines studied in this research. Closed-loop EoL recycling provides great potential to improve the sustainability of OWE projects by reducing the reliance on virgin materials and promoting a more circular and environmentally responsible approach to material usage. While EoL recycling can now only replace a relatively small portion of primary materials, adopting circular strategies based on material EoL recycling is anticipated to enhance the availability of recycled materials and align better with the increasing volumes of decommissioned materials.

To mitigate full life cycle (cradle-to-grave) environmental impacts, the OWE industry should focus on the manufacturing phase, particularly concerning the manufacturing of steel, fibers, and key metals, since they contribute significantly to the overall impacts. Further, O&M phase requires increased scrutiny, considering the potential impact escalation due to larger turbine sizes and expansion into deeper waters with harsher marine environments. Moreover, more attention should be given to the EoL recycling phase, since it could largely alleviate raw material requirements and reduce related environmental impacts. Overall, cleaner OWE technological development, including turbine size expansion, lifetime extension, and technology innovation will reduce the environmental impacts.

Our findings indicate that there are no net adverse impacts on benthic communities during OWF operation. The presence of artificial reefs can result in biodiversity increases, while seabed occupation may lead to minor biodiversity losses. The strategies for foundation removal (e.g., leaving at the site, partial removal, or full decommissioning) warrant thorough consideration. To enhance the understanding of biodiversity changes on a larger scale, additional onsite sampling efforts for OWFs are necessary. Moreover, there is a need for the development of cumulative methods that integrate knowledge of other species, interventions, turbine life cycles, and technologies into a more comprehensive perspective.

Furthermore, we integrate GIS model, dMFA and prospective LCA to spatial analysis, and illustrate the results in the North Sea. We found that dedicated efforts are needed on mitigation strategies to lower the overall environmental footprint of OWE development. Future installation should move to the northern North Sea and avoid central regions of the North Sea. To mitigate inevitable nongeographic adverse environmental impacts, it is crucial to make substantial investments in OWE technological advancement, main turbine size enlargement. The policy makers should collaborate with OWE developers and the supply chains by incorporating stakeholder participation cross regions to avoid most-impactful locations and minimize the overall environmental impacts in the North Sea.

To conclude, in order to keep the pace or even accelerate the clean energy transition, the findings of the thesis could help to identify green opportunities in the supply chains of the OWE sector, facilitate the optimization of the portfolio of OWE technological development, and identify the locations with the least environmental impacts for OWE site development.

6.6 References

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Chapter 7

Appendix

Supporting Information for chapter 2

S2.2 Data and methods

S2.2.2 Material flow model

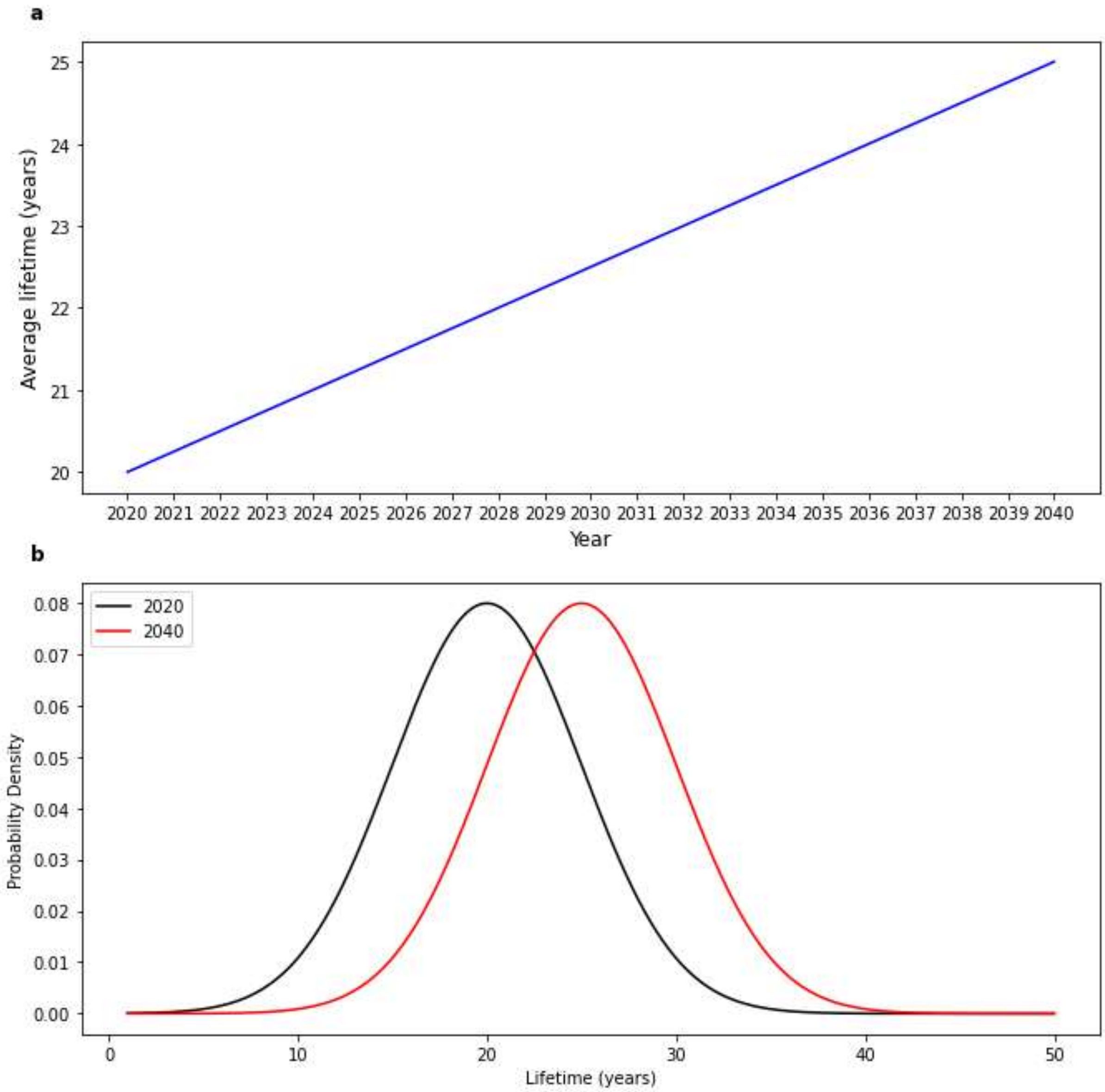

Fig S2.1: Lifetime distribution information. **a**: Assumed average lifetime from 2020 to 2040; **b**: Lifetime probability density in 2020 and 2040.

S2.2.3 Installed capacity development

The offshore wind energy outlook of the International Energy Agency (IEA) [1] provides two capacity scenarios, namely state policy (SP) and sustainable development (SD) scenarios. In the SP scenario, 77, 165, 262, and 342 GW offshore wind capacities will be installed in 2025, 2030, 2035, and 2040, respectively. In the SD scenario, 101, 225, 385, and 562 GW offshore wind capacities will be installed in 2025, 2030, 2035, and 2040, respectively. To forecast the OWE installed capacities, [2] and [3] estimated the future global offshore wind industry growth. In their reports provided annual OWE installation capacity from 2000 to 2030. In this paper, the average of these two predictions were used and a linear regression was then used to capture the trend of installation capacity towards 2040, in line with the two capacity scenarios in the IEA offshore wind energy outlook.

S2.2.4 Technology development

S2.2.4.1 Turbine size development

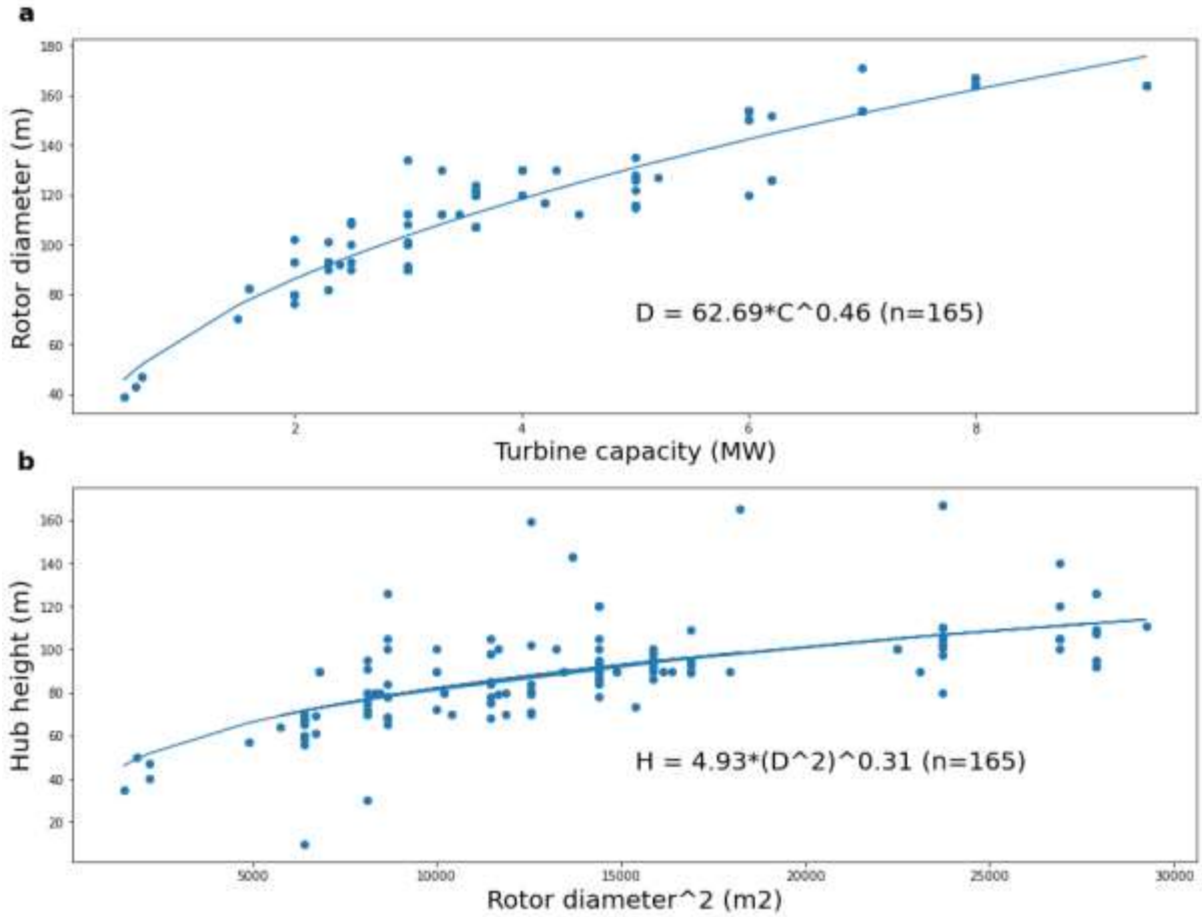

Fig S2.2: Curve fitting and extrapolation. **a**: rotor diameter scaling via turbine capacity; **b**: hub height scaling via square of rotor diameter

S2.2.4.2 Development of market shares

Three technology scenarios, i.e., Conventional technology (CT), Advanced technology (AT), and New technology (NT), were developed to show OWE technological roadmaps as of 2030. A detailed introduction of three scenarios and the corresponding marker share data are shown below.

- **Conventional technology (CT):** CT scenario is considered as a baseline scenario. In this scenario, large-scale market entry of PM-based and direct-drive (DD) systems is not expected as the pressure for innovation is low, and still expensive. On a different note, the manufacturers will replace their PM-based portfolio with PM free generators to limit its dependency towards REEs [4]. Therefore, the market share of SCIG and DFIG will still retain high. High overall efficiency and reliability make EESG the third generator type besides SCIG and DFIG. Despite its heavier mass, the current logistical difficulty of transportation with high lifting capacities is expected to be overcome. For blades, glass fibre will be mainly used in all blades since carbon fibre is still costly. For towers, steel towers are assumed to be used in all offshore wind projects since hybrid towers are 4 times heavier than steel towers, which are more costly [5]. For foundations, it is assumed that fixed-Bottom based foundations, mainly monopile foundations, will be used. Floating foundations promise relief from water depth cost penalties, but it is still too early to fully understand these costs relative to fixed-bottom foundations on a commercial scale [6]. Jacket foundations are relatively economical in terms of steel consumption and it is no evidence to show its limitation on deep water depth [7]. Therefore, it is assumed that monopile and jacket foundations will be installed, with a market share of 90% and 10%, respectively, in 2040.

- **Advanced technology (AT)**: To avoid technically, logistically and economically challenging turbine masses, the AT scenario assumes a technology shift towards lighter and more efficient generator types. PMSG-DD, PMSG-GB and DFIG, being the systems with the lowest failure rates [8], are expected to remain the solely deployed nacelles offshore up to 2040. Owing to its higher efficiency and reliability, the PMSG-DD is assumed to dominate the market, followed by the PMSG-GB and DFIG [9]. PMSG-GB and PMSG-DD have reached a prominent role in the European market in recent years. On the contrary, in Asia, DFIG configuration is mainly losing ground in favour of type PMSG-DD although this evolution is not homogenous. New concepts like PDD and SDD are not considered in this scenario. For rotors, carbon fibres are expected to be used more as it increases stiffness at light weight limiting critical blade deflections and aerodynamic performance losses. It is assumed that the market share of carbon fibres and glass fibres are roughly equal at half and half in 2040. For towers, hybrid towers start to commercializing with its greater market share from 2030 to 2040. For foundations, monopile foundations will still dominate the fix-bottom based foundation market. As water depths greater than 30 m, jacket foundations are usually deployed as they provide a wider substructure base which is better suited to neutralising the overturning forces [10] and have less reaction to wave resonance [11]. However, looking at recent deployment trends, we assume monopile foundations to be economical at even deeper waters and, hence, displacing jacket foundations. Currently, floating foundations are still in the development phase despite some successful applications. However, the floating foundations would further gain importance as they become more mature and cost-effective and are assumed to enter the market gradually [12]. Therefore, monopile foundations followed by floating foundations, mainly semi-submersible foundations, are assumed to be dominating the future market as of 2030.
- **New technology (NT)**: With the assumption of market entry of the innovative PDD and SDD wind turbines, NT scenario is considered as a promising scenario. Because of the uncertainties on the superconductor's prices, it cannot be predicted which of these technologies may be preferred by wind turbine suppliers. Hence, it is assumed that PDD has the same market shares as the SDD drive trains in the future. As wind turbine manufacturers have been finding out ways to make DD nacelles competitive with gearbox-based ones, the DFIG and PMSG-GB are expected to lose shares. The PMSG-DD, despite its higher weight, is expected to remain the preferred drive train type among the conventional systems. For blades, the materials for blades are expected to be a combination of different types of fibres. Biological fibres, such as Kanaf fibre is introduced in combination with glass and carbon fibres [13]. For towers, steel-based towers will still be used in the future, but most likely when it comes to wind tower projects in which new heights need to be achieved, investors might be more oriented towards a concrete or hybrid (concrete-steel) solution [3]. For foundations, floating foundations are assumed to dominate the future market as wind turbines are moving farther from shore into deeper waters. According to the offshore wind technical potential reported by [1], there are 4 times more OWE located in deep depth areas and the construction sites are expected to gradually shift towards water depths up to 60 m. For example, in the United States, more than 58% of the total technical offshore wind resource is located in water depths greater than 60 m, and in Europe, that number is 80% [14]. Monopile foundations will lose market share but still take some percentages as most of wind turbines in shallow waters use monopile concepts. Jacket structures become more susceptible to stress amplification, with the natural frequency of the structure approaching that of the wave periods in the offshore environment. This meant that fixed jacket structures became less practical in deeper water [15]. For floating foundations, the semi-submersible takes large percentages and other two types, namely TLP and spar are more suitable for very deep-water sites. The spar shows the largest extreme values for most motion response parameters and all loads on the turbine, which means a turbine will be loaded most severely on a spar foundation [16]. The TLP allows very

little movement in heave, pitch and roll [15]. Therefore, it is assumed that semi-submersible concepts will dominate the market, followed by TLP and spar floating foundations as of 2030.

S2.2.6 Material requirements

S2.2.6.1 Calculation of total mass

The mass of advanced and new technologies, e.g., advanced and new nacelle designs, carbon and biological fibres, hybrid tower, and floating foundations, following assumptions were made:

The PMSG-GB (PMSG-HS and PMSG-MS) has higher speed, so the total weight of the generator is much smaller compared to that of PMSG-DD and EESG. On the other hand, the PMSG-DD is smaller than EESG because of less cooling requirement and the permanent magnet. Due to limited data availability, the difference between the upscaling trends of EESG and DFIG from [17] is used in order to obtain the upscaling trend of the EESG. The PMSG-DD is reported to be 23 % lighter than the EESG [18]. Due to lack of data on the development trend of the innovative drive train concepts, the mass of PDD and SDD is based on assumptions from [19]. Gains associated with PDD and SDD technology include improvements in performance owing to a decrease in weight and savings in terms of no mechanical gearbox and contain fewer copper windings [20]. Therefore, it is assumed that SDD is 1% lighter than that of PMSG-MS and PDD has a 27 % weight reduction of the nacelle compared to the reference PMSG-MS nacelle [19].

Horizontal Axis Wind Turbines (HAWT) with three blades are currently mainly being used. Hub and blades are the main components of the rotor in mass and, therefore, most commonly reported on. Carbon fibre composites are assumed to be about 15% lighter than fibreglass composites [21]. Because of environmental issues (e.g. artificial fibre produces long-time pollution) and increased paper consumption, the application of biological fibres has drawn tremendous attention in the world [22]. Therefore, biological fibres are assumed to be used in the innovative technology scenarios. As of the weight, glass fibre composites are assumed about 1.75 times heavier than biological fibres [23].

The hybrid towers which combine concrete with steel is assumed 4 times heavier than traditional steel towers [5].

Eight foundation types are classified into three clusters by their mass magnitude: cluster one (G-B, MP, and HRPC), cluster two (SBT and Jacket), and cluster three (S-S, Spar and TLP). Due to lacking of data, foundations in the same group are assumed with the same foundation-to-turbine ratio. The average distance to the shore of the OWE projects has been rapidly increasing over the years (projects commissioned in 2013 was around 25 km; the value which increased to 42 km in 2015). Greater distances to shore usually result in deeper waters [24], which brings potentially more materials for the construction of the supporting structure [25] in next decades. Therefore, the increase in the mass of foundations is assumed linear with the increase in average depth at which future turbines will be built on [26].

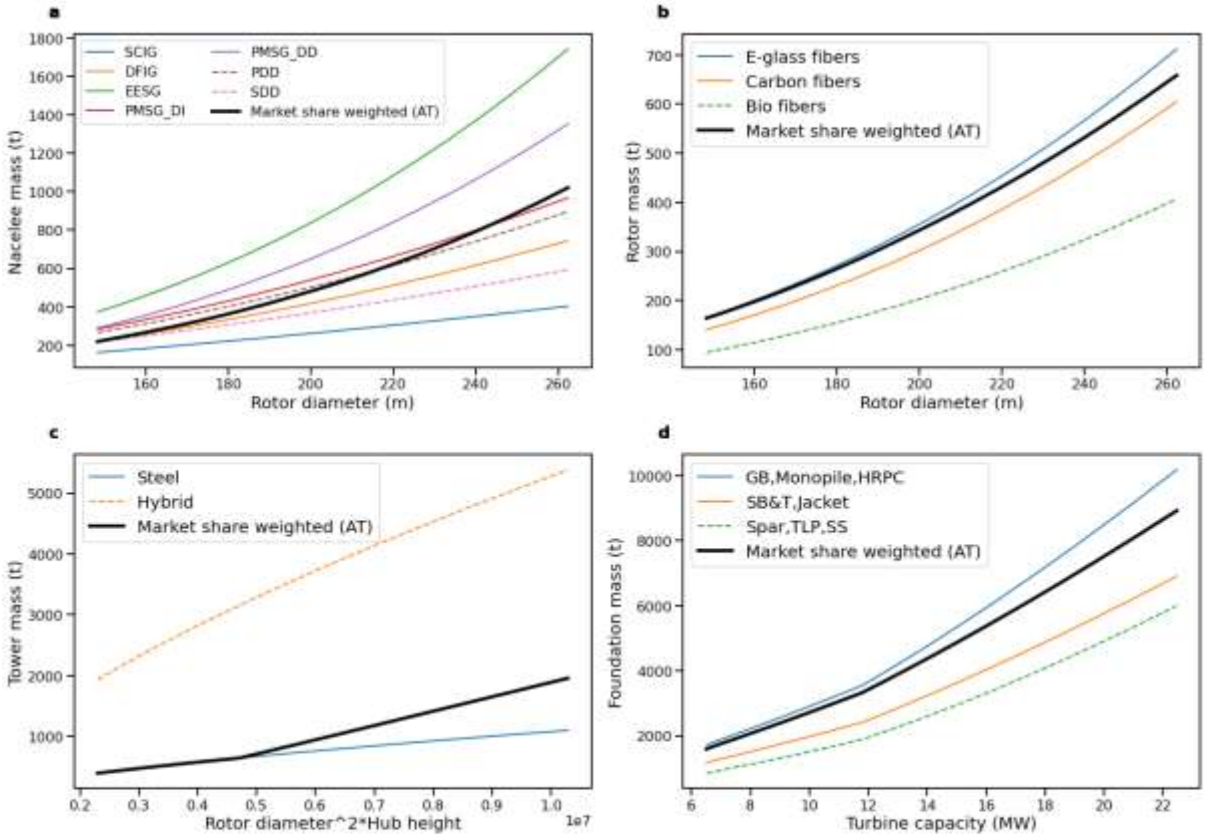

Fig S2.3: Technology mass calculation.

S2.2.7 Recycling scenarios

Table S2.1: Recycling rates data. Materials marked in Italic, star, bold are bulk materials, key metals and REEs, respectively

Material	EoL100	EoL_U[27]	EoL_D[27]
Iron	100%	0%	0%
Fe_H	100%	90%	52%
Fe_L	100%	0%	0%
Concrete	100%	0%	0%
Cu*	100%	53%	42%
Al*	100%	70%	42%
EE	100%	0%	0%
Si	100%	0%	0%
F_G	100%	0%	0%
F_C	100%	0%	0%
F_B	100%	0%	0%
Resin	100%	0%	0%
Nd[28]	100%	21%	1%
Dy[28]	100%	21%	1%
Pr[28]	100%	21%	1%
Tb[28]	100%	21%	1%
Y	100%	0%	0%
B	100%	1%	1%
Polymer	100%	0%	0%

Cr*	100%	93%	87%
Mn*	100%	53%	53%
Mo*	100%	30%	30%
Ni*	100%	63%	57%
Zn*	100%	60%	19%

S2.2.8 Sensitivity analysis

S2.2.8.1 Changes of lifetime

A list of current decommissioned offshore wind farms (to end of 2019): Yttre Stengrund (14 years) and Utgrunden I (18 years) (Sweden), Vindeby (25 years) (Denmark), Windfloat I (5 years) (Portugal), Hoostiel (3 years) (Germany), Blyth (13 years) and Beatrice Demo (8 years) (the UK), Lely (20 years) (Netherlands).

S2.3 Results

S2.3.1 Mass and material intensity developments

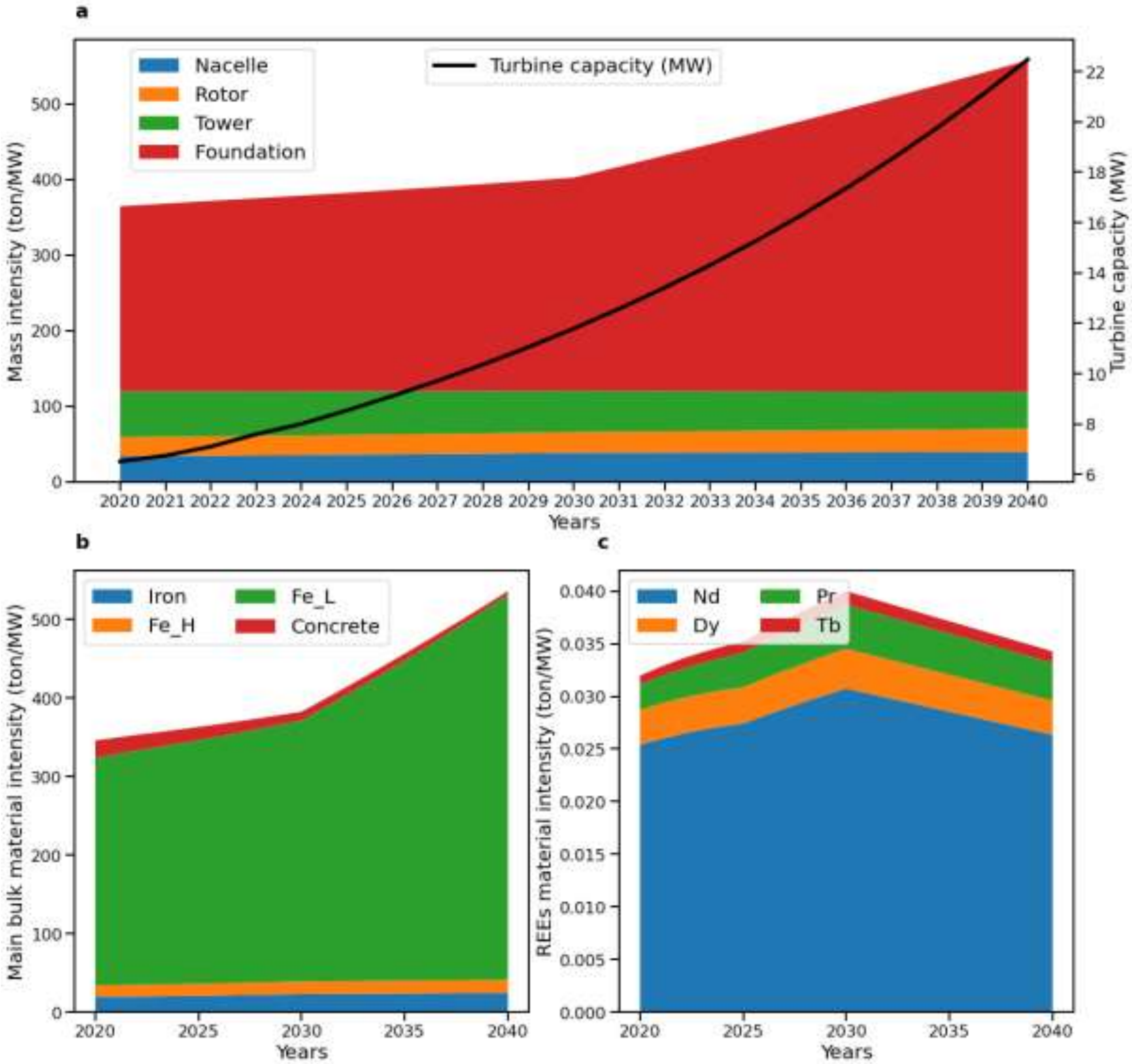

Fig S2.4-A: Mass and material intensity changes (based on CT scenario); **a**: Mass intensity changes for four components; **b**: Bulk materials intensity changes from 2020 to 2040; **c:** REEs intensity changes from 2020 to 2040.

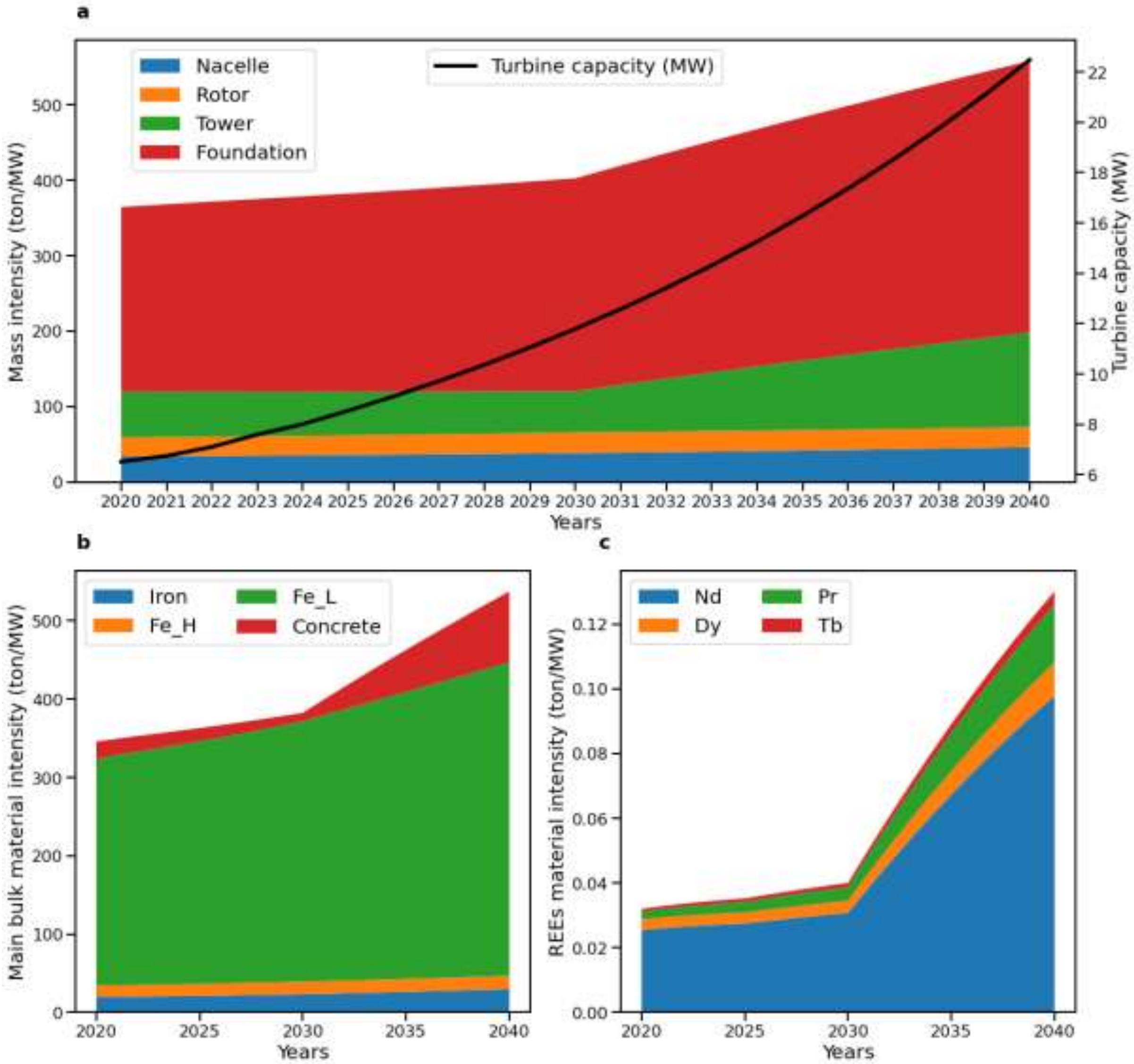

Fig S2.4-B: Mass and material intensity changes (based on NT scenario); **a**: Mass intensity changes for four components; **b**: Bulk materials intensity changes from 2020 to 2040; **c:** REEs intensity changes from 2020 to 2040.

S2.3.2 Material demand comparison

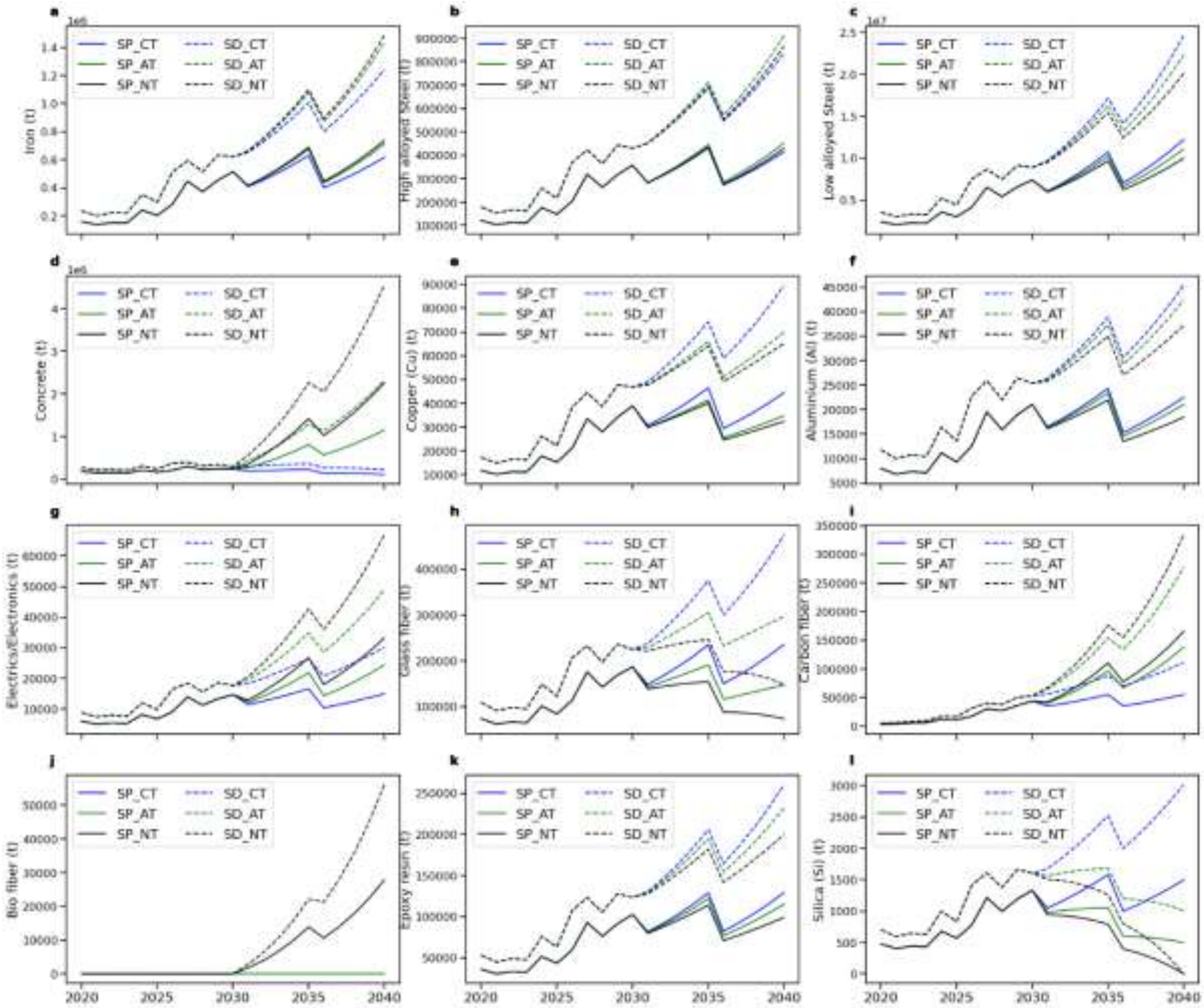

Fig S2.5-A: Material demand from 2020 to 2040 under SP and SD capacity scenarios and CT, AT and NT technology scenarios

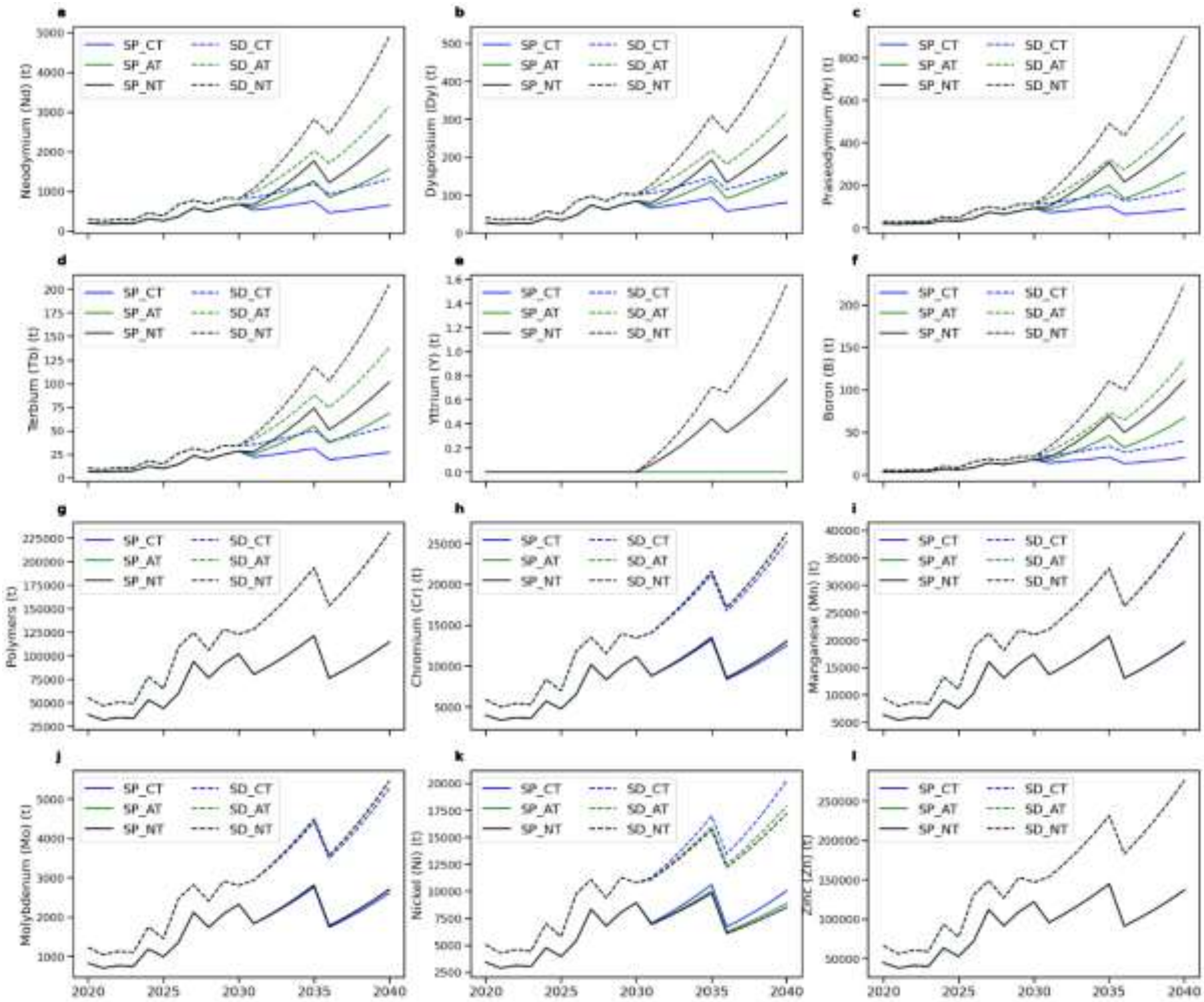

Fig S2.5-B: Material demand from 2020 to 2040 under SP and SD capacity scenarios and CT, AT and NT technology scenarios

Table S2.2: Cumulative material demand under SD-AT scenario, and EoL100, EoL_C and EoL_O recycling routes from 2020 to 2040. Materials marked in Italic, star, bold are bulk materials, key metals and REEs, respectively.

Materials	**2020-2030**				**2030-2040**			
	EoL0	EoL100	EoL_O	EoL_C	EoL0	EoL100	EoL_O	EoL_C
Iron	4.4	4.3	/	/	10.0	8.8	/	/
Fe_H	3.2	3.1	3.1	3.2	6.5	5.8	5.9	6.1
Fe_L	64.1	62.2	/	/	151.0	134.0	/	/
Concrete	3.1	3.1	/	/	12.6	11.0	/	/
EE	0.1	0.1	/	/	0.3	0.3	/	/
Polymers	0.9	0.9	/	/	1.7	1.6	/	/
Resin	0.9	0.9	/	/	1.8	1.6	/	/
F_G	1.8	1.7	/	/	2.7	2.4	/	/
F_C	0.3	0.3	/	/	1.5	1.3	/	/
F_B	/	/	/	/	/	/	/	/
Nd	5.8	5.6	5.8	5.8	19.2	17.0	19.2	19.2
Dy	0.7	0.7	0.7	0.7	2.0	1.8	2.0	2.0
Pr	0.7	0.7	0.7	0.7	3.1	2.7	3.1	3.1
Tb	0.2	0.2	0.2	0.2	0.8	0.7	0.8	0.8
Y	/	/	/	/	/	/	/	/

Cu*	328.8	319.0	323.6	324.7	584.6	520.0	550.3	557.4
Al*	195.5	189.8	191.5	193.1	335.0	297.5	308.8	319.3
Cr*	101.1	98.2	98.4	98.6	196.0	173.8	175.4	176.7
Mn*	159.9	155.2	157.4	157.4	299.5	265.6	281.6	281.6
Mo*	21.2	20.5	21.0	21.0	40.8	36.2	39.4	39.4
Ni*	83.6	81.2	82.0	82.2	142.9	126.9	132.8	133.8
Zn*	1120.3	1087.8	1100.8	1114.2	2089.5	1853.5	1947.9	2044.7
Si	12.1	11.7	/	/	13.8	12.4	/	/
B	0.1	0.1	0.1	0.1	0.7	0.6	0.7	0.7

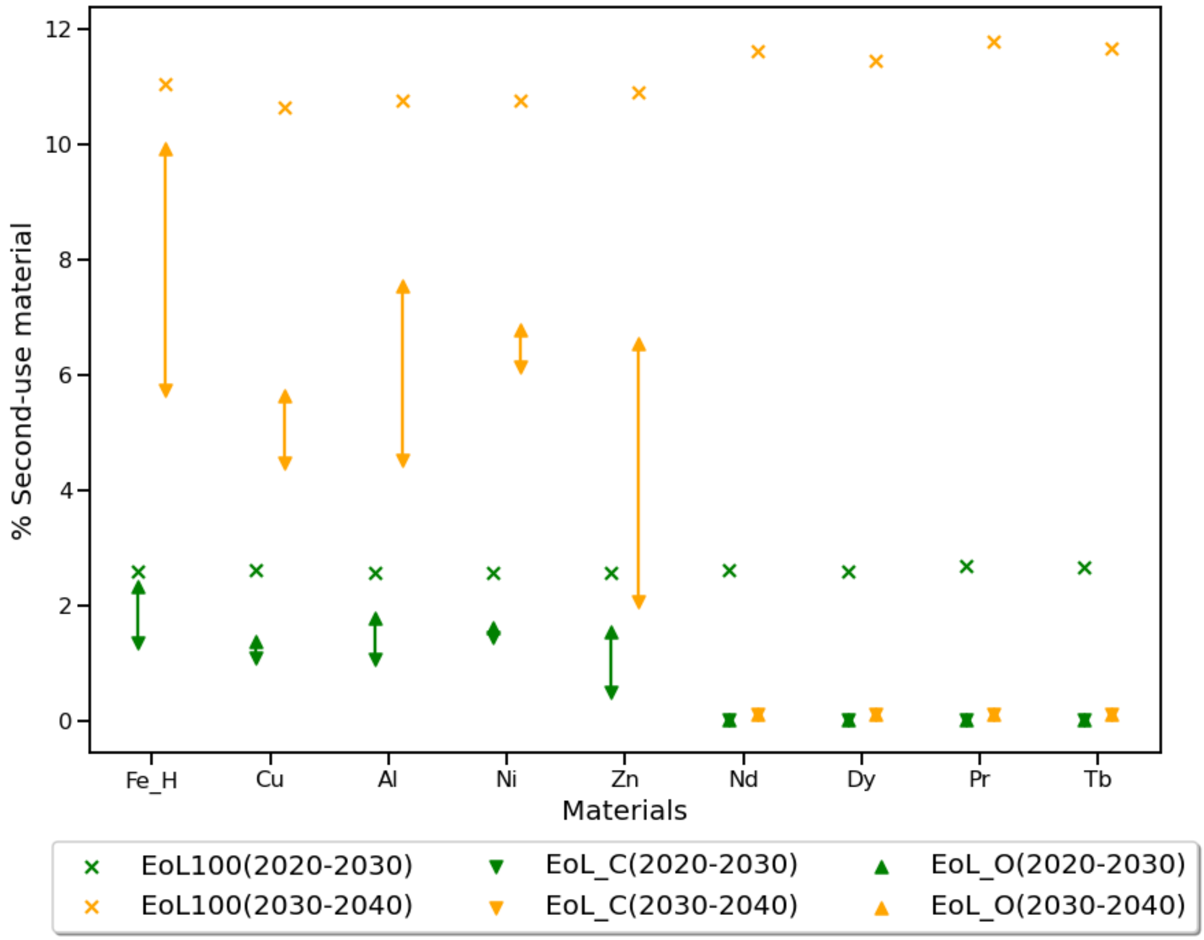

Fig S2.6: Percentage of cumulative (2020-2030 and 2030-2040) second-use material under one hypothetic scenario (EoL100 scenario) and two recycling scenarios (EoL_C and EoL_O). The bars between EoL_C and EoL_O show the range of percentage of second-use materials.

S2.3.3 Sensitivity analysis results

Table S2.4: Sensitivity analysis on changes of technological market share and material intensity. Materials marked in italic, star, bold are bulk materials, key metals and REEs, respectively

Material	Technological market share changes	Material intensity changes	Cumulative demand changes
Nd	PMSG-DD (+50%)	-	+189%
Nd	PMSG-DD (-50%)	-	-161%
Dy	PDD (+50%)	-	+302%
Dy	SDD (+50%)	-	+385%

Steel_L	MP (-50%)	-	-42%
Steel_L	S-S (+50%)	-	+39%
Iron	-	+20%	-11%
Iron	-	-20%	+33%
Cu*	-	+20%	-13%
Cu*	-	-20%	+30%
Al*	-	+20%	-13%
Al*	-	-20%	+30%
Ni*	-	+20%	-13%
Ni*	-	-20%	+30%
Zn*	-	+20%	-13%
Zn*	-	-20%	+31%
Nd	-	+20%	-9%
Nd	-	-20%	+38%
Dy	-	+20%	-10%
Dy	-	-20%	+36%

Table S2.3: Cumulative material demand from 2020 to 2040 under different lifetimes and distributions.

Material	Lifetime (yrs)	Distributions				Scenarios					
		Normal		Weibull		SP			SD		
		Mean	Std.[3]	Scale	Shape	CT	AT	NT	CT	AT	NT
Iron (Mt)	11.4[1]	11.4	7.2	-	-	11.1	11.7	11.9	17.7	18.9	19.2
	20	20	5	-	-	8.3	8.8	8.9	13.8	14.6	14.8
	20	20	7.2	-	-	8.5	8.9	9.1	13.9	14.8	15.0
	25	25	5	-	-	7.7	8.1	8.2	12.9	13.6	13.8
	20-25[2]	20-25	5	-	-	8.2	8.6	8.7	13.5	14.4	14.6
	20-25	-	-	20-25	5	8.4	8.8	8.9	13.8	14.6	14.8
Steel_L (Mt)	11.4	11.4	7.2	-	-	182.7	175.1	167.6	297.0	283.3	270.1
	20	20	5	-	-	136.5	131.1	125.9	229.0	218.9	209.1
	20	20	7.2	-	-	139.0	133.6	128.2	232.2	222.0	212.0
	25	25	5	-	-	124.9	120.2	115.7	213.3	204.2	195.4
	20-25	20-25	5	-	-	133.8	128.6	123.6	225.0	215.2	205.7
	20-25	-	-	20-25	5	136.9	131.5	126.3	229.1	219.0	209.3
Concrete (Mt)	11.4	11.4	7.2	-	-	5.0	12.6	20.6	7.6	21.1	35.3
	20	20	5	-	-	3.9	9.2	14.9	6.1	16.1	26.7
	20	20	7.2	-	-	3.9	9.4	15.2	6.2	16.3	27.1
	25	25	5	-	-	3.7	8.3	13.3	5.8	14.8	24.4
	20-25	20-25	5	-	-	3.8	9.0	14.4	6.0	15.7	26.0
	20-25	-	-	20-25	5	3.9	9.2	14.8	6.1	16.0	26.6
Cu (kt)	11.4	11.4	7.2	-	-	817.9	749.2	732.2	1310.1	1188.2	1158.1
	20	20	5	-	-	616.8	568.7	556.8	1016.7	926.5	904.2
	20	20	7.2	-	-	627.3	577.8	565.6	1030.2	938.1	915.3
	25	25	5	-	-	568.0	525.9	515.5	951.6	870.0	849.8
	20-25	20-25	5	-	-	606.1	559.8	548.3	1001.0	913.3	891.7
	20-25	-	-	20-25	5	618.8	570.8	558.9	1017.8	927.8	905.6
Al (kt)	11.4	11.4	7.2	-	-	445.9	434.1	415.2	710.0	689.2	655.8
	20	20	5	-	-	338.1	329.8	316.6	553.6	538.2	513.4
	20	20	7.2	-	-	343.6	335.1	321.5	560.6	544.9	519.7
	25	25	5	-	-	312.4	305.1	293.5	519.5	505.5	483.1
	20-25	20-25	5	-	-	332.6	324.6	311.9	545.5	530.5	506.5
	20-25	-	-	20-25	5	339.3	331.0	317.8	554.3	538.9	514.3
REEs[4] (kt)	11.4	11.4	7.2	-	-	17.5	26.4	35.2	27.8	43.5	59.2
	20	20	5	-	-	13.3	19.5	25.7	21.7	33.3	44.9
	20	20	7.2	-	-	13.5	19.9	26.3	22.0	33.8	45.6
	25	25	5	-	-	12.2	17.7	23.1	20.3	30.9	41.3
	20-25	20-25	5	-	-	13.0	19.0	25.0	21.3	32.7	43.9
	20-25	-	-	20-25	5	13.3	19.5	25.7	21.7	33.3	44.9

[1]Historical decommission data; [2] This paper used; [3] standard deviation; **[4]** The sum of Nd, Dy, Pr, Tb and Y

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Supporting Information for chapter 3

S3.2 Methods and data

S3.2.1 Estimation of OWE electricity production

The OWE electricity production was calculated based on three key parameters, i.e. capacity factor (CF), lifetime, and nominal capacity (NC). Multiple CFs ranging from 28-60% in the year range 2009-2020 were reported in the literature [1–9] depending on site characteristics (e.g. wind resources) and turbine technology (e.g. gearbox-based or direct drive nacelles). CF is expected to increase as larger wind turbine moving further from shore with better wind resources. Multiply component technology enhancement (e.g. use of permanent magnet-based and direct drive nacelles) will largely increase CF [10–12]. For simplicity, the medium value was used as the estimation of current (in 2020) CF and the maximum value was applied for the expected CF in 2040. This paper assumed dynamic CFs with 50% in 2020 that linearly increases to 60% in 2040. The designed lifetime of offshore wind turbines was estimated to be 20 to 25 years [13]. We applied dynamic 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, which is in line with our previous paper [14]. Ordinary least squares (OLS) regression was used to model future NC projections based on existed projects from 4C offshore [15]. More information on lifetime and NC modeling could be found in **2.2** and **2.4.1** in our previous research [14], respectively. **Figures S1** and **S2** show the estimation of CF and nominal capacity, and lifetime, respectively.

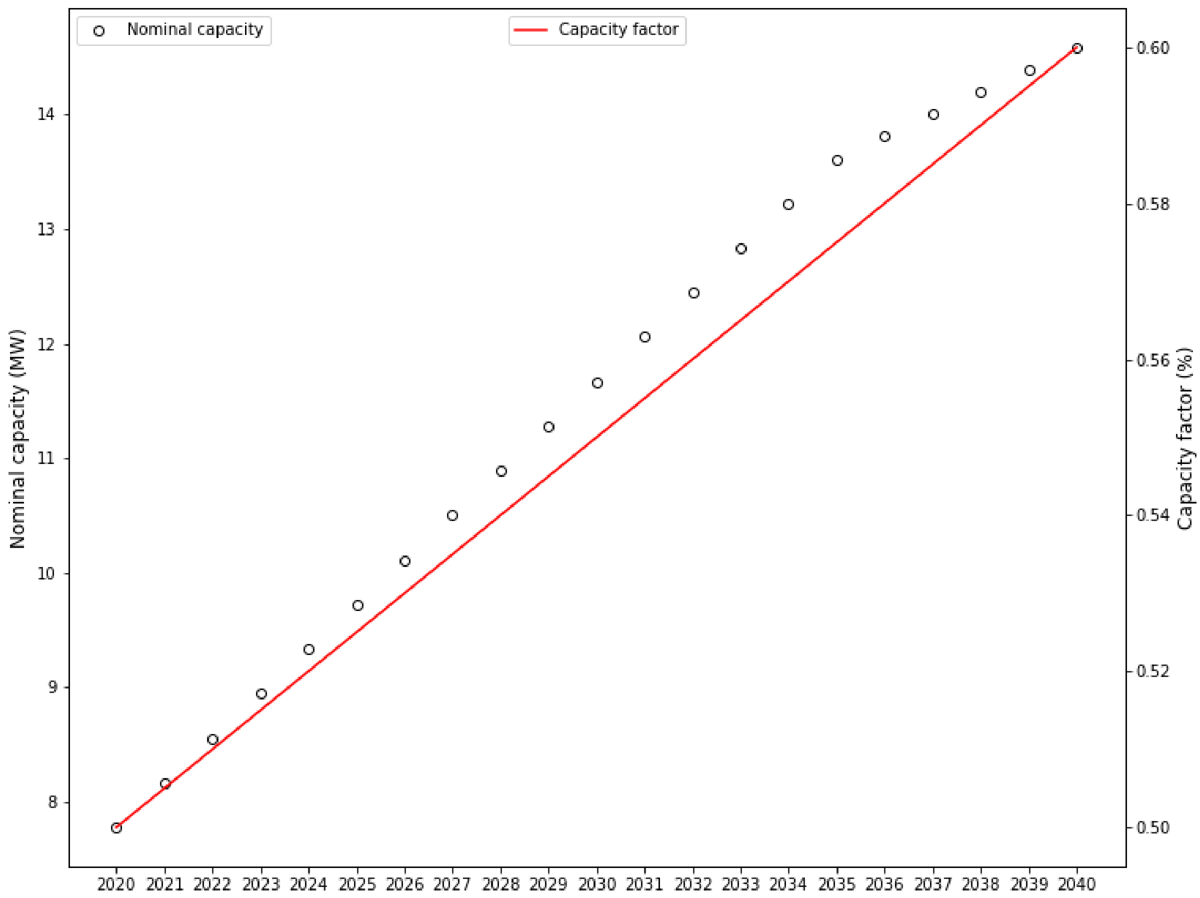

Figure S3.1: Capacity factor and nominal capacity development from 2020 to 2040

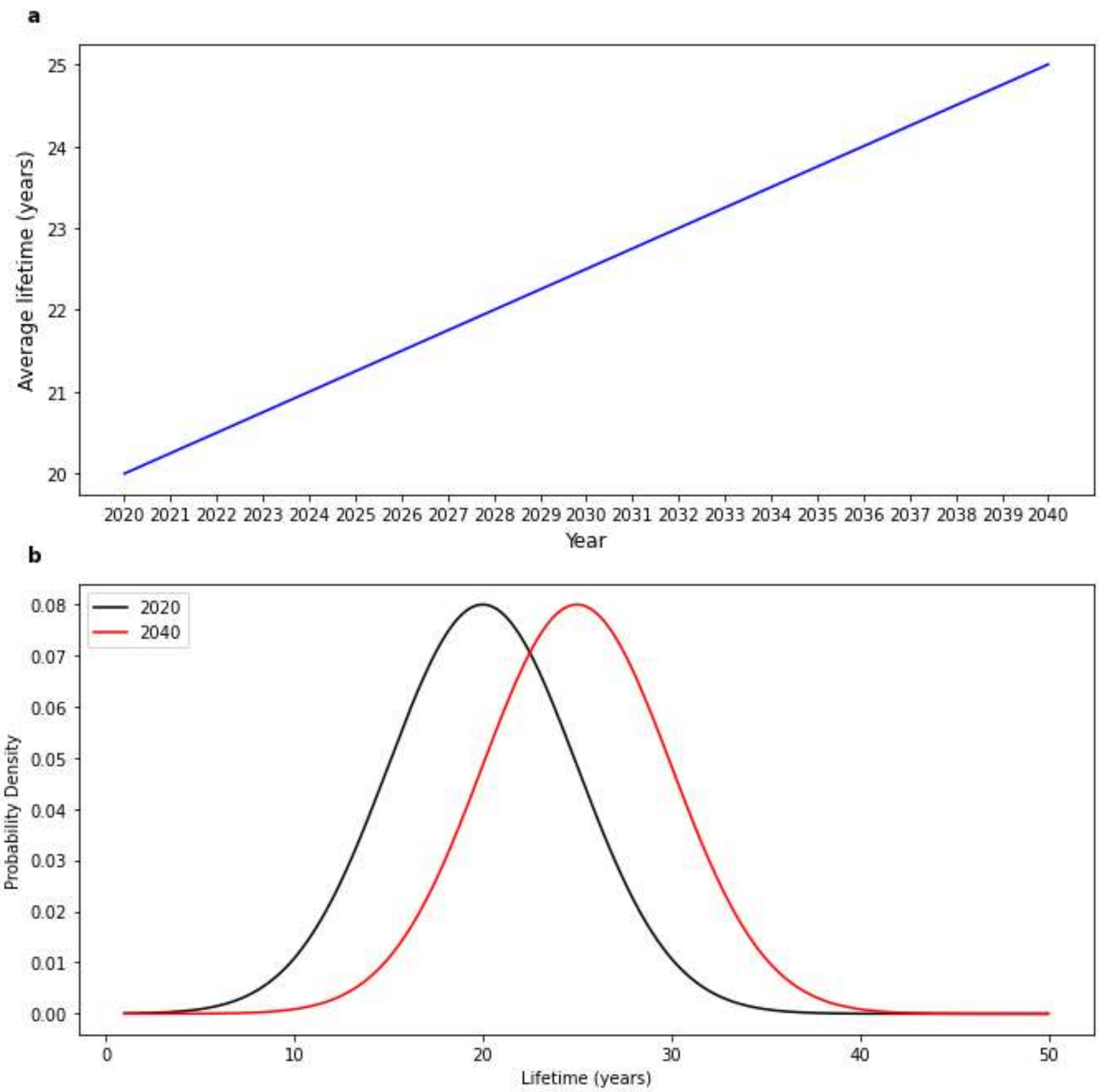

Figure S3.2: Turbine lifetime development from 2020 to 2040

S3.2.3 Life cycle inventory analysis

Dynamic parameterized life cycle inventories were generated in this paper. Besides key parameters, i.e. CF, lifetime, and NC, turbine size (including rotor diameter and hub height) and distance from shore are another two main parameters. Several processes were adjusted by these two parameters (details provided in **Para** in **Supporting Information II**). OLS regression was used to model the future projections of turbine size based on existed projects from 4C offshore [15] (**Figure 4** in [14]). Future average distance from shore was estimated based on Fraunhofer IEE [16] (**Figure S3**).

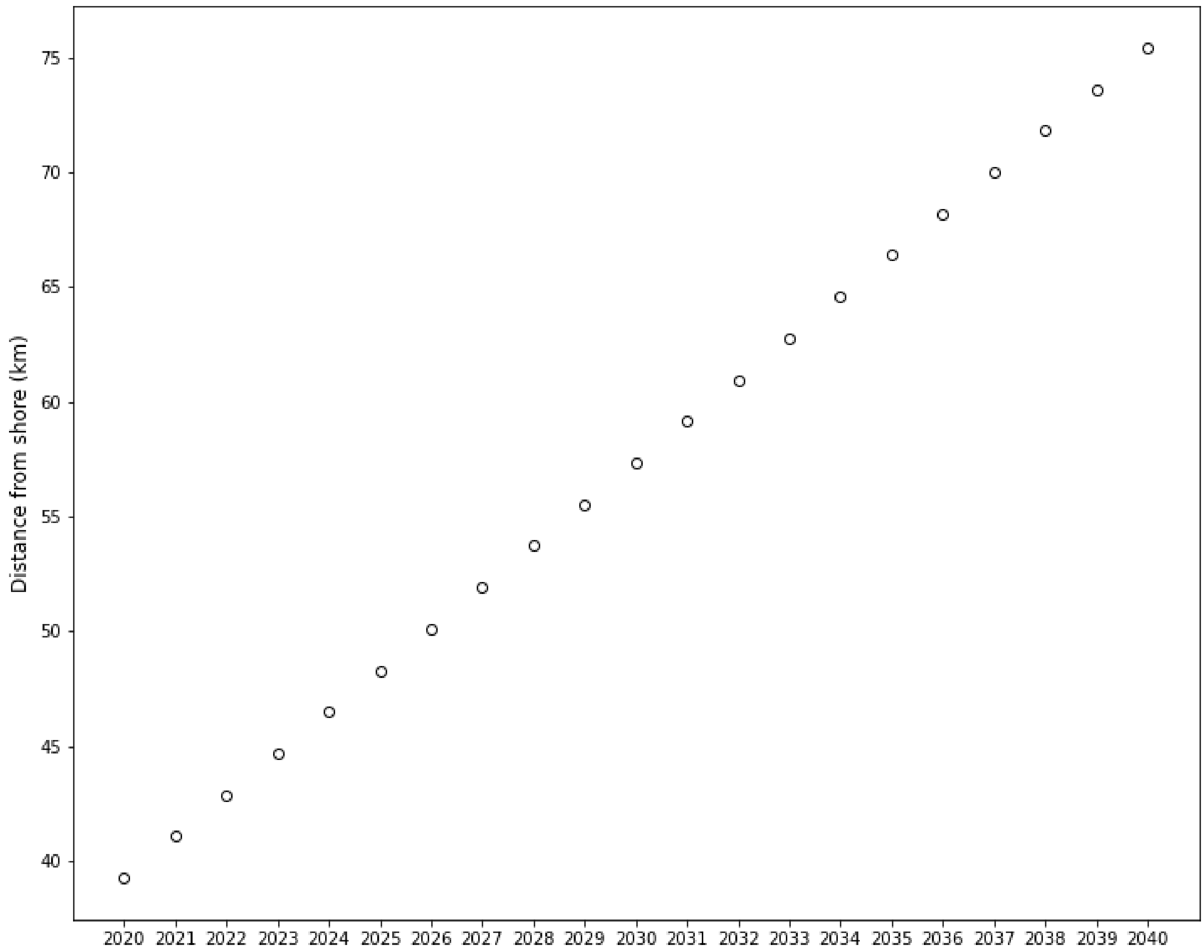

Figure S3.3: Estimation of average distance from shore.

S3.2.3.1 Manufacturing

S3.2.3.1.1 Manufacturing of turbines and foundations

The material requirements for manufacturing turbines and foundations from 2020 to 2040 were calculated based on the dynamic material flow analysis (dMFA) [14] and used in this paper. A wide assortment of materials was considered, which including bulk materials, rare earth elements (REEs), key metals, and other materials for manufacturing 24 component technologies in the nacelle, rotor, tower, and foundation.

S3.2.3.1.2 Manufacturing of transmission

Material use for manufacturing offshore wind transmission (cables and substation infrastructures) was calculated based on the following assumptions and estimation. Internal cable material requirements were calculated based on cable length and material intensity. Internal cable length was determined by turbine layout. The spacing between turbines in a column would be 5 to 10 times of rotor diameters and spacing between columns would be 7 to 12 times of rotor diameters [17]. As turbine size grows, the spacing is likely to increase. Therefore, the upper bounds were used in this paper. Five types of internal cables (i.e. 3x95 mm2 Cu, 3x150 mm2 Cu, 3x240 mm2 Cu, 3x400 mm2 Cu, 3x630 mm2 Cu) were found currently in the market. In simplicity, the average material intensity value of these five types was used in this paper (shown in **Table S1**). External cables consist of submarine cables, onshore aerial and underground cables. Due to lacking of data and ignorable length, onshore aerial and underground cables were excluded in this paper. Submarine cable length was determined by distance from shore. We considered submarine cable length equal to distance from shore. External cable material intensity (shown in **Table S1**) has been derived from [9]. A substation was assumed to consist of two ABB's transformers and one foundation per wind turbine. Data of the mass of materials and energy use were derived from ABB's report of Environmental Product Declaration [18]. Substation foundation was assumed to be identical to one fix-bottom based (monopile) foundation.

Table S3.1: Material intensity (t/km) of cables. * The average of abovementioned five types of internal cables [9].

	Total weight (t/km)	Conductor (copper)	Insulation (polyethelene)	Lead sheath	Galvanized steel	Outer layer (polypropylene)
Internal submarine cables (33kv)*	26.4	22.6%	6.2%	26.2%	41%	4.2%
External submarine cables (132kv)	74	27%	8.7%	25%	35%	4.9%

S3.2.3.2 Installation

Installation of turbine and transmission is with less technological spectrum but the installation processes vary significantly among foundation types [2].

S3.2.3.2.1 Installation of foundation

The foundation installation processes vary among foundation types. Eight foundations [14] were classified into four types by their installation processes, i.e. foundation type I: Gravity-Base and High-Rise Pile Cap; type II: Monopile; type III: tripot and Jacket; Type IV: floating foundations (Semi-Submersible, Spar and TLP). For type I and II foundations, sour protection is needed before installation setup. Type II and III foundations need driving piles into the seabed. While type IV relies on mooring systems. Processes related to foundations installation were adapted from [19]. The details of foundation installation activities can be found in **Table S2.** This paper also included the impacts of land-use transformation during foundation installation. The land-use impact was characterized by land transformation and land occupation. The coverage of one foundation and its scour protection vary from roughly 1195 square meters (m2) (type I), 291 m2 (type II), 763 m2 (type III), to 22 m2 (type IV) [2]. The land transformation is measured for the land cover change from one type to another. The land occupation measures how long a certain amount of area has been covered by one land cover type. Details are shown in **Table S3**.

Table S3.2: Marine activities related to installing one offshore wind foundation. Fuel rate = engine power (kW) × specific fuel consumption (g/kWh)/conversion factors (kg/l) × average load (%); HFO: Heavy fuel oil. Conversion factors (kg/l) for HFO: 1l = 0.983kg; conversion factors (kg/l) for diesel: 1l = 0.832kg

Foundation type[1]	Activity		Fuel, Equipment	# of equipment [19]	Work time (h) [19]	Fuel rate (l/h) [2]
I	Substrate clearance	Transport of excavator	HFO, Barge	1	72	100
		Dredging	Diesel, Excavator	1	72	0.455
		Disposal of substrate materials	HFO, Barge	1	70	100
	Substrate replacement	Transport of rock	HFO, Vessel	1	8.47	100
		Dumping of rock	HFO, Vessel	1	72	100
	Installation	Transport of foundation	Diesel, Tugboat	2	135	322.6
		Transport of jack-up	Diesel, Tugboat	2	1.8	322.6
		Construction of foundation	HFO, Jack-up vessel	1	24	170
	Scour protection	Transport of rock	HFO, Vessel	1	8.47	100
		Dumping of rock	HFO, Vessel	1	72	100
II	Driving pile	Transportation of pump/generator	HFO, Barge	1	24	100
		Injection of grout	Diesel, Pump/generator	1	24	185
	Installation	Tugboats for transport of foundations	Diesel, Tugboat	2	10.27	322.6
		Transport of jack-up	Diesel, Tugboat	2	3.6	322.6
		Construction of foundation	HFO, Jack-up vessel	1	24	170
	Scour protection	Transport of rock	HFO, Vessel	1	5.13	100
		Dumping of rock	HFO, Vessel	1	29	100
III	Driving pile	Transportation of pump/generator	HFO, Barge	1	24	100
		injection of grout	Diesel, Pump/generator	1	72	185
	Installation	Tugboats for transport of foundation	Diesel, Tugboat	2	144	322.6
		Transport of jack-up	Diesel, Tugboat	2	144	322.6
		Construction of foundation	HFO, Jack-up vessel	1	72	170
IV	Mooring	Transport of suction caisson	Diesel, Tugboat	1	24	322.6

	Pump out water	Diesel, Pump/generator	1	24	185
Installation	Tugboats for transport of foundation and ballast	Diesel, Tugboat	2	168	322.6
	Transport of jack-up	Diesel, Tugboat	2	144	322.6
	Construction of foundation	HFO, Jack-up vessel	1	24	170

Table S3.3: Activities related to land occupation and transformation during installation of one foundation [19].

Foundation type	**Activity**	**Amount**	**Unit**
I	Gravel, unspecified, at mine/CH U (stone bed, 2m depth per base)	1669.0	t
	Gravel, unspecified, at mine/CH U (scour protection)	1794.5	t
	Occupation, water bodies, artificial	35837.7	m2a(m2*year)
	Transformation, from sea and ocean	1194.6	m2
	Transformation, to water bodies, artificial	1194.6	m2
II	Gravel, unspecified, at mine/CH U (per base)	687.5	t
	Occupation, water bodies, artificial	8740.3	m2a(m2*year)
	Transformation, from sea and ocean	291.3	m2
	Transformation, to water bodies, artificial	291.3	m2
III	Occupation, water bodies, artificial	22902.2	m2a(m2*year)
	Transformation, from sea and ocean	763.4	m2
	Transformation, to water bodies, artificial	763.4	m2
IV	Concrete, normal, at plant (suction caission)	500.0	t
	Occupation, water bodies, artificial	651.9	m2a(m2*year)
	Transformation, from sea and ocean	21.7	m2
	Transformation, to water bodies, artificial	21.7	m2

S3.2.3.2.2 Installation of turbine

The turbine installation activities mainly include marine transportation of components from the harbor to erection site and component assembly by jack-up vessel. The installation time (work time) is nowadays only marginally more efficient per turbine as methods and procedures to install that were learnt and already well managed are not necessarily valid with the large turbines [20]. Therefore, this paper assumed turbine installation time is stable towards 2040. The fuel consumption of these processes was calculated based on [21]. The details of turbine installation activities can be found in **Table S3.4**.

Table S3.4: Marine activities related to installing one offshore wind turbine.

Activity	Fuel, Equipment	# of equipment [21]	Work time (h) [21]	Fuel rate (l/h) [21]
Transport of jack-up	Diesel, Tugboat	2	48	322.6
Assembly of wind turbine	HFO, Jack-up vessel	1	24	170

S3.2.3.2.3 Installation of transmission infrastructure

Installation of transmission includes installation of transformer, substations and cables. Installation of cables is related to laying the cabling and assembling contain processes [2]. Each process needs different equipment, which should be mobilized from where they are before beginning on-site operation and demobilized to where they are after finishing the work. Work time for these processes was collected from [22] (See **Table S3.5**).

S3.2.3.3 Operations and maintenance (O&M)

O&M processes involve inspections and maintenance of the physical plant and systems are mostly dependent on turbine failure rates [23]. This paper considered preventative and corrective maintenance.

S3.2.3.3.1 Preventative maintenance (scheduled)

Preventative maintenance (scheduled) consists of regular inspection of turbines, cables and substations. These processes were modeled based on vessel work time and fuel consumptions.

S3.2.3.3.2 Corrective maintenance (unscheduled)

Corrective maintenance includes unscheduled inspection and repair of turbines, cables and substations (shown in **Table S3.6**). Generators and blades are two most vulnerable components of offshore wind turbines [24]. The biggest contributor to the failure cost for offshore wind turbines is the generator and gearbox (if any) major replacement in the nacelle [25]. Due to complex long-term working conditions, blades tend to experience many internal (e.g. the fatigue failure) and external (e.g. environmental conditions) damages [26]. Work time for replacement of blades was assumed the same as replacement of nacelle due to lacking of data. Replacement processes were modeled based on [2].

S3.2.3.3.3 Maintenance strategy

According to A Guide to UK Offshore Wind Operations and Maintenance [23], workboats are the most economic option for near-shore sites while the support by helicopters (heli-support) is necessary for sites further from shore. Helicopter transport in cases where difficult weather conditions prevent access by workboats. Further, for offshore wind farms located in deep water, more helicopters are needed to support offshore wind farm O&M. Port-based workboats become the only practical option for cases. However, lacking detailed representations of different vessels involved makes assessments of these activities in LCAs tentative. 50% marine vessel and 50% Jack-up vessel were assumed to be used during replacement processes. 100 flight-hours per wind turbine along 25 years life time is reported in [9]. Thus, this paper assumed 4 flight-hours per year per turbine.

Table S3.5: Marine activities related to installing transmission infrastructures for one wind turbine.

Activity			**Fuel, Equipment**	**Mobilization and demobilization time (h)** [2]	**Work time (h/km)** [2]	**Fuel rate (l/h)** [2]
Transformer substation installation [19]			HFO, jack-up vessel		8	170
Route clearance	Pre-sweep route	Dredging	HFO, vessel	96	24	100
	Route clearance	Anchor Handler	HFO, vessel	96	3.24	100
In-field operation	Tie-in and installation	Cable laying	HFO, vessel with plough	384	24	572.9
		Support	Diesel, vessel	96	24	262.5
		Burial assistance	Diesel, vessel		24	262.5
	Scour protection	Transportation of rock	HFO, vessel		0.128	100
		Rock placement	HFO, vessel		2	100
Shore connection	Installation	Cable laying	HFO, vessel with plough		3.53	572.9
	Scour protection	Transportation of rock	HFO, vessel		0.128	100
		Rock placement	HFO, vessel		2	100
Shore landing	Installation	Cable laying	HFO, vessel with plough		1.6	572.9
		Support	Diesel, vessel		4	262.5
	Shore spread	Cable yarder with sled winch	Diesel, winch	24	4	0.455

Table S3.6: Marine activities related to O&M (per incident per turbine per year).

Activity		**Fuel, Equipment**	**Work time (h)** [2]	**Fuel rate (l/h)** [2]
Preventative maintenance	Regular inspection of turbines	Diesel, Vessel	60	262.5
	Regular inspection of cables	Diesel, Vessel	336	150
	Regular inspection of substations	Diesel, Vessel	180	262.5
Corrective maintenance	Irregular inspection and repair	Diesel, Vessel	0.48	262.5
		Helicopter [9]	4	83.1[27]
Corrective maintenance	Replacement of nacelle	HFO, 50% Vessel and 50% Jack-up vessel	48	100, 170
	Replacement of blades [2]	HFO, 50% Vessel and 50% Jack-up vessel	48	100, 170
	Replacement of small components	HFO, 50% Vessel and 50% Jack-up vessel	0.96	100, 170

S3.2.3.4 Decommissioning

S3.2.3.4.1 Decommissioning of turbines

Wind turbines should be entirely removed from the site and then dissembled onshore. A heavy lift vessel or dynamic positioning vessel will usually be used [28]. The procedure performed will depend on the size and weight of the turbine, and will determine the lifting capacity and vessel's deck space. The emissions of decommission processes are mainly related to transportation of decommissioned wind turbines. The details of turbine decommission marine activities can be found in **Table S7**.

S3.2.3.4.2 Decommissioning of foundations

This paper assumed foundations will be decommissioned. However, deep foundations may be costly to remove and it may have severe impacts on marine environment. Normally, foundations can be kept in site and available for repowering (replacement of the existing turbines into more powerful ones). Foundation lifetime is longer than turbines with approximately 100 year [29]. When foundations reach EoLs, there are two removal options proposed: the complete removal and cutting from a certain depth below the mud line and leaving the rest in situ [28]. But these processes are out of the discussion of this paper. Details can be found in [28].

S3.2.3.4.3 Decommissioning of transmission pieces

This paper assumed cables will be left in situ. On the electrical side, array and export cables (transmission cables) could last more than 40 years, and the transformers 35 years [21]. Submarine cables (both internal and external cables) are usually buried into depths of more than a meter below the seabed, which will not pose safety risks for marine users and have limited environmental or pollution impacts [28]. The complete removal is considered to cause substantial damage and disruption to the seabed given the extensive length of the cables [30].

Table S3.7: Marine activities related to decommissioning of one offshore wind turbine.

Activity	Fuel, Equipment	# of equipment [21]	Work time (h) [21]	Fuel rate (l/h) [21]
Transport of jack-up	Diesel, Tugboat	2	24	322.6
Assembly of wind turbine	HFO, Jack-up vessel	1	12	170

S3.2.3 Life cycle impact assessment

Table S3.8: A list of impact categories. Impact categories that marked in bulk were considered most related to OWE.

ReCiPe Midpoint (H) V1.13	
Name	**Unit**
agricultural land occupation, ALOP	square meter - year
climate change, GWP100	kg CO2-Eq
fossil depletion, FDP	kg oil-Eq
freshwater ecotoxicity, FETPinf	kg 1,4-DC.
freshwater eutrophication, FEP	kg P-Eq 13
human toxicity, HTPinf	kg 1,4-DC.
ionising radiation, IRP_HE	kg U235-Eq
marine ecotoxicity, METPinf	kg 1,4-DC.
marine eutrophication, MEP	kg N-Eq 46
metal depletion, MDP	kg Fe-Eq
natural land transformation, NLTP	square meter

ozone depletion, ODPinf	kg CFC-11.
particulate matter formation, PMFP	kg PM10-Eq
photochemical oxidant formation, POFP	kg NMVOC-.
terrestrial acidification, TAP100	kg SO2-Eq
terrestrial ecotoxicity, TETPinf	kg 1,4-DC.
urban land occupation, ULOP	square meter-year
water depletion, WDP	m3 water-.

Climate change, marine ecotoxicity, marine eutrophication, and metal depletion were considered as the most relevant impact categories in this study. OWE is key to energy transition and considered as a promising renewable energy source to mitigate greenhouse gases emissions (GHGs). Climate change is a widely used impact category to represent GHGs. OWE is located over shallow open waters in the sea and moving further into deep waters. Marine ecotoxicity and marine eutrophication are two impact categories directly linked to marine environment. Metal depletion will likely be a concern as several metals (e.g. steel, copper, and aluminum) are required along with the large-scale expansion of OWE development. This study mainly focus on these four impact categories but the environmental impact results of other impact categories could be found in **Results** in **Supporting Information II**.

Table S3.9: An overview of parameters related to the impacts of EP by the OWE. ✓ (✗) indicate the parameters that are (not) directly related to life cycle stage or component.

Parameters	**Life cycle stage**				**Component**			
	Manufacturing	Installation	O&M	Decommissioning	Nacelle	Rotor	Tower	Foundation
Capacity factor (CF)	✓	✓	✓	✓	✓	✓	✓	✓
Lifetime	✓	✓	✓	✓	✓	✓	✓	✓
Nominal capacity (NC)	✓	✓	✓	✓	✓	✓	✓	✓
Turbine size	✓	✗	✓	✗	✓	✓	✓	✓
Distance from shore	✗	✓	✓	✓	✗	✗	✗	✗
Technology market shares	✓	✓	✓	✓	✓	✓	✓	✓
Maintenance times	✗	✗	✓	✗	✓	✓	✗	✗
Replacement rates	✗	✗	✓	✗	✓	✓	✗	✗
Transportation strategy	✗	✗	✓	✗	✗	✗	✗	✗

S3.3 Results and discussion

S3.3.1 Environmental impact intensity

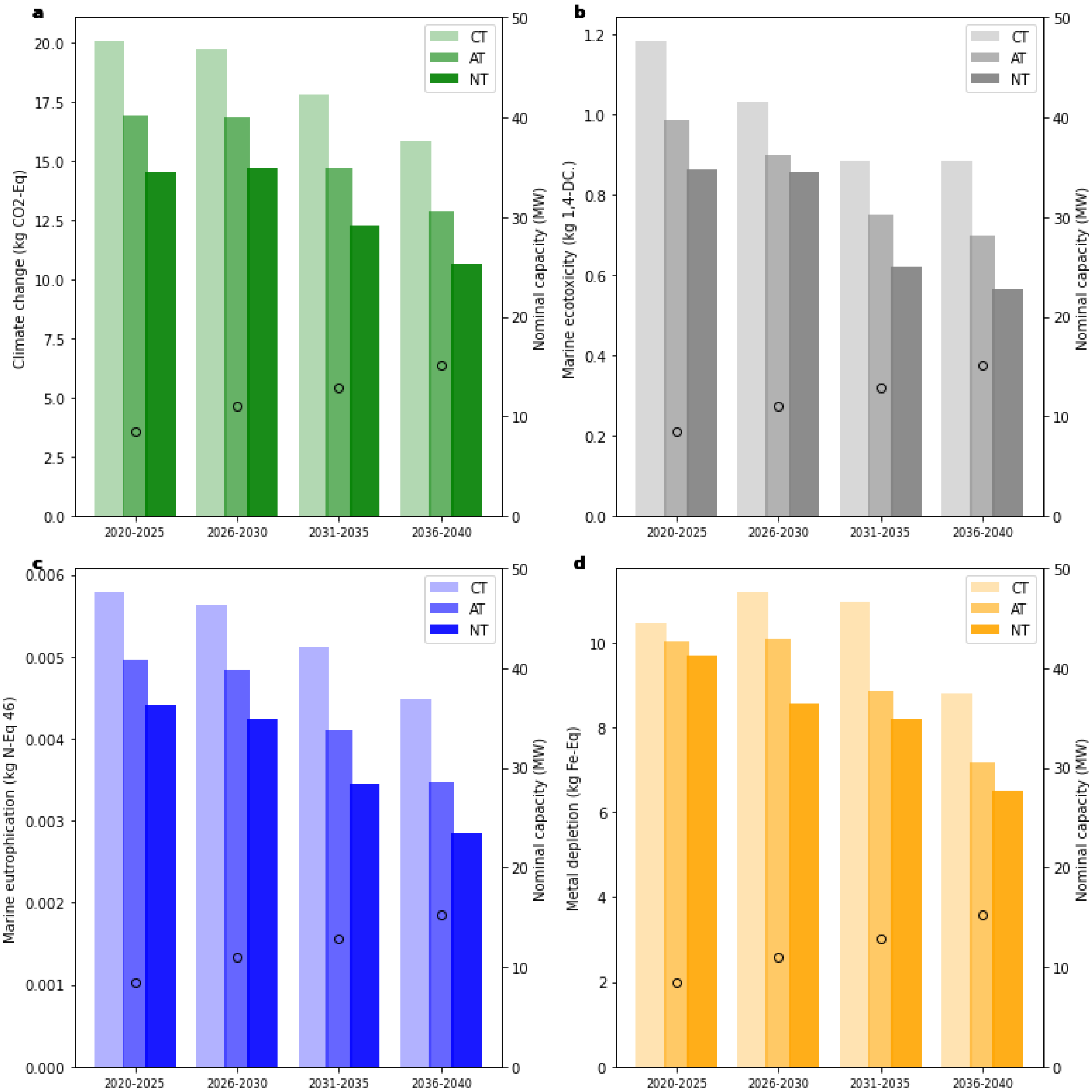

Figure S3.4: Environmental impacts per MWh (5-year average), under EoL_O recycling scenario. The bars from light color to dark color correspond to the impacts based on conventional technology (CT), advanced technology (AT), and new technology (NT) scenarios, respectively. The dots indicate the average nominal capacity at a given period.

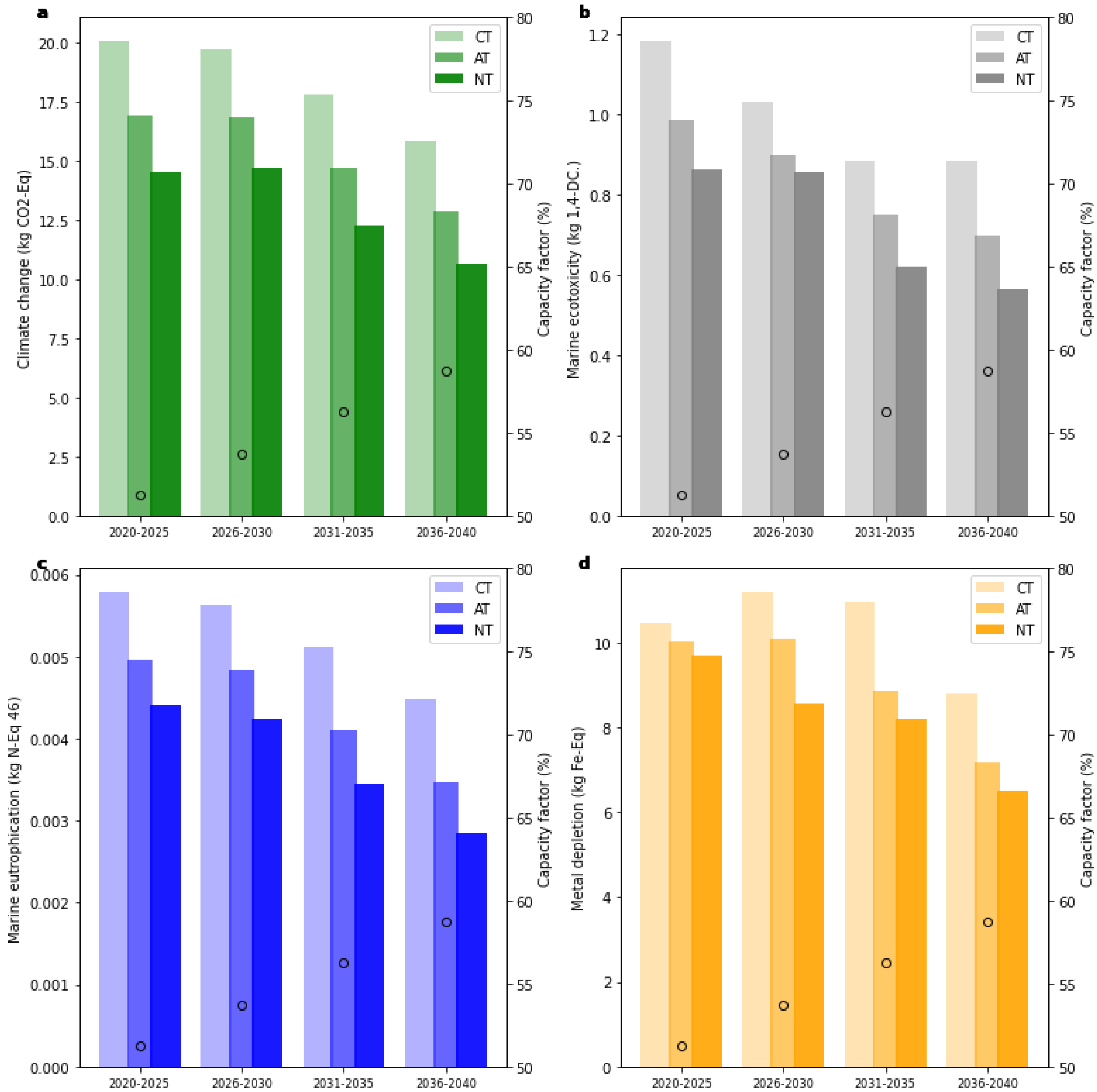

Figure S3.5: Environmental impacts per MWh (5-year average), under EoL_O recycling scenario. The bars from light color to dark color correspond to the impacts based on conventional technology (CT), advanced technology (AT), and new technology (NT) scenarios, respectively. The dots indicate the average capacity factor (CF) at a given period.

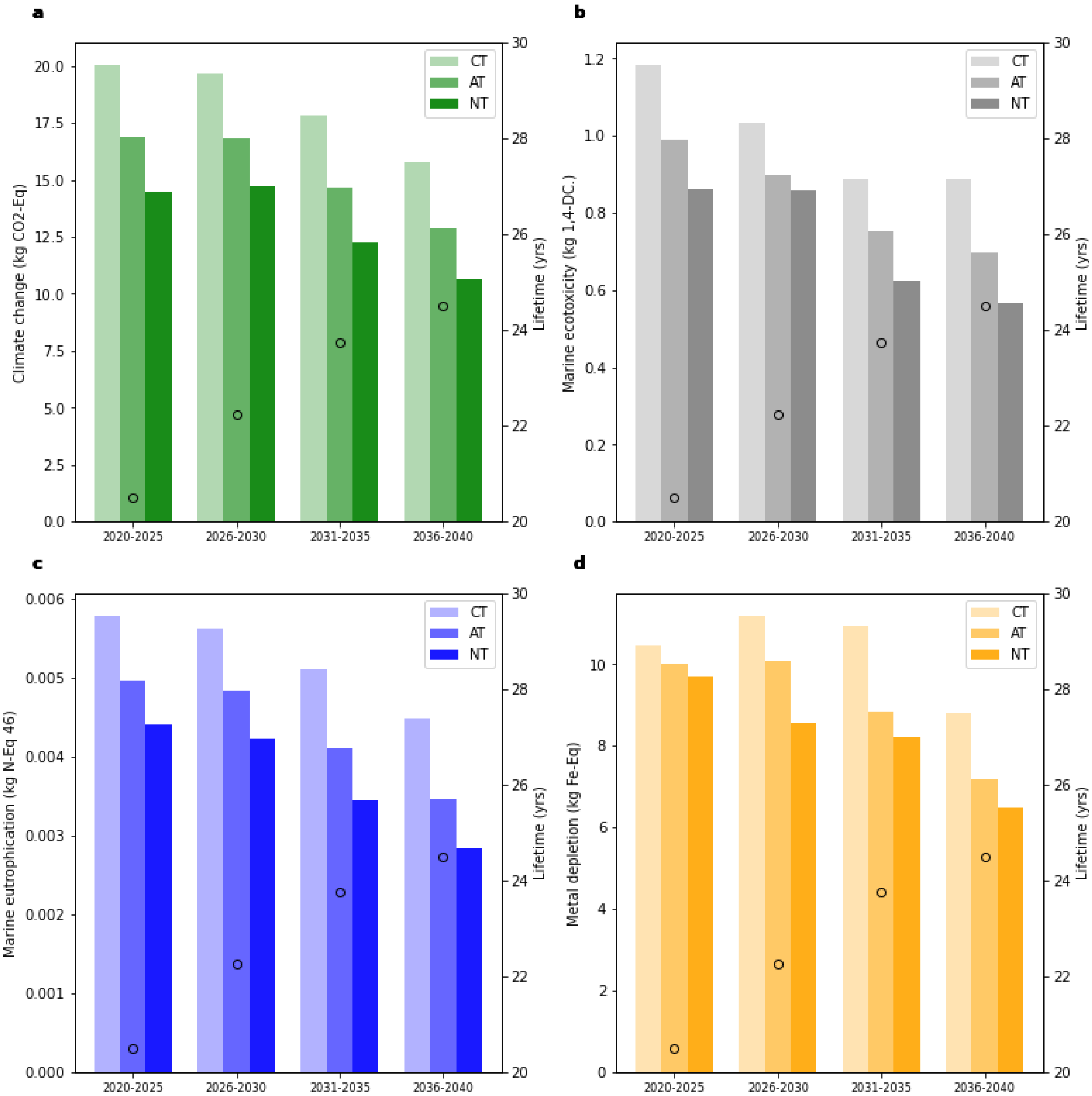

Figure S3.6: Environmental impacts per MWh (5-year average), under EoL_O recycling scenario. The bars from light color to dark color correspond to the impacts based on conventional technology (CT), advanced technology (AT), and new technology (NT) scenarios, respectively. The dots indicate the average lifetime at a given period.

The environmental impact intensities are influenced by several combined effects: **1)** increased lifetime leads to increased accumulative electricity production (**Figure S3.6**). The environmental impacts per MW (**Figure S3.7**) only slightly increase from 2020 to 2030 for all impact categories, which verifies the significance of lifetime extension on impact intensity decline; **2)** Nominal capacity will continue to increase in the future and leads to more powerful turbines, which have a larger rotor diameter corresponding to a high ratio of m2-of-swept-area-per-MW. According to **Figure S3.4**, climate change related GHG from 2030 to 2035, and from 2035 to 2040, is 2.0 (~13%) and 3.3 (~21%) kg CO2-eq./MWh lower than the average value from 2020 to 2030, respectively, when nominal capacity increases from 7.8 MW in 2020 to 15.6 MW in 2040 (twofold to 2020). **3)** Advanced and new technology development increase the capacity factor and further decrease the impact intensities (**Figure S3.5**).

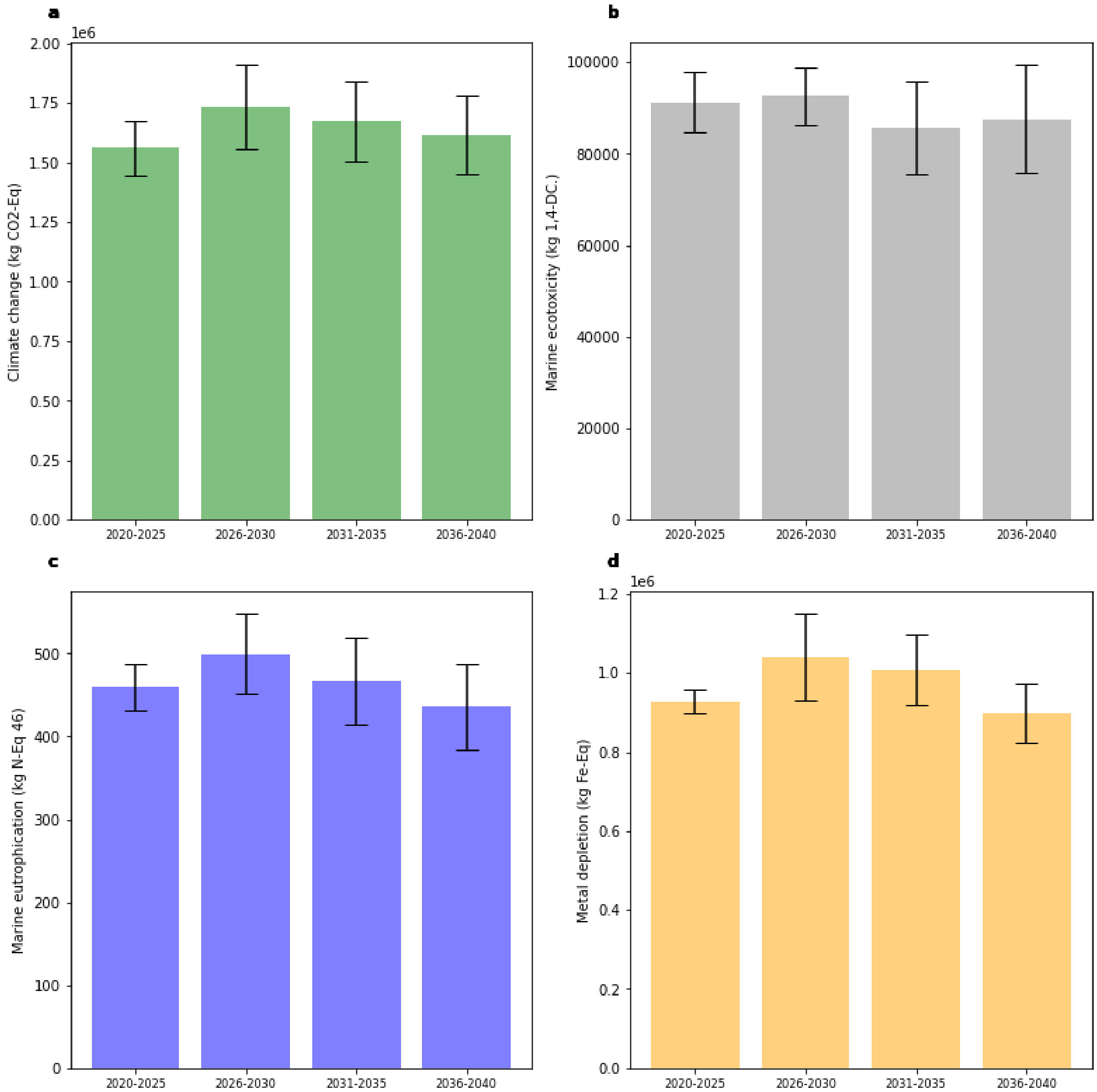

Figure S3.7: Environmental impacts per MW (5-year average). The main bars correspond to the values based on advanced technology (AT) scenario; the upper and lower bounds of error bars show the values based on conventional technology (CT) and new technology (NT) scenarios, respectively.

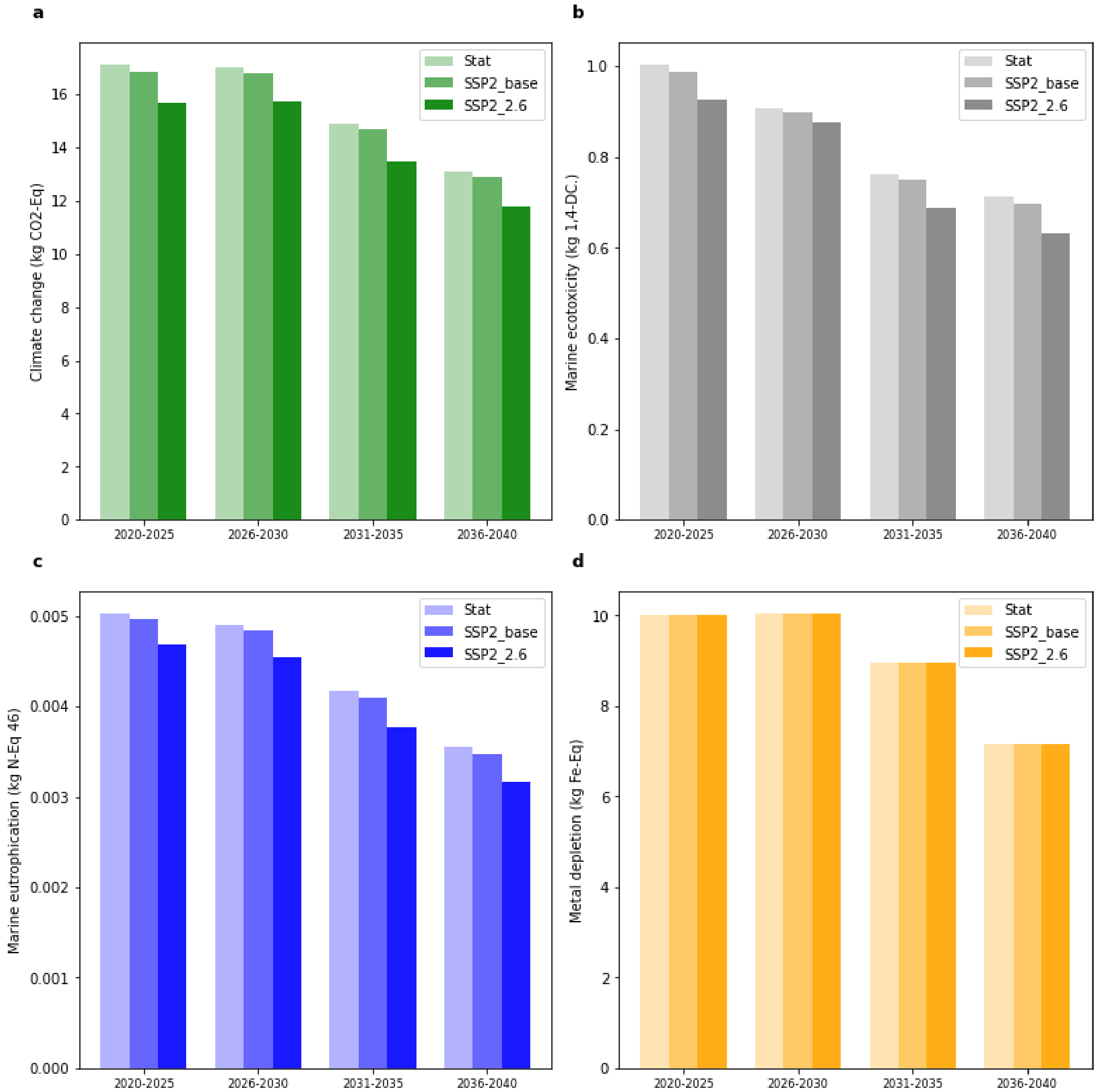

Figure S3.8: Comparative analysis on background scenarios, based on AT technology scenario and EoL_O recycling scenario. Stat: business as usual scenario (based on current background system, no changes); SSP2_base: Middle of the Road base scenario; SSP2_RCP2.6: Middle of the Road scenario that follows RCP2.6.

S3.3.2 Fleet environmental impact

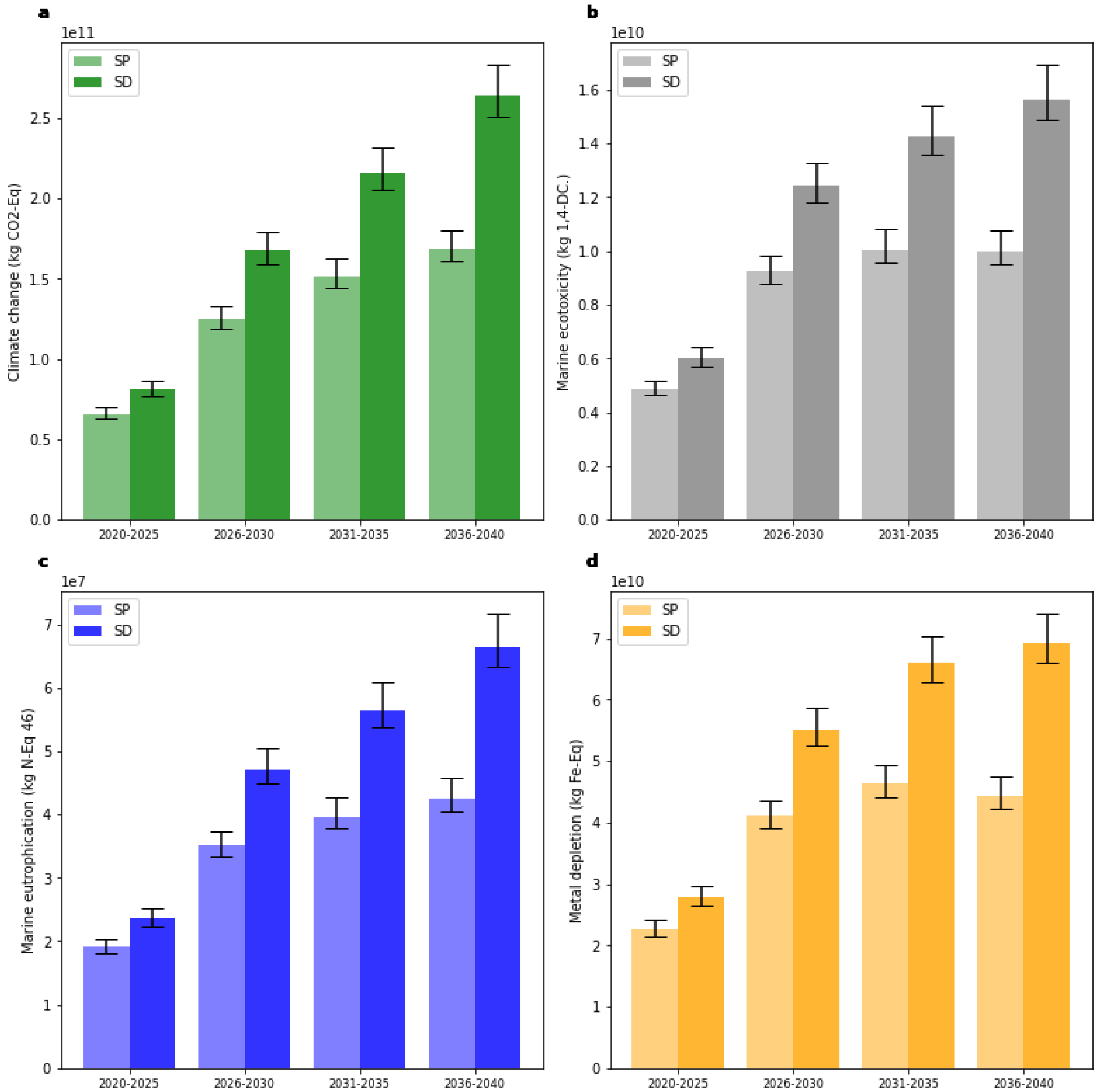

Figure S3.9: Total environmental impacts (5-year average), under EoL_O recycling scenario and SSP2-base background scenario. The bars with light and dark color represent the values based on stated policy (SP) and sustainable development (SD) capacity scenarios, respectively. The main bars correspond to the values based on advanced technology (AT) scenario; the upper and lower bounds of error bars show the values based on conventional technology (CT) and new technology (NT) scenarios, respectively. The current electricity mix was calculated based on the processes ‘’market group for electricity, high voltage’’ in ecoinvent.

S3.3.3 Contribution analysis

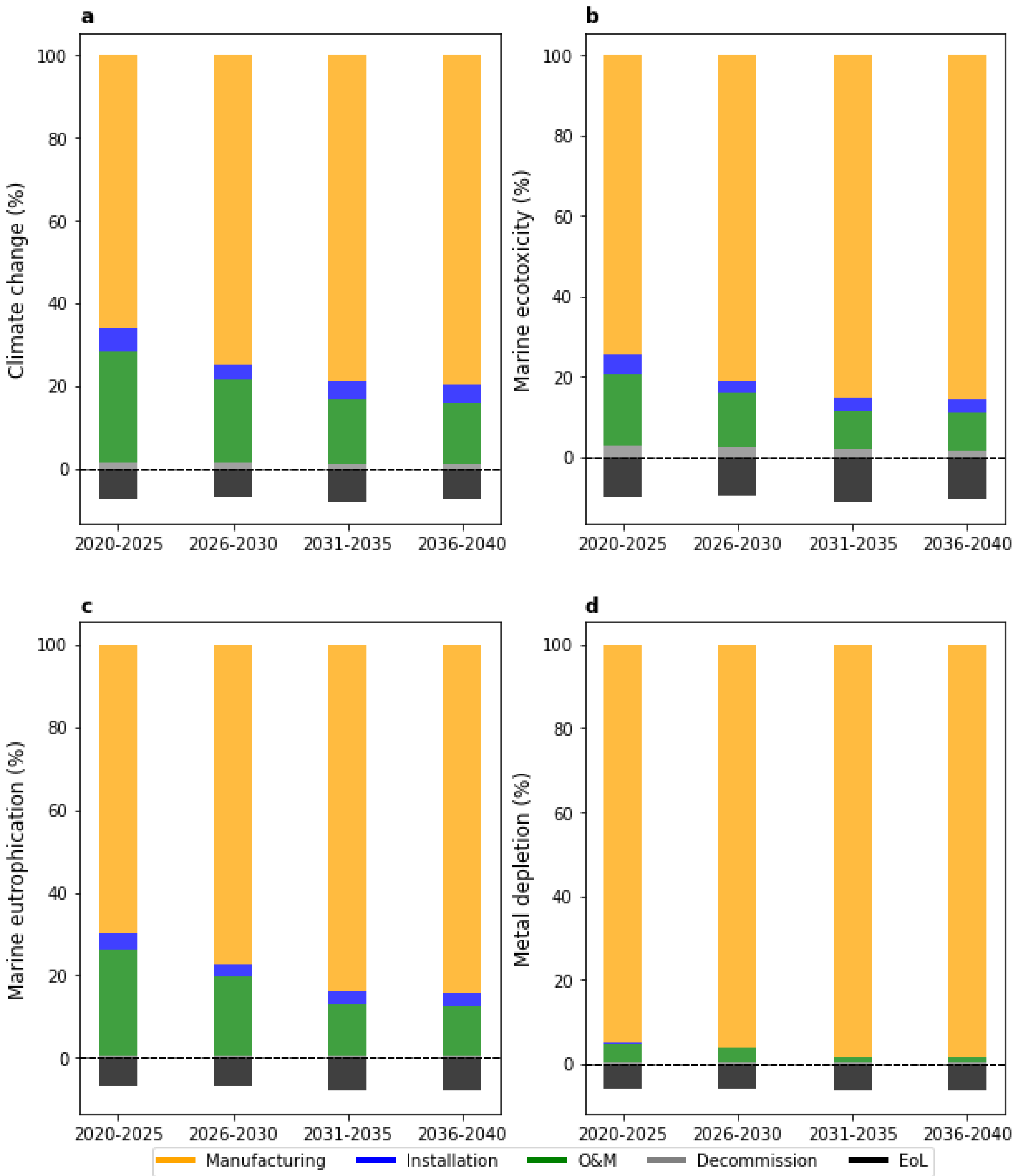

Figure S3.10: Contribution analysis on life cycle stage, i.e. manufacturing, installation, O&M, decommissioning, and EoL recycling, based on AT technology scenario, EoL_O recycling scenario, and SSP2-base background scenario. The black crosses show the percentages of impacts could be offset by EoL recycling.

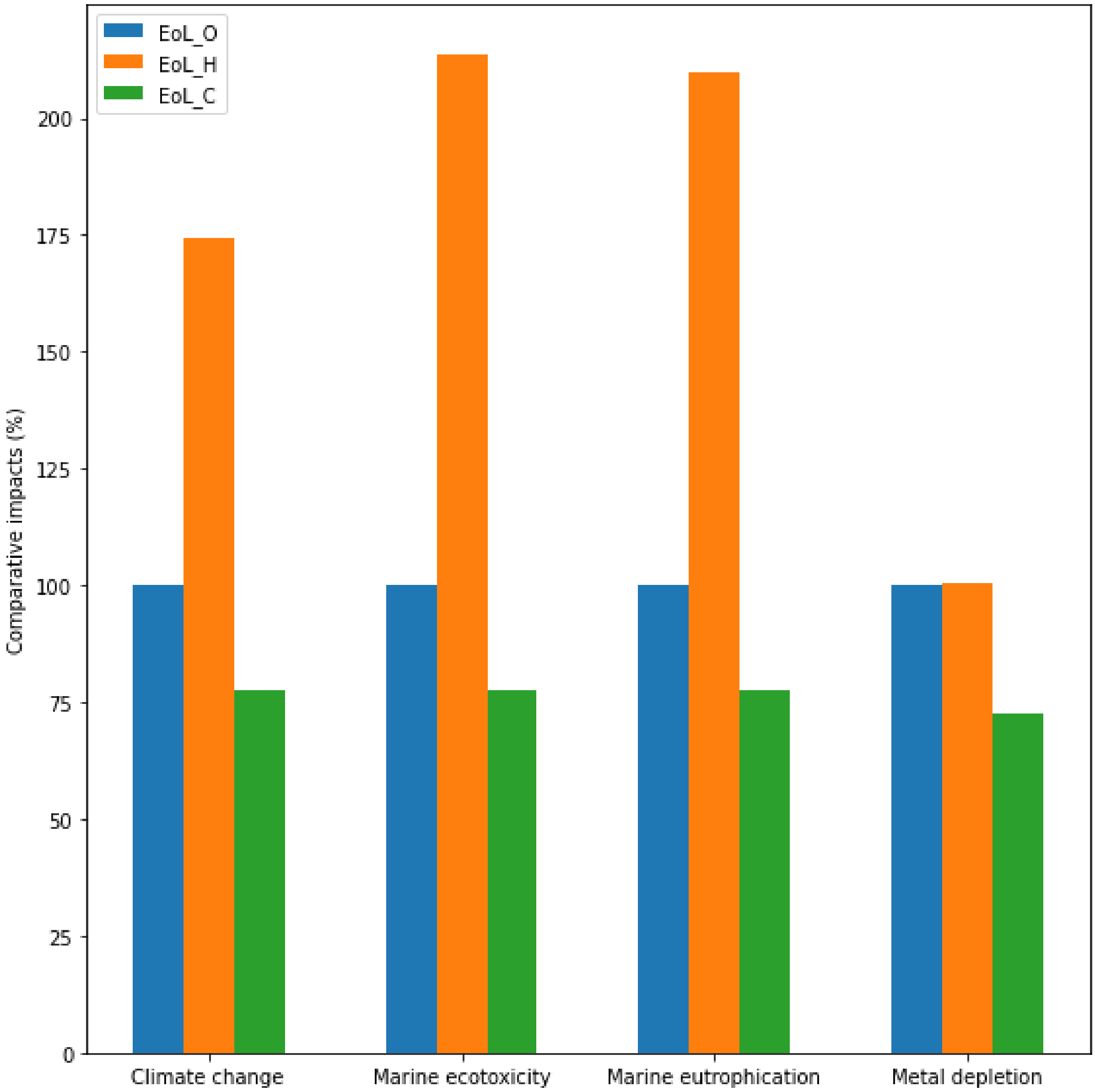

Figure S3.11: Comparison analysis on average (from 2020 to 2040) environmental impact reduction, under three EoL recycling scenarios, i.e. hypnotical EoL scenarios (EoL_H), optimistic EoL (EoL_O), and EoL conservative EoL (EoL_C), in terms of climate change, marine ecotoxicity, marine eutrophication, and metal depletion. Base EoL recycling scenario: EoL_O.

S3.3.4 Sensitivity analysis

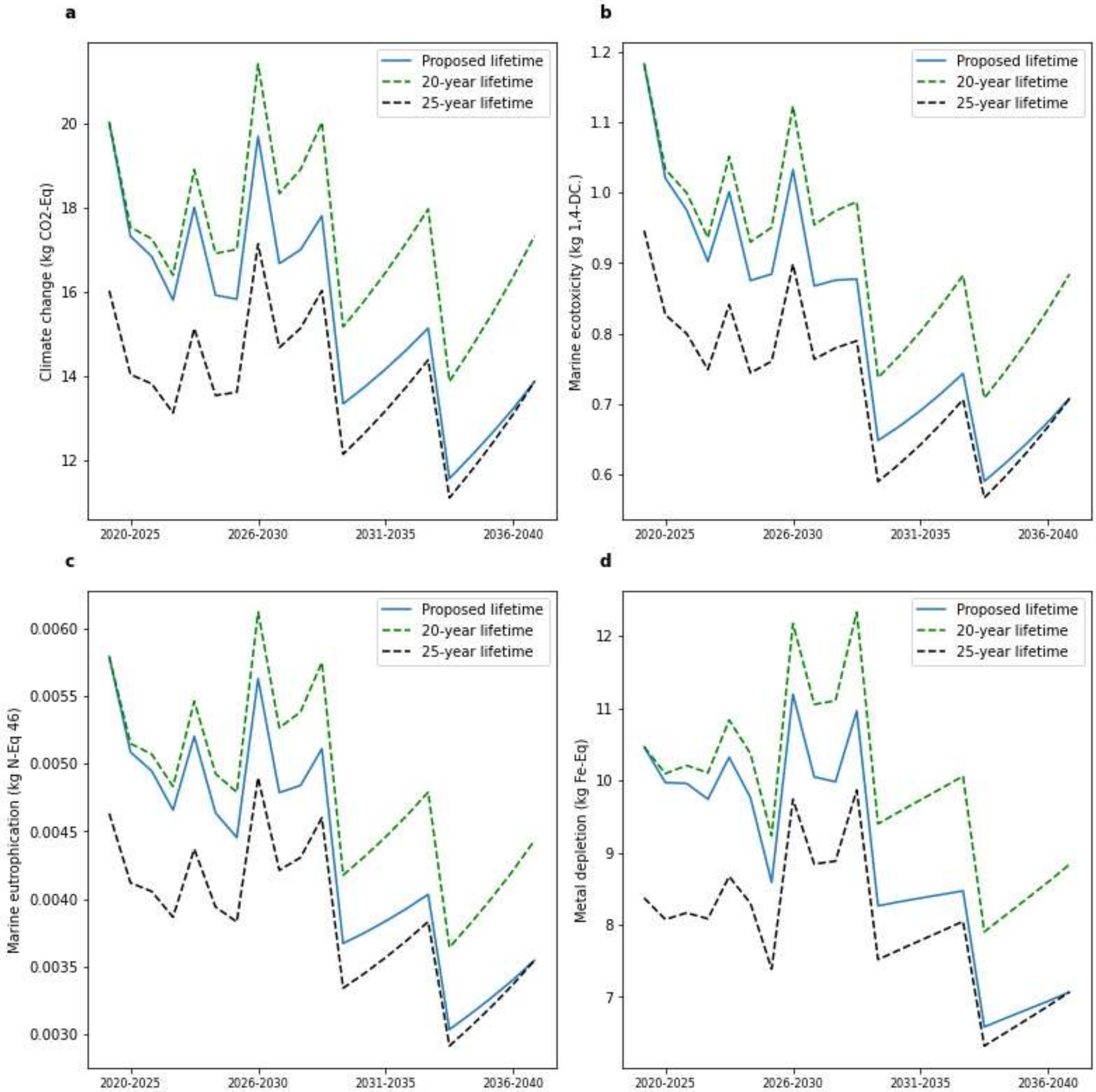

Figure S3.12: Sensitivity analysis on lifetime. Proposed lifetime indicates the lifetime assumed in this paper: dynamic lifetimes with a 20-year mean in 2020 that increases to a 25-year mean in 2040, and a 5-year standard deviation Normal distribution; A linear dynamic change was assumed for lifetimes from 2020 to 2040.

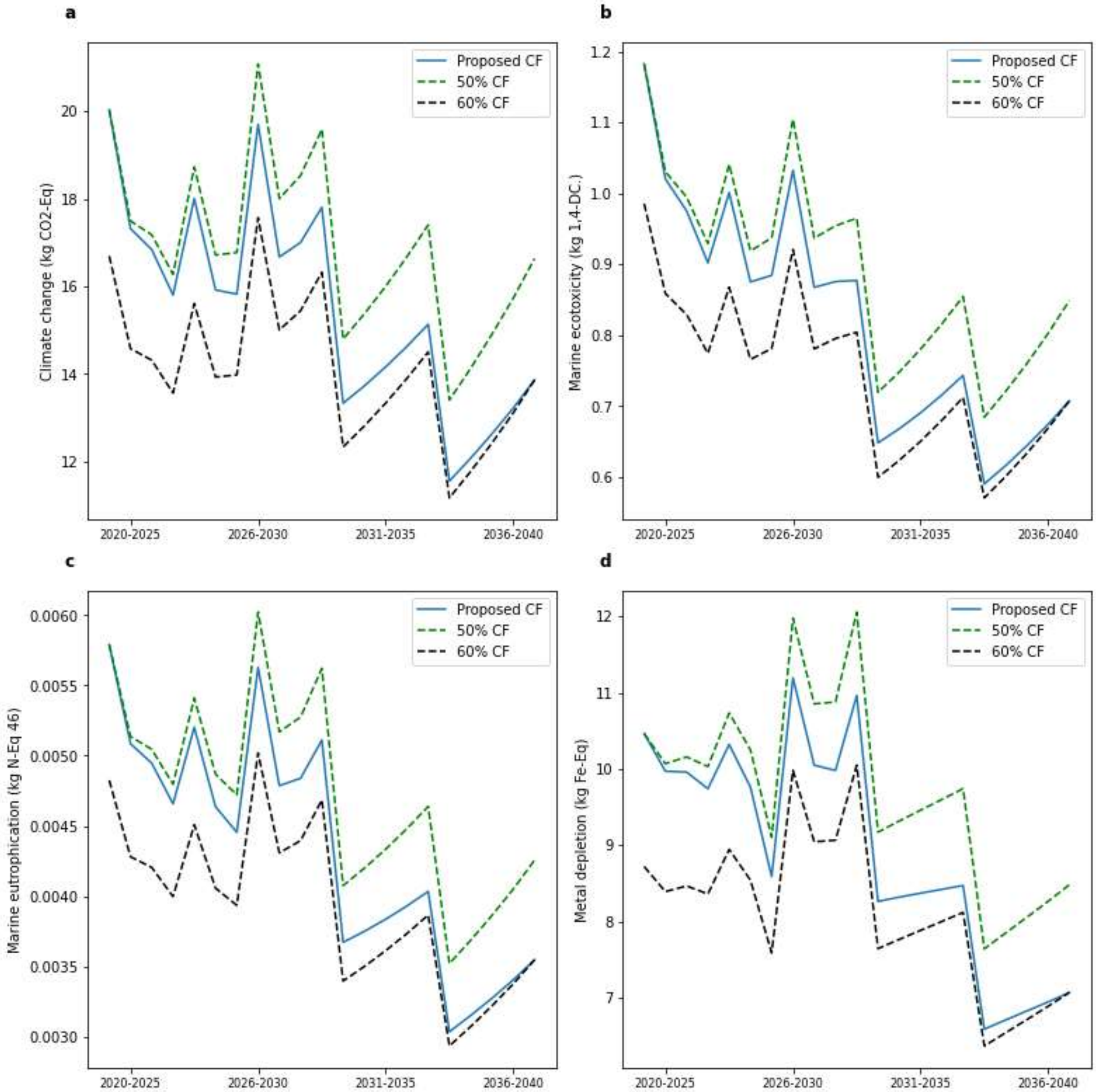

Figure S3.13: Sensitivity analysis on CF. Proposed CF indicates the lifetime assumed in this paper: 50% in 2020 and 60% in 2040, respectively. A linear dynamic change was assumed for CF from 2020 to 2040.

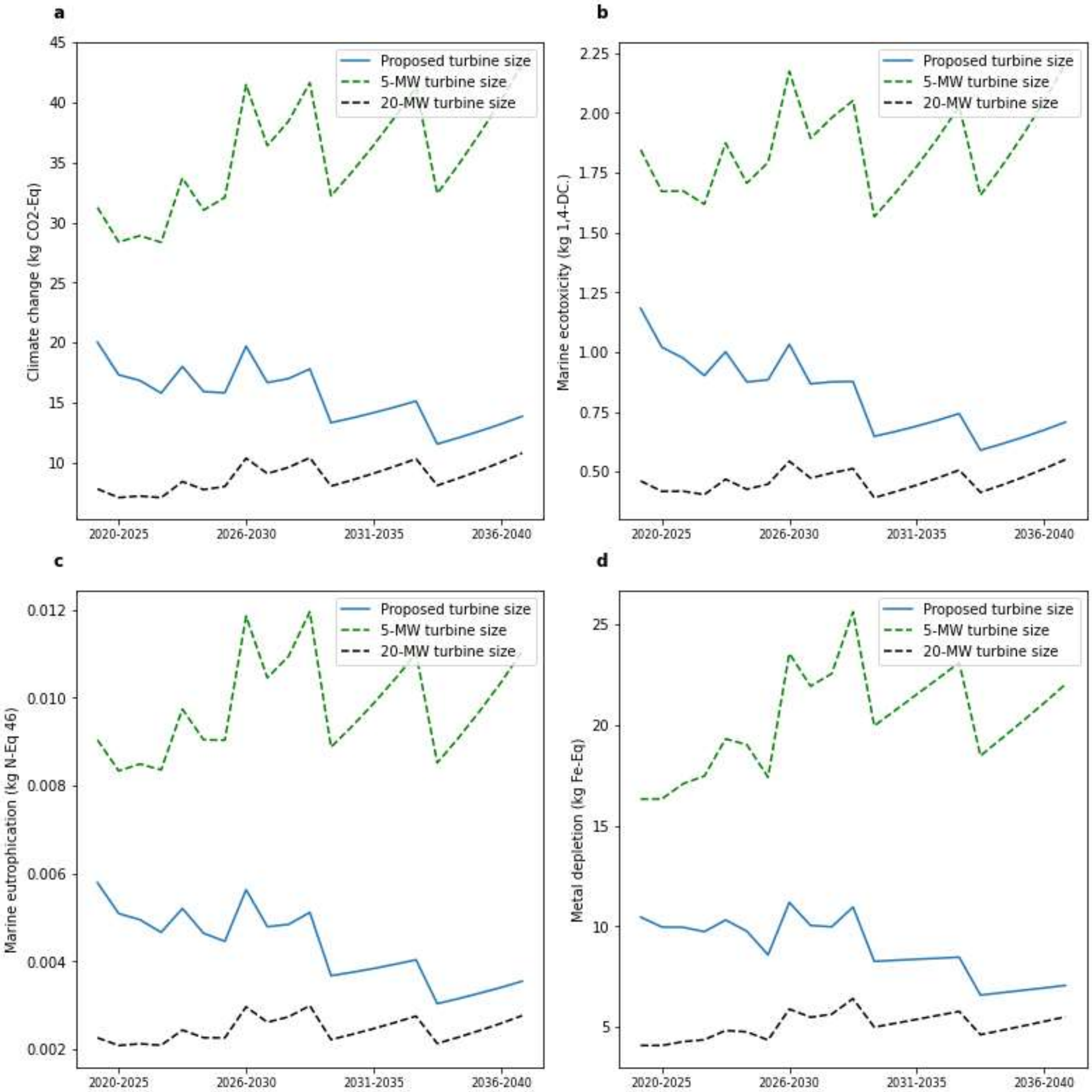

Figure S3.14: Sensitivity analysis on turbine size (nominal capacity). The proposed nominal capacity is estimated by the OLS regression based on projects from 4C offshore [15].

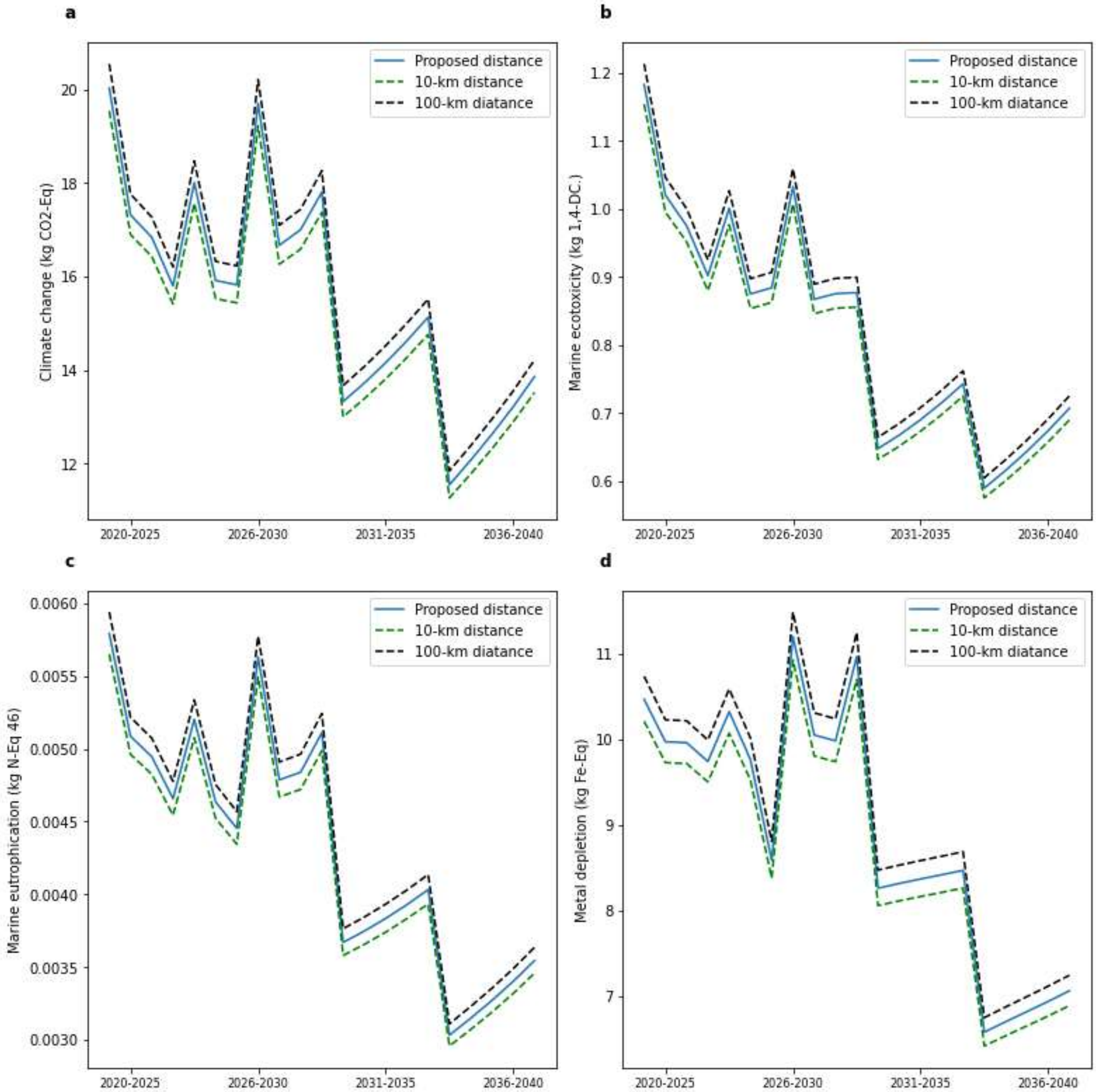

Figure S3.15: Sensitivity analysis on distance from shore. The proposed distance from shore was estimated by the OLS based on projects from 4C offshore [15].

S3.3.5 Limitations and outlook

Marine transportation is normally modeled through theoretical considerations of energy use in transporting a mass over an assumed distance (tkm) [34]. OWE case is specific as most of the time that marine vessels and supporting equipment spend is at site, e.g. unloading components on top of the foundation. Specialized vessels are often required during transportation, uploading, and maintenance. In ecoinvent, barge, transoceanic freight ship, and port facilities are only represented for marine transportation [34]. This study modeled marine transportation based on the work time of vessels and supporting equipment, and associated fuel consumptions (**Table S3.2**, **S3.4, S3.5,** and **S3.6**). Currently, most offshore wind turbines are transported from harbor to site by tugboats [35] and installed by jack-up crane vessels in water depths up to 50 m [36]. However, when wind turbines move further from shore with deep waters, specialized vessels are essential for transportation. Floating crane vessels are required to satisfy the high dynamic lifts of components for installing offshore wind turbines in even deeper waters [37]. Moreover, larger turbine turbines in harsher environment will receive fatigue and corrosion damage, which require larger supporting infrastructures (e.g. specialized equipment and vessels) [32]. The availability of these infrastructures is a major challenge. There are numerous vessels in the small-scale market but more optimized vessels are still in the design phase. The scaling of background infrastructure and introduction of novel transportation technologies will likely further increase the impacts of installation, O&M, and decommissioning.

Table S3.10: Contribution analysis by the process, life cycle stage, component, and process in manufacturing and O&M, based on the AT scenario and EoL_O recycling scenario.

Impact category	Contributions						
	Contributions by life cycle stage						
Climate change	Manufacturing (~75%)	Installation (~5%)	O&M (~19%)	Decommissioning (~1%)	EoL (~-7%)		
Marine ecotoxicity	Manufacturing (~87%)	Installation (~3%)	O&M (~8%)	Decommissioning (~2%)	EoL (~-11%)		
Marine eutrophication	Manufacturing (~79%)	Installation (~4%)	O&M (~17%)	Decommissioning (~0%)	EoL (~-7%)		
Metal depletion	Manufacturing (~98%)	Installation (~0%)	O&M (~2%)	Decommissioning (~0%)	EoL (~-6%)		
	Contributions by component						
Climate change	Turbines (~56%)	Foundations (~41%)	Transmission (~3%)				
Marine ecotoxicity	Turbines (~64%)	Foundations (~34%)	Transmission (~2%)				
Marine eutrophication	Turbines (~57%)	Foundations (~40%)	Transmission (~3%)				
Metal depletion	Turbines (~77%)	Foundations (~19%)	Transmission (~4%)				
	Contributions by process						
Climate change	Reinforcing steel (~45%)	Diesel (~14%)	Carbon fiber (~11%)	Electricity (~6%)	Glass fiber (~5%)	Others (~19%)	
Marine ecotoxicity	Reinforcing steel (~43%)	Copper (~20%)	Low-alloyed steel (~10%)	Electronics (~7%)	Carbon fiber (~6%)	Others (~14%)	
Marine eutrophication	Reinforcing steel (~41%)	Glass fiber (~15%)	Diesel (~10%)	Carbon fiber (~8%)	Low-alloyed steel (~6%)	Electricity (~5%)	Others (~14%)
Metal depletion	Zinc (~52%)	Reinforcing steel (~21%)	Copper (~9%)	Low-alloyed steel (~7%)	Lead (~5%)	Others (~5%)	
	Contributions by process in manufacturing						
Climate change	Reinforcing steel (~60%)	Carbon fiber (~15%)	Glass fiber (~7%)	Electricity (~7%)	Low-alloyed steel (~5%)	Others (~6%)	
Marine ecotoxicity	Reinforcing steel (~49%)	Copper (~23%)	Low-alloyed steel (~11%)	Electronics (~6%)	Carbon fiber (~6%)	Others (~5%)	
Marine eutrophication	Reinforcing steel (~52%)	Glass fiber (~19%)	Carbon fiber (~10%)	Low-alloyed steel (~7%)	Electricity (~6%)	Others (~6%)	
Metal depletion	Zinc (~53%)	Reinforcing steel (~21%)	Copper (~9%)	Low-alloyed steel (~7%)	Lead (~5%)	Electronics (~3%)	Others (~2%)
	Contributions by process in O&M						
Climate change	Replacement of materials (~47%)	Diesel (~43%)	Heavy fuel oil (~10%)	Others (~0%)			
Marine ecotoxicity	Replacement of materials (~53%)	Diesel (~42%)	Others (~5%)				
Marine eutrophication	Replacement of materials (~52%)	Diesel (~37%)	Heavy fuel oil (~10%)	Others (~1%)			
Metal depletion	Replacement of materials (~99%)	Others (~0%)					

Table S3.11: Results of sensitivity analysis on embedded parameters, based on the AT technology scenario and EoL_O recycling scenario. Variation of impacts is calculated based on the cumulative impacts from 2020 to 2040.

Parameters		**Variation**	**Variation of climate change**	**Variation of marine ecotoxicity**	**Variation of marine eutrophication**	**Variation of metal depletion**
Technology market shares	PMSG-GB	+20%	+2.9%	+3.1%	+3.4%	+3.2%
	PMSG-GB	-20%	-2.3%	-2.3%	-2.3%	-2.3%
	PMSG-DD	+20%	+3.6%	+3.6%	+4.0%	3.8%
	PMSG-DD	-20%	-4.3%	-4.4%	-4.6%	-4.5%
	Semi-submersible	+20%	-9.4%	-9.1%	-9.5%	-9.3%
	Semi-submersible	-20%	+2.4%	+2.5%	+2.7%	+2.5%
Maintenance times		+20%	+0.7%	+0.7%	+0.9%	+0.8%
		-20%	-0.7%	-0.7%	-0.9%	-0.8%
Replacement rates		+20%	+1.3%	+1.3%	+1.5%	+1.4%
		-20%	-1.3%	-1.3%	-1.5%	-1.4%
Transportation strategy	Helicopter support	+20%	+0.5%	+0.5%	+0.6%	+0.6%
		-20%	-0.5%	-0.5%	-0.6%	-0.6%
Recycling rates		+20%	-4.0%	-4.0%	-4.4%	-4.1%
		-20%	+4.1%	+4.1%	+4.4%	+4.2%
Waste treatment	landfill processes	+20%	+2.0%	+2.1%	+2.2%	+2.2%
		-20%	-2.0%	-2.1%	-2.2%	-2.2%

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Supporting Information for chapter 4

S4.2.1 Scope and study area

Table S4.1: Sample data overview, with columns for offshore wind farm name (Wind farm), number of turbines in the wind farm (# Turbines), wind farm status (Status), and installation age (Age).

Wind farm	# Turbines	Status	Age											
			0	1	2	3	4	5	6	7	8	9	10	11
Belwind	55	In operation	4	12	18	9	6	3	3	0	3	3	3	0
C-power	54	In operation	56	60	31	34	15	31	51	51	59	44	36	36
Horn Rev 1	80	In operation	0	257	268	268	0	0	0	0	0	0	0	0
Alpha Ventus	12	In operation	0	36	72	72	36	0	0	0	0	0	0	0
BeoFino[1]	-	-	0	5	32	63	78	40	0	0	0	0	0	0
DanTysk	80	In operation	0	0	0	0	0	18	18	0	0	0	0	0
Prinses Amalia	60	In operation	0	0	0	0	10	132	133	10	0	0	0	0
Total			60	370	421	446	145	224	205	61	62	47	39	36

S4.2.4 Biodiversity model fit and estimation

The Q-Q plot was used to visually check the assumption of normality. The results show that the models do not raise significant concern with normality of residuals (**Figures S4.1** and **S4.2**), also given that linear mixed-effect models are quite robust to violations of the assumption [3].

The model residuals were plotted against the fitted values to check homogeneity of variance. The results suggest that homogeneity of variance can be assumed (**Figures S4.3** and **S4.4**).

The variance inflation factor [4] was used to check the possible multicollinearity between predictors. The variance inflation factors were <2.5 for all predictors; therefore, multicollinearity was not an issue for the considered predictors [4].

The Monte Carlo cross-validation was further conducted to judge the performance of the GLMM model. The dataset used to build the GLMM is randomly divided into training set (80%) and validation set (20%). The accuracy of the GLMM is calculated through prediction error-based indicators, i.e. mean squared error (MSE), mean absolute error (MAE), mean absolute percentage error (MAPE) and coefficient of determination (R^2). The simulation was conducted 50 times and the average values were used (**Table S4.2**). The results indicate the high and acceptable accuracy of the GLMM for species abundance and richness, respectively.

Table S4.2: Model validation results.

Species richness				**Species abundance**			
MSE	MAE	MAPE	R^2	MSE	MAE	MAPE	R^2
27.11	4.23	0.27	42%	556192.36	1452.15	0.18	87%

[1] Research platform

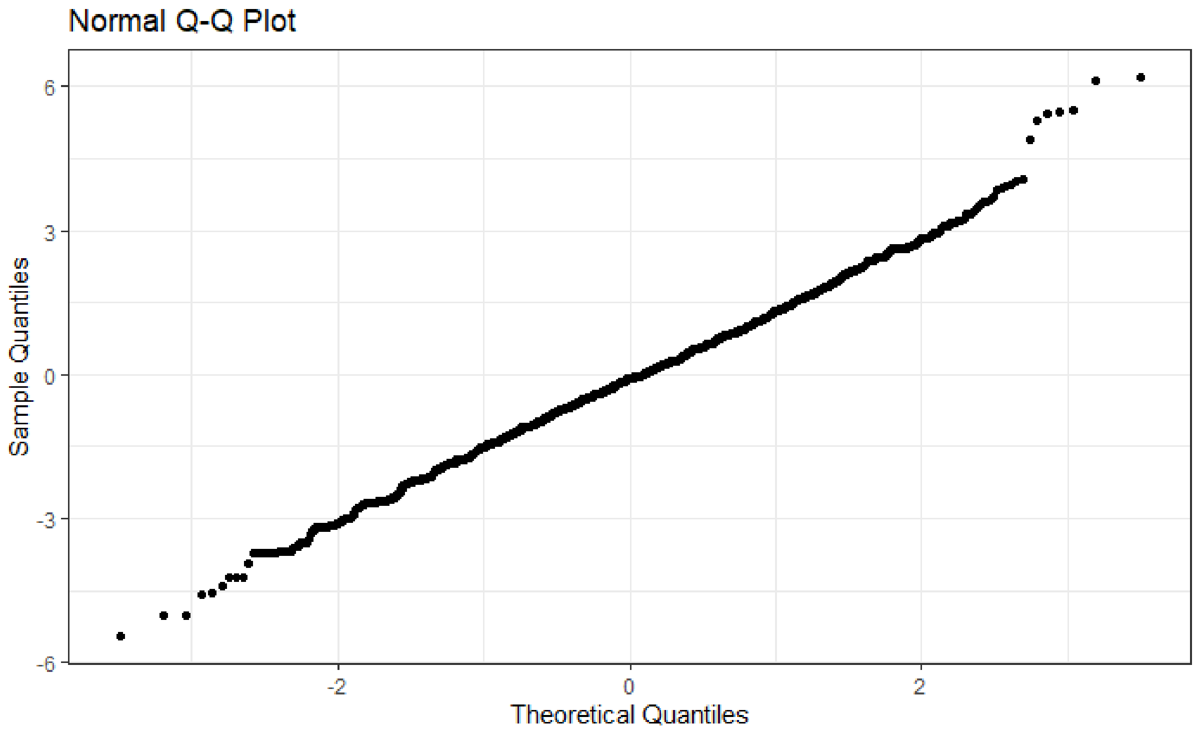

Figure S4.1: Q-Q plot of the species richness model for a normal distribution of the residuals.

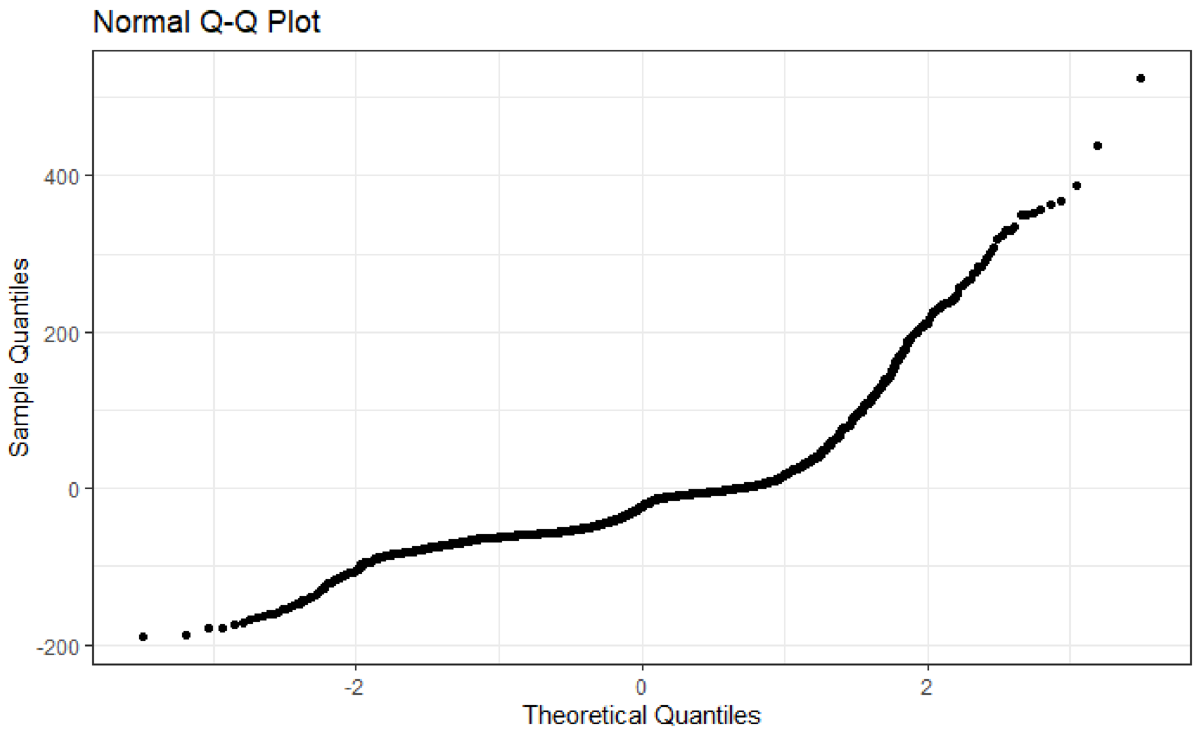

Figure S4.2: Q-Q plot of the species abundance model for a normal distribution of the residuals.

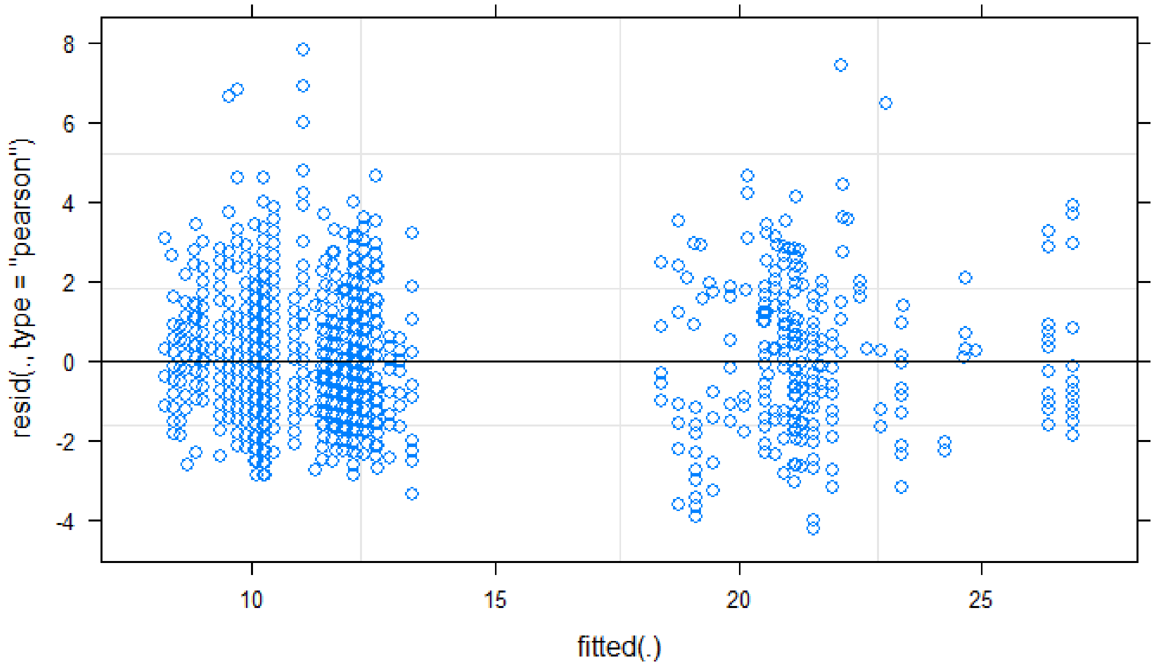

Figure S4.3: Model residuals against the fitted values for the species richness model.

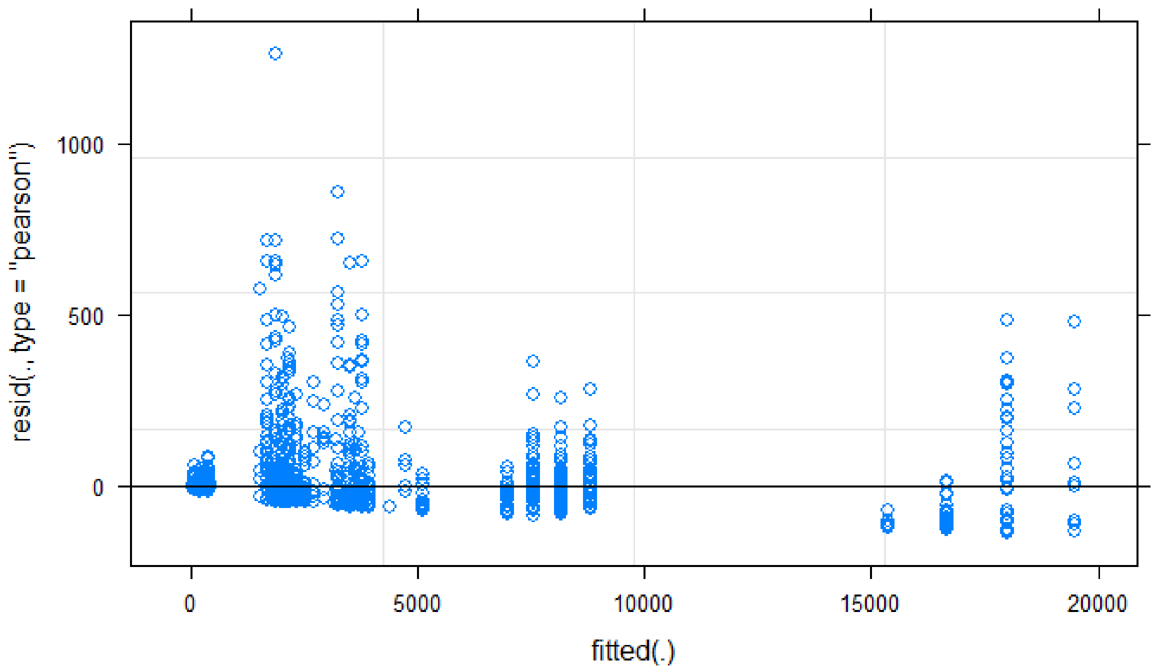

Figure S4.4: Model residuals against the fitted values for the species abundance model.

S4.2.5 Characterization factor (CF) development

Table S4.3: Species richness and abundance of oil and gas platforms (**Outside_Hard**) (BS, D15, Halfweg, K9-A, L10-A, L10-G, L15-A, and Q13).

Station	Age max (yrs)	Richness	Abundance (ind./m^2)

BS	8	27.36	10900.45
D15	17	30.76	28297.81
Halfweg	21	28.02	16166.75
K9-A	19	28.73	8552.54
L10-A	44	33.29	23926.99
L10-G	32	24.76	12450.51
L15-A	23	48.85	21866.71
Q13	2	17.33	59166.70

S4.2.6 Inventory analysis and impact assessment

OWE foundation size was assumed to determine the affected area by artificial reef and seabed occupation effects. Foundation size is found linearly related to the turbine size [1]. We calculated affected areas based on the assumptions from Negro et al. [1] (**Table S4.4**). The area subjected to trawling avoidance depends on the OWF size, which is determined by the spacing between turbines and columns (**Table S4.4**). The estimation of spacing between turbines and columns (i.e. spatial configuration in which turbines are aligned in a wind farm) was based on rotor diameter. As turbine size grows, the spacing between turbines and the spacing between columns are expected to grow.

Table S4.4: Estimation of turbine size, OWF layout and impact areas.

	2020	**2025**	**2030**	**2040**	**2050**
Single turbine capacity (MW) [2]	6	8	12	15	20
Rotor diameter (m) [2]	120	150	200	250	300
Spacing between columns (km) [2]	1.44	1.80	2.40	3.00	3.60
Spacing between turbines (km) [2]	1.20	1.50	2.00	2.50	3.00
Affected areas by artificial reef (km^2/turbine)	0.06	0.09	0.13	0.16	0.19
Affected areas by seabed occupation (km^2/turbine)	0.06	0.09	0.13	0.16	0.19
Affected areas by trawling avoidance (km^2/turbine)	0.71	1.60	2.84	4.44	6.39
Affected areas by artificial reef (km^2/MW)	0.01	0.01	0.01	0.01	0.01
Affected areas by seabed occupation (km^2/MW)	0.01	0.01	0.01	0.01	0.01
Affected areas by trawling avoidance (km^2/MW)	0.09	0.20	0.24	0.30	0.32

S4.3.1 Biodiversity evolution in different effect locations (ELs) and substrate types (STs)

Table S4.5: Summary statistics of the GLMM, with columns for estimate of independent variables (Estimate), standard error (SE), and p-value (P, <0.001 = ***, <0.05 = *), rows for installation age (Age, years since installation), effect locations (EL_Near: Near, EL_Out: Outside), substrate type (ST_Soft: Soft), adjusted R^2 (R^2) for the model, and statistical power (SP) based on 95% confidence interval. Reference level for EL: EL_Immediate. Reference level for ST: ST_Hard.

	Species richness			**Species abundance**		
	Estimate	SE	P	Estimate	SE	P
Age	0.02	0.00	***	0.08	0.00	***
EL_Near	0.02	0.02	0.27	-0.55	0.00	***
EL_Outside	0.28	0.03	***	-0.02	0.01	***
ST_Soft	-0.91	0.03	***	-3.76	0.00	***
R^2			39%			85%
SP			100%			100%

Table S4.6: Biodiversity (species richness and abundance) evolution and resulting characterization factors (CF) for artificial reefs (AR), seabed occupation (SO), and trawling avoidance (TA). LL: lower limit of 95% confidence interval; UL: upper limit of confidence interval. Note that CF_{TA} are calculated based on the average of negative values of PDF.

		Immediate-Hard	Immediate-Soft	Near-Soft	Outside-Soft	CF_{AR}	CF_{SO}	CF_{TA}
Richness	LL	13.23	5.04	4.97	6.29	-1.21	-0.41	-0.10
	Mean	20.17	8.09	8.26	10.70	-0.88	0.02	-0.01
	UL	27.56	11.61	12.30	16.31	-0.58	0.39	0.00
Abundance	LL	6325.56	146.06	84.41	141.06	-77.99	-2.14	-0.01
	Mean	11388.3	265.49	153.82	259.57	-42.87	-0.73	0.00
	UL	20502.59	482.54	280.28	477.63	-23.37	0.05	0.00

S4.3.4 Sensitivity analysis

Table S4.7: Sensitivity analysis results for characterization factors.

		Default	+50% of 500 m buffer	-50% of 500 m buffer	+50% of 250 m	-50% of 250 m	Until age 11[2]	At age 12 [3]	Leave 20% samples
Richness	CF_{AR}	-0.88	-0.89	-0.88	-0.92	-0.88	-0.88	-0.88	-0.90
	CF_{SO}	0.02	0.02	0.02	-0.06	0.02	0.02	0.02	0.02
	CF_{TA}	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	0.00	0.00
Abundance	CF_{AR}	-42.87	-42.88	-42.86	-39.44	-45.07	-43.55	-42.87	-42.93
	CF_{SO}	-0.73	-0.73	-0.75	-0.77	-0.77	-0.75	-0.72	-0.73
	CF_{TA}	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	0.00

S4.4.4.2 Effect of geography and range

Table S4.8: Species richness and abundance of Block Island wind farm (**Immediate_Hard**) [5].

Age	Richness	Abundance (ind./m^2)
1	19.52	151.41
2	22.95	572.50
3	24.86	464.37

S4.4.4.4 Technology

Table S4.9: Installation of different types of foundations [2].

Foundation type	Foundation name	Suitable water depth	Suitable seabed type	Stressor	Foundation size (m^2) [6]
I	Gravity-Base High-Rise Pile Cap	Shallow (normally <10m, up to 30m)	Compacted clay, sandy soil, and rock	Substrate clearance Substrate replacement Driving pile Scour protection	1195
II	Monopile	Shallow (20-40m)	All	Driving pile Scour protection	291

[2] Only considering observations (i.e. until age 11).
[3] Max modelled average within the data range (i.e. at age 12).

III	Tripot Jacket	Median (5-50m), could be very deep	Soft clay with varying depth	Driving pile	763
IV	Semi-Submersible Spar TLP	Deep (>60m)	Not clear	Mooring installation	22

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S5.2 Results

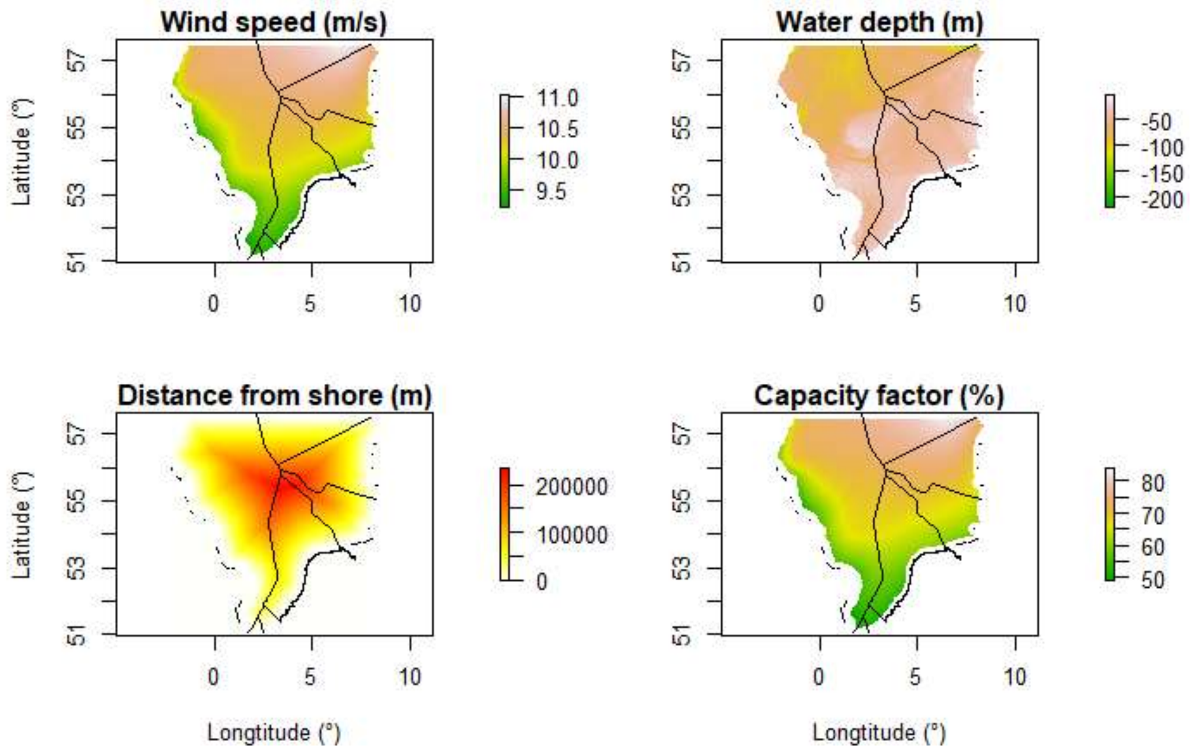

Figure S5.1: Geographical site parameters (wind speed, water depth, and distance from shore) and capacity factors of the North Sea.

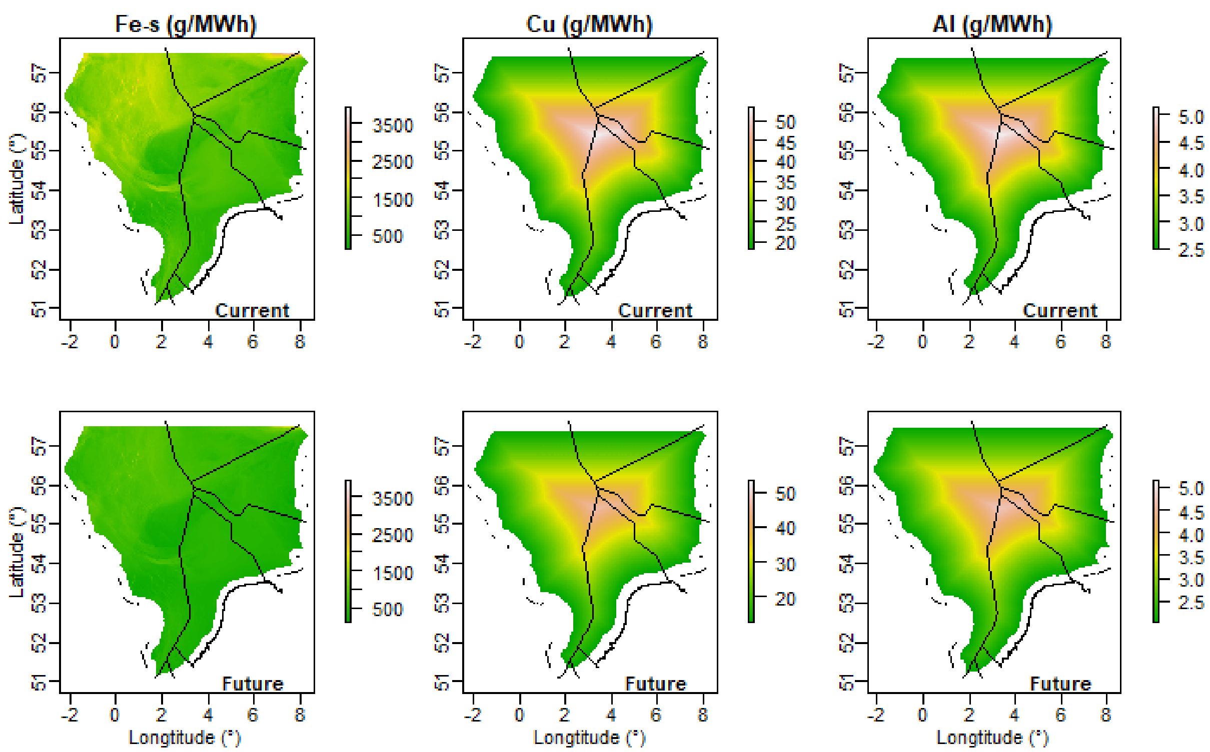

Figure S5.2: Demand for low-alloyed steel (steel), copper, and aluminum, per MWh electricity produced, of offshore wind energy development in the North Sea, based on present day (2020) and future (2040) technology mix.

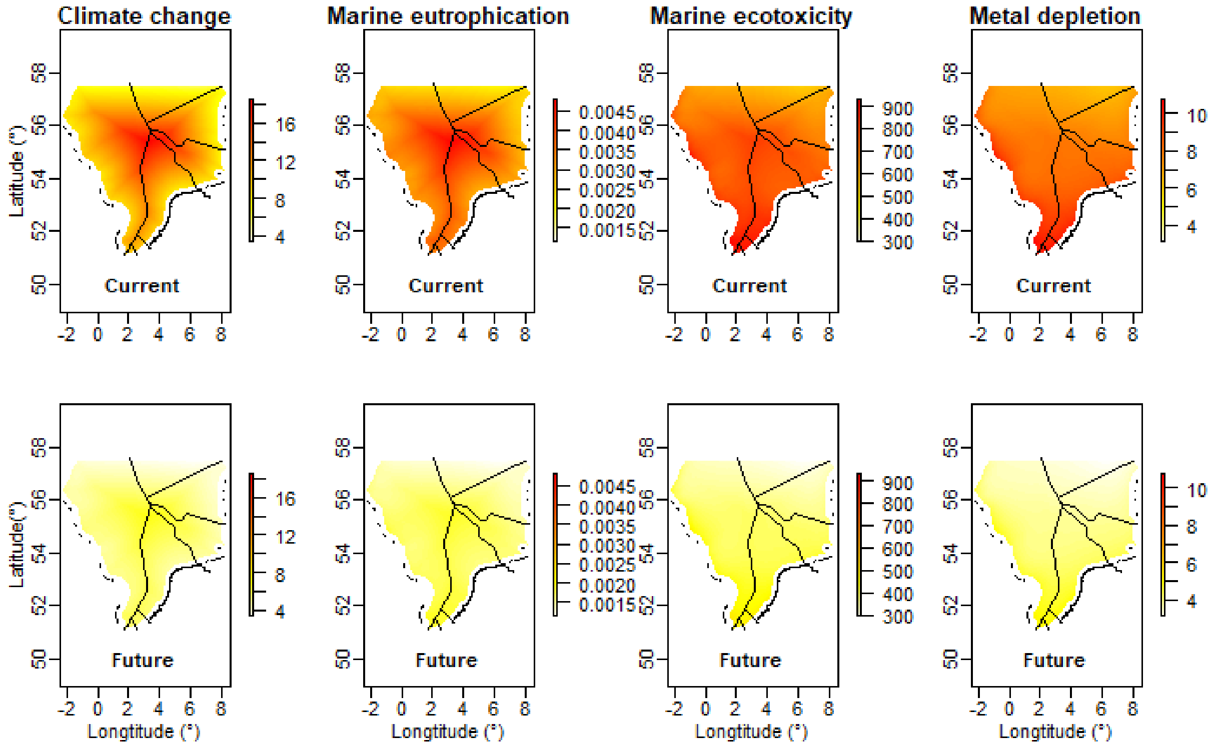

Figure S5.3: Life cycle impact categories, i.e. climate change (kg CO_2-Eq/MWh), marine ecotoxicity (kg 1,4-DC-Eq. /MWh), marine eutrophication (kg N-Eq MWh), and metal depletion (kg Fe-Eq/MWh), of offshore wind energy development in the North Sea, based on current (2020) and future (2040) technology mix.

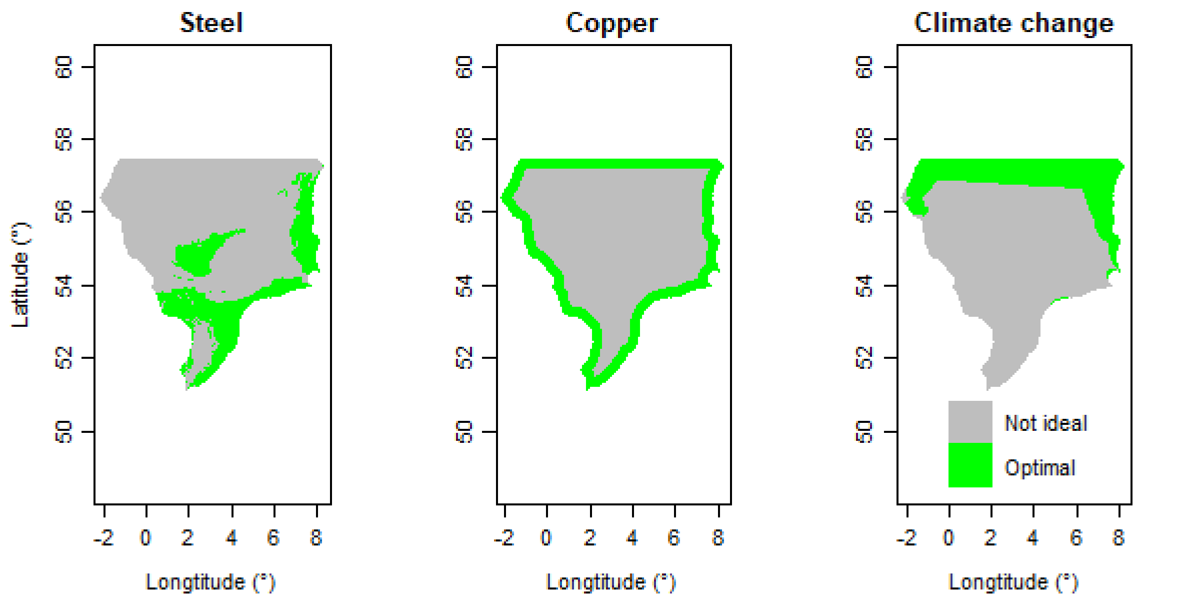

Figure S5.4: The optimal locations of for installing 180 GW in capacity of OWFs in terms of demand for steel and copper, and climate change (GHG emissions) per MWh electricity produced throughout the full turbine life cycle using future technology mix.

Table S5.1: Geographic characteristics of each exclusive economic zone (EEZ) in the North Sea, based on current (2020) and future (2040) technology mix; geographic characteristics of existing and in-development (In-dev) offshore wind farms in the North Sea.

Geographical site factor	**Belgian**		**Danish**		**Dutch**		**French**		**German**		**Norwegian**		**United Kingdom**	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Capacity factor (%)	53.05	68.05	73.63	84.46	63.78	81.82	52.20	66.96	66.21	84.94	78.09	91.02	67.18	86.18
Distance from shore (km)	11.94		76.69		67.42		56.71		68.50		50.07		66.26	
Water depth (m)	-30.25		-42.85		-36.45		-31.95		-36.59		-68.51		-59.77	
	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev	Existing	In-dev
Capacity factor (%)	52.56	-	67.69	74.13	54.89	57.53	-	-	63.61	64.77	-	-	61.53	67.95
Distance from shore (km)	12.52	-	6.72	67.96	15.95	30.18	-	-	38.26	71.81	-	-	45.20	67.16
Water depth (m)	-28.36	-	-14.41	-39.15	-29.86	-28.49	-	-	-30.78	-38.80	-	-	-31.30	-52.68

Table S5.2: Overview of the present day technologies and estimates of a future, emergent technology mix. For detailed information on Life cycle inventories and similar we refer to our earlier work in [4,5]

		Current (2020) technology mix	**Future (2040) technology mix [4, 5]**
Turbine size	Nominal capacity (MW)	~6.5	~15.6
	Rotor diameter (m)	148	262
	Hub height (m)	115	156
Turbine lifetime (years)		20	25
Component technology	Nacelle	Permanent magnet (PM) free generator technologies, like DFIG and SCIG still dominate the market	Market share of PM-based generator technologies is rising
	Blades	Both glass and carbon fibres are used	More carbon fibres will be used
	Tower	Only steel towers are used	Hybrid towers will be used
Maintenance times		Two times unscheduled and four times scheduled maintenance per year per turbine during life time	Two times unscheduled and two times scheduled maintenance per year per turbine during life time
Replacement rates		High annual replacement rates (~5%)	Moderate replacement rates
Transportation means		All transport is by vessels	20% of wind turbines were assumed to be supported transported by helicopters

Background system	Background system, such as energy mix, in 2020	Background system, such as energy mix, in 2020, based on SSP2 scenarios from the IMAGE integrated assessment model

Table S5.3: The demand for steel and copper, and climate change (GHG emissions) per MWh electricity produced throughout the full turbine life cycle using current and future technology mix for installing 180 GW in capacity of OWFs, under spatially optimal locations in terms of demand for steel and copper, and climate change (GHG emissions) per MWh electricity produced throughout the full turbine life cycle.

	Steel (g)		Copper (g)		Climate change (kg CO_2-Eq)	
	Current	Future	Current	Future	Current	Future
Spatially optimal locations in terms of demand for steel	569	346	26	19	10.9	5.2
Spatially optimal locations in terms of demand for copper	954	546	18	13	8.8	4.6
Spatially optimal locations in terms of demand for GHG emissions	1066	648	20	16	8.1	4.2

S5.4 Methods

Capacity factor (CF) is calculated based on site-specific wind speed.

$$\boldsymbol{CF} = \pi/2 \times \left(\frac{\boldsymbol{D}}{2}\right)^2 \times \mathbf{WS}^3 \times \rho \times \eta/C$$

Where D is the rotor diameter, WS is wind speed, ρ is air density, η is efficiency factor and C is the nominal capacity. We use default air density and efficiency factor values from [1].

There are mainly two types of foundations, i.e. fixed-bottom based and floating foundations. The floating foundations are suitable for deep waters but the North Sea is characterized by relatively shallow waters. Further, floating foundation technologies are still evolving and have not been deployed at a commercial scale. Monopile foundations dominate the global fixed-bottom based foundation market (> 80%) and were widely used in the North Sea. Therefore, Monopile foundations are assumed to be used in the North Sea. Material requirement for Monopile foundations is based on foundation weight (FW) and Fe intensity (100% of low alloyed steel). FW is found linear to foundation diameter (FD) and water depth (WD).

$$\boldsymbol{FW} = 137.92 + 2.27 \times \left(\frac{\boldsymbol{FD}}{\mathbf{2}}\right)^2 \times \boldsymbol{WD}$$

This estimation is from the statistical analysis of foundation parameters (see Source data) based on multiple historical offshore wind farms [2]. Material requirement for inter array cables is modelled in line with [3]. We assume two units of transformers and one substation foundation per wind farm. Onshore infrastructure is not included due to site specification and data scarcity.

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Summary

The rapid proliferation of offshore wind farms (OWFs) plays a great role in decarbonizing and reducing greenhouse gas (GHG) emissions. Unlocking the full potentials of offshore wind energy (OWE) could meet the world's future electricity demand 11 times over, thanks to the high wind resources at sea and the large surface areas available. The OWE sector has experienced a remarkable growth in the last decades due to consistent reduction of levelized cost of energy. In 2019, OWE had only a total capacity of 23 GW and accounted for 0.3% of global power generation. However, a total of 342-560 GW installed OWE capacity is foreseen by 2040. Realizing such large-scale OWE developments will require substantial quantities of materials, and will be associated with climate, biodiversity, and other impacts on the environment. OWE technologies will see continuous improvements, including turbine size enlargement, life time extension, and component technology development. Furthermore, more OWFs are moving farther offshore to harvest better wind resources, but then have to build in deeper waters. All such factors play a role in the environmental footprint of OWE development.

This thesis aims to address the OWE-related environmental impacts. This results in the main research question (RQ): what are the environmental impacts of OWE development? The main question consists of the following four sub RQs:

RQ1: What is the future material demand for global OWE development? (Chapter 2)

RQ2: What are the cradle-to-the-grave environmental impacts of global OWE development? (Chapter 3)

RQ3: What are the OWE development impacts on the marine biodiversity? (Chapter 4)

RQ4: How can the environmental footprint of OWE development be reduced by optimal spatial planning in combination with technical innovation, illustrated by the case of the North Sea? (Chapter 5)

We answer the above-mentioned RQs by using or developing several methods. We use dynamic material flow analysis (dMFA) to quantify the material demand for manufacturing of OWE infrastructures. We combine dMFA with prospective life cycle assessment (LCA) to evaluate cradle-to-grave future environmental impacts of OWE development. We develop characterization factors (CFs) for life cycle impact assessment (LCIA) to calculate marine biodiversity change by the OWF operation. Further, we integrate the dMFA and prospective LCA calculations in a spatially explicit manner by calculating the influence of geographic site-specific factors such as wind speeds, distance to shore, and ocean depth, on material requirements and environmental impacts over the turbine life cycle per MWh electricity produced. We illustrate this approach with a case study for the North Sea.

In Chapter 2 we develop a three-level (i.e., capacity, technology, and material level) dMFA model to assess the primary raw material demand and secondary material supply of global OWE development, including bulk materials, rare earth elements, key metals, and other materials for manufacturing offshore wind turbines and foundations. The newly commissioned (inflow) and decommissioned (outflow) offshore wind capacities, technologies, or materials are calculated from the assumed development of in-use (stock) capacities, technologies, or materials lifetime distribution. Our results show that substantial amounts of raw material are required for OWE development from 2020 to 2040, including 129-235 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. We find mass intensity (e.g. kg/MW) will increase over time (increase from 365.2 t/MW in 2020 to 559.6 t/MW in 2040). Low-alloyed steel (account for ~82% of total mass) represent the main mass demand of future OWE technologies. The foundation requires most of the low-alloyed steel and accounts for 84%-85% cumulative requirements from 2020 to 2040. Further,

closed-loop recycling and lifetime extension will reduce approximately 3% and 12% of material requirements for OWE, between 2020 and 2030, and between 2030 and 2040, respectively.

In Chapter 3 we build a prospective LCA model to quantify current and future environmental impacts of OWE development on a global scale until 2040. Dynamic parameterized life cycle inventories (LCIs) are built by including high technology resolution supply chains notably by focusing on installation, operation and maintenance (O&M), decommissioning, and end of life (EoL) recycling. LCIs for a given year (from 2020 to 2040) are adjusted by underlying dynamic trends, including turbine size enlargement, moving further from shore, component technology and closed-loop EoL recycling development. Furthermore, LCA results are calculated based on futurized background LCI data. Our results indicate that the GHG intensity (per MWh) experiences a ~21% drop from 2020 to 2040. Similar reductions are found for marine ecotoxicity (~25% drop), marine eutrophication (~22% drop), and metal depletion (~16% drop). The deployment of OWE will cumulatively (2020-2040) result in a contribution of 2.6-3.6 Gt CO2-eq to climate change. However, this compares to 124-207 Gt CO2-eq emissions (48-58 times more) that would be generated when producing the same quantity of electricity with the global electricity mix of 2020. Further, manufacturing contributes to the largest portion (i.e. ~75%-~98%), of cumulative (2020-2040) environmental impacts, with this contribution increasing from 2020 to 2040, followed by O&M. 6-9% of the cumulative OWE related environmental impacts could be reduced by EoL recycling and the substitution of raw materials.

In Chapter 4 we use both sediment infauna and hard substrate epifauna samples from OWFs and their control sites, and research platform in Denmark, Germany, the Netherlands, and Belgium to quantify three main interventions from OWF operations on marine biodiversity (macrobenthic communities), i.e. seabed occupation, artificial reefs, and trawling avoidance. Three associated CFs are developed based on the difference in biodiversity between the OWE intervention (i.e. seabed occupation, artificial reefs, or trawling avoidance) and the associated reference state. With the developed CFs, we find species richness and abundance on hard substrates are greatly higher than on soft sediment and will increase over time since OWF construction. There are no net adverse impacts during OWF operation on benthic communities - although seabed occupation will also incur in minor biodiversity losses in the soft sediment, artificial reefs could lead to a doubling of species richness and a two order-of-magnitude increase of species abundance. Our study provides a stepping stone towards a better understanding of marine biodiversity change caused by OWE development and a new perspective on sustainable OWF management. Future works should extend monitoring time series in more site conditions and conduct scenarios to have more insights on OWE development impacts on marine biodiversity and different trajectories of future biodiversity evolution.

In Chapter 5, we spatially analyze the North Sea's OWE environmental footprints per MWh electricity produced across the full OWE turbine life cycle including EoL, such as material demand, impacts on biodiversity, and impacts on global warming. We consider finished material demand for manufacturing offshore wind turbines, foundations and transmission components, and associated life cycle impacts on carbon and climate. We calculate these OWFs' energy generation potential, taking into account future technological developments by comparing present day (2020) technologies and estimates for future technology mix for the year 2040. We find that optimal location and cleaner technological development have the potential to halve all the current environmental footprints of North Sea OWFs. To lower the overall environmental footprint, future OWFs are recommended to be sited in the northern and avoid central North Sea areas. The northern North Sea regions are the optimal locations in terms of GHG emission per MWh electricity produced along the turbine life cycle. Although the region has deeper waters requiring more steel for foundations, it shows larger potentials of electricity output due to the more favorable wind resources in that area. The central North Sea has as drawback average wind resources in combination with a large distance to shore leading to high material needs and related GHG emissions related to transmission infrastructure, while there is overlap with biodiversity exclusion zones. To further mitigate footprints that are not reliant on the optimal spatial siting of OWFs, it is crucial to make substantial investments in technological advancement of OWE, mainly turbine size enlargement. Floating foundation technologies are important to mitigate the drawback of high material requirements when OWE are placed in deeper waters which often have better wind resources.

Overall, the large-scale OWE development will require substantial quantities of bulk and critical raw materials, for manufacturing offshore wind turbines, foundations, and transmission components. The manufacturing, installation, and operation of OWFs have additional indirect impacts on the environment such as GHG emissions and marine biodiversity due to, among others, energy use in material manufacturing, seabed occupation, material and personnel transport. To reduce material use, OWE innovations should focus on extending the lifetime of turbines, improvement of material efficiency, as well as the enhancement and introduction of new technologies. To reduce the associated impacts on the climate, more efforts should mainly be focused on turbine size enlargement. More attention should be paid to the OWF manufacturing phase, especially manufacturing of steel, fibres, and key metals, as it contributes to the largest portion of environmental impacts. Impacts in the O&M phase are not ignorable and will likely increase when turbines moving farther from shore and towards deeper waters in harsher marine environments. Application of circular strategies such as life time extension, circular design, component re-use and finally EoL material recycling is crucial to lower material requirements and related life environmental impacts. OWE development should also take into account cumulative impacts on biodiversity and other impacts on the environment. Further, dedicated efforts are needed on site selection to evaluate of the major hotspots in environmental impacts, and the least-impactful locations for OWE development. Our comprehensive analysis can be an inspiration for governments for a strategic planning of OWE locations. This should not only take into account the direct (e.g. biodiversity) impacts of the chosen locations, but also the spatially dependent life cycle impacts of OWFs per MWh of electricity produced. Furthermore, in order to keep the pace or even accelerate the clean energy transition, the findings of the thesis can help to identify green opportunities in the supply chains of the OWE sector and could facilitate the optimization of the portfolio of OWE technology development.

Samenvatting

De snelle uitbreiding van offshore wind farms (OWFs) en offshore wind energy (OWE), windmolenparken en windenergie op zee, speelt een grote rol in de decarbonisatie van ons energiesysteem en het verminderen van de uitstoot van broeikasgassen. Door het benutten van het volle potentieel van windenergie op zee kan tot wel 11 keer aan de toekomstige wereldwijde vraag aan elektriciteit worden voldaan. Dit komt door de grote hoeveelheid wind op zee en de grootte van het beschikbare oppervlakte voor windenergie. De OWE sector is de afgelopen decennia opmerkelijk hard gegroeid, door een consistente vermindering in de gemiddelde kosten van windenergie. In 2019 had OWE een totale capaciteit van 23 GW, en daarmee een aandeel van 0.3% in de wereldwijde energieopwekking. Voor 2040 wordt echter een geïnstalleerde capaciteit van 342-560 GW verwacht. Het realiseren van zulke grootschalige OWE ontwikkelingen vereist grote hoeveelheden aan materialen. De winning en productie hiervan zal leiden tot impact op het klimaat, de biodiversiteit en het milieu. OWE technologieën zullen continu worden verbeterd, onder andere door het vergroten van turbines, het verlengen van de levensduur, en het optimaliseren van de verschillende onderdelen. Bovendien zal windenergie op zee steeds vaker op grotere afstand van de kust worden gerealiseerd om meer wind te kunnen vangen, waardoor de windmolens in dieper water moeten worden gebouwd. Deze factoren spelen allemaal een rol in de ecologische voetafdruk van OWE ontwikkeling.

Deze thesis behandelt de OWE-gerelateerde impact op het milieu. Dit leidt tot de volgende onderzoeksvraag (OV): wat is de milieu-impact van OWE ontwikkeling? De hoofdvraag bestaat uit de volgende vier subvragen (SV):

SV1: Wat is de toekomstige materiaalbehoefte voor wereldwijde OWE ontwikkeling? (Hoofdstuk 2)

SV2: Wat is de wieg-tot-graf milieu-impact van wereldwijde OWE ontwikkeling? (Hoofdstuk 3)

SV3: Welke gevolgen heeft OWE ontwikkeling voor de mariene biodiversiteit? (Hoofdstuk 4)

Sv4: Hoe kan de milieu-impact van OWE ontwikkeling worden verminderd door optimale ruimtelijke planning en technische innovatie, geïllustreerd met het voorbeeld van de Noordzee? (Hoofdstuk 5)

We beantwoorden de genoemde onderzoeksvragen door het gebruiken of ontwikkelen van verschillende methoden. We gebruiken dynamic material flow analysis (dMFA) om de materiaalbehoefte voor het produceren van OWE infrastructuur te kwantificeren. Dit combineren we met prospective life cycle assessment (LCA) om de wieg-tot-graf milieu-impact van toekomstige OWE ontwikkeling te evalueren. We ontwikkelen characterization factors (CFs) voor life cycle impact assessment (LCIA) om de veranderingen in mariene biodiversiteit door OWFs te berekenen. Verder integreren we dMFA en prospective LCA berekeningen op een ruimtelijk expliciete manier. We kijken naar de invloed van geografische factoren zoals windsnelheid, afstand tot de kust, en diepte van de zee op de materiaalbehoefte en milieu-impact van de levenscyclus van een windturbine, per geproduceerde MWh elektriciteit. We illustreren deze benadering met een case studie van de Noordzee.

In Hoofdstuk 2 ontwikkelen we een dMFA model (rekening houdend met capaciteit, technologie en materiaal) om de primaire materiaalbehoefte en secundaire materiaaltoevoer van wereldwijde OWE ontwikkeling te onderzoeken. Het gaat hierbij bijvoorbeeld aan bulkmaterialen, zeldzame aardmetalen, en andere materialen voor het produceren van windturbines op zee. We berekenen de nieuw te bouwen (inflow) en af te breken (outflow) windturbines in termen van de aangenomen ontwikkeling van capaciteit, technologieën en materialen die in gebruik zijn, en de verwachte levensduur daarvan. Onze resultaten laten zien dat er substantiële hoeveelheden materiaal nodig zijn voor OWE ontwikkeling van 2020 tot 2040. Het gaat b.v. om 129-235 Mt staal, 8.2-14.6 Mt ijzer, 3.8-25.9 Mt beton, 0.5-1.0 Mt koper en 0.3-0.5 Mt aluminium. Onze bevindingen geven weer dat de massa-intensiteit (kg/MW) over de tijd zal toenemen (van 365.2 t/MW in 2020 tot 559.6 t/MW in 2040). Laag gelegeerd staal is verantwoordelijk voor het grootste aandeel in de vraag naar materiaal voor toekomstige OWE

technologieën (~82% van de totale massa). Het meeste van dit laag gelegeerde staal is nodig voor de fundering van de windturbines, met een cumulatief aandeel van 84-85% van 2020 tot 2040. Closed-loop recycling en het verlengen van de levensduur kunnen bijdragen aan het verminderen van de materiaalbehoefte voor OWE, Het gaat om verminderingen met 3% tussen 2020 en 2030 en met 12% tussen 2030 en 2040.

In Hoofdstuk 3 creëren we een prospective LCA model om de huidige en toekomstige milieu-impact van OWE ontwikkeling op een wereldwijde schaal te kwantificeren tot 2040. In het hoofdstuk ontwikkelen we dynamische geparametriseerde life cycle inventories (LCIs), met hoge technologische resolutie en gedetailleerde aanvoerketens. We kijken hierbij naar de installatie, gebruik en onderhoud, het ontmantelen en end of life (EOL) recycling van OWE. We passen de LCIs voor een specifiek jaar tussen 2020 tot 2040 aan op basis van diverse trends, zoals het vergroten van de turbines, het plaatsen van turbines verder van de kust, het toepassen van nieuwe technologieën en het ontwikkelen van closed-loop EOL recycling. Verder zijn de LCA resultaten berekend op basis van achtergrond-data die rekening houden met toekomstige ontwikkelingen, zoals het verlagen van de koolstofemissies uit het electriciteitssysteem. Onze resultaten laten zien dat de intensiteit van broeikasgassen (per MWh geinstalleerde capaciteit) met ~21% afneemt van 2020 tot 2040. Soortgelijke dalingen vinden plaats voor mariene ecotoxiciteit (~25% daling), mariene eutrofiëring (~22% daling), en de uitputting van metalen (~16% daling). De toepassing van OWE zal cumulatief (van 2020-2040) leiden tot een bijdrage van 2.6-3.6 Gt CO2-eq aan klimaatverandering. Als dezelfde hoeveelheid elektriciteit met de wereldwijde elektriciteitsmix van 2020 zou worden geproduceerd, zou dit echter leiden tot de uitstoot van 124-207 Gt CO2-eq (48-58 keer zoveel). De productie van OWE is verantwoordelijk voor het grootste gedeelte (~75%-~95%) aan de cumulatieve milieu-impact tussen 2020 en 2040, gevolgd door het gebruik en onderhoud. Rond de 6-9% van de cumulatieve OWE-gerelateerde milieu-impact kan worden verminderd door EOL recycling en het vervangen van primaire materialen.

In Hoofdstuk 4 gebruiken we monsters met infauna bevattend sediment epifauna bevattende harde ondergrond, genomen rondom OWFs en controleplekken zonder OWFs in Denemarken, Duitsland, Nederland en België, om de gevolgen van OWE op mariene biodiversiteit te kwantificeren. OWFs zorgen met name voor drie interventies. Ze bedekken de zeebodem, vormen kunstmatige riffen, maar vermijden ook de sleepnetvisserij. Het hoofdstuk ontwikkelt drie karakteristatiefactoren (CFs), gebaseerd op het verschil in biodiversiteit bepaald uit monsters rond OWFs en de controleplekken. Door middel van de ontwikkelde CFs laten we zien dat de soortenrijkdom en -overvloed op harde ondergrond veel groter is dan op zacht sediment, en bovendien zal toenemen gedurende de tijd na het bouwen van OWFs. Er zijn geen netto negatieve gevolgen op de benthische gemeenschap gedurende het gebruik van OWFs. Hoewel het bedekken van de zeebodem zal leiden tot beperkte biodiversiteitsverliezen in het zachte sediment, kunnen kunstmatige riffen leiden tot een verdubbeling van de soortenrijkdom en een toename van soortenovervloed van twee ordes van grootte. Ons onderzoek dient als een eerste stap naar een beter begrip van de impact op mariene biodiversiteit veroorzaakt door OWE ontwikkeling, en helpt bij een duurzaam management van OWFs. Toekomstig onderzoek waar in verschillende plekken onder verschillende omstandigheden worden gemonitord is nodig om nog meer inzicht te verkrijgen in de gevolgen voor de mariene biodiversiteit van OWE ontwikkeling.

In Hoofdstuk 5 analyseren we de ruimtelijke milieu-impact van OWE in de Noordzee, per geproduceerde MWh elektriciteit, over de gehele levenscyclus van OWE turbines (inclusief EOL). Hierbij kijken we naar materiaalbehoefte, impact op de biodiversiteit, en impact op klimaatverandering. Materiaalbehoefte omvat hierbij de productie van windturbines, de funderingen en transmissie componenten, en de life cycle impacts van CO2 emissies op het klimaat. We berekenen de potentiële energie-opwekking van deze OWFs, waarbij we rekening hebben gehouden met technologische ontwikkelingen tussen 2020 en 2040. Onze bevindingen laten zien dat het vinden van de optimale locatie en het efficiënter maken van technologieën potentieel kunnen leiden tot een halvering van de milieu-impacts over de levensyclus van OWFs op de Noordzee. Om de totale milieu-impact te verlagen zullen toekomstige OWFs in noordelijke Noordzee gebieden moeten worden geplaatst. Gebieden in het centrum van de Noordzee moeten worden vermeden. De noordelijke gebieden zijn de optimale locatie, rekening houdend met de uitstoot van broeikasgassen over de gehele levenscyclus van de windturbines per MWh geproduceerde elektriciteit. Hoewel in dit gebied sprake is van dieper water, waardoor er meer staal nodig is voor de fundering van de OWFs, is er een grotere potentie voor elektriciteitsproductie door de betere windomstandigheden in dit gebied. De centrale Noordzee heeft een gemiddelde windsterkte, en dit in combinatie met een grote afstand tot de kust zorgt voor een hogere materiaalbehoefte en een hogere uitstoot van broeikasgassen gerelateerd aan de transmissie infrastructuur. Bovendien is er overlap met uitsluitingszones voor biodiversiteit. Om de ecologische voetafdruk verder te verminderen, onafhankelijk van de locatie van OWFs, is het cruciaal om te investeren in technologische verbetering van OWE. Hierbij is vooral het vergroten van de turbines van belang. Ook zijn drijvende fundering technologieën belangrijk om de hoge materiaalbehoefte van OWE in diep water met betere windcondities te verminderen.

Al met al zal de grootschalige ontwikkeling van OWE een substantiële hoeveelheid aan bulk en kritieke materialen vereisen, voor het produceren van OWFs, de bijbehorende funderingen en de transmissie-infrastructuur. Het produceren, installeren en gebruiken van OWFs heeft indirecte impact op het milieu, bijvoorbeeld door de uitstoot van broeikasgassen, of op mariene biodiversiteit. Dit komt onder andere door het produceren van de materialen, het bedekken van de zeebodem, en het transport van materiaal en personeel. Om materiaalgebruik te verminderen zouden innovaties moeten plaatsvinden op het gebied van het verlengen van de levensduur van turbines, het verbeteren van materiaal-efficiëntie, en het verbeteren en introduceren van nieuwe technologieën. Om de impact op het klimaat te verminderen zou vooral moeten worden gekeken naar het vergroten van turbines. Ook moet aandacht worden besteed aan het verminderen van emissies voor de productie van OWF, vooral aan het produceren van staal, vezels en andere belangrijke metalen. De productie hiervan zorgt voor het grootste aandeel in de milieu-impact. Impact in de gebruiks- en onderhoudsfase kan echter niet worden genegeerd, en zal waarschijnlijk toenemen als OWFs verder van de kust worden gebouwd in dieper water.

De toepassing van circulaire strategieën zoals het verlengen van de levensduur, circulair design, het hergebruiken van onderdelen en EOL materiaal recycling is cruciaal om de materiaalbehoefte en de gerelateerde milieu-impact te verminderen. De cumulatieve impact op biodiversiteit, en andere gevolgen voor het milieu, moeten worden meegenomen in de ontwikkeling van OWE. Bovendien is het essentieel om de belangrijkste hotspots in milieueffecten te identificeren en locaties te selecteren met de minste impact voor OWFs. Onze analyse kan dienen als inspiratie voor overheidsinstanties en de strategische planning van OWE-locaties stimuleren. Hierbij dient niet alleen de directe milieu-impact van OWE-locaties, zoals die op de biodiversiteit, te worden overwogen, maar ook de impact gedurende de gehele levenscyclus per geproduceerde MWh elektriciteit. Bovendien kunnen de bevindingen uit dit proefschrift helpen bij het identificeren van duurzaamheidskansen, zowel binnen de toeleveringsketens van OWE als in de ontwikkeling en optimalisatie van OWE-technologieën. Op deze manier wordt bijgedragen aan de voortgang en mogelijk zelfs versnellen van de energietransitie.

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Curriculum Vitae

Chen Li was born in Jiaxing, Zhejiang province, China, where he graduated from Yuanji senior high school in June 2012. In September 2012, he moved to northwest China for his bachelor study. He obtained his bachelor’s degree in statistics at Shanxi University of Finance and Economics in June 2016. In September 2016, he moved to Dongbei University of Finance and Economics in northeast China for his master study. He obtained his master’s degree in statistics in January 2019. From April to June 2019, he worked as algorithm engineer for the development of medical artificial intelligence products. In September 2019, he started his PhD in the Institute of Environmental Sciences (CML) at Leiden University on the topic of environmental impact assessment of the offshore wind energy development. Since July 2022, he has been working as consultant in the wind energy industry. After his PhD, he will continue to work as a postdoctoral researcher at CML, and meanwhile, keep the role in industry as a project engineer for a floating wind farm project.

List of publications

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Experiences

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