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Environmental assessment and guidance for the future offshore wind energy 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 2040¹. A key reason for this rapid development is the continuing reduction in the levelized cost of energy². While OWE development is an effective way to reduce energy-related greenhouse gas (GHG) emissions³, 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 development⁴.

Life cycle assessment (LCA) studies have shown the significance of lifetime and capacity factors (CFs) for environmental impacts of electricity generation by the OWE⁵⁻⁸. 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 MW²¹, and 10 MW²²), 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 2030¹. Permanent magnet (PM) based generator technology allows wind turbines to operate at lower speeds and thus have higher efficiencies and energy yields²⁹. Moreover, there are few environmental assessments for emerging technologies, like superconducting generators³⁰, new fibre technologies³¹ in blades, hybrid tower concepts³², and spar and TLP floating foundations³³. 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 MW³⁴). 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 database³⁵ and information from SSP2 scenarios from the IMAGE integrated assessment model³⁶. 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.

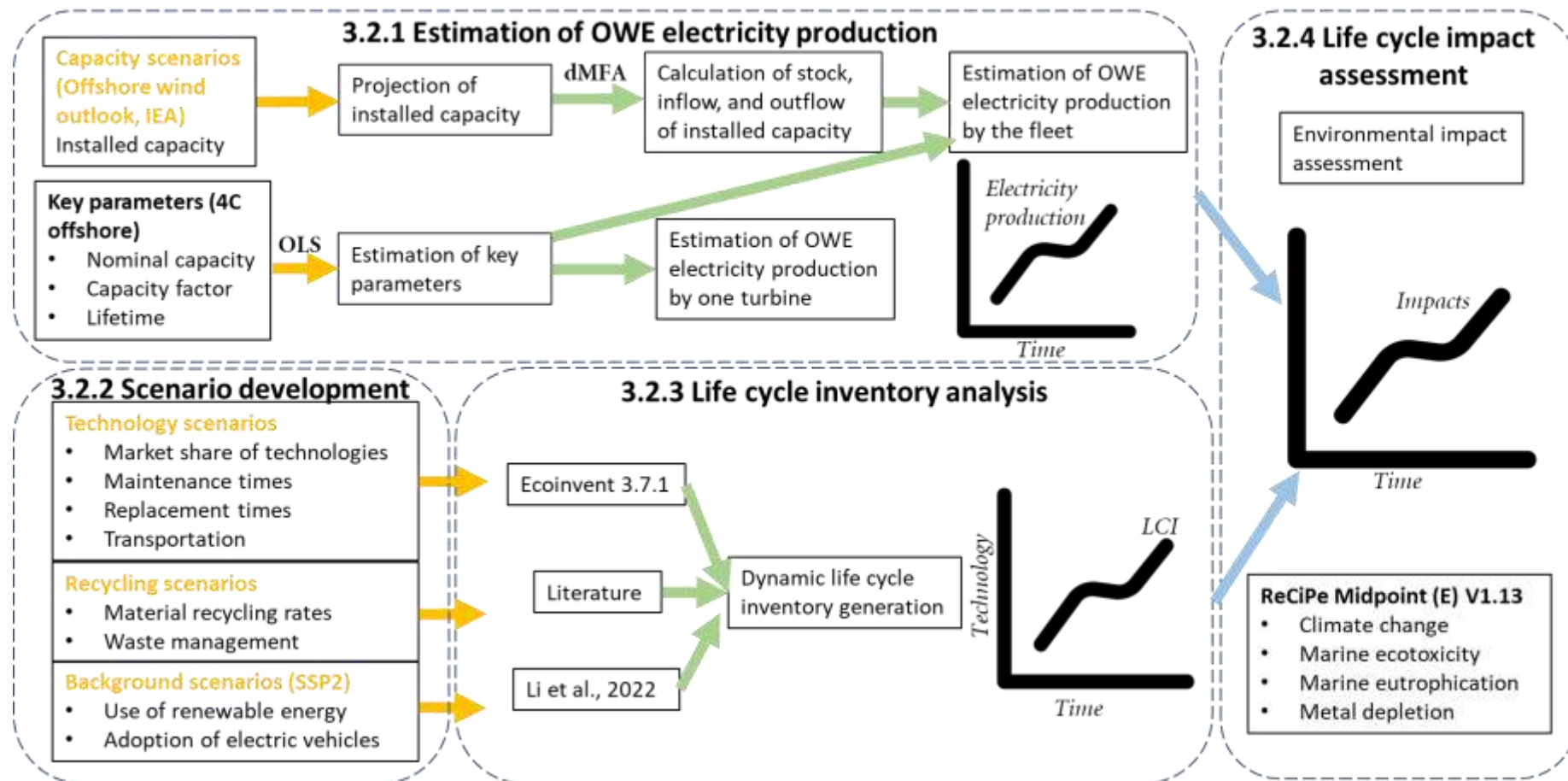


Figure 3.1: The environmental impact calculation overview.

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**.

$$EP_t^{Turbine} = CF_t \times Lifetime_t \times NC_t \quad (1)$$

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.

$$EP_t^{Fleet} = CF_t \times Lifetime_t \times S_t \quad (2)$$

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-RCP2.6³⁹ were derived using the *premise* framework⁴⁰ 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, respectively⁴¹. 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 paper³⁷ 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 Browser⁴⁵. 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 work³⁷. Energy use for material processing, miscellaneous collection, and assembly was taken from ecoinvent³⁵ 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 times⁴⁷. Eight foundations³⁷ 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 from⁴⁸, 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 types⁴⁹. This paper adopted turbine installation processes from¹⁴ 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 on⁵⁰.

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 turbine¹³. 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 installation⁵³. 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 reported⁵⁴ 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 landfilling⁵⁴. 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 Browser⁵⁷ according to ReCiPe Midpoint (H) V1.13⁵⁸ 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)).

$$EI_t^{MWh} = \frac{LCEI_t}{EP_t} \times \frac{1}{NC_t} \quad (3)$$

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, respectively³⁷.

$$EI_t^{Fleet} = \frac{1}{EP_t} \times \frac{1}{NC_t} \times (LCEI_t^{Manufacturing} \times I_t + LCEI_t^{Installation} \times I_t + LCEI_t^{OM} \times S_t + LCEI_t^{Decommissioning} \times O_t) \quad (4)$$

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.

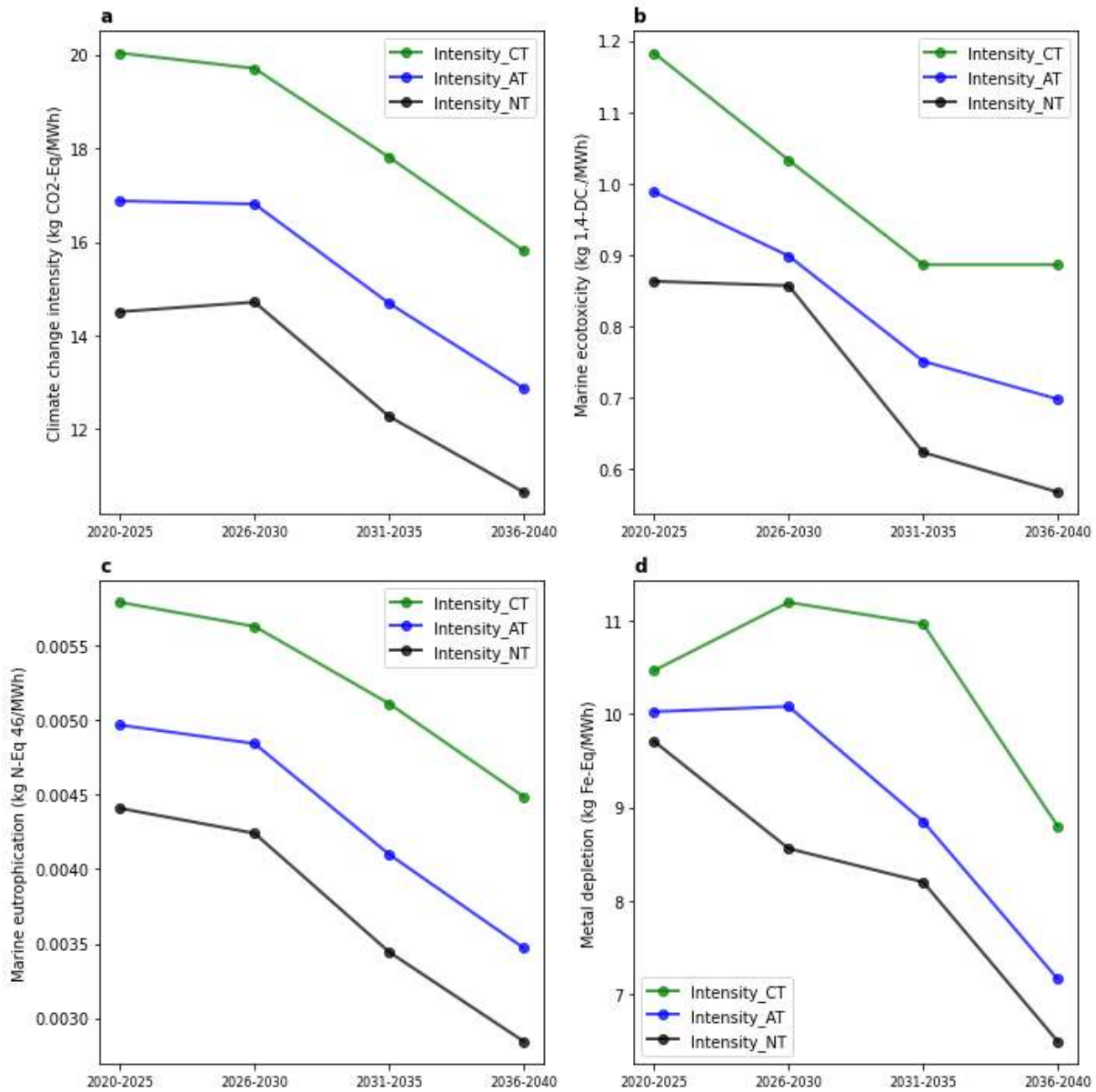


Figure 3.2: Environmental impacts per MWh, 5-year average, based on conventional technology (CT), advanced technology (AT), and new technology (NT) scenarios, under EoL_O recycling scenario, and SSP2-base background scenario.

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 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. 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.

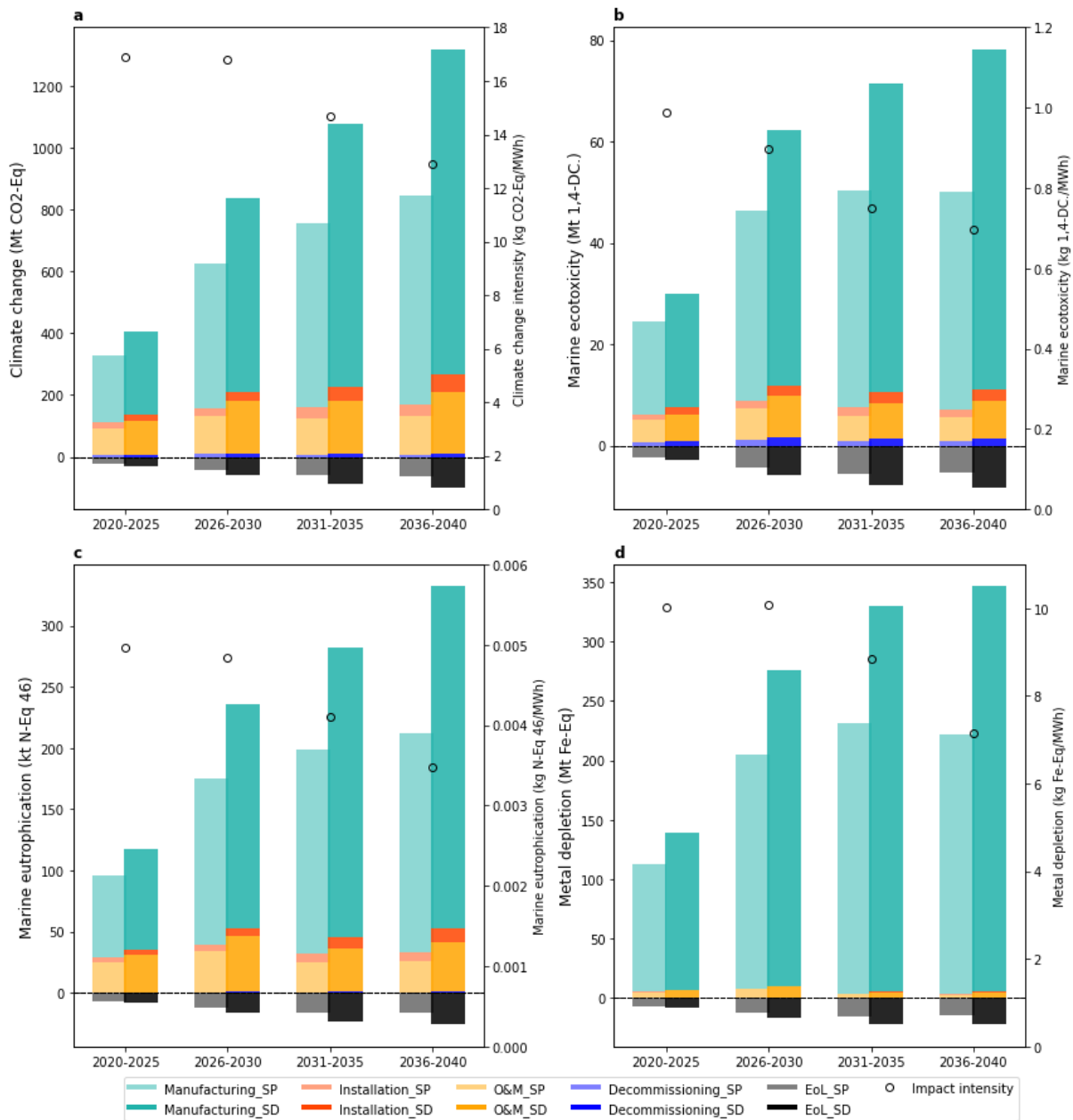


Figure 3.3: 5-year cumulative fleet environmental impacts contribution analysis by life cycle stage, for the stated policy (SP) and sustainable development (SD) capacity scenarios. 5-year average fleet environmental impact intensity (per MWh) for the AD technology scenario, EoL_O recycling scenario, 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 electricity⁶²), 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 habitat⁶⁴. 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 technologies⁶⁵. This innovation will likely reduce installation- and decommission-relevant environmental impacts⁶⁶.

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 environments⁷⁰.

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 potential⁷², 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 blades⁷³ and Vestas also aims to make fully recyclable blades by 2030⁴².

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 challenges³⁷. The industry has strengthened the interest in recovering REEs from OWE facilities and 21% recycling rates are expected⁷⁴. Greater PM sizes and thus material contents, would facilitate the recovery of such magnets and their REEs at the product's end-of-life stage⁷¹. 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.

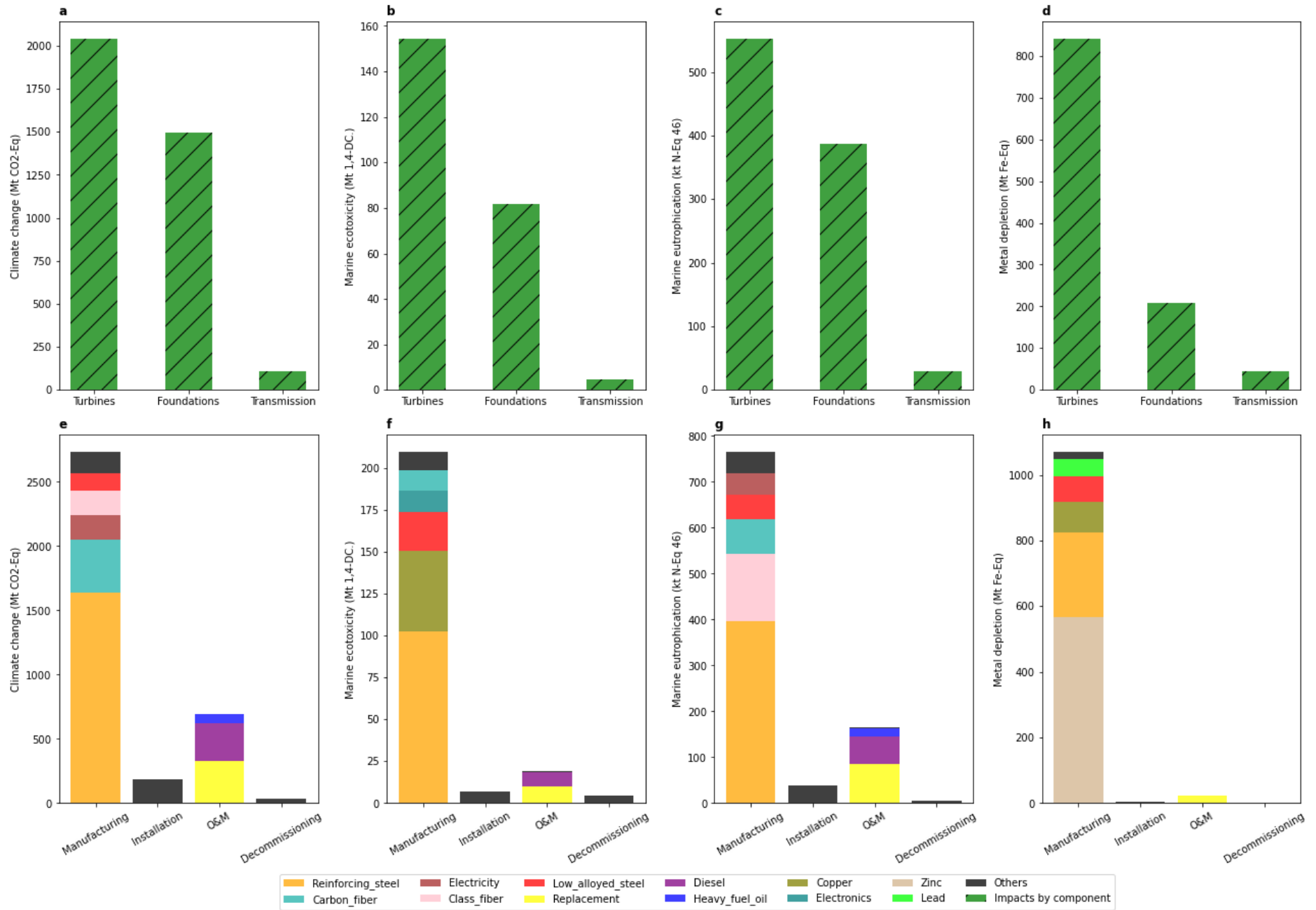


Figure 3.4: a-d: Contribution analysis by component; e-h: Contribution analysis by major processes in each of life cycle stage. All contribution analysis was conducted for cumulated (2020-2040) impacts, under SD capacity scenario, AD technology scenario, EoL_O recycling scenario, and SSP2-base background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

- (1) IEA. Offshore Wind Outlook **2019**.
- (2) Veers, P.; Dykes, K.; Lantz, E.; Barth, S.; Bottasso, C. L.; Carlson, O.; Clifton, A.; Green, J.; Green, P.; Holttinen, H.; Laird, D.; Lehtomäki, V.; Lundquist, J. K.; Manwell, J.; Marquis, M.; Meneveau, C.; Moriarty, P.; Munduate, X.; Muskulus, M.; Naughton, J.; Pao, L.; Paquette, J.; Peinke, J.; Robertson, A.; Rodrigo, J. S.; Sempreviva, A. M.; Smith, J. C.; Tuohy, A.; Wisser, R. Grand Challenges in the Science of Wind Energy. *Science* (80-.). **2019**, *366* (6464). <https://doi.org/10.1126/science.aau2027>.
- (3) Clean Energy Council. Benefits of Wind Energy in Australia. **2021**.
- (4) Bailey, H.; Brookes, K. L.; Thompson, P. M. Assessing Environmental Impacts of Offshore Wind Farms: Lessons Learned and Recommendations for the Future. *Aquat. Biosyst.* **2014**, *10* (1), 1–13. <https://doi.org/10.1186/2046-9063-10-8>.
- (5) Raadal, H. L.; Vold, B. I.; Myhr, A.; Nygaard, T. A. GHG Emissions and Energy Performance of Offshore Wind Power. *Renew. Energy* **2014**, *66*, 314–324. <https://doi.org/10.1016/j.renene.2013.11.075>.
- (6) Elginöz, N.; Bas, B. Life Cycle Assessment of a Multi-Use Offshore Platform: Combining Wind and Wave Energy Production. *Ocean Eng.* **2017**, *145* (September), 430–443. <https://doi.org/10.1016/j.oceaneng.2017.09.005>.
- (7) Tsai, L.; Kelly, J. C.; Simon, B. S.; Chalot, R. M.; Keoleian, G. A. Life Cycle Assessment of Offshore Wind Farm Siting: Effects of Locational Factors, Lake Depth, and Distance from Shore. *J. Ind. Ecol.* **2016**, *20* (6), 1370–1383. <https://doi.org/10.1111/jiec.12400>.
- (8) Wang, S.; Wang, S.; Liu, J. Life-Cycle Green-House Gas Emissions of Onshore and Offshore Wind Turbines. *J. Clean. Prod.* **2019**, *210*, 804–810. <https://doi.org/10.1016/j.jclepro.2018.11.031>.
- (9) Xie, J. bo; Fu, J. xun; Liu, S. yu; Hwang, W. sing. Assessments of Carbon Footprint and Energy Analysis of Three Wind Farms. *J. Clean. Prod.* **2020**, *254*, 120159. <https://doi.org/10.1016/j.jclepro.2020.120159>.
- (10) Arvesen, A.; Nes, R. N.; Huertas-Hernando, D.; Hertwich, E. G. Life Cycle Assessment of an Offshore Grid Interconnecting Wind Farms and Customers across the North Sea. *Int. J. Life Cycle Assess.* **2014**, *19* (4), 826–837. <https://doi.org/10.1007/s11367-014-0709-2>.
- (11) Huang, Y. F.; Gan, X. J.; Chiueh, P. Te. Life Cycle Assessment and Net Energy Analysis of Offshore Wind Power Systems. *Renew. Energy* **2017**, *102*, 98–106. <https://doi.org/10.1016/j.renene.2016.10.050>.
- (12) Sacchi, R.; Besseau, R.; Pérez-López, P.; Blanc, I. Exploring Technologically, Temporally and Geographically-Sensitive Life Cycle Inventories for Wind Turbines: A Parameterized Model for Denmark. *Renew. Energy* **2019**, *132*, 1238–1250. <https://doi.org/10.1016/j.renene.2018.09.020>.
- (13) Arvesen, A.; Birkeland, C.; Hertwich, E. G. The Importance of Ships and Spare Parts in LCAs

- of Offshore Wind Power. *Environ. Sci. Technol.* **2013**, *47* (6), 2948–2956. <https://doi.org/10.1021/es304509r>.
- (14) Birkeland, C. Assessing the Life Cycle Environmental Impacts of Offshore Wind Power Generation and Power Transmission in the North Sea. **2011**, No. June.
 - (15) Weinzettel, J.; Reenaas, M.; Solli, C.; Hertwich, E. G. Life Cycle Assessment of a Floating Offshore Wind Turbine. *Renew. Energy* **2009**, *34* (3), 742–747. <https://doi.org/10.1016/j.renene.2008.04.004>.
 - (16) Wagner, H. J.; Baack, C.; Eickelkamp, T.; Epe, A.; Lohmann, J.; Troy, S. Life Cycle Assessment of the Offshore Wind Farm Alpha Ventus. *Energy* **2011**, *36* (5), 2459–2464. <https://doi.org/10.1016/j.energy.2011.01.036>.
 - (17) Bonou, A.; Laurent, A.; Olsen, S. I. Life Cycle Assessment of Onshore and Offshore Wind Energy-from Theory to Application. *Appl. Energy* **2016**, *180*, 327–337. <https://doi.org/10.1016/j.apenergy.2016.07.058>.
 - (18) Poujol, B.; Prieur-Vernat, A.; Dubranna, J.; Besseau, R.; Blanc, I.; Pérez-López, P. Site-Specific Life Cycle Assessment of a Pilot Floating Offshore Wind Farm Based on Suppliers' Data and Geo-Located Wind Data. *J. Ind. Ecol.* **2020**, *24* (1), 248–262. <https://doi.org/10.1111/jiec.12989>.
 - (19) Reimers, B.; Özdirik, B.; Kaltschmitt, M. Greenhouse Gas Emissions from Electricity Generated by Offshore Wind Farms. *Renew. Energy* **2014**, *72*, 428–438. <https://doi.org/10.1016/j.renene.2014.07.023>.
 - (20) Yang, J.; Chang, Y.; Zhang, L.; Hao, Y.; Yan, Q.; Wang, C. The Life-Cycle Energy and Environmental Emissions of a Typical Offshore Wind Farm in China. *J. Clean. Prod.* **2018**, *180*, 316–324. <https://doi.org/10.1016/j.jclepro.2018.01.082>.
 - (21) Ma, C.; Bang, J.-I.; Tarantino, E.; Vela, A.; Yamane, D. Life Cycle Assessment of Greenhouse Gas Emissions for Floating Offshore Wind Energy in California. **2019**, No. May, 56.
 - (22) Moghadam, F. K.; Nejad, A. R. Evaluation of PMSG-Based Drivetrain Technologies for 10-MW Floating Offshore Wind Turbines: Pros and Cons in a Life Cycle Perspective. *Wind Energy* **2020**, *23* (7), 1542–1563. <https://doi.org/10.1002/we.2499>.
 - (23) Crawford, R. H. Life Cycle Energy and Greenhouse Emissions Analysis of Wind Turbines and the Effect of Size on Energy Yield. *Renew. Sustain. Energy Rev.* **2009**, *13* (9), 2653–2660. <https://doi.org/10.1016/j.rser.2009.07.008>.
 - (24) Venås, C. Life Cycle Assessment of Electric Power Generation by Wind Turbines Containing Rare Earth Magnets. Master Thesis. Norwegian University of Science and Technology. Norway. **2015**, No. June, 125.
 - (25) Ma, C.; Bang, J.-I.; Tarantino, E.; Vela, A.; Yamane, D. Life Cycle Assessment of Greenhouse Gas Emissions for Floating Offshore Wind Energy in California. *Appl. Sci.* **2019**, No. May, 56.
 - (26) Caduff, M.; Huijbregts, M. A. J.; Koehler, A.; Althaus, H. J.; Hellweg, S. Scaling Relationships in Life Cycle Assessment: The Case of Heat Production from Biomass and Heat Pumps. *J. Ind. Ecol.* **2014**, *18* (3), 393–406. <https://doi.org/10.1111/jiec.12122>.
 - (27) Caduff, M.; Huijbregts, M. A. J.; Althaus, H. J.; Koehler, A.; Hellweg, S. Wind Power Electricity: The Bigger the Turbine, the Greener the Electricity? *Environ. Sci. Technol.* **2012**, *46* (9), 4725–4733. <https://doi.org/10.1021/es204108n>.
 - (28) Chaviaropoulos, P. K.; Sieros, G. Design of Low Induction Rotors for Use in Large Offshore Wind Farms. *Ewea 2014* **2014**, No. June, 51–55.
 - (29) Zeng, Z.; Ziegler, A. D.; Searchinger, T.; Yang, L.; Chen, A.; Ju, K.; Piao, S.; Li, L. Z. X.;

- Ciais, P.; Chen, D.; Liu, J.; Azorin-Molina, C.; Chappell, A.; Medvigy, D.; Wood, E. F. A Reversal in Global Terrestrial Stilling and Its Implications for Wind Energy Production. *Nat. Clim. Chang.* **2019**, *9* (12), 979–985. <https://doi.org/10.1038/s41558-019-0622-6>.
- (30) Jensen, B. B.; Mijatovic, N.; Abrahamsen, A. B. Development of Superconducting Wind Turbine Generators. *Eur. Wind Energy Conf. Exhib. 2012, EWEC 2012* **2012**, *1*, 169–178.
- (31) Lefeuvre, A.; Garnier, S.; Jacquemin, L.; Pillain, B.; Sonnemann, G. Anticipating In-Use Stocks of Carbon Fibre Reinforced Polymers and Related Waste Generated by the Wind Power Sector until 2050. *Resour. Conserv. Recycl.* **2019**, *141* (October 2018), 30–39. <https://doi.org/10.1016/j.resconrec.2018.10.008>.
- (32) Alvarez-Anton, L.; Koob, M.; Diaz, J.; Minnert, J. Optimization of a Hybrid Tower for Onshore Wind Turbines by Building Information Modeling and Prefabrication Techniques. *Vis. Eng.* **2016**, *4* (1), 1–9. <https://doi.org/10.1186/s40327-015-0032-4>.
- (33) Manzano-Agugliaro, F.; Sánchez-Calero, M.; Alcayde, A.; San-Antonio-gómez, C.; Perea-Moreno, A. J.; Salmeron-Manzano, E. Wind Turbines Offshore Foundations and Connections to Grid. *Inventions* **2020**, *5* (1), 1–25. <https://doi.org/10.3390/inventions5010008>.
- (34) Jonkman, J.; Butterfield, S.; Musial, W.; Scott, G. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. *Contract* **2009**, No. February, 1–75.
- (35) Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. Theecoinvent Database Version 3 (Part I): Overview and Methodology. *Int. J. Life Cycle Assess.* **2016**, *21* (9), 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- (36) Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, A. *Image 3.0*; 2014.
- (37) Li, Chen, José M. Mogollón, Arnold Tukker, Jianning Dong, Dominic von Terzi, Chunbo Zhang, and Bernhard Steubing. "Future material requirements for global sustainable offshore wind energy development." *Renewable and Sustainable Energy Reviews* 164 (2022): 112603.
- (38) Fricko, O.; Havlik, P.; Rogelj, J.; Klimont, Z.; Gusti, M.; Johnson, N.; Kolp, P.; Strubegger, M.; Valin, H.; Amann, M.; Ermolieva, T.; Forsell, N.; Herrero, M.; Heyes, C.; Kindermann, G.; Krey, V.; McCollum, D. L.; Obersteiner, M.; Pachauri, S.; Rao, S.; Schmid, E.; Schoepp, W.; Riahi, K. The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century. *Glob. Environ. Chang.* **2017**, *42*, 251–267. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>.
- (39) O'Neill, B. C.; Kriegler, E.; Riahi, K.; Ebi, K. L.; Hallegatte, S.; Carter, T. R.; Mathur, R.; van Vuuren, D. P. A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways. *Clim. Change* **2014**, *122* (3), 387–400. <https://doi.org/10.1007/s10584-013-0905-2>.
- (40) Sacchi, R.; Terlouw, T.; Siala, K.; Dirnaichner, A.; Bauer, C.; Cox, B.; Mutel, C.; Daioglou, V.; Luderer, G. PROspective EnvironMental Impact AsSEment (Premise): A Streamlined Approach to Producing Databases for Prospective Life Cycle Assessment Using Integrated Assessment Models. *Renew. Sustain. Energy Rev.* **2022**, *160* (February), 112311. <https://doi.org/10.1016/j.rser.2022.112311>.
- (41) Mendoza Beltran, A.; Cox, B.; Mutel, C.; van Vuuren, D. P.; Font Vivanco, D.; Deetman, S.; Edelenbosch, O. Y.; Guinée, J.; Tukker, A. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *J. Ind. Ecol.* **2018**, *00* (0), 1–16. <https://doi.org/10.1111/jiec.12825>.
- (42) Vestas Wind Systems AS. The Vestas Sustainability Report 2020 Introduction About This Report. **2020**.

- (43) ABB. ABB Wind Turbine Converters PCS6000, Full Power Converter, up to 12 MW. **2019**, 12.
- (44) Home | Van Oord. <https://www.vanoord.com/en/> (accessed Sep 2021).
- (45) Steubing, B.; de Koning, D. Making the Use of Future Scenarios in LCA More Practical: The Superstructure Approach (in Review). *Int. J. Life Cycle Assess.* **2021**, No. 0123456789. <https://doi.org/10.1007/s11367-021-01974-2>.
- (46) Paterson, J.; D'Amico, F.; Thies, P. R.; Kurt, R. E.; Harrison, G. Offshore Wind Installation Vessels – A Comparative Assessment for UK Offshore Rounds 1 and 2. *Ocean Eng.* **2018**, *148* (August 2017), 637–649. <https://doi.org/10.1016/j.oceaneng.2017.08.008>.
- (47) Rademakers, L.W.M.M. , H. Braam, M. B.Zaaijer, G. J. W. V. B. Assessment and Optimisation of Operation and Maintenance of Offshore Wind Turbines. *Proc. EWECE* **2003**, 8–12.
- (48) Sustainable Society Consultant. **2012**.
- (49) Lacal-Arántegui, R.; Yusta, J. M.; Domínguez-Navarro, J. A. Offshore Wind Installation: Analysing the Evidence behind Improvements in Installation Time. *Renew. Sustain. Energy Rev.* **2018**, *92* (May), 133–145. <https://doi.org/10.1016/j.rser.2018.04.044>.
- (50) Parliament, E.; States, M.; Podimata, R. A.; Ftt, T.; Ftt, T.; Kong, H.; Ftt, A.; Eu-wide, P. Press Release Press Release. **2011**, No. 20120523, 32–33.
- (51) Tveiten, C. K.; Albrechtsen, E.; Hofmann, M.; Jersin, E.; Leira, B.; Norddal, P. K. HSE Challenges Related to Offshore Renewable Energy. **2011**, 1–85.
- (52) Jensen, J. P.; Skelton, K. Wind Turbine Blade Recycling: Experiences, Challenges and Possibilities in a Circular Economy. *Renew. Sustain. Energy Rev.* **2018**, *97* (July), 165–176. <https://doi.org/10.1016/j.rser.2018.08.041>.
- (53) Press, I. ReviewReviewed Work (s): Voices of AppalachiaReview by : Tim W . Jackson Source : Journal of Appalachian Studies , Vol . 21 , No. 1 (Spring 2015), Pp . 148-150 Published by : University of Illinois Press on Behalf of the Appalachian Studies Stable UR. **2015**, *21* (1), 148–150.
- (54) Liu, P.; Meng, F.; Barlow, C. Y. Wind Turbine Blade End-of-Life Options: An Eco-Audit Comparison. *J. Clean. Prod.* **2019**, *212*, 1268–1281. <https://doi.org/10.1016/j.jclepro.2018.12.043>.
- (55) Jagadish, P. R.; Khalid, M.; Li, L. P.; Hajibeigy, M. T.; Amin, N.; Walvekar, R.; Chan, A. Cost Effective Thermoelectric Composites from Recycled Carbon Fibre: From Waste to Energy. *J. Clean. Prod.* **2018**, *195*, 1015–1025. <https://doi.org/10.1016/j.jclepro.2018.05.238>.
- (56) The Crown Estate. Offshore Wind Operational Report 2015. *Gwec* **2015**, No. December.
- (57) Steubing, B.; de Koning, D.; Haas, A.; Mutel, C. L. The Activity Browser — An Open Source LCA Software Building on Top of the Brightway Framework. *Softw. Impacts* **2020**, *3* (December 2019), 100012. <https://doi.org/10.1016/j.simpa.2019.100012>.
- (58) Huijbregts, M. A. J.; Steinmann, Z. J. N.; Elshout, P. M. F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe2016: A Harmonised Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. *Int. J. Life Cycle Assess.* **2017**, *22* (2), 138–147. <https://doi.org/10.1007/s11367-016-1246-y>.
- (59) Mendecka, B.; Lombardi, L. Life Cycle Environmental Impacts of Wind Energy Technologies: A Review of Simplified Models and Harmonization of the Results. *Renew. Sustain. Energy Rev.* **2019**, *111* (May), 462–480. <https://doi.org/10.1016/j.rser.2019.05.019>.

- (60) Raadal, H. L.; Vold, B. I.; Myhr, A.; Nygaard, T. A. GHG Emissions and Energy Performance of Offshore Wind Power. *Renew. Energy* **2014**, *66*, 314–324. <https://doi.org/10.1016/j.renene.2013.11.075>.
- (61) Bhandari, R.; Kumar, B.; Mayer, F. Life Cycle Greenhouse Gas Emission from Wind Farms in Reference to Turbine Sizes and Capacity Factors. *J. Clean. Prod.* **2020**, *277*, 123385. <https://doi.org/10.1016/j.jclepro.2020.123385>.
- (62) International Energy Agency. IEA – International Energy Agency - IEA. *CO2 Emissions from Fuel Combustion*. 2020.
- (63) Bergström, L.; Kautsky, L.; Malm, T.; Rosenberg, R.; Wahlberg, M.; Åstrand Capetillo, N.; Wilhelmsson, D. Effects of Offshore Wind Farms on Marine Wildlife - A Generalized Impact Assessment. *Environ. Res. Lett.* **2014**, *9* (3). <https://doi.org/10.1088/1748-9326/9/3/034012>.
- (64) Coolen, J. W. P.; Van Der Weide, B.; Cuperus, J.; Blomberg, M.; Van Moorsel, G. W. N. M.; Faasse, M. A.; Bos, O. G.; Degraer, S.; Lindeboom, H. J. Benthic Biodiversity on Old Platforms, Young Wind Farms, and Rocky Reefs. *ICES J. Mar. Sci.* **2020**, *77* (3), 1250–1265. <https://doi.org/10.1093/icesjms/fsy092>.
- (65) Asgarpour, M. *Assembly, Transportation, Installation and Commissioning of Offshore Wind Farms*; Elsevier Ltd, 2016. <https://doi.org/10.1016/B978-0-08-100779-2.00017-9>.
- (66) IRENA. *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*; 2016.
- (67) Thomson, C.; Harrison, G. P. Life Cycle Costs and Carbon Emissions of Wind Power Executive Summary. *ClimateXChange* **2015**, 68.
- (68) Arvesen, A.; Hertwich, E. G. Assessing the Life Cycle Environmental Impacts of Wind Power: A Review of Present Knowledge and Research Needs. *Renew. Sustain. Energy Rev.* **2012**, *16* (8), 5994–6006. <https://doi.org/10.1016/j.rser.2012.06.023>.
- (69) Ren, Z.; Verma, A. S.; Li, Y.; Teuwen, J. J. E.; Jiang, Z. Offshore Wind Turbine Operations and Maintenance: A State-of-the-Art Review. *Renew. Sustain. Energy Rev.* **2021**, *144* (March). <https://doi.org/10.1016/j.rser.2021.110886>.
- (70) Caglayan, D. G.; Ryberg, D. S.; Heinrichs, H.; Linßen, J.; Stolten, D.; Robinius, M. The Techno-Economic Potential of Offshore Wind Energy with Optimized Future Turbine Designs in Europe. *Appl. Energy* **2019**, *255* (September), 113794. <https://doi.org/10.1016/j.apenergy.2019.113794>.
- (71) Nagle, A. J.; Delaney, E. L.; Bank, L. C.; Leahy, P. G. A Comparative Life Cycle Assessment between Landfilling and Co-Processing of Waste from Decommissioned Irish Wind Turbine Blades. *J. Clean. Prod.* **2020**, *277*, 123321. <https://doi.org/10.1016/j.jclepro.2020.123321>.
- (72) Jensen, J. P. Evaluating the Environmental Impacts of Recycling Wind Turbines. *Wind Energy* **2019**, *22* (2), 316–326. <https://doi.org/10.1002/we.2287>.
- (73) Gamesa, S.; Gamesa, S.; Gamesa, S.; Gamesa, D. S.; Gamesa, S.; Renewables, E. D. F.; Wind, G.; Council, E.; Gamesa, S.; Gamesa, S.; Recyclableblade, T.; Gamesa, S.; Nauen, A.; Gamesa, S.; Recyclableblade, S. G.; Gamesa, S. Press Release Siemens Gamesa Pioneers Wind Circularity : Launch of World ' s First Recyclable Wind Turbine Blade for Commercial Use Offshore. **2022**, No. September 2021.
- (74) Reimer, M. V.; Schenk-Mathes, H. Y.; Hoffmann, M. F.; Elwert, T. Recycling Decisions in 2020, 2030, and 2040—When Can Substantial NdFeB Extraction Be Expected in the EU? *Metals (Basel)*. **2018**, *8* (11). <https://doi.org/10.3390/met8110867>.
- (75) Topham, E.; McMillan, D.; Bradley, S.; Hart, E. Recycling Offshore Wind Farms at Decommissioning Stage. *Energy Policy* **2019**, *129* (September 2018), 698–709.

<https://doi.org/10.1016/j.enpol.2019.01.072>.

- (76) Lan, K.; Yao, Y. Dynamic Life Cycle Assessment of Energy Technologies under Different Greenhouse Gas Concentration Pathways. *Environ. Sci. Technol.* **2022**, *56* (2), 1395–1404. <https://doi.org/10.1021/acs.est.1c05923>.
- (77) Scheidat, M.; Tougaard, J.; Brasseur, S.; Carstensen, J.; Van Polanen Petel, T.; Teilmann, J.; Reijnders, P. Harbour Porpoises (*Phocoena Phocoena*) and Wind Farms: A Case Study in the Dutch North Sea. *Environ. Res. Lett.* **2011**, *6* (2). <https://doi.org/10.1088/1748-9326/6/2/025102>.
- (78) Andersson, M. H.; Sigray, P.; Persson, L. K. G. *Operational Wind Farm Noise and Shipping Noise Compared with Estimated Zones of Audibility for Four Species of Fish.*; 2011; Vol. 129. <https://doi.org/10.1121/1.3588249>.
- (79) Wilhelmsson, D. *Greening Blue Energy: Identifying and Managing the Biodiversity Risks and Opportunities of off Shore Renewable Energy*; 2010.