Environmental assessment and guidance for the future offshore wind energy development

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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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