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Environmental Life Cycle Assessment of multi-use of marine space: A comparative analysis of offshore wind energy and mussel farming in the Belgian Continental Shelf with terrestrial alternatives

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ABSTRACT

The Belgian Continental Shelf is a highly used part of the North Sea, where many different maritime activities thrive, such as shipping, fishing and energy production. Offshore wind energy in particular has gained importance in the region and concessions zones are allowed to be combined with aquaculture activities. It is unclear what the environmental impact of maritime multi-use is, from a life-cycle perspective, where there is potential to create synergies in the value chains, and how similar the impact compares to currently used alternatives. Therefore, this study performs a Life Cycle Assessment on a combination of a full scale existing wind energy farm and a mussel farm design. When analyzing the net environmental impact results of the multi-use offshore farm at the level of three areas of protection, i.e. human health, ecosystem quality and natural resources, it shows that the mussel farm contributes relatively the most to the net impacts, while the majority of the avoided burdens are attributed to the wind farm. Mainly the supply chain of materials required to manufacture its components followed by the operational activities of the multi-use offshore farm contribute to the environmental footprint. Moreover, taking advantage of joint activities, i.e. combined transport between the wind and mussel farm during operational activities (Scenario 1) and at decommissioning phase (Scenario 2) did not show a significant reduction in the overall net impacts of a multi-use farm. The life cycle assessment results of a multi-use offshore farm are furthermore compared with relevant terrestrial benchmarks in Belgium, i.e. nuclear energy and pork meat production. While the benchmarks have a high burden on the area of protection ecosystem quality due water and land use requirements, the multi-use farm mainly impacts the remaining areas of protection, i.e. human health and natural resources, again as a consequence of the burdens of its supply chain. This study reveals the potential of offshore multi-use farms in terms of environmental sustainability, offering valuable insights to policy-makers and value chain actors, and generally contributes to well-informed decision-making.

1. Introduction

Increasing usage of marine resources raises the pressure on ecosystems and leads to a competitive environment as various activities take place in the same space. Co-locating activities is considered a way to minimize conflicts over space and resource use, create economic opportunities and reduce environmental pressures on marine ecosystems (Maar et al., 2023; Guyot-Téphany et al., 2024). Initially, this concept of co-location or multi-use focused on the integration of aquaculture with offshore wind energy production. However, it has since been extended to various combinations, such as integrating wind and wave energy or repurposing decommissioned oil and gas platforms (Buck et al., 2017; Lukic et al., 2018; Dalton et al., 2019; Schupp et al., 2019; Maar et al., 2023; Guyot-Téphany et al., 2024).

The multi-use concept entered the EU political agenda through the European Union Blue Growth Strategy and has since been integrated into other policies (Guyot-Téphany et al., 2024). For instance, the EU Integrated Marine Policy includes multi-use of marine space and

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resources in its strategy aiming to provide an integrated approach for the maritime governance by increasing coordination and cooperation of different marine sectors and maximizing the sustainable use of the oceans and seas (EC, 2007). Furthermore, the Maritime Spatial Planning Directive (2014/89/EU) (EC, 2014) requires Member States to implement a marine spatial plan (MSP) by the end of 2021, regulating the usage of marine space,. The mentioned Directive 2014/89/EU also targets to encourage countries on integrating multi-use of marine resources into their country specific MSPs in a way that is aligned with their national plans and legislations. As a result, multi-use of marine space and resources has been incorporated into the MSPs of different countries at varying levels of detail (European MSP Platform, 2023).

Belgium is one of the first countries who regulated its marine space and activities through an MSP (2020–2026 (see Belgisch Staatsblad, 2019). The Belgian marine space is relatively small, covering 0.5% of the North Sea's surface with a size of 3454 km^2, 65 km of coastline, and extends a maximum distance of 83 km seaward. However, it is home to a variety of activities with different characteristics in terms of time and space (i.e. energy production, shipping, dredging, fishing, aquaculture, sand extraction, coastal protection, military activities, tourism, preservation of cultural heritage, research, commercial, and industrial activities) (FDS, 2020). Careful management of these activities is crucial for maximizing the utilization of resources in this marine area, but equally important is to consider the area's biocapacity while safeguarding the marine environment. The Belgian MSP actively promotes the multifaceted utilization of marine space, specifically emphasizing its application for energy, cable and pipelines (i.e. areas for renewable energy production via offshore wind farms or OWFs). Notably, two OWF areas are identified within this plan, which are also designated as aquaculture zones (Belgium Government, 2020). Starting in 2016, a series of pilot-scale projects were initiated to explore the feasibility of integrating diverse aquaculture practices, including mussel, seaweed, oyster, and/or scallop farming, within the vicinity of wind farm sites. These initiatives were often conducted within the framework of nationally and/or internationally funded projects like EDULIS, Wier & Wind, UNITED, etc., and other integration options (Supplementary Material, Table S1).

Although the MSP encourages the multiple use of marine space, concerns persist regarding the potential environmental impacts of combined activities at sea and their associated value chains. The assessment of the cumulative effects from human activities both at sea and on land is a requirement of the Marine Strategic framework Directive (MSFD) (Korpinen et al., 2020). A tool often used to quantify environmental impacts associated with all the stages of the lifecycle of a good or service is Life Cycle Assessment (LCA), which also holds value in providing decision support to relevant stakeholders and informing policy making (Sala et al., 2021). LCA traditionally focuses on energy and material inputs, land use changes, waste generation and emissions, thus evaluating the environmental impacts associated with these inputs and releases (Finnveden and Potting, 2014). However, LCA studies on multi-use activities are extremely scarce, particularly for the marine environment. Few reports or scientific papers are available, developed in the context of EU funded projects (e.g. TROPOS, H2Ocean, MERMAID), where the environmental sustainability of conceptual multi-use offshore platform designs, based on low technology readiness level (TRL) (3–4) experiments, is assessed (Utomo et al., 2014; Díaz-Simal et al., 2015; Bas et al., 2017; Elginoz and Bas, 2017; Koundouri et al., 2017; Söderqvist et al., 2017). The LCA studies showed significant variation in their geographical coverage, encompassing regions such as the Mediterranean Sea, Atlantic Ocean and Baltic Sea. In the majority of cases, these studies involved the integration of aquaculture activities (mostly fish breeding) within existing OWFs. Only one study focused on the potential combination of mussel and seaweed farming with wind energy, hypothetically proposing its location in the North Sea (Söderqvist et al., 2017). This study relied on inventory data for the mussel farm sourced from earlier studies (Fry et al., 2012; Winther et al., 2009), which originally belong to Scottish and Norwegian aquaculture systems. Only the impact on Global Warming Potential was quantified, with no comparisons made to relevant benchmarks, and there was an absence of analysis regarding the potential benefits and/or drawbacks of the multi-use activities, i.e. there were no synergies amongst their value chains investigated. Furthermore, Bas et al. (2017), Koundouri et al. (2017) and Söderqvist et al. (2017) lacked an examination of LCA results robustness, as they did not include scenario and/or uncertainty analyses in their LCA assessments. Elginoz and Bas (2017) did include a scenario analysis, but they focused on the end-of-life of components of multi-use activities rather than on potential synergies.

The purpose of this study is to conduct the first comprehensive LCA study on a marine multi-use offshore farm (MUOF), more specifically on the combination of an offshore wind and a blue mussel farm (OWF and OMF, respectively) located in the Belgian Continental Shelf (BCS), generating a "basket of products" annually, including energy and mussels. For this, significant efforts were dedicated to collect primary data or to find the best available proxy data, as this was identified as a weakness in the current state of the art. While the inventory for the OWF is based on an existing wind farm, the inventory for the designed OMF is primarily based on expert interviews and pilot scale projects conducted in the BCS. Furthermore, the potential to reduce the overall net environmental impact of the MUOF is explored by developing two scenarios in which joint transport between the OMF and OWF operations is considered an important factor. The goal is to better understand the potential of MUOF to not only share marine space but also to merge their value chains at some points. To determine the potential importance of an MUOF for Belgium, this study includes a quantitative comparison of the environmental impacts with relevant terrestrial benchmarks (nuclear energy and pork meat, both highly produced and consumed domestically). To assess the robustness of the results, an uncertainty analysis is performed.

2. Materials and methods

2.1. Description of marine multi-use offshore farm

A MUOF is developed, integrating a full scale, yet designed, offshore mussel farm (OMF) into an existing offshore wind farm (OWF) in the Belgian Continental Shelf (BCS). Fig. 1 shows a simplified representation (not to scale) of the MUOF. A further description of these two activities is provided in Section 2.1.1. and Section 2.1.2.

2.1.1. The OMF

The design of the OMF is based on the availability of space within the wind energy zone under study. This design relies on a pilot scale project in the BCS (i.e., EDULIS) (Pribadi et al., 2019). This approach ensures that the OMF design aligns with the BCS conditions (Pribadi et al., 2019; Stechele et al., 2022). More information about the design can be found in Section 2.1 in Supporting Material (SM). The OMF consists of multiple mussel farming lots (MFLs) (Fig. 1, and Figs. S1 and S2 in SM). Each MFL is integrated into the available space between four wind turbines, with all MLFs corresponding to 25% of the total area of the OWF to allow an efficient operation of both farms (Buck et al., 2010; Stenberg et al., 2011). A minimum distance of 150 m from each wind turbine is considered for this placement (Buck et al., 2010). One single MFL consists of seven cultivation rows, each having three longline systems connected. This setup is widely employed in the aquaculture sector to ensure cost-effective solutions for material, installation and operations. The number of cultivation rows (i.e., seven) is determined based on specific criteria, which requires that the distance between two parallel longlines must be at least 1.5 times the existing water depth (Bonardelli et al., 2019).

Each longline system consists of a backbone rope, cultivation ropes (V-shaped), SPAR buoys, buoys, and mooring system (anchors and mooring chains). The connection between longline systems is facilitated

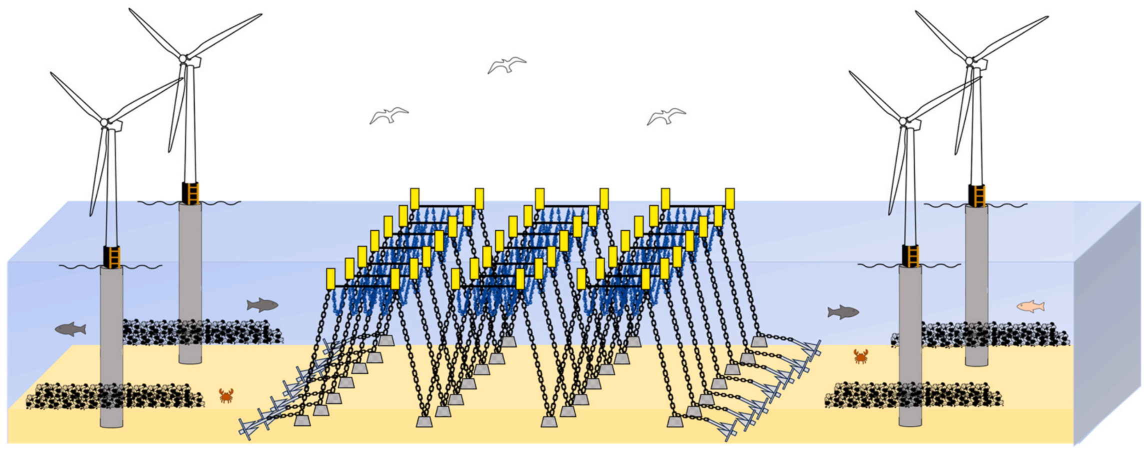

Fig. 1. Simplified schematic of the design of one mussel farming lot, installed between 4 wind turbines. This construction is repeated multiple times ensuring a full integration of the mussel and wind energy farms. Source: Adapted and modified from Bonardelli et al. (2019).

by a shared gravity anchor (Fig. 1). Considering the North Sea conditions, which is a harsh marine environment with a high risk of damages to the aquaculture setup installed, a stable system is crucial to reduce the risks. To achieve this, additional rings, shackles, and ropes are used to connect cultivation rows (6 connection ropes in total between the rows). Also, a catenary type of mooring system, which is a common application in the design of aquaculture systems (Lin et al., 2016), is added to the design for each corner of one MFL.

The system components' essential attributes, including their type, materials, dimensions and weights, are carefully evaluated to closely align with the original pilot-scale project design of Pribadi et al. (2019). To ensure a conservative approach, components are chosen to withstand proof loads estimated to be twice as high as the base design (a simplified approach). This accounts for additional drag forces from surface water waves acting on the system, caused by the combined movement of three connected longlines with shared gravity anchors. The selection of components relies on aquaculture sector product catalogues, prioritizing local suppliers and including some from distant countries to establish a realistic supply chain aligned with the case study area.

2.1.2. The OWF

The design of the studied OWF is based on an existing and operational farm located in the BCS. Exact details on the design of the OWF's components cannot be disclosed for confidentiality reasons, therefore, mainly ranges and aggregated values are given. More details on the data inventory for the OWF can be found in Section 2.2.2, SM and De Luca Peña et al. (2024). The OWF is located approximately 35–55 km from the Belgian coastline covering an area between 14 and 20 km^2. The number of wind turbines ranges between 20 and 75 with a capacity between 3 and 10 MW. The foundations of the OWF are comprised of monopiles and their transition pieces, whose length varies depending on the water depth. The electricity produced by the wind turbines is transported to an offshore high voltage station (OHVS) via infield cables with a total length between 30 and 50 km. The collected electricity in the OHVS is transported to shore via a subsea export cable with a length between 40 and 60 km. On shore, the subsea export cable is connected to a land cable, which transports the electricity to an onshore high voltage station for voltage control. From this onshore station, the electricity is transmitted to the high voltage transmission grid operated by ELIA (electricity system operator in Belgium) (De Luca Peña et al., 2024).

2.2. LCA study of the MUOF

A LCA study is conducted following the guidelines defined by ISO 14040–14044 standards. According to these guidelines, a LCA study is comprised by four stages: definition of goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation (ISO, 2006). In the following sections, more details are presented for each stage.

2.2.1. Goal and scope

The aim of this study is to determine the environmental impacts of a MUOF in the BCS, first for a base case where both activities' value chains are considered independently and thus separate, but also for different scenarios considering synergies amongst the value chain operations and furthermore, a comparison with currently used terrestrial local alternatives (Section 2.3) is foreseen. The lifetimes of the OWF and the OMF are 25 years and 12 years, respectively. It is assumed that the OMF will be installed right after the installation of the OWF and will be decommissioned after 12 years. Subsequently, it will be reinstalled, and both OMF and OWF will be decommissioned together after another 12 years. The total net electricity production for a 25-year period by the OWF is 12,986,055 MWh (Personal communication with concession holders, 2022) and the net quantity of mussels produced (after 30% loss mainly during harvest, Aubin et al. (2018)) by the OMF is 4604 ton (fresh weight, with shells, based on the EDULIS project and personal communication with OMFs experts, 2023) throughout its lifetime of 12 years.

The functional unit (FU) considered in this study is a basket of products, i.e. the average annual production of mussels and electricity from a MUOF. For electricity, results are expressed for 519,442 MWh. For the mussels, the Nutrient Density Score (NDS) is used and set at 8,677,441 NDS (equal to 368.3 tons of mussels). The NDS was selected as FU because it can better express food functionality (McLaren et al., 2021). The selected NDS was based on the model of Drewnowski et al. (2009) and Hallström et al. (2019), which considers the content of desirable and non-desirable nutrients per 100g and relates it to a reference value, i.e. the daily or maximum recommend intake of a nutrient. More details on the selection of the NDS and the background calculations can be found in Tables S23, S24, S25 and S26 in SM.

The system boundaries in this study are cradle-to-grave covering the manufacturing, installation, operation and maintenance (O&M), decommissioning and End-of-Life (EoL) phases of the MUOF. Fig. 2 shows the interaction between the two activities in a simplified way (not scaled). This assessment does not include the transmission of electricity to households and industry, nor the packaging of mussels, transportation to retailers and consumption of mussels. Fig. 3, a simplified flow chart, includes the main life cycle phases and processes of both components of the MUOF.

2.2.2. Inventory

The foreground data collected for the OMF is primarily derived from

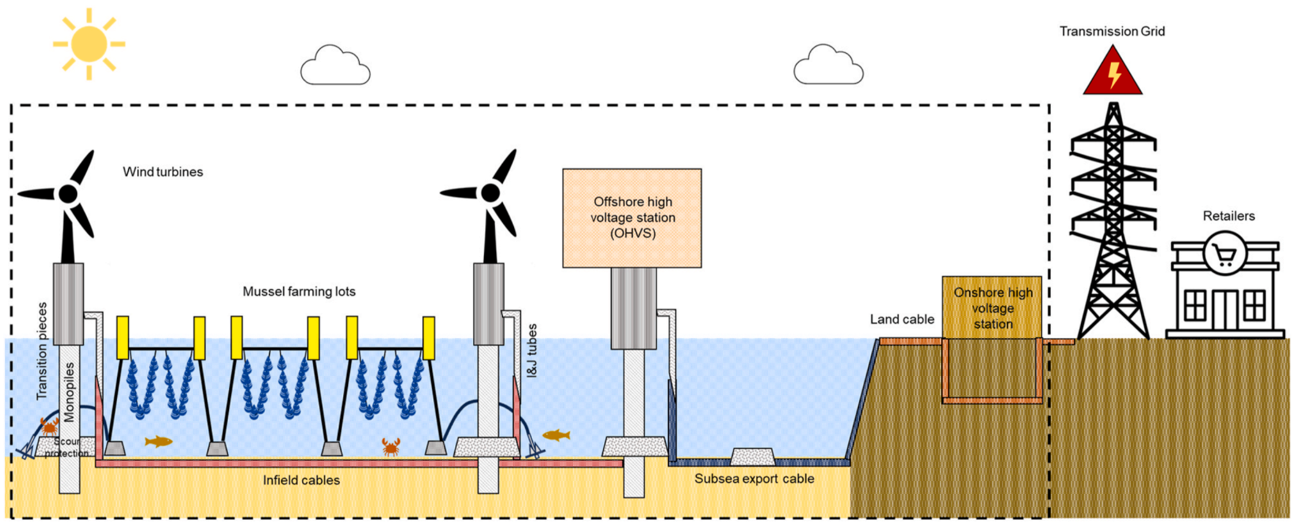

Fig. 2. Components of a multi-use offshore farm. The system boundaries are depicted with a black-dashed line.

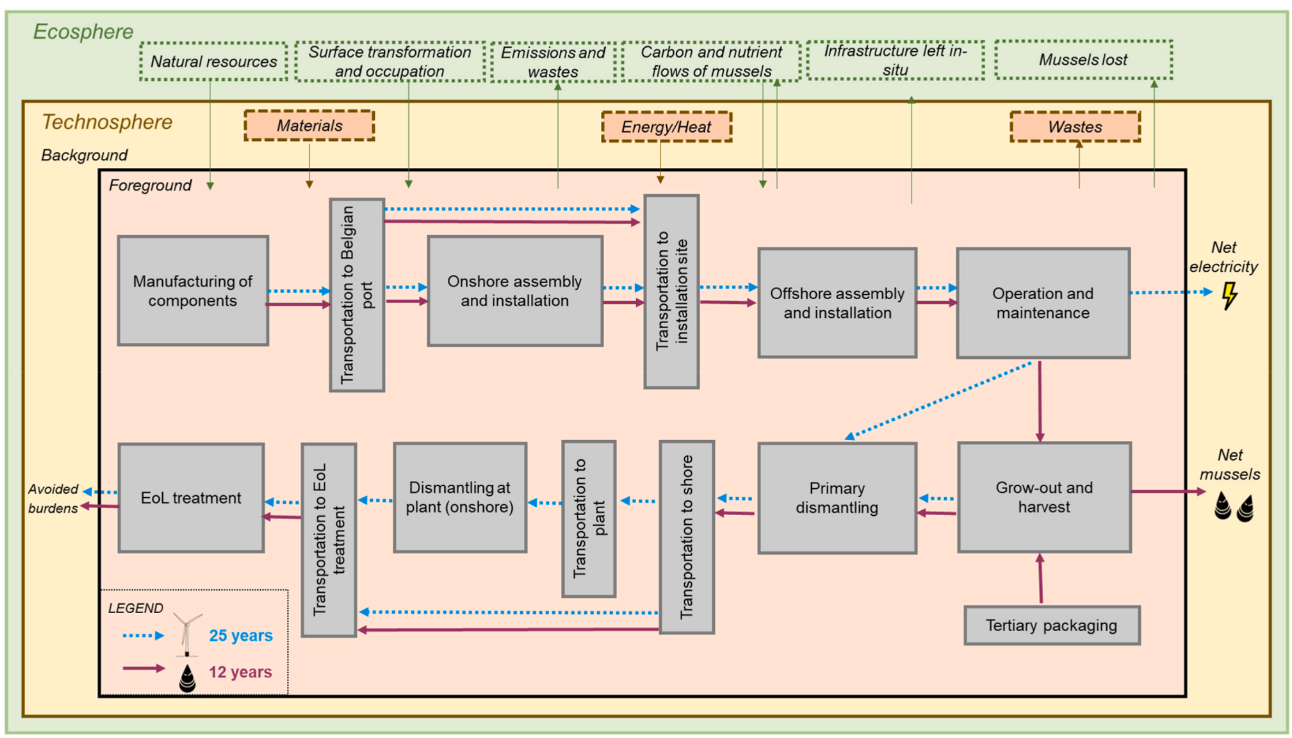

Fig. 3. Process scheme showing the life cycle phases and flow chart of a MUOF. *Grey boxes:* depict all life cycle stages of the MUOF. Blue dotted line: material and energy flows related to the value chain of OWF with a lifetime of 25 years; Purple full line: material and energy flows related to the value chain of OMF with a lifetime of 12 years. In this study, the impacts of mussels on the carbon flows are considered by following the holistic approach of Filgueira et al. (2019) (more details in Section 2.2.3 in SM). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a pilot scale study (Pribadi et al., 2019). Additionally, the design was refined by using commercial aquaculture equipment catalogues and through insights gathered in a series of (inter)national expert meetings. Once the design of the OMF was established, the LCI of the foreground processes was completed based on an exhaustive literature study. For the OWF on the other hand, the foreground data was mainly comprised by primary data including confidential data from the OWF's concession holders and publicly-available data (Personal communication with concession holders, 2022). Secondary sources including peer-reviewed articles (Kouloumpis and Azapagic, 2022; Tsai et al., 2016), master theses (Birkeland, 2011; Vanderveken, 2022) and life cycle databases were used to fill data gaps in the inventory.

For the background system, which includes upstream and downstream processes not considered in the foreground system, e.g. extraction and production of raw materials, ecoinvent v3.8 database was used to obtain this background data for both the OMF and OWF.

A detailed description of all life cycle stages (i.e. from cradle to grave including avoided burdens), as well as the estimations and assumptions made in the LCI of the OMF and OWF are presented in Sections 2 and 3 in SM and De Luca Peña et al. (2024).

2.2.3. *Impact assessment*

SimaPro V9.2.0.2 software was used to conduct the LCA study and the chosen life cycle impact assessment (LCIA) method was ReCiPe 2016

V1.05 (H) (Huijbregts et al., 2017), which quantifies the environmental impacts, at the endpoint level, on three Areas of Protection (AoPs) as human health (HH), ecosystem quality (EQ) and natural resources (NR), and at 18 midpoint impact categories.

2.2.3.1. Multi-use scenarios. To present the potential environmental gains associated with synergies between value chain processes of both MUOF activities, a scenario analysis is conducted as part of this study. This involved exploring the state-of-the-art literature and conducting expert meetings and surveys to determine the potential synergies between the OWF and OMF resulting in the development of two scenarios (van den Burg et al. (2017); Michler-Cieluch et al., 2009; Griffin et al., 2015; Jansen et al., 2016; Buck et al., 2017; Schupp et al., 2019; Soma et al., 2019; van den Burg et al. (2017); Personal Communication with OWFs and OMFs experts, 2023).

The first scenario assumes that the O&M activities of the OMF can be shared with the ones of the OWF. Based on expert opinions, the monitoring of the OMF system (including visual checks, remotely-operated-vehicle monitoring, and environmental criteria sampling) can be performed by OWF crew members during their routine trips, hence it is assumed that 50% of the regular monitoring trips can be shared between the OWF and OMF (Fig. S9 in SM).

According to expert opinions, the EoL phase of the MUOF could potentially offer points for joined actions during the decommissioning of both activities. Therefore, the second scenario considers shared transportation during the MUOF decommissioning. However, the lifetime of the two activities differs, i.e., the OMF has a lifetime of 12 years while the OWF has a lifetime of 25 years, meaning that the OMF is decommissioned once alone, reinstalled and then decommissioned together with the OWF. It is assumed that the OMF components covering the sea surface are dismantled first, allowing more free space for dismantling large OWF components. Moreover, this offers the possibility of a joint dismantling operation for the components on the seabed (anchors and mooring chains, foundations), which can be carried out and transported by a common jack-up vessel (the dimensions and weight of the anchors and mooring chains are suitable to place them in the free space between the OWF components, staying below the vessel's full load capacity) (see Fig. S10 in SM). Larger ships, such as the jack-up vessels, carrying the turbines leave space on the deck to accommodate additional items like ropes and anchors. While the turbines occupy significant volume, the ships have the capacity to handle more weight, allowing smaller pieces to be included. This means that trips with big and medium sized vessels used in the base case for the EoL of the OMF are no longer necessary as all equipment can be carried with the jack up vessels of the OWF, however, additional loads on those vessels consume more fuel, and this is accounted for through a sensitivity analyses (assumption of a 20%–50% more fuel compared to the base case).

2.3. Benchmark

To better understand the environmental performance of a MUOF, generating protein rich mussels and renewable energy as a basket of products, this study includes the analysis of relevant benchmarks. To select those, two criteria were taken into account: (1) importance within the food and energy market in Belgium, i.e. the alternative protein-rich food and energy supply to be compared with must be *produced* and *highly consumed* in Belgium, as it would be especially informative for national policy-makers to determine whether a MUOF could replace today's alternatives and (2) data availability and accessibility. Based on these criteria, nuclear energy and pork chop loin meat production were selected as benchmarks for the OWF and OMF, respectively. More details on the selection criteria for both terrestrial benchmarks can be found in Sections 4.1.1. and 4.2.2. in SM.

When analyzing the environmental performance of MUOF with its benchmarks, a cradle-to-gate system boundary is applied, including manufacturing, installation and operational activities. The distribution of electricity and meat (i.e. to retailers and consumers), consumption stage, primary and secondary packaging and EoL activities (e.g. dismantling of infrastructure, EoL treatments) are not covered because of data limitations, especially for the nuclear energy benchmark. The FU is the same as the base case (i.e. annual production of electricity and mussels of a MUOF) to allow for comparability (Fig. 4).

Secondary data was used from processes in agribalyse 3 and ecoinvent v3.8 (cut-off allocation – unit) to model the production of pork meat and nuclear energy, respectively. Details on the processes can be found in Sections 4.1.2 and 4.2.2. in SM.

2.4. Uncertainty analysis

To assess the uncertainty in the LCA results, a Monte Carlo analysis was conducted using SimaPro. Before running the analysis, a probability distribution was assigned to the parameters (i.e. LCI data) by applying a qualitative assessment known as the pedigree matrix approach. This approach consists of five data quality indicators: reliability, completeness, temporal correlation, geographical correlation and technology correlation. Each data point of the foreground system (i.e. LCI data) is assigned a score from 1 to 5 for each indicator, with 1 representing high and 5 representing low data quality (Weidema et al., 2013). More details on the pedigree matrix applied are found in Table S27 in SM.

Based on each combination of indicators and scores, SimaPro obtains uncertainty factors used to calculate an aggregated standard deviation (SD) for each foreground data input (Weidema et al., 2013). A lognormal probability distribution is also automatically assigned to each input because the equation to calculate the standard deviation is only valid for lognormally distributed data and is the standard way to model uncertainties in ecoinvent (Weidema et al., 2013). However, SimaPro lacks the capacity to generate uncertainty of intermediate products (i.e. output flows) by accounting for the standard deviation in the LCI inputs. To address this limitation, the function *estimateSumLognormal*, from the R package "lognorm" (Wutzler, 2022) and based on the methodology of Lo (2012), was modified and applied to estimate the sum of lognormal distributions, providing a value for the uncertainty of intermediate products. Further details are available in Fig. S11, Box S2 and Box S3 in SM.

Subsequently, a Monte Carlo analysis was performed in SimaPro with 1000 iterations and a confidence interval of 95%, which is in the range of the recommended iterations (Heijungs, 2020). An uncertainty range was obtained for both midpoint and endpoint results for the OWF, OMF, the developed scenarios and the terrestrial benchmarks (see Fig. 5).

3. Results

The results presented in this section comprise the environmental impacts quantified from the hotspot analysis of the MUOF (Section 3.1), the scenarios analysis (Section 3.2), the benchmark analysis (Section 3.3) and uncertainty analysis (Section 3.4).

3.1. Hotspot analysis (base case)

The net environmental impacts (i.e. total footprint minus the beneficial impact of the avoided products) of cradle-to-grave analysis of the MUOF is quantified (per FU) for three AoPs, HH, NR and EQ. The OMF has the largest contribution to the net impacts compared to the OWF on the three AoPs (HH: 71.1%; EQ: 68.95; NR: 58.5%) (see Table 1 and Figs. S12 and S13 in SM).

Looking at the results of the avoided burdens, it is clear that the OWF has the greatest benefits from the avoided products (i.e. avoiding the extraction of virgin materials through recycling and making use of recovered energy, e.g. from incineration) compared to the OMF (Table 1). This mainly occurs due to the recycling of steel from the

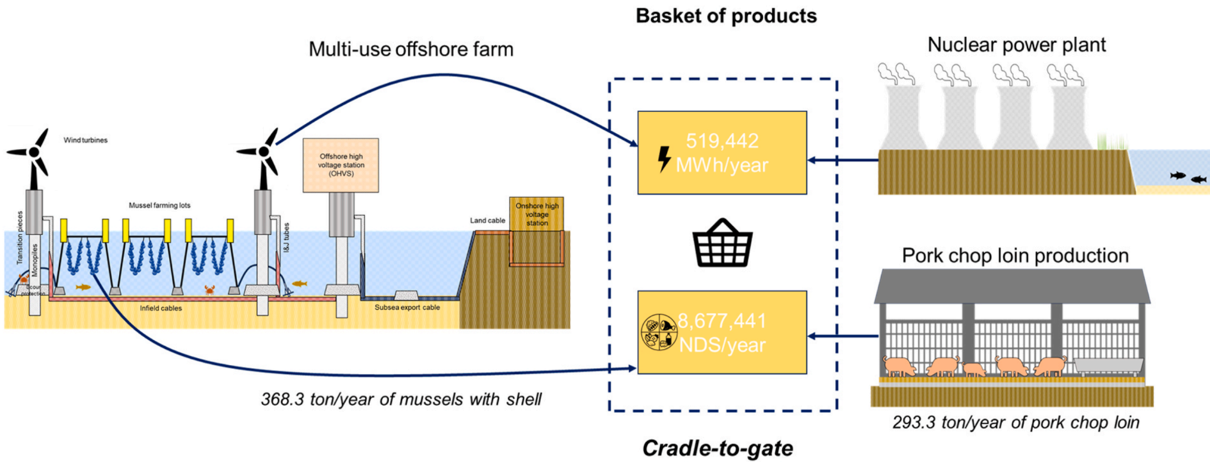

Fig. 4. Representation of the basket of products as functional unit of the LCA study.

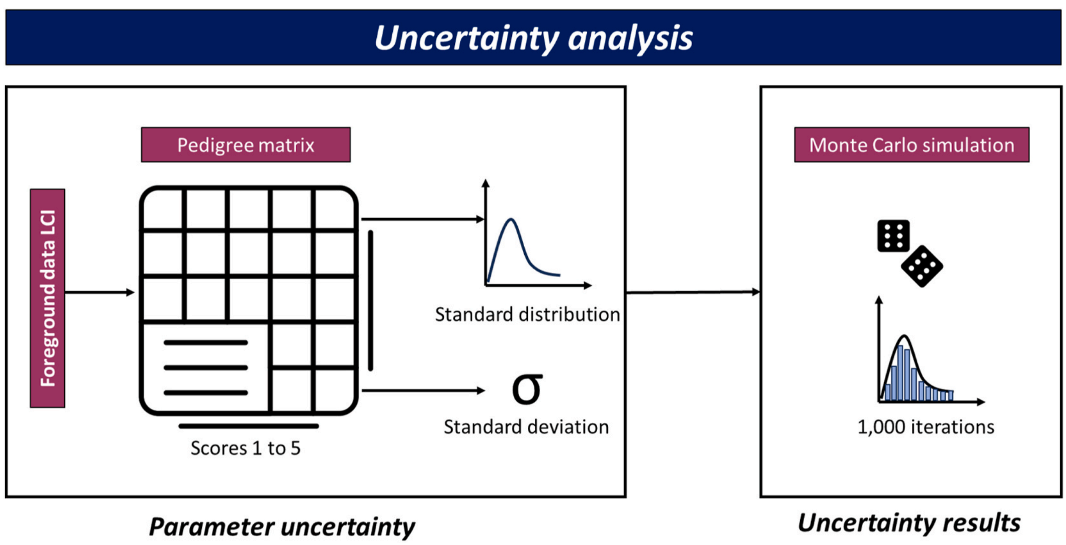

Fig. 5. Uncertainty analysis conducted in this study. First, the parameter uncertainty from the foreground LCI data was obtained by conducting a Pedigree matrix and by using a R code to generate uncertainty of intermediate products. After assigning a standard distribution to the data, a Monte Carlo simulation was executed using SimaPro.

different components of the OWF but particularly of the wind turbines and foundations. Similarly for the OMF, recycling steel from Danforth anchors and mooring chains also generates most of the benefits as avoided products.

The midpoint impact categories that contributed the most to the burdens of the MUOF on the AoP HH were fine particulate matter (OWF: 53.1%; OMF: 48.8%) and global warming (OWF: 26.1%; OMF: 34.7%) coming mainly from processes related to the supply of primary and secondary materials (Figs. S14 and S15 and Tables S28, S29, S34, S36 in SM), such as steel. These materials are used to manufacture the components of the OWF and OMF, particularly the OWF's monopiles and wind turbines (De Luca Peña et al., 2024), and the OMF's Danforth anchors, mooring chains, gravity anchors and SPAR buoys (Fig. S16 in SM), from which the Danforth anchors contributed to 62.2% of the burdens coming from the OMF's manufacturing stage on the AoP HH. While 80.5% of the burdens of the OWF on the AoP HH are attributed to the manufacturing stage, 47.7% and 36.0% of the OMF's burdens occur during the manufacturing and O&M stages, respectively (Tables S35, S37 in SM). The latter occurs due to OMF's high maintenance requirements (i.e. 89.4% including the supply chain of the replaced of components, diesel consumption and offshore transportation of replaced components). A small part of the OMF's burdens on the AoP HH in the O&M stage occur due to energy required for monitoring and cleaning activities (10.5%) (Table S46 in SM).

For the AoP EQ, the midpoint impact categories that contributed the most to its burdens were global warming (terrestrial ecosystems) (OWF: 47.2%; OMF: 57.9%), terrestrial acidification (OWF: 27.0%; OMF: 21.2%) and ozone formation (terrestrial ecosystems) (OWF: 11.0%; OMF: 12.0%). Again, for the OWF, these impacts are mainly associated to the supply chain of materials to manufacture the OWF's components (Tables S30 and S31 in SM; De Luca Peña et al., 2024), while for the OMF, processes coming for the manufacturing (45.9%), O&M (34.5%) and EoL (5.3%) stages, such as the combustion of diesel during transportation, pig iron production and the incineration of the OMF's components containing plastic (e.g. ropes, buoys and aux pieces) had the highest contribution of the OMF's burdens on the AoP EQ (Tables S38, S39, S40, S41 in SM). Similarly to the OWF, over half (56.3%) of the burdens of the manufacturing stage on the AoP EQ are attributed to the galvanized steel required to manufacture the Danforth anchors followed by clinker needed (e.g. in cement production) in the manufacturing of gravity anchors (14.5%) (Fig. S16 in SM).

Finally, the AoP NR was highly impacted by the fossil resource

Table 1
Total net environmental burdens per total average annual production of an MUOF (519,442 MWh and 368.3 ton of mussels with a total NDS of 8,677,441).

Impacts of MUOF components	Areas of protection		
	Human Health (DALY/FU)	Ecosystem Quality (species. yr/FU)	Natural Resources (USD2013/FU)
OWF			
Burdens	1.5E+01	2.5E-02	4.6E+05
Avoided burdens	−1.1E+01	−1.7E-02	−2.4E+05
Net impact for the OWF	3.5+E00	7.7E-03	2.3E+05
OWF contribution in net impact of the MUOF (%)	*28.9%*	*31.1%*	*41.5%*
OMF			
Burdens	1.4E+01	2.5E-02	4.3E+05
Avoided burdens	−5.0+E00	−7.7E-03	−1.1E+05
Net impact for the OMF	8.6E+00	1.7E-02	3.2E+05
OMF contribution in net impact of the MUOF (%)	*71.1%*	*68.9%*	*58.5%*
MUOF			
Net impact for the MUOF	*1.2E+01*	*2.5E-02*	*5.4E+05*

scarcity impact category (OWF: 86.1%; OMF: 92.5%) due to the production of nylon 6-6 (needed for the manufacturing of the wind turbines' blades), ethylene (needed in the manufacturing of the OMF's SPAR buoys) and the production of petroleum, propylene and natural gas, which are mainly associated to the production of steel to manufacture OWF's components, such as wind turbines and foundations (De Luca Peña et al., 2024) and OMF's components, such as Danforth anchors, but also for the production of diesel associated to transportation, offshore installation and O&M of the OWF and OMF (Tables S32, S33, S42, S43, S44, S45 in SM). In this case the Danforth anchors contributed to 40.9% of the OMF's manufacturing stage impacts on the AoP NR, while the SPAR buoys had a contribution of 30.0% (Fig. S16 in SM).

3.2. Scenario analysis

3.2.1. Scenario 1: sharing of marine transportation for offshore monitoring activities

Sharing trips for monitoring purposes of the OWF and OMF did not result in a notable reduction in the net impact of the MUOF (AoP HH: 1.7%; AoP EQ: 1.6%; AoP NR: 1.0%) (Table S49 in SM). However, looking only at the impact of the O&M stage, a reduction of 3.9%, 4.5% and 3.0% for the AoPs HH, EQ and NR (Fig. 6), respectively, is obtained. According to these results, the joint trips show mainly a positive effect on the AoP EQ, particularly the impact categories terrestrial ozone formation and terrestrial acidification, as those are especially influenced by combustion of diesel.

3.2.2. Scenario 2: sharing of marine transportation at the EoL phase

As in Scenario 1, sharing of trips during the offshore decommissioning of the MUOF had a minimal reduction on its overall net impact (i.e. less than 1% for all AoPs) (Table S49 in SM). When zooming in on the impact of transporting dismantled components to shore, a reduction appears by approximately 28% for the AoPs HH and EQ, and, in average, 19% for the AoP NR (Fig. 6). The sensitivity analysis for a 20–50% increase in fuel consumption due to additional loads showed no significant changes in the AoPs HH and EQ where the 20% fuel scenario decreased the impact with 0.4% compared to the 50% fuel scenario, but 8% benefit was obtained in the AoP NR for the 20% fuel scenario. The impacts of transporting dismantled components to shore on the three AoPs mainly come from the combustion of diesel in vessels, whose reduction provide benefits to all impact categories (Tables S53, S54, S55 in SM).

3.3. Benchmark

As mentioned in Section 2.3, the system boundaries for the benchmark analysis are cradle-to-gate. The findings indicate that the MUOF's impacts primarily stem from its manufacturing and infrastructure, while this is not the case for the benchmark where the operational activities are the major contributors to their overall burdens. At a AoP level, the MUOF had the largest impact on the AoPs HH and NR, while the nuclear power plant and pork meat production have a slightly higher impact on the AoP EQ than the MUOF (Fig. 7). Within the AoP HH, the impact categories global warming and fine particulate matter formation contributed the most to the burdens of both the MUOF and benchmarks (Fig. 7, Tables S59, S60 in SM). These burdens are mainly attributed to the supply chain of materials to manufacture the MUOF's components, and the energy requirements (i.e. combustion of diesel and electricity use) during the operation of a nuclear power plant and pig farm. It is also noticeable that the nuclear power plant and pork meat production have a considerable impact on the water consumption impact category due to the use of decarbonized water to cool down the nuclear power plants and also the use of water to produce maize feed for pigs (De Luca Peña et al., 2024) (Tables S59 and S60 in SM). For the AoP EQ, the most affected impact categories by the MUOF where global warming and terrestrial acidification, which again are associated to the supply chain of materials to manufacture the components of the MUOF. On the other hand, the nuclear power plant and pork meat production contributed the most to the burdens on land use followed by water consumption (Fig. 7). Over 90% of the land use impacts are attributed to pork meat mainly coming from animal feed production (i.e. soft wheat, maize rapeseed, winter forage barley) (Table S60 in SM). Meanwhile, over 96% of the impacts on water consumption occur due to the use of decarbonized water to cool down the nuclear plant (Table S60 in SM). Finally, for the AoP NR, both the MUOF and benchmarks had a remarkable high impact on the fossil resource scarcity impact category (i.e. over 80% of the impacts on the AoP NR) (Table S59 in SM) due to the production of diesel, petroleum, natural gas, ethylene, polyethylene, which are needed during the manufacturing of components, e.g. SPAR buoys or steel for foundations, or during the operational stage of the MUOF and benchmarks, e.g. energy requirements, such as the combustion of diesel, during operation activities in the nuclear power plant and pig farm.

3.4. Uncertainty analysis

The Monte Carlo analysis shows that the impact categories with the highest SD within the AoP HH were water consumption, human carcinogenic toxicity and human non-carcinogenic toxicity for both the OWF and OMF, but the impact categories global warming and fine particulate matter formation also had a high SD particularly for the OMF. For the AoP EQ, water consumption (terrestrial) was again the impact category with the highest uncertainty for both the OWF and OMF, while for the AoP NR, most of the uncertainty is attributed to the fossil resource scarcity impact category (Tables S47 and S48 in SM). For the scenario analysis, the contributing impact categories remained the same as the base case (Tables S56, S57 and S58 in SM). In the benchmark analysis (excluding the EoL phase), the highest uncertainty of the OWF and OMF is attributed to the same impact categories as explained before, but this contribution changed slightly for nuclear energy and pork meat production. For the AoP HH, human non-carcinogenic toxicity contributes the most to the uncertainty for nuclear energy and pork meat production, but there are other impact categories having a relatively high uncertainty such as water consumption and ionizing radiation for nuclear energy and global warming for pork meat. For the AoP EQ, water consumption contributes the most to the uncertainty of the nuclear power plant, but this is different for pork meat, where land use is the largest contributor. As with the MUOF, the uncertainty of the AoP NR comes

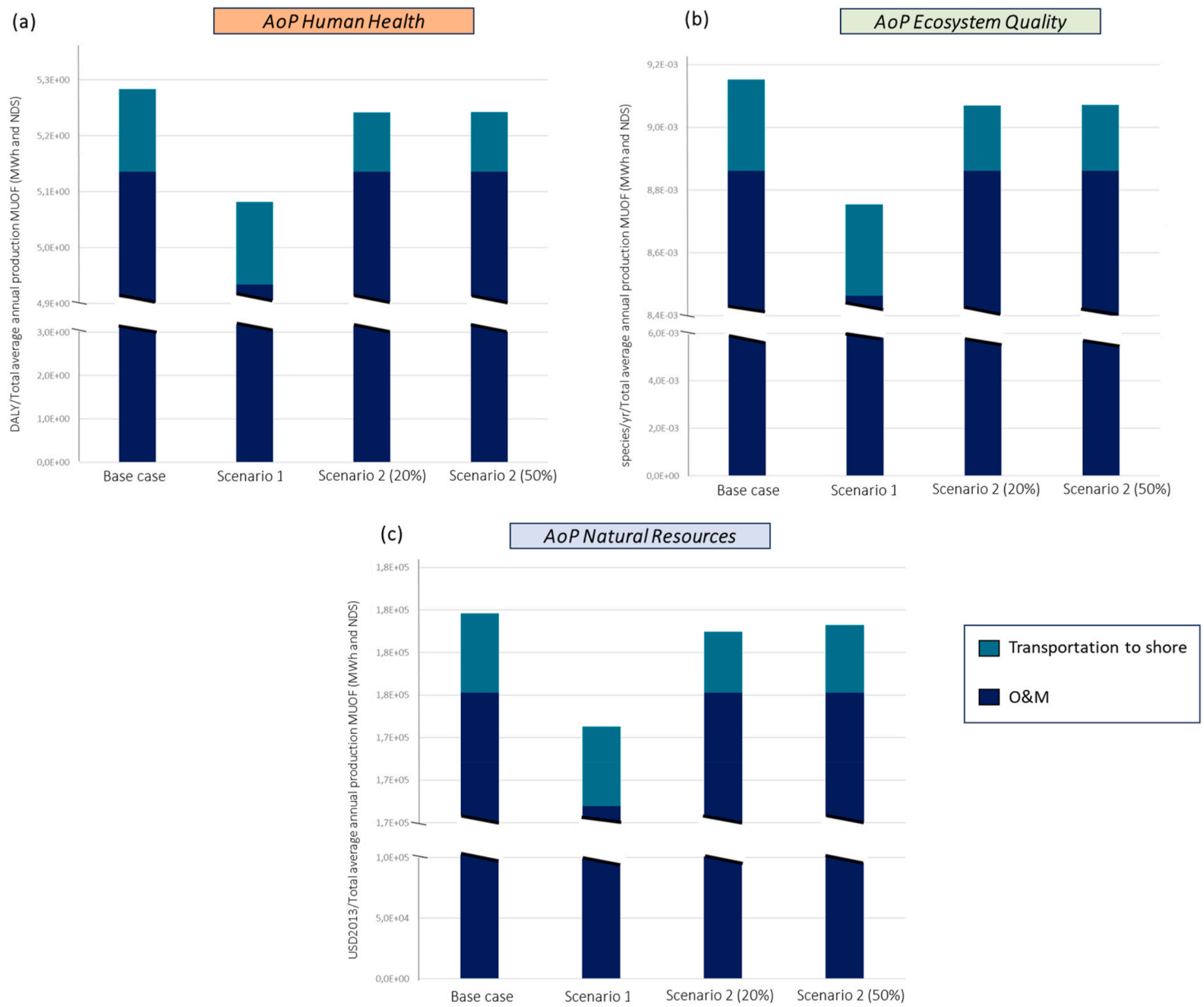

Fig. 6. Burdens of the O&M and transportation to shore (after dismantling) stages of a MUOF under different scenarios. These scenarios are (1) base case: no sharing of offshore monitoring and EoL activities, (2) scenario 1: sharing of offshore monitoring activities, (3) scenario 2 (20%): sharing of marine transportation at the EoL phase with 20% more fuel consumption due to additional load, (4) scenario 2 (50%): sharing of marine transportation at the EoL phase with 50% more fuel consumption due to additional load. The scenario results are presented for the (a) AoP human health, (b) AoP ecosystem quality and (c) AoP natural resources. The axis has been split to have a better visualization of the impact reduction.

mainly from the fossil resource scarcity (Tables S61, S62, S63, and S64 in SM).

4. Discussion

4.1. Comparison with similar LCA studies

LCA studies on the multi-use of marine space are relatively scarce, particularly those that integrate mussel farming with wind energy (see Section 1). The LCA study by Söderqvist et al. (2017) examined the combination of mussel and seaweed farming with wind energy in the Dutch part of the North Sea. However, there are differences in the scope and environmental impacts considered in comparison to our study. For instance, Söderqvist et al. (2017) focused solely on one impact category, namely Global Warming Potential, and assessed the impacts of an OWF and OMF individually rather than as a basket of products. Consequently, these differences in scope hinder a fair quantitative comparative analysis. Additionally, Söderqvist et al. (2017) did not specify which processes or components contributed the most to the assessed impact category, further complicating direct comparisons.

Looking at LCA studies on OMFs in the scientific literature, most studies focus on different farming systems (e.g. rafts, longlines, bouchot) which are mainly suitable at locations allowing nearshore mussel cultivation and thus considering also different marine conditions from the offshore environment at the BCS (e.g., Winther et al., 2009; Iribarren, 2010; Fry et al., 2012; Aubin et al., 2018; Tamburini et al., 2020; Caruso et al., 2022; Tamburini et al., 2022; Thomas et al., 2022). The system boundaries of these studies are mainly cradle-to-gate using the amount of mussels harvested (and packaged) as FU which differs from this study. A variety of LCIA methods have been used, but generally the trend shows that fuel and electricity consumption (e.g. marine vessels in the O&M stage) and the manufacturing of components (e.g. ropes, buoys and components with steel such as shackles) are the main contributors for the environmental impacts of an OMF. While the latter is consistent with this study, there are some differences, e.g., the material supply chain especially for the production of Danforth anchors is the largest contributor to the net impacts of the OMF, which can be explained by the system design established for offshore conditions (i.e. heavier/stronger system components are required), and the impacts from the O&M stage are mainly attributed to the replacement of components, which can be explained by the harsh conditions of the offshore marine environment. In comparison with the OMF, more LCA studies are performed on OWFs in the state-of-the-art, assessing the environmental impact of wind turbines with different characteristics (i.e. technologies, nr. turbines, etc.).

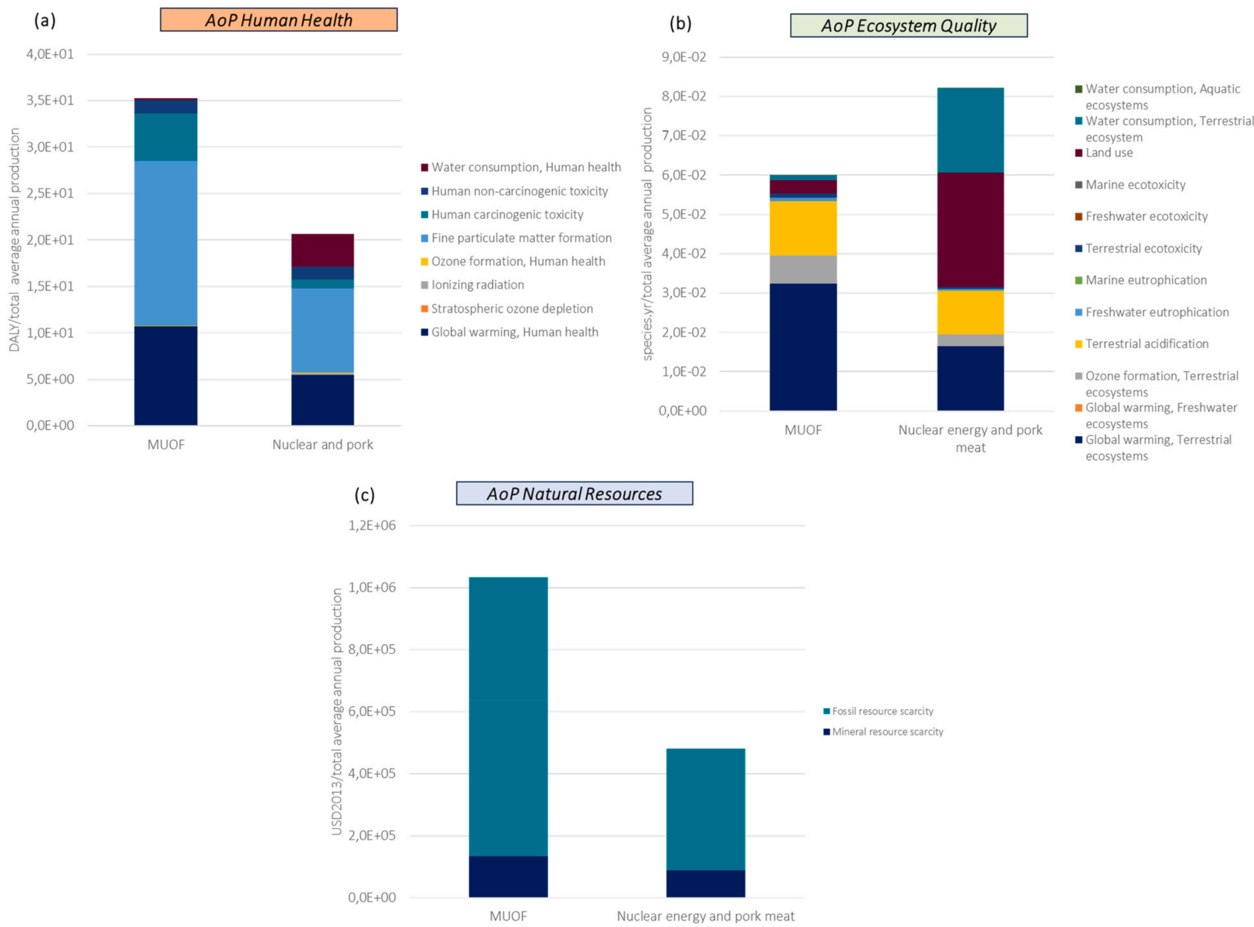

Fig. 7. Quantification of the burdens of an MUOF and a relevant benchmark for Belgium, i.e. nuclear energy production and pork meat production. The system boundaries for the benchmark analysis are cradle-to-gate and the FU is the total average annual production. The benchmark analysis results are presented for the (a) AoP human health, (b) AoP ecosystem quality and (c) AoP natural resources.

Furthermore, the variety of LCIA methods used to quantify different types of environmental impacts, hampers a fair quantitative comparison with the results obtained in this study (Bonou et al., 2016; Chipindula et al., 2018; Huang et al., 2017; Kouloumpis and Azapagic, 2022; Poujol et al., 2020; Raadal et al., 2014; Reimers et al., 2014; Tsai et al., 2016). These studies have used cradle-to-grave system boundaries, with some even accounting for the benefits of recycling, similar to this study (Huang et al., 2017; Chipindula et al., 2018). When qualitatively comparing the results of these studies with this work, it became clear that the supply chain up to the manufacturing of the OWF components has the highest contribution to the net environmental impact, usually followed by the O&M stage. This is mainly due to the need for significant amounts of raw materials, particularly metals such as iron for steel production, which is the main material used to construct wind turbines and foundations. Regarding impact categories, these studies have determined that climate change, respiratory organics (e.g., particulate matter), and fossil fuels are the most impacted, aligning with findings from this work (Bonou et al., 2016; Huang et al., 2017; Poujol et al., 2020; Kouloumpis and Azapagic, 2022).

A meta-analysis is required to make a fair quantitative comparison of the results of this work with other LCA studies on MUOFs, or single-use OMFs and OWFs. This approach would not only synthesize data from different studies through statistical methods but also provide a transparent analysis of the key contributors to the environmental impacts (Wolf et al., 2016). Future research should include such an assessment to better understand the quantitative differences in the results.

4.2. Challenges and perspectives

4.2.1. Data availability and accessibility of the MUOF

While the data for the OWF's foreground system are based on mainly primary data, gaps of which are filled in with literature data or mass and energy balances, the OMF's LCI is based mainly on secondary data (scientific literature including pilot projects) and expert interviews. Since the design and value chain were modelled, it was challenging to construct a dataset representative of a full scale OMF in the BCS. The lack of primary data of a full-scale OMF can compromise the reliability of the results. Obtaining accurate data on, for example, direct emissions, resource use, value chain processes and other factors is crucial for a realistic model. Although this article checks the robustness of the results through uncertainty analysis (Section 3.4), it would be useful to obtain data from a real MUOF (Section 4.2.8) or from more advanced modelling using engineering techniques to design the MUOF especially considering the offshore harsh conditions, which would be more time- and data-intensive (Section 2.2.1 in SM).

4.2.2. NDS as part of the FU

This study followed the recommendations provided by McLaren et al. (2021) on the use of NDS as a FU for food-related items. Although the NDS can better express food functionality than e.g. protein content or calories, there is no consensus on which is the most appropriate method to calculate the NDS and currently depends on the scope of the case study and the practitioner's judgement (Hallström et al., 2018; McLaren et al., 2021). The scores obtained using different methodologies can vary greatly in complexity, as the number of nutrients considered may differ, energy content considered, weights applied, or capping of nutrients applied (Hallström et al., 2018; McLaren et al., 2021). The method used in this study is a common way in calculating NDSs and allows for the comparison of similar food groups (i.e. protein), but it also has drawbacks because it does not take into account the water content, serving size and protein quality of the foods, and subtracting one unit of a disqualifying nutrient or adding one unit of a qualitative nutrient does not necessarily mean that the nutritional value of the food is reduced or increased, respectively (Hallström et al., 2018; McAuliffe et al., 2023; McLaren et al., 2021). In this study, the NDS method chosen, based on McLaren et al. (2021), was considered to best fit the objectives and scope of the paper. It could be interesting to investigate the effect of other NDS methods on the final LCA results.

4.2.3. Scenario analysis

Although the design and value chain of the OMF is based on literature, pilot-scale experiments and discussions with experts in the field, the proposed scenarios for joint transportation at different process stages are worth exploring since multi-use of space, especially offshore in the BCS, is strongly encouraged by the Belgian government (FDS, 2020). The scenarios were developed with the support of (inter)national experts who answered surveys with open-ended questions developed by the co-authors. Scenario 1 (sharing transportation during the O&M phase) may be challenging to actually arrange because it requires highly trained personnel (with experience in both monitoring OMF and OWF activities), optimal time management and management of vessel space, and when there are different owners of the two activities, it may hinder smooth and efficient coordination (Personal communication with OWFs and OMFs experts, 2023). As for scenario 2 (transport sharing during the EoL phase), experts believe that the decommissioning of both the OMF and OWF could offer opportunities for joint actions. The scenario developed for this study could potentially work for the older generation of OWFs (where turbines are not that high). The components of newer OWFs will take up the whole jack-up or service vessel (optimization of deck space to make it economically feasible), lacking space to carry parts of the OMF (Personal communication with OWFs and OMFs experts, 2023). Nevertheless, in future research, it would be worth exploring other decommissioning scenarios that are deemed relevant by multiple experts. As this study is a prospective analysis, and gives a first rough indication about a potential reduction in net environmental impact, it is worth to analyze the potential synergies along the value chains of both activities based on primary data, once a full scale MUOF is installed under real-life conditions.

4.2.4. Selection and modelling of benchmarks

In this study the loin (i.e. one pork cut) was selected for benchmarking because, similar to mussels, it is rich in proteins, this piece of pork in particular is highly produced and consumed in Flanders (Personal communication with food expert, 2023), next to other pieces of meat that are highly valued in this market, such as the belly part (bacon) and the ham (Personal communication with food expert, 2023). A similar methodology was followed to select the benchmark for energy production, i.e. the most produced and consumed type in Flanders is nuclear energy. Life cycle inventory data for both pork-meat and nuclear energy was taken from databases such as ecoinvent and agribalyse, but data on the EoL phase was lacking, hindering a full analysis at cradle-to-grave boundaries with the MUOF. Furthermore, it wasn't possible to use Belgian data for pork meat production as agribalyse only provides French data. This study took into account the point of view of policy makers and investors when selecting benchmarks, but other points of view could also be interesting to explore, such as the current electricity mix, plant-based proteins or aquaculture products such as fish, or generalized food mixes of Flanders, although the latter is not readily available in LCI databases. The selection of benchmarks for LCA studies often relies on subjective judgement, a viewpoint taken (Gül et al., 2015), and is therefore a complex process that involves balancing scientific rigor with practical considerations and stakeholder perspectives. To mitigate subjectivity, transparency in the selection process and rationale for benchmark choices is crucial.

4.2.5. Uncertainty analysis

Reporting uncertainty is becoming important in LCA studies as it provides valuable information for stakeholders and decision-makers (Michiels and Geeraerd, 2020). This study used a procedural estimation (i.e. Pedigree matrix) to determine the probability distributions of the LCI inputs (i.e. foreground data) and then conducted Monte-Carlo simulations to estimate the probability distributions of the results. While this method can provide a good overview of the uncertainty in the model, there are some challenges. First of all, the Monte-Carlo method can be computationally expensive, especially when the number of simulations are increased. Secondly, the study of Heijungs (2020) found that combining the Pedigree matrix approach and the Monte-Carlo method, which is often done in LCA studies including this one, is actually incompatible due to a lack of accuracy and precision in the parameters of the input distribution (i.e. LCI inputs) (Heijungs, 2020). Heijungs (2020) does not recommend a way to address this problem and emphasizes that more research is needed on uncertainty in LCA.

Distinguishing between different sources of uncertainty is an important aspect to consider in future research. This study only considered the parameter uncertainty of foreground and background LCI data, but it would be good to include other sources and distinguish between them (e.g. AzariJafari et al. (2018)) to have a more comprehensive overview of the uncertainty in a MUOF model. Furthermore, uncertainty arises from both foreground parameters (e.g., collected LCI data) and background systems (e.g., data from databases) (Kim et al., 2022). It is crucial to identify which parameters contribute most to the overall uncertainty. Most attention has been given to the foreground system, while the background is often overlooked (Kim et al., 2022). LCA modelling software such as SimaPro cannot clearly distinguish which parameters (from the background or foreground data) contribute most to the uncertainty on the results. Therefore, future work should focus on enhancing this aspect, including conducting a global sensitivity analysis on different parameters from both the background and foreground systems for a more comprehensive uncertainty analysis (Kim et al., 2022). This analysis might require the support of other software such as Python, R, and Oracle Crystal Ball (Michiels and Geeraerd, 2020; Kim et al., 2022).

Moreover, it is important to note that when performing a Monte Carlo analysis for the MUOF and benchmarks, most of the parameters derived from both the foreground and background data had an assigned lognormal distribution. However, this was not the case for the pork production process, whose parameters (i.e. background data) had mostly an undefined distribution potentially affecting the accuracy of the analysis. In a future study, the latter should be taken into account to make a data quality assessment of the background processes used in the analysis.

4.2.6. Life cycle impact assessment

While this paper focusses on regional to global environmental impacts such as eutrophication, human toxicity and climate change caused due to the value chain of the MUOF, assessed through the LCA method ReCiPe 2016 V1.05 (H), it doesn't include local impacts such as changes to the local marine environment, e.g. changes to the epibenthic marine biodiversity, or water quality, or the local terrestrial environment for that matter (cfr. Taelman et al., 2023). These effects can be quantified through ecosystem services assessment, as shown in few papers for case studies on offshore wind energy (De Luca Peña et al., 2024; Li et al., 2023; Ter Hofstede et al., 2022). Thus, a next step should be to quantify the environmental impacts more holistically, to aggregate local and global environmental burdens and benefits of a MUOF. However, this requires a lot of other data, and because monitoring is not possible when there is no installed and fully operational MUOF in the BCS, data collection is challenging (Sections 4.2.1 and 4.2.8). Joint activities create especially in very busy marine areas such as the Belgian Continental Shelf a large advantage as it saves space for other activities to thrive. However, LCA is a tool that focusses on analyzing the potential environmental impact of products, and doesn't evaluate this benefit obtained, partially also because spatial differentiation (especially in the marine environment) is still under development. Ecosystem based approaches such as the SCAIRM method (Piet et al., 2023) may be a way forward to better address this particular positive effect of multi-use. Furthermore, it would be interesting to quantify the cumulative effect of global challenges such as ocean acidification and global warming on, and its interaction with, marine activities in LCA, both for current and predicted future-climate conditions (as e.g. elaborated by Voet et al., 2023 on carbon assimilation as well as an organic enrichment of underlying sediments). Moreover, the social and economic pillar of sustainability is not addressed in this paper and results of such an assessment would provide a better understanding of all potential sustainability issues of an MUOF (avoiding any trade-offs).

4.2.7. Transferability

LCA is a standardized methodology by ISO (2006), having the ability to apply the principles, methods, and tools of LCA across different contexts, products, processes, and regions, thus harmonizing the approach to assess the environmental sustainability of MUOFs. However, this requires collecting data to build inventories specific to the goal and scope being assessed. If next to the regional/global impacts addressed with LCA also local environmental impacts need to be evaluated, site-specific data and indicators (e.g., ecological data, relevant ecosystem services) must be gathered to reflect the local context, which may differ largely from the BCS region considered in this work. For local environmental impact assessment, there is a lack of standardization which hampers its transferability. Additionally, it is important to note that there are currently no operational large-scale MUOFs outside the BCS—only pilot projects exist. Consequently, reproducing this prospective analysis in other regions may face similar challenges, such as a lack of available data (Section 4.2.1).

4.2.8. Development of a real MUOF

Although many policies support marine multi-use, it still seems difficult to establish a MUOF. Factors preventing this development can be costs (need for highly trained staff, lots of transportation to offshore sites for mussel farming, lower yields of mussels than nearshore because of offshore lower nutrient density conditions), long and difficult permitting processes, the uncertainty surrounding ownership and responsibility (wind farm operators have exclusive rights to the space between wind turbines but the Belgian government retains the right to lease out the area between turbines to multi-users), lack of data to feed a prospective environmental analysis, taking into account carrying capacity as an important factor when scaling the OMF (Paulson, 2022). Even if a MUOF is established, it will remain a challenge because proper coordination between different sectors is needed to optimize the use of limited marine space while minimizing conflicts and environmental impacts. The latter involves engaging different stakeholders, sharing of data and knowledge, establish adaptive management strategies that can be adjusted based on evolving conditions and new information, conduct monitoring of environmental parameters and assessment of ecological risks, sharing of equipment and staff, etc.

5. Conclusions

A detailed LCA study on an innovative MUOF in the BCS, combining an existing OWF with a designed full-scale OMF, was conducted to determine its potential environmental performance. Results indicate that the OMF activity contributes the most to the net environmental impacts of a MUOF (see Section 3.1).

At an impact category level, global warming, fine particulate matter formation, terrestrial acidification, ozone formation and fossil resources scarcity contribute to the MUOF's overall burdens. These burdens primarily arise from processes related to the supply of primary and secondary materials to manufacture the MUOF's components (e.g. OWF: wind turbines and foundations; OMF: Danforth anchors, gravity anchors, mooring chains, SPAR buoys) and the combustion of fuel during the MUOF's operation. These findings indicate that especially efforts are needed at both the manufacturing and O&M stage to optimize the environmental performance of the MUOF.

The scenario results did not show a significant reduction on the overall net impacts of MUOF, but these benefits were more visible at the process stage level, i.e. benefits were clear at the O&M and dismantling stages of a MUOF (see Section 3.2) stemming from less combustion of fuel. Furthermore, the benchmark results indicate that the MUOF has higher burdens on the AoPs HH and NR in comparison to the terrestrial benchmarks. This is primarily due to the supply chain of materials needed for manufacturing its components. Meanwhile, the AoP EQ was affected the most by the benchmarks due to water and land use requirements for cooling the nuclear power plant's reactors and the production of animal feed, respectively. The Monte Carlo analysis indicates a high uncertainty in some of the impact categories, particularly within the AoP HH, e.g. water consumption, human carcinogenic toxicity, human non-carcinogenic toxicity, global warming and fine particulate matter.

This article seeks to guide sustainable blue growth by analyzing the potential environmental impacts of multiple uses of the sea from a life-cycle perspective, to strengthen the science-policy interfaces in marine and maritime-related fields and contribute to accelerating impact-oriented research and development in the blue economy.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used ChatGTP in order to erase spelling mistakes and improve the English writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Laura Vittoria De Luca Peña: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bilge Bas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jo Dewulf:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sander W.K. van den Burg:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Sue Ellen Taelman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143271.

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