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Life cycle assessment of floating offshore wind farms: an evaluation of operation and maintenance

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Abstract

One of the key objectives for renewable energy technologies is to reduce the environmental impact of energy generation. Floating offshore wind technologies have been developed in recent years to exploit the wind energy resource available at deep waters where bottom-fixed technologies are not economical. However, few studies exist that analyse the environmental impact of such technologies. Particularly, offshore activities such as those required for Operation and Maintenance (O&M) are not represented in detail in previous studies. The present study addresses these gaps by performing a Life Cycle Assessment using an advanced O&M model to quantify the environmental impact of a floating offshore wind farm. Different O&M philosophies - assuming towing to shore for major operations vs. performing all operations on site - and their impact are evaluated and discussed for two case studies inspired by real pilot park deployments. The results show mean Global Warming Potential (GWP) values between 25.6 and 45.2 gCO_2 eq/kWh depending on the assumed O&M strategy and vessels, with the contribution of the OM phase to GWP ranging from 21 to 49%, and of OM vessels from 6 to 40%. Assuming O&M strategies to be the same for fixed and floating offshore wind could result in a 20.4% underestimate of GWP, whereas the vessel choice resulted in up to 34.8% difference in the estimated GWP. An environmental impact perspective provides key insights on the choice of different designs, operation strategies and asset management, and thus should be used in the decision-making process.

Keywords: Life cycle assessment, Environmental impact, Offshore wind, O&M, Vessels

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Nomenclature	Definition	Units
AHTS	Anchor Handling Tug Supply vessel	NA
BFOW	Bottom-Fixed Offshore Wind	NA
CLV	Cable Laying Vessel	NA
CTV	Crew Transfer Vessel	NA
DP	Dynamic Positioning	NA
FLV	Field Support Vessel	NA
FOW	Floating Offshore Wind	NA
GWP	Global Warming Potential	gCO_2 eq/kWh
HLV	Heavy Lift Vessel	NA
JUB	Jack-Up Barge	NA
LCA	Life Cycle Assessment	NA
LCOE	Levelised Cost Of Energy	€/MWh
O&M	Operation and Maintenance	NA
PSV	Platform Supply Vesse	NA
RIB	Rigid Inflatable Boat	NA
ROV	Remotely Operated Vehicle	NA

1. Introduction

Floating technologies are being developed due to the large potential for offshore wind energy generation in deep-water sites that can not be exploited through existing bottom-fixed technologies. These novel floating offshore wind technologies have been extensively analysed and discussed from a techno-economic perspective [1]. However, only a few studies exist that aim at assessing their environmental impact [2, 3, 4, 5, 6, 7] . Simultaneously, one of the main motivations for the development of renewable energy technologies is that they are expected to have a significantly lower environmental impact than fossil fuel-based energy generating technologies and, therefore, can contribute to reduce anthropogenic greenhouse gas emissions. A common method used to quantify the environmental impact of technologies is the Life Cycle Assessment (LCA) method. This type of assessment accounts for all the stages involved in the life of a project, from extraction of the raw materials, manufacture, installation, maintenance, and decommissioning of the devices.

The environmental impact of offshore wind farms using the LCA method has been extensively studied for Bottom-Fixed Offshore Wind (BFOW) technologies such as in [8, 9, 10, 11] and also, to a lesser extent, for Floating Offshore Wind (FOW) technologies, where a reduced numbers of studies are available to the authors' knowledge, such as [2, 5, 7]. The main limitations found in the literature are: (1) in the considered turbine ratings generally up to 5MW that do not represent current development trends and (2) in the representation of offshore activities, such as O&M operations, due to lack of available information and detailed modelling. A more detailed discussion of the assumptions used in previous studies is provided in section 2.

To address these gaps, the present study performs an LCA of floating offshore wind farms considering the required O&M operations with the help of a detailed O&M model - representing unplanned maintenance events based on failure rates, using site specific metocean conditions to calculate weather windows and considering vessel characteristics to calculate fuel consumption. The effects of the assumed O&M strategies and vessel selection on the environmental impacts are discussed. This analysis is performed based on two existing pilot parks off the east coast of Scotland, where turbines with rated power of 6 and 9.5MW have been deployed. In order to do so, publicly available data on the used components, materials, weights, supply chains, installation processes, and vessel selection were gathered, and completed with realistic estimations based either on previous studies or experts elicitation. The results of this study offer a detailed representation of the environmental impacts associated with floating offshore wind farms and highlight the importance of accounting for O&M operations. This analysis supports the identification of hotspots - components or processes resulting in larger environmental impacts within the system - to guide and support the development of improved floating offshore wind system designs with lower environmental impacts.

The paper is structured as follows. Further background on previous studies is provided in section 2. The method used to perform the LCA study is introduced in section 3. The results are presented in section 4 and then discussed in section 5. Finally, conclusions are drawn in section 6.

2. Background

In this section, an overview of the context in which the paper is set is provided. This includes some background on the floating offshore wind sector, the state-of-the-art in LCA applied to both bottom-fixed and floating offshore wind, and the representation of marine operations in previous studies. This context supports the comparison of the results to previous studies and highlights the novelty of the methods used in this study.

2.1. Floating offshore wind

The offshore wind sector has experienced a significant growth in recent years with an increase of offshore wind capacity by around 30% per year since 2010 [12]. Additionally, the size of the largest available wind turbines has been increasing from 3 MW in 2010 to 8 MW in 2016 [12], with expected ratings of up 15-20 MW by 2030 [12]. Capacity factors have also increased from 38 to 43% from 2010 to 2018 [12] and are expected to reach 55% by 2030 [13].

Although most of the deployed technologies are bottom-fixed through monopiles or jackets, floating offshore wind technologies are being developed that have the potential to unlock resource areas at water depths larger than 50-60 m at which bottom-fixed foundations are not economical. This also offers the opportunity for deployments further offshore where higher and more constant wind speeds can be found, and less social conflicts (e.g. visual impact of the turbine or competition for the use of sea areas) exist. Pre-commercial and small commercial deployments already exist, for example, in Japan, France and Portugal [14]. Two pilot parks have been deployed off the east coast of Scotland to date (see Figure 1), which are used as inspiration for the two case studies considered here, due to the partial availability of publicly available data. The main characteristics of the pilot parks of Hywind and Kincardine are detailed in the following paragraphs.

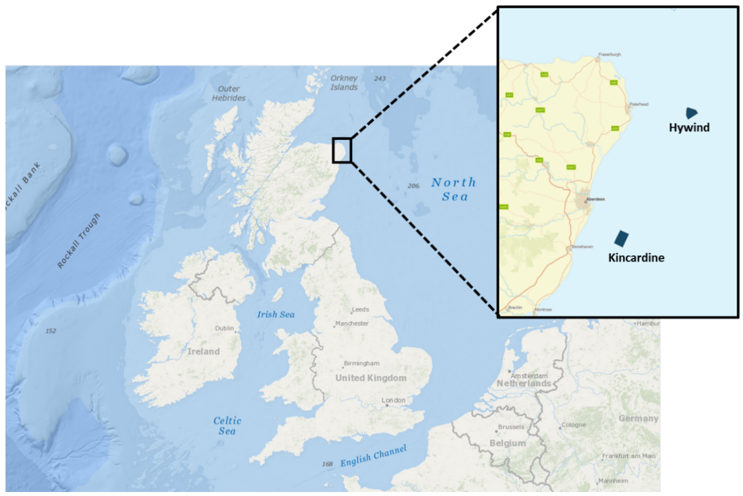


Figure 1: Location of Hywind Scotland and Kincardine floating wind pilot parks [15].

Hywind Scotland [16, 17, 18] is a demonstration project in operation from 2017, which consists of five 6 MW SWT-6.0-120 direct drive turbines combined with a spar-type foundation. It is located 25 km east of Peterhead at a water depth ranging from 95m to 129 m. The mooring system for each turbine is composed of three studless steel chains connected to suction bucket anchors.

Kincardine [19, 20] is a pilot park currently under development at the south-east of Aberdeen, Scotland. It consists of five v164-9.5 turbines of 9.5MW and one 2MW device. This is because the Kincardine pilot park was built in two phases, where in the first phase only one 2MW turbine was installed, and in a second phase five turbines of 9.5MW with other changes in system design were introduced. Due to the different devices used within the two phases, only Phase 2 is considered in this study to facilitate the analysis of the results. It is located at a distance of 15km from the coast, and at a water depth ranging from 60m to 80m. In this case, the floating platform is a semi-submersible type, held in place by four steel chain mooring lines, each of which is connected to a drag-embedment anchor.

2.2. Previous offshore wind LCA studies

Wind energy generation technologies and projects have been extensively studied from an environmental impact perspective. In a recent literature review by Mendecka et al. [21], up to 148 different wind LCA studies were reported, of which a total of 32 were for offshore technologies. However, only a total of 6 studies for floating offshore wind were identified by the authors to date.

For floating offshore wind, the first LCA study was performed by Weinzettel et al. [2], where a wind farm with 40 5MW turbines was studied. This was followed by a study by Raadal et al. [3] for a wind farm with 100 5MW turbines, based on the NREL 5MW reference turbine [22]. In that study, the focus was on the analysis of different foundation designs, and five different floating offshore wind concepts plus a bottom-fixed one were investigated. A study by Tsai et al. [5] investigated the suitability of different foundation types in combination with 3MW turbines for a deployment in the Great Lakes (USA) at different distances from shore and water depths with the help of LCA. Despite market trends projecting increasing turbine sizes, only three studies were found where turbines with capacities larger than 5MW were considered (see Figure 2a, reporting previously considered turbine ratings and farm sizes). These comprise (1) a study by Dragan et al. [4] as part of the LEANWIND project, where the LCA was performed on the foundations only and a number of foundations were considered for a 5 and an 8MW turbine; (2) a study by Bang et al. [6], where greenhouse gas emissions of a representative floating offshore wind project in California with 75 8MW turbines were analysed; and (3) a study by Poujol et al. [7], where four 6MW turbines to be deployed in the Mediterranean sea were used to calculate a number of environmental impact indicators. These studies have established the environmental impact analysis of floating offshore wind technologies and highlight the importance of including LCA in the design process of these technologies. These initial efforts have also led to the development of LCA-based decision making tools such as developed within the H2020 ENERGEO project [23, 24].

In summary, there are a number of limitations in floating offshore wind LCA studies to date. A reduced number of LCA studies of floating offshore wind technologies, compared to offshore bottom-fixed turbines, was identified by the authors. The rating of the turbines considered in these studies may not represent the market trends, with only few studies considering turbines larger than 5MW.

2.3. Representation of marine operations

Marine operations have been represented at different levels of detail in LCA studies. In studies where environmental impacts linked to the operational phase are considered, fuel consumption associated to the vessel use and/or the replaced parts are examined. The importance of correctly representing vessel operations in the environmental impact assessment of offshore wind farms was highlighted by Andersen et al. in [25]. However, the lack of operational experience and data on offshore wind farm operations, and the limitations of the databases used for LCA assessment such as Ecoinvent [26] has led many studies to simplify the representation of offshore operations. However, in the last version of this database the selection of vessels, for instance, and their associated impacts was significantly expanded. For these reasons, some previous LCA studies have assumed, for example, the same type of operation as for onshore wind turbines through road transport but with a higher frequency of occurrence for offshore cases, such as Rashedi et al. in [27] and Wang et al. in [10]. Others have focused on the consideration of spare part requirements, such as Bonou et al. [9]. Finally, some studies have assumed that most operations can be performed by helicopter, such as in [28, 10, 2], although some vessel requirements were considered in [28]. In some cases, the assumptions regarding representation of offshore operations are unfortunately not provided, perhaps due to data confidentiality [29, 3, 7].

Although no clear trend between O&M representation detail and environmental impact can be inferred from previous studies (see Figure 2b), in studies where the O&M was considered in more detail (where assumptions and required work vessels were reported) a significant contribution to the total Global Warming Potential (GWP)[1] was found. In cases where O&M vessels were not considered or O&M assumptions were not provided in detail a contribution of O&M of around 5% or less was observed, as shown in Figure 2b), whereas Andersen et al. [25] estimated a contribution of O&M of 28% to the GWP when considering vessels in more detail. No trends could be observed in terms of GWP values depending on farm size or turbine rating from these previous studies.

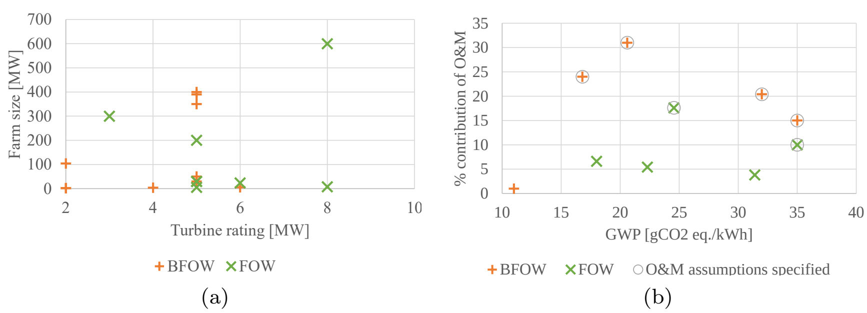


Figure 2: Summary of previously considered characteristics and obtained results in offshore wind LCA studies, including both bottom-fixed (BFOW) and floating (FOW) technologies. (a) Considered turbine rating and farm size, (b) Obtained Global Warming Potential (GWP) and percentage contribution of O&M to GWP. Data is based on LCA studies listed in Table 1.

On the contrary, some techno-economic studies exist that have used detailed O&M models to represent offshore operations and the required vessels and transit times in more detail. An example for this in bottom-fixed offshore wind is the work by Ioannou et al. [31] and for floating offshore wind the studies by

[1]GWP '*is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The usually used time period is 100 years.*' [30]. The GWP associated to an energy generating technology represents the equivalent weight of CO_2 that will generate the greenhouse gas emissions occurring throughout the life of the project. This equivalent weight is reported relative to the generated electricity, so that the relative GWP has units of gCO_2-eq/kWh.

Myhr et al. [32] and Rinaldi et al. [15]. Additionally, some specifications on the planned offshore activities and vessels can be found in the public documents of the studied floating offshore wind pilot parks, such as the Kincardine vessel management plan [33].

To provide further detail on how marine operations have been considered in previous studies, an extensive overview of the assumptions used in environmental impact assessment and techno-economic studies is provided in Tables 1 and 2, respectively. Within the techno-economic studies subcategory, both theoretical studies referred to as 'LCOE' studies and documents reviewing planned operations or referring to real wind farm operations are included. These are referred to by the corresponding wind farm name. For both types of studies, the considered vehicles for the different types of operations are summarised in these tables too. A number of different vessels are reported, amongst which Anchor Handling Tug Supply (AHTS) vessels, Cable Laying Vessels (CLVs), Crew Transfer Vessels (CTVs), Field Support Vessels (FSVs), Heavy Lift Vessels (HLVs), Jack-Up Barges (JUBs), Remotely Operated Vehicles (ROVs), Platform Supply Vessels (PSVs), and Rigid Inflatable Boats (RIBs). A difference in fuel consumption during standby and operation was reported by Reimers et al. [8], where 10% fuel consumption was assumed in standby and 100% was considered in transit mode. This proportion may vary extensively depending on the vessel typology, especially for those vessels equipped with dynamic positioning (DP) capabilities. From the literature summarised in Tables 1 and 2, a large range in vessel assumptions, number of operations per year, and how O&M is represented can be observed. In particular, it becomes evident that the approach used to represent O&M differs between LCA and LCOE studies, where in the latter more detailed models based on components failure rates are employed to quantify the costs associated to the operational lifetime. On the contrary, in LCA studies the number of maintenance activities and the vessels selection is mainly based on general assumptions, rather than on O&M models or components' failure rates.

Overall, the variability in the detail of the considered O&M operations, despite the identified importance of vessel operations in offshore wind LCA studies [25], points to the need for a more thorough study of the effect of O&M strategies from an environmental perspective. In the present study, a detailed O&M model will be used to consider the impact of different O&M strategies on the LCA results. To this end, the approaches encountered in literature and summarised above for marine operations representation and vessel selection are considered. Due to the project specific plans being the closest to real operational data for floating offshore wind, these have been taken as main reference for the assumptions on offshore operations. More details on these choices are provided in section 3.2.3.

3. Methods

The methodology used to perform the LCA study is presented in this section. The method aligns with the LCA principles and framework, as well as general re-

Table 1: Representation of marine operations in previous LCA offshore wind studies. Note that the number of interventions per year and turbine may be provided as an aggregated value of the different types of operations.

Reference	Technology	O&M considered as	Vehicles	# interventions /turbine/year
Birkeland [34]	BFOW	Replacement of heavy component	Vessel + jack-up	0.015
		Replacement of large part	Vessel + build up internal crane	0.109
		Replacement of small part	Vessel + permanent internal crane	0.356
		Replacement of man carried part or inspection	Vessel or helicopter	1.069
Wagner et al. [35]	BFOW	Operation	Helicopter	5
			Shipping services	7.5
		Replacement of 0.5 gear boxes and 1.25 rotor blades		0.05
Rashedi et al. [27]	BFOW	Additional visits and lubrication oil considered for offshore vs onshore	Car	8
Arvesen et al. [25]	BFOW	Replacement of large part	Vessel + Support vessel	0.075
		Replacement of small part	Support vessel	0.362
Reimers et al. [8][a]	BFOW	Planned	onshore/ Hotel ship + RIB / Mother ship + CTV	120h /60h/ 360h
		Unplanned	40% Helicopter + JUB, 60% CTV + JUB	6.27/3.14/12.5
Bonou et al. [9]	BFOW	Service parts	Not specified	Not specified
Huang et al. [28]	BFOW	Scheduled maintenance	1 x Vessel, 4x helicopter	5
		Replacement of 1 rotor blade and 1/3 nacelles	-	0.05
Piasecka et al. [29]	BFOW	Not specified	Not specified	Not specified
Wang et al. [10]	BFOW	Planned	Truck	3
			Helicopter	4h
		Replacement of rotor blade, gearbox, and generator	-	0.05
Weinzettel et al. [2]	FOW	Regular inspections	Helicopter	3
		Irregular inspections	Helicopter	1
		Onshore repair	Barge	1
Raadal et al. [3]	FOW	Towing for maintenance	Not specified	Not specified
Tsai et al. [5]	FOW	Preventative maintenance	Vessel	24 days
		Corrective maintenance as in [34]	[34]	1.55
Bang et al. [6]	FOW	Scheduled maintenance - turbine	Small boat + Helicopter	2.5
		Scheduled maintenance - cables	Specialised vessel + ROV	0.5
		Unscheduled maintenance	Specialised vessel + Crane vessel	3.75
Poujol et al. [7]	FOW	Not specified	CTV + Dynamic positioning vessel + tugboat + multicat	Not specified

[a]Different O&M scenarios are considered.

Table 2: Representation of marine operations in previous techno-economic offshore wind studies. Note that the number of interventions per year and turbine may be provided as an aggregated value of the different types of operations.

Reference	Technology	Type	O&M considered as	Vehicles	# interventions /turbine/year
Nilsson et al. [36]	BFOW	Vatenfall farm	Scheduled maintenance	Not specified	2
		Elsam farm	Scheduled maintenance	Not specified	2-4
			Unscheduled maintenance	Not specified	4-12
			Replacement of 36% gearboxes, 66% generators, 3.3% transformers and 10% blades	-	0.05
Dinwoodie et al. [37]	BFOW	LCOE	Manual reset	CTV	7.5
			Minor repair	CTV	3
			Medium repair	CTV	0.275
			Major repair	FSV	0.04
			Major replacement	HLV	0.08
			Annual service	CTV	1
Ioannou et al. [38]	BFOW	LCOE	Calendar-based maintenance	4 CTVs	1.2
			Condition-based maintenance	-	0
			Unplanned corrective maintenance	Helicopter, Jack-up vessel, Diving support vessel, CLV	6.862 [a]
Kolios et al. [39]	BFOW	LCOE	Calendar-based maintenance	Not specified	1
			Unplanned corrective maintenance	Not specified	Based on failure rates
Myhr et al. [32]	FOW	LCOE	Calendar-based maintenance	Mother vessel	1.43
			Condition-based	CLVs or AHTS vessels for cable maintenance, PSVs for component and helicopters for special transport	0.04
			Unplanned corrective	CLVs or AHTS vessels for cable maintenance, PSVs for component and helicopters for special transport	1.2
OWIH [40]	FOW	LCOE	Towing	1 large tugboat + 1 small tubgboat + 1 AHTS	-
			Offsite operation	Crawler	-
			On site operation	HLV/CTV	-
KOWL [33]	FOW	Kincardine farm	Operation	Vessel	13
			Towing	2 tugs 30-40t BP or 1 AHTS or tug > 100t BP	-

[a] Based on sum of failure rates for minor repairs

quirements and guidelines, which are compiled within ISO standards 14040 [41] and 14044 [42], as well as in the Product Life Cycle Accounting and Reporting Standard [43] used, for example, in previous studies for the comparison of different materials [44]. This study is performed as a conventional process-based LCA, which is the recommended method for calculating carbon footprints and embodied energy [45]. For this purpose, the SimaPro 9.1 software [46] is employed with background data sourced from the Ecoinvent database v3.6 [26]. The main stages of an LCA as defined by the existing guidelines and standards include: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation. These four stages are described in detail in the following subsections.

3.1. Goal and scope

The goal of this study is to perform a lifecycle assessment of two floating offshore wind farms, taking into account all lifecycle stages. The main focus is to provide a detailed LCA of floating offshore wind farms, enabling the comparison of the impact of different operation and maintenance strategies on the overall results. Two floating offshore wind farms, inspired by existing pilot parks, are used as case studies for which the environmental impacts are assessed. In this regard, the goal is not to compare the environmental impact of the two farms. That is, because only publicly available data and engineering assessment were used for the inventory analysis, and so results presented here approximate the components and processes used in reality. This study is, therefore, addressed to researchers, technology developers and project planners to provide insights into the potential environmental impact hotpots associated to floating offshore wind farms and gain an additional perspective on the choice of component designs and maintenance strategies other than the usually used techno-economic perspective.

The scope of this study is a cradle to grave LCA of two case studies inspired by existing and under construction floating offshore wind pilot parks located off the east coast of Scotland. The first case study ('Spar') is inspired by the Hywind deployment and the second ('Semi-sub') by the Kincardine deployment introduced in section 2.1. An overview of the assumed and estimated characteristics of the two case studies is provided in Table 3. A schematic of floating wind turbines with a spar and semi-submersible substructure is shown in Figure 3.

3.1.1. System boundaries

As previously indicated, an LCA considers a number of life cycle stages from the raw material extraction, to component manufacturing, installation, maintenance and decommissioning activities. A simplified overview of the considered processes following a *cradle to grave* system boundary can be seen in Figure 4. Focus is given to the offshore infrastructure and logistics, hence the grid connection through an onshore substation was not considered. Note that in the two case studies, as well as in the existing pilot parks which inspired them, no offshore substation is used.

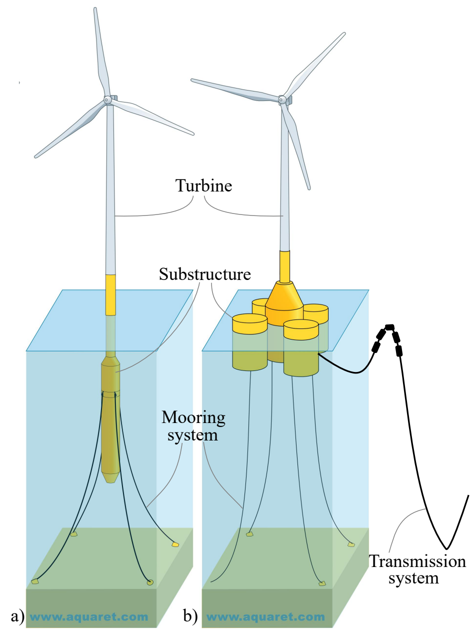


Figure 3: Schematic of floating offshore wind turbines with different platforms: a) a spar, and b) a semi-submersible. Adapted from [47], reproduced with permission from aquaret.com © Aqua-RET Project (EU Lifelong Learning Programme Agreement no LLP/LdV/TOI/2009/IRL – 515).

3.1.2. Functional unit

The functional unit that has been chosen to facilitate comparability with other LCA results is 1 kWh net of electricity produced from the wind farm and delivered to the grid. Thus environmental impacts are provided per kWh, where electrical losses and availability due to downtime are accounted for in the calculation of the electricity production over the lifetime of the projects.

3.2. Inventory analysis

The foreground data represent the technological system to be analysed. In this case, these data involve the components of the floating offshore wind farm and their weights and manufacturing processes, but also details on the materials, assets and processes required for installation, maintenance and decommissioning. The equivalent materials and processes and their associated gross embodied carbon and energy are obtained from the Ecoinvent v3.6 [26] database. This is a commercial life-cycle inventory database that is regularly updated and has been widely used in previous LCA studies. The detailed inventory is provided in the supplementary material.

Table 3: Overview of the assumed and estimated characteristics of the two case studies inspired by existing pilot parks.

Characteristic	**Spar case study**	**Semi-sub case study**	**Source**
Water depth [m]	95-129	60-80	[16, 19]
Distance to shore [km]	25	15	[14]
Turbine rating [MW]	6	9.5	[14]
Number of turbines	5	5	[14]
Turbine model	SWT-6.0-120	v164-9.5	[48, 19]
Substructure	Spar	Semi-submersible	[16, 49]
Installation port	Peterhead	Dundee	[50, 51]
O&M port	Peterhead	Aberdeen	[52, 33]
Lifetime [years]	25	25	[19]

3.2.1. Materials and Manufacturing

Wind turbine

Detailed information on the weights and materials of the specific wind turbines used in the pilot parks was not available from the suppliers and previous studies had only considered smaller turbines of up to 5MW. In previous studies where larger turbines had been considered, Dragan et al. [4] focus on the floating foundation and do not require a turbine inventory; Bang et al. [6] apply regression based on a number of smaller turbines; and Poujol et al. report on a commercial technology, and do not provide the inventory assumptions. For this reason, the 6MW [53, 54] and 9.5MW [55, 56, 57] turbines were modelled adjusting the information publicly available about these turbines (the overall tower and nacelle weights for the former, and the nacelle and blade weights for the latter). The missing materials and weight distribution were then assumed to align with NREL's 15MW offshore reference turbine [58] (see supplementary material for further details). To determine the blade weight for the 6MW turbine and the tower weight for the 9.5 MW turbine, regression was used based on the information provided for the 5MW [22], 10MW [59] and 15MW [58] reference turbines and the information available for the 6MW and 9.5MW turbines. The regression functions and the estimated data are shown in Figure 5 (a) regarding the blade mass, and in Figure 5 (b) regarding the tower mass. Although a relationship between blade mass and blade length was reported in [60], the blade length for the 6MW turbine was not available so that the regression was performed based on turbine rating. The blade mass is assumed to be composed by 75% of Glass fibre Reinforced Plastic (GRP) and by 25% of epoxy resin based on a recent review on materials for wind turbine blades [61], although for smaller turbines ratios of 60% GRP and 40% epoxy have also been reported [62].

Another aspect that needs to be considered is the generator transmission system. The turbine used for the Spar case study is gearless, which aligns well with the 15MW NREL turbine used for the weight distribution. However, the turbine assumed for the Semi-sub case study has a gearbox and this needs to

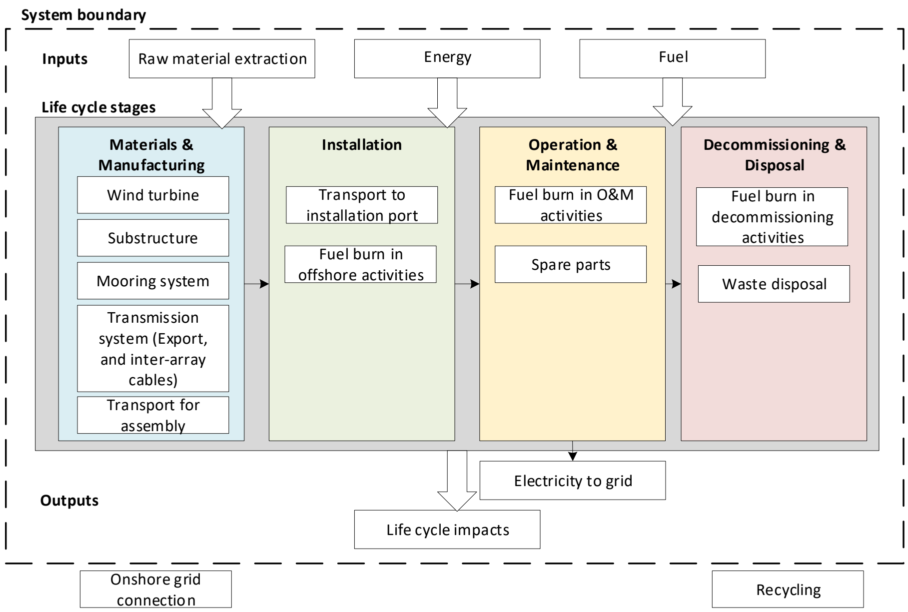


Figure 4: System boundaries considered for the LCA assessment.

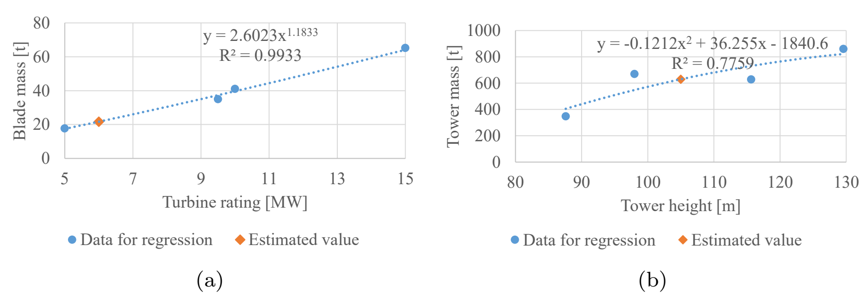


Figure 5: Regression function used to estimate (a) the blade mass of the 6MW turbine, (b) the tower mass of the 9.5MW turbine

be considered. For this purpose, previous LCA studies were reviewed, where turbines with gearboxes were considered. In [25] the percentage weight of the generator was 13.8%, and the gearbox 35.2% with respect to the total nacelle weight. In [10], the gearbox contributed 18.3% and the generator 14.0% to the total nacelle weight. It was mentioned in [63] that the nacelle weight can be considered to be 1/3 gearbox, 1/3 generator and 1/3 frame and machinery. Based on these previous studies, the direct drive generator weight contribution of 45.3% was split equally between the generator and gearbox for the Semi-sub, so that 22.6% (88.3t) of the total nacelle weight was assumed for each of these components.

Finally, for the Spar, the nacelle and the tower are considered to be assembled in Norway after being transported from Germany and Spain respectively based on the information gathered by Hannon et al. in [14] on the Hywind project. This is considered as road transport employing the distance between the countries based on Google Maps [64] approximations and the weights of the single components to calculate the total Tonne-kilometres (tkm)[2].

Floating substructure

The weights and materials for the floating substructure were obtained from public documents. For the Spar case study, a spar type floating substructure with a weight of 2300t of steel was assumed based on [17]. Since also iron ore is used for ballast (5000t) this is included here. For the Semi-sub case study, a Windfloat type semi-submersible with a weight of 2750t of steel was assumed based on [49]. Only water is used in this case for ballast.

Mooring system

The mooring system includes the mooring lines and the anchors. For the Spar, three 720m long mooring chains per device were used [17] in combination with three 100t suction anchors [18]. The weight per length of chain was approximated based on [66, 67] to be 0.38 t/m. For the Semi-sub, four 780m long mooring chains per device were used [19] in combination with four 20t drag embedment anchors [19]. The weight per length of chain is approximated to be 0.4 t/m based on the Spar assumptions.

Power transmission

Both export and inter-array cables are considered here. For the Spar, a 27.5km export cable is assumed [17] and a total of 6km of dynamic inter-array cables are included [18]. Two different cable cross-sections are provided in [18] for the static and dynamic cables, and different material contributions to the total cable weights are estimated based on these. The total weights per length are estimated to be 28.1 kg/m and 54.42 kg/m for the static and dynamic parts,

[2]‘*A tonne-kilometre, abbreviated as tkm, is a unit of measure of freight transport which represents the transport of one tonne of goods [...] by a given transport mode [...] over a distance of one kilometre.*’ [65]

respectively. For the Semi-sub, two export cables of 17.1 and 18.5km each and a total of 6.6km of dynamic inter-array cable are included [20]. The same cross-section is used for both static and dynamic cables as reported in [20]. This is an Ethylene Propylene Rubber (EPR) insulated Double Wire Armour (DWA) 33kV cable with a weight per length of 57 kg/m. No offshore substation was used in the pilot parks so this is not considered here. The onshore substation is outside of the system boundary considered for the present analysis, which focuses on the offshore infrastructure.

Summary

The contribution of the different materials to the overall weight is shown in Figure 6. It becomes clear that for the Semi-sub steel has the largest material contribution which amounts to 93.1%, followed by copper with 2.2%. For the Spar, due to the large weight of iron ore used for ballasting, the percentage contribution of steel is reduced to 46.0%, whereas iron ore amounts 51.1% of the total weight. Due to the larger overall weight, other materials have smaller contributions to the total material weight, with the third highest contribution stemming from copper with only 0.8%.

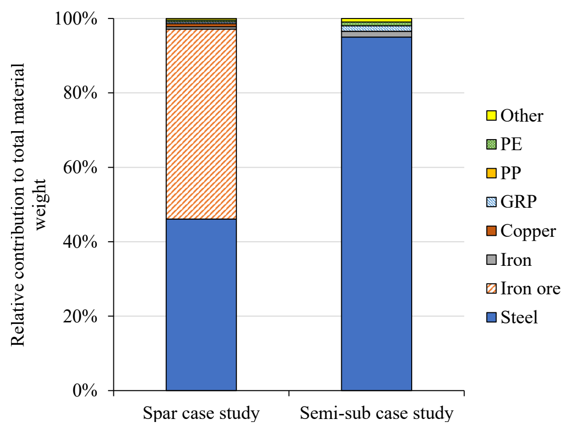


Figure 6: Material contributions to overall weight for the two considered case studies, with total weights of 9,791t and 5,446t for the Spar and the Semi-sub case study, respectively. PolyEthylene (PE), and PolyPropylene (PP) was considered in the power transmission, and Glass Reinforced Plastic (GRP) in the turbine blades.

3.2.2. *Installation*

To represent the transport to the assembly port, the suppliers for each of the components and the location of their headquarters was considered as the starting point based on the information provided in [14]. The distance to the installation port was approximated using Google Maps average km indication for each trip assuming ship freight transport. Taking into account this distance and the components' weight, transport to the assembly port was approximated in tkm. The ferry transport process from the Ecoinvent database was used, which represents a conservative assumption versus using a container ship in terms of impact, because it is expected to be more representative of the types of vessels used for transport such as barges.

Additionally, the installation procedures including required transit and operation times, and vessels were modeled based on the installation information provided for the Hywind project by Equinor in [67]. The distance to port, length of cable, and number of mooring systems was adapted for the Semi-sub case study. This is considered a fair approximation, since the vessel and time assumptions aligned well with the higher level information provided for the Kincardine project in [33]. The distance to the respective installation ports of Peterhead and Dundee were calculated to be 25 and 32km, respectively.

To represent the offshore activities associated to installation and O&M, the fleet of vessels shown in Table 4 were considered. Different fuel consumption values for different operating conditions were taken into account based on the percentage difference between economy transit and other operating conditions, as shown in Caterpillar's guide [68]. The operating conditions assumed for each vessel are also provided in Table 4. The vessels considered are: Crew Transport Vessel (CTV), Fast Supply Vessel (FSV), Heavy Lift Vessel (HLV), tugboat, Anchor Handling Tug Supply (AHTS) vessel, and Cable Lay Vessel (CLV). The Thiaft vessel is a particularly large HLV. After calculating the total amount of liters of fuel consumed by these vessels, the total amount of tkm was calculated based on the kg consumption per tkm of the ferry transport process from the Ecoinvent database. The baseline case was defined based on the vessels expected to be used within the Kincardine project [33], as reported in section 2.3.

3.2.3. Operation and maintenance

The O&M model used in this work is a validated tool for the characterisation and optimisation of the Key Performance Indicators (KPIs) of an offshore renewable energy farm during its operational lifetime. This model was presented and discussed in detail in [76, 77, 15], and verified in [78]. In [15], it was also applied for techno-economic analysis of these two case studies. However, a brief overview of its functioning is provided here for context. The O&M tool exploits a time-domain stochastic approach, based on the Markov Chain Monte Carlo technique, to model all the relevant aspects of an offshore wind farm operation, including environmental resource, reliability and power performance of the devices, maintenance vessels and related accessibility due to weather, and both corrective and preventive maintenance regimes. Following simulation, a series of results describing the farm energetic production, availability, maintainability and economic performance, are obtained.

Within this work, this O&M model was used to estimate the contributions of the O&M activities to the LCA assessment. These were considered through the fuel consumption during offshore operations and transits, as well as the number of spare parts used for replacements of failed components. The fleet of vessels shown in Table 4 was considered. The inputs used for the initial reliability assessment, the main failure rate assumptions, are included in the

Table 4: Assumed vessel fleet for installation and O&M activities, including vessel consumption estimates.

Vessel type	Speed [km/h]	Fuel Consumption [l/h]			Operational mode	Ref.
		In transit	Towing	In operation		
Considered for installation and O&M						
CTV	44.50	381	-	229	Standby	[69]
FSV	18.52	196	-	392	Dynamic positioning	[70]
HLV	23.15	1127	-	56	Anchored	[71]
Tugboat	22.20	448	596	-	Towing	[72]
AHTS	18.5	1046	1942	1046	Dynamic positioning + Standby	[73]
Thiaft (HLV)	11.11	2266	-	113	Anchored	[74, 75]
Considered for installation only						
CLV	4.63	780	-	1560	Dynamic positioning	[73]

Appendix. Based on the O&M model results and the failure rates [79], the number of turbine components requiring full replacement for both case studies for the whole farm and lifetime are considered to be:

- 4 generators,
- 6 gearboxes (Semi-sub only),
- 18 changes of lubrication oil, and
- 17 changes of different power electronics components.

Components such as the mooring lines, anchors, and power cables are assumed to be always replaced rather than repaired, but are different for the two case studies. Thus the following are replaced for the Spar and the Semi-sub case study, respectively:

- 17 and 24 mooring lines,
- 18 and 25 anchors, and
- 1 and 0 export cables.

The export cable is not replaced for the Semi-sub, since two export cables are assumed, and so the component is considered to be redundant. The full replacement of the export cable is considered to be a rather conservative assumption, since some of the failures will be repairable without requiring full replacement of the component [80].

Two different O&M philosophies were considered in this study. (1) O&M operations tailored to floating offshore wind technologies were considered, where turbines can be disconnected and towed to shore for major maintenance operations and large component exchange.(2) O&M operations as considered in bottom-fixed technologies were considered, where all O&M activities take place offshore and no towing of the turbines to shore is possible. These two scenarios are reported separately, and will be referred to as O&M towing strategy, and O&M offshore strategy, respectively. Additionally, a sensitivity on the vessels employed for these two scenarios was performed, resulting in a total of six O&M scenarios, which are summarised in Table 5.

Table 5: Considered O&M scenarios, including different vessels employed for major operations in each scenario to study sensitivity to vessel assumptions. The baseline case is highlighted in grey.

Scenario	**Vessels used for major operations**
O&M towing strategy - Turbine towed to port for major operations	
a	1 AHTS
b	1 tugboat
c	2 tugboats
d	2 tugboats + 1 AHTS
O&M offshore strategy - All major operations offshore	
a	HLV
b	Thiaft

As a result of the O&M model the net capacity factor for each case study and O&M strategy is provided in Table 6. Site-specific resource data and the respective turbine power curves were used for this purpose. Given the relatively short distance between the two considered pilot parks, an offshore location halfway between these two farms (57°17'N, 1°27'W) was used as the hypothetical location for both case studies. Resource data were retrieved from free-access online portals, namely the MARENDATA [81] and the Hycom [82] platforms. Differences in capacity factor between the two case studies stem from the different power curves of the turbine models, their suitability to the wind resource on site and the different downtime periods due to failures for the components of the two devices.

An average capacity factor of 53.8% has been reported for the first 2.2 years of operation of the Hywind project [83]. Capacity factors previously reported for bottom-fixed offshore wind farms amount 38.4% in average [84]. The obtained capacity factor values are, therefore, considered to be in the expected range. A sensitivity on the assumed energy production is performed as part of the uncertainty analysis.

Table 6: Resulting capacity factors for O&M strategies.

	Spar case study	Semi-sub case study
O&M towing strategy - Turbine towed to port for major operations		
Capacity factor [%]	50.2	40.2
O&M offshore strategy - All major operations offshore		
Capacity factor [%]	49.4	39.6

3.2.4. Decommissioning and disposal

Decommissioning is assumed to be equivalent to a reversed installation process, and so it is considered through the same amount of fuel consumption. Since the allocation with cut-off by classification method is used, no recycling is considered in the end-of-life scenario. That is, because recycled content is already considered in the background data, and this would result in double-counting of the recycling benefits. In this regard, 90% of recycled steel is assumed and the iron ore used for ballast is assumed to be re-purposed or recycled after the operational life - so these materials are assumed to leave the system boundary at the end-of-life without resulting in any environmental penalty or credit. The remaining materials are assumed to be sent to municipal landfill at the end-of-life.

3.3. Impact assessment

The software SimaPro 9.1 is used for the impact assessment. The ReCiPe Midpoint (H) 2016, heirarchist version, with European normalisation [85] is applied given its robustness and widespread use [21, 45]. The corresponding emissions and resource extractions are translated into 18 impact categories listed in Table 7. The midpoint approach is chosen in line with the recent energy and environmental policies to improve transparency and comparability [21, 45]. The Cumulative Energy Demand (CED) method V1.11 is used to analyse energy consumption. From the CED, the Energy PayBack Time (EPBT) of a wind farm can be estimated as the number of years needed for the farm to generate as much energy as the sum of the embodied energy of its whole life cycle, i.e. the primary energy spent during manufacturing, installation and maintenance stages. A low EPBT value corresponds to high energy efficiency. In all cases, allocation with cut-off by classification is used as system model, so that emissions avoided by using recycled materials are considered, following the guidance [43].

Although water consumption (WC) is quantified through the ReCiPe Midpoint (H) method, the results were found to be very uncertain, in terms of the uncertainty associated to the background data - with the 95% interval for this impact category showing a range in percentage change of up to -6408% to 5052% and a coefficient of variance one to three orders of magnitude higher than for any other impact category. For this reason, results for this impact category are not provided here. That is a total of 18 impact categories are reported in this study using the units listed in Table 7, if not otherwise indicated.

Table 7: List of environmental impact categories evaluated through the ReCiPe Midpoint (H) and Cumulative Energy Demand methods.

	Impact category	Acronym	Unit
1	Fine particulate matter formation	FPM	g PM2.5 eq/kWh
2	Fossil resource scarcity	FRS	g oil eq/kWh
3	Freshwater ecotoxicity	F Etox	g 1,4-DCB/kWh
4	Freshwater eutrophication	F Eut	g P eq/kWh
5	Global warming[3]	GW	gCO_2 eq/kWh
6	Human carcinogenic toxicity	HT-C	g 1,4-DCB/kWh
7	Human non-carcinogenic toxicity	HT-nonC	g 1,4-DCB/kWh
8	Ionizing radiation	IR	Bq Co-60 eq/kWh
9	Land use	LU	m2a crop eq/kWh
10	Marine ecotoxicity	M Etox	g 1,4-DCB/kWh
11	Marine eutrophication	M Eut	g N eq/kWh
12	Mineral resource scarcity	MRS	g Cu eq/kWh
13	Ozone formation, Human health	OF-HH	g NOx eq/kWh
14	Ozone formation, Terrestrial ecosystems	OF-TE	g NOx eq/kWh
15	Stratospheric ozone depletion	SOD	g CFC11 eq/kWh
16	Terrestrial acidification	TA	g SO2 eq/kWh
17	Terrestrial ecotoxicity	T Etox	g 1,4-DCB/kWh
18	Water consumption	WC	m3/kWh
19	Cumulative energy demand	CED	kJ/kWh

3.4. Interpretation

In the interpretation stage, the LCA impacts across 18 impact categories are shown for the two case studies. The sensitivity of these results to the assumed O&M strategy and the vessels used is assessed. Additionally, the sensitivity of the results to the uncertainty in the background data is shown based on Monte Carlo analysis. Note that uncertainty in the background data is defined by lognormal distributions in SimaPro by default. The sensitivity to some of the model assumptions such as the produced energy over the operational life, the assembly contribution, and the transport to the installation port are also analysed. Results are not compared with other forms of electricity generation provided in the Ecoinvent database, due to inconsistencies in scope and methods. However, the global warming potential range obtained in the present study is compared with previous literature discussed in section 2. The role of O&M activities and their representation in LCA studies is further discussed based on the results. Finally, the hotspots in terms of components or processes with high environmental impacts are identified, and recommendations are provided to mitigate their impacts.

[3]GWP and GW are equivalent in this case.

4. Results

In this section, the results obtained for the baseline case are presented in detail first, followed by the study of the sensitivity of the results to the O&M strategy. Finally, the results are discussed based on the uncertainty of the Ecoinvent background data and the sensitivity of the outputs to a number of key input parameters.

4.1. Baseline scenario LCA impacts

The baseline scenario for the two case studies is represented by the O&M scenario 1-a, i.e. the case considering that turbines are towed to shore for major operations and that an AHTS is used for this purpose.

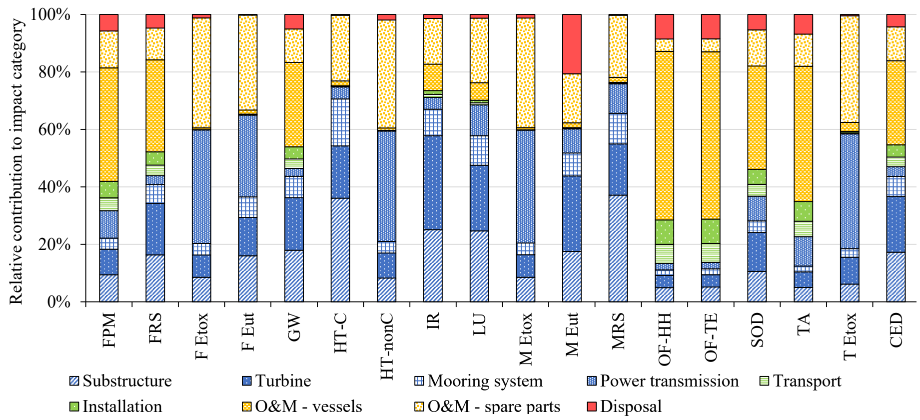
The resultant values for the 18 considered impact categories are summarised in Tables 8 and 9 for the Spar and Semi-sub case study, respectively. The contribution of different components and processes to each of the impact categories is shown in Figures 7a and 7b for the Spar and Semi-sub, respectively.

The GWP is estimated to be 36.0-44.0 gCO_2 eq/kWh for the Spar, and 31.1-37.4 gCO_2 eq/kWh for the Semi-sub. Based on the obtained CED, the EPBT is determined to be 3.3-4.3 years for the Spar and 2.8-3.7 years for the Semi-sub.

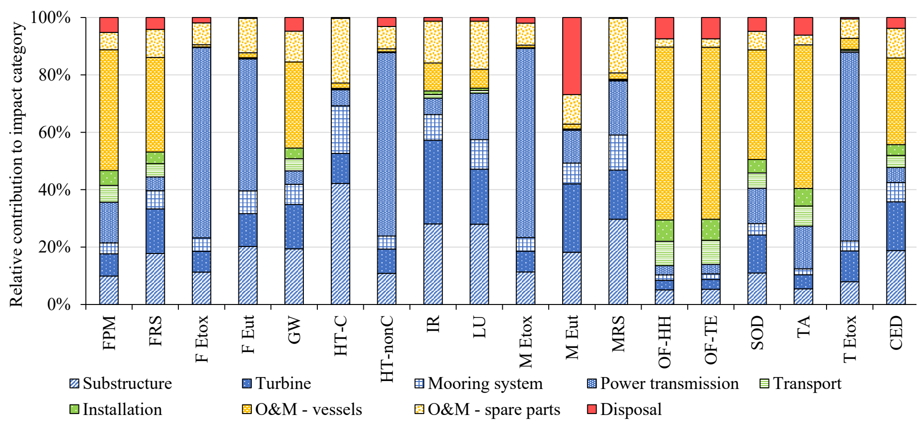
Regarding the contributions to GW in Figure 7a (a) from the different life cycle stages, it can be seen that the largest contributions for the Spar stem from the materials and manufacturing phase (46.4%) followed by the O&M (41.0%) and the installation phase (7.6%). Within that, the components and processes with the largest contribution are the O&M vessels (29.3%), followed by the turbine (18.3%) and the substructure (17.9%). As shown in Figure 7a (b) for the Semi-sub, the largest life cycle stage contributions stem from the materials and manufacturing phase (46.6%) followed by the O&M (40.7%) and the installation phase (7.9%). Within the Semi-sub case study, the components and processes with the largest contribution to GW are the O&M vessels (30.0%), followed by the substructure (19.4%) and the turbine (15.5%).

A large contribution of the power transmission is observed in both case studies on freshwater ecotoxicity (F Etox), freshwater eutrophication (F Eut), human non-carcinogenic toxicity (HT-nonC), marine ecotoxicity (M Etox) and terrestrial ecotoxicity (T Etox). These stem from the sulfidic tailings generated from copper mining. Sulfidic tailings contain abundant reactive minerals rich in heavy metals [86]. In the Spar case study, the export cable is replaced once during the operational life, based on the O&M model results. As mentioned before, this is not the case for the Semi-sub, since the component is considered redundant in the O&M model. For this reason, for the Spar, a significant contribution of the O&M spare parts can also be observed for these impacts categories.

O&M vessels have the largest contribution on ozone formation (OF-HH, and OF-TE), stratospheric ozone depletion (SOD) and terrestrial acidification (TA). This is due to all greenhouse gas emissions (CO, CO_2, NO_x, SO_2, particulates, etc.) associated with the fuel combustion.



(a) Spar case study



(b) Semi-sub case study

Figure 7: Relative contributions of the life cycle processes to the different impact categories.

Table 8: Impact category values for baseline scenario in the Spar case study. Refer to Table 7 for impact category definitions and units.

Impact category	**Mean**	**Median**	**2.50%**	**97.50%**
FPM	0.19	0.19	0.17	0.22
FRS	10.57	10.54	9.48	11.92
F Etox	17.56	17.21	12.96	24.29
F Eut	0.03	0.03	0.02	0.05
GW	39.25	38.99	35.96	43.99
HT-C	14.27	13.11	7.04	29.41
HT-nonC	219.50	215.15	159.14	301.62
IR	1.21	0.76	0.26	4.88
LU	6.28E-04	6.14E-04	5.00E-04	8.41E-04
M Etox	22.28	21.90	16.65	30.57
M Eut	2.34E-03	2.28E-03	1.92E-03	3.11E-03
MRS	1.48	1.45	1.16	1.97
OF-HH	0.42	0.41	0.30	0.57
OF-TE	0.42	0.42	0.31	0.58
SOD	2.26E-05	2.23E-05	1.79E-05	2.94E-05
TA	0.51	0.50	0.45	0.56
T Etox	933.39	838.63	481.83	2026.64
CED	536.83	534.78	470.73	617.48

Table 9: Impact category values for baseline scenario in the Semi-sub case study. Refer to Table 7 for impact category definitions and units.

Impact category	**Mean**	**Median**	**2.50%**	**97.50%**
FPM	0.16	0.16	0.15	0.18
FRS	9.12	9.09	8.21	10.13
F Etox	12.54	12.23	9.17	17.74
F Eut	0.02	0.02	0.01	0.03
GW	33.89	33.81	31.08	37.37
HT-C	11.49	10.63	5.89	22.85
HT-nonC	159.60	157.31	116.45	219.77
IR	1.08	0.66	0.22	4.77
LU	5.119E-04	5.002E-04	4.066E-04	6.799E-04
M Etox	15.95	15.57	11.81	22.25
M Eut	2.108E-03	2.059E-03	1.725E-03	2.823E-03
MRS	1.05	1.03	0.80	1.38
OF-HH	0.36	0.36	0.25	0.50
OF-TE	0.37	0.36	0.26	0.50
SOD	1.879E-05	1.855E-05	1.496E-05	2.392E-05
TA	0.42	0.42	0.38	0.48
T Etox	687.69	623.43	362.94	1410.53
CED	462.17	460.10	404.34	532.21

4.2. Sensitivity of results to O&M strategy

The Life Cycle Impact Assessment (LCIA) for the five different O&M scenarios are provided in Tables 10 and 11 for the Spar and the Semi-sub case study, respectively.

For the Spar, assuming the O&M towing strategy (towing the turbines to shore for major repairs) results in mean values for the GWP of 32.4-45.2 gCO_2 eq/kWh, whereas assuming O&M offshore strategy (major repairs taking place offshore) results in mean values of 30.2-32.7 gCO_2 eq/kWh. For the Semi-sub, assuming the O&M towing strategy results in mean values of GWP of 27.7-39.4 gCO_2 eq/kWh, whereas assuming O&M offshore strategy results in mean values of 25.6-27.6 gCO_2 eq/kWh. The mean GWP ranges only overlap slightly for the two O&M strategies - in general, the O&M towing strategy results are higher than the O&M offshore strategy results. This is true for impact categories, where O&M vessels have a large impact, such as the ozone formation impact categories. For impact categories, where O&M vessels do not have a large impact, the O&M towing strategy results are lower than the O&M offshore strategy results. That is because of the slightly lower capacity factors estimated with the O&M offshore strategy. If comparing the overall mean GWP values of the two O&M strategies, these results indicate a percentage difference, due to the assumed O&M strategy of 18.5-20.4%. If comparing the largest variation in GWP within one O&M strategy, the results indicate a percentage difference, due to the choice of vessels of 33.2-34.8%.

The O&M vessels contribution varies across the different impact categories depending on the used assumptions. It can be seen that for ozone formation impact categories (OF-HH, and OF-TE) the contribution varies from about 20 to 70% and for GWP from about 6 to 40%.

Table 10: Impact category mean values for the different O&M scenarios within the Spar case study. Refer to Table 7 for impact category definitions and units. The heat map is used to aid visualisation of the results, ranging from green to indicate lower impact values to red for higher impact values.

Impact	**O&M towing**				**O&M offshore**	
category	**a**	**b**	**c**	**d**	**a**	**b**
FPM	0.19	0.15	0.17	0.23	0.13	0.15
FRS	10.59	8.58	9.47	12.38	7.91	8.66
F Etox	17.63	17.56	17.59	17.69	17.81	17.83
F Eut	2.92E-02	2.89E-02	2.90E-02	2.94E-02	2.93E-02	2.94E-02
GW	39.16	32.36	35.40	45.23	30.17	32.68
HT-C	14.23	14.08	14.15	14.35	14.24	14.30
HT-nonC	221.65	220.52	221.02	222.66	223.47	223.88
IR	1.27	1.20	1.24	1.34	1.20	1.22
LU	6.33E-04	6.22E-04	6.32E-04	6.53E-04	6.14E-04	6.22E-04
M Etox	22.38	22.29	22.33	22.47	22.59	22.63
M Eut	2.34E-03	2.31E-03	2.33E-03	2.36E-03	2.34E-03	2.35E-03
MRS	1.47	1.46	1.46	1.49	1.47	1.48
OF-HH	0.42	0.27	0.34	0.55	0.22	0.27
OF-TE	0.42	0.28	0.34	0.55	0.22	0.28
SOD	2.24E-05	1.76E-05	1.98E-05	2.67E-05	1.60E-05	1.78E-05
TA	0.51	0.37	0.43	0.63	0.31	0.37
T Etox	951.72	933.94	941.88	967.59	941.27	947.85
CED	536.68	443.68	485.19	619.72	407.30	441.21

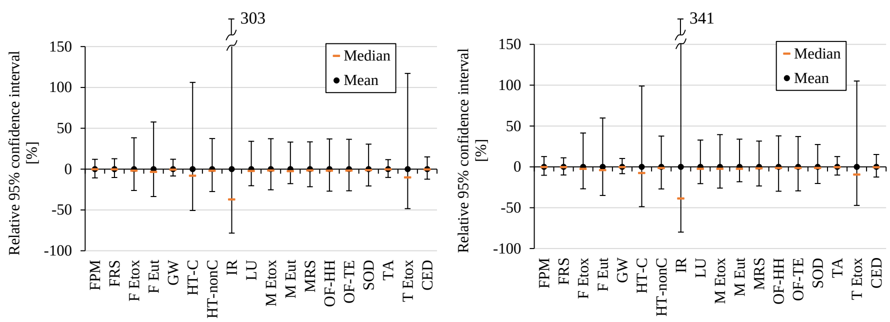
Table 11: Impact category mean values for the different O&M scenarios within the Semi-sub case study. Refer to Table 7 for impact category definitions and units.The heat map is used to aid visualisation of the results, ranging from green to indicate lower impact values to red for higher impact values.

Impact	**O&M towing**				**O&M offshore**	
category	**a**	**b**	**c**	**d**	**a**	**b**
FPM	0.16	0.12	0.14	0.20	0.11	0.12
FRS	9.12	7.29	8.11	10.74	6.65	7.26
F Etox	12.50	12.44	12.47	12.55	12.57	12.59
F Eut	2.18E-02	2.16E-02	2.17E-02	2.20E-02	2.17E-02	2.18E-02
GW	33.88	27.71	30.46	39.38	25.57	27.61
HT-C	11.49	11.36	11.42	11.61	11.45	11.49
HT-nonC	159.46	158.44	158.89	160.38	159.95	160.29
IR	1.07	1.01	1.03	1.12	0.99	1.01
LU	6.33E-04	6.22E-04	6.32E-04	6.53E-04	6.14E-04	6.22E-04
M Etox	15.90	15.81	15.85	15.98	15.97	16.00
M Eut	2.12E-03	2.10E-03	2.10E-03	2.14E-03	2.11E-03	2.12E-03
MRS	1.05	1.03	1.04	1.06	1.04	1.04
OF-HH	0.36	0.23	0.29	0.48	0.18	0.22
OF-TE	0.36	0.23	0.29	0.48	0.18	0.23
SOD	1.88E-05	1.44E-05	1.64E-05	2.26E-05	1.29E-05	1.43E-05
TA	0.42	0.29	0.35	0.54	0.25	0.29
T Etox	690.52	674.37	681.56	704.91	676.09	681.43
CED	461.69	377.18	414.83	536.98	347.95	375.89

4.3. Uncertainty analysis

4.3.1. Uncertainty of background data

The mean, median and 95% confidence interval for the different impact categories were provided in Tables 8 and 9 for the Spar and Semi-sub case study, respectively. They were obtained by performing a Monte Carlo simulation with the SimaPro software, to take into account uncertainties implicit within the background data provided in the Ecoinvent database. An overview of the percentage change in the 95 percentile are shown in Figure 8 (a) and (b) for the Spar and Semi-sub case study, respectively. As it can be seen from this figure, the indicators showing the largest 95% range are IR (-78.4% to 303.1% for the Spar, and -79.9% to 341.2% for the Semi-sub), T-Etox (-48.4% to 117.1% for the Spar, and -47.2% to 105.1% for the Semi-sub), and HT-C (-50.6% to 106.1% for the Spar, and -48.7% to 99.0% for the Semi-sub). As mentioned earlier results for WC were not considered due to the 95% interval in this case ranging from -6054.2% to 4472.1% for the Spar, and -5913.8% to 4564.9% for the Semi-sub. For GW a percentage change variation between -8.4% and 12.1% for the Spar, and of -8.3% and 10.3% for the Semi-sub is observed. This is one of the lowest uncertainty ranges amongst all the indicators. This is important, since it is the most often quoted impact category in line with environmental guidelines.



(a) Spar case study

(b) Semi-sub case study

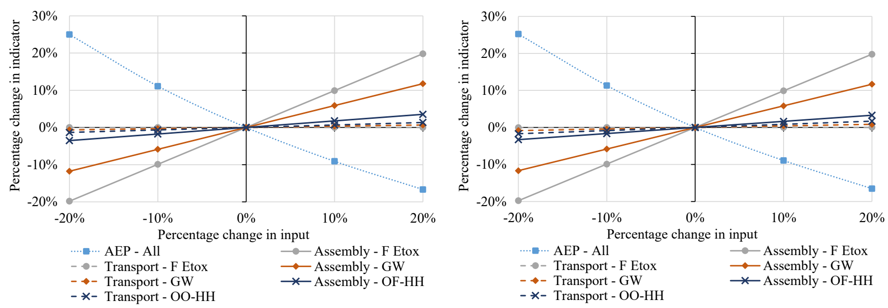
Figure 8: Relative 95% confidence interval based on background data uncertainty for the different impact categories.

4.3.2. Sensitivity of results to uncertain input parameters

The sensitivity of the studied impact categories to input parameter changes was considered and the overall results can be seen in Figure 9.

The capacity factor and lifetime have been found in the past to have a large impact on the results, given that kWh is used as functional unit [21]. Since both these parameters mainly affect the overall energy produced, the impact of ±20% change in Annual Energy Production (AEP), and therefore in overall energy produced was investigated. Because this parameter is normalising all impact categories in the same way, the impact on the outcome, in terms of percentage change, is the same for all impact categories. Additionally, given that a number of assumptions were used to quantify the materials and processes involved in the manufacture and assembly of each case study, the impact of varying the overall amount of required materials and processes (Assembly) by ±20% was also investigated. The impact of varying the required transport (in terms of tkm) from the component manufacturer to installation port by ±20% was also analysed, given that this had been approximated using Google Maps.

As it can be seen from Figure 9, the results are most sensitive to changes in AEP in all impact categories. The impact in changes of Transport and Assembly are shown for impact categories F Etox, and OO-HH which showed the largest and smallest percentage change in outputs, to display the overall percentage change range of all impact categories. Very similar trends are observed for both case studies.



(a) Spar case study

(b) Semi-sub case study

Figure 9: Sensitivity of results on single input variations.

If taking the GW impact category as example, a relatively low uncertainty in the GW results due to the background data was observed, which amounted up to -8.4 to +12.1% variation. In comparison, variations of up to 20% in overall assembly or transport requirements resulted in up to ±11.8% and ±0.84% change in GW values, respectively. These would be within the uncertainty range due to the uncertainty in the background data. AEP has a larger impact on the results over all impact categories. However, this was estimated based on 25 years of resource data and the turbines power curve, accounting for availability and downtime due to failures. So, in the present case such large variations in AEP for the studied cases would not actually be expected. As mentioned before, an average capacity factor of 53.8% has been reported for the Hywind project to date [83]. This would represent a 7.3% change of the estimated value. For the Spar case study this would translate into a 7.5% GW reduction.

5. Discussion

5.1. How do results compare to literature?

Although various measures can be used to quantify the environmental impact in different contexts while using the LCA method, the relative Global Warming Potential (GWP) or GW is reported here to provide context on the environmental impacts associated to these technologies to date. This measure is commonly reported for energy generating technologies in line with energy and environmental policies.

Today the GWP for floating offshore wind technologies has been estimated to be between 11.5 [2]-38.1 [5] gCO_2 eq/kWh, which tends to be slightly higher than current estimates for bottom-fixed turbines with around 7.8-32.0 gCO_2 eq/kWh [21]. These numbers are, however, still much lower than the estimated for the fossil fuel-based technologies, such as 1,054 gCO_2 eq/kWh for lignite, 888 gCO_2 eq/kWh for coal, 733 gCO_2 eq/kWh for oil and 499 gCO_2 eq/kWh natural gas [87].

The results obtained in the present study show that if assuming the same O&M strategy as in bottom-fixed offshore wind, the mean GW values (25.6-32.7 gCO_2 eq/kWh) fall within the range of values previously estimated in literature. However, it is considered unlikely that major repairs can be performed offshore with standard heavy lift crane vessels, due to (1) the larger mobility of the floating wind turbine system, (2) the increasing hub-heights of the larger turbines used further offshore, and (3) the large water depths, which would not allow for the fixed positioning of the work vessels. So the mean values obtained here when using O&M strategies tailored to floating offshore wind technologies (27.7-45.2 gCO_2 eq/kWh) are considered to be more representative of the environmental impacts of these technologies.

It should be noted that deployments with five turbines were studied here, whereas larger wind farm deployments are expected in the future. Since this would result in more energy produced over the lifetime of the project, but a shared use of certain components such as the power transmission, but also of maintenance vessels and learning/optimisation of marine operations for larger farms, slightly lower impacts could be expected for larger farm deployments. Additionally, the values obtained here are a snapshot in time, since if the energy mix becomes de-carbonised values will reduce. In that case, O&M contributions will still remain unless low-carbon e-shipping or hydrogen vessels are introduced.

5.2. What is the impact of detailed O&M estimations on the LCA assessment?

As shown from the O&M sensitivity study the obtained global warming results can vary by up to 29.6% depending on the vessel selection and by up to 20.0% depending on the O&M strategy. The overall contribution of O&M vessels to global warming varies between 14 and 40% depending on the studied cases when considering towing of the turbines to shore for major repairs; whereas the overall contribution of O&M activities, including spare parts, ranges from 26 to 49%. This stands in contrast with some of the reviewed literature, where O&M was not considered in detail, and where the overall O&M contribution was found to be 5% or lower.

This indicates that not taking into account the impact of detailed O&M estimations in LCA studies may result in a considerable underestimation of the technology's impacts. Including more detailed O&M estimations results in a significant variation of the estimated impact values, and a significant difference in the contribution of O&M to the overall results.

5.3. What environmental impact hotspots were identified and how can they be mitigated?

The O&M vessel use was found to be an environmental impact hotspot for ozone formation impact categories, stratospheric ozone depletion, terrestrial acidification and fine particulate matter formation. Previous studies have explored the selection of O&M strategies for floating offshore wind farms from a techno-economic perspective [40], and a preliminary LCA study was performed to quantify the CO_2 emissions from vessel fuel consumption for two O&M scenarios [88]. Given the large impact that the strategy and vessel choice can have, it is recommended to consider LCA in this selection process. The use of more efficient vessels and the minimisation of the overall number of trips would be key to reduce the environmental impact of floating offshore wind farms.

The power transmission was found to be a hotspot in terms of freshwater ecotoxicity (F Etox), freshwater eutrophication (F Eut), human non-carcinogenic toxicity (HT-nonC), marine ecotoxicity (M Etox) and terrestrial ecotoxicity (T Etox) due to the sulfidic tailings generated from copper mining. To reduce these impacts, recycling options for copper should be investigated further. In more general terms, more sustainable copper mining processes should be studied.

The substructure and turbine have also relatively high contributions to a number of impact categories. The use of materials with lower overall impacts such as concrete instead of steel could be considered, although recyclability of this material would need to be investigated further. Leaner structures designed to reduce weight could be considered for both the turbine tower and the substructure. Finally, the use of glass fibre for the turbine blades constitutes about 9% of the turbine's global warming impacts. The recyclability of wind turbine blades, is an issue, which is being investigated [89] and which although not being identified as a hotspot here, could also contribute to reduce the overall impacts.

6. Conclusions

A Life Cycle Assessment (LCA) of two floating offshore wind parks was performed, by using a detailed O&M model to better estimate O&M impacts and to be able to compare the impact of the choice of O&M strategies and vessels on 18 different environmental impact categories.

This study represents an important addition to the literature on the environmental impacts of floating offshore wind. This study also provides for the first time insights for the LCA modelling of floating wind turbines larger than 5MW.

The more detailed representation of O&M activities in the LCA was found to result in overall higher environmental impacts than previously considered in the literature, as well as a higher O&M contributions to these impacts. Assuming O&M operations for floating offshore wind farms to be equivalent to bottom-fixed offshore wind farms resulted in up to 20.4% underestimation in Global Warming Potential (GWP). The vessel choice was found to result in up to 34.8% difference in the estimated GWP value.

Hotspots of high environmental impact were found through this study, amongst which the O&M vessels, the power transmission, and the large amount of steel used for the turbine and floating substations. To minimise these impacts, it is recommended to apply LCA for the selection of O&M strategies and assets management, where the number of trips should be minimised and the vessel efficiency improved. To this end, more advanced O&M models should be developed that not only use optimisation methods to minimise the costs [90] but also include environmental impact minimisation objectives. Further investigation of the possibilities for recycling of copper is found to be key to reduce the impacts associated to the power transmission. Finally, the development of lean structural designs for the turbine tower and the floating substructure has a significant potential to improve the environmental impacts of floating offshore wind technologies.

It was shown that O&M activities have a significant environmental impact in floating offshore wind farms, and need to be considered in detail to not underestimate the technologies' impacts. Although a detailed O&M model was used here, the O&M model assumptions and representation could be further refined to analyse the impact of other factors associated with the O&M activities. If O&M data was available the O&M model could be validated and with it the impacts associated with that phase. Additionally, it was found that the operational phase is often not considered, or well represented in previous LCA studies, which makes these less comparable. The Ecoinvent database was found to be limited in the ability to consider impacts associated to typical vessels used for O&M operations since it includes only environmental impacts associated to vessels used for freight transport. However, to the knowledge of the authors this is the case also in other commercial and open-source life-cycle inventory databases. To improve the analysis of offshore operations in the future, environmental impacts specific to the types of vessel used for offshore maintenance operations based on their efficiency and operating conditions should be recorded in the database. Alternatively, the best representation with the available data needs to be studied further to support LCA practitioners consider O&M impacts as reliably as possible. A recommendation for future studies is to consider O&M activities in more detail, and to further exploit LCA to support the selection of the most suitable assets and strategies, as a complimentary perspective to techno-economic assessment.

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Table A.12: Assumed taxonomy for the Spar case study specific components and related properties [91, 67, 92, 93, 94, 95].

Subsystem / Component	Repair / replacement time [hours]	Annual Failure rate [failures /turbine /year]	Cost of component [£]	Onshore Maintenance [Yes / No]
Floating platform (Spar)	12	0.0438	6,618,480[4]	Yes
Mooring lines	12	0.14892	570,152	No
Anchors	12	0.15768	983,180	No
Power cable (inter-array)	12	0.0000323	703,890[5]	No
Export cable	24	0.167	6,050,000	No

Table A.13: Assumed taxonomy for the Semi-sub case study specific components and related properties [92, 94, 95, 96].

Subsystem / Component	Repair / replacement time [hours]	Annual Failure rate [failures /turbine /year]	Cost of component [£]	Onshore Maintenance [Yes / No]
Floating platform (Semi-sub)	12	0.98112	10,551,200[6]	Yes
Mooring lines	12	0.14892	557,568	No
Anchors	12	0.15768	109,348	No
Power cable (inter-array)	12	0.0000323	828,048[7]	No
Export cable	24	0.167	4,522,980	No

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Appendix A. Case studies assumptions

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[4]Note that only 1% of the spar platform capital costs (£66,184) are considered as repair costs

[5]This includes the cost of accessories. It is expected that if an inter-array cable is replaced, the accessories will be replaced as well.

[6]Note that only 1% of the Semi-sub platform capital costs (£105,512) are considered as repair costs;

[7]This includes the cost of accessories.

[8]Considered only for the Semi-sub case study (inspired by Kincardine) since the device used in the Spar case study (inspired by Hywind) is direct drive (gearless).

Table A.14: Taxonomy for the wind turbine and related properties. Adjusted from [79].

Subsystem / Component	Repair / replacement time [hours]	Annual Failure rate [failures /turbine /year]	Cost of component [£]	Onshore Maintenance [Yes / No]
Pitch & Hydraulic system	89	1.076	65,910	No
Generator	67	0.999	25,973	Yes
Gearbox[8]	44.5	0.633	20,512	Yes
Blades	31.25	0.52	18,037	Yes
Grease, Oil, Cooling Liquids	22	0.471	5,253	No
Electrical comp	20.75	0.435	4,550	No
Contactor, Circuit breaker, relay	17.5	0.43	4,565	No
Controls	17.5	0.428	4,431	No
Safety	13.25	0.392	4,306	No
Sensors	12.75	0.346	3,995	No
Pumps, Motors	11	0.346	3,544	No
Hub	8.3	0.235	1,126	No
Heaters, Coolers	8	0.213	1,075	No
Yaw system	7.3	0.189	990	No
Tower, Foundation	7	0.05	918	No
Power supply, Converter	8	0.18	750	No
Transformer	3.6	0.065	527	No

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