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Floating wind power in deep-sea area: Life cycle assessment of environmental impacts

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ABSTRACT

Floating offshore wind power, an emerging technology in the offshore wind industry, has attracted increasing attention for its potential to cooperate with other renewable energies to decarbonize energy systems. The environmental effects of the floating offshore wind farm in deep-sea areas should be considered, and methods to enhance the low-carbon effect should be devised. There have been a few studies assessing the environmental effects of the floating offshore wind farm, but the scales of these studies were relatively small. This study evaluated the environmental impacts of a floating wind farm with 100 wind turbines of 6.7 MW using life cycle assessment (LCA) method, based on the Chinese core life cycle database. Results showed that the carbon footprint of the wind farm was 25.76 g CO_2-eq/kWh, which was relatively low in terms of global warming potential. Additionally, the floating offshore wind farm contributed most to eutrophication potential. A ± 20% variation in steel resulted in a ±3% to ±15% variation in the indicator score of each environmental category, indicating that the environmental performance of the wind farm was mainly influenced by this parameter. Moreover, scenario analysis showed that electric arc furnace routes can reduce the cumulative greenhouse gas emissions from upstream process of the floating offshore wind farm by 1.75 Mt CO_2-eq by 2030. Emission reduction of the steel industry will further reduce the carbon footprint of the floating offshore wind farm. In the future, more baseline data need to be collected to improve the reliability of LCA. The effects of the floating offshore wind farm on marine ecology and atmospheric physical characteristics remain to be investigated in depth.

1. Introduction

1.1. Background

Currently, conventional energy sources based on fossil fuels are one of the main economic drivers in the world [1]. However, utilization of fossil fuels has brought enormous challenges such as global climate change [2,3] and depletion of conventional energy in the face of increasing energy demand [4]. A global transformation of energy systems is underway to mitigate climate change and satisfy the increasing energy demand [5]. It is clear that future growth in energy production will be primarily in the new frame of renewable energy systems (RESs) [6]. The use of low-carbon electricity as end-use of energy will be a main pillar in the transformation of energy systems [7].

Nearly 290 GW of new renewable energy was added globally in 2021. As a result, in which the installed capacity of wind power increased significantly [8]. The market share of offshore wind power is increasing remarkably, and the installed capacity of offshore wind power

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Abbreviations: ES, renewable energy system; GWEC, Global Wind Energy Council; LCOE, levelized cost of energy; LCA, life cycle assessment; OWF, offshore wind farm; GHG, greenhouse gas; LCI, life cycle inventory; O&M, operation and maintenance; ISO, International Standardization Organization; CLCD, Chinese core life cycle database; LCIA, life cycle impact assessment; GWP, global warming potential; ADP, abiotic depletion potential; AP, acidification potential; EP, eutrophication potential; RI, particulate matter; ODP, ozone depletion potential; PED, primary energy demand; BF-BOF, blast furnace and basic oxygen furnace; EAF, electric arc furnace; IEA, International Energy Agency; PV, photovoltaic; US, United States; ROI, return on investment.

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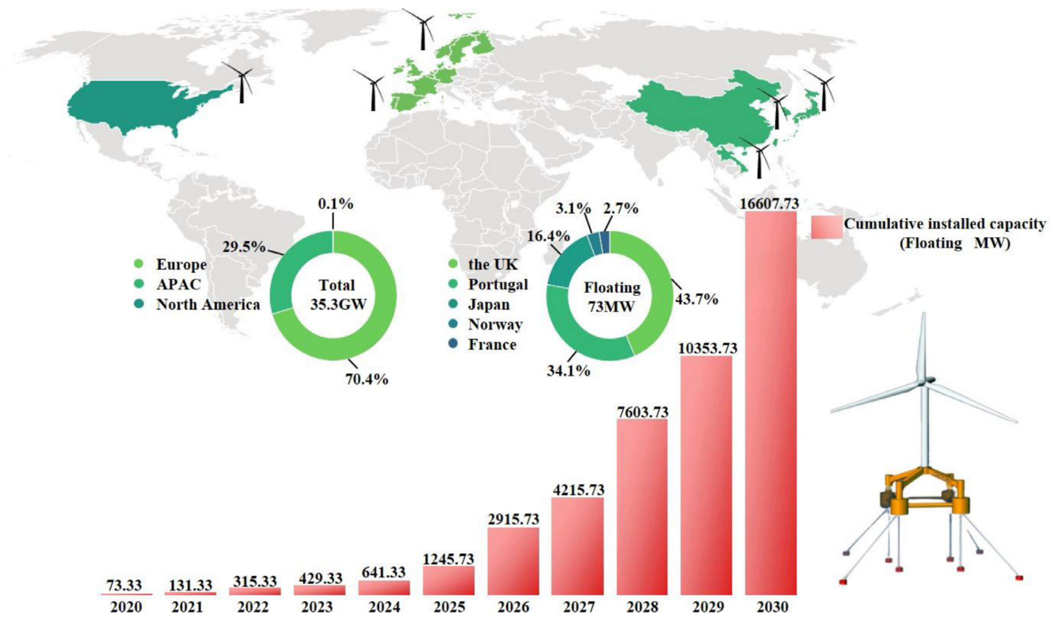


Fig. 1. Installed capacity and spatial distribution of offshore wind power. | Data source: Global offshore wind report 2021 by the Global Wind Energy Council (GWEC) [12].

is expected to see massive growth in the coming decades, with projected increase from 34 GW in 2020 to 380 GW by 2030 and to over 2000 GW by 2050 [9].

Most offshore wind power technologies involve fixing wind turbines to the water depths of around 30–50 m using the bottom-fixed technologies of monopile, conduit frame or gravity [10]. Higher and more constant wind speeds in deep-water areas at depths greater than 50 m can bring more electricity production, but the conventional bottom-fixed technologies are not economical in this case [11]. Thanks to the continuous development of floating technologies, it has become possible to deploy large-scale offshore wind turbines in deeper water areas. Floating offshore wind power is attracting increasing attention for its potential to cooperate with other renewable energies to decarbonize energy systems. Although it currently accounts for only 0.2% of the total installed offshore wind capacity, this emerging technology will grow significantly over the next decade (Fig. 1) [12].

1.2. Literature review

1.2.1. Previous studies in floating offshore wind power

Up to now, the floating wind power technologies are still evolving and have not been deployed at a commercial scale [13]. Using floating offshore wind power as a keyword on the Web of Science Core Collection to search, a total of 893 studies have been reported. Fig. 2 shows the keyword co-occurrence knowledge map conducted by VOSviewer. The node size indicates the frequency of keywords. These high-frequency keywords strongly related to floating wind power research were divided into 5 clusters. These words are mostly related to the structural design of wind turbines and the dynamics of system, indicating that the studies on floating wind power are still mainly focused on the technical performance of wind turbines and the stability of floating substructures. López-Queija et al. [14] conducted a critical review of the state-of-art of floating wind turbine control technologies. Their results indicated that wind turbine control and structural control are two main control research fields in future. A comparative analysis of the techniques proposed to upscale floating structures for larger wind energy systems was carried out by Sergiienko et al. [13]. Their study focused on the system dynamics and showed that waterplane area does not govern the design of a semi-submersible platform. Keighobadi et al. [15] updated the model of a floating wind turbine and ran simulations in the presence of disturbances. In their study, a method using dynamic surface control to achieve stability of a floating wind turbine was described. In addition, a few studies have also discussed the economic feasibility of the floating offshore wind farm (OWF). Myhr et al. [10] analyzed and compared the levelized cost of energy (LCOE) of five different offshore floating wind turbines. They indicated that LCOE of the floating turbines deployed in large scale and at depths of 50–150 m was comparable to that of bottom-fixed turbines. A study by Maienza et al. [16] analyzed the economic sustainability of the new technology by developing a life cycle cost model for OWFs. Their results showed that the average LCOE of the OWF was 9.74 €c/kWh, which was at the lower bound of the typical range for a bottom-fixed OWF. In a recent study, Zhang et al. [17] developed an integrated approach to estimate the LCOE of floating wind power. Their results indicated that the side-by-side layout for wind turbines can reduce LCOE.

1.2.2. Previous LCA studies in floating offshore wind power

Evaluating the potential of floating wind power is more than just considering the criterion of obtaining more stable technology and harvesting more friendly economical value in the design process. Better environmental performance throughout its lifetime will make this new technology more competitive, especially in the case of large-scale deployments. Life cycle environmental impact analysis has already become a major task for the evaluation of new energy technologies [18]. Life cycle assessment (LCA) is a powerful tool for quantifying the environmental impacts of the energy technologies over their life cycle. LCA results can help us understand the optimal environmental output within the selected energy production model, inform policy decisions, and guide the development of the energy sector [19].

The environmental impacts of wind power have been extensively studied based on the LCA approach. A literature review by Mendecka and Lombardi [20] reported up to 148 different wind power LCA studies, among which 32 studies were on the offshore technologies. Nevertheless, only nine LCA studies on floating wind power were identified in the Web of Science to date. The number of LCA studies on this topic is small, which may result from the technology development is still ongoing [13] and the publicly available data used to perform LCA assessment are limited.

The first LCA study on the floating wind power was performed by Weinzettel et al. [21] on a wind farm with 40 floating turbines of 5

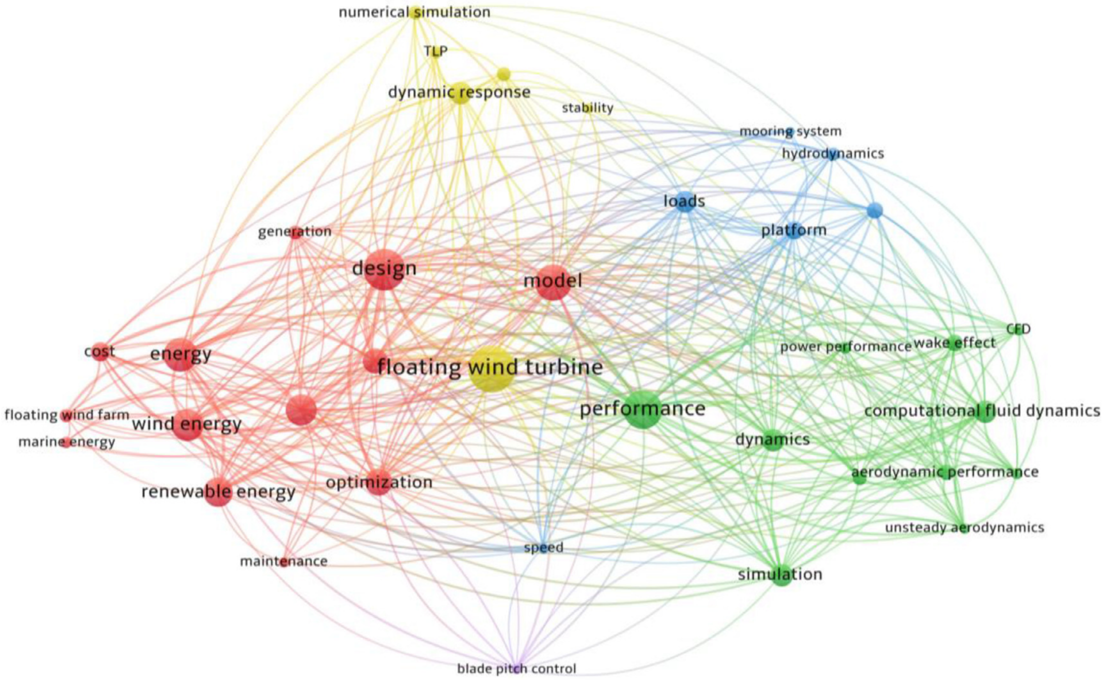


Fig. 2. Visualization atlas of the keyword co-occurrence analysis on the studies related to floating offshore wind power. | The keyword co-occurrence analysis was conducted using the bibliometric software of VOSviewer.

MW. Their results showed that when a higher capacity factor was assumed for the floating OWF, the environmental impacts of the floating OWF were comparable to those of the conventional OWF. Later, an analysis of the greenhouse gas (GHG) emissions and energy performance of an OWF with 100 turbines of 5 MW and six different offshore foundation designs was carried out by Raadal et al. [22]. Tsai et al. [23] compared the environmental benefits of OWF deployment at different distances from shore and water depths based on the U.S. life cycle inventory (LCI) data. One hundred turbines of 3 MW in combination with different types of offshore foundations were considered in their study. Elginoz and Bas [24] executed an LCA study for a multi-use offshore floating platform combining wind and wave energy production. Chipindula et al. [25] conducted a comparative study for the life cycle environmental impacts of three small-scale wind farms at onshore, shallow, and deep-water locations in Texas and the adjoining gulf coast. Wang et al. [26] examined the life-cycle GHG emissions for 2 MW onshore and floating wind turbines, considering only the life cycle of the wind turbine itself. A study by Poujol et al. [27] calculated several environmental impact indicators for a 24 MW floating OWF. Yildiz et al. [28] compared the LCA results of a 2 MW barge-type floating wind turbine with the LCA results of other types of wind turbines. In a recent LCA study by Garcia-Teruel et al. [11], the environmental impacts of two floating OWFs based on two pilot projects were analyzed. The impacts of operation and maintenance (O&M) strategies and vessel choices on the LCA results were highlighted.

1.2.3. Aim and contribution of this work

In summary, there are a few limitations in the floating OWF LCA studies conducted to date. The number of LCA studies on the floating OWFs is less than on the onshore and bottom-fixed offshore wind power technologies. Additionally, the power ratings of the wind turbines considered in most studies were no more than 5 MW, and the scales of the wind farms were relatively small, which may not represent future market trends. Moreover, research on floating OWFs in China started late. The first engineering demonstration floating wind power project jointly developed by China Three Gorges Corporation and Mingyang Smart Energy Group was just connected to the grid in 2021. Therefore, the existing LCA studies mentioned above were based on pilot projects abroad. The background data used in these studies to perform LCA were based on foreign life cycle databases, such as the ecoinvent database. Most LCI data included in these databases were collected based on foreign cases, so LCA results based on these data may not be representative of floating OWFs in China.

To address these gaps, an LCA of the floating OWF was conducted, in which China LCI data were prioritized, though the same material and process parameters can be found in other databases. This analysis was performed using a case study, where 100 wind turbines of 6.7 MW were considered from a large-scale deployment perspective. It should be noted that the current trend in the wind turbine industry is towards 5–10 MW turbines [29]. Although turbines with higher power ratings have been manufactured, 6.7 MW was chosen for this study due to the availability of the data. Uncertainties of the input parameters and background data were discussed in detail after obtaining the LCA results for the baseline case study. Moreover, from the view of large-scale deployment in the next decade, scenario analysis was carried out to discuss the impact associated with different steel production routes on the cumulative GHG emissions from the upstream process of the floating OWF.

Following the introduction, the methods to evaluate the environmental performance of floating wind power deployment are discussed in Section 2. The LCA assessment is elaborated in detail by conducting a case study in Section 3. The results of evaluation are analyzed and discussed in detail in Section 4. The essential conclusions are summed up in Section 5. Finally, some policy recommendations for more sustainable development of floating wind power are given in Section 6.

This study provides new insights into the environmental benefits for floating OWF deployment. The relevant process conditions and procedures in this LCA study are universal, although the LCA analysis was performed based on an individual case. The future LCA study on floating wind power can be expanded to apply on this basis, as technology continues to evolve, and more primary data become available. In addition, the results of this study point to the components or processes resulting in large environmental impacts within the system, thus guiding the development of improved designs for floating OWFs with lower environmental burden.

2. Methods

In this section, the overview of the method to evaluate the life-cycle environmental impacts of floating OWF will be described. In addition, the analysis methods of the uncertainties in foreground and background data will also be described. And the scenario setting will be presented in detail.

2.1. Life cycle assessment

LCA method is widely used to evaluate the environmental burdens of a product or process from materials extraction to waste disposal. Over time, the evaluation system of LCA has been gradually mature [19]. A conventional process-based analysis was used in this LCA study. The main LCA processes follow the principles and framework in International Standardization Organization (ISO) standards 14040 [30] and 14044 [31], which include: (1) Goal and scope definition, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation. These four steps will be described in detail and applied to a case study in Section 3, in order to clearly elaborate how the process-based LCA is conducted to evaluate the environmental impacts of floating wind power.

2.2. Sensitivity analyses

Sensitivity analysis was used to discuss the uncertainty of the LCA results. The uncertainties affecting the results in this study came from the foreground data and background data, since most of the data used to perform this LCA were obtained from literature and databases.

To evaluate the uncertainties of the foreground data, the inputs whose relative contributions to indicator scores exceeded 5% in at least one impact category were identified. Then the effects of a ±20% change to the individual inputs on the results were evaluated [27]. For the uncertainty analysis of the background data, a Monte Carlo simulation based on the pedigree matrix approach was carried out. A confidence interval of 95% was set in this process [27].

2.3. Scenario definition

Life cycle thinking highlights that the sustainable development for a product or system should involve consideration of both the manufacturing process and the upstream activities [32]. Many materials are input into the floating OWF, among which, steel is most in demand. The steel industry is an energy-intensive sector with high GHG emissions. The technological routes for steel production determine the GHG emission intensity in the manufacturing process, which affects the carbon footprint of the floating OWF to a large extent. The installed capacity of the floating OWF will grow rapidly in next decade according to the offshore wind power technology route [12], which is bound to promote significant growth in steel demand. Therefore, from the view of large-scale deployment in the next decade, five scenarios were set to discuss the impact associated with different steel production routes on the cumulative GHG emissions from the upstream process of the floating OWF. Note that the cumulative emissions referred to here were not the sum of the GHG emissions from all life cycle stages, but rather the portion from the steel input. In other words, the focus of the scenario analysis is the impact of upstream steel production processes on the carbon footprint of the floating OWF. The production routes considered in these scenarios were based on blast furnace and basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) production, which are the two main steel production routes.

The cumulative GHG emissions were calculated by Eq. (1). Specific scenario definitions are shown in Table 1. The steel demand and the GHG emission intensity in the production process were set by referring to studies by Farina and Anctil [33] and Hasanbeigi [34], respectively.

$$CEy = \sum_{i=1}^{n} CEi, y - 1 + (AEi, y \cdot SDi, y \cdot GEIi, y) \tag{1}$$

where, CE_y is the cumulative GHG emissions in year *y; $CE_{i,\ y\ \text{-}\ 1}$* is the cumulative emissions of country *i* in year *y - 1; $AE_{i,\ y}$* is the new added installed capacity of floating wind power in country *i* in year *y; $SD_{i,\ y}$* is the steel demand in floating wind power of country *i* in year *y*; and $GEI_{i,\ y}$ is the GHG emission intensity of steel production for country *i* in year *y*.

3. Case study—LCA analysis

In this section, a floating OWF with 100 turbines of 6.7 MW was assumed and used as the object to perform the LCA analysis following the processes mentioned in Section 2.1. The data used to conduct this case study mainly referred to the public literature and related reports, due to the limited data availability from the actual projects in China.

3.1. Goal and scope

The goal of this study was to quantify the environmental impacts resulting from resource and energy consumption in all life cycle stages of the floating OWF based primarily on China LCI data. The focus was mainly to perform a detailed LCA of the floating OWF to provide a new reference for large-scale deployment in the future.

The scope of this LCA study was from cradle to grave. Therefore, the whole life cycle of the floating OWF was divided into four stages: (1) components manufacturing and transport, (2) wind farm construction, (3) O&M, and (4) decommissioning activity. A simplified overview of the system boundary is presented in Fig. 3. The assumed and estimated characteristics of this case study are provided in Table 2. The system was defined as one OWF, which consisted of 100 floating wind turbines and one power transmission system. In addition, 1 kWh of electricity produced from the OWF and delivered to the grid was chosen as the functional unit to facilitate comparability with other LCA results or other renewable energy technologies. Thus, the environmental impacts were provided per kWh.

3.2. Inventory analysis

Inventory analysis is necessary for building the life cycle model [39]. Each procedure divided into the system boundary is defined as a unit process, which consists of foreground data and background data [40]. The foreground data represent the technological system to be modeled and analyzed. Therefore, these data were directly investigated and collected. In fact, foreground data are the details of the materials, energies, and their amounts for each life cycle stage of the system. The equivalent materials, processes, and their associated gross embodied carbon and energy were obtained by linking to the relevant background data included in life cycle database. The Chinese core life cycle database (CLCD) [41] was prioritized in this study. If the corresponding background data could not be found in CLCD, the ecoinvent [42] data were chosen. Fig. 4 shows that the material flows of this case study during the lifetime. The necessary descriptions, assumptions, and data sources of each life cycle stage are given in the four following subsections. The detailed inventory is provided in Appendix A.

3.2.1. Component manufacturing and transport

This stage involved the manufacture and transport of various components in the floating OWF. Electricity generated by offshore wind turbines was converted to high voltage direct current and then transmitted to shore. This is the current leading approach for connecting wind farms far from shore [43]. As a result, components in the floating OWF consisted of wind turbines, floating foundations (floaters), and a power

Table 1
Scenario definitions.

Scenario	Description	Additional notes
S1: Entirety	The GHG emission intensity is the average level of the whole steel industry.	The average level depends on the structure of the whole steel industry and the proportion of each production route [34].
S2: BF-BOF	The GHG emission intensity is the level under the BF-BOF production route.	BF-BOF is also called the primary production route [34].
S3: EAF	The GHG emission intensity is the level under the EAF production route.	EAF is also called the secondary production route [34].
S4: Entirety optimizing	Based on scenario 1, the GHG emission intensity will linearly reach 1.1 t CO_2-eq in 2025 and 0.9 t CO_2-eq in 2030.	The values are predicted by International Energy Agency (IEA) [35]. If the emission intensity in some countries has been at or below 1.1/0.9 before 2025/2030, the original emission intensity is still used to perform the calculation.
S5: EAF optimizing	Based on scenario 3, the GHG emission intensity was assumed to linearly reach 0.68 t CO_2-eq in 2025 and 0.47 t CO_2-eq in 2030.	The values were assumed based on the projections made by IEA. If the emission intensity in some countries has been at or below 0.68/0.47 before 2025/2030, the original emission intensity was still used to perform the calculation.

Fig. 3. System boundary of the floating offshore wind power. | (I) Components manufacturing and transport, (II) wind farm construction, (III) O&M, and (IV) decommissioning activity.

Table 2
Overview of the assumed and estimated characteristics of this case study.

Characteristic	Parameter	Reference
Water depth [m]	60–80	[36]
Distance to shore [km]	12–20	[23,24,36]
Turbine model	GW-150-6700	[37]
Turbine power rating [MW]	6.7	[29,37]
Number of turbines	100	[22]
Maximum annual generating capacity of turbine [GWh]	22.75	[37]
Capacity factor	53.8%	[38]
Foundation type	Semi-submersible	[16,36]
Lifetime [years]	25	[29,36]

transmission system. Wind turbines are largely similar between offshore and onshore wind farms. Each wind turbine mainly included four parts: rotor, nacelle, tower, and transmission cable. Steel, copper, glass fiber and resin were the main raw materials used to manufacture these components. The specific materials and their quantities were estimated with reference to the supplier's data [37]. The floaters, which are essential for wind turbine deployment at different water depths [44], consisted of a floating platform and a mooring system. The semi-submersible platform is considered to be more economical than other floating platform types [16], so it was considered in this study. The platform was applied to the water depth of 60–80 m [36], whose weight and material were estimated based on a public document [45]. It was modeled as a steel structure with a weight of 2750 t in this study. The mooring system included mooring chains and anchors. The weight per length of chain

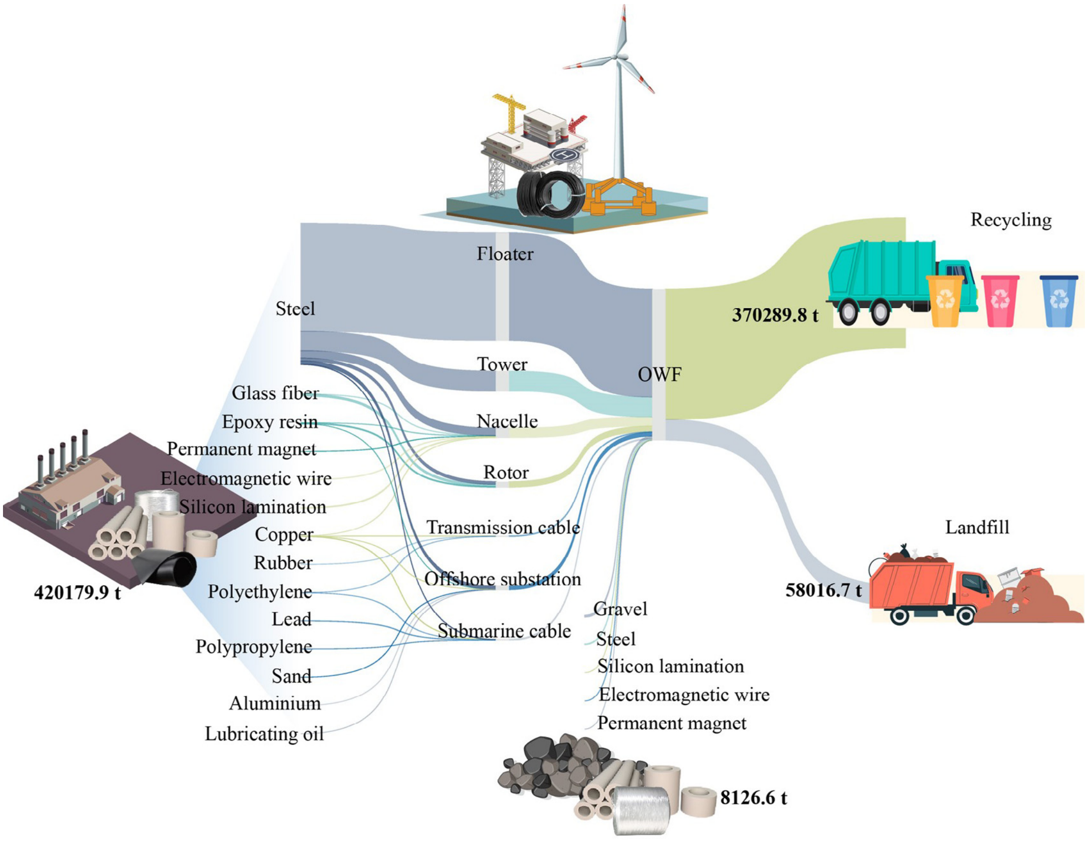


Fig. 4. Material flows of the floating OWF during its lifetime.

was approximated to be 0.38 t/m [46]. Each semi-submersible platform was equipped with four 195 m mooring chains and four 5 t drag embedment anchors [36]. The power transmission system included an offshore substation and submarine cables. The offshore substation consisted of a Jacket structure and upper electrical equipment. Submarine cables consisted of inter-array cables (33 kV) and export cable (132 kV). A 20 km export cable and 45 km inter-array cables were assumed. The specific materials and their amounts for the system were estimated with reference to the data provided by Elginoz and Bas [24].

All components of the wind turbines were assumed to be trucked to the assembly port after being manufactured at the supplier's manufacturing site. Floaters are generally constructed in a shipyard [47]. Thus, these substructures were assumed to be towed directly to the assembly port by barge. And each part of the power transmission system was assumed to be directly transported to the installation site by lorry and barge. Moreover, transport for the raw materials was also considered. Considering the distance and component weight, all transportations occurring in this stage were approximated in tkm.

3.2.2. *Wind farm construction*

This stage mainly involved the installation of the floating wind turbines and offshore substation. In addition, laying of the submarine cables was included. It was assumed that the floating wind turbines were first assembled at the assembly port and integrally towed to the floating OWF. Then installation of the offshore substation and submarine cables was carried out in the floating OWF.

Installation procedures for the floating wind turbines involved the use of fuel oil facilities like jack-up vessels and tugboats. The operation time for each jack-up vessel to assemble and transport one turbine was generally one day [48]. Five jack-up vessels were assumed to work for 24 h per day in this study. Fuel oil consumption for the operation of one vessel was calculated at 170 l/h [23]. Additionally, transport for the jack-up vessels was included in this stage. Each jack-up vessel was towed by two tugboats. The fuel oil consumption for one tugboat was calculated at 596 l/h [11]. As mentioned above, the offshore substation included two parts of the Jacket structure and the substation equipment on top of it. In this study, the installation processes for the substation were assumed to be the same as that of a wind turbine. Moreover, 5517 m^3 excavation with a hydraulic digger was estimated for seabed preparation and 3990 t gravel was used for scour protection [24]. The laying of the submarine cables included route clearance, tie-in, and in-field installation. Excavation volumes of the trenches for inter-array and export cables were estimated as 0.6 m^3 and 0.8 m^3 per meter cable, respectively [24].

3.2.3. *O&M*

The O&M concept considered in this study was that turbines can be disconnected and towed to shore for major maintenance operations and core components replacement [11]. A lifetime of 25 years was assumed for this floating OWF [36]. Two types of services were considered for the floating OWF maintenance: maintenance and corrective maintenance.

Regarding the preventative maintenance, frequency per year was assumed to be 2.5 days per wind turbine, 7.5 days for the substation, and 14 days for the cables. Each day was assumed to include 24 h of working time [23]. Regarding the corrective maintenance, replacing failed core components is one of the most common tasks. In this study, the generator was assumed to be the core turbine component that needs to be replaced completely when failures occur. Failures in other components were considered to be repairable without replacement [23]. The number of generators requiring full replacement for the floating OWF through its lifetime was considered as four, and the annual failure rate

Table 3
Overview of the environmental impact indicators evaluated in this case.

Impact category	Acronym	Unit
Global warming potential	GWP_{100}	kg CO_2 eq
Abiotic depletion potential	ADP	kg Sb eq
Acidification potential	AP	kg SO_2 eq
Eutrophication potential	EP	kg PO_4^{3-} eq
Particulate matter	RI	kg PM2.5 eq
Ozone depletion potential	ODP	kg CFC-11 eq
Primary energy demand	PED	MJ

was considered as 0.999 failures per year [11]. In addition, the mooring chains and anchors were assumed to be replaced rather than repaired. A total of 24 mooring chains and 25 anchors needed to be replaced in the floating OWF's lifetime, and their failure rates were considered as 0.148 and 0.157 failures per year, respectively [11].

3.2.4. Decommissioning activity

At end of the lifetime, all components of the wind turbines and topside of the substation were assumed to be removed, whereas submarine cables and mooring systems were assumed to be left on the sea floor. Decommissioning was assumed as a reverse installation process in this study. Therefore, the energy consumption for component disassembly was the same as in the assembly process. The material recovery rates were set in the background data, so the recycling model was not considered at this stage. Metals of steel, cast iron, copper, aluminum and lead were 90% recovered [23]. The environmental burdens of subsequent material treating activities were not included in this study since it considered that these burdens should be allocated to the users of recycled material and the waste disposal systems [22].

3.3. Impact assessment

Generally, one of several life cycle impact assessment (LCIA) methods such as ReCiPe (H) [49], is selected to perform the impact assessments. Environmental impact indicators like climate change, acidification, and resource depletion are generally included in these LCIA methods. The inventory collected in the previous step will first be converted into the aggregated results for different resource consumption or pollutant emission. Then the results will be calculated as the relevant indicator scores after determining the LCIA method [50]. The calculation process for the indicator scores can be described using the following equation:

$$EIj = \sum_{i=1}^{n} Ei \cdot CFij \tag{2}$$

where, EI_j is the score of the indicator *j;* E_i represents the consumption of resource *i* or the emission of pollutant *i* (i.e., the aggregated results from inventory conversion); and CF_{ij} is the equivalent coefficient of parameter *i* to indicator *j* (i.e., characterization factor).

The LCIA method selected in this study was CML 2002 [51], which has strong versatility due to the lack of regional difference in the characterization factor of each indicator. Additionally, multi-indicators analysis is necessary to understand the environmental performance of the RES in multiple dimensions [52]. Thus, seven impact categories were selected in this study. The details are shown in Table 3. It should be noted that eFootprint [53], which was developed by China and is the world's first online LCA evaluation system, was used to perform the inventory conversion and indicator calculation in this study.

Note that in this study, these indicator scores were normalized to dimensionless values using Eq. (3) to allow for comparability between different indicators.

$$NEIj = EIj/NRj \tag{3}$$

Table 4
Normalization factors.

Impact category	value	Unit
GWP_{100}	4.18E+13	kg CO_2 eq
ADP	7.78E+12	kg Sb eq
AP	3.78E+11	kg SO_2 eq
EP	3.77E+09	kg PO_4^{3-} eq
RI	9.92E+10	kg PM2.5 eq
ODP	2.10E+08	kg CFC-11 eq
PED	3.80E+14	MJ

where, NEI_j is the normalized value of the indicator *j*; and NR_j is the normalization baseline value for the indicator *j*. The normalization factors representing the global level in the study by Sleeswijk et al. [54] were used as the baseline value in this study. The specific normalization baseline values are shown in Table 4.

3.4. Interpretation

The interpretation of this LCA study involved the results of seven impact categories for the baseline case. Except for GWP_{100}, the indicators were not compared with other forms of renewable energy generation discussed in previous studies, due to inconsistencies in the LCIA methods and selected indicators. Additionally, uncertainties of the foreground data and background data were discussed in detail. The specific interpretation for the results of this LCA study was carried out in detail in Section 4.

4. Results and discussion

In this section, the LCA results for the baseline case will be discussed and analyzed. The GHG emissions from different types of renewable energy generation will be compared and discussed. The results of the five scenarios will be discussed in detail. And the limitations of this study will be discussed.

4.1. LCA results of the baseline case

As shown in Fig. 5a, among all life cycle stages, the largest contributors to the environmental impacts were the components manufacturing and transport and the O&M. The contributions of the components manufacturing and transport stage to environmental impact categories accounted for more than 80%, ranging from 84.14% (PED) to 97.92% (RI), except in the case of ODP, where this stage accounted for only 36.97%. However, the contributions of transport to all environmental categories were very small, at only 0.05% to 2.52%. Manufacturing of the wind turbines and floaters was the key contributor in this stage. Many materials were used to manufacture these components, among which, steel accounted for the largest share, indicating that the processing of this material requires careful consideration. It is worth noting that the impacts of submarine cable manufacturing on ADP and EP were obvious, accounting for 63.91% and 28.06%, respectively. The O&M phase made the largest contribution to ODP at 59.41%. In this stage, preventive maintenance contributed more than 65% to all environmental impact categories. Especially in ODP, the contribution was as high as 98.6%. For the construction and decommissioning phase, the relative contributions to all categories were no more than 5%. As with the O&M phase, the relative contributions of these two stages to ODP were more prominent compared to other impact categories. A common feature of these three stages was that they all involved the frequent operation of fuel machinery.

Normalization made each environmental impact category comparable at a uniform level. Fig. 5b shows that the OWF wind had the greatest contribution to EP, compared with other environmental impact categories. It also indicates that floating wind power has relatively low GWP. The carbon footprint of the floating OWF was small compared to other

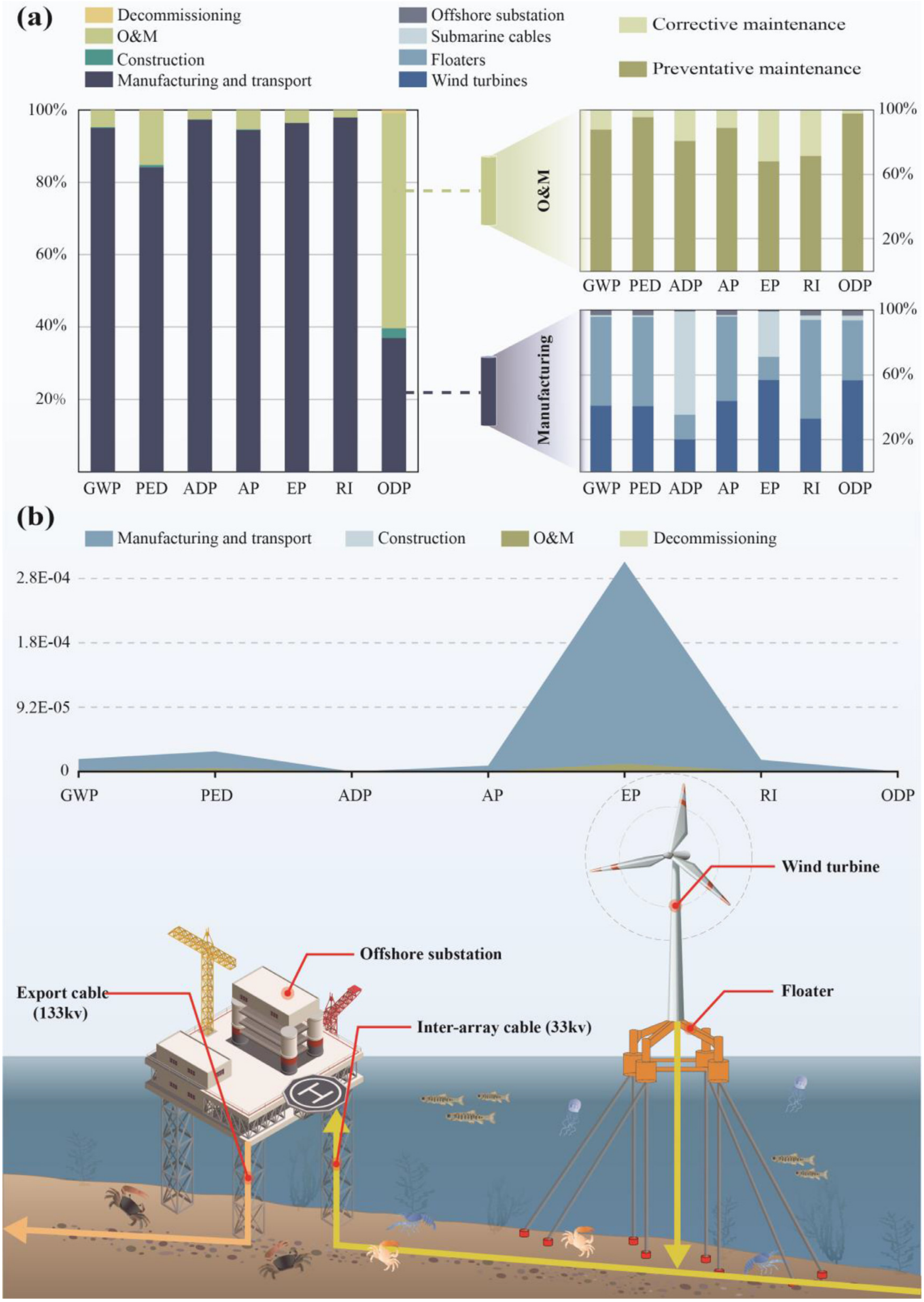
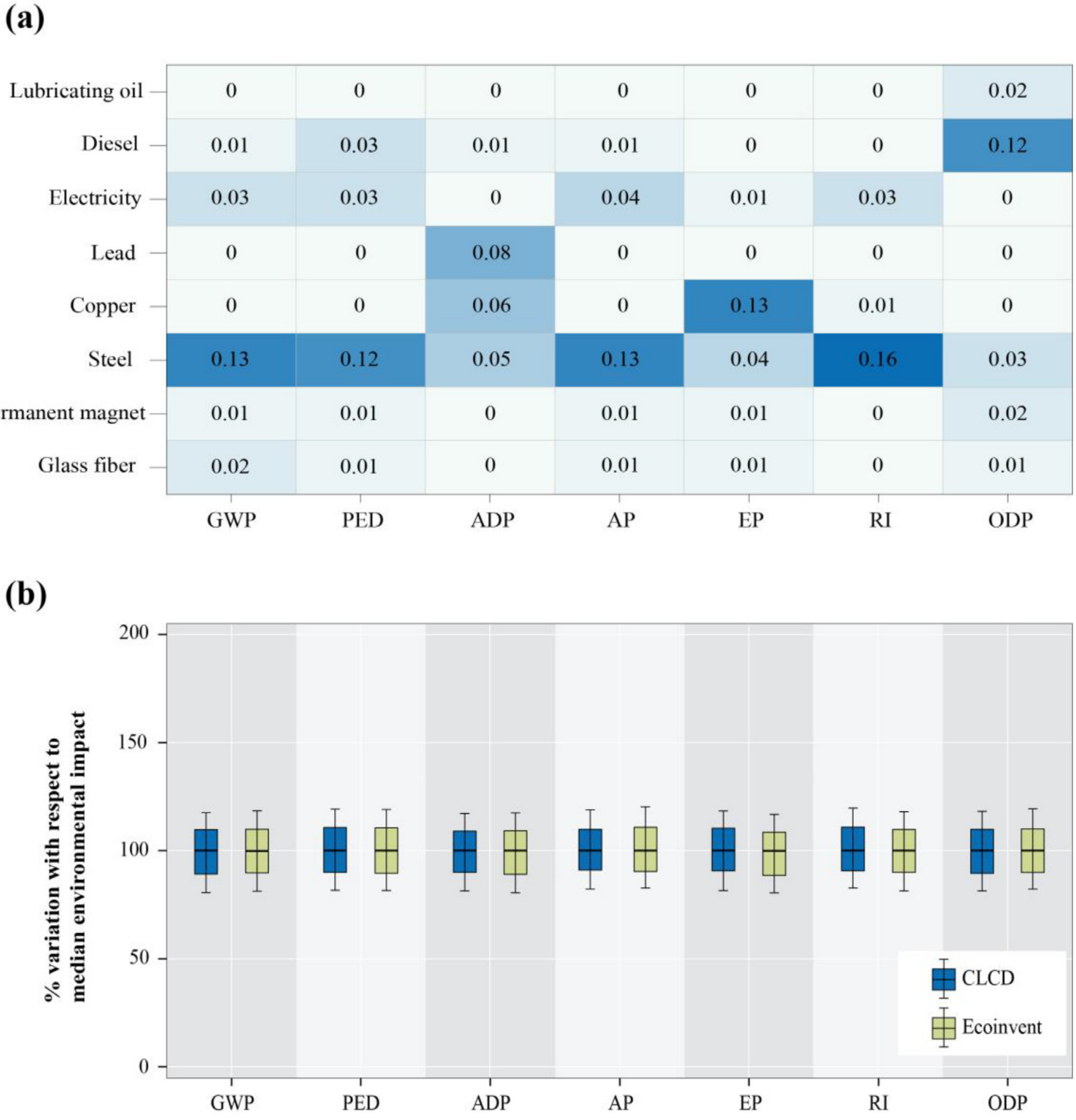


Fig. 5. Life cycle environmental impacts for the baseline case. | (a) Relative contributions of the floating OWF to each impact category in each life cycle stage. (b) Normalized analysis of the LCA results.

environmental footprints such as EP and PED. The GHG emissions of the four life cycle stages were 24.5, 0.05, 1.21 and 0.02 g CO_2-eq/kWh, respectively. Furthermore, the environmental burdens of the floating OWF mainly came from the components manufacturing at the beginning of its lifetime.

4.2. Sensitivity analysis of the LCA results

The input parameters shown in Fig. 6a were those whose relative contributions to the indicator scores exceeded 5% in at least one environmental category. Fig. 6a shows the effects of a ± 20% change for these individual inputs on LCA results. Steel was the main parameter



	GWP	PED	ADP	AP	EP	RI	ODP
Lubricating oil	0	0	0	0	0	0	0.02
Diesel	0.01	0.03	0.01	0.01	0	0	0.12
Electricity	0.03	0.03	0	0.04	0.01	0.03	0
Lead	0	0	0.08	0	0	0	0
Copper	0	0	0.06	0	0.13	0.01	0
Steel	0.13	0.12	0.05	0.13	0.04	0.16	0.03
Permanent magnet	0.01	0.01	0	0.01	0.01	0	0.02
Glass fiber	0.02	0.01	0	0.01	0.01	0	0.01

Fig. 6. Sensitivity analysis of the LCA results. | (a) Given the uncertainties of the foreground data, the effects of ±20% variation in input parameters on the LCA results. (b) Statistical distribution of the LCA results in each impact category considering the uncertainties in background data (representing percentiles 2.5, 25, 50, 75, and 97.5, i.e., 95% confidence interval).

affecting the environmental performance of the floating OWF. A ± 20% change in this parameter resulted in a ± 3% to ± 15% change in the indicator score of each environmental category. As mentioned above, steel was the main material used to manufacture the turbine components and floaters, so the upstream production processes should be taken seriously. Additionally, copper which was highly sensitive to EP, was the main material used in the submarine cables manufacturing. Notably, copper can be recycled continuously without compromising its characteristics. Since the floating OWF contributed more to EP than other impact categories, developing approaches for recycling submarine cables is very important for improving the environmental performance of the floating OWF. Other inputs related to components manufacturing and other stages had limited effects on the variability of the LCA results, remaining below ± 3% in most categories.

The background database used in this study was mainly the CLCD. Some unit processes, however, were linked to the ecoinvent database, as the relevant process data could not be found in the CLCD database. The results in Fig. 6b indicate that the uncertainty in the background data provided by the two LCA databases was low in all selected impact categories. For all indicator scores, 95% of the values ranged between ± 20% of the median.

4.3. Comparison of the GHG emissions from renewable energy generation

As mentioned in Section 3, the indicators and LCIA methods were inconsistent across different LCA studies, so only the GHG emission intensity was compared and discussed in this study. Fig. 7 shows an approximate range of the GHG emissions intensity for different types of renewable energy generation. It should be noted that the values in Fig. 7 were only used to determine an approximate level of the life cycle GHG emissions for different renewable energy technologies, due to differences in system boundaries, technology assumptions, and methodologies. Rigorous direct comparisons require extensive LCI coordination efforts to rectify differences in analytical assumptions between studies [55], which is beyond the scope of this study.

The life cycle GHG emission intensity of the floating OWF evaluated in this study was 25.76 g CO_2-eq/kWh. This result was within the range of the most existing LCA studies for the floating wind power, which was about 12 to 44 g CO_2-eq/kWh. The life cycle GHG emissions of the floating OWF with one hundred wind turbines of 5 MW discussed by Raadal et al. [22] were between 18 and 31.40 g CO_2-eq/kWh. And for a floating OWF with one hundred turbines of 3 MW, Tsai et al. [23] indicated that the GHG emissions ranged from 32.88 to 38.10 g CO_2-eq/kWh. A

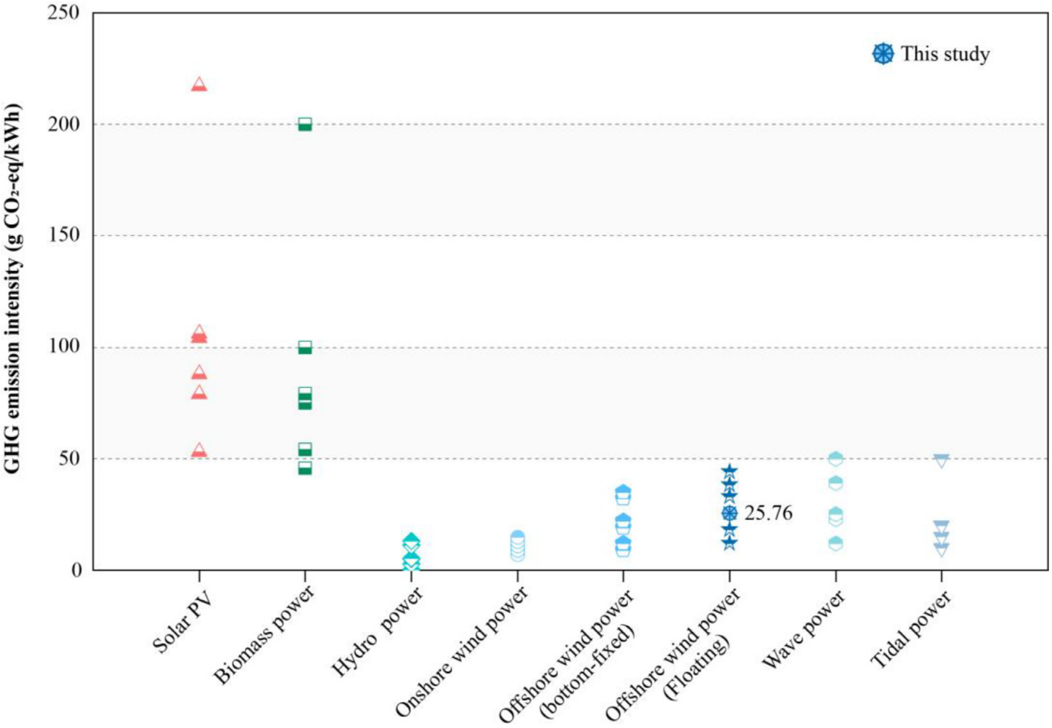


Fig. 7. GHG emissions intensity for different types of renewable energy generation [11,22,23,56–58].

recent study performed by Garcia-Teruel et al. [11] showed that the GHG emission intensity for a floating OWF was roughly from 31.10 to 37.40 g CO_2-eq/kWh. This result corresponded to the case considering five wind turbines of 9.5 MW in combination with semi-submersible floaters. To sum up, large-scale floating wind power deployment will not bring a large carbon footprint. Additionally, the higher power rating of the wind turbine may be beneficial to the GWP for the floating OWF.

Overall, solar photovoltaic (PV) and biomass power have the highest emission intensities among renewable energy generation technologies. The emission intensity of PV is roughly 53 to 217 g CO_2-eq/kWh, and that of biomass power is between 46 and 200 g CO_2-eq/kWh [56]. PV is one of the most promising renewable energy generation technologies. The solar radiation it utilizes is practically unlimited relative to the scale of human demand. However, the manufacturing of the core raw materials needed for PV, such as polysilicon and aluminum, is an energy-intensive process. The GHG emission intensity of aluminum production is as high as 17 t CO_2-eq/t [59], much higher than that of the crude steel production. Regarding biomass power, various forms of bioenergy and different ways to utilize these forms of bioenergy have resulted in an extremely wide estimated range of the life cycle GHG emissions. In addition, information on the life cycle GHG emissions from other marine technologies such as wave power and tidal energy, is extremely limited [56]. This lack of information reflects the immaturity of current marine energy technologies. Moreover, the carbon footprints of hydropower and onshore wind are low to date. Considering only the activities related to infrastructure construction, and not considering the emissions from the decomposition of biomass submerged by water, the highest emission intensity is only 11.2 g CO_2-eq/kWh [57]. And the emission intensity for most onshore wind is roughly 7.1 to 14.8 g CO_2-eq/kWh [58]. But it is clear that the use of land space is gradually becoming saturated. Therefore, offshore wind power is competitive and has great potential among renewable energy generation technologies. The floating OWF has a relatively optimistic outlook even though the technology has a greater upfront investment and more complex offshore operations compared to the bottom-fixed technology. While bringing greater productivity, its GHG emissions are comparable or lower than those of the bottom-fixed technology as the capacity factor increases and the failure rate decreases.

4.4. Scenario analysis

The new installed capacity of the floating OWF will break megawatt level by 2026, reaching 1.67 GW (Fig. 8a). If the average GHG emission intensity from the steel production across the whole steel industry is used for calculation, the cumulative emissions will reach nearly 2.98 Mt CO_2-eq by 2030 (S1). If the BF-BOF routes are followed, the cumulative emissions will reach nearly 4.11 Mt CO_2-eq by 2030 (S2). Under the EAF routes, however, the value can be reduced by approximately 2.88 Mt CO_2-eq compared to scenario 2, reaching 1.23 Mt CO_2-eq (S3). Thus, steel production routes significantly affect the future GHG emissions of floating OWF. According to the net-zero scenario of the steel production from 2018 to 2030 projected by IEA, the average GHG emission intensity of global steel production will decrease linearly to 1.1 t CO_2-eq/t by 2025 and linearly to 0.9 t CO_2-eq/t by 2030 [35]. If the average emission intensity of the steel production in each country reaches the predicted level, the cumulative emissions can be reduced by approximately 1 Mt CO_2-eq compared to scenario 1 (S4). If the EAF production routes are further optimized, the value may be as low as 1.03 Mt CO_2-eq by 2030 (S5). This is much lower than other scenarios. From the results above, it is clear that the EAF production route is optimal for reducing the GHG emissions. EAF production is a secondary steel production process that primarily uses steel scrap, which plays an important role in reducing the GHG emission intensity from the production process [60].

The curves of the cumulative GHG emissions do not change significantly before 2025. One of the most direct reasons is the scale of installed capacity is small. The cumulative installed capacity will only reach around 645 MW in 2024. And the increase is relatively slow during the period of 2020–2024. In addition, floating wind power will be deployed mainly in Europe before 2025. The average GHG emission intensity of steel production in Europe is not high, at about 1.15 t CO_2-eq/t (Fig. 8b). Thus, there is no significant growth change in the curves. After 2025, Asia and North America will be the main markets

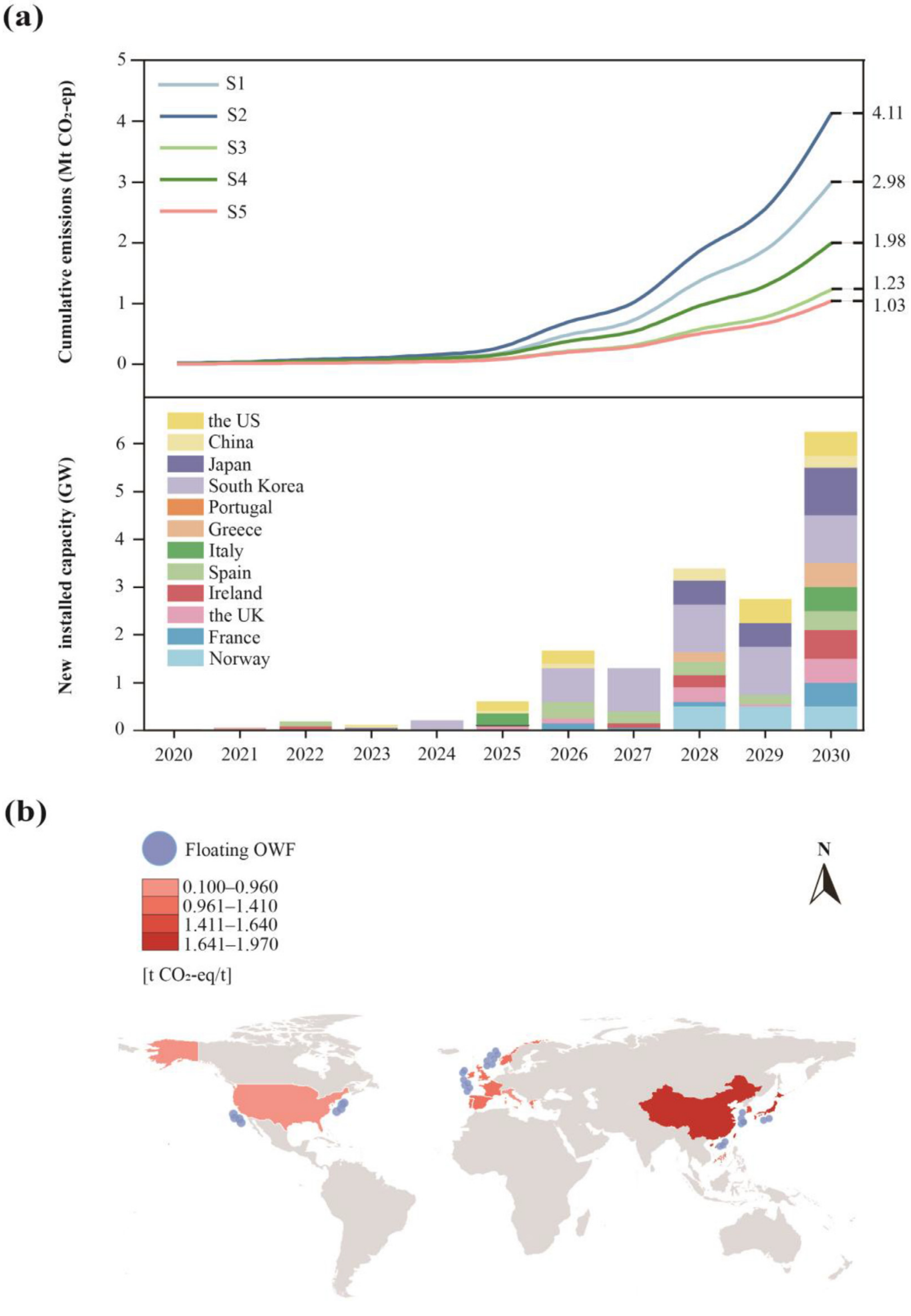


Fig. 8. GHG emissions from global floating wind power deployment for 2020–2030. | (a) Prediction of the cumulative GHG emissions of offshore wind power technology with various steel production routes. The new installed capacity was provided by GWEC's Global Offshore Wind Report 2021 [12]. (b) Average GHG emission intensity of steel production in different countries, where large-scale floating OWFs will be deployed.

for floating wind power. And as can be seen from Fig. 8b, the average emission intensity of steel production in Asia is much higher compared to Europe, at about 1.83 t CO_2-eq/t. Therefore, the curves begin to rise sharply from 2026. It is worth mentioning that the average emission intensity in the United States (US) is only around 0.96 t CO_2-eq/t, due to a high proportion of EAF production in its steel industry. Moreover, the average emission intensity in China is the highest, reaching around 1.97 t CO2-eq/t. This is because over 90% of steel is produced through the BF-BOF routes in China, and pig iron is usually preferred as the raw material rather than scrap steel in its EAF routes [34]. Hence, clean EAF routes and the utilization of steel scrap are essential to lowering the GHGs emission intensity of floating wind power.

4.5. Limitations

The environmental impacts discussed in this study were the GHG emissions and other harmful pollutant emissions resulting from the resource and energy consumption in all life cycle stages of a floating OWF. However, the environmental impacts of deploying a floating OWF are not limited to those caused by resource and energy consumption. The impacts of wind farm construction and operation on the marine benthic environment and atmospheric physical characteristics were not included in the assessment scope of this study. For example, the hard substructures introduced into the marine environment may result in different ecological effects [61]. The wake effect caused by wind turbine operation may affect local temperature, precipitation, and wind speed. For a more comprehensive and multi-dimensional environmental impact assessment, these physical and ecological impacts on the marine environment should be included in the assessment system in the future.

The LCA method used in this study was process-based. This traditional LCA method can only trace upwards a finite layer of material inputs and associated environmental burdens due to limitations in data and workload [62]. Namely, this method can only consider some relevant supply chain paths in an economic system. A hybrid LCA method can be used in future research to make up for this deficiency. The hybrid LCA method combines traditional process-based LCA with environmentally extended input-output analysis. Generally, the hybrid LCA can be divided into three steps [62]: (1) The production chain of a product is divided according to the process-based LCA and an inventory of direct material inputs for each chain is constructed, (2) The Leontief inverse matrix of input-output model is used to calculate the cumulative environmental stress factors of the relevant sectors corresponding to the direct input materials. The Leontief inverse matrix considers all supply chain paths within the economic system, thus extending the system boundaries of traditional LCA [63], and (3) The life cycle environmental impacts of the system can be calculated through the direct material inputs inventory and the cumulative environmental stress factors of the relevant sectors for each material. In addition, the method used to analyze the uncertainty of the foreground data is not appropriate to identify possible interactions between parameters. Variance-based global sensitivity analysis may be applied in the future to further refine the solution to the foreground data uncertainty. This approach utilizes the second moment properties to compute the sensitivity index of a variable [64]. Moreover, Chakraborty et al. [65]. proposed a hybrid sensitivity analysis approach coupled polynomial correlated function expansion with distribution-based sensitivity analysis. This hybrid method can perform sensitivity analysis of the system entailing both dependent and independent random variables without the need of any specific transformations.

The foreground data used to perform this LCA study were mainly from the literature and related reports. Primary data from actual projects are extremely important to the quality of LCA results. However, the latest primary data have not been collected because domestic floating offshore wind power has just entered the engineering demonstration stage. In addition, there has been no relevant research in China. Thus, the LCA results of this study can only provide a general reference. With the continuous improvement of floating offshore wind power technology, as much baseline data as possible should be collected to reflect the real situation of the system.

5. Conclusions

In this study, seven environmental impact indicators were calculated for a OWF with 100 turbines of 6.7 MW using the LCA method, and background data were mainly from the Chinese core life cycle database (CLCD). From the view of global deployment, the impacts of the different steel production routes on the cumulative GHG emissions of floating OWF were analyzed. Limitations of this study were discussed. The main conclusions can be drawn as follows:

(1) The case study indicated that floating wind power has the greatest impact on eutrophication. Copper strongly affects this impact category. A ± 20% change in this parameter resulted in a ± 13% change in the indicator score. And steel was the main parameter affecting the environmental performance of the floating OWF. A ± 20% change in this parameter resulted in a ± 3% to ± 15% change in the indicator score of each environmental category. Additionally, the carbon footprint of this floating OWF was 25.76 g CO_2-eq/kWh. This result is relatively optimistic compared to other renewable energy generation methods.

(2) Floating offshore wind power will grow rapidly in 2026, and the cumulative installed capacity will reach approximately 16.6 GW by 2030. The impact of steel production routes on the carbon footprint of floating wind power is great. Under the blast furnace and basic oxygen furnace routes, the cumulative GHG emissions from the upstream process of floating wind power will reach 4.11 Mt CO_2-eq by 2030. If the electric arc furnace routes are followed, the value will be only up to 1.23 Mt CO_2-eq. Asia and North America will be the main markets for floating wind power after 2025, however, the average GHG emissions intensity of steel production in Asia is much higher than in North America, at about 1.83 t CO_2-eq/t. The value in North America is relatively low at about 0.96 t CO_2-eq/t, due to a high proportion of EAF production in its steel industry.

(3) The environmental impacts discussed in this study were those resulting from the resource and energy consumption in all life cycle stages of the floating OWF. Physical and ecological impacts were not considered in the assessment scope. In addition, the LCA method used in this study can only trace upwards a finite layer of material inputs and associated environmental burdens due to limitations in data and workload. A hybrid LCA method can be used in future research to make up for this deficiency. And the method used to analyze the uncertainty of the foreground data is not appropriate to identify possible interactions between parameters. Variance-based global sensitivity analysis may be applied in the future to further refine the solution to the foreground data uncertainty. Moreover, the foreground data used to perform this LCA study were mainly from literature and related reports. More baseline data should be collected in the future to improve the reliability of the LCA.

6. Policy implications

Floating offshore wind power technologies are developing rapidly. Larger-scale floating OWF will be deployed in Asia, Europe, and North America in next decade. Studies have shown that the life cycle GHG emissions of large-scale deployment are relatively low. In this respect, floating wind power is competitive in promoting the transformation of energy systems. However, in other environmental categories such as eutrophication, the negative impacts cannot be ignored. Additionally, life cycle thinking emphasizes that the sustainable development of a system should consider upstream production activities. Therefore, some policy recommendations for more sustainable development of floating offshore wind power are given below:

(1) The floating offshore wind power industry should develop methods for recycling submarine cables. Copper is the main raw material used for the cables, and manufacturing copper components leads to increased eutrophication. Fortunately, copper has the potential to be recycled continuously without compromising its characteristics. If copper is recycled,

the environmental performance of the floating OWF will improve.

Additionally, steel production routes greatly affect the carbon footprint of floating wind power. The steel sector should optimize the production process continuously to make it cleaner. The share of electric arc furnace (EAF) production routes in the whole steel industry can be increased and the EAF production technology can be further improved, so that the average GHG emissions- intensity from steel production can be further reduced, thus minimizing the GHG emissions of the floating OWF in the manufacturing phase. The remanufacturing process of the wind turbine could make a positive impact as well. Steel makes up 80% of wind turbine components. If each component is remanufactured to reach or exceed the original specifications, it will not only shorten the delivery time of the equipment but also improve the return on investment (ROI).

Moreover, if the utilization rate of steel scrap as the raw material in the EAF production routes is increased, the GHG emissions intensity from the production process can be significantly reduced.

(1) From the national level, individual countries should actively promote technological innovation and transformation to low-carbon technologies. Accelerating the decarbonization of the electricity grid is one of the most important means to reduce the GHG emissions from manufacturing process. Regions with large-scale floating wind power deployment in the future can increase the share of clean fuels used in all life cycle stages. Governments can adopt financial incentives to enhance the development and implementation of cleaning technologies such as waste-heat and waste-energy recycling technologies.
(2) More baseline data need to be collected to improve the environmental impact assessment system. A more comprehensive marine environment monitoring system should be established so that the ecological risks can be evaluated. Assessment methods should be further refined to reflect the environmental performance of floating OWFs in more dimensions in the future.

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

Data will be made available on request.

Acknowledgments

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Appendix A. Life cycle inventory

Item	Component	Quantity	Material/Energy	Amount	Unit	Database
Wind turbine [29,37]		**1**				
	Rotor	**1**		**1.58E+02**	**t**	
	Blade	3	Glass fiber	5.46E+01	t	Ecoinvent 3.5
		1	Epoxy resin	2.52E+01	t	Ecoinvent 3.5
	Hub	1	Steel	3.14E+01	t	CLCD-China
	Pitch system	**1**	Steel	4.72E+01	t	CLCD-China
	Nacelle	1	Glass fiber	**2.67E+02**	**t**	Ecoinvent 3.5
	Cover	1	Epoxy resin	7.80E+00	t	Ecoinvent 3.5
		1	Steel	6.40E+00	t	CLCD-China
	Frame	1	Steel	4.58E+01	t	CLCD-China
	Generator	1	Permanent magnet	1.12E+02	t	Ecoinvent 3.5
		1	Electromagnetic wire	3.90E+00	t	CLCD-China
		1	Silicon lamination	1.25E+01	t	CLCD-China
		1	Steel	2.35E+01	t	CLCD-China
	Low voltage transformer	1	Copper	1.21E+01 1.90E+00	t	CLCD-China
		1	Steel	2.13E+01 4.70E+00	t	CLCD-China
	Yaw system	1	Steel	1.50E+01 **5.58E+02**	t	CLCD-China
	Hydraulic system		Steel	1.20E+02 4.16E+02	t	CLCD-China
	Control cabinet		Steel	2.00E+01	t	CLCD-China
	Tower		Steel		**t**	CLCD-China
	Transition part		Steel		t	CLCD-China
	Principal part				t	
	Connection				t	
	Cooling system	1	Steel	2.80E+00 **1.73E+01**	t	CLCD-China
	Transmission cable	**1**	Copper	1.00E+01 4.00E+00	**t**	CLCD-China
	Energy consumption		Rubber	3.30E+00	t	Ecoinvent 3.5
			Polyethylene	1.25E+03	t	CLCD-China
			Electricity		t	CLCD-China
					MWh	
Floater [36,45,46]		**1**				
	Floating platform	**1**		**2.75E+03** 2.75E+03	**t**	
	Semi-substructure	1	Steel	**3.16E+02** 2.96E+02	t	CLCD-China
	Mooring system	**1**	Steel	2.00E+01	**t**	CLCD-China
	Mooring chain	4	Steel		t	CLCD-China
	Anchor	4			t	

(continued on next page)

Item	Component	Quantity	Material/Energy	Amount	Unit	Database
Power transmission system [24]		**1**				
	Inter-array cables—33kV	**5**		**1.31E+03** 2.77E+02	**t**	
	Export cable—133kV	**1**	Copper	3.55E+02	t	CLCD-China
			Lead	8.35E+01	t	CLCD-China
			Polyethylene	5.48E+01	t	CLCD-China
			Polypropylene	5.38E+02 **1.76E+03**	t	CLCD-China
			Steel	4.41E+02	t	CLCD-China
			Copper	4.43E+02	**t**	CLCD-China
			Lead	1.57E+02	t	CLCD-China
			Polyethylene	8.76E+01	t	CLCD-China
			Polypropylene	6.31E+02	t	CLCD-China
			Steel		t	CLCD-China
					t	
	Offshore substation	**1**		**1.04E+04** 1.38E+02	**t**	
	Energy consumption		Sand	1.73E+01 9.86E+03	t	CLCD-China
			Epoxy resin	7.56E+01 7.45E-01	t	Cut-off[1]
			Steel	3.00E+00 1.01E+02	t	CLCD-China
			Aluminum	4.26E+00 1.84E+02	t	Cut-off
			Cast iron	5.52E-01	t	Cut-off
			Chromium steel	1.52E-01	t	Cut-off
			Copper	4.48E-01	t	Cut-off
			Glass fiber	2.07E-02	t	Cut-off
			Lubricating oil	3.66E-01	t	Ecoinvent 3.5
			Polyester resin	6.90E-02	t	Cut-off
			Polyethylene	3.45E-01	t	Cut-off
			Rubber	6.90E-03	t	Cut-off
			Nickel	3.68E+00	t	Cut-off
			Alkyd paint	1.90E+03	t	Cut-off
			Kraft paper	1.95E+05	t	Cut-off
			Polycarbonate	6.23E+01	t	Cut-off
			Silver	2.37E+01	t	Cut-off
			Sulphur hexafluoride		t	Cut-off
			Electricity		MWh	CLCD-China
			Natural gas		m^3	CLCD-China
			Diesel		t	CLCD-China
			Heavy fuel oil		t	CLCD-China

[1] This study followed the 1% cut-off rule: when the weight of an ordinary material is less than 1% of the product weight, the upstream production data of the material can be ignored.

		Heavy fuel oil	2.37E+01	t	CLCD-China
Transportation					
	Raw materials—lorry, 46 t		6.30E+07	tkm	CLCD-China
	Turbine parts—lorry,46 t		5.01E+06	tkm	CLCD-China
	Floater—barge		6.13E+04	tkm	Ecoinvent 3.5
	Inter-array cables—lorry, 46 t		1.57E+05	tkm	CLCD-China
	Inter-array cables—barge		1.96E+04	tkm	Ecoinvent 3.5
	Export cable—lorry, 46 t		2.11E+05	tkm	CLCD-China
	Export cable—barge		2.64E+04	tkm	Ecoinvent 3.5
	Offshore substation—lorry, 46 t		3.45E+06	tkm	CLCD-China
	Offshore substation—barge		2.16E+05	tkm	Ecoinvent 3.5
Installation [11,23,24,48]					
	Wind turbines pre-installation				
	Transport for jack-up vessels	Diesel	2.40E+02	t	CLCD-China
	Assembly and transport of turbines	Heavy fuel oil	3.84E+02	t	CLCD-China
	Turbine installation	Diesel	3.73E+02	t	CLCD-China
	Pump out water	Heavy fuel oil	7.67E+02	t	CLCD-China
	Turbine fixed in installation site	Diesel	9.15E+00	t	CLCD-China
	Submarine cables	Heavy fuel oil	4.30E+04	m^3	Ecoinvent 3.5
	Route clearance	Gravel	2.30E+02	t	CLCD-China
	Excavation for seabed preparation	Diesel	1.63E+03	t	CLCD-China
	Tie-in and installation		5.52E+03	m^3	Ecoinvent 3.5
	Scour protection		4.81E+01	t	CLCD-China
	Offshore substation				
	Excavation for seabed preparation				
	Transport for jack-up vessel				
	Topside installation	Heavy fuel oil	3.80E+00	t	CLCD-China
	Scour protection	Gravel	3.99E+03	t	CLCD-China

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		Heavy fuel oil	2.37E+01	t	CLCD-China
O&M [11,23,36]					
	Preventative maintenance	Diesel	3.31E+04	t	CLCD-China
	Turbine maintenance	Lubricating oil	3.05E+03	t	Ecoinvent 3.5
	Substation maintenance	Diesel	9.92E+02	t	CLCD-China
	Cables maintenance	Lubricating oil	6.35E+02	t	Ecoinvent 3.5
	Corrective maintenance	Diesel	1.06E+03	t	CLCD-China
		Heavy fuel oil	1.49E+06	tkm	Ecoinvent 3.5
	Turbines towed to port	Steel	2.67E+02	t	CLCD-China
	Replacement of heavy component	Permanent magnet	4.48E+02	t	CLCD-China
		Electromagnetic wire	1.56E+01	t	Ecoinvent 3.5
	Materials for generators	Silicon lamination	5.00E+01	t	CLCD-China
		Steel	9.40E+01	t	CLCD-China
			1.90E+03	t	CLCD-China
	Materials for mooring system				
Decommissioning [22,23]					
	Wind turbines decommissioning	Heavy fuel oil	3.84E+02	t	CLCD-China
	Transport and removal of turbines	Diesel	2.40E+02	t	CLCD-China
		Heavy fuel oil	3.80E+00	t	CLCD-China
	Transport for jack-up vessels	Diesel	4.81E+01	t	CLCD-China
	Offshore substation decommissioning				
	Topside removal				
	Transport for jack-up vessel				

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