Floating versus offshore wind turbines

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FLOATING VERSUS OFFSHORE WIND TURBINES: A COMPARATIVE LIFE CYCLE ASSESSMENT

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Abstract. *The technology and utilisation of wind energy systems is growing rapidly. The floating wind turbine system is a large-scale power plant and state-of-the-art technology. However, the environmental impacts of such a system should be considered and compared to that of onshore and offshore wind energy systems. The environmental impact of the barge-type floating wind turbines is investigated using life cycle assessment methodology and comparing data between onshore, offshore and floating wind turbines. The foundation of the floating is square, ring-shaped (open in its centre) and connected to the seabed with synthetic fibre-nylon rope and an anchorage system. The manufacture, operation, disposal and recycling stages of the wind turbine have been evaluated. For the barge-type floating wind turbine, it has been found that the largest environmental impact comes from the manufacturing stage. Global warming potential and energy payback time of the barge-type floating wind turbine is higher than onshore, offshore (2MW) and floating (5MW) wind turbines. Global warming potential of the barge-type floating wind turbine was found 18.6 gCO_2eq./kWh. Moreover, it has been found that the recycling stage is a positive contribution in terms of environmental impact.*

1 INTRODUCTION

Despite progress toward the seventh United Nations Sustainable Development Goal, and positive evidence that energy is becoming more sustainable and widely available, the world continues to rely on traditional fossil fuels [1]. The latter is the primary cause of climate change, accounting for roughly 60% of total world greenhouse gas emissions [1].

The world's population is growing, and so are energy demands. Also, climate change is a menace to the entire world. Renewable energy can be used to address rising energy demands and climate change. Wind energy is a clean, renewable, and safe form of energy. Wind energy is renewable, inexhaustible, CO_2-free, and environmentally friendly. It has no harmful effects on natural vegetation or human health, does not use fossil fuels, isn't radioactive, and is rapidly developing technologically. Wind energy production is expected to exceed 650 GW by 2020, up from 59.7 GW the previous year [2]. In terms of market size, the growth rate of wind energy in 2019 was 10.1 percent greater than in 2018, but lower than in 2017 and 2016. In 2019, China and the United States, which have the largest wind markets in the last five years, installed 27.5 and 9.1 GW of wind energy, respectively. Despite the fact that European countries installed 15.4 GW of wind energy capacity in 2019, the rate of growth was 27 percent greater than the previous year but 10% lower than the rate in 2017 [2,3,4]. According to the 2019 report "Wind Energy in Europe: Outlook to 2023" [5], it is expected that Germany, Spain, and the United Kingdom's wind energy capacity would increase dramatically by 2023. From 2019 to 2023, a total of 65 GW of wind energy will be installed across nine European countries. In the coming years, Germany will add 11.2 GW of onshore wind energy, making it the European continent's leader in this sector. Furthermore, in terms of onshore wind capacity, Spain (8.7 GW), France (8.1 GW), and Sweden (7.5 GW) behind Germany. The UK will install 6.4 GW of offshore wind energy during the next five years, followed by the Netherlands (4 GW), Germany (2.9 GW), Denmark (1.7 GW), and France (1.7 GW) (1.3 GW). The United Kingdom will overtake Germany as Europe's leader in offshore wind energy [5,6].

Thanks to new technologies, wind turbines which have taller structures, longer blades, and set up different locations can be constructed and thus wind energy capacity is rising. Onshore wind turbines with innovative hybrid structures have higher hub heights, allowing for better wind energy generation at higher elevations [7]. Floating wind turbines, being a recent high-innovation development in the wind energy sector, are located in deep waters where fixed-bottom offshore wind towers are not feasible because of the cost of the foundation and the lack of technology [8,9]. The carbon emissions emitted during the manufacture, installation, operation, and disposal of these new wind turbine structures must also be considered. Given these innovative turbine constructions, this study focuses on evaluating the environmental implications of floating wind turbines using the life cycle assessment methodology.

2 LIFE CYCLE ASSESSMENT—AN OVERVIEW

Sustainability revolves around achieving an equal balance among the economic, environmental, and social factors throughout the life cycle of any given product [10]. Based on the ISO 14040 and 14044 standards, the LCA is a rigorous approach for evaluating the environmental effect of energy, raw materials, and waste, as well as emissions originating from a product, process, or service [11,12]. The LCA is carried out in the four phases outlined below. The objective, scope, methodology, and limits of the system are specified in the first phase, and the life cycle inventory (LCI) is determined in the second phase, with inputs and outputs at the system's borders. The third phase is to conduct a life cycle impact assessment (LCIA) using inventory data obtained and assembled in the previous phase to estimate environmental effect potentials, and the results are interpreted in the fourth phase [10].

The LCA methodology used in this research. The system boundary encompasses the six stages: manufacturing, transportation, erection, operation and maintenance, disposal, and recycling. The following should be highlighted in relation to the six stages of the LCA for wind turbines:

1. Production/Manufacture: the materials and parts are selected and made for the wind turbine. The tower, blades, nacelle, foundation, etc. are produced.
2. Transportation: the manufactured parts are transferred to the area where the system will be installed. Here, the distance between the factory and the installation area is important.
3. Erection: installation of the system is completed. The wind turbine parts must be of movable size.
4. Operation and maintenance: operation and periodic maintenance of the system are carried out.
5. Disposal: a turbine that has completed its life cycle is dismantled.
6. Recycling: any recyclable materials are sent back to the manufacturer. Other materials are sent to the landfill. [11].

Until date, LCA studies have concentrated on various wind turbine designs and sizes, both onshore and offshore. Demir and Taskin investigated the environmental impact of various heights and sizes of onshore wind turbines [13]. To reduce environmental emissions, they counsel large-scale wind turbines made of alternative environmentally benign materials. The LCA of 2 and 1.8 MW steel wind towers was conducted by Guezuragaet et al. [14]. They emphasised the greater environmental emissions that occurred during the production process. The LCA of concrete, steel, and composite wind turbine towers of various heights and diameters was studied by Gervásio et al. [15]. Steel towers have been said to have a lower environmental impact than other types of towers, according to study of Gervásio et al. The environmental impact of two tall hybrid towers was studied by Gkantou et al. [7]. The towers were made up of two sections: a top tubular section and a bottom lattice section with four or six legs. The four-legged hybrid tower had less of an impact on the environment than the six-legged hybrid tower. Stavridou et al. compared a 2 MW tall tubular tower against a lattice wind tower, concluding that the lattice tower has a smaller environmental impact and a shorter energy payback period [16]. Furthermore, Kaldellis and Apostolou investigated the life cycle energy and CO_2 emissions of offshore and onshore wind energy systems [17]. Offshore wind turbines have a high carbon footprint, but they are the best option due to their high energy efficiency. Huang et al. assessed the life-cycle assessment of offshore aeolian farms using two different substations (onshore and offshore) [18]. They emphasised that the offshore substation has a high environmental impact; they also concluded that the impact can be mitigated by using recycled materials.

Four research on the LCA of floating wind turbines have been published so far. Weinzettel et al. compared the life cycle assessments of a 5 MW sway floating wind power plant, a 2 MW offshore turbine, and a natural gas power system [19]. The floating wind power plant's energy payback time and CO_2 emissions were calculated to be 5.2 months and 3 $\times 10^{-4}$ kg, respectively. The sway floating wind power plant has a lower environmental impact than a 2 MW offshore wind power plant or a natural gas electricity system in their study. Randal et al. compared the greenhouse gas (GHG) emissions and energy performance of six different wind turbines [20]. These wind turbines have a variety of foundation and mooring designs, including spar, two tension-leg-buoy (MIT and UMaine TLB), sway, semi-submersible floating, and jacket bottom-fixed. According to Randal et al., the MIT TLB had the smallest GHG emissions at 18.0 g CO_2 eq./kWh, even though its semi-submersible design had a higher value (31.4 gCO_2eq./kWh). Elginoz and Bas examined the life cycle impact of a floating multiuse offshore platform farm that combines a wind and a wave energy system [21]. In addition, this study compares a spar platform to a single-use semi-submersible platform over a 25-year lifetime. As a result of their research, they deduced that the semisubmersible floating wind turbine has a high value of terrestrial ecotoxicity, freshwater aquatic ecotoxicity, and eutrophication. The economic and environmental impact of a tension leg platform floating wind turbine was investigated by Kausche et al. [22]. The first goal of their research was to look into ways to reduce the economic impact and investment costs, and the second was to reduce CO_2 emissions during the system's manufacturing process. Steel-concrete, steel-reinforced concrete, and steel structure floating wind turbines were designed and evaluated in terms of economic and environmental impact. In terms of CO_2 emissions, the steel-concrete turbine has a lower value of around 395 t/MW, while the steel-concrete wind turbine has the best economic result.

The LCAs of wind turbines were analysed using criteria such as turbine size, height, design, location, and type of turbine as a result of a thorough literature research. The current study intends to evaluate the environmental consequences of the barge-type floating wind turbine to the environmental impacts of the spar floating, onshore, and jacket offshore wind turbines in light of the literature review.

3 LIFE CYCLE ANALYSIS OF A FLOATING WIND TURBINE

The LCA of a barge-type floating wind tower was investigated in this study using the boundaries presented section 2. This study relied on both real site data and published data [23,24,25]. The floating wind turbine's life cycle assessment was then carried out using the open-source GEMIS 5 software [26].

With regard to the barge-type floating wind turbine design, a 60 m steel tube tower made up of two pieces makes up the wind tower. The lower half is 25 metres long, and the upper part is 35 metres long. The tower and the transition piece weigh a total of 133 tonnes (t) and 50 tonnes (t), respectively. The turbine is a 2 MW Vestas 80V with a blade length of 40 metres [23,24]. The floating foundation is a square ring-shaped platform made of concrete (C55/67) and steel reinforcement that is open in the centre, 36 m wide, 9.5 m high, and 7.5 m draught (Figure 1). This steel component is intended to be used as a grilled plate on the platform. Pool is a square ring with a diameter of 20 m and a diameter of 20 m. The semi-taut mooring system is used. For deep water, this anchoring method is a great option [27]. Synthetic fibre-nylon ropes connect the floating platform to the seabed in this mooring line system. The rope's main advantage is that it is resistant to corrosion [22,24,25,28].

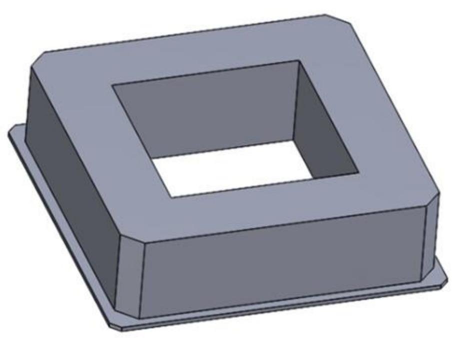

Figure 1. Platform of the barge-type floating wind turbine

3.1 Manufacture stage

European contractor companies developed the barge-type floating wind turbine. The mass distribution of the system is shown in Table 1. The platform with the mooring system has the most mass, as depicted. The mooring system is comprised of steel, cast iron, polyurethane foam, and nylon fibres, and the floating wind turbine platform is made of concrete and steel. The fluke and shank, with dimensions of 7 m x 4 m x 1 m and 3 m x 7 m x 3 m, respectively, are the two sections of the anchor. The tower, nacelle, and rotor are the other components of the system, all of which were made in Spain. Steel, aluminium, cast iron, glass fiber-reinforced plastic, and copper make up the nacelle. Three blades constructed of glass fiber-reinforced plastic and cast iron make up the rotor [24].

Components	Unit	Value
Rotor	tonne	28.5
Nacelle	tonne	64
Tower	tonne	183
Platform	tonne	5472.5

Table 1: Mass distribution of the barge-type floating wind turbine

3.2 Transportation stage

This stage entails moving all components from the factory/workshop to the construction site. This stage's LCA is dependent on by the type of vehicle, distance (factory to site area), and emissions produced during fuel production [7].

3.3 Erection stage

The land erection stage was completed with the use of a forklift and a heavy mobile crane. In addition to the sea erection stage, the floating wind turbine was hauled by three tugboats to the sea area of construction.

3.4 Operation and maintenance stage

During the operation stage, it was estimated that the barge-type floating wind turbine would have operated for 3000 hours per year [28]. The yearly electricity generation is 6 GWh, based on the performance of the wind turbine. During the maintenance stage, it is assumed that the wind turbine gearbox will need to be replaced once during the turbine's lifetime, and that all components will need to be inspected and greased twice a year by qualified professionals.

3.5 Disposal and recycling stages

The parts of the barge-type floating wind turbine that have completed their life cycle are either transferred to a landfill area or sent for recycling.

4. LIFE CYCLE INVENTORY (LCI)

A life cycle inventory (LCI) consists of energy requirements and input-output material flows of a product system. A wind turbine's LCI is its energy requirements and input-output data, which are derived from the product's manufacturing, transportation, erection, operation and maintenance, and disposal stages [7]. The obtained data was categorised and entered into the software according to the life cycle stages and product units. Table 2 shows the data collected from the barge-type floating wind turbine.

Component	Stage	Comment	Unit
Tower	Manufacture	Steel	133 t
Tower	Manufacture	Steel (Transition part)	50 t
Rotor	Manufacture	Glass Fibre	23.5 t
Rotor	Manufacture	Cast Iron	5 t
Nacelle	Manufacture	Steel	35 t
Nacelle	Manufacture	Aluminium	2 t
Nacelle	Manufacture	Copper	7 t
Nacelle	Manufacture	Glass-Reinforced Plastic	4 t
Nacelle	Manufacture	Cast Iron	16 t
Platform	Manufacture	Concrete	4350 t
Platform	Manufacture	Steel	912.5 t
Platform	Manufacture	Cast Iron	60 t
Platform	Manufacture	Nylon Fibre	126 t
Platform	Manufacture	Polyurethane	24 t
Tower-RNA [1]	Transport	Vessel	165,300 tkm
Tower-RNA	Transport	Truck	13,775 tkm
Platform	Transport	Truck	87,000 tkm
Platform	Transport	Truck	16,560 tkm
Platform	Transport	Truck	77,450 tkm
Platform	Transport	Truck	94,500 tkm
Platform	Transport	Truck	2400 tkm
Platform	Transport	Truck	6000 tkm
Tower	Erection	Crane	7.92 h
Rotor	Erection	Crane	10.56 h
Nacelle	Erection	Crane	10.56 h
Platform	Erection	Crane and Tugboat	105.56 h
Tower	Disposal & Recycling	Landfill	27.45 t
Rotor	Disposal & Recycling	Landfill	24.25 t
Nacelle	Disposal & Recycling	Landfill	12.55 t
Platform	Disposal & Recycling	Landfill	4500.675 t
Tower	Disposal & Recycling	Transport to	549 tkm
Rotor	Disposal & Recycling	Transport to	485 tkm
Nacelle	Disposal & Recycling	Transport to	251 tkm
Foundation	Disposal & Recycling	Transport to	900,013.5 tkm

Table 2: Data collection—life cycle inventory [7,8,24,25,29].

RNA[1]: rotor-nacelle assembly

5 RESULTS

The LCA for the barge-type floating wind turbine consider all stages of the life cycle, from raw materials through disposal. The lifetime of the floating wind turbine is assumed to be 20 years.

- Abiotic depletion potential for fossil fuels (ADPF) focused on the non-renewable resource is measured in mega joules (MJ);
- Global warming potential (GWP) is related to CO_2 emissions measured in CO_2-equivalent;

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- The acidification potential (AP) values represent the total amount of acidic air emissions. This is calculated in terms of SO_2-equivalent;
- The ratio of primary energy to yearly energy generated by a wind turbine is known as the energy payback time (EPT). This time is calculated in months and years [7].

Figures 2 and 3 show the global warming potential, AP, and ADPF of each component and life cycle stage. In terms of global warming potential, acidification potential, and abiotic depletion potential for fossil fuels, the foundation component has the highest proportion of all components, as seen in Figure 4. The foundation component accounts for 81 % of the floating wind turbine's total equivalent GWP. This could be related to the use of steel, concrete, nylon fibre and polyurethane, and the long usage of the crane and tugboats. Similarly, the ADPF and acidification potential percentage of the foundation component is higher than the other 78% and 79%, components respectively. The tower component has the second greatest GWP and ADPF, at 10% and 11%, respectively. Both the tower and nacelle components have the second highest AP, which is reported to be 9%. The use of huge quantities of iron and steel in the nacelle's production/manufacture stage is the main reason for its high value. The rotor component, on the other hand, has the lowest GWP, AP, and ADPF values, coming in at approximately 4%.

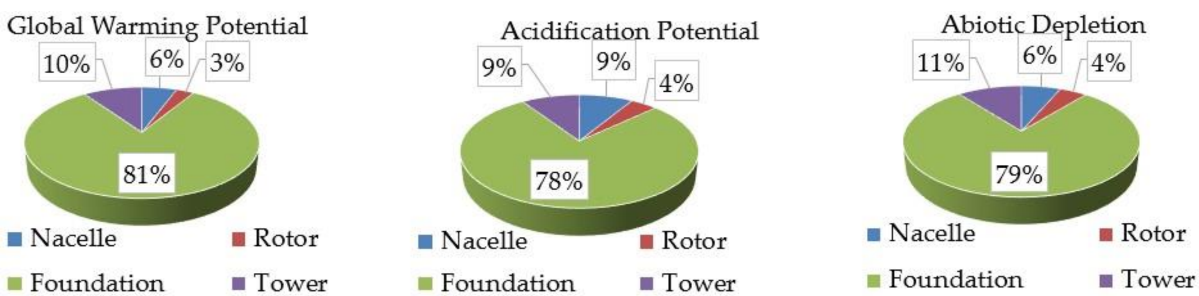

Figure 2. Contribution of the parts of the floating wind turbine to GWP, AP and ADPF

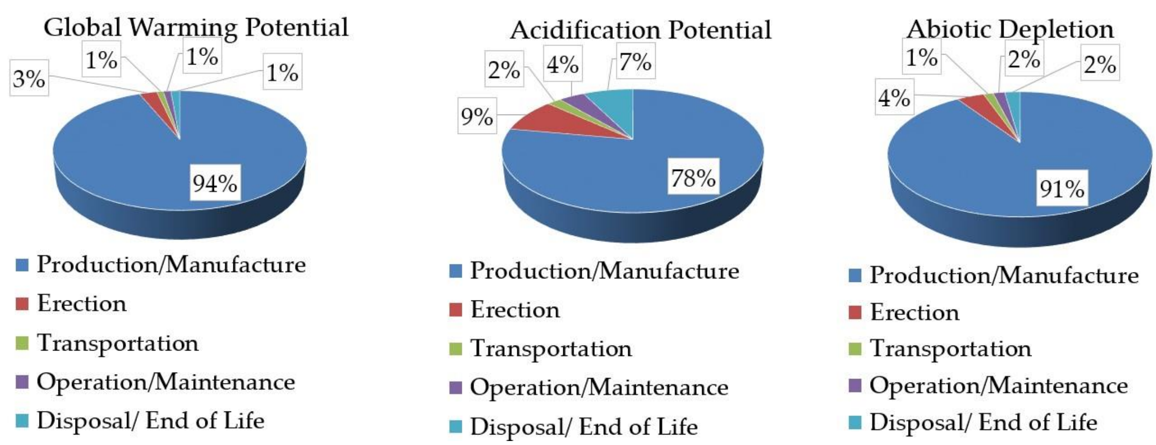

Figure 3. Contribution of each life cycle stage of the floating wind turbine to GWP, AP and ADPF

Figure 3 shows that production/manufacture is the stage with the greatest contribution of global warming potential (CO_2), acidification potential (SO_2), and abiotic depletion potential for fossil fuels in terms of share among life cycle stages (MJ). The transportation stage has the least contribution to GWP, AP, and ADPF. When analysing the contribution to GWP, AP, and ADPF, it is obvious that the erection stage is substantially higher than the other stages. Since this erection stage involves fuel consumption and long-term crane and tugboats operation, the GWP, AP, and

ADPF values are projected to be greater than in earlier stages. In terms of energy performance, the energy payback time, as defined in this section, has been calculated as 1.13 years. EPT values ranged from 1.6 to 2.7 years in the aforementioned studies. As a matter of fact, EPT and energy performance of the wind energy have opposite correlations. Hence, it is expected that the smaller the EPT, the better the energy performance.

5.1 Comparison of the barge-type floating wind turbine LCA results with those of other types of wind turbines

In this part, the results of the LCA of the barge-type floating wind turbine are compared with those from 2 MW onshore, 2 MW offshore and 5 MW floating wind turbines [18,22]. According to the GWP results given Figure 4, the barge-type floating wind turbine contributes the most (18.6 gCO_2 eq./kWh), while the 2 MW onshore wind turbine contributes the least (7.09 gCO_2eq./kWh). One of the most essential considerations is that the barge-type floating wind turbine platform is constructed with a substantial amount of concrete and steel. Therefore, the respective value was expected to be high. Furthermore, the installation of floating and offshore wind towers is more time-consuming and requires the use of large cranes, hydraulic hammers, heavy-duty forklifts, pile drives, vessels, and tugboats. The operation of this equipment consumes fossil fuel resources, having, as consequence of this consumption, high CO_2 emissions to the atmosphere.

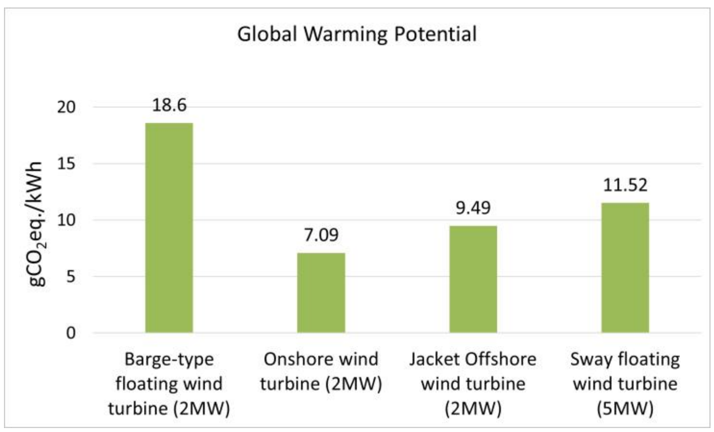

Figure 4. Total global warming potential for floating, onshore, and offshore wind turbine

As shown in Figure 5, despite the fact that the AP of the barge-type floating wind turbine is nearly 15 times greater than that of the onshore and jacket offshore wind turbines, the AP value of the floating wind turbine (5 MW) is greater than that of the barge-type floating wind turbine (representing 0.11 and 0.05 gCO_2 eq./kWh, respectively). The reason for the high AP value is due to the usage of iron and steel in all components (nacelle, tower and foundation) and construction. These differences between the on-/offshore and floating wind turbines are due to the high usage of iron in the platform, the mooring system and the nacelle. Since the sway floating turbine (5 MW) is large-scale, it consists of a high amount of iron material in the nacelle part, so the amount of iron used causes the AP value to be increased.

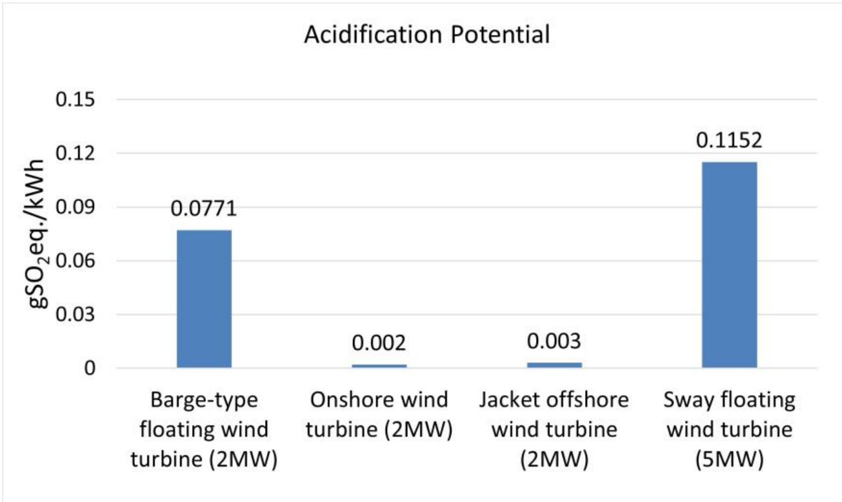

Figure 5. Total acidification potential for floating, onshore, and offshore wind turbine.

6 CONCLUSIONS

Previous studies have focused on the LCA of sway, spar, tension-leg-buoy, semisubmersible, and tension-leg-platform wind turbines excluding the barge-type floating one. In this paper, the life cycle analysis of the barge-type floating wind turbine was performed, and the LCA of the barge-type floating wind turbine was compared to the LCA of 2 MW, onshore, offshore and 5 MW sway-type floating wind turbines by considering global warming potential and acidification potential. The manufacturing stage of the barge-type floating wind turbine has a high GWP and AP. The usage of a large amount of steel, nylon fibre, and concrete is the main cause for this. The other LCA stages contribute less than 6% of the overall GWP contribution. In terms of acidification potential, the 5 MW floating wind turbine was shown to have the largest contribution to SO_2 emissions. The use of cast iron for the mooring system of the floating wind turbine accounts for the maximum value. The GWP can be decreased by using alternative materials, components and recycling materials. Specifically, it is recommended during the development of the manufacturing stage to decrease environmental impacts.

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