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Article

Life Cycle Assessment of a Barge-Type Floating Wind Turbine and Comparison with Other Types of Wind Turbines

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Abstract: The intensive increase of global warming every year affects our world negatively and severely. The use of renewable energy sources has gained importance in reducing and eliminating the effect of global warming. To this end, new technologies are being developed to facilitate the use of these resources. One of these technological developments is the floating wind turbine. In order to evaluate the respective environmental footprint of these systems, a life cycle assessment (LCA) is herein applied. In this study, the environmental impact of floating wind turbines is investigated using a life cycle assessment approach and the results are compared with the respective ones of onshore and jacket offshore wind turbines of the same power capacity. The studied floating wind turbine has a square foundation that is open at its centre and is connected to the seabed with a synthetic fibre-nylon anchorage system. The environmental impact of all life cycles of such a structure, i.e., the manufacture, the operation, the disposal, and the recycling stages of the wind turbines, has been evaluated. For these floating wind turbines, it has been found that the greatest environmental impact corresponds to the manufacturing stage, whilst the global warming potential and the energy payback time of a 2 MW floating wind turbine of a barge-type platform is higher than that of the onshore, the jacket offshore (2 MW) and the floating (5 MW) wind turbines on a sway floating platform.

Keywords: floating wind turbine; offshore wind turbine; life cycle assessment (LCA); global warming potential (GWP); acidification potential (AP); abiotic depletion potential for fossil fuels (ADPF); renewable energy



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1. Introduction

Despite the fact that progress is being made towards the seventh UN sustainable development goal [1], with encouraging signs that energy is becoming more sustainable and widely available, the world still relies on traditional fossil energy. The latter is the dominant contributor to climate change, accounting for around 60% of the total global greenhouse gases emissions [1].

According to the long-term climate change strategy recently agreed, universal access to affordable, sustainable energy services should be ensured by 2030, and society should be climate-neutral by 2050 [2]. According to this, wind energy stands as a prominent renewable source that encourages the development of innovative wind energy systems with enhanced output generation capacity. Such new developments are floating wind turbines or very tall onshore turbines [2].

Increasing environmental problems, energy costs, and diminishing nonrenewable energy sources oblige people to prefer renewable energy sources such as wind, solar, and hydropower [3]. Renewable energy sources are provided from natural resources and are sustainable energies. Renewable energy sources are not only clean, safe, and environmentally friendly, but also cost-effective and inexhaustible [4]. The negative impacts of renewable energy resources are limited and insignificant compared to the other traditional energy resources as sustainable energy has a limited negative impact on natural vegetation

and human health, does not burn fossil sources, has no radioactive effect, and is experiencing rapid technological development [5]. Wind energy is the foremost renewable energy, offering clean energy, economic advantages, and a clear way to reduce greenhouse gas emissions (GHG) [5].

In 2020, wind energy production reached over 650 GW around the world, with 59.7 GW added in the previous year [6]. In 2019, the growth rate of wind energy was 10.1% higher than the 2018 rate in terms of market size, but less than in 2017 and 2016. China and the US, having the biggest wind market size of the last five years, installed wind energy amounting to 27.5 and 9.1 GW, respectively, in 2019. Although European countries erected 15.4 GW of wind energy capacity in 2019, the growth rate of wind energy was 27% higher than the previous year but 10% less than the rate in 2017 [6–8].

According to the 2019 report “*Wind Energy in Europe: Outlook to 2023*” [9], it is accepted that the wind energy capacity of Germany, Spain and the UK will sharply rise by 2023. Installation of 65 GW of wind energy is planned across nine European countries from 2019 to 2023. Germany will install 11.2 GW of onshore wind energy in these years and will be the leader in onshore wind energy in the European continent. Furthermore, Spain (8.7 GW), France (8.1 GW) and Sweden (7.5 GW) come after Germany in terms of onshore wind capacity. Concerning offshore wind energy, the UK will install 6.4 GW of wind energy over five years, followed by The Netherlands (4 GW), Germany (2.9 GW), Denmark (1.7 GW), and France (1.3 GW). The UK will become the leader in offshore wind energy in Europe [9,10].

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 new hybrid structures have taller hub heights and allow better operation of wind energy in higher locations [11]. 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 [12]. Along with the design of these new wind turbine structures, the carbon emissions emitted during their manufacture, installation, operation, and disposal must also be considered. Given these new turbine structures, this study focuses on the environmental impacts 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 [13]. The LCA is a rigorous method that evaluates the environmental impact of energy, raw materials and waste, and emissions resulting from a product, process, or service based on the ISO 14040 and 14044 standards [14,15]. The LCA is carried out in the following four standard steps. In the first step, the purpose, scope, methodologies, and limits of the system are determined, and, in the second step, the life cycle inventory (LCI) is determined with inputs and outputs at the boundaries of the system. In the third step, a life cycle impact assessment (LCIA) is performed with environmental impact potentials determined using inventory data collected and compiled in the previous step, and the results are interpreted in the fourth step [13].

The LCA methodology adopted for this study is depicted in Figure 1. The system boundary (Section 3.2) includes the following six stages that have been considered in all analyses: manufacture, transportation, erection, operation and maintenance, disposal and recycling. With reference to the six stages of the wind turbines’ LCA (Figure 1), the following should be noted:

1. During the production and manufacture stage, the materials and parts are selected and made for the wind turbine, i.e., the tower, blades, nacelle, foundation, etc. are produced.
2. During 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 the critical impact factor.
3. During the erection, the installation of the system is completed. The wind turbine parts must be modular and of movable size.
4. Concerning the operation and maintenance of the system, a periodic maintenance of the system carried out systematically that has to be taken into account.
5. For the disposal, a turbine that has completed its life cycle is dismantled.
6. During the recycling, any recyclable materials are submitted to the manufacturer and the remaining materials are sent to landfill [14,15].

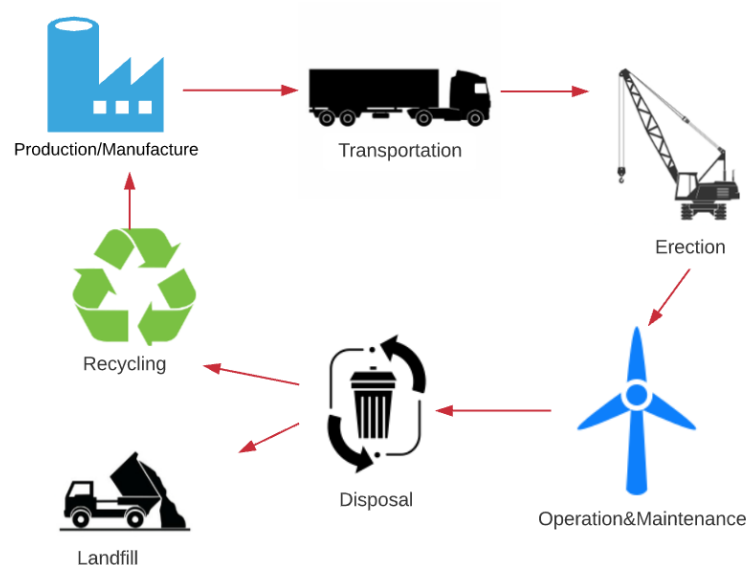


Figure 1. Life cycle assessment stages of a wind energy system.

Until now, LCA studies have been focused on different wind turbine designs and sizes of onshore and offshore wind turbines. Demir and Taskin [16] studied the environmental impact of onshore wind turbines having different heights and sizes. They recommend large-size wind turbines with alternative environmentally friendly materials to decrease the environmental emissions. Guezuraga et al. [17] conducted the LCA of 2 and 1.8 MW steel wind towers. They highlighted higher environmental emissions during the manufacturing phase. Gervásio et al. [18] focused on the LCA of concrete, steel, and composite wind turbine towers having different heights and sizes. It has been pointed out that the environmental impact of using steel towers is less than other towers. Gkantou et al. [11] focused on the environmental impact of two tall hybrid towers. The towers consisted of two parts, a top tubular part and the bottom lattice part with either four or six legs. The four-legged hybrid tower exhibited a lower environmental impact than the six-legged one. Stavridou et al. [19] analysed comparatively a 2 MW tall tubular tower and a lattice wind tower and concluded that the lattice tower has lower environmental impact and energy-payback time. Alsaleh and Sattler [20] studied the environmental impact of large onshore wind farms in the US. The manufacturing stage was more than 60% of the total CO₂ contribution. Moreover, extension of the lifetime of the wind farm, such as to 25 and 35 years, was analysed. These extended lifetimes have lower impacts per kWh of electricity generated. Lanzen and Wachsmann [21] compared the LCA of wind turbines in different geographical locations (e.g., Brazil and Germany) considering the manufacturing locations of the components. They considered the distance from the manufacturing area of wind turbine components to the place of operation of the wind turbine in five different scenarios,

such as production in Germany and operation in Brazil. The scenario of production and operation in Brazil has a lower kg CO₂/kWh than other scenarios. In addition, Kaldellis and Apostolou [22] studied the life cycle energy and CO₂ emission comparison of offshore and onshore wind energy systems. Offshore wind turbines have a large carbon footprint; however, they are the best choice considering their high energy efficiency. Huang et al. [23] evaluated the LCA of offshore aeolian farms considering two different substations (onshore and offshore). They highlighted that the high environmental impact corresponds to the offshore substation; they also concluded that the impact could be moderated using recycled materials. Considering twenty past studies, Bhandari et al. [24] investigated the GHG emissions and the annual energy yields (AEY) of single onshore and offshore wind turbines. The results of Bhandari et al. highlighted a correlation between the GHG to the AEY for onshore wind farms and single wind turbines. Kasner et al. [25] investigated the energy efficiency and environmental effects of wind turbines with a lifespan of 25 years and 50 years, using the sustainable modernization method. To increase the lifetime of the wind turbine to 50 years, it was extended by replacing components, such as rotor, blades, structure parts etc., and maintaining them at the required time. In this study, they analysed the environmental impacts of a wind turbine with a life of 50 years and a new wind turbine that has completed its 25-year lifetime and which will operate again for 25 years. They highlighted that the greenhouse gas emission of the wind turbine with a lifetime 50 years, is lower by 40–50% than that of two wind turbines during their 25-year life periods [25].

LCA of onshore and offshore wind turbines has been investigated in the past as shown in Table 1. These past studies have focused on a wind turbine in a specific area, comparing other wind turbines or renewable energy sources (solar), different heights, wind tower materials (steel, concrete, etc.), and wind turbine size. The results of these LCA studies, environmental impacts and energy payback time of a wind turbine have been calculated and these results have been interpreted.

Table 1. Past studies of LCA of onshore and offshore wind turbine towers.

Authors	Tower Type	Height (m)	Size (MW)	Location	Contributions
Bonou et al. [26]	Onshore and offshore	99.5–92.5 onshore 68.25–87.72 offshore	2.3–3.2 onshore 4.0–6.0 offshore	Europe	The GHG emissions of offshore wind turbine are higher due to more materials and resources (fuel, oil, etc.) for erection and maintenance.
Al-Behadili and El-Osta [27]	Onshore	71	1.65	Libya	Using recycled wind turbine materials gains a reduction of CO ₂ emissions by 55%.
Siddiqui and Dincer [28]	-	-	2.0	Canada	Wind energy has a large environmental impact compared nuclear and hydropower due to its manufacturing stage.
Wang and Sun [29]	Onshore and offshore		1.6 and 3.0	China	Using the short route would decrease the CO ₂ emissions of the transportation stage.
Uddin and Kumar [30]	Vertical and horizontal axis		0.3 and 0.5	Thailand	Reuse of materials could reduce environmental impacts by about 15%.
Oebels and Pacca [31]	Onshore		2.0 and 3.0	Brazil	Steel materials comprise more than 50% of the total CO ₂ emissions.
Wagner et al. [32]	Offshore	-	5.0	German	The foundation and submarine cables cause an increase in total CO ₂ emissions.
Vargas et al. [33]	-	-	2.0	Mexico	The largest energy requirement and environmental impacts come from the nacelle and tower.
Martinez et al. [34]	Onshore	70	2.0	Spain	The largest environmental impacts and energy requirement come from the foundation and nacelle, respectively.
Tremeac and Meunier [35]	Onshore	124	4.5 and 0.25	France	Minimizing the transportation stage, such as short routes and vehicles emitting lower CO ₂ , can be achieved.
Xu et al. [36]	Onshore	65, 50	1.5 and 0.75	China	Taller wind turbines can improve environmental impact indicators.
Chipindula et al. [37]	Onshore and offshore	-	1.0, 2.0, 2.3 and 5.0	Texas	There is an inverse correlation between EPT and the turbine size. If the size increases, EPT decreases.

The first floating wind turbine was built in Scotland in 2017 by Equinor and Masdar Companies [38]. This newly developed wind turbine attracted the interest of researchers who perform LCA on wind turbines. Currently, four studies related to LCA of floating wind turbines have been published [Table 2]. Weinzettel et al. [39] focused on comparative LCA of a 5 MW sway floating wind power plant, a 2 MW offshore turbine, and a natural gas electricity system. The energy payback time and the CO₂ emissions of the floating wind power plant were calculated at 5.2 months and 3×10^{-4} kg, respectively. This comparative study shows that the sway floating wind power plant has less environmental impact than the 2 MW offshore wind power plant and a natural gas electricity system. Randal et al. [40] compared the GHG emission and energy performance of six different wind turbines. These wind turbines have different foundations and mooring designs: spar, two tension-leg-buoy (MIT and UMaine TLB), sway, semisubmersible floating, and jacket bottom-fixed designs. According to the results of Randal et al., the lowest GHG emission was of the MIT TLB at 18.0 g CO₂ eq./kWh, while the semisubmersible design had a higher value (31.4 gCO₂ eq./kWh). Furthermore, they stated that wind turbines with a higher energy payback ratio and lower energy payback time have the best energy performance. Taking account of that shows that MIT TLB and jacket offshore wind turbines have the best performance, and steel platforms and anchor cables have high contributions to the total CO₂ emissions. Elginos and Bas [41] focused on the life cycle assessment of a floating multiuse offshore platform farm that combines a wind and a wave energy system, considering the overall environmental impact. In addition, this study includes a comparative analysis of a spar platform with a single-use semisubmersible one over a lifespan of 25 years. As a result of their research, for the semisubmersible floating wind turbine they concluded that the amount of terrestrial ecotoxicity, freshwater aquatic ecotoxicity and eutrophication is high. Kausche et al. [42] investigated the economic and environmental impact of a tension leg platform floating wind turbine. The first objective of their study was to investigate a possible reduction of the economic impact and investment cost, and the second one was the curtailment of CO₂ emissions during the manufacturing process of the system. Three types of floating wind turbines, steel-concrete, steel-reinforced concrete, and steel structure, were designed and analysed considering the economic and environmental impact. Concerning the CO₂ emissions, the steel-concrete turbine has a lower value of about 395 t/MW, while the best economic result corresponds to the steel-concrete wind turbine [42]. As can be observed in Table 2, the published literature on floating wind turbine towers has been collected and presented in chronological order. The four studies focused on the LCA of five different types of floating platforms, sway, spar, TLB, semisubmersible, and TLP.

Table 2. Literature on LCA of floating wind turbine towers.

Researchers	Year	Hub-Height (m)	Wind Turbine Size (MW)	Water Depth (m)	General Description
Weinzettel et al. [39]	2009	200	5	100–300	Sway floating wind turbine (5 MW) and an offshore wind turbine (2 MW) were examined considering LCA and energy payback time.
Raadal et al. [40]	2014	90	5	100	UMaine spar, MIT TLB (tension-leg-buoy), sway (tension-leg-spar), UMaine semisubmersible, UMaine TLP (tension-leg-platform) and OC4 jacket turbines were investigated considering their LCAs.
Elginos and Bas [41]	2017	90	5	-	The LCAs of semisubmersible and spar platform floating wind turbines were analysed and compared.
Kausche et al. [42]	2018	-	6	40–200	Different material combinations of floating wind tower (tension-leg-platform) were investigated. These combinations were steel, steel-concrete, and steel-reinforced concrete.

As a result of a comprehensive literature review, the LCAs of wind turbines were analysed considering parameters such as turbine size, height, design, location, type of turbine. In the light of the literature review, the present study aims to analyse the environmental impacts of the barge-type floating wind turbine and compare it to the environmental impacts of the spar floating, the onshore, and the jacket offshore wind turbines.

3. Life Cycle Assessment of a Floating Wind Turbine Tower

3.1. The Barge-Type Floating Wind Turbine

For the present study, the LCA of a barge-type floating wind tower was examined considering the boundaries shown in Figure 1. Realistic site data [37,43] and published data [44] were used in this work. The LCA of the floating wind turbine was then conducted using the open-source Gemis 5 software [45]. The software can also perform life cycle costing (LCC) and social life cycle assessment, calculate the carbon and water footprints, produce the environmental product declaration (EPD) and investigate the integrated product policy (IPP). The software is used in the Europa database and it details the required primary energy for the process, the amount of emissions, and the energy flow of the system. The software calculates carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). The unit of these gases is measured in equivalents kg/kWh [17].

The barge-type floating wind tower consists of a 60 m steel tubular tower which is made of two parts. The length of the lower part is 25 m, and the top part is 35 m. The total weights of the tower and the transition piece are 133 tonnes (t) and 50 tonnes (t), respectively. The turbine is a 2 MW Vestas 80V (40 m blade length) [37,43].

The floating foundation is a barge-type platform that is a square ring-shaped (open in its centre, 36 m wide, 9.5 m high, 7.5 m draft) and made of concrete (C55/67) and steel reinforcement (Figure 2). This steel part is designed as a grilled plate in the platform (Figure 3). The square ring shape is named pool, and dimension 20 × 20 m (Figure 3). The mooring system is semitaut. This mooring system is the best solution for deep water [38]. In this mooring line system, synthetic fibre-nylon ropes connect the floating platform to the seabed. The significant advantage of the rope is that it is not prone to corrosion [42–44,46].

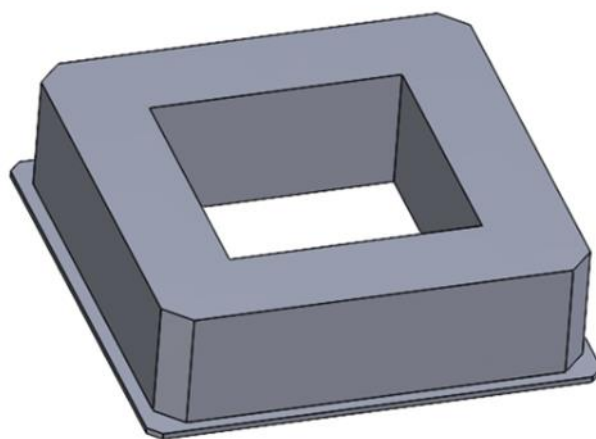


Figure 2. A barge-type platform.

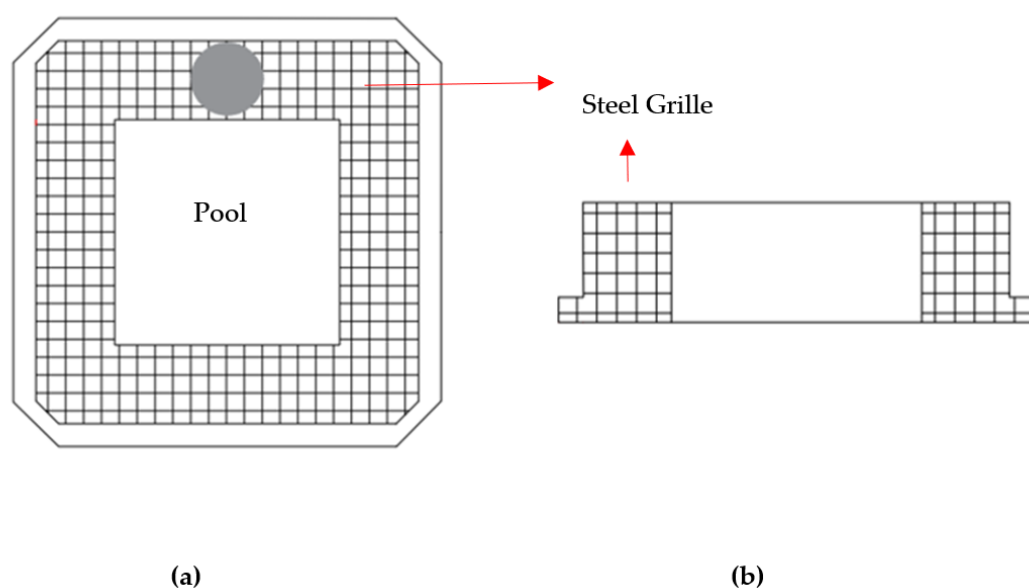


Figure 3. Top (a) and side (b) view of the barge-type platform.

3.2. Boundary System

The boundary system is the stage that materials, energy inflows and outflows and the life cycle stages are specified in a product [28]. In Figure 1, the boundary system of the life cycle assessment for a wind turbine are depicted. In the present analysis, all life cycle stages have been considered.

3.2.1. Manufacture Stage

The barge-type floating wind turbine was manufactured by European contractor companies. In Table 3 the mass distribution of the system is presented. It is shown that the platform including the mooring system has the largest mass. Here, the floating wind turbine platform is made of concrete and steel and the mooring system is composed of steel, cast iron, polyurethane foam, and nylon fibres. The anchors comprise two parts: the fluke and shank, with dimensions of $7\text{ m} \times 4\text{ m} \times 1\text{ m}$ and $3\text{ m} \times 7\text{ m} \times 3\text{ m}$, respectively. The other parts of the system are the tower, the nacelle, and the rotor, which were manufactured in Spain. The nacelle is made of steel, aluminium, cast iron, glass fibre-reinforced plastic, and copper. The rotor consists of three blades which are made of glass fibre-reinforced plastic and cast iron [43].

Table 3. Mass distribution of the barge-type floating wind turbine [33,43,44].

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

3.2.2. Transportation Stage

This stage involves transporting all components from the factory/workshop to the site area. LCA of this stage is dependent on the type of vehicle, distance (factory to site area), and the emissions during the production of fuels [11]. In this study, cargo vessels and road transportation were utilised. Moreover, in Section 5.2, different transportation scenarios are considered and analysed.

3.2.3. Erection Stage

In this stage, a forklift and a heavy mobile crane were utilised for the land erection stage. In addition to the sea erection stage, the floating wind turbine was transported by three tugboats to the area of construction (Figure 4).

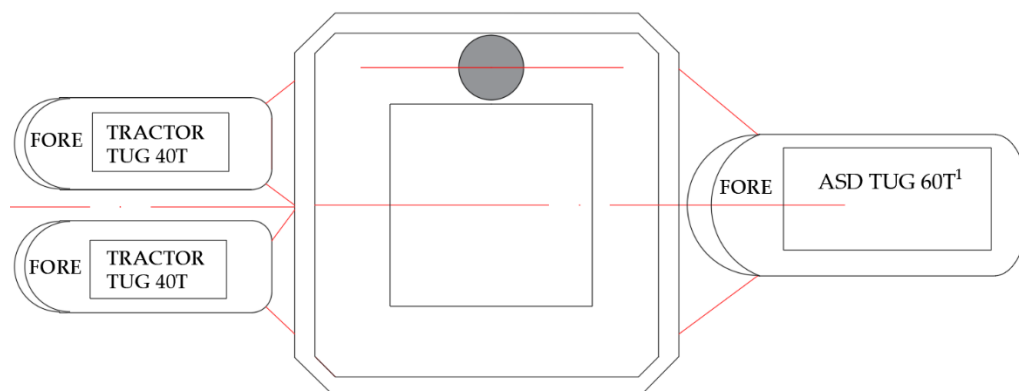


Figure 4. Sea installation stage of the barge-type floating wind turbine. ¹ ASD TUG 60T: azimuthing stern-drive tug is a kind of tug that performs towing over the bow, and its weight is 60 tonnes.

3.2.4. Operation and Maintenance Stage

In the operation stage, it was considered that the operation time of the barge-type platform would have been 3000 h per year [46]. Taking into account the performance of the wind turbine, the annual electricity generation is 6 GWh. During the maintenance stage, it is assumed that the wind energy systems gearbox has to be changed once in the lifetime of the turbine, and that all components must be examined and lubricated twice a year by specialised personnel.

3.2.5. Disposal and End-of-Life Stage

Following the operation and maintenance stage of the wind turbine tower, the next and final stage is its disposal at the end of its life. The end-of-life stage is conducted according to previous studies [9]. Concrete, glass fibre and nylon fibre materials are landfilled 20 km away from the coast. Here the recyclable percentage of steel and cast iron was assumed to be 85% [11]. Further assumptions are as follows [47,48]:

- Copper and aluminium: recycling 90%;
- Concrete, glass fibre and glass-reinforced plastic: landfill 100%;
- Nylon fibre: recycling 100%;
- Polyurethane foam: recycling 80%.

4. Life Cycle Inventory (LCI)

A life cycle inventory (LCI) comprises energy requirements and input-output material flows of a product system. The LCI of a wind turbine is its energy requirements and input-output data, which come from the manufacture, transportation, erection, operation and maintenance, and disposal steps of the product [11]. The LCI refers to the tower, the nacelle, the foundation and the rotor of the floating wind turbine tower and the respective data have been collected in order to carry out the LCA. According to the life cycle stages and product units, the derived data were categorized and imported to the software. The collected data from the barge-type floating wind turbine are presented in Table 4. This table provides information categorised by life stage and structure components.

Table 4. Data collection—life cycle inventory [11,33,43,44].

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 ²	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
NACELLA	Erection	Crane	10.56 h
PLATFORM	Erection	Crane and Tugboat	105.56 h
TOWER	Disposal & End of Life	Landfill	27.45 t
ROTOR	Disposal & End of Life	Landfill	24.25 t
NACELLE	Disposal & End of Life	Landfill	12.55 t
PLATFORM	Disposal & End of Life	Landfill	4500.675 t
TOWER	Disposal & End of Life	Transport to	549 tkm
ROTOR	Disposal & End of Life	Transport to	485 tkm
NACELLE	Disposal & End of Life	Transport to	251 tkm
FOUNDATION	Disposal & End of Life	Transport to	900,013.5 tkm

² RNA: rotor-nacelle assembly.

5. LCA Results for the Barge-Type Floating Wind Turbine

The LCA of the barge-type floating wind turbine included all life cycle stages from raw materials to the end of its life. The lifespan of the floating wind turbine is assumed to be 20 years [11].

Table 5 contains a summary of the LCA of the barge-type floating wind turbine. The majority of the past studies focused on the following four environmental impacts: global warming potential (GWP), acidification potential (AP), abiotic depletion potential for fossil fuels (ADPF), and energy payback time, where

Table 5. Summary of results.

LCA Results	Unit	Value
Abiotic depletion potential for fossil fuels (ADPF)	MJ	18,429,264
Acidification potential (AP)	kg SO ₂ eq.	5945
Global warming potential (GWP)	kg CO ₂ eq.	2,187,947
Energy payback time (EPT)	years	1.13

- Abiotic depletion potential for fossil fuels focused on the non-renewable resource is measured in MJ;
- Global warming potential is related to CO₂ emissions measured in CO₂-equivalent;

- AP values show aggregated acid air emissions measured in SO₂-equivalent;
- The energy payback time, a ratio of primary energy to annual energy produced by a wind turbine, is calculated in months and years [11].

The global warming potential, AP, and ADPF of each component and life cycle stage are presented in Figures 5 and 6. As can be observed in Figure 5, it can be seen that the foundation component has the largest percentage of all the components in measures of global warming potential, acidification potential, and abiotic depletion potential for fossil fuels. The foundation component constitutes 81% of the total equivalent GWP of the floating wind turbine. This could be related to the use of steel, concrete, nylon fibre and polyurethane, and the long usage of the crane and tugs. Likewise, the ADPF and acidification potential percentage of the foundation component is higher than the other 78% and 79%, components respectively. The second highest GWP and ADPF is the tower component, at 10% and 11%, respectively. The second highest AP is reported at 9% for both the tower and nacelle components. The main reason for this high value for the nacelle is using large amounts of iron and steel in its production/manufacture stage. On the other hand, the lowest value of GWP, AP and ADPF is obtained at nearly 4% for the rotor component.

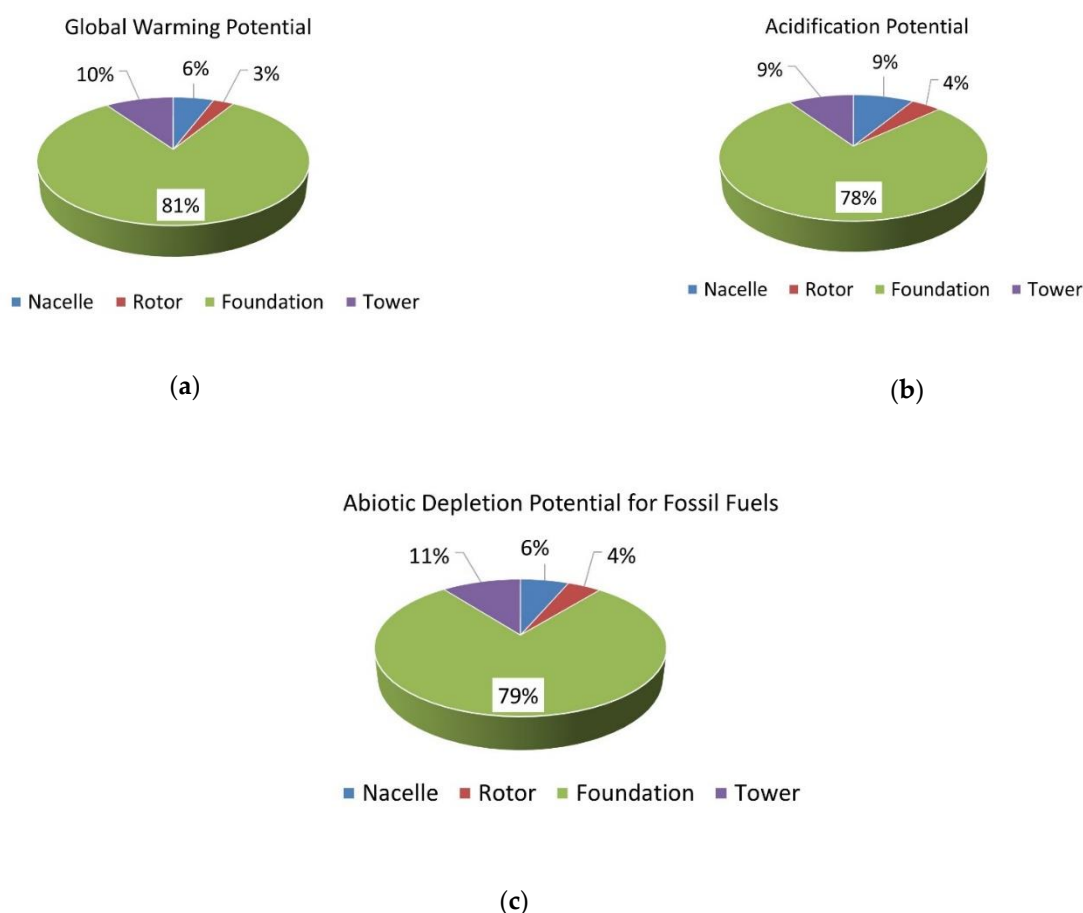


Figure 5. Contribution of the parts of the floating wind turbine to GWP (a), AP (b) and ADPF (c).

As far as the share among the life cycle stages is concerned, Figure 6 demonstrates that production/manufacture is the stage with the biggest contribution of global warming potential (CO₂), acidification potential (SO₂), and abiotic depletion potential for fossil fuels (MJ). GWP of the production/manufacture stage is 94%. As a matter of fact, in line with past studies [11,16–25], Tables 1 and 2 show the largest GWP contribution comes from the production/manufacture stage in wind turbines. It can be decreased using alternative

materials with the lowest CO₂ emissions or reducing the amounts of concrete and steel for the production/manufacture stage. The lowest contribution to GWP, AP and ADPF are derived from the transportation stage. It can be clearly seen that the erection stage is much higher compared to that of other stages, considering the contribution to GWP, AP, and ADPF. Given that the erection stage entails consumption of fuel, long-time usage of the crane and tugs, the amounts of GWP, AP, and ADPF are expected to be higher than other stages in the erection stage. Regarding energy performance, the energy payback time, as defined in this section, has been calculated as 1.13 years. In the aforementioned studies, EPT values were reported between 1.6 and 2.7 years. 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.

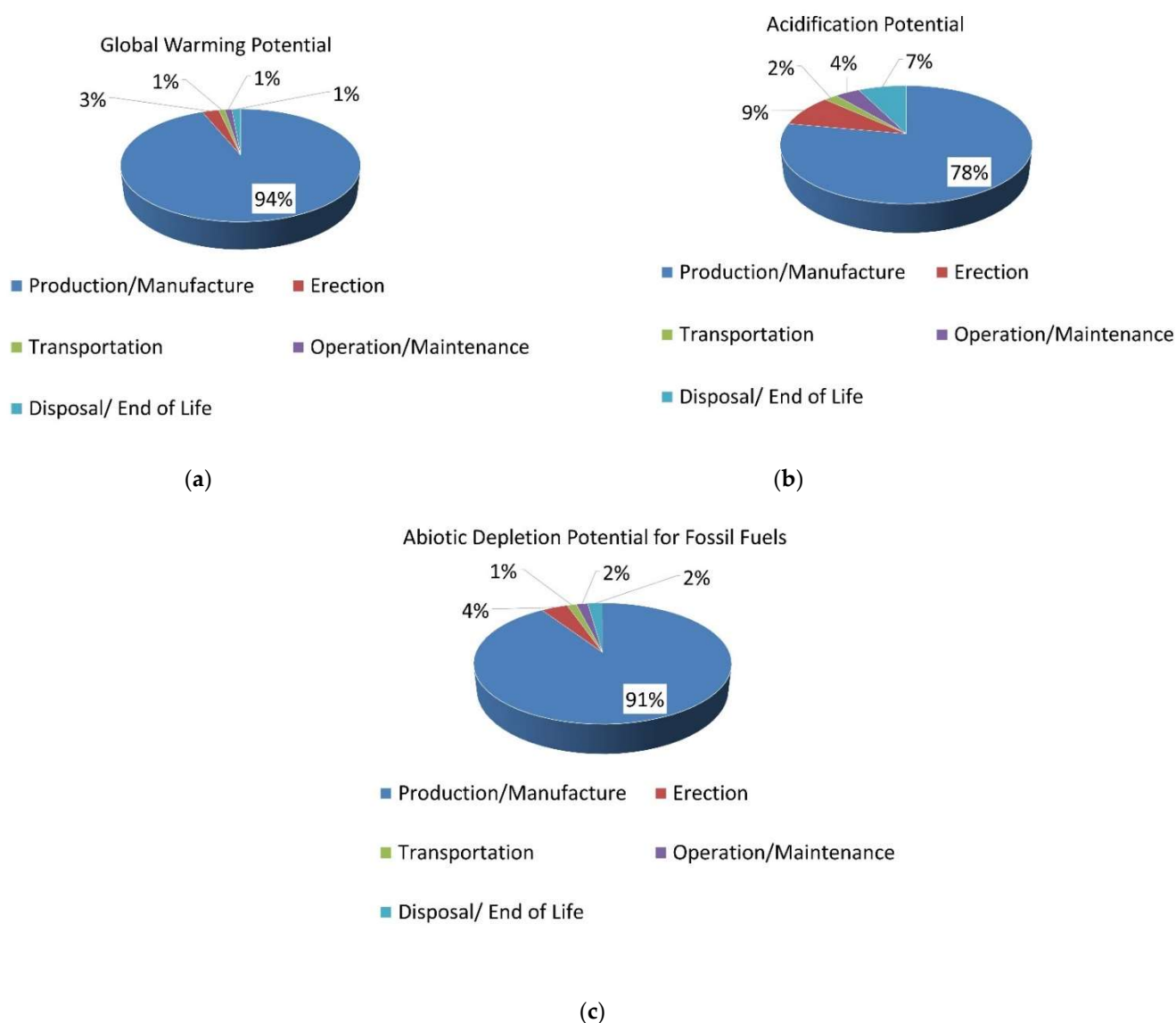


Figure 6. Contribution of each life cycle stage of the floating wind turbine to GWP (a), AP (b) and ADPF (c).

5.1. Comparison of the Barge-Type Floating Wind Turbine LCA Results with Those of Other Types of Wind Turbines

In this section, the results of the LCA of the barge-type floating wind turbine are compared with those from onshore (2MW-398 tonne), offshore (2MW-979 tonne) and floating (5MW-4225 tonne) wind turbines. The data for the LCAs for these wind turbines have been already published in [37,39]. The LCA of these turbines correspond to g/kWh of electricity produced. Abiotic depletion potential for fossil fuels (measured in MJ), GWP (gCO₂eq./kWh), AP (gSO₂eq./kWh) and the energy payback time (months) of all turbines have been included. Regarding the results of GWP shown in Figure 7, the largest GWP contribution is 18.6 gCO₂ eq./kWh for the barge-type floating wind turbine, while the lowest contribution is from the 2MW onshore wind turbine (representing 7.09 gCO₂eq./kWh). One of the most important factors is that the barge-type floating wind turbine platform is made using a high amount of concrete and steel. Therefore, the respective value was expected to be high. Furthermore, the installation of floating and offshore wind towers takes a longer time, and uses heavy cranes, hydraulic hammers, heavy-duty forklifts, pile drivers, vessels, and tugboats. The operation of this equipment consumes fossil fuel resources, having, as consequence of this consumption, high CO₂ emissions to the atmosphere.

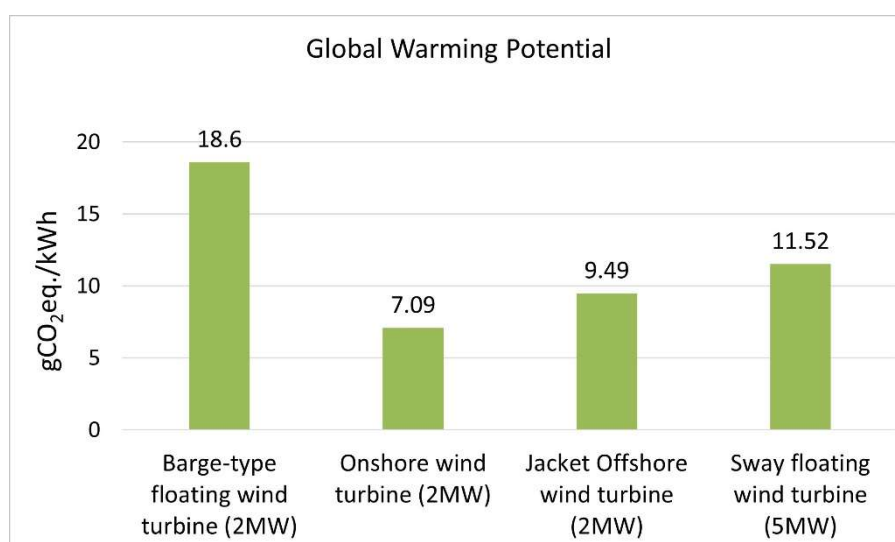


Figure 7. Total global warming potential for floating, onshore, and offshore wind turbine.

As can be observed in Figure 8, there are four comparable different types of wind turbines with regard to the AP contribution. Although the AP of the barge-type floating wind turbine is nearly 15 times larger than the onshore and jacket offshore wind turbine, the AP value of the floating wind turbine (5 MW) has a higher value than the barge-type floating wind turbine (representing 0.11 and 0.05 gCO₂ 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.

Energy payback time of the barge-type floating wind turbine is slightly higher, as shown in Figure 9. This value was expected because the total mass of the barge-type floating wind turbine, and the duration of the erection stage and the transportation stage, are larger than the others. It should be noted that although the barge-type floating wind turbine has a large mass and long erection time, the energy payback time and CO₂ emissions of the floating wind turbine are not higher than the other ones (Figures 7 and 9). The EPT of the

onshore turbine is lower than the others. That is due to the turbine having less mass, a short erection time, and less fuel consumption.

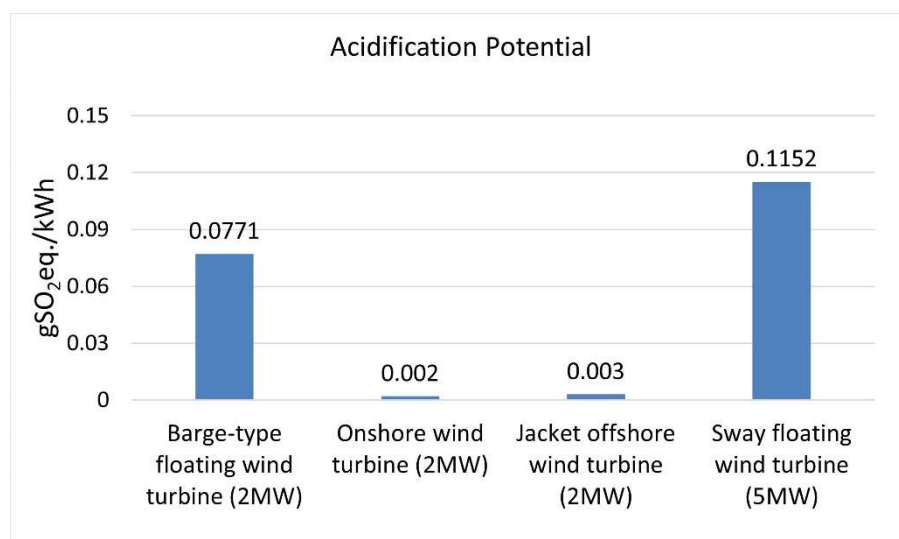


Figure 8. Total acidification potential for floating, onshore, and offshore wind turbine.

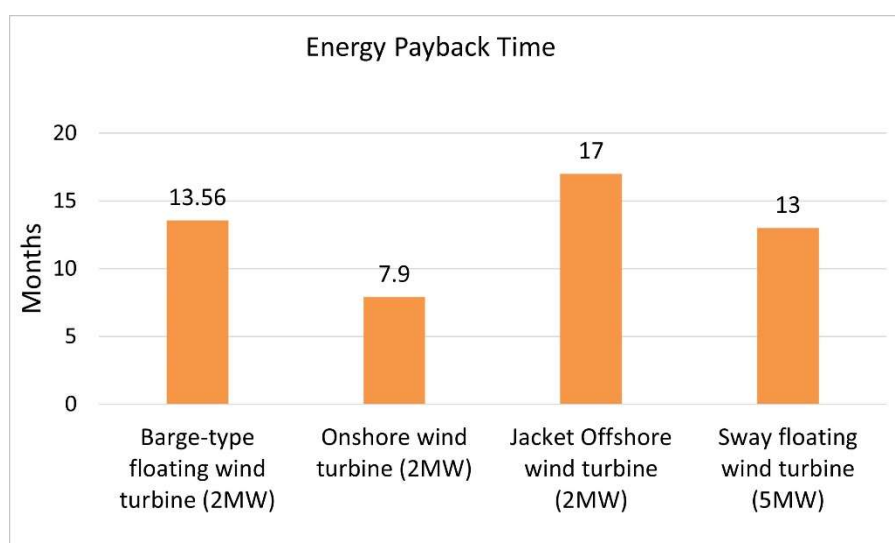


Figure 9. Energy payback time for floating, onshore, and offshore wind turbines.

5.2. LCA of the Barge-Type Wind Turbine Transportations Scenarios

In this section, the transportation stage of the barge-type floating wind turbine are analysed considering different scenarios, such as, truck, train and vessel. The three manufacture locations were Spain, The Netherlands and Belgium. Truck, vessel, train, and hybrid models have been considered as transportation stage scenarios. These scenarios were modelled to investigate their effect on environmental impacts. The hybrid model was analysed for the LCA of the barge-type floating wind turbine (see Section 5.1). In the truck, train, and vessel scenarios, all components of the barge-type floating wind turbine were transported by road, railway, and seaway, respectively. Moreover, Table 6 shows total distance of components transportation such as road, railway and sea distances. Concerning the results, the total CO₂ emissions (tonnes) and CO₂e (g/kWh) emissions for the whole the LCA of the barge-type floating wind turbine are shown in Table 7. As a result of these scenarios, the total distance of the train scenario was higher than other scenarios, while, regarding total CO₂ and g CO₂eq./kWh, the train scenario had lower values, 20.6 tonnes,

and 0.172 g/kWh, respectively. Although the total transportation distance is the shortest by sea, it is the transportation mode with the highest carbon emissions and g CO₂eq./kWh. This was analysed for the hybrid scenario in the LCA of the barge-type floating wind turbine. The main reason for this is that the parts such as blades, nacelle, and towers are large. Moreover, the seaway is preferred in order to transport these parts without any damage and to avoid jeopardizing other traffic.

Table 6. Transportation distance.

Scenario	Road Distance (km)	Railway Distance (km)	Seaway Distance (km)
Truck	2720	-	-
Train	670	2270	-
Vessel	570	-	2022
Hybrid	2190	-	600

Table 7. Results for different transportation scenarios.

	Units	Hybrid Scenario	Truck Scenario	Train Scenario	Vessel Scenario
Total CO ₂	tonnes	21.3	22.6	20.6	25.9
CO ₂	g.eq./kWh	0.178	0.188	0.172	0.216

6. Conclusions

Previous studies have focused on the LCA of sway, spar, TLB, semisubmersible, and TLP wind turbines excluding the barge-type floating one. In this paper, the life cycle assessment 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, acidification potential, and energy payback time. The LCA of the barge-type floating wind turbine illustrates that the manufacture stage has high GWP and AP. The principal reason for this is the use of a high quantity of steel, nylon fibre and concrete. The other LCA stages do not exceed 6% of the total value of GWP contribution.

CO₂ emissions of all turbines varies from 7.09 to 22.3 g CO₂ eq./kWh. The energy payback time varies from 7.9 to 20.3 months. The barge-type floating wind turbine has a higher CO₂ and energy payback time when compared with other wind turbines, whilst the results of the onshore wind turbine show less CO₂ and SO₂ and low energy payback time. Regarding acidification potential, the highest contribution to SO₂ emissions was calculated for the 5 MW floating wind turbine. This highest value is related to the use of cast iron for the mooring system of the floating wind turbine. Given these results, the 2 MW onshore wind turbine is the most environmentally friendly and has the best energy performance.

GWP and energy payback time 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. In this study, GWP and energy payback time were found to be the highest in the barge-type floating wind turbine. Thus, further research is recommended on whether GWP and energy payback time can be decreased and annual energy yield can be increased. In light of the results of the present study, the following recommendations can be made:

- The energy capacity of the barge-type floating wind turbine should be increased. With this rise, the GWP emissions will reduce, and energy payback time will decrease while increasing the annual energy yield.
- The platform and the tower, which are the most energy-consuming parts of the structure, should be designed optimally to save materials. The platform of the barge-type floating wind turbine is made of concrete and steel. Hence, a type of concrete having less CO₂ emissions or an advanced high-strength concrete (saving material) could be preferred.

- As floating wind turbines are located in deep water, a combination of a platform of the barge-type wind turbine that includes a wave energy system should be developed. This combination could decrease the equivalent CO₂ emissions by increasing the annual energy yield as described in [24].
- The lifetime of the wind turbine could be extended, e.g., to 25 or 30 years. Thus, the environmental impact (CO₂ and SO₂) per kWh of electricity generated would diminish.

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