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DOI:
10.3390/wind2020014

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Yildiz, N, Hemida, H & Baniotopoulos, C 2022, 'Maintenance and end-of-life analysis in LCA for barge-type floating wind turbine', *Wind*, vol. 2, no. 2, pp. 246-259. https://doi.org/10.3390/wind2020014

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Article

Maintenance and End-of-Life Analysis in LCA for Barge-Type Floating Wind Turbine

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Abstract: This paper is aimed at improving the maintenance and end-of-life steps in the associated Life Cycle Assessment (LCA) of barge-type floating wind turbines to reduce their environmental impact. Maintenance and end-of-life steps are given special attention since these phases have received only cursory focus in previous LCA studies. Different maintenance and end-of-life scenarios have been considered in the analysis. From the LCA results, it has been found that by applying on-site and onshore maintenance strategies, the lifetime of the turbine can be extended. Four alternative scenarios for the end-of-life step have been examined: mechanical recycling, mechanical-incineration, incineration processes, and landfill. The environmental impacts of these scenarios are evaluated using the LCA methodology. The investigation showed that the lowest environmental impacts correspond to the onshore maintenance and the mechanical recycling scenarios. These CO_2 emissions of these scenarios are 13.68 g CO_2 eq/kWh and 0.107 g CO_2 eq/kWh, respectively.

Keywords: end of life; floating wind turbine; Life Cycle Assessment (LCA); global warming potential (GWP); incineration; mechanical recycling; maintenance; renewable energy

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Citation: Yildiz, N.; Hemida, H.; Baniotopoulos, C. Maintenance and End-of-Life Analysis in LCA for Barge-Type Floating Wind Turbine. *Wind* **2022**, 2, 246–259. https://doi.org/10.3390/wind2020014

Academic Editor: Yingyi Liu

Received: 3 March 2022
Accepted: 15 April 2022
Published: 26 April 2022

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1. Introduction

The increase in environmental issues related to the use of fossil fuels plays an important role in the development and widespread use of renewable energy sources, such as hydro, solar, and wind energy. These renewable energy sources lead to lower environmental impact [1]. The COP26 Green Zone Conference [2] has highlighted that governments are indeed being required to submit ambitious carbon reduction plans for 2030, with the objective of achieving net-zero emissions by mid-century.

According to the DNV GL report [3], usage of non-renewable energy resources is presumed to diminish by about 43.2% between 2019 and 2050, while the total amount of renewable energy resources should rise by 551.7% over the same period. Today, electricity generation from wind energy constitutes 5% of all electricity generation worldwide and is anticipated to reach 30% by 2050 [3]. In recent years, there has been a significant interest in wind energy all over the world due to its natural, clean, and economic nature. Due to both the economic and environmental benefits of wind energy, it is also gaining importance in the global energy industry in the fight against climate change [4]. In 2021, 17 GW of wind power capacity were installed in Europe, bringing its total wind power capacity to 236 GW [5]. In 2019, wind energy saved 118 million tonnes of CO_2 in Europe, and it is expected to save 270 million tonnes of CO_2 per annum by 2030 [6,7].

Of the different possible wind energy systems, floating wind power technology represents the fastest growing sector and is considered a promising way to use the ocean's energy. It is known that around Europe, and especially in the Mediterranean Sea, the water is deep, and thus, floating platforms represent the most suitable form of technology for offshore wind turbines [5,6]. Currently, floating wind energy contributes a total capacity of 73.33 MW, of which 32 MW is operating in the UK [5–7]. The floating wind turbines are normally of large sizes and are located in areas of high wind potential. The energy yield of floating wind turbines could meet current energy demands and provide the largest reduction in world CO_2 emissions [8]. However, the use of floating wind power brings certain difficulties with regard to installation and maintenance activities by the fact that high wind, waves, and the mooring system can complicate these processes [8].

Wind energies do not emit greenhouse gases when they generate electricity, but they do emit greenhouse gases during the fabrication of parts, transportation of parts, installation, maintenance, and decommissioning of the system. The Life Cycle Assessment (LCA) methodology is an excellent tool with which to analyse the environmental impact of wind energy devices, and this analysis meticulously examines the environmental impact of all steps to such systems over their entire lifetime. According to a review in the literature, the greenhouse gas (GHG) potential of a wind turbine during its life cycle is crucially dependent on certain framework conditions. Many LCA studies have focused on technologies of wind power plants. These technologies include the materials used for the wind tower and foundation and different wind turbine designs [9–12]. The LCA of concrete, steel, and composite wind turbine towers of various heights and capacities was investigated by Gervásio et al. [9], who showed that steel towers have a lower environmental impact than other types of towers. Gkantou et al. [13] studied four- and six-leg hybrid towers, where the former was shown to have a lesser environmental impact than the latter. Weinzettel et al. [14], Randal et al. [15], Elginoz and Bas [16], Kausche et al. [17], and Yildiz et al. [18] studied the LCA of floating wind turbines with various designs and foundations, encompassing sway, spar, tension-leg-buoy, semi-submersible, and barge-floating wind turbines. They compared the environmental impacts of floating wind turbines to those of offshore, onshore, and natural gas power facilities, as well as their energy payback times. Another factor to take into account is the wind turbine's height and size. Onshore and offshore wind turbines of various sizes and heights were compared in terms of life cycle environmental impacts by Bonou et al. [19], Xu et al. [20], Chipindula et al. [21], and Demir and Taskin [22]. These studies generally indicate that the lowest environmental impacts can be attained by using taller wind turbines and that there is an inverse association between energy payback time (EPT) and wind turbine size. Moreover, the location of wind turbine has a significant effect on the LCA [23–26]. Al-Behadili and El-Osta [23], Oebels and Pacca [24], and Properzi et al. [23] examined the environmental impacts of wind turbines in Libya, Brazil, and Denmark, respectively. Lenzen and Wachsmann [26] focused on the LCA of wind turbines in different geographical regions (for example, Brazil and Germany) while taking component manufacturing sites into account. Their study highlighted that CO_2 emissions from the manufacturing process and operation of wind turbines in Brazil are five times fewer than those in Germany. Kasner et al. [27] used the sustainable modernisation method to investigate the energy efficiency and environmental effects of wind turbines with lifetimes of 25 and 50 years. To prolong the wind turbine's lifetime to 50 years, components such as the rotor, blades, and structural elements were replaced and maintained on a regular basis. Throughout this research, they compared the environmental impacts of a wind turbine with a 50-year lifetime with a new wind turbine with a 25-year lifetime that would run for another 25 years. They emphasised that the greenhouse gas emissions of a wind turbine with a lifetime of 50 years are 40–50% lower than those of two wind turbines with 25-year life cycles.

As a result of these developments in wind energy systems, the LCA methodology is used to learn how the system affects the environment. Moreover, the above-mentioned analyses generally examined the environmental effects of wind turbines' production, transfer, recycling, disposal, and designs. In contrast to prior research, Nagle et al. [28] used the LCA methodology to assess the environmental impacts of disposing of Irish wind turbine blade waste. They focused on three different LCA disposal scenarios: co-processing cement kilns in Germany and co-processing and landfill in Ireland. According to waste management for wind turbine blades, they highlighted that all co-processing scenarios have a beneficial environmental impact. Martinez et al. [29] have created and analysed different LCA scenarios for a 2 MW onshore wind turbine in terms of the maintenance, decreased disposal of materials, and increased blade recycling of wind turbines. The values of these scenarios changed by about 14% and 20%. According to the basic scenario, the recycling blade scenario has the least environmental impact. Arvesen et al. [30] accentuated the importance of the LCA with regard to maintenance and installation activities for the offshore wind farm. They emphasised operation and maintenance activities that had been undervalued or neglected in previous analyses, where these activities should be reconsidered in terms of the global warming potential (GWP). It can be observed that the maintenance assumptions used in these aforementioned studies are constrained and dependent solely on manufacturer data [31]. Furthermore, mechanical recycling and mechanical-incineration scenarios were not taken into account in previous research when evaluating the end-of-life (EoL) environmental impacts for composite materials.

Previously, LCA studies concentrated on the entire life cycle of wind turbines have been conducted, but most of these studies refer to either transfer of composite materials to landfill or implement an incinerator process. Therefore, this study includes the recycling and the mechanical-incineration processes, considering the associated environmental impacts. Moreover, according to previous LCA studies, the maintenance step has been subjected to complete assumption or cursory consideration. In some studies [10,11,18,22,29], maintenance steps include changing the gearbox, blades, and lubricant. In this study, however, the focus is on assessing the environmental impact of wind turbines by performing a life cycle analysis, which comprises fuel use throughout maintenance, oil consumption during maintenance, and replaced parts. Life cycle assessment of floating wind turbines is limited in the literature, and maintenance and end-of-life steps are assumed constant or ignored. Moreover, two steps of the turbine's life cycle maintenance and end-of-life were included in the LCA for the barge-type floating wind turbine. The ultimate goal is to improve the environmental impact of the barge-type floating wind turbine by considering various different scenarios. Thus, the main contributions of this study are follows:

- To assess the environmental impacts of on-site and onshore maintenance scenarios for a barge-type floating wind turbine.
- To investigate the environmental impacts of composite material mechanical recycling, mechanical-incineration, and incineration processes.
- To reduce the environmental impact of barge-type floating wind turbines, taking maintenance and end-of-life scenarios into account.

The structure of the paper is organised as follows: Section 2 focuses on the LCA methodology and details of the barge-type floating wind turbine, such as design and dimensions. The brief information on wind turbine maintenance and the details of maintenance scenarios are in Sections 3 and 4 presents end-of-life scenarios. The results of maintenance and end-of-life scenarios are presented and discussed in Section 5. The paper concludes with Section 6, which provides maintenance and end-of-life scenarios suggestions for sustainable development of the barge-type floating wind turbine.

2. Methods

Based on the basic principles established by the ISO 14040 [32] and ISO 14044 [33] standards, the LCA is a common approach to identifying, measuring, and quantifying the environmental impact of every stage of a product's lifetime. This methodology comprises four fundamental stages: the goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the results [32,33]. The objective, scope, methodology, and boundaries of the system are specified in the first stage, and the life cycle inventory (LCI) is elaborated in the second stage, with inputs and outputs at the system's boundaries. A life cycle impact assessment (LCIA) is conducted in the third stage with environmental impact potentials determined from inventory data that were collected and compiled in the previous step. The results are then interpreted in the fourth stage [32,33].

The LCA methodology for wind energy comprises five steps: manufacture, transportation, installation, operation and maintenance, and end of life during its whole lifetime. These steps are shown representatively in Figure 1. At the manufacturing step, wind turbine components, which are composed of blades, nacelles, a tower, and the foundation, are produced. In the transportation step, these components are transported to the site. In this step, the appropriate form of transport is selected according to the location of the wind turbine to be installed. During the installation step, the wind turbine components are erected by professionals using cranes. Wind turbine components must be modular and moveable. In operation and maintenance, a maintenance strategy that requires regular maintenance and in a methodical manner must be taken into account during the lifetime of the wind turbine. For the end-of-life step, at the end of its useful life, the wind turbine is disassembled and can either be recycled, go to landfill, or be incinerated according to the properties of the particular material in question [32,33].

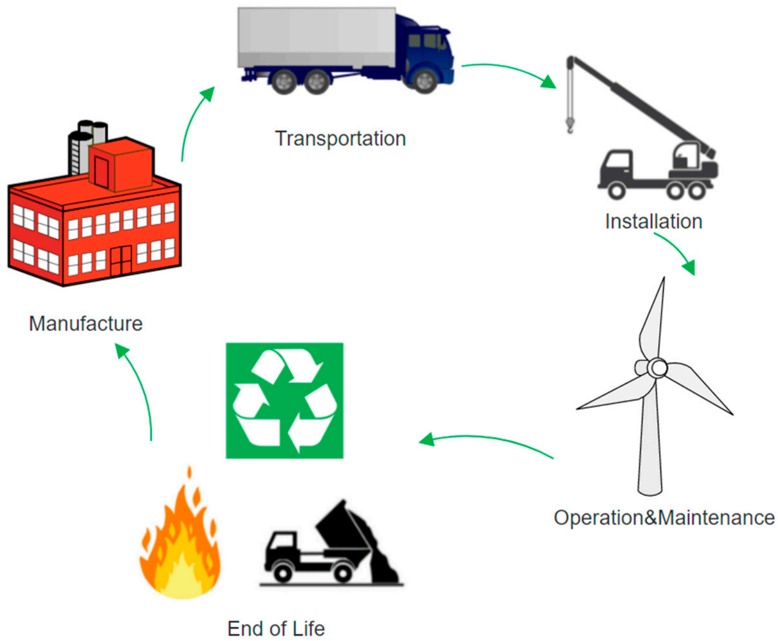

Figure 1. LCA steps of a wind energy system.

The Barge-Type Floating Wind Turbine

In this case study, a barge-type floating wind turbine has been considered for the LCA methodology. The main reasons for choosing this type of barge-type wind turbine are the novelty of the design of the platform and that it is the first floating wind turbine of its type [34]. The proposed one used here comprises 60-metre steel tube towers and has a 40-m blade length. The foundation is of a box-like shape that is 36 m wide, 9.5 m high, and 7.5 m draft and is made of concrete (C55/67) with steel reinforcement. The foundation has a pool with a diameter of 20 m × 20 m. Thanks to the special mooring system, with two anchor lines at the front and four at the rear, the barge-type floating wind turbine can remain stable [18,35,36]. The data for the barge-type floating wind turbine are presented in Tables 1 and 2.

Table 1. Characteristics of the barge-type floating wind turbine [18,35,36].

Design Features of the Wind Turbine	Details
Capacity	2 MW
Rotor model	V80 model Vesta
Foundation type	Barge
Mooring system	Semi-taut
Water depth	33 m
Coast distance	22 km

Table 2. Life cycle inventory of the barge-type floating wind tower [18,35,36].

Component	Step	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 reinforce plastic	4 t
Nacelle	Manufacture	Cast Iron	16 t
Foundation (Platform)	Manufacture	Concrete	4350 t
Foundation (Platform)	Manufacture	Steel	700 t
Foundation (Mooring System)	Manufacture	Nylon Fibre	126 t
Foundation (Mooring System)	Manufacture	Steel	212.5 t
Foundation (Mooring System)	Manufacture	Polyurethane	24 t
Foundation (Mooring System)	Manufacture	Cast Iron	60 t
Tower-Rotor-Nacelle	Transport	Vessel	165,300 tkm
Tower-Rotor-Nacelle	Transport	Truck	13,775 tkm
Foundation (Platform)	Transport	Truck	87,000 tkm
Foundation (Platform)	Transport	Truck	16,560 tkm
Foundation (Mooring System)	Transport	Truck	77,450 tkm
Foundation (Mooring System)	Transport	Truck	94,500 tkm
Foundation (Mooring System)	Transport	Truck	2400 tkm
Foundation (Mooring System)	Transport	Truck	6000 tkm
Tower	Erection	Crane	7.92 h
Rotor	Erection	Crane	10.56 h
Nacelle	Erection	Crane	10.56 h
Foundation (Platform and Mooring System)	Erection	Crane and Tugboat	105.56 h

During the operation stage, it was estimated that the offshore wind turbines (fixed-base and floating platform) would operate for 3000 h per year [18,37]. The limitations of this study are that the yearly electricity generation is 6 GWh, based on the performance of the 2 MW barge-type floating wind turbine. The turbine is located in the northeast of the Atlantic Ocean at a distance of 22 km from the port. Assumptions related to the materials used are as shown in Table 3.

Table 3. Percentage of recyclable material [13,18].

Material	Recyclable Percentage (%)
Steel	85
Cast Iron	85
Copper	90
Aluminium	90
Nylon Fibre	100
Polyurethane Foam	80

3. Wind Turbine Maintenance

Maintenance and repair deficiencies in wind turbines are ones of the main reasons for failing to maintain maximum energy efficiency. For instance, factors such as freezing cold, storm, precipitation, lightning strike, negligence during installation, transportation, lifting operations, and damage caused by metal fatigue in wind turbines can reduce the overall efficiency of wind farms and cause interruptions in energy production [38]. Thus, regular maintenance is required to ensure the maximum power yield and longest lifetime.

The maintenance of wind turbines can be categorized as either corrective or preventive maintenance [36]. Preventive maintenance is carried out at predetermined intervals or according to specified criteria and aims to reduce the possibility of malfunction or disruption of the operation of the wind turbine [39–41]. Preventive maintenance means that maintenance is planned and periodic, and it is carried out at equal intervals to prevent malfunctions from occurring [35,36]. On the other hand, corrective maintenance is carried out after fault detection and intended to bring the wind turbine components to a state where they can perform their desired function [39–41].

The consequences and costs of dealing with component failures in offshore wind turbines (OWT) are much more critical because this requires considerable additional time and increased maintenance costs for repair ships to visit the site and fix the faults. Moreover, the long distance between an offshore wind farm and a port or coast decreases accessibility and increases downtime. In maintenance tasks, long waiting times as a result of weather issues causes an increase in maintenance costs and greater energy loss [38].

The floating wind turbine is an energy system with a complex mooring system located in deep waters, operating in harsh weather and climatic conditions [42,43]. The use of floating offshore wind turbines, like other wind and renewable energies, is rapidly increasing [44]. Thanks to the developing technology, these floating turbines should be carefully and periodically maintained so that they can produce energy for longer and better. Minor maintenance on floating wind turbines is similar to a fixed base offshore wind turbine. This similarity is the transfer of technicians to the wind power platform [45]. Another maintenance strategy is to take the tower to the port for comprehensive maintenance by separating the wind turbine from its connection, namely, the mooring system [46–48]. For port maintenance to be feasible, ease of towing and mooring and easy connection and disconnection of electrical connections are required [49]. Tugboats are used to perform these operations.

Maintenance Scenarios

In this study, the LCA of different maintenance scenarios has been considered. These scenarios are divided into two different maintenance strategies, on site and onshore (Figures 2 and 3). Moreover, with the strict maintenance strategies implemented in these scenarios, it is planned to increase the operating life of the barge-type floating wind turbine to 25 and 30 years, based on the maintenance scenario used. In some of these scenarios, the replacement of certain parts, such as the gear box and blades of the turbine, is also taken into account.

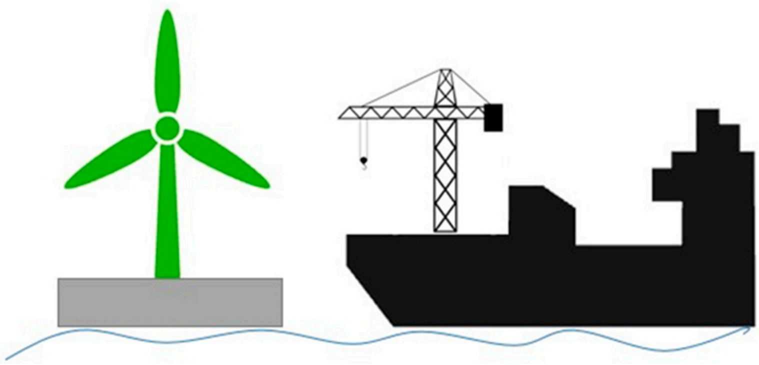

Figure 2. On-site maintenance scenario for the barge-type floating wind turbine.

The maintenance of the wind turbine throughout its lifetime, according to the manufacturer's preventative maintenance criteria, as well as major correction, are all included in the operating and maintenance step [34]. Recent studies [35–50] showed that wind farms operating for more than five years require major corrective maintenance [34]. However, preventive maintenance strategies are intended to optimize maintenance costs, mitigate unplanned maintenance, minimize weather effects, and optimize maintenance tasks [48–50]. On the other hand, routine inspections are performed on most wind farms, followed by a scheduled check every two or three weeks. Visual detection may identify partial defects such as corrosion and leaking. By performing an advanced inspection, surface cracks in the blades, short circuits in the generator, and overheating in the gearbox can be detected, and intervention can take place immediately. Inspection findings offer information regarding component and structural impairment of wind turbines, allowing managers to make appropriate maintenance decisions [51].

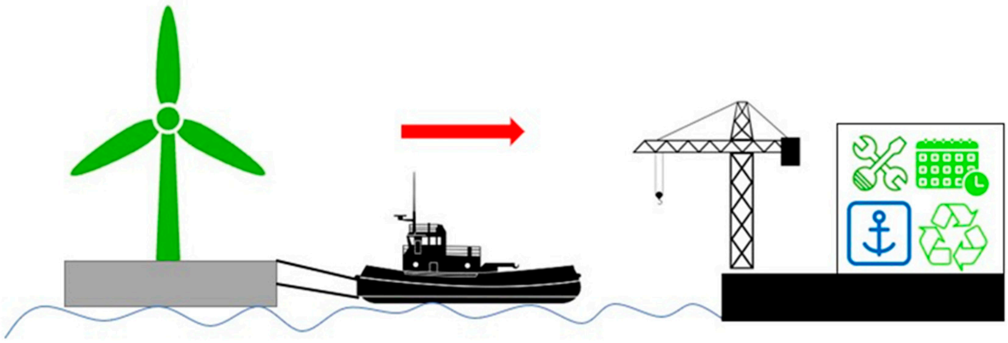

Figure 3. Onshore maintenance scenario for the barge-type floating wind turbine.

In this study, different maintenance scenarios have been proposed considering corrective and preventive maintenance strategies for the barge-type floating wind turbine, and the LCAs of these scenarios have been analysed. These scenarios have focused on rising maintenance throughout the lifetime of the barge-type floating wind turbine, with the implementation of on-site and onshore maintenance strategies. Furthermore, the aim is to extend the life of the turbine by replacing the gearbox and blades, which are important components of the wind turbine, with new ones in other on-site and onshore maintenance scenarios. In addition to the implementation of these scenarios, 375 kg of oil is used every year for lubrication of the barge-type floating wind turbine [11]. Using the LCA methodology, the environmental impact of these maintenance strategies can be ascertained. The data for these scenarios were imported into the GEMIS software [52] database. The data considered in these scenarios include fuel consumption by vehicles, quantity of components replaced, and oil used for lubrication. Tables 4 and 5 detail these maintenance scenarios and fuel consumption of vehicles.

Table 4. Details of maintenance scenarios.

Scenario Name	Place of Maintenance Scenarios	Prevention Maintenance and Inspections (a Year)	Unscheduled Maintenance (a Year)	Lifetime of the Wind Turbine (Year)	Vehicles Used	Components Replaced
M1	On site	12	1	20	Workboat	-
M2	On site	12	1	25	Workboat and Mother vessel	Gearbox
M3	On site	12	1	25	Workboat and Mother vessel	Gearbox and blades
M4	On site	12	1	30	Workboat and Mother vessel	Gearbox and blades
M5	Onshore	12	1	25	Workboat, Crane, and Tugboats	Gearbox
M6	Onshore	12	1	30	Workboat, Crane, and Tugboats	Gearbox and blades

Table 5. Overview of offshore vessel operations during maintenance and dismantling [30,53].

Type of Vehicles	Fuel Rate (L/h)
Workboat	99
Mother vessel	360
Tugboat	320
Crane	160

4. End-of-Life Scenarios

Another essential element from an environmental standpoint is to carefully analyse the wind turbine's decommissioning and recycling [53,54]. When a wind turbine has achieved its specified life expectancy (20–30 years), can no longer perform its function due to failure or material fatigue, or no longer meets the demands or expectations of the user, it will be taken out of operation [48]. Materials from decommissioned wind turbines must be handled according to the European Waste Framework Directive [55] to minimise their environmental effect. Waste reduction, reuse (components etc.), recycling, incineration, and landfill are the five basic principles for disposal according to the Directive.

In this study, different scenarios are considered for the disposal step from the life cycle assessment point of view. Following the European Waste Framework Directive [55,56], these scenarios are recycling and incineration processes. Both of these scenarios have focused on the turbine blades to reduce the environmental impact of the barge-type wind turbine.

In recycling scenarios, mechanical recycling techniques were employed. Mechanical recycling is the process of converting wind turbine blades into glass fibre and fine materials for composite polymer applications by cutting, shredding, grinding, or crushing [4,57–60]. Glass fibre recovery is around 21% efficient, while polymer filler recovery is 30% [61]. Shredders cut waste into 50–100 mm pieces, which are subsequently grounded further in a hammer mill for size reduction [4]. Glass fibre obtained by mechanical recycling can be used in the production of untreated glass fibre [4]. Due to undesirable bonding between coarse particles and composite materials, the remaining 49% coarse component cannot be effectively reused [60]. In this study, recycling scenarios have considered two different approaches after the mechanical recycling process. The first scenario involves transferring the waste to landfill after mechanical recycling, whereas the second involves transferring waste to an incinerator after mechanical recycling.

Another end-of-life scenario is related to the incineration process. Composite materials are converted to the appropriate size for burning by cutting, and the incineration is performed by mixing the composite material with a different waste. Mineral filler materials used in the composite and glass fibre are non-combustible, while polymers and carbon fibres are materials that increase the heat value in the incineration process [4,61,62].

In the end-of-life scenarios, the barge-type floating wind turbine is decommissioned once its lifespan is reached. Recyclable components and materials, such as steel, copper, etc., are transported to the factory or stored for reuse in a new wind turbine. In the basic and first scenario, all waste is transported to landfill. Concerning glass fibre, firstly, it is transferred to the cutting process to cut into small pieces. Since the turbine blades are large in volume, they can be cut to facilitate transportation and also to reduce the space needed for storage. In this study, a second end-of-life scenario is glass fibre which is used in a mechanical recycling process. The waste remaining from the mechanical process is transferred to landfill. In the third scenario, after the implementation of cutting and mechanical processes to process the glass fibre, the leftover from these processes is taken for incineration. Following this scenario, ash is sent to landfill for safe storage. In the final scenario, the incineration process is performed after cutting the glass fibre. In this combustion process, a large amount of heat and ash is obtained. The ash from the incineration process is discharged to landfill. These end-of-life scenarios are depicted in Figure 4.

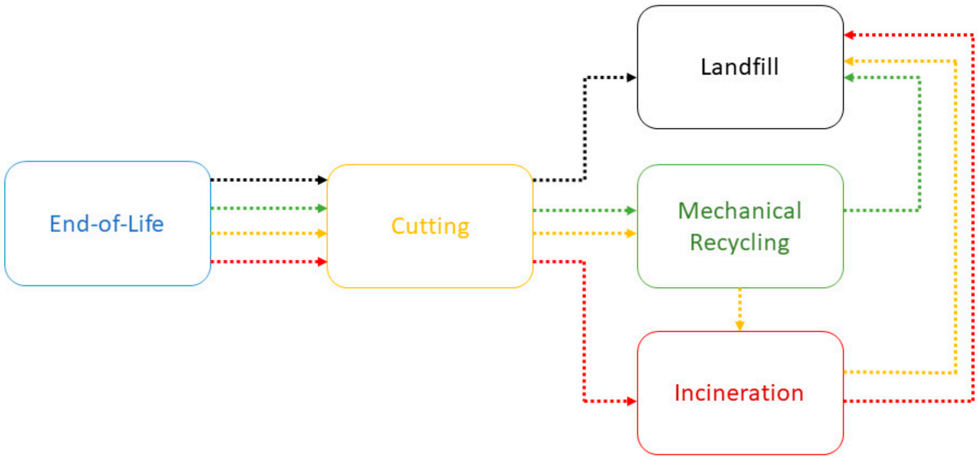

Figure 4. End-of-life scenarios for the barge-type floating wind turbine.

5. Analysed Scenarios and Results

5.1. Maintenance Scenario Results

The environmental impacts of maintenance scenarios for the barge-type floating wind turbine are evaluated using the LCA methodology. The operation and maintenance step in the LCA consists of the maintenance activity required by the wind turbine during its lifetime. In this study, different maintenance scenarios have been proposed, and the Global Warming Potential (GWP) of these scenarios has been evaluated for the barge-type floating wind turbine using the LCA methodology. In the present study, the LCA of these scenarios uses g/kWh as a functional unit for electricity produced.

In Figure 5, the contribution to GWP of the maintenance step is demonstrated. Considering the different maintenance scenarios, the LCA of the barge-type wind turbine was re-evaluated for each maintenance scenario in Figure 6. The largest and smallest GWPs were found for the M3 and M1 scenarios, respectively (1.146 gCO_2eq./kWh for M1 and 2.247 gCO_2eq./kWh for M3). The low GWP of the M1 scenario is related to the fact that the main components, such as blades and nacelle, are not changed, and heavy maintenance in the wind turbine in the operation and maintenance step is not undertaken. As can be observed in Figure 6, considering all LCA steps, the LCA1 scenario has the largest GWP contribution, representing 18.66 gCO_2 eq./kWh more than other scenarios. Moreover, this is slightly higher than for basic scenarios. The lowest contribution to CO_2 emissions were reported for the LCA6 scenario. This is related to extending the life of the wind turbine through the application of an intensive maintenance scenario. The LCA6 scenario has a much lower GWP, even though a large number of components are changed, such as gearbox and a full set of blades, in the maintenance step. Another reason for the lower GWP is that the M6 scenario requires an onshore maintenance strategy, and the fuel consumption of the tugboats is lower than that of mother vessels. The GWP difference between the M4 and M6 scenarios is where the turbine is maintained (onsite or onshore), and which vehicles (mother vessel or tugboats) are used in the maintenance strategies.

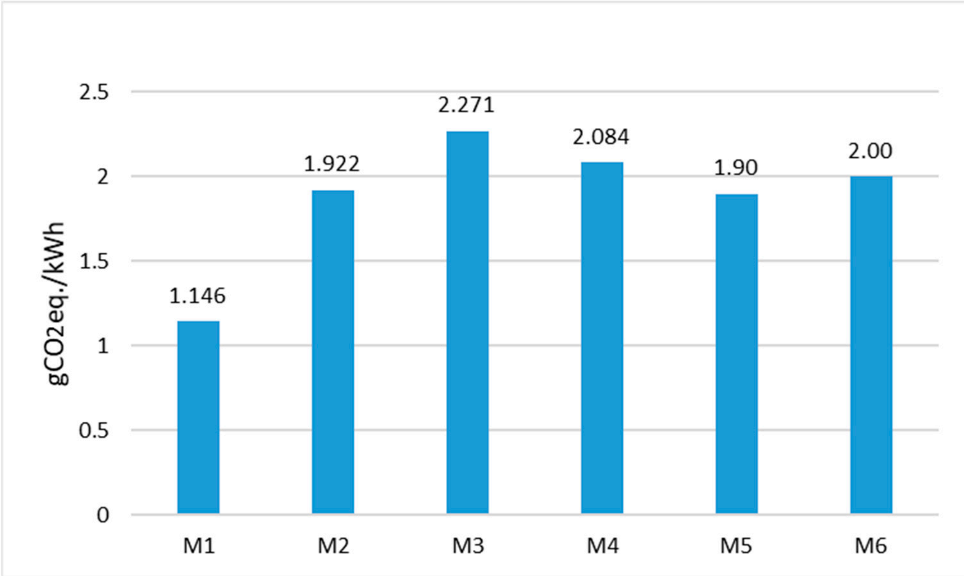

Figure 5. GWP contribution of maintenance scenarios for the barge-type floating wind turbine.

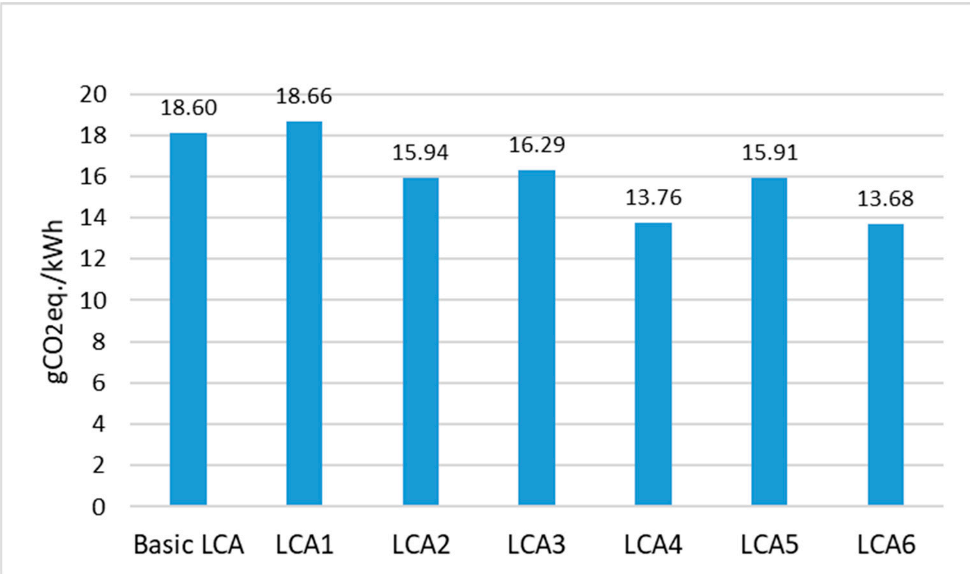

Figure 6. Total GWP of the barge-type floating wind turbine considering maintenance scenarios.

5.2. End-of-Life Scenario Results

In this section, the end-of-life scenarios for waste materials have been studied in accordance with the European Waste Framework Directive, and the global warming potential of these scenarios has been analysed. In these scenarios, four different end-of-life scenarios have been considered: landfill, mechanical recycling, mechanical recycling and incineration, and incineration (Figure 4). In Figure 4, the transportation distances for each process are assumed to be 100 km, and the energy consumption of the equipment used in the cutting and mechanical recycling processes is input into the GEMIS software. All the LCA results correspond to g/kWh of electricity produced.

As can be observed in Figure 7, the GWP of the mechanical recycling and landfill scenarios is lower than for other scenarios, and indeed, both these scenarios are very close to each other (representing 0.107 and 0.106 gCO_2 eq./kWh, respectively). Although the GWP contribution of the landfill scenario is low, transporting composite materials to landfill is considered illegal in several EU countries [29]. Another reason is that landfill tax is collected by governments every year as a result of dumping waste composite materials. Landfill tax in the UK is currently about £113 per tonne [63]. Furthermore, 0.138 gCO_2 eq./kWh glass fibre is recovered in the mechanical recycling and mechanical recycling and incineration scenarios, and this contributes to the decrease in total GWP contribution from the barge-type floating wind turbine. With regard to the incineration process, when waste glass fibre is incinerated, heat emanates into the environment due to the incineration process, and which can be converted into electrical energy. The larger GWP contributions are 0.190 and 0.166 gCO_2 eq./kWh for the incineration and mechanical and incineration scenarios, respectively. Both scenarios obtained higher values for heat (representing 352 and 246.4 GJ, respectively). These are not large, however, when compared to the overall environmental impact of the wind turbine. Nevertheless, the results obtained from these scenarios enable waste treatment and recycling to be improved and the barge-type floating wind turbine to be more sustainable.

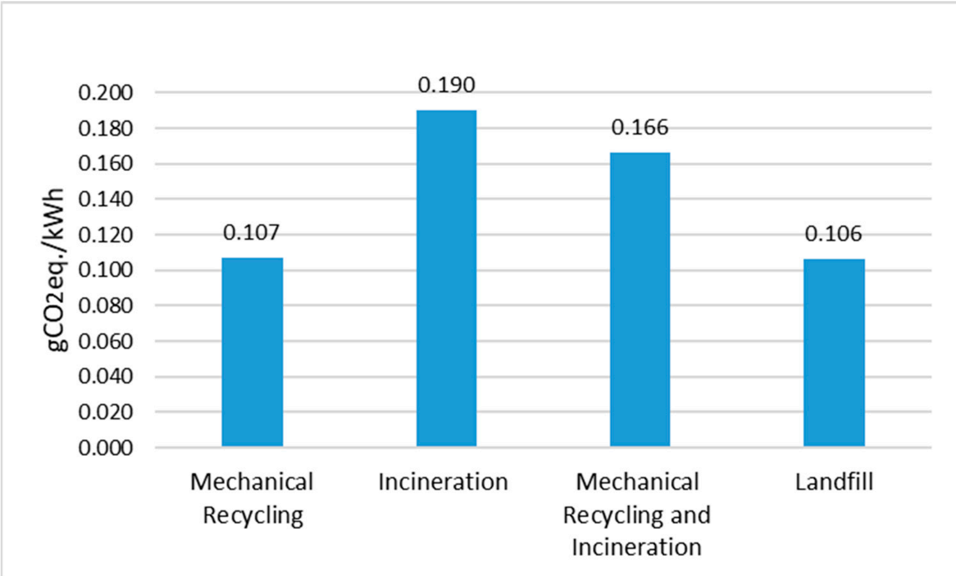

Figure 7. GWP contribution of the end-of-life scenarios for the barge-type floating wind turbine.

6. Conclusions

The LCA of a barge-type wind turbine has been conducted. The wind turbine is assumed to be 22 km from the port with a power rating of 2 MW. This study focuses on improving the maintenance and end-of-life steps for the development of the LCA of the wind turbine. The maintenance scenarios have focused on increasing maintenance throughout the lifetime of the wind turbine, with the implementation of on-site and onshore maintenance strategies. Four different scenarios have been assessed for the end-of-life steps; landfill, mechanical recycling, mechanical recycling and incineration, and incineration scenarios have all been taken into consideration. The GWP of the barge-type wind turbine with a 30-year onshore maintenance scenario is approximately 26% lower than the basic scenarios. For the end-of-life, GWP has been used as indicator to investigate the effect of mechanical recycling, mechanical-incineration, incineration, and landfill scenarios. A considerable amount of the composite material is recycled in the mechanical recycling scenario. The recovered material reduces the GWP for the manufacture stage in the LCA by about 0.69%. Although the GWP contribution is large in the incineration of composites scenarios, heat is released in the combustion process that can be usefully converted into electrical energy. The GWP contribution of the end-of-life scenarios is not very high compared to the total GWP of the LCA of the wind turbine. However, these scenarios give an idea of how to improve the waste treatment of wind turbines. The results of this study indicate that the total GWP contribution could be lowered by increasing maintenance, extending the lifetime of the wind turbine and increasing material recycling. Taking into consideration the findings of the current research, it is possible to make the following recommendations:

- The environmental impacts of these scenarios might be examined in more depth, such as acidification potential, abiotic depletion potential for fossil fuels, etc.
- The energy payback time of these scenarios should be addressed.
- Only the CO_2 emissions of these scenarios were evaluated in comparison in this study. Nevertheless, the costs of these scenarios could well be computed, and a comprehensive comparison could be performed.

Author Contributions: Conceptualization, N.Y.; methodology, N.Y.; software, N.Y.; validation, N.Y.; formal analysis, N.Y.; investigation, N.Y.; resources, N.Y.; data curation, N.Y.; writing–original draft preparation, N.Y.; writing—review and editing, N.Y., H.H., and C.B.; visualization, N.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are included in the paper, and no further data are stored anywhere.

Acknowledgments: The first author would like to acknowledge the Ministry of National Education of Turkey for the financial support of his research activity. The second and third authors acknowledge with thanks COST Action 20109 MODENERLANDS for the support given in the field of the article. The third author would also like to acknowledge with thanks the Alexander von Humboldt Stiftung for continuous support given to his research work.

Conflicts of Interest: The authors declare no conflict of interest.

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