A life cycle assessment of the end-of-life solutions for wind turbine blades

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Preface

This bachelor thesis was written at the Department of Mechanical and Marine Engineering at the Western University of Applied Sciences (WNUAS) for the Energy Technology programme. This thesis was assigned by Professor Richard J. Grant on behalf of WNUAS. The aim of this thesis has been to assess the different end-of-life solutions for wind turbine blades through a life cycle approach.

We would like to thank our supervisor Professor Richard J. Grant, for exemplary help and guidance through this project. Furthermore, we highly appreciate the support and assistance we have received from several individuals.

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Abstract

The increase in environmental issues related to fossil fuels plays a vital role in the development and extensive use of renewable energy sources. Worldwide, many countries invest in wind energy to achieve their climate target by reducing emissions. Renewable energy sources have a lower environmental impact, and one of Europe's fastest-growing energy sources is offshore wind.

The growth in offshore wind initially creates a waste problem, as the wind turbine blades consist of non-recyclable composite. Recycling these composites has been investigated for several years but remains a challenge. Therefore, there is a pressing need to assess the end-of-life solutions for wind turbine blades.

This thesis aims to evaluate the end-of-life solutions in an offshore wind farm's life cycle to reduce the environmental impact. The end-of-life phase, specifically the wind turbine blades, is given special attention since they rarely are considered in previous life cycle assessment studies. The waste management hierarchy is the foundation for the scenarios in the case study. Three different end-of-life scenarios have been considered in the analysis: landfill, co-processing, and repurposing.

The scenarios evaluate the environmental impacts using the life cycle assessment methodology. The energy consumption, emissions, and costs are evaluated for the different scenarios. This study shows that repurposing is the most beneficial solution according to the waste management hierarchy, as the wind turbine blades serves a valuable purpose as tiny houses and roofing.

Sammendrag

Økningen i miljørelaterte problemer knyttet til fossilt brensel spiller en viktig rolle i utviklingen og bruken av fornybare energikilder. På verdensbasis investerer mange land i vindkraft for å nå sine klimamål ved å redusere utslippene. Fornybare energikilder har lavere miljøpåvirkning, og havvind er en av Europas raskest voksende energikilde.

Veksten i havvind skaper et avfallsproblem, siden vindturbinbladene er laget av ikke-resirkulerbar kompositt. Resirkuleringen av disse komposittene har i flere år blitt undersøkt, men forblir en utfordring. Derfor er det et pressende behov for å vurdere håndteringen av vindturbinblader etter livsløpet.

Denne rapporten evaluerer livsløpsløsningene for en havvindpark for å kartlegge miljøpåvirkningen. Slutten på livsløpet for havvindsparker, spesielt for vindturbinbladene, får spesiell oppmerksomhet i denne rapporten siden de sjelden vurderes i tidligere livssyklusstudier. Avfallshierarkiet er grunnlaget for scenarioene i casestudiet. Tre ulike scenarier for slutten av livsløpet er vurdert i analysen: avfallsdeponi, mekanisk resirkulering og endret bruksområde.

Miljøkonsekvensene av scenariene evalueres ved hjelp av en livssyklusvurdering metodologi. Energiforbruket, utslippene, og kostnadene er evaluert for de ulike scenarioene. Case studiet viser at endret bruksområde er den mest fordelaktige løsningen, siden vindturbinblader kan holde på verdien i produktet som som mikrohus og tak.

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Abbreviations

BW = Blade waste

CFRP = Carbon fibre reinforced plastic

EC = Energy consumption

EI = Energy intensity

EMI = Emission intensity

EOL = End-of-life

EPR = Extended producer responsibility

EU = European Union

FRP = Fibre-reinforced plastic

GFRP = Glass fibre reinforced plastic

HAWT = Horizontal-axis wind turbine

LCA = Life cycle assessment

LCI = Life cycle inventory

LCIA = Life cycle inventory assessment

O&M = Operation and maintenance

OWF = Offshore wind farm

OWT = Offshore wind turbine

T&I = Transportation and installation

WF = Wind farm

WMH = Waste management hierarchy

WT = Wind turbine

WTB = Wind turbine blades

1. Introduction

1.1 Background

Over the last century, the world's energy consumption has increased significantly. Economic growth, modern technology available to an even greater percentage of people, and a substantially increased global population are some of the main reasons. Several sectors are being electrified due to environmental reasons, impacting the demand for delivered electricity. This, in combination with an emphasis on reducing the use of fossil fuels, means that renewable energy will contribute to the future energy supply alongside decarbonisation, which also involves sustainable low carbon energy sources such as nuclear [1].

To counteract today's climate changes, countries worldwide should be able to use resources for low carbon energy production and cope with a constantly evolving society. However, many countries depend on their fossil energy production to deliver enough electricity. Renewable energy production requires financial resources and a well thought out plan, and energy should be delivered in a sustainable but affordable way. The wind is a perpetual resource, unlike fossil fuels. Due to the goal of reducing the world's emissions, many countries have pursued an active climate policy, which has led to lower costs for renewable energy production, including wind power [2].

Many countries are investing in wind power to achieve their climate target. According to IRENA, the International Renewable Energy Agency, offshore and onshore wind combined will generate about 35 % of the world's electricity demand by 2050 [3]. One of Europe's fastest-growing energy sources is offshore wind, behind solar power and onshore wind. On average, 3 GW has been installed yearly, and this number will increase to well over 10 GW by 2030. In 2021 the installed offshore wind power in Europe was just over 25 GW, but the European Union (EU) is expected to have installed 60 GW, and Great Britain 40 GW by 2030. The goal for Europe in 2050 is a total output of 300 GW [4]. The climate goals drive the surge of renewable power generation, and offshore wind can provide stable electricity production due to the high and generally predictable wind conditions.

The growth in offshore wind entails more wind turbines that must be treated after the initially designed lifetime. An offshore wind turbine (OWT) is mainly made of recyclable material, except for the wind turbine blades, which are made of non-recyclable composite. Even though a WT has operated throughout its designed lifetime, a sensible solution is still needed for handling the wind turbine blades (WTBs) after decommissioning. To this day, most of the decommissioned WTBs are being landfilled. Other solutions like recycling and repurposing the WTBs are currently being tested, but there is no standard way of treatment due to the lack of experience.

1.2 Aim and objectives

The aim of this thesis is to assess various end-of-life (EOL) solutions for WTBs after decommissioning. Thus, evaluating the environmental impact related to the various solutions through a life cycle assessment (LCA) of an offshore wind farm (WF).

In this report, the case study divides into two parts to make it clearer for the reader. The first part of the case study evaluates the offshore WF and considers the entire WTs. The EOL includes the typical solutions for the components, except for the WTBs. To better understand the EOL of WTBs, it divides into a separate case study. The case studies have a life cycle approach which evaluates energy input and emission output.

In order to achieve this aim, the thesis will be executed by accomplishing a number of objectives:

1. Conduct a LCA for an OWF with 30 units of 3.0 MW WTs.
2. Evaluate three scenarios for EOL solutions for the specific OWF with a life cycle approach. Whereas the three scenarios are landfill, co-processing, and repurpose.
3. Compare the energy consumption, emissions, and costs for the EOL solutions considering the results from the LCA.

2. Literature review

2.1 The components of an offshore wind turbine

The main components of an OWT divide into three categories: support structure, WT, and electrical supplies. The support structure consists of the foundation, transition piece, and scour protection. The WT comprises the tower, nacelle, hub, and rotor blades. Most WTs are typically characterised by a three-bladed rotor driving a horizontally mounted generator. Furthermore, electrical supplies comprise cables and substations [5].

2.1.1 Support structures

OWTs substructures can generally be categorised into two different kinds of foundations: floating and bottom-fixed. Most bottom-fixed substructures are monopile and jacket substructures. Both are steel structures fixed to the seabed driven by piles or suction buckets. Bottom-fixed structures are limited to 50-80 m because at a greater depth, they will become less economical than floating foundations. The most common structure among the offshore foundations is the monopile because of its simple installation process in shallow water depths [5].

2.1.2 Tower, nacelle, and hub

The generic design of a WT is a rotor-nacelle assembly and the tower, see Figure 1. The nacelle is mounted on the tower and can vary in shape and size depending on the WT. The nacelle consists of a generator driven by a high-speed shaft. The high-speed shaft is usually connected to the low-speed shaft by a gearbox. The low-speed shaft goes out of the nacelle, where the rotor hub is placed [6].

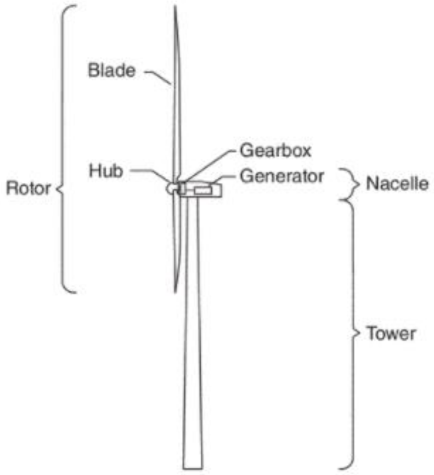

Figure 1. Rotor-nacelle assembly and tower [6].

Since the inception of the wind industry, WT towers have been considered one of the key components. This is because they perform two fundamental functions: provide access to a wind resource by supporting the rotor at a sufficient hub height and provide a safe and reliable load path from the WT to the foundation. Tubular towers are the most common for OWTs and are typically made up of a cylindrical segment of 20-30 m in length. The rotor-nacelle assembly and tower are transported separately and bolted together at their ends at the erection site [7].

2.1.3 Wind turbine blade design

The rotor with its blades is the part of the WT that extracts kinetic energy from the wind, which then converts it into mechanical power and further into electricity. WT rotors can be divided into those driven by the drag on the blades and those driven by the lift on the aerofoils. Furthermore, they can be divided into horizontal axis wind turbines (HAWTs) and vertical axis wind turbines. The three-bladed HAWT with the rotor upstream of the tower is the dominating concept of today. Further in this thesis, there will only be descriptions of the HAWTs concept [8].

2.1.4 Materials in wind turbine blades

In the wind industry's early days, steel was most commonly used for WTBs. This was because of its high stiffness and well-understood processing techniques. For modern WTBs, the specific strength of steel is too low, and it is too difficult to form twist optimised blades. Aluminium was also used, but it was found to be too fatigue-sensitive and insufficiently stiff [9]. Currently, the commonly used materials are fibre reinforced plastics (FRP), which consist of a polymer matrix reinforced with fibres. These materials are chosen because of their high specific stiffness, good fatigue properties, low density, and the ability to tailor the material properties in different directions [9].

Glass fibre is the most used reinforcement material. Another choice is carbon fibre which is stronger, stiffer, more fatigue-resistant and less dense than glass fibre but costs significantly more. Because of the cost, the use of carbon fibre is limited to local reinforcement and the blade spar [9]. In Table 1 a comparison of the system properties of E-glass and carbon fibre is shown.

Table 1. Fibre system properties for glass and carbon fibre.

	Glass fibre	Carbon fibre
Stiffness [GPa]	72	350
Tensile strength [MPa]	3500	4000
Density strength [kg/m^3]	2540	1770

The purpose of the polymer matrix is to bind the fibres together so they can act in unison. The polymer can either be thermosetting or thermoplastic, and both material types have a relatively low Young's modulus. The matrix gives the composite improved toughness [9].

Thermosetting matrix materials are processed by combining a resin with a hardener, which reacts with the resin to promote crosslinking between the polymer chains. This curing reaction is irreversible, so thermoset plastics are hard to recycle. The used materials are typically polyesters, vinyl esters and epoxies. Polyesters have been widely used in the industry's earlier days, but epoxy resins are now becoming the commonly used material [9].

Thermoplastic matrix materials are not currently widely used for utility-scale WTBs. The large size of WTBs makes it hard to achieve the high processing temperatures required for matrix materials. Recycling the WTBs at the EOL is easier done with thermoplastics, and the ability to do this makes them more attractive [9].

2.2 Decommissioning of offshore wind farms

2.2.1 General aspects of decommissioning

The typically designed lifetime of WTs is 20 years, and after their service life, they need to be decommissioned. The reason for the decommissioning may vary. Some reasons may be the components reaching their EOL or the maintenance costs being too high for the WF to continue its operation [10].

The current regulations require OWF operators to decommission and remove all facilities of the OWF at some point. The decommissioning process is a reverse installation process but could potentially be more hazardous and challenging than the installation phase [11]. The removal of underwater infrastructure, the WTs and foundations are included in the process. Specialised equipment and vessels similar to the ones used during the installation are required [12].

In general, the decommissioning of offshore wind projects can be divided into three different phases. Firstly, the preliminary work to plan the program and achieve the required permits. This is followed by the process itself, which corresponds to removing the components. Finally, the monitoring phase will check that the site is left as it should. While older publications offer a theoretical description of the process from a technical point of view, recent contributions have been able to extract conclusions from the comparison to the actual experiences in Europe [12].

2.2.2 Market outlook for Europe

Europe is the leading continent for the offshore wind industry, with a total installed capacity of 28 GW [13]. Development for offshore wind started later than onshore wind, and the offshore wind industry is still relatively young. However, the situation will significantly change in the upcoming years. According to WindEurope, the annual installation is expected to increase from 3 GW to 5.6 GW over the next five years [13]. Europe has already experienced the EOL and decommissioning of several projects in the offshore wind industry. However, these WFs are minor compared to today's standards. The eight OWFs that have been decommissioned only have 32 WTs combined, as shown in Table 2. Both the number of WTs in a WF as well as the size of them will increase significantly in the years to come [12].

Table 2. Offshore wind farms which have been decommissioned in Europe [12].

Wind farm	No. of turbines	Total capacity [MW]	Location	Year
Yttre Stengrund	5	10	Sweden	2015
Hooksiel	1	5	Germany	2016
Lely	4	2	Netherland	2016
Beatrice Demonstration	2	5	United Kingdom	2016
Vindeby	11	5	Denmark	2017
Utgrunden	7	10.5	Sweden	2018
Blyth	2	4	United Kingdom	2019
Total	**32**	**41.5**	**-**	**-**

Over 1800 OWTs will be decommissioned between 2020 and 2030, and because of the growth in the industry, the number will increase to nearly 20,000 between 2030 and 2040 [12]. The annual number of OWTs reaching the EOL in Europe is shown in Figure 2.

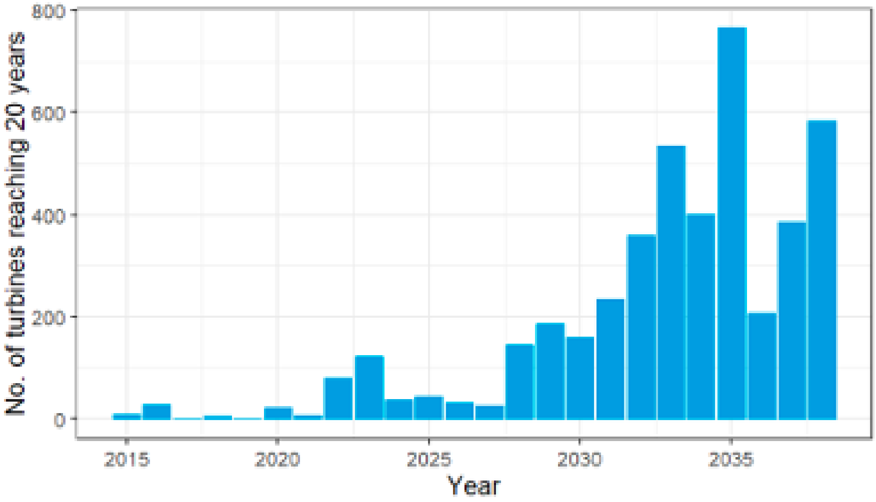

Figure 2. Number of wind turbines reaching 20 years annually in Europe [12].

2.3 Challenges of decommissioning

Today, only two OWFs have reached their initially designed lifetime before decommissioning: the projects Lely and Vindeby. For the rest of the OWFs, decommissioning occurred before reaching the end of their designed lifetime [12]. This indicates many uncertainties and unexpected challenges affecting the decommissioning process.

There are often high variations between decommissioning processes, and therefore, difficult to provide a standardised method. However, classifying the key challenges can provide a plan for recommended execution [12]. The challenges can be divided into four groups: environmental impact, planning of decommissioning, vessels availability, and regulations.

2.3.1 Environmental impact

Firstly, deciding whether the OWF will be totally or partially removed is crucial. To leave the site as it was before commissioning is often believed to be environmentally beneficial. However, recent studies show that partial removal of the OWF may be better for the marine environment [12]. After 20 years, marine life has adapted to its surroundings, and the subsea cables buried under the seabed could be left on site. All cables must be excavated upon a total decommissioning of the OWF. This would cause a significant marine disturbance and a higher cost, given the combined length of the cables. On the other hand, a complete removal could restore shipping and fishing activities, among others [14]. Inexperience makes this a difficult decision as there are both advantages and disadvantages for a total or partial removal.

When the decision of partial or total removal has been made, it must be ensured that the decommissioning is carried out as sustainably as possible. This mainly involves the reuse and recycling of the different components. Most of the WT components are metal (tower, generator, parts from the hub and nacelle, etc.) which corresponds to approximately 95 % of the WT. With a lot of experience in the recycling of these materials, this is not a challenge. The remaining 5 % of the WT is mainly the WTBs which are made of composite and are currently non-recyclable [12].

The WTBs entail major challenges in both recycling and transport logistics. The evolution of offshore wind is also likely to have a negative effect on the WTBs' recyclability. A study shows that the amount of raw material needed for one big WT is greater than for two small WTs with equivalent installed capacity [10].

2.3.2 Planning of decommissioning and vessels availability

A plan for the decommissioning process should be made at the beginning of the project, where a detailed plan is beneficial. However, because of little experience in this field of the industry, this is not a simple task. There is no specific method to execute the decommissioning process, and new methods or tools can be implemented within the service life of an OWF [12].

Every project is different, and the plan must be made based on the characteristics of the specific OWF. Different parameters like water depth, WT size, type of foundation, distance from shore, and nearest operating port must be taken into consideration. The availability of specialised vessels can be compromised with the installation of new OWFs and the need for maintenance on currently operating offshore installations [12]. However, more vessels will likely be put in operation to compensate for the growth in the offshore industry.

The various components of an OWF have differently designed lifetimes. Electric infrastructure such as cables could last up to 50 years, foundations up to 100 years, while the lifetime for the WTs is 20 years [15]. The lifetime of every component for an OWF should be taken into consideration when planning the decommissioning process. With cables that can last over twice as long, and foundations that can last up to five times longer, the OWF site can be leased for longer than the planned lifetime, and new OWFs can be installed using the same infrastructure. This strategy is currently performed in several decommissioning projects in the UK and is also observed in the Danish wind farm Nysted [15].

Decommissioning plans are made years prior to the process, and significant changes regarding the technical implementation can emerge. Due to the large development in offshore wind, WTs can become obsolete quickly, and the availability of spare parts will therefore be reduced [12].

2.4 Waste management hierarchy

The waste management hierarchy (WMH) evaluates resource and energy consumption alongside protecting the environment for future generations. The aim is to extract the most practical benefits from products and generate the smallest amount of waste. Proper use of the WMH can reduce pollution, conserve resources, create jobs, save energy, and stimulate the development of green technologies. The European Waste Framework Directive defines basic concepts of related waste management and establishes the WMH [16] [17].

The hierarchy ranks waste management options in order of preference. The most preferred option is prevention, where it is possible to reduce waste by designing the products for easier recycling and dismantling by minimising the number of materials in the design. Reuse is the second preferred option and aims to make it easier to repair or refurbish products to use for the same purpose. Repurposing is reusing an existing part for a different application. Recycling is converting waste into a new substance product. Energy recovery includes, for example, pyrolysis, which produces energy and materials from waste. The least preferred option is disposal which is incineration without energy recovery and landfill. The various ranks of the WMH are illustrated in Figure 3 [18].

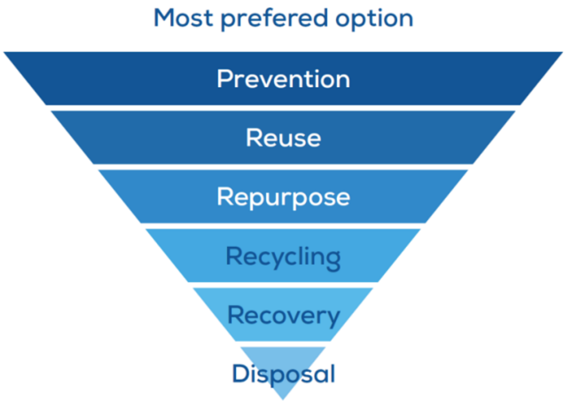

Figure 3. Waste managment hierachy [67].

WTBs are made of composite materials, and 2.5 million tonne of this material are currently being used in the wind energy sector. Fifteen thousand WTBs will be decommissioned between 2019 and 2024 [19]. The collection, transportation, and waste management of the WTBs require a logistical and technological solution. The industry wants to exploit the WTBs where it gives the most value [19].

2.4.1 Circularity by design

Circular material use, including recycling, reuse, and refurbishment, aims to reduce the economy's dependence on the extraction and import of raw materials and waste generation. Circularity by design has the potential to promote both economic and environmental benefits. The circular economy concept is that the value of materials and products is kept as high as possible for the longest period and then recycled. This concept minimises the need for input of new material and energy, thereby reducing environmental pressure linked to the life cycle of products [20].

Clean material extraction is crucial for maintaining the material's performance and quality in the recycling processes. Material performance, safety, and the cost will determine whether second-handed consumers will buy the recycled product [20].

2.5 Regulations

For the composite waste sector, few regulatory requirements have been implemented. However, there is a common drive toward more circularity in Europe, as shown by the EU Circular Economy Action Plan from 2020 [21]. Four countries have made an apparent reference to composite waste in their legislation. Finland, the Netherlands, Austria, and Germany all forbid composites from being incinerated or landfilled [16].

2.5.1 Legislative content in the European Union

Legislation is a solid lever to push the establishment of new sustainable behaviours in the wind energy industry. Today, there is limited legislation regulating the treatment of WTBs or composite materials in the EU. Due to the wind generation market's development at different paces at an international level, the existing national legislation is not aligned with the EU. The decommissioning practice has only started to emerge in the countries with a mature market with repowering and decommissioning activity [22].

To incentivise recycling, the authorities use different regulatory instruments, such as landfill bans, taxes, and extended producer responsibility (EPR) requirements. Additional standards and legislations for the procedures and processes related to the continued operations and reuse will also play an essential part in the solution that the industry could implement in terms of repurposing, recycling, and recovery [22].

Composite blades, according to the European classification of waste, are most often categorised with code 17 02 03: plastic waste from construction and demolition. It is important that the correct and suitable code is applied to blade waste by the national authorities. The code should ensure efficient separate collection and sorting to help identify suitable waste treatment options [16].

2.5.2 Extended producer responsibility

The purpose of EPR is to transfer the responsibility of the waste management from the public authority or the consumer to the manufacturer of the product [23]. EPR ensures that the product can be recycled at the EOL and is especially interesting for cases where there are no financial or economic incentives to collect and recycle the waste products. There are currently no economic incentives to recycle glass fibre-reinforced plastics (GFRP), and EPR appears as an adequate policy tool to support the implementation of waste management solutions for WTBs [22].

Implementing EPR in the wind energy sector will be a barrier for developers. However, ensuring a significant recycling rate of WTBs can be promoted using alternative yet similar measures. A decree published in June 2020 in France sets specific recycling rates for WTBs without detailing the responsible party to achieve these targets. The requirements for WTBs are: "From the permits accepted after July 1, 2022, a minimum of 35 % of the rotor mass should be reused or recycled. Permits after January 1, 2023, the minimum is set to 45 % of the rotor mass. And by January 1, 2025, 55 % of the rotor mass should be reused or recycled." [22]. However, according to the WMH, the recycling of WTBs uses energy to convert the blades into something with less value and is therefore not an ideal solution.

Other incentives for the manufacturers of WTs for more recyclability than EPR, besides legislation, may be new and more cost-effective materials. This could be triggered by a breakthrough in the technological aspects of WTBs, allowing recycled materials to re-enter the manufacturing process. Resulting in lower costs of virgin materials and closing today's linear economy into a circular economy [22].

2.6 Current end-of-life alternatives

2.6.1 Life extension

One of the approaches to delay the waste management issue is extending the durability of the WTBs. Durability is one of the most obvious strategies for reducing waste and increasing material productivity. Today there are several options to increase the service time of WTBs, among them, using more durable materials, better maintenance, repair, reuse, and refurbishment [24].

The damaging mechanisms for WTBs include surface erosion and debonding adhesive joint degradation. There are several strategies which can be implemented to increase the WTBs' durability and prevent degradation. For surface erosion, new engineered coating materials are developed. The approach is to develop durable composite laminates, including using lighter and stronger fibres. The use of lighter materials allows for reducing the WTBs weight and, therefore, ensuring lower weight loads on the blades. For erosion protection, a load reducing strategy can be used as a so-called erosion safe control. Recently, the life extension of WTBs called easy-healing or self-healing materials have attracted growing interest [24].

It should be noted that including different materials in the WTB conflicts with the circular design of composites and recycling at EOL. Fewer combinations of different materials and broader use of the same materials would make the WTBs more sustainable [24].

2.6.2 Recycling and reusing wind turbine blades

While life extension and reuse efforts can delay the EOL of the WTBs, the old WTBs must be disposed of or recycled at some point. The recycling technologies are classified into different groups:

- Primary recycling: recycling products for the same use.
- Secondary recycling: recycling products for use other than their original use.
- Tertiary recycling: recovering petrochemical components of plastics via a chemical process.
- Quaternary recycling: incinerating plastics to recover energy in the form of heat [24].

Before involving the composite materials recycling technologies, the possibility of reuse should be considered. The refurbishment of WTBs can allow for enlarging blade size, improving structural parameters, and removing defects. There are several companies that offer WT upgrading approaches, such as extending the useful life, increasing the wind energy production, the output, and the profit [24].

2.6.3 Recyclable polymers

Reuse, recycling, recovery, and remanufacturing of WTBs, coming to the end of their life, represent a challenge for the energy industry. Today, new WTs are developed, manufactured, and installed. In view of the EOL phase for WTs, the problem should be solved at its source. This can be achieved by developing sustainable and recyclable WTBs to prevent the reappearance of the same problem in the future [24].

The composites are made from strong stiff fibres and a tough polymer matrix. The first approach should be to make composites recyclable, including making the polymer matrix easily removable, degradable, or even reusable. This allows the reuse of the fibres. By using thermosets instead of the common epoxy or polyesters, this can be achieved. An alternative can be to use bio-based/biodegradable fibres or lumbers such as wood, bamboo, plant-based composites, or bio-based polymers [24].

2.6.4 Today's refurbishment market

Innovations in wind technology have drastically increased the power output of new WTs compared to older ones. By repowering a WF, it is replacing older and smaller WTs with generally larger and more efficient ones to increase the electricity generation. An inoperative WT can be operational again by refurbishing or replacing components [25].

Refurbished WTs are often still capable of attaining their purpose for several years for a fraction of the cost of a new WT [25]. If the WT is not recycled, the decommissioned WT can end up in the second-handed market. Refurbishment companies look to acquire used WTs that they can refurbish and resell to a third party. The amount of required work is circumstantial for the specific WT, varying from basic repairs to significant overhauls [25].

There are numerous refurbished WTs that are fully functional for producing more electricity but are not currently operative. These WTs can be sold and bought at a global marketplace platform, which has several thousand used WTs for sale. It is also possible to buy and sell used components to extend the lifetime of the WTs. It is possible to advertise used WTs categorised by hub height, rated power, location, year of manufacture, manufacturer, and model. Putting a WT or WF up for sale before the decommissioning can be beneficial because it can enlarge the interest group.

2.6.5 The situation in the UK

Numerous research projects in recycling FRP have been carried out in the UK [26]. Most of them have demonstrated technically viable methods for reclaiming the fibres and reusing them in various applications. Bringing these processes and the recycled products to the market has been challenging. Expensive testing, designing, and changing standards need to be undertaken for products to be accepted in the production industry with recycled FRP products. It is also challenging to find the investment required for a probable low-profit margin product in the UK [26].

Recycling CFRP (Carbon fibre reinforced plastic) has progressed because of the high value in carbon fibre, and some large aerospace companies have supported the development. However, the value of GFRP is much lower, and therefore the interest in investing is limited [26].

The most promising approach for recycling WTBs is co-processing with refuse-derived fuel in cement kilns. This type of process is practised in Germany and is starting to emerge in the UK. It may be beneficial for the UK to develop a supply chain for co-processing of GFRP waste in cement kilns and to integrate it with existing waste management. It is desirable that the co-processing supply chain soon will be available in the UK, as it is in Germany. Some companies in the UK are now sending their GFRP waste to energy recovery plants abroad [26] [27].

2.7 Repurposing of wind turbine blades

WTBs often end up in landfills, and the magnitude of this waste problem is significant. Repurposing WTBs can keep the value of the material as high as possible after its initial service life. Although the designed lifetime for most WFs is 20 years, the WTBs are highly durable and can last for over 100 years when repurposed [28]. GFRP, used in WTBs, offer good properties as the material is lightweight but strong and can be used for complex shapes in various designs [29].

Before repurposing the WTBs, getting acquainted with their structure is beneficial. The shear web (3) and spar caps (4), as well as the leading (1) and trailing edge (2), are set up to provide minimum weight and a high level of stiffness throughout the blade, as illustrated in Figure 4.

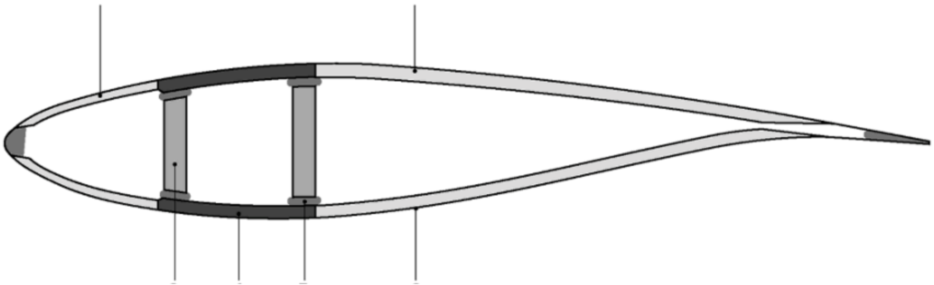

Figure 4. Cross-section of a WTB. 1: leading-edge, 2: trailing edge, 3: shear web, 4: spar caps, 5: adhesive bonds, 6: coating [29].

Notice that the shape and size also change with the length, as shown in Figure 5. The WTBs are optimised through years of engineering development to provide the highest efficiency while still being able to withstand the cyclic forces affecting them. This indicates that the physical condition of the blades may still be good after years of operation [29].

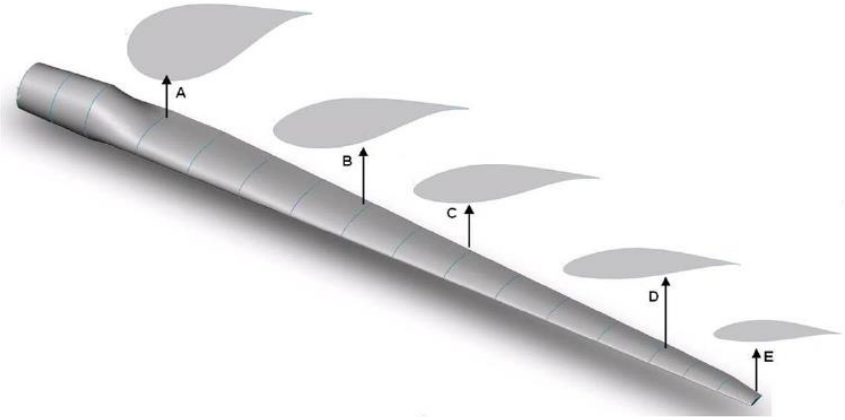

Figure 5. Cross section: changing longitudinally [66].

Several companies are already testing various products made of retired WTBs. Based on the growth in the wind industry and the amount of decommissioned WTBs that are going to need treatment, an industrial-scale solution is necessary. A collaboration between USA's and Ireland's research team from Georgia Tech, Queen's University Belfast (QBC), City University Of New York (CUNY), and University College Cork (UCC), called the Re-Wind project is studying sustainable strategies for repurposing WTBs. The team consists of engineers, architects, geologists, politicians, and development experts [30]. Re-Wind shows a variety of repurposing concepts. The company demonstrates the feasibility of repurposing and emphasise that large-scale realisation needs to be studied closely in terms of costs, logistics, material quality, and social acceptance [29].

Another company working with repurposing WTBs is ANMET. The specialising waste company was founded in 1999 and expanded its offer to include recycling and repurposing WTBs with their subsidiary called "AIRchitecture" in 2015 [31]. ANMET is constantly working on new solutions and technologies in the industry, and some of the designs can be seen in Figure 6.

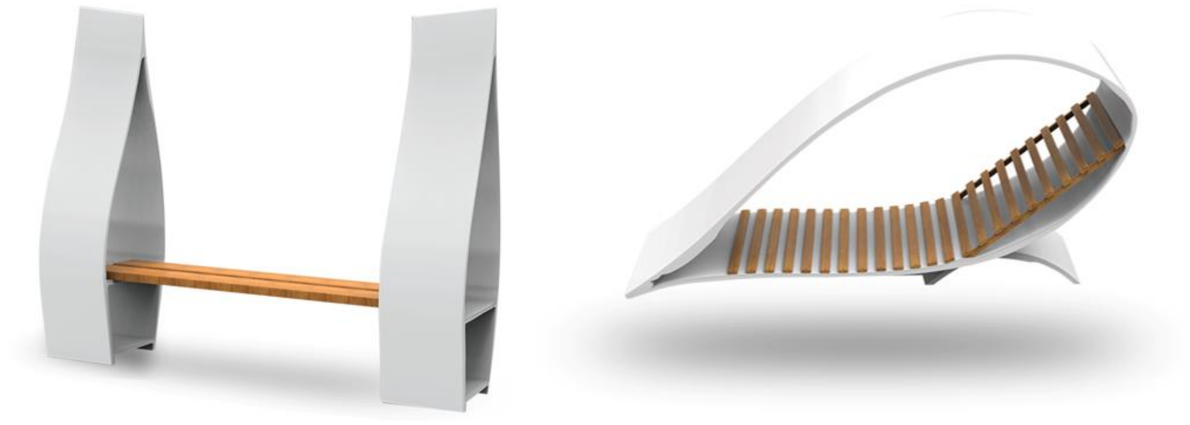

Figure 6. Wind turbine blade repurposed as a bench and chair [31].

Many suggestions have been made over the last couple of years, like the ones proposed by Re-Wind. They are repurposing the WTBs for bridges and powerline structures without any cutting, as illustrated in Figure 7. Other solutions require the WTB to be divided into smaller sections, which will increase production time significantly. However, from a logistical and manageability perspective, it has advantages.

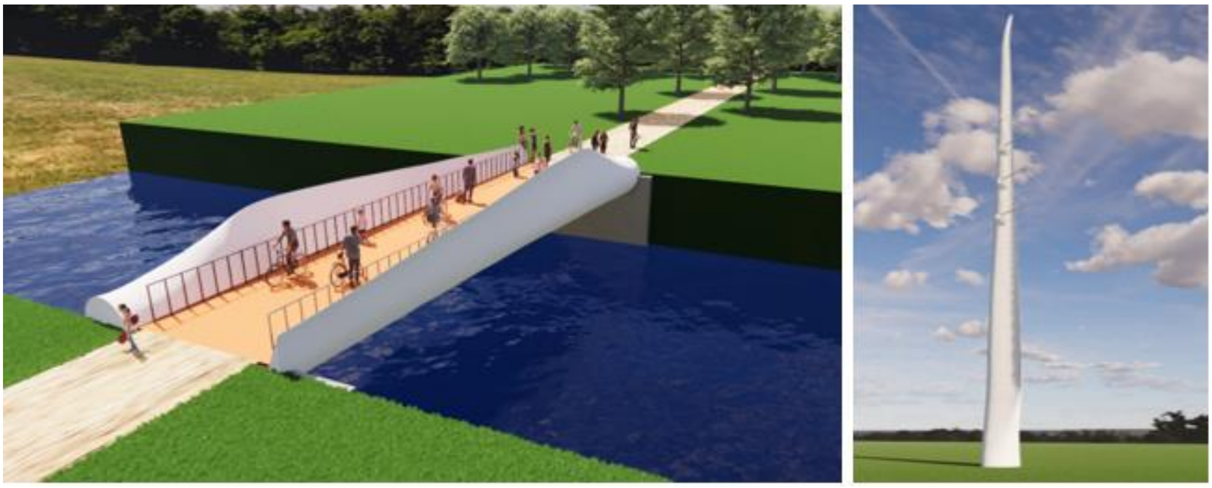

Figure 7. Wind turbine blade repurposed as a bridge and powerline structure [32].

Smaller sections can be used as roofing for bus stops, charging stations, chairs, benches and even dividers for cows at farms. Cutting the WTBs into smaller and easily usable pieces will diversify the possibilities for repurposing applications. If the parts are being divided into small enough sections, the complex shape of a WTB will no longer be as relevant. However, as illustrated in Figure 8, the value will decrease by putting more time and energy into handling the WTBs.

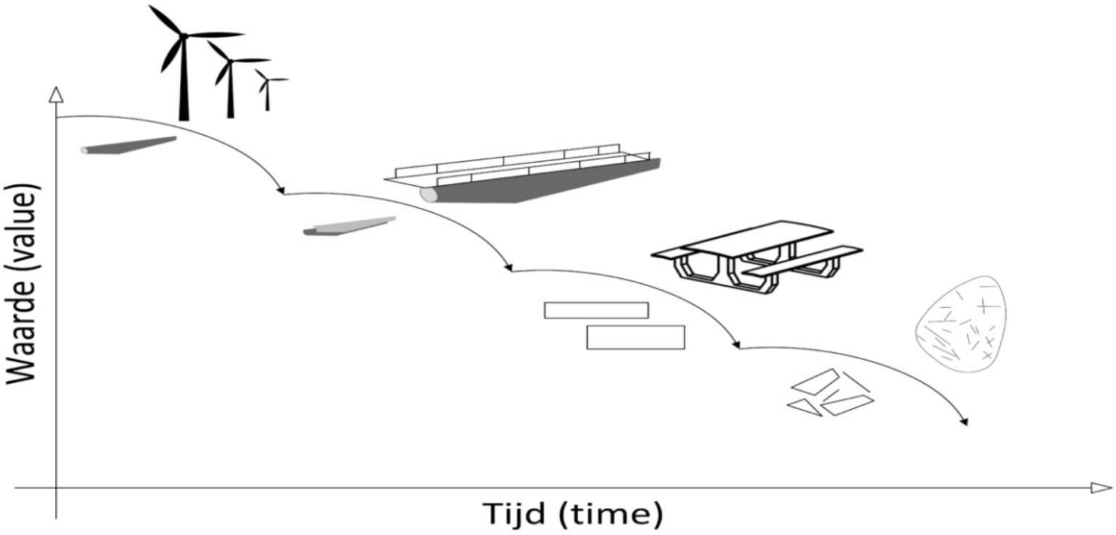

Figure 8. Time and value of a WTB [33].

The number of possibilities for repurposing is mainly limited by the complexity of the WTBs and the possibility for large-scale production. Companies like Re-Wind and ANMET show several designs from different sections of the WTBs. The challenge is to find solutions that can repurpose a significant amount of the WTB waste without overproduction of certain products. However, if the suggested designs are made and the repurposing industry grows, the products might differ in the overall perspective. Companies specialising in repurposing WTB prove potential that can inspire other industries and businesses with similar interests.

3. Methodology

This section describes the methods used in the report, which includes literature studies, software, and a life cycle assessment (LCA). It also outlines the numerical methods used to calculate the WT's life cycle energy consumption (EC) and emissions as well as for the EOL solutions. The Kentish Flats Offshore Wind Farm was chosen to be analysed to demonstrate the impact of the WTs from a life cycle perspective and to investigate an end-of-life (EOL) solution for the WTBs. This exact wind farm was chosen because of its representative size with thirty 3.0 MW WTs and a total effect of 90 MW.

3.1 Life cycle assessment

LCA includes the extraction, processing, manufacturing, transportation, assembly, replacement parts, maintenance, and EOL treatment. Firstly, the LCA will be executed for the entire wind turbine, and then three different scenarios for the EOL of the WTBs will be evaluated. In this report, the international standard ISO 14040 for LCAs have been used [34]. In the case studies, the same assumptions and methodology will be used, which are gathered from several different LCA studies for OWFs.

Generally, an LCA is completed in four stages:

1. Define the goal and scope
2. Conduct a life cycle inventory analysis
3. Conduct a life cycle impact assessment
4. Interpret the results [34].

3.1.1 Life cycle inventory

In the life cycle inventory (LCI) analysis of the life cycle assessment, material inputs, energy, and emissions for various processes within the system boundary are quantified. Within this stage, all appropriate data is gathered and organised [34]. Without an LCI, the foundation for evaluating environmental effects would have been difficult. The data for the LCI has been collected directly from organisations, firms, and existing databases.

A LCI permits quantifying the contribution of the different life cycle stages of a WF to the priority of environmental problems [34]. The LCA for this report is divided into four phases, and the system boundary is shown in Figure 9.

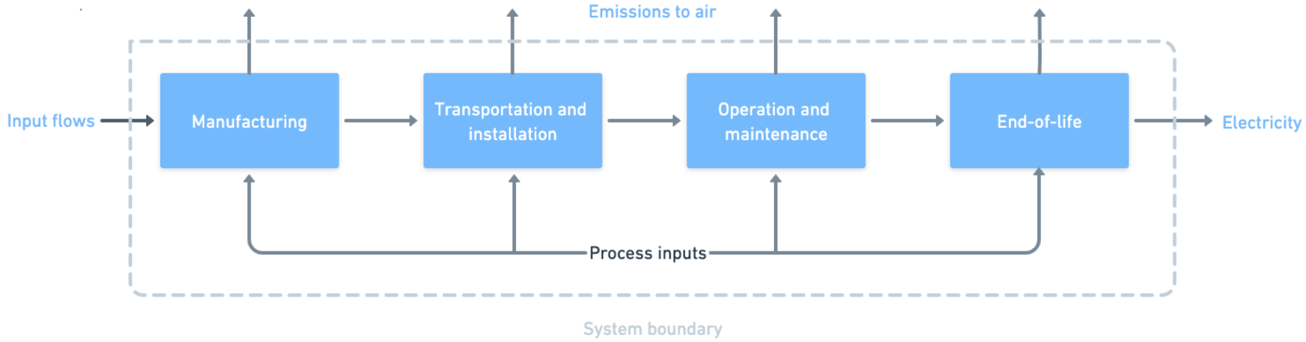

Figure 9. System boundaries for the life cycle assessment.

The different phases can be explained as follows:

1. Manufacturing comprises the raw material extraction, as well as processing (concrete, aluminium, steel glass fibre, carbon fibre, etc.) needed to manufacture the tower, nacelle, hub, blades, and foundation.
2. Transportation and installation (T&I) consider both the transportation needed to move the components to the farm site and the transportation for the assembly and erection of the WT.
3. Operation and maintenance (O&M) of the WTs, includes transportation, maintenance, replacement parts, and installation.
4. End-of-life (EOL) for the OWF considers the dismantling of the WTs and the transportation from the erection site. This also includes recycling of some components and depositing inert components in landfills [35].

3.1.2 Life cycle impact assessment

The life cycle impact assessment (LCIA) converts inventory data into information about environmental effects. It aims to evaluate the significance of potential environmental impacts using the results of the LCI. In general, this process involves associating inventory data with specific environmental impacts. The level of detail, choice of impacts evaluated, and methodologies depends on the goal and scope of the study [34]. In the case studies, this includes the EC, emissions, as well as energy intensity (EI) and emission intensity (EMI).

3.1.3 Life cycle interpretation

Interpretation is the phase of the LCA in which the findings from the inventory analysis and the impact assessment are combined. In the case of LCI studies, the findings of the inventory analysis is consistent with the defined goal and scope. This is to reach conclusions and recommendations. The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected consistent with the defined goal. In this thesis, this will be done in the results and discussion [34].

3.2 Software

In this report, there are used different software to achieve the results. The various software is SimaPro, Creo Parametric, Microsoft Excel and Qblade. The transport distances are found using Google Maps. Values displayed in the tables is rounded off for readability, which creates a margin of error. The extended values and full calculations are shown in the appendixes.

3.2.1 SimaPro and Ecoinvent

To gather information for the LCA, the software SimaPro has been used. SimaPro is a software which was developed by PRé Consultants to conduct life cycle analyses. The tool can be used to model and analyse complex life cycles, but in this report, SimaPro has only been used to gather information from the databases [36].

SimaPro includes several LCI databases, including the renowned ecoinvent v3 database. Ecoinvent is a not-for-profit organisation dedicated to promoting and supporting the availability of environmental data worldwide. The association is the world's biggest LCI database and contains over 19,000 different datasets. All databases are transparent and updated if new data is available [37].

The dataset for transportation in ecoinvent is titled "Transport, freight, lorry 16-32 tonne {RoW}". This form of transport selected assumes its emissions and EC based on the weight of the load and how far its transported in tonne-kilometre (tkm), and is used in all scenarios.

For emissions and EC from the production of cement, concrete tiles and wooden cladding the following datasets are used; “Cement, Portland {US} production…”, “Concrete roof tile {RoW} production…” and “Wood cladding, softwood {GLO}…”. For the datasets from SimaPro used in the report see the relevant appendix. Numbers used in the calculations that are not accessible from SimaPro are collected from scientific reports.

3.2.2 Creo Parametric and Qblade

Qblade is an open-source WT calculation software. The integration of the XFOIL/XFLR5 functionality allows the user to design custom aerofoils and compute their performance [38] [39]. The software is used to show WTB designs and the repurposing applications. A reference 5-MW WT from the National Renewable Energy Laboratory is used in this case [39]. See Appendix 1 for the distributed blade aerodynamic properties for the specific WT.

Creo Parametric is a 3D CAD modelling software with model-based definition, additive manufacturing, simulations, and design. PTC`s developers created Creo Parametric as a foundation software that allows users the ability to expand deeper functionality with different components [40]. The software is used to create different repurposing solutions for the WTB. Since the information about the Vestas V90 WTB is not in the public domain, a 5 MW reference WTB is used to construct the blade roof and tiny house [41].

3.3 Numerical method

The life cycle processes organise into four stages: manufacturing, transportation and installation, operation, and maintenance, and dismantling and end-of-life. The total emissions and EC are the sum of these four stages and are described as:

$$E_{Total} = E_M + E_{TI} + E_{OM} + E_{DE} \tag{1}$$

The subscript M indicates manufacturing, TI for transportation and installation, OM for operation and maintenance, and EOL for end-of-life. This is a general equation and can also be used in the same way for other inputs.

Emissions and EC for each stage are calculated as:

$$E_{sum} = \sum (input_i \times E_i) \tag{2}$$

The E_i is the emission or EC intensity coefficient of the i-th input of the WT, and $input_i$ is the amount of the i-th input. The intensity of the system is calculated as follows:

$$EI = \frac{E_{sum}}{W} \tag{3}$$

Where E_{sum} is the sum of the emissions or EC, W is the output of the WF, and EI is the intensity.

To calculate the emissions from transportation, tkm has been used. This has been calculated for both land and sea transportation as follows:

$$TKM = \sum (mass_i \times distance_i) \tag{4}$$

Where $mass_i$ is the mass (tonne) of the components and $distance_i$ is the transportation distance (km) which is summed for all masses and distances.

4. Case study: Life cycle assessment of an offshore wind farm

A 90 MW WF represents a typical farm size for 3.0 MW WTs. The scope of this study is a cradle-to-grave LCA which considers WT manufacturing, T&I, O&M, and EOL. In this study, the transformers, substations, and cables are neglected.

The Kentish Flats Offshore Wind Farm is located on the southern side of the Thames Outer Estuary, approximately 8.5 to 13 km north of Herne Bay on the North Coast of Kent. It was commissioned in 2005 and is up for evaluation for decommissioning in a couple of years [42].

4.1 Functional unit

The functional unit for an LCA must be defined, which provides a clear description of the function of the product. The functional unit is set as 1 kWh electricity generated at the WF, and the EC and emissions are estimated. The emissions are expressed as kg CO_2-equivalent ($CO_{2(eq)}$), while the EC is expressed as MJ. The intensity is defined as the value of emissions or EC per kWh of electricity generated. This functional unit is only valid for the first part of the case study.

4.2 System details

The WT model is a 3.0 MW, pitch regulated upwind WT with active yaw and a three-blade rotor. The WTBs are 44 m in length with a rotor diameter of 90 m and full blade pitch. Each WT has a conical tubular 3-parted modular tower with a hub height of 80 m which is 70 m above mean sea level [43]. The main characteristics of the WF are shown in Table 3.

Table 3. Characteristics for the offshore wind farm.

Characteristics for the OWF	
Type of wind turbine	V90-3.0MW
Number of turbines	30
Total output (MW)	90
Expected annual output (kWh)	280,000,000
Hub height	70 m
Blade length/rotor diameter	44/90 m
Length of mono-pile	38-44 m
Depth of water	5 m

The expected output does not correspond with the actual output of the WF which is 233 GWh annually [44]. The rotor assembly is the key module of the WT and is consists of the blades, hub, nacelle and bearing. The rotor assembly is connected to the nacelle assembly, which is attached to the top of the tower. The nacelle assembly comprises a fibreglass housing that protects the gearbox, generator, hydraulic system, main shaft, and yaw/pitch system from the weather. The tower is made of conical steel sections, which are bolted together. The structure used to support the WTs is a monopile foundation [43].

The nacelle and hub were assembled with two blades into a so-called "bunny ears" configuration as illustrated in Figure 10. Completion of the WT installation is done in three lifts. The first lift is the complete tower, the second is the nacelle with the "bunny ears", and the last one is the final WTB [42].

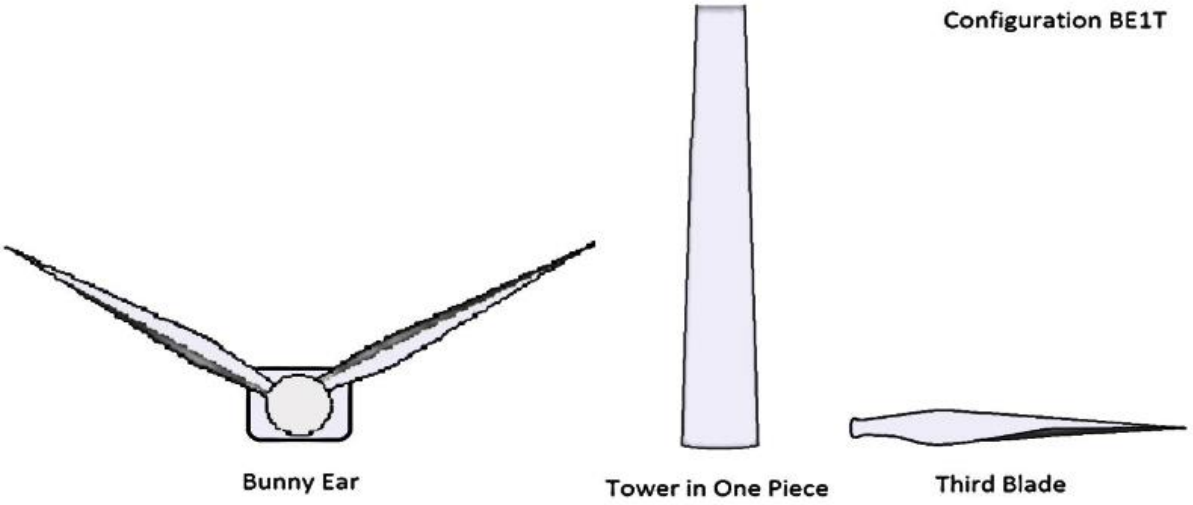

Figure 10. "Bunny ear" configuration, the tower and third blade [45].

The lifetime of this WF is 20 years which corresponds with the design lifetime of the chosen WT. This applies to all components of the WF, except some replacement parts [35]. The actual lifetime of a WF is uncertain, which means the WF can be decommissioned before or after its designed lifetime.

4.3 Life cycle inventory

WTs consist of many mechanical and electrical assemblies, which comprises many sub-components. Therefore, it is challenging to gather all the information from the different suppliers that provide the WT components. Because of this, there are used assumptions for different parts of the analysis. The information contained in the life cycle inventory is described for each LCA phase.

To compile the LCI for the WTs, they were reduced into their major assemblies, sub-components, and respective materials. Since specific information was not available about parts such as the paint, and minor components such as bolts, fasteners, and internal wires, these were neglected. This is because the EC required for wiring, grid connection, and transformers may be equivalent for different WTs and thus have little impact on the result.

4.3.1 Manufacturing

The bill of materials for the V90-3.0 MW WT is gathered in Table 4. Information regarding components, materials and masses was obtained from the manufacturer. The ratio of materials in the components is calculated using percentages from the same WT from an earlier report [46]. All information obtained is in the public domain.

Table 4. Bill of materials for the V90-3.0 MW [43] [42].

Component	Sub-component	Materials	Total mass (kg)
Tower		Steel	108,000
Rotor	Blade (x3)	Fibreglass	11,880
		Epoxy	7920
	Hub	Cast iron	7600
		Aluminium	400
Nacelle	Generator	Aluminium	3010
		Steel	5160
	Frame, machinery, shell	Copper	2184
		Steel	30,940
		Aluminium	3276
	Gearbox	Copper	230
		Steel	22,540
		Aluminium	230
Foundation		Concrete	261,900
		Steel	8100

The WTBs are made of fibreglass reinforced epoxy in a sandwich construction, where it is assumed a general weight distribution of 60 % glass fibre and 40 % epoxy resin. The nacelle consists of the frame, machinery, shell, gearbox, and generator. The whole assembly is mounted on a bed frame made of cast iron and surrounded by a nacelle cover [43]. The bed frame is included in the "frame, machinery, and shell" subcategory. The tower is mainly made of steel and is the only material accounted for in the subcategory. The values used to calculate the emissions and EC for manufacturing per kg of the material are shown in Table 5. The values are gathered from various scientific reports.

Table 5. Embodied energy for the respective materials [47] [48] [49].

Material	Emissions [kg $CO_{2(eq)}$/kg]	Energy [MJ/kg]
Steel	1.8	20.6
Concrete	0.1	0.8
Glass fibre	2.9	51.1
Epoxy	6.3	118.3
Copper	2.7	42.4
Aluminium	8.4	47.0
Cast iron	1.5	8.6

4.3.2 Transportation and installation

Transportation from emissions caused by the extraction and production of fuel is neglected. Each component is assumed to be transported to the assembly site from the components manufacturer by lorry and ship and is measured in tkm. The unit tkm is equivalent to the transport of one tonne of product over one kilometre.

All of the components are manufactured in Vestas's facilities in Germany and Denmark, except the foundation. The foundation is manufactured by MT Højgaard, and it is assumed that the facility is close to its headquarters in Denmark. All the components are transported to the Port of Felixstowe, where the WTs were partly assembled [50]. The transportation input for the WTs are shown in Table 6 and were calculated using Equation 4.

Table 6. Transport distances from the manufacturing facilities.

Component	Port	Lorry [tkm]	Ship [tkm]
Nacelle	Esbjerg, Denmark	87,360	671,580
Hub	Esbjerg, Denmark	19,200	147,600
Blades	Esbjerg, Denmark	41,580	365,310
Generator	Hamburg, Germany	24,510	357,330
Tower	Hamburg, Germany	307,800	2,170,800
Foundation	Copenhagen, Denmark	364,500	9,477,000
Gearbox	Hamburg, Germany	462,300	462,300

For the installation on the erection site, the WT is shipped sequentially and installed by various vessels. The EC for the vessels is provided by either marine gas oil (MGO) or heavy fuel oil (HFO). On average, the installation time of a complete WT required 24 h, and the installation of the foundation required 4 h. This included transport to the site, positioning, pre-load, and three lifts [50]. It is therefore assumed that the vessels for the installation all operated for 24 h for the WT installation, and 4 h for the foundation installation.

The assumed installation vessels used were jack-up vessels, crane vessels, and tugboats. The information on vessels used in the T&I, O&M, and EOL of the WF is based on information from an earlier report [51]. The work hours have been adjusted to Vattenfalls statements about the installation process. The number of vessels, fuel type, fuel rate, and work hours for the installation are listed in Table 7.

Table 7. Vessels, fuel rate and work hours in the installation phase.

Activity	No. of vessels	Fuel type	Fuel rate [L/h]	Work hours [h]
Foundation				
Vessel for transport of rock for scour protection	1	HFO	360	120
Vessel for transport of rock for scour protection	1	HFO	210	120
Jack-up vessel for transport and installation of foundations	1	HFO	87	120
Tugboats for transport of foundations and jack-up vessels	2	MGO	320	240
Wind turbine				
Crane vessel for the installation of wind turbines	1	HFO	160	720
Tugboats for transport and installation of wind turbines	2	MGO	320	1440

The values used to calculate the emissions and EC for transportation are listed in Table 8. The values for MGO and HFO are also used in the O&M and EOL stage of the LCA.

Table 8. Energy and emission input in the T&I, O&M, and EOL.

	Energy [MJ/tkm]	Emissions [kg $CO_{2(eq)}$/tkm]
Container ship	0.0003	0.0005
Lorry	0.0089	0.1400
	Energy [MJ/L]	**Energy [kg $CO_{2(eq)}$/MJ]**
HFO	38.3	0.095
MGO	34.5	0.092

4.3.3 Operation and maintenance

The operation and maintenance (O&M) deals with the general running of the WF. Activities here include renovation and replacement of worn parts over the lifetime of the WF [35]. Because of the lack of available information, the oil changes and lubricants have been neglected. The main structural components of a WT can last beyond the designed lifetime. However, regular replacement of moving components such as the generator and gearbox are required. The maintenance activities can be divided into planned and unplanned services [50]. In this report, both activities are analysed. It is assumed that half of the generators and gearboxes need replacement during the 20 years, where the value from the manufacturing is used.

The planned maintenance is required to inspect the main components and replace minor parts. For this WF, this includes various activities such as servicing and inspections. The different inspections can be for equipment, safety, fire or etc. The scheduled maintenance for this specific WF is carried out in intervals of six months to a year [50]. It is assumed that the maintenance is performed from Felixstowe, where the transportation of the service crew is realised by a support vessel. The number of vessels, fuel type, fuel rate, and work hours are listed in Table 9.

Table 9. Vessels, fuel type, fuel rate and work hours used in the O&M phase.

Activity	No. of vessels	Fuel type	Fuel rate [L/h]	Work hours [h]
Support vessel for maintenance of wind turbines	1	MGO	99	11300
Crane vessel for replacement of large parts	1	HFO	160	416

The unplanned maintenance activities are everything from minor technical issues to larger-scale WF problems. The larger-scale problems can have more serious implications for the O&M resources. This can also affect the WFs annual output because of periods of downtime for the WTs.

4.3.4 End-of-life

The last stage for a WF is the EOL phase. At this stage, the main goal is to address waste recycling and disposal to reduce its impact on the environment. For this report, it is assumed partial decommissioning, where the offshore substructure will remain to secure the marine environment. Since the decommissioning process of a WT is understood to be the reverse of the installation process, the work hours are assumed to be the same as for the installation. The number of vessels, fuel type, fuel rate, and workhours required at the EOL stage are listed in Table 10.

Table 10. Vessels, fuel type, fuel rate and work hours used in the EOL phase.

Activity	No. of vessels	Fuel type	Fuel rate [L/h]	Work hours [h]
Crane vessel for the dismantling of wind turbines	1	HFO	160	720
Tugboats for transport and dismantling of wind turbines	2	MGO	320	1440

The recyclable materials from the OWF are steel, aluminium, copper, and other metals. In this case, it is assumed to have a 92% recycling rate, where the remaining 8% is landfilled. Glass fibres and polymers from the WTBs is excluded as this will be investigated further in the second part of the case study. The recycling rates for the different materials are adopted from a previous report from Vestas and are listed in Table 11.

Table 11. Recycling rates of the materials [35].

Material	Treatment
Steel	92% recycled + 8% landfilled
Aluminium	92% recycled + 8% landfilled
Copper	92% recycled + 8% landfilled
All other materials	100% landfilled

The values used to calculate the emissions and EC for recycling and landfilling are listed in Table 12.

Table 12. Values for the recycling of the respective materials [52].

Material	Energy [MJ/kg]	Emissions [kg $CO_{2(eq)}$/kg]
Steel	7.5	0.84
Copper	10.6	0.88
Aluminium	44.6	3.54
Landfill	0.04	0.0009

4.4 Results

4.4.1 Energy consumption

The life cycle energy of the WF was calculated to be 254.9E+06 MJ, which includes recycling activities. Without the energy savings from the material recycling, the EC is 300.2E+06 MJ. The recycling activities decrease the WFs life cycle energy by 15.2 %. The EI is how much energy the system contains per kWh electricity generated. The total output of the WF is 233 GWh, and the EI of the system is 54.7E+03 MJ/kWh.

Figure 11 shows that manufacturing was the most significant contributor to the total EC, with 58 %. The second highest contributors were O&M and T&I, which both have 17 %. In Table 12 it is shown that T&I accounts for 52.7E+06 MJ, while the O&M accounts for 52.1E+06 MJ. Therefore, the T&I contributes to a slightly higher consumption. In the T&I phase, it is only accounted for the fuels used in the vessels and the transportation of the components to the erection site. While in the O&M, the energy input is the fuels used for the vessels and the manufacturing of the replacement parts

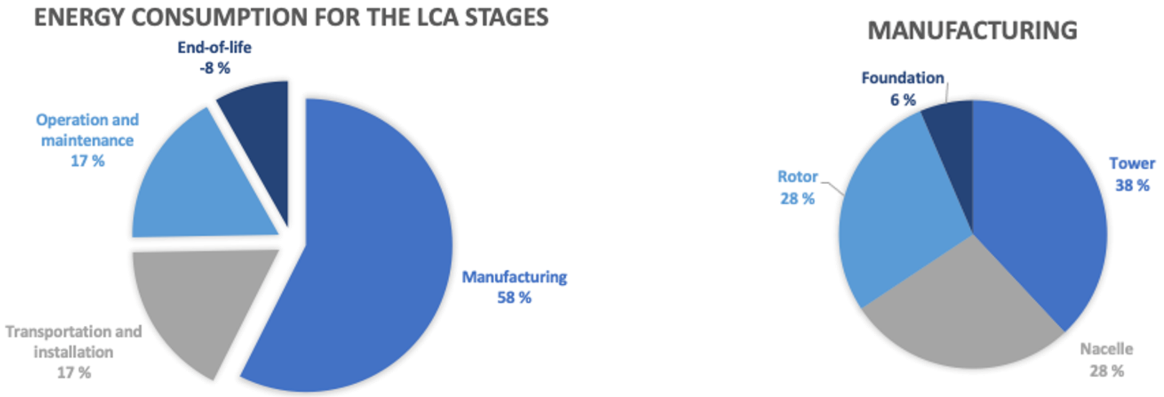

Figure 11. Energy consumption for the LCA stages and for manufacturing.

In the manufacturing process, the most energy-consuming component is the tower with 38 %, the nacelle with 28 %, the rotor with 28 %, and the foundation with 6 %, as shown in Figure 11. The tower has the highest EC because it consists primarily of steel, which is a highly energy-consuming material. The rotor consists of the WTBs and hub, where the WTBs accounts for 95 % of the EC, which is 1.54E+06 MJ.

A detailed overview of the EC for the WF is shown in Table 12. This is divided into the LCA phases as well as the various subcategories. To calculate the EC for the individual subcategories, Equation 2 was used. To calculate the total EC, Equation 1 was used, and for the EI, Equation 3 was used. The complete calculations for all the input data in Table 13 can be found in Appendix 2.

Table 13. Detailed overview of energy consumption and emissions related to the wind farm.

	EC [MJ]	EI [MJ/kWh]
Manufacturing		
Tower	66.6E+06	14.3E-03
Nacelle	48.4E+06	10.4E-03
Blades	46.3E+06	9.9E-03
Hub	2.5E+06	0.54E-03
Foundation	11.3E+06	2.4E-03
Sum	***175.1E+06***	***37.6E-03***
Transportation and installation		
Transportation	10.8E+06	2.3E-03
Installation	41.9E+06	9.0E-03
Sum	***52.7E+06***	***11.3E-03***
Operation and maintenance		
Maintenance	42.1E+06	8.8E-03
Replacement parts	11.0E+06	2.4E-03
Sum	***52.1E+06***	***11.2E-03***
End-of-life		
Dismantling	20.3E+06	4.4E-03
Recycling	-45.3E+06	-9.7E-03
Landfill	17.6E+03	3.8E-06
Sum	***-25.0E+06***	***-5.4E-03***
Total	**254,9E+06**	**54,7E-03**

4.4.2 Emissions

Over the entire life cycle of the investigated WF, 212.3E+05 kg $CO_{2\ (eq)}$ were released. The emissions saving from the recycling activities reduce the emissions by 18.2% and account for a reduction of -47.7E+05 kg $CO_{2(eq)}$. The EMI of the WF is 4.56 g $CO_{2(eq)}$/kWh. The full overview of the emissions is shown in Table 13.

To calculate the emissions, it was used the same equations as for the EC. For the individual subcategories, Equation 2 was used. To calculate the total emissions, Equation 1 was used, and for the EMI, Equation 3 was used. The complete calculations for all the input data in Table 14 can be found in Appendix 2.

Table 14. Emissions and emission intensity related to the wind farm.

	Emissions [kg $CO_{2(eq)}$]	**EMI [g $CO_{2(eq)}$/kWh]**
Manufacturing		
Tower	58.0E+05	1.24
Nacelle	49.8E+05	1.07
Blades	25.3E+05	0.54
Hub	4.4E+05	0.09
Foundation	13.8E+05	0.30
Sum	***151.3E+05***	***3.25***
Transportation and installation		
Transportation	1.9E+05	0.04
Installation	38.7E+05	0.83
Sum	***40.6E+05***	***0.87***
Operation and maintenance		
Maintenance	37.8E+05	0.81
Replacement parts	11.6E+05	0.25
Sum	***49.4E+05***	***1.06***
End-of-life		
Dismantling	18.8E+05	0.40
Recycling	-47.7E+05	-1.02
Landfill	3.97E+02	0.0001
Sum	***-29.0E+05***	***-0.62***
Total	**212,3E+05**	**4.56**

Manufacturing is also the biggest contributor to the emissions, as it was for EC. The distribution of the total emissions is 58 % for manufacturing, 18 % for O&M, 15 % for T&I, and -11 % for the EOL as shown in Figure 12. The distribution of the emissions is generally similar to the EC, except for the minor difference in T&I. The production of the WT accounts for 91 % of the total emissions from this phase, while the remaining 9 % is from the manufacturing of the foundation.

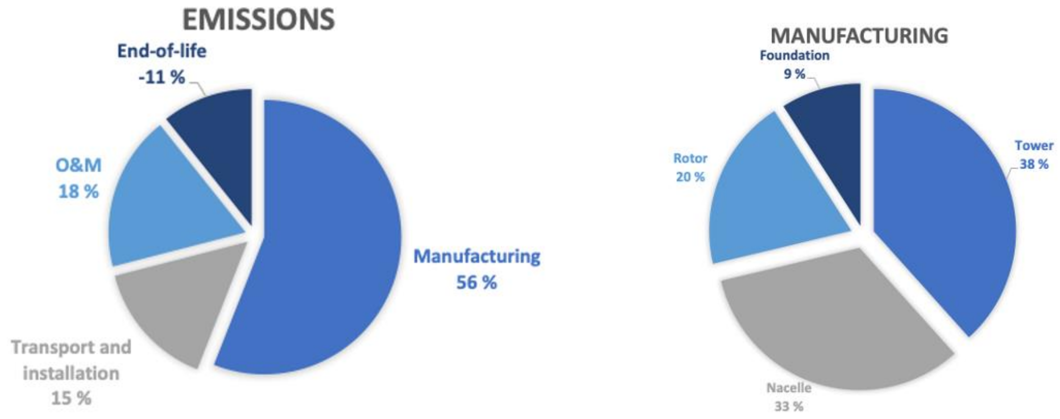

Figure 12. Emissions from all of the LCA stages and manufacturing.

4.5 Discussion

The distribution posts for the emissions and EC are very similar, except for the O&M and T&I. For the EC, this is almost equal, while the O&M phase has a significantly higher emission rate. The reasoning for this is that the transportation in the T&I has a lower emission ratio than the installation, where they are similar in the EC. The values used in this report were for tkm, which is not always the most accurate way to calculate emissions and EC. The inaccuracy is caused because of the lack of knowledge about the load of the means of transport.

It can also be noted that the emissions from transportation versus installation had a significant difference as illustrated in Figure 13. The transportation of the entire WF only accounts for 5 % of the emissions from this phase and 20 % of the EC. This may indicate that using tkm to calculate emissions is not ideal as there may be uncertainties related to the result.

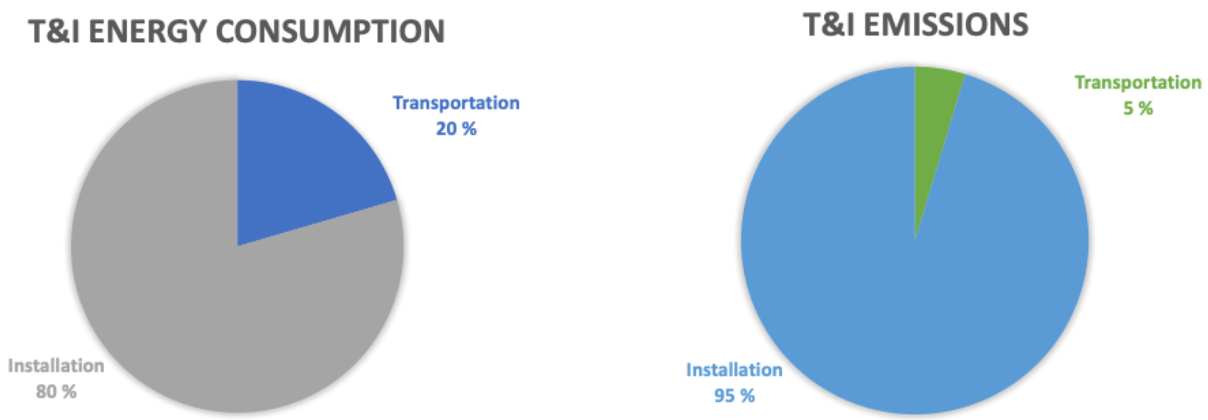

Figure 13. Energy consumption and emissions for T&I.

For the O&M, a very similar ratio for the emissions and EC is shown in Figure 14. Maintenance accounts for 79 % of the EC and 77 % of the emissions. The maintenance is an important aspect to remember when making an LCA, considering it is the only phase that accounts for the WTs over the lifetime. If the change of oil and lubricants were included for the replacement parts, this section might have had a more significant impact on the results. As there was no available data for this input it was neglected.

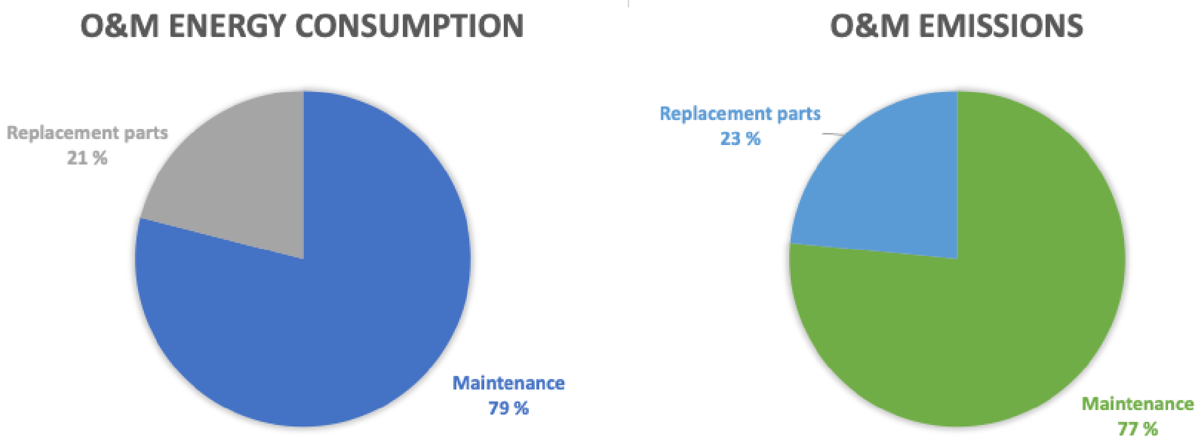

Figure 14. Energy consumption and emissions for O&M.

The most consuming phase was the manufacturing for both the input and output. The reasoning for this is that the WT consists of highly energy-consuming materials like steel, aluminium, and glass fibre. The WTBs accounts for 95 % of the EC consumption from the rotor. This is equal to 27 % of the total EC of the manufacturing phase. The WTBs in the rotor account for 85 % of the emissions and are equivalent to 17 % of the total emissions from manufacturing. This is because of the high embodied energy in the glass fibre and epoxy used in manufacturing. Glass fibre is a composite, which has the highest embodied energy of all the materials in the WT. As shown in Figure 15, the distribution of emissions and EC are generally the same.

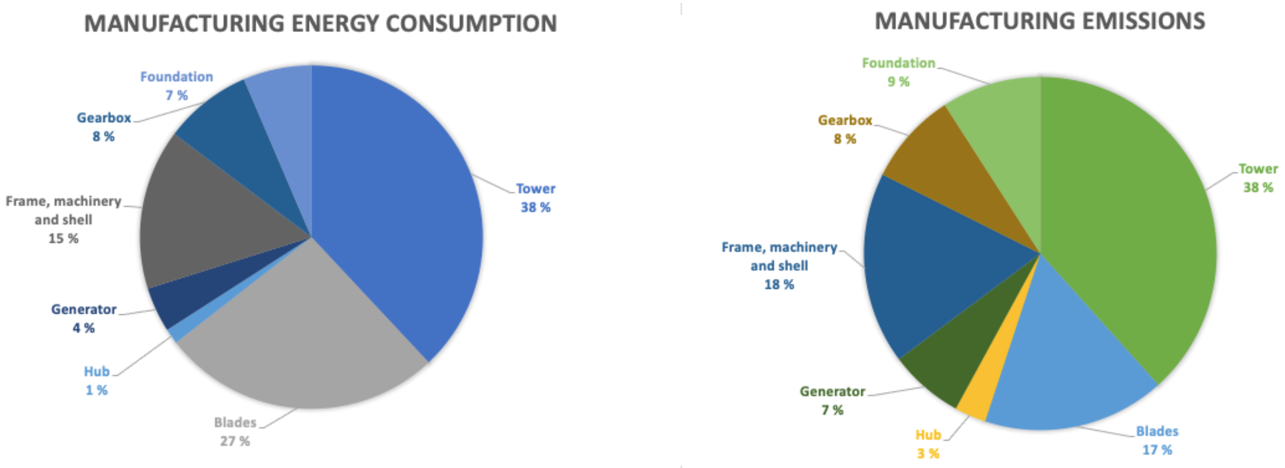

Figure 15. Energy consumption and emissions for manufacturing.

In the EOL, the emission savings from the recycling is higher than the energy savings in ratio to the other values. Its savings was 15.2 % for the EC and 18.5 % for the emissions. When comparing the dismantling, recycling, and landfill, the landfilling is so insignificant that it rounds off to 0 % for both as illustrated in Figure 16. This is likely because of the decision of partial removal where all the concrete, which usually is landfilled, is excluded. This as well as excluding the polymers, would have had an impact on the results. The recycling activities reduce the EOL phase by -69 % for the EC and -72 % for the emissions. The small distribution from the dismantling is also because of the partial removal, as the contribution from the dismantling of the foundation would have increased the total results for this phase.

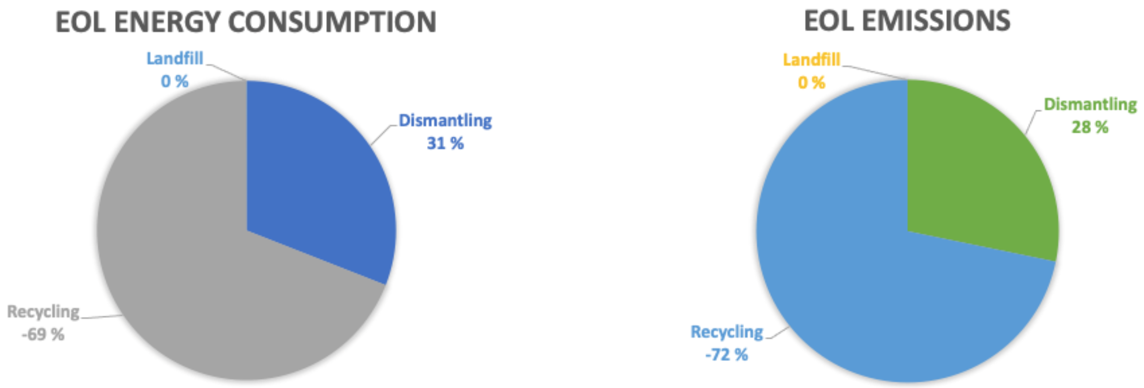

Figure 16. Energy consumption and emissions in end-of-life.

5. Case study: End-of-life solutions for wind turbine blades

For the second part of the case study, the various EOL solutions for WTBs will be assessed. The case study is presented with a life cycle approach where the waste management hierarchy (WMH) is used as a foundation. The sustainable waste management can be ranked from the least favoured to the preferred option as disposal, recovery, recycling, repurpose, reuse, and prevention. This is also how the different scenarios in the case study will be presented. In this report, only disposal, recycling and recovery, and repurposing will be investigated, as shown in Figure 17.

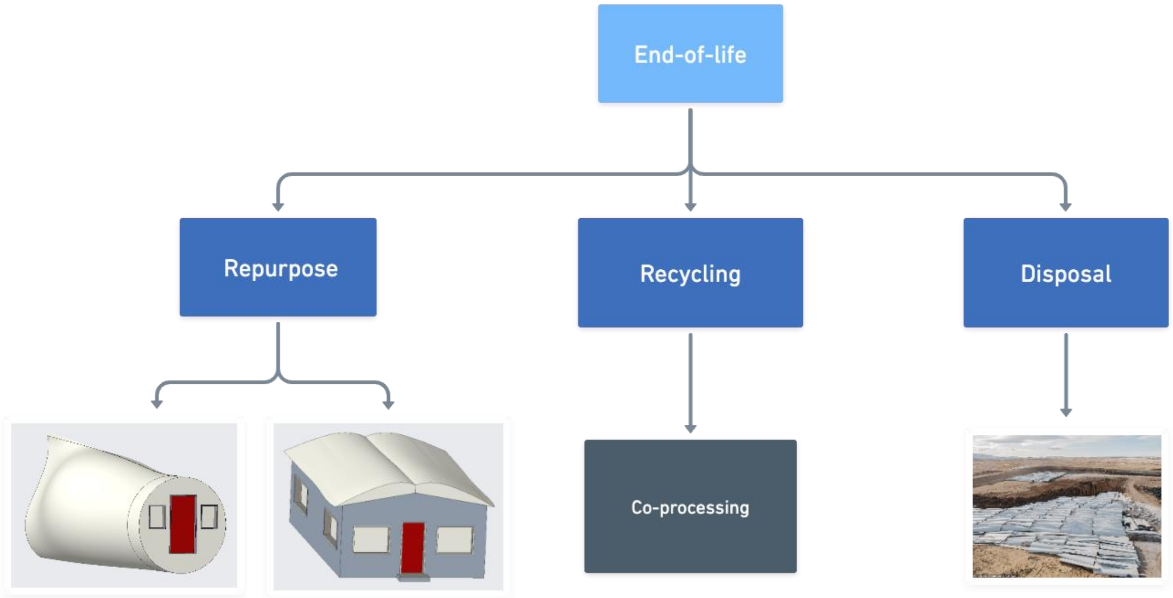

Figure 17. End-of-life solutions for wind turbine blades.

The other parts in the hierarchy are reuse and prevention. The first step in the waste hierarchy is preventing blade waste through substitution and reduction efforts in design. For example, reducing the overall mass of the blades results in less material recycling. Designing the WTBs for easy upgrade, for example, modular blades, extending the lifetime, and decreasing failure rate is ideal [19] [16].

Before waste treatment, the blade should be reused. Routine servicing and repair are crucial to achieving a blade's designed lifetime. Site inspections, review of maintenance actions performed on the module since commissioning, and a fatigue load analysis must be conducted. This might lead to necessary repair or reinforcement of certain areas before reuse [16].

5.1 Landfill

When the WF has reached the end of its lifetime, the 90 WTBs will be shipped to the Port of Felixstowe, northeast of London. The WTBs must be cut into pieces for easier transport and then loaded onto lorries. The burial of the blades is neglected in the calculations.

5.1.1 Transport

To achieve the most cost-efficient and environmentally friendly disposal of the blade waste a landfill site close to the WF has been selected for this scenario. The nearest disposal site that accepts inert waste and has enough remaining waste capacity is the Shrublands Quarry in Suffolk. The transportation distance from the Port of Felixstowe to the landfill site is 35 km northwest of Ipswich. The transportation type used is a lorry for 16-32 tonne which is used for all scenarios.

A singular blade has a high volume to weight ratio with 44 m in length, a 3.5-meter chord at the blade root and a weight of 6600 kg [43].

5.1.2 Cost of disposal

The cost of disposal of the WTBs can be divided into three categories: transportation, gate fees, and landfill taxes. The landfill taxes for standard rate waste disposal in the UK is 115 EUR/t [53]. According to the Waste and Resources Action Programme report for 2019/2022, the median gate fee is 29 EUR/t which is used in this scenario [54]. This brings the total cost of disposal, excluding transport, to 144 EUR/t. When calculating the cost of transportation, the total cost per tkm for a lorry is defined as EUR 0.35, including the operator's cost [55]. The total cost for transportation and disposal of the blades from the Port of Felixstowe is EUR 92,813, as shown in Table 15.

Table 15. The costs associated with landfilling.

Type	Unit	Transportation	Gate fees	Landfill taxes	Total cost
Mass	t	594	594	594	-
Tonne-kilometre	tkm	20,790	-	-	-
Cost per tkm	EUR/tkm	0,35	-	-	-
Cost per tonne	EUR/t	12	29	115	156
Total cost	**EUR**	**7277**	**17,226**	**68,310**	**92,813**

5.1.3 Total emissions, costs, and energy consumption

Emissions and EC, in this case, are purely the emissions and energy input from the transportation of the WTBs. As displayed in Table 16, the total emissions are 2911 kg $CO_{2(eq)}$, and the total EC is 184 MJ. The transportation input data for costs, emissions and EC is used in all the scenarios, see Appendix 3 for the full calculations.

Table 16. Total energy consumption, emissions, and costs for disposal.

	Unit	Energy [MJ]	[kg $CO_{2(eq)}$]	Cost [EUR]
Transport distance	tkm	20,790	20,790	20,790
Per tkm	[ ]/tkm	0.009	0.14	0.35
Per tonne	[ ]/t	0.31	4.9	12
Total		**184**	**2911**	**92,813**

5.2 Cement co-processing

WTBs are mainly manufactured by glass fibre reinforced plastics (GFRP), which are currently impossible to separate into its initial materials. One solution to reuse the blade's material is to shred it for use in cement production. Co-processing is a method used for waste management where mineral materials are recycled, and energy recovery is performed in one industrial process [56].

In this case study, organic materials of the composite are burned for fuel as a partial replacement for coal, which provides the EC for the cement production. At the same time, materials from the WTBs, mainly glass fibre, replace raw materials in the cement [56]. This scenario can be divided into three different phases: shredding, transportation, and co-processing.

5.2.1 Shredding

A hypothetical pre-treatment plant is installed at the Port of Felixstowe. Treating the WTBs at the port will make transportation logistics easier, as the lorries can transport shredded material more easily than entire WTBs. Firstly, the WTBs need to be cut into smaller pieces to fit into an industrial shredding machine, and the carbon reinforcement needs to be removed. The sections are then put into an industrial shredding machine which divides the composite into smaller pieces before being put into another machine for fine shredding [57]. A magnet is used to collect metal parts for traditional recycling within this process. Both the removal of the carbon reinforcement and metal is neglected in further calculations.

Shredding machines are typically electrically operated and therefore, emissions are believed to be insignificant. However, this depends on whether the electricity is coming from renewable energy or fossil fuels. The cost for shredding machines is hard to estimate as it depends on the shredding efficiency and the amount of material that needs to be shredded. Because of data limitations for shredding machines for composite material, it is necessary to neglect both emissions and costs related to this process. The required energy to shred the blades is 0.17 MJ/kg [58]. Given that each blade weighs 6600 kg, the total weight for 30 WTs with 90 blades combined is 594,000 kg which results in an EC of 100,980 MJ. Equation 2 was used in the calculations shown in Table 17.

Table 17. Energy consumption for shredding.

Shredding	**Value**
Energy consumption [MJ/kg]	0.17
Mass [t]	594
Total energy consumption [MJ]	**100,980**

5.2.2 Transport

The shredded material is transported from the Port of Felixstowe to Southern Cement LTD, located in Ipswich. The total distance for the transportation in this scenario is 21 km. This results in emissions of 1746 kg $CO_{2(eq)}$, and a total EC of 110 MJ. The transportation cost was found to be 0.35 EUR/tkm, which leads to a total cost of EUR 4366. The transport distances in tkm are calculated using Equation 4. In the rest of the calculations Equation 2 was used, and the results can be found in Table 18.

Table 18. Energy consumption, emissions, and costs from transportation in co-processing.

	Unit	**Energy [MJ]**	**Emission [kg $CO_{2(eq)}$]**	**Cost [EUR]**
Transport distance	tkm	12,474	12,474	12,474
Per tkm	[ ]/tkm	0.009	0.14	0.35
Per tonne transported	[ ]/t	0.186	2.94	7.35
Total		**110.5**	**1746**	**4366**

5.2.3 Cement production

Today, there are not many companies working with the co-processing of WTBs in cement production. This recycling method was developed by a German company called Geocycle [59]. Recent studies show that co-processing can be applied to existing cement facilities without significant investment in new equipment or other installations [60]. Therefore, it is assumed that a local cement facility will be able to process the composite. In this case, transportation logistics, emissions, EC, and costs are all positively affected by the choice of location.

The challenge is to figure out how much cement is produced per tonne of shredded material from the blades, as some of the materials are burned as fuel, while other is replacing the raw materials in cement. Fiberline, a Danish composite manufacturer, and Holcim, a German cement factory, have after a collaboration announced that Fiberline's blade waste has the potential to replace several of the materials required for cement production as shown in Table 19 [61].

Table 19. Material replacement in co-processing.

Material replacement	Ratio [%]
Coal	45
Sand	20
Limestone	20
Alumina	15

Based on these numbers, it is assumed that 45 % of the blade waste is burned for fuel in the cement kiln, and the remaining 55 % is replacing raw materials in the cement production. Recent studies state that 10 % of the material used in cement can be replaced by composite waste from WTBs while maintaining the material properties of regular cement [61]. If 55 % of the blade waste will substitute raw material in cement production, it will be equivalent to a total of 326,700 kg of composite. Assuming 10 % of the cement will be made of blade waste, it results in a total of 3267 tonne of cement. The overview of the cement production is listed in Table 20.

Table 20. Overview for cement production.

Cement co-processing	Unit	Value
Material burned	%	45
Material to cement additive	%	55
Input: Total blade weight	t	594
Output: BW cement additive	t	327
BW / cement ratio	%	10
Total cement production	**t**	**3267**

Using blade waste for cement production includes a partial replacement of coal and raw materials, therefore, the emissions can be reduced. According to AOC, the emissions can be reduced up to 16 % depending on the technology at the cement facility. Therefore, a 16 % reduction is assumed in this scenario [62]. The cement production has a total emission of approximately 2.5 million kg $CO_{2(eq)}$. Using blade waste as an additive in this process, it is possible to save 405,000 kg CO_2, which results in the total emission of 2.1 million kg $CO_{2(eq)}$. The emissions, costs, and EC is shown in Table 21.

Table 21. Energy consumption, emission, and costs from cement production.

	Energy [MJ]	Emission [kg $CO_{2(eq)}$]	Costs [EUR]
Per kg cement produced	0.05	0.78	0.36
Total without reduction	153,784	2,531,328	213,840
Reduction [16%]	-	405,012	-
Total	**153,784**	**2,126,316**	**213,840**

The EC for producing 3267 tonne of cement, where 10 % is represented by the blade waste, is found to be approximately 150,000 MJ. The blades will provide energy by replacing coal, but these calculations are neglected due to data limitations. The cost of this process is 360 EUR/t treated, and with a total of 594 tonne going into the cement kiln, this results in a total cost of EUR 213,840 [59].

The final results from the shredding, transportation, and cement production are presented in Table 22. This shows that the total emissions are 2.1 million kg $CO_{2(eq)}$, the total EC is 253,895 million MJ, and a total cost of EUR 218,206, see Appendix 4

Table 22. Energy consumption, emissions, and costs.

	Energy [MJ]	Emissions [kg $CO_{2(eq)}$]	Costs [EUR]
Shredding	100,980	-	-
Transportation	110.5	1746	4366
Cement production	153,784	2,126,316	213,840
Total	**254,875**	**2,128,062**	**218,206**

5.3 Repurpose

Currently, there are a few different solutions for handling the WTBs when reaching the EOL. However, solutions like landfill and cement co-processing will not maintain the value as much as repurposing or reusing them. As mentioned in Section 2.7 there are numerous solutions and designs for repurposing, suggested by companies like Re-Wind and ANMET.

In this scenario of the case study, the possibilities of repurposing the blades as roofing for small houses and tiny houses will be investigated. Every part of the blade should still be useful after decommissioning. If the blades are being repurposed as tiny houses and roofing for small houses, dividing the blade into different sections is necessary. In this case, the blade is divided into four sections which will be repurposed for various applications.

The blade used for modelling is a 5.0 MW reference WT, where the blade has different dimensions than for the V90-3.0 MW WT. The blade which is used is 62.9 m long and is theoretically an enlarged version of the original blade. Because of this, the calculations made in this scenario will be a little larger than it would be for the V90 blade.

5.3.1 Sections of the blade

Figure 18 illustrates the solutions for different sections of the blade. The first section of the blade is between where it would be connected to the hub and Mid-section 1. This is where the shape of the blade goes from a round shape at the root, to a flatter shape in Mid-section 1. Mid-section 2, as well as the Blade tip, will not be considered in this scenario and can be used for other repurposing applications.

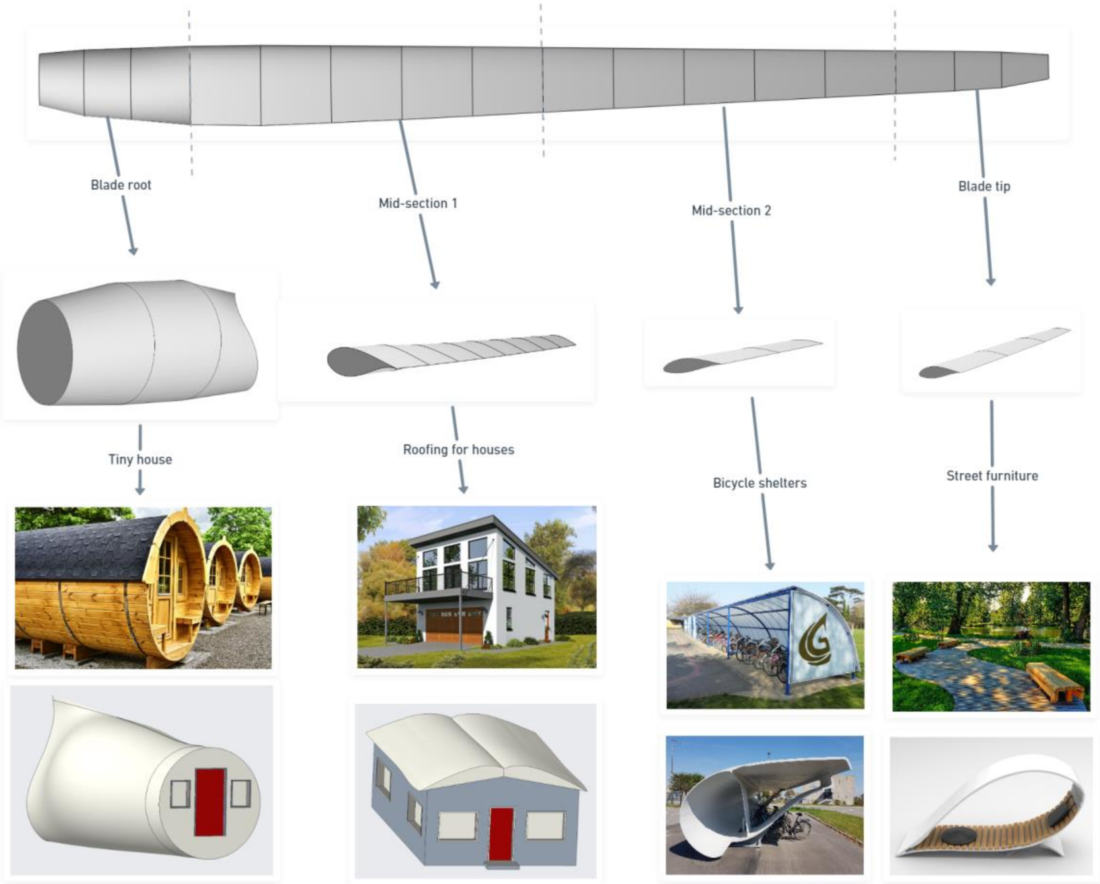

Figure 18. Sections of the blade.

5.3.2 Tiny houses

In this case study, the root of the blade will be repurposed as tiny houses. The root section is measured to be 12 m long with a diameter of 4.5 m at the widest part. The size of this section of the blade can be compared to caravans, larger boats, and small cabins. By raising the floor about one meter, which is inspired by aeroplanes, the usable area will be bigger and leave room for storage, water tanks, and electrical components beneath. The dimensions used for the tiny house is found using Creo.

The unit will have an opening at its end which can be sealed off with 10.2 m^2 of wooden cladding. A main door and two small windows with the dimensions $90 \times 210\ \mathrm{cm}$ and $60 \times 80\ \mathrm{cm}$ are installed. The tiny house can either be supported by columns on each side or lowered approximately 90 cm into the terrain. This can be done with pressure-resistant insulation underneath for structural support and a better indoor climate, as illustrated in Figure 19. A 5 cm insulation from the inside is also assumed to be installed. The WF will provide

90 tiny houses, assuming that every blade is in a reusable condition after being decommissioned. Repurposing the root section as a tiny house will result in a total floor area of 34 m^2. This leaves enough space for people wanting a budget home, such as students, minimalists, or commuters.

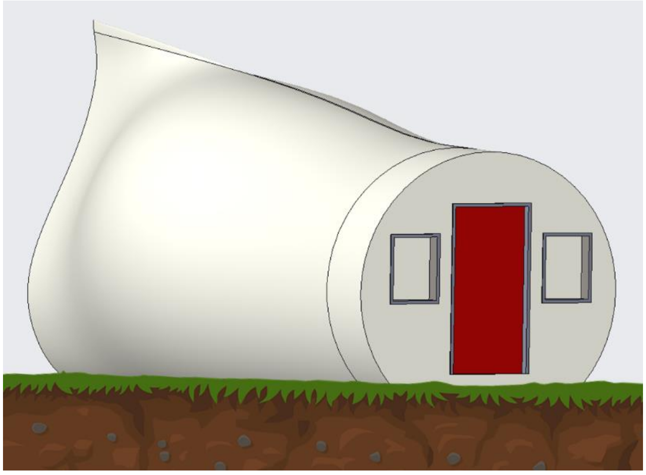

Figure 19. Tiny house from a wind turbine blade.

5.3.3 Roofing for houses

The next section of the blade, named mid-section 1, can be repurposed as roofing. The blade section is firstly divided like the root section. Further, it is divided once more across the chord line to provide more roofs from each blade. The shape of the blade is constantly changing longitudinally. Therefore, the leading edge is removed so the edges of the blades will be completely sealed together. Figure 20 illustrates that the blade is slimmer at the front compared to the back. This provides a natural drainage system as there is a slight slope towards the outer edge of the blade.

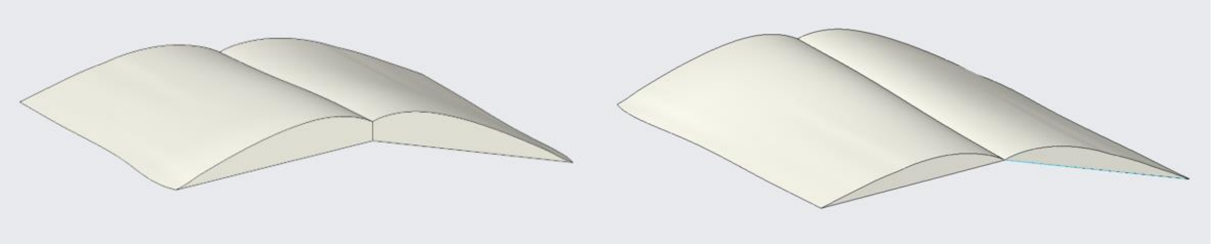

Figure 20. Roofing made from wind turbine blades: front and back.

The blades are sorted into pairs of upwind sides and pairs of downwind sides of the blade. Meaning that two turbine blades combined result in two roofs. One roof is manufactured by the upwind side and the other by the downwind side. This is because of visual geometric difference. The top and bottom edges have the same cross-sectional length, height, and material construction [63]. On the other hand, the bottom roof frame has an inflexion point along its curvature, and the top frame has a concave-down curvature. Before or after the blade sections are mounted as roofing for houses, each end of the blade must be sealed together with other materials as the blades are primarily hollow on the inside. The completed roof will look something like Figure 21 for more modelling illustrations see Appendix 5.

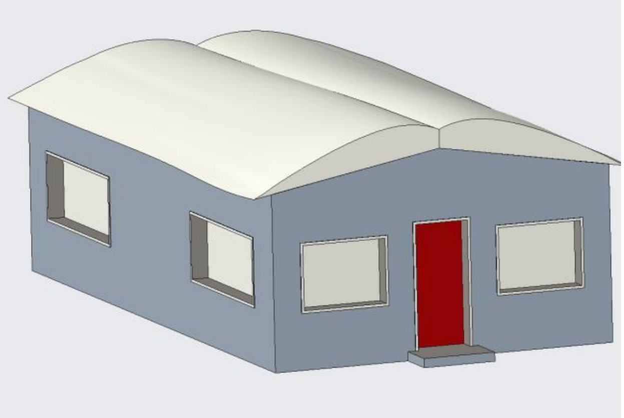

Figure 21. Illustration of a house with wind turbine blade roofing.

5.3.4 Emissions, costs, and energy consumption

Transportation of all the blades from the Port of Felixstowe to a hypothetical factory in Ipswich resulted in a total of 1663 kg $CO_{2(eq)}$ emissions and EC of 105 MJ. The cost was calculated to be EUR 4158 as shown in Table 23. The two different repurposing concepts are divided into various sections as it is necessary with a further explanation of how these results were calculated.

Table 23. Energy consumption, emissions, costs from transportation in repurpose.

	Energy [MJ]	Emission [kg $CO_{2(eq)}$]	Cost [EUR]
Transportation per tkm	0.0089	0.14	0.35
Total	**106**	**1663**	**4158**

Using an inbuilt tool in Creo Parametric, the volume of the blade root–section was found to be 119 m^3. An equivalent tiny house has a total of 110.8 m^2 of walls, being built with wooden cladding and a roof of 33 m^2 and the data for the tiny house is listed in Table 24.

Table 24. Input data for a traditional tiny house.

	Unit	Value
Area of concrete roof tiles	m^2	33
Amount of roof tiles	kg/m^2	53
Total amount of roof tiles	kg	1749
Area of wood panelling	m^2	110.8

Calculations for the emission and EC for both the wood panelling and the roof made of concrete tiles are presented in Table 25. The production of the material needed for each tiny house results in an emission of 377 kg $CO_{2(eq)}$ and an EC of 128 MJ. The total for 90 tiny houses is 33,970 kg $CO_{2(eq)}$ and an EC of 11,504 MJ as shown in Table 25.

Table 25. Energy consumption and emissions for tiny houses.

	Unit	Energy [MJ]	$CO_{2(eq)}$ [kg]
Per kg roof	[ ]/kg	0.071	0.171
Roof tiny house	-	124	300
Per m^2 wood panelling	[ ]/m^2	0.037	0.773
Wood panelling tiny house	-	3.7	78
Sum per tiny house	**-**	**128**	**377**
Total for 90 tiny houses	**-**	**11,504**	**33,970**

Mid-section 1 is being repurposed as roofing. The area of the roof using blades was found to be $84m^2$ and the area for roofing is shown in Table 26.

Table 26. Area for roofing.

	Unit	Values
Area	m^2	84
Amount of roof tiles	kg/m^2	53
Total amount of roof tiles	**kg/m^2**	**4452**

Manufacturing a single equivalent traditional roof made of concrete tiles results in 763 kg $CO_{2(eq)}$ and an EC of 316 MJ. Calculations, total emissions, and energy consumption is presented in Table 27.

Table 27. Energy consumption and emissions for roofing.

	Unit	Energy [MJ]	Emissions [kg $CO_{2(eq)}$]
Per kg roof	[ ]/kg	0.071	0.171
Per roof	-	316	763
Total for 90 roofs	**-**	**28,439**	**68,623**

In this scenario, one blade is being repurposed as both a tiny house as well as roofing. Each blade is becoming one tiny house and one roof, resulting in a total of 104,173 kg $CO_{2(eq)}$ emissions and an EC of 39,705 MJ. These values are not related to the actual repurposing process of a blade but are presented to show the possible savings, as these are comparative alternatives. Processes like the construction of the tiny house and roofing are neglected from the calculations. The cost of the suggested repurposing products is excluded, as this has not been done before. The results for both alternatives are shown in Table 28 for the full calculations see Appendix 6.

Table 28. Energy consumption, emissions, and costs from roofing.

Type	Energy [MJ]	Emission [kg CO2]	Cost [EUR]
Transportation to factory	105	1663	4158
Tiny house equivalent	11,504	33,970	-
Concrete roof tiles	28,439	68,623	-
Total	**40,048**	**104,256**	**4158**

6. Discussion

There is a significant amount of energy and emissions from the WTBs manufacturing, and it is currently not possible to recycle the materials. Therefore, there is a need to investigate different solutions for handling the WTBs at EOL. The three solutions are compared considering the WMH. The most emphasised aspect is the value of the products, considering the energy that has gone to producing the WTBs. Also, keeping in mind that the EC, emissions, and costs should be kept as low as possible.

6.1 Life cycle assessment

The recycling of the materials in the WF has an overall reduction of 15.2 % of the EC, and 18.2 % of the emissions. Since it is assumed partial removal of the WF, the landfilling of the foundation is excluded. In the recycling of the materials used in the WF, the blades are the only component which is non-recyclable. Therefore, the only materials accounted for in the recycling are steel, aluminium, cast iron, and copper. Because of no available data for the recycling values of cast iron, this was included in the steel category. As illustrated in Figure 22, the GFRP in the WTBs accounts for 10 % of the total weight in the material recycling. Steel accounts for 95 % of the recyclable materials, aluminium for 4 % and copper for 1 %.

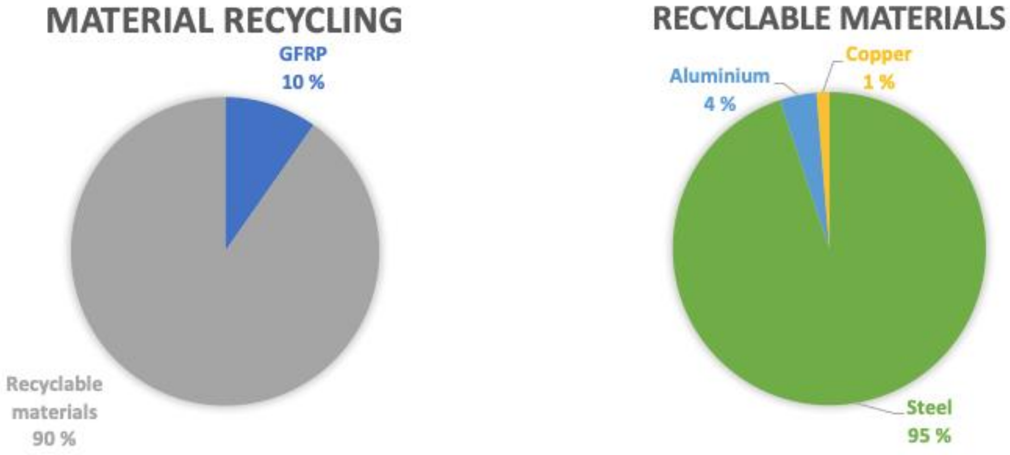

Figure 22. Material recycling and recyclable materials in the WF.

The recycling savings for steel is 7.5 MJ/kg, while the manufacturing of steel is 20.55 MJ/kg. Therefore, the recycling of steel accounts for 37 % of the original material production. Steel and copper have a low energy saving compared to the aluminium. In Table 29, it is shown the percentages for the energy savings for the recyclable materials. Aluminium has a high energy saving of 95 %, because the recycling production only accounts for 2.4 MJ/kg.

Table 29. Energy and emission savings from recycling.

Material	Energy [MJ/kg]	Energy savings [MJ/kg]	Ratio [%]
Steel	20.55	7.5	36
Copper	42.4	10.6	25
Aluminium	47	44.6	95
	Emissions [kg $CO_{2(eq)}$/kg]	Emissions savings [kg $CO_{2(eq)}$/kg]	Ratio [%]
Steel	1.8	0.84	47
Copper	2.7	0.88	33
Aluminium	8.4	3.54	42

The emissions savings for the recycling of the materials is higher than for the EC. Steel has the highest emission saving with 47 %, copper with 25 %, and aluminium with 42 %. The total emissions from manufacturing recyclable materials are 11.2E+06 kg $CO_{2(eq)}$, and an emission saving of 4.77E+06 kg $CO_{2(eq)}$. In total this is an emission saving of 43 %. The total energy savings from the recycling of the recyclable materials is 45.3E+07 MJ, where the total energy consumption of manufacturing is 39.2E+07 MJ. In total this is an energy saving of 39 % of the original EC.

The total emissions and EC for manufacturing of the blades is 46.3E+06 MJ and 2.53E+06 kg $CO_{2(eq)}$. This is equivalent to 27 % of the EC and 17 % of the emissions from the total manufacturing phase. Since a significant amount of the total emissions and EC is from the blades it should not go to waste after the EOL of the WF.

6.2 Landfill

According to the WMH, disposal of WTBs in a landfill without any energy recovery is the least preferred waste treatment method. However, this is the most practised method today. Bans of WTB disposal drives the wind industry to look for more environmentally friendly solutions. It is important to consider the amount of energy that has gone into manufacturing of the blades.

The EC for disposal of the blades is 184 MJ, which is calculated without considering the energy needed to cut the blades into sections for easier transportation. Also, the energy used for excavation of the disposal site, burial, and transfer lifting equipment is neglected. Therefore, the EC will realistically be higher. However, the amount of energy is still insignificant compared to the energy used during the manufacturing. Calculations for emissions are also neglecting several phases of the landfilling process, and the total emission was found to be 2911 kg $CO_{2(eq)}$.

EC and emissions per tkm are the unit used for these calculations. Realistically, this would impact the amount of blade waste the lorry can transport per trip, as the blades have a high volume to weight ratio. A lorry will not be able to transport 32 tonnes of blades because of their size. Theoretically, no return trips are included, as the tkm unit gives no results when the lorry does not have any load. Therefore, using tkm as a unit for the calculations will cause a margin of error. This method is used in all scenarios.

6.3 Co-processing

The results in the landfill scenario are quite low compared to co-processing, where the blades are being shredded and used in cement production. The energy required for producing cement while using all the blade material was calculated to be 254,875 MJ. This is almost 1400 times more than for landfilling. However, this involves producing 3267 tonne cement, where only 10 % is represented by material from WTBs. As explained in Section 5.2.3, it is assumed that 55 % of the blade waste is burned as a replacement of coal, meaning that less coal is needed for the cement production.

Through energy recovery in the cement kiln, energy is also saved; however, this is neglected. On the other hand, the material needs to be shredded and transported, which increases the EC. The shredding process accounts for about 40 % of the total EC required in this scenario. Also, transporting large turbine blades have an impact, which means that ultimately, using blade waste in cement production could have a greater EC compared to the traditional method, depending on the amount of energy savings by replacing coal with raw material from WTBs.

Energy production from fossil fuels, like coal in this scenario, is strongly related to high numbers of $CO_{2(eq)}$ emissions. Replacing coal with shredded blade waste makes it possible to reduce the emission from cement production by up to 16 %, which is the reduction considered in the calculations in this report. However, the possible saving depends on the available technology of the specific cement factory and the quantity of shredded material [62]. Therefore, reducing the emissions by 16 % might not be realistic.

The total emission coming from the production of 3267 tonne cement, using blades from the Kentish Flats OWF, is calculated to be over 2,1 million kg $CO_{2(eq)}$. Because of this large number, it will only be fair to compare the actual savings achieved by this solution. Approximately 405,000 kg $CO_{2(eq)}$ can potentially be saved, which would otherwise be contaminated through traditional cement production.

6.4 Repurpose

The numbers found in this scenario represents a traditional tiny house and roof built with normal wood panelling and concrete roof tiles. This shows the possible savings which can be achieved by using part of a WTB for manufacturing equivalent products. By using existing blades, all the emissions and EC related to production of wood panelling and concrete tiles are avoided. Transportation of the blades adds to the emission and EC in this scenario. Dividing the blades into different sections, as well as assembling a complete and sealed tiny house and roof, are excluded. However, the traditional construction of the two products is also neglected, and therefore, serves as a justification.

The energy needed for producing both a tiny house and a roof is calculated to be 39,705 MJ, which is the amount of energy that can possibly be saved. Emissions are calculated to be 104,173 kg $CO_{2(eq)}$. These numbers are solely from transportation. Tiny houses are normally built with wooden panelling and roof made of either asphalt shingles, metal roof panels or concrete roof tiles. The last-mentioned is used in this scenario.

Wooden panelling has an estimated lifetime of 40-50 years, while concrete roof tiles have 40-60 years [64] [65]. Marcin Sobczyk, one of ANMETs product developers, state that a bridge made of a decommissioned WTB should last for at least a hundred years. Therefore, it is also reasonable to believe that tiny houses and roofs made from the same material should last as long [28]. If so, at least two sets of traditional tiny houses and roofs must be made in the lifespan of one repurposed turbine blade. In that case, the energy, emission, and the cost will be doubled for the traditional products.

Neither disposal or co-processing is a sustainable way to handle the WTBs after its serviced lifetime, and this needs to be addressed. The wind generation industry needs to change for the better, due to the shear quantum of WTBs coming up for decommissioning. The repurposing alternatives of the blade suggested in this report can be up scaled and applied all around the world as there will always be a demand for housing. Architects and engineers need to adapt WTB waste into a potential building material. In Figure 23 a hypothetical illustration of a roof is presented.

C

Figure 23. Illustration of a hypothetically wind turbine roof.

The technology for recycling of the WTBs will most likely progress in the coming decades. Temporary landfilling of the blades until the industry finds a way to recycle the material is an option. However, the value of the blade is not exploited during this period, and it is not guaranteed it will be possible to recycle the material in the future. If the blades are repurposed into something useful, the value is kept as high as possible until the technology for recycling of the blades are present. This will hopefully close the loop for the blades from a linear to a circular life cycle.

The total EC, emissions, and costs from the investigated scenarios is shown in Table 30. When comparing the EC and emissions from the EOL case study to the values in the original manufacturing of the WTBs, all of the values are minor. Based on the results presented in Table 30, the EC of repurposing the WTBs as tiny houses and roofing is only 0.09 % of the manufacturing, and the emissions is 4.1 %. This means that the total EC and emissions of the WTBs life cycle will not be significantly increased, while increasing the lifetime with over 100 years.

Table 30. Energy consumption, emissions, and costs from the different scenarios and manufacturing.

	Energy [MJ]	Emission [kg $CO_{2(eq)}$]	Cost [EUR]
Production of WTBs	46,300,000	2,530,000	-
Landfill	184	2911	92,813
Co-processing	254,875	-405,000	218,206
Repurpose	39,705	104,173	-

6.5 Source data

This report is a comparative life cycle assessment where the results assess the different EOL solutions for WTBs. The results highlight the most significant contributors to emissions and EC in the various phases. Because of little access to reliable data, the extent of the scope turned out to be difficult and time-consuming. The data collection was an ongoing procedure throughout the process, which led to constant changes in the calculations to get the most realistic result.

To limit the extent of the thesis, several system boundaries were set. There have been several assumptions and neglections because of the limitations. Therefore, only the input and output assessed are the EC and emissions. As a result, several components of the OWF have not been included, such as transformers, substations, and cables. As well as different process inputs in the EOL study because there simply has not been available data.

The system boundaries, limitations, and assumptions have compromised the accuracy of the assessment. It is important to emphasise that the neglections and assumptions would have affected the results. Therefore, it will be a margin of error in the total energy consumption and emissions related to the analysis.

7. Conclusion and further work

7.1 Conclusion

This thesis has assessed the end-of-life for wind turbine blades for three scenarios: landfill, co-processing, and repurpose.

- The results from the LCA of the chosen wind farm is an EC of 254.9E+06 MJ and an EI of 54.7 MJ/kWh. The emissions accounts for 21.23E+06 kg $CO_{2\ (eq)}$ and an EMI of 4.56 g $CO_{2(eq)}$/kWh.
- The total EC and emissions from the manufacturing of the WTBs are 46.3E+06 MJ and 2.53E+06 kg $CO_{2\ (eq)}$. This equals to 27 % of the total EC and 17% in the total emissions in the manufacturing phase.
- Landfill has an EC of 184 MJ and an emission of 2911 kg CO_2, which is coming from transportation. When turbine blades are buried underground, there is no value to exploit, even though there might be a solution in the future.
- By using blade waste in cement production, up to 16 % of the emissions can be saved. 10 % of the cement mix consists of shredded blade waste, and the total cement produced in this case study is 3267 tonne. This process results in approximately 2.5 million tonne of CO_2, and 2.1 million after savings. EC for this scenario is calculated to be 250,000 MJ.
- Repurposing decommissioned WTBs is the most preferred solution. Using WTBs as tiny houses and roofs is a reasonable solution that serves a purpose. New waste-treatment methods can emerge while the blades are being repurposed while keeping the value as high as possible within that timeframe. The total EC and emission are 39,705 kg $CO_{2(eq)}$ and 104,173 MJ. Considering the amount of energy and emissions that have gone into the production of the wind farm, these numbers are relatively small.

7.2 Suggestions to further work

Further work should include legislation, standards, and development in the waste management of blades. It is necessary to establish a standard for decommissioning, where the collection of WTBs at end-of-life has a standardised treatment. In addition to this, specific guidelines for the EOL should be implemented, including other alternatives than landfilling.

There should also be an increasing development of the second-hand market as reusing the components of wind turbines is one of the most preferred ranks in the waste management hierarchy.

There is a need for technology to predict the availability of WTBs and methods to assess the state of the decommissioned WTBs. This method could help facilitate the reuse and repurpose applications. The most apparent solution is designing the WTBs, so it is possible to recycle the blades. Therefore, methods for designing WTBs for recycling should be investigated further.

A further investigation into the possible repurposing applications is essential as there is great potential. Using the wind turbine blades as roofing and tiny houses is a financial and environmentally beneficial solution. Therefore, the establishment of companies that provide these services is essential.

7.3 Sources of error

- Assumptions made in this thesis only apply to this report
- Because of data limitations in several of the processes in this LCA, neglections were made, which have had an impact on the results.
- By conducting a sensitivity analysis, the margin of error could have been estimated.
- Using the tkm unit when calculating transportations by lorries means that the lorries do not have an EC nor emission without load.,
- The collection of data from multiple sources was done to provide enough data to complete the calculations. This could potentially have led to some of the results being inaccurate due to different ratios between the sources.

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