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TNO report

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Sustainable designs for Wind Turbine Blades

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Abbreviations

AEP	Annual Energy Production
CFRP	Carbon Fibre Reinforced Polymer
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide equivalent or CO_2 equivalent. A metric measure used to compare the emissions from various greenhouse gases based on their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential
DCB	Dichlorobenzene. A metric measure used to compare toxicity based on tolerable concentrations in air, water, air quality guidelines, tolerable daily intake and acceptable daily intake for human toxicity.
EoL	End of Life
GFRP	Glass Fibre Reinforced Polymer
JUV	Jack-Up Vessel
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LE	Leading Edge
LEE	Leading Edge Erosion
LEP	Leading Edge Protection
LCoE	Levelized Cost of Energy
MTTF	Mean Time to Failure
OEM	Original Equipment Manufacturer (Wind turbine manufacturer)
OWF	Offshore Wind Farm
O&M	Operation and Maintenance
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
SOV	Surface Operation Vessel
WTB	Wind turbine blade
WTG	Wind turbine generator

Summary

With the recent cost breakthroughs, offshore wind is now established as a crucial pillar of the Dutch energy transition. Developing an affordable, low-carbon energy system in the Netherlands necessitates a large-scale rollout of offshore wind power capacity in the Dutch part of the North Sea – to potentially 35-75 GW by the year 2050. “The Netherlands Long-Term Offshore Wind R&D Agenda” calls for further reductions in LCoE. However, sustainability in offshore wind industry is also needed to be addressed to successfully roll out such a vast amount of offshore wind power capacity.

Sustainable design and end of life solution (EoL) of composite wind turbine blades (WTBs) contribute to a circular economy. The state of the art in life cycle assessment (LCA) study is limited. This is due to the limited availability of life cycle inventory data, describing the impacts of materials and methods used in WTB manufacturing and EoL solutions are available mainly on a small scale and limited to co-cement processing and incineration.

The innovation idea of this project is to develop new innovative sustainable blade design concepts including materials and modular design which can be more easily separated and recycled. The modular design could help to solve the leading-edge erosion (LEE) challenge on the wind turbine blade.

The project aims to investigate concepts for the next generation of wind turbine blades with focus on sustainable design:

- Investigation of a general LCA for composite offshore wind turbine blades.
- Investigation of innovative solutions like leading edge insert, alternative composite materials and mounting technologies for separation of different materials and waste streams.

The main research questions to be answered:

- What are the sustainable design criteria for the next generation large wind turbine blades?
- What is the effect of design modifications on the LCA and circularity?
- What should be the next step for sustainable and fully circular wind turbine development?

The main conclusions of this study are:

- A circular approach should already be kept in mind when designing wind turbine blades.
- Segmentation of blades has advantages in manufacturing, transportation, reduced maintenance costs, and potentially increasing recyclability.
- The study investigates the impacts on balsa wood vs PET foam, different types of resins (epoxy, polyester, polyamide and methyl methacrylate), different end of life scenarios (landfill, incineration, mechanical recycling, pyrolysis and solvolysis).
- A changeable tip section is explored. Segmentation of a blade can reduce the environmental impacts when the lifetime of the wind turbine blade sections is the same as that for the whole blade and recycling routes such as pyrolysis and solvolysis are used.
- The most optimized solution will be using thermoplastic (methyl methacrylate), recycling with a high content of fibre reused (pyrolysis or solvolysis), segmented blade with the same lifetime expectation as the unsegmented blade. This combination can potentially reduce the global warming impacts compared to the current practice or incineration by:
  - 4.6% or 0.28 gram- CO2-eq/kWh or 26.10 kilotons CO2-eq in the wind farm lifetime or for pyrolysis
  - 7.8% or 0.48 gram-eq CO2/kWh or 44.75 kilotons CO2-eq in the wind farm lifetime for solvolysis

Contents

1 Introduction

With the recent cost breakthroughs, offshore wind is now established as a crucial pillar of the Dutch energy transition. Developing an affordable, low-carbon energy system in the Netherlands necessitates a large-scale rollout of offshore wind power capacity in the Dutch part of the North Sea – to potentially 35-75 GW by the year 2050. “The Netherlands Long-Term Offshore Wind R&D Agenda” calls for further reductions in LCoE [1]. However, sustainability in offshore wind industry is also needed to be addressed to successfully roll out such a vast amount of offshore wind power capacity.

Sustainable design and end of life solution (EoL) of composite wind turbine blades (WTBs) contribute to a circular economy. The state of the art in life cycle assessment (LCA) study is limited. This is due to the limited availability of life cycle inventory data, describing the impacts of materials and methods used in WTB manufacturing and EoL solutions are available mainly on a small scale and limited to co-cement processing and incineration.

In parallel, leading-edge erosion is a current issue in rotor blade performance. The largest blades are deployed offshore, where noise restrictions are lower and therefore tip speeds can be higher. This leads to increased leading-edge erosion, which is a larger issue offshore than onshore in terms of operation and maintenance.

The project aims to investigate concepts for the next generation of wind turbine blades with focus on sustainable design:

- Investigation of a general LCA for composite offshore wind turbine blades.
- Investigation of innovative solutions like leading edge insert, alternative composite materials and mounting technologies for separation of different materials and waste streams.

The main research questions to be answered:

RQ 1) What are the sustainable design criteria for the next generation large wind turbine blades?
RQ 2) What is the effect of design modifications on the LCA and circularity?
RQ 3) What should be the next step for sustainable and fully circular wind turbine development?

The report covers the innovative ideas to develop sustainable blade design concepts including materials and modular design which can be more easily separated and recycled. Chapter 2 describes the wind turbine blade design and materials. Chapter 3 describes the end-of-life scenarios of wind turbine blade. Few EoL scenarios are described and further investigated in life cycle assessment study in Chapter 5. Furthermore, chapter 4 describes the leading-edge erosion challenges and innovations in design. Next is Chapter 5, this chapter describes the life cycle assessment study for an offshore wind farm, focusing on different scenarios in wind turbine blades, including design, O&M and EoL. Finally, chapter 6 concludes the study and gives recommendations for the topic.

This project was carried out in the framework of TNO’s internal R&D instrument ‘Kennis en Innovatie Project’-programme 2020 (KIP), aimed at gathering knowledge, improving team expertise and investigating promising innovative ideas.

2 Wind turbine blades design and material

Typical rotor blades are hollow composite structures. A prevailing design currently adopted by OEMs is illustrated in Figure 1. This blade is made of two shell sides and one or several shear webs. The components are manufactured individually and then joined using structural adhesives. Both shells and webs are predominantly made up of glass fibre reinforced plastic (GFRP) sandwich construction, the core typically made from PVC or PET foam or balsa wood [2]. The shell may be reinforced with carbon fibre reinforced polymer (CFRP) material above and below the web flanges, which is called spar cap.

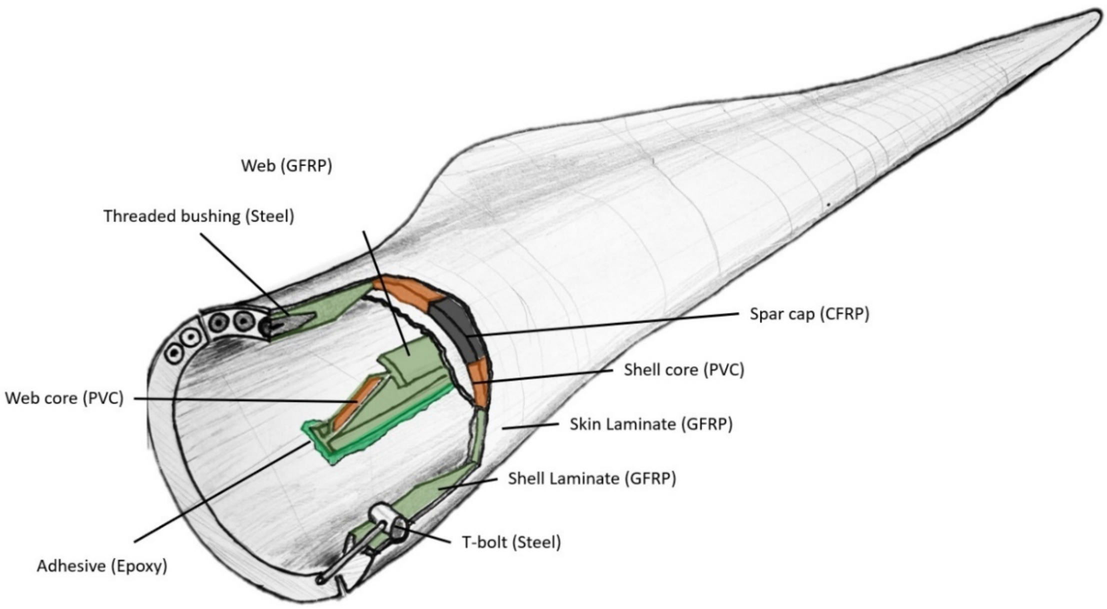


Figure 1 Illustration of a wind turbine blade. Usually, only one of the fastener types is found in a blade root – the two types are shown together for illustration.

Another common architecture of blades is based on a structural spar and an airfoil shaped shell instead of a web. The spar, which can be thought of a beam with a box cross-section takes the majority of the loads. This design is not illustrated here.

The part of the blade which is closest to the nacelle is called the root of the blade. This root has a cylindrical cross section and is made of monolithic GFRP (i.e. no sandwich inside). Threaded fasteners are used to attach the blade root to the pitch bearings and the fasteners require a metallic interface in the blade root. There are several designs to provide this metallic interface. Two popular designs are threaded bushings as illustrated on the left side of the root, or a 'T-bolt' design sketched on the right-hand side. Threaded bushings come in various forms and are either directly infused, prefabricated with a GFRP interface or bonded into a bore hole at the root. T-bolt designs require transverse drilling into the blade root to insert a metallic barrel nut.

Following the blade geometry from root to tip, the outer cylindrical shape of the blade transitions into an airfoil design and the shell thickness is reduced. The double curvature required to make this transition is challenging for the manufacturing process as it requires the fabric to be draped evenly into the mold without creating creases.

Stresses caused by gravity and aerodynamic loads increase towards the root on the one side, and relative wind speed increases towards the tip on the other side. Hence, the root part of the blade is dominated by structural considerations while aerodynamics plays an increasingly important role closer to the tip. Aerodynamic loads (flap loads) can be high and beside sustaining the loads without (fatigue) damage. Large blades need also to be sufficiently stiff to not collide with the tower (upwind turbine). Hence carbon fibre reinforced plastic (CFRP) material may be introduced in the spar cap to increase flap bending stiffness. In the illustration, the shell is designed in parts as a sandwich construction with a PVC core and GFRP skins to maximize specific bending stiffness.

Shear loads are taken by the shear web which is bonded into the blade. Again, this is another challenging step during manufacturing. The shear web is glued between the shells as they are joined. Ultrasonic testing is used to verify that the adhesive sufficiently joins the web flanges to the shell sides.

The shell may contain other materials, meshes, receptors for lightning protection, leading edge protection or sensing functionalities, but these features vary much between manufacturers. For longevity and aerodynamic performance, the blade surface plays an important role.

Aerodynamic losses due to a damaged leading-edge lead to a loss in energy production between 2% and 25% [3]. As a result, the leading-edge part of a blade few meters towards the tip may be covered with a leading-edge protection (LEP) like additional coating, tape or other features to delay the degradation of the surface.

A typical rotor blade is an integral structure, meaning that it is avoided to incorporate any connections other than the interface between fibres and resin of which the rotor blade is manufactured. The reason for this is, that the performance of a composite in which fibres are cut is inferior to that of a composite with continuous fibres. Nevertheless, there are several reasons for including connections anyway [4]:

- The glued connection between prefabricated parts within the composite blade structure (such as the abovementioned web-shell connection);
- Split blade/modular blade connections, which are connections between different pre-manufactured blade segments (predominantly bolted connections), in order to facilitate transport and installation, especially in complex terrain;
- Connections between load carrying components and aerodynamic fairings;
- The blade root connection, which is the bolted connection between the blade and the turbine interface.

Based on the ample experience with structural connections in blades, modular design may also be feasible to facilitate decommissioning and recycling.

3 Wind turbine blade end-of-life scenarios

In the design process of wind turbines, end-of-life (EoL) solutions have lack of attention because manufacturers have focussed on reducing cost and increasing production volume. After 20-25 years of operational life, operators/owners need to choose between various EoL solutions: complete decommissioning and recycling or scrapping materials and components, extension of lifetime, dismantling, and offering the turbine on the repowering market.

Realizing that during the coming 5 years, somewhat more than 22 GW of installed wind power, mostly land-based, will come to the end of the design life span (WindEurope), the issue of EoL-solutions becomes increasingly more important. The first offshore wind farms have also reached the end-of-life (Vindeby (DK) and Blyth (GB)). Applying EoL not only is a cost issue, but it also provides opportunities for new business and technology innovations.

3.1 Type of end-of-life scenarios for WTB

The first question that the operators will encounter at the asset's EoL is whether they can extend its operational life or not, which components should be replaced to achieve lifetime extension. The goal should be achieving a circular offshore wind farm so the environmental impacts from the energy production can be lowered and materials can be preserved.

A fully integrated circular scenario does include recycling of used materials. This part of the strategy needs to be supplemented with the approach to prevent or reduce waste. According to EU's waste hierarchy scheme (see Figure 2), the order of treating material and components is: prevent, reuse, repair/repurpose, recycle, recover and finally dispose [5]. This should become an important basis of the design philosophy of wind turbine systems. To a certain extent, this requires re-thinking and re-designing of common wind turbine concepts.

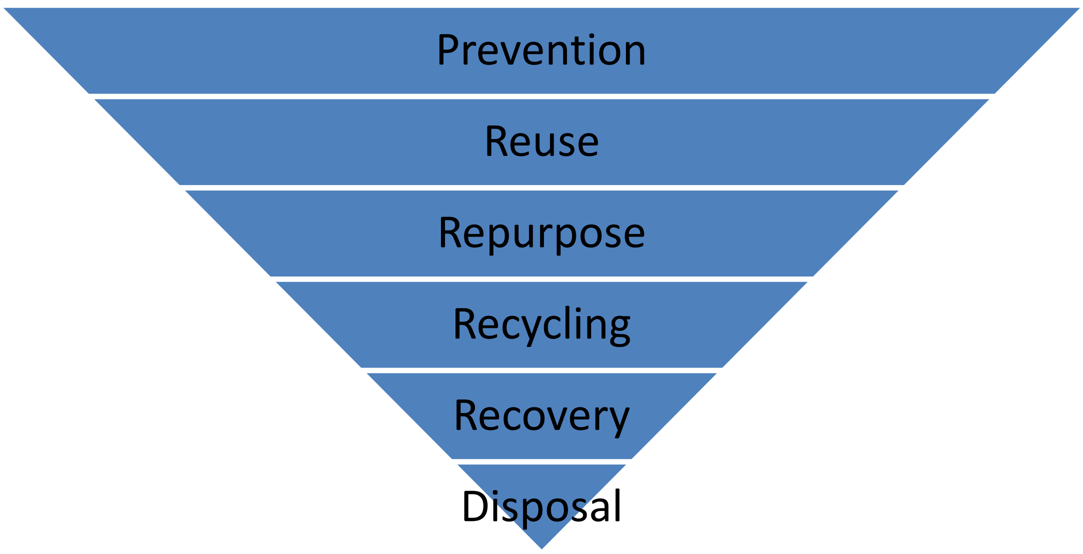


Figure 2 Waste Hierarchy Scheme (higher is preferable)

Many wind energy companies have started to incorporate a sustainable approach in their production chain. Companies like Siemens [6], LM Wind Power [7], GE Renewables, etc. are taking a sustainable approach, such as life cycle assessment (LCA), according to ISO

14006:2011 Environmental management systems [8]. However, it still is a great challenge to make the entire wind energy application chain 100% circular and zero-waste technology.

There are 3 main EoL strategies for wind turbines that can be further investigated:

- **Lifetime extension** (reuse in the hierarchy context)**.** It can be enabled by monitoring the essential parameters and structural health to accurately calculate the remaining lifetime of the offshore wind turbine blades – this may still be positive after completion of the design life, if the operational loads have been lower than the design loads.
- **Remanufacturing** (repurpose in the hierarchy context) of components. For wind turbines, this contributes to the use of "as-new" components from decommissioned wind turbines.
- **Recycling** (recycling in the hierarchy context) of materials of various categories (composites and plastics on the one hand and metals, concrete, other precious materials such as rare earth elements, on the other). Recycling essentially is reusing materials as feedstock for fabrication of new products.
- **Recovery** (recovery in the hierarchy context). Recovering energy from the waste, often by incineration.

A combination of different EoL solutions is possible. An extension of the Lifetime Extension approach may precede a later recycling or remanufacturing action. The cheapest and the best short-term solution is always lifetime extension. By extending the life of wind turbine blades, the impacts of material extraction are spread in a longer time. However, eventually, the wind turbine components need to be decommissioned.

The EoL solution needs to be a fully-fledged design condition of the design of a wind turbine system. The selection of sustainable materials, the design of the production and assembly processes and concepts enable creating fully separated material streams.

In this report, environmental impacts from various available recycling technologies of WTB are investigated. The boxes in purple in Figure 3 will be modelled as life cycle assessment EoL scenarios (Chapter 5)

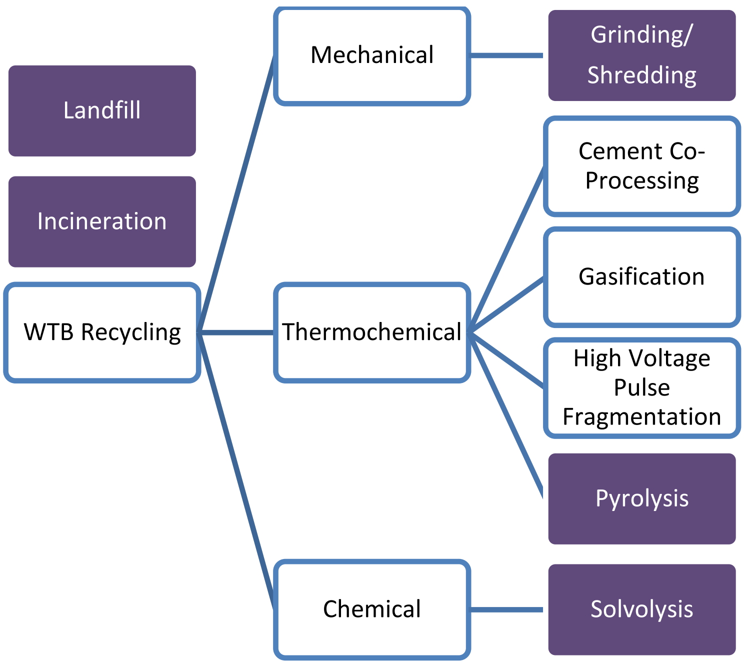


Figure 3 Wind turbine blades material End of Life scenarios

3.2 Landfill

The cheapest option is landfill. However, many countries, especially in Europe, have banned or implemented landfill taxes. At the national level, four countries make a clear reference to composite waste in their waste legislation: Germany, Austria, the Netherlands and Finland. These countries forbid composites from being landfilled or incinerated. Specifically, in the Netherlands, in principle the composite waste is banned from landfill. However, wind farm operators can benefit from an “exemption” if the cost of alternative treatment is higher than 200€/tonnes. According to the survey conducted by WindEurope, the cost of mechanically recycling wind turbine blades in the Netherlands ranges between 500-1,000€/tonnes including onsite pre-cut, transport and processing. Mechanical recycling itself costs between 150-300€/tonnes. This means landfilling is still practised [9].

Bloomberg reported the landfill practice in Wyoming (Figure 4) [10]. Urgent solutions to recycle, reuse and repurpose of wind turbine blades hence are required to avoid future problems. Furthermore, upscaling and positive business case will be the key to have a successful recycling implementation.

Figure 4 Bloomberg reported wind turbine blade landfill in Wyoming, USA

3.3 Incineration

Incineration is defined as burning the wind turbine blades completely with temperature above 850^{o}C. The outputs of the process are energy recovery which usually is used by the municipality, and ash [11]. There are various types of incinerators, for example moving grate incinerator and rotary kiln depending on the volume, sizes, and hazard of the waste to be destroyed. [12]

Specific for wind turbine blade, after it is decommissioned, it is cut down to reasonable size and mixed to municipal waste. Then it is incinerated to produce heat. The advantage of incineration compared to landfill is that some combustible materials have heating value that get recovered as energy which can be used for electricity. However, incineration is not recycling by any means: no materials can get recovered to be used in new product with economic value. Furthermore, the glass fibre is considered incombustible. It is mostly the polymers and carbon fibre (if present) that create calorific value. The ash content is very high and has to be dealt with (landfilled) after incineration [13].

Incineration is still considered in many countries. This is because landfill requires much more space and a commercial recycling plant for wind turbine blades is not yet ready and available. In the Netherlands itself, as mentioned in section 3.2, there is an exemption for the operators when recycling cost is higher than 200€/tonnes [9]. In this case, both incineration and landfill for composite material is also still a practice in the Netherlands.

3.4 Mechanical recycling

Through mechanical recycling, the blades are cut up into scraps or smaller pieces that can be further crushed, shredded and milled. The results are called recyclate which may be divided into fibres and resin. The copper can also be sifted out. These recyclate may be used in various applications, such as an alternative to wood fibre in particle board, or as a reinforcement in cement or asphalt [13].

This type of recycling is commonly called grinding or shredding. There are both advantages and disadvantages of grinding as EoL scenario for wind turbine blades. In general, it does not require high technology equipment: cutting machine, crusher, shredder and miller. As it does not involve chemicals, the pollution of water and atmosphere is limited compared to the other types of recycling. Some drawbacks include high demand in energy consumption, wear and tear of the machines, and the low quality of the recyclate. We compare mechanical recycling with 1.93MJ/kg and 5.53MJ/kg of composite materials for the study. The recyclate has very low quality compared to the virgin materials giving the recyclate very low economic value [11].

Some notable products from mechanical recycling are:

1. The composite materials are transformed into small pellets and sold to be used in injection mould and extrusion manufacturing processes. The brand is called EcoPoly Pellets and only available in the USA [14].
2. Zagons Logistik in Germany performs industrial-scale recycling blade materials for feedstock in cement production. Holcim cement plant uses the recyclate for further processing into a fully functional product. Furthermore, the blades are also used as co-processing and substitution for fossil fuel in the plant. It is reported that each ton of blade can substitute half a tonne of hard coal [13] [15].

3.5 Thermochemical recycling - Pyrolysis

There are four types of thermochemical processes commonly known. They are distinguished mainly based on the amount of oxygen present in the process. When there is no oxygen, pyrolysis takes place; in the presence of limited oxygen the main process is gasification; when there is excess oxygen combustion or incineration occur. Even though incineration is shown in Figure 5, incineration burns the composite at a high temperature resulting in only ashes. This means no fibre can be recycled. Hence it is only considered a recovery of the heat from the exothermic process. Pyrolysis is a thermochemical process that is resulting in materials considered recyclate which has a certain economic value.

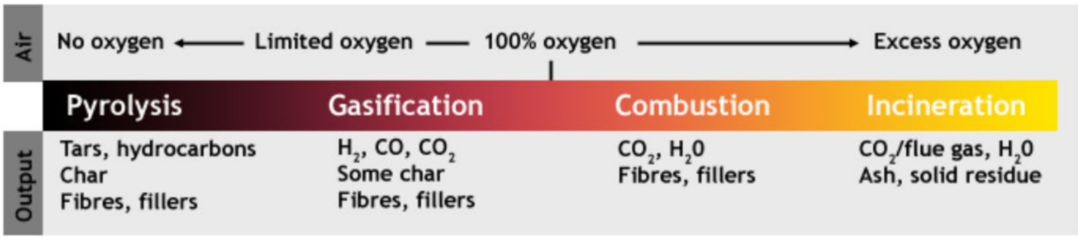


Figure 5 Types of thermochemical recycling (difference between pyrolysis, gasification, combustion and incineration) [11]

In this project, pyrolysis is chosen as an example of thermochemical recycling for composite material. Pyrolysis is a process to decompose polymers in inert atmosphere or without presence of oxygen. The operating temperature for this process is between 300 to 800°C, but in average the operating temperature for composite is between 450-700°C. The process is endothermic hence requires external energy source. Job et al. found that the conventual pyrolysis energy demand is between 23-30 MJ/kg [16]. Another type of pyrolysis is microwave pyrolysis. It is estimated that this process is more energy efficient requiring only 5-10 MJ/kg. More research needs to be done to ensure pyrolysis can be scaled up as required by the composite waste demand, especially on the economic aspects and the quality of the recyclate [11].

The product of pyrolysis can be optimised based on different goals, recovery of the fibres or recovery of the oil and gas. The recovered oil fraction can be used as the source of energy hence reducing the external energy requirement and sometime sufficient to heat the process. However, this process requires additional separation and purification process. The output is generally containing of 50% up to 67%-weight solid, 10-50%-weight liquid, and 5-15%-weight gas product [11].

Figure 6 shows a representation of pyrolysis process.

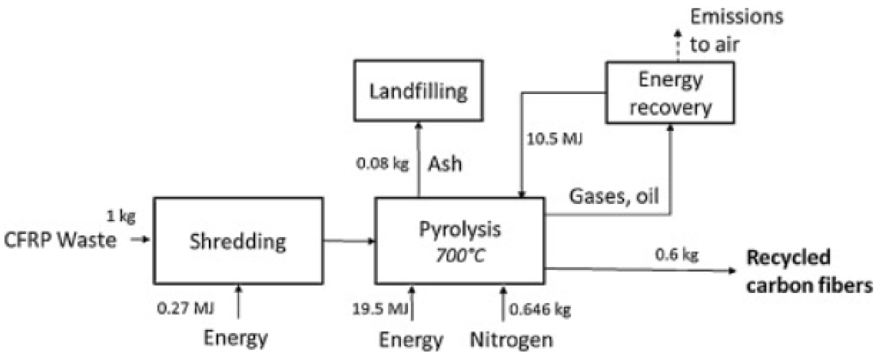


Figure 6 Representation of pyrolysis process (used for LCA in chapter 5)

3.6 Chemical recycling – Solvolysis

Chemical recycling is sometime referred as solvolysis, a process which decompose or depolymerize composite matrix using heated solvents or solvent mixtures. To be noted, the solvent can be water and it can be called hydrolysis. Even though it is in earlier development compare to other end of life routes, solvolysis shows benefit on the quality of the recyclate. For example, glass fibre, when it suffers degradation due to heat the recyclate is much lower quality then the virgin one hence low commercial value. Therefore, there are many researches that focus on mild condition of solvolysis (low temperature and pressure).

Figure 7 shows a representation of solvolysis or hydrolysis process.

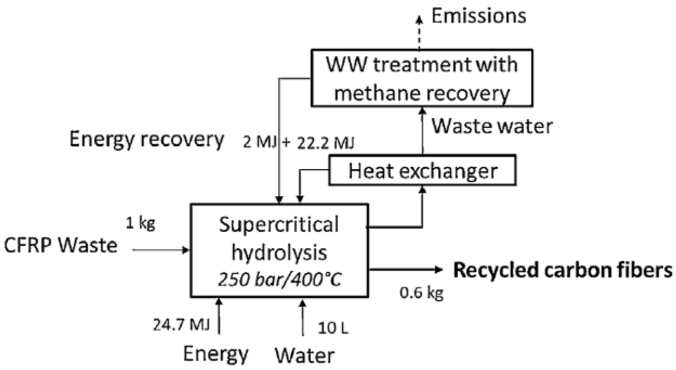


Figure 7 Representation of optimized supercritical hydrolysis (used for LCA in chapter 5)

4 Innovation in blade designs

4.1 Leading Edge Protection

Erosion of the wind turbine blades coating materials has become one of the most serious and important issue in the offshore wind industry. The most damaged part of the rotor blade by erosion is the leading edge, the damaged leading edge caused by erosion is illustrated in Figure 8. Erosion reduces not only the reliability of the blade, but also has significant impact on aerodynamics efficiency and annual energy production.

Figure 8 Leading edge erosion

Periodic replacement and maintenance of damaged blades is associated with significant time and costs, mainly the costs associated with periodic replacement of blade or repairing of the blade coating on the leading edge. The high cost of the blades made it necessary to find a new method for their reliable protection.

Erosion damage usually caused by repeated interaction of the rain droplets on the leading edge. Protection coatings on the leading edge can delay development of leading-edge erosion (LEE). Currently, considerable experience has been gained through applying of various methods of wind turbine blades protection.

The high blade tip velocities associated with large blades makes the impact of rain especially demanding.

Ways to prevent leading edge erosion

A lot of research has been undertaken to understand the mechanisms of LEE. The damage process of LEE is complicated. Upon impact of a water droplet at high speed, shock waves are triggered and cause stress concentration on discontinuities. These repeated shock waves cause fatigue in the material. Beside the shock waves, a second effect is further eroding the substrate which is called water-jetting. Very rapid water jets splash radially away from the impact. These jets tear-off already loose or cracked material [17]. Hence, the materials to delay this process need to be very carefully selected.

There are several LEP products available on the market. Products come in different form and materials:

- LE protection coating system
- Tape [18]
- Shells, thermoplastic [19], [20] and polyurethane shell [21]
- Tiles, nickel cobalt alloy tiles [21], illustrated in Figure 9

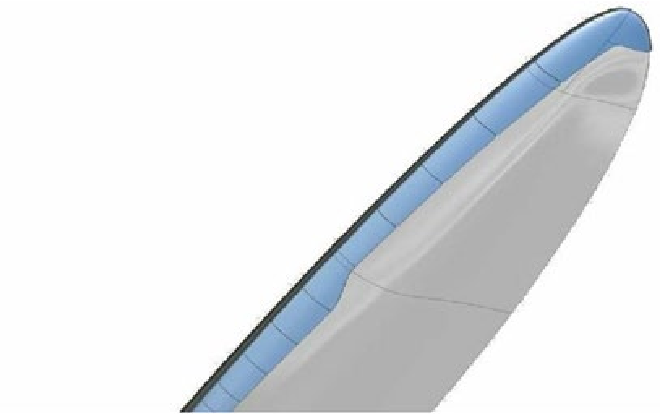


Figure 9 The LEFT project is to integrate a Ni-Co protection system into the leading edge of a turbine

4.2 Proposed innovation

4.2.1 Modular blade

One of the ideas is to develop changeable tip section (~10-30% of the blade length) fabricated from thermoplastic composite material and a thermoplastic LEE protective coating.

A modular design would have several advantages in terms of transportation, cost, sustainability and adaptability to different site condition. **Modular design**, or modularity in design, is a design theory and practice that subdivides a system into smaller parts called modules which can be independently created, modified, replaced or exchanged between different systems. (Wikipedia) An example of a modular blade design is a family of blades, which share the same root module, but accept several tip modules. These tip modules could take into account different site conditions. Low wind conditions could demand a longer tip and sites with heavy precipitation would need additional reinforcements of the leading edge. This would drive down manufacturing costs as the same tooling for the root part of the blade (moulds etc) could be used for various blade configurations. Modules could also take the form of splitting structural functions from aerodynamic functions. For example, a generic spar box could be paired with various foil shells. Or a blade root module with various number of bolts.

Modularization based on **segmentation** of blades into several parts would have the additional benefit that it can drastically decrease the transportation cost, by allowing to assemble the blade on site and hence allow use or reuse of standard equipment such as cranes, vessels and so on. The concept of a segmented blades is illustrated in Figure 10.

Nowadays new materials and new technologies allowed to produce extremely long (>100 m) blades without any aerodynamical losses. The Netherlands' Long-Term Offshore Wind R&D

Agenda [22] required to come up with a modular design that can be scaled yet meet the fatigue life and strength required for long-term operation.

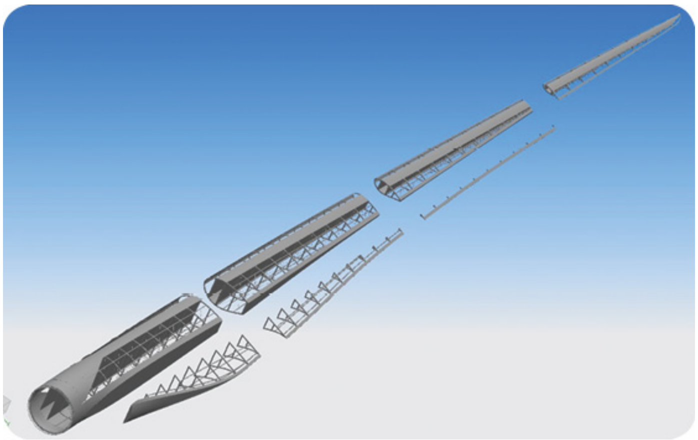


Figure 10 Illustration of a segmented blade.

Modular blades and segmented blades in particular require joints and connections in composites. Research questions which would need to be addressed to fully benefit from the claimed advantages are:

- Can we improve sustainability with modular design by re-using parts of a blade or facilitating recycling of blade modules?
- Can we achieve sufficient structural strength and stiffness?
- Can we keep the aerodynamic properties?
- Can we remain competitive for total costs in terms of manufacturing, logistics and installation?

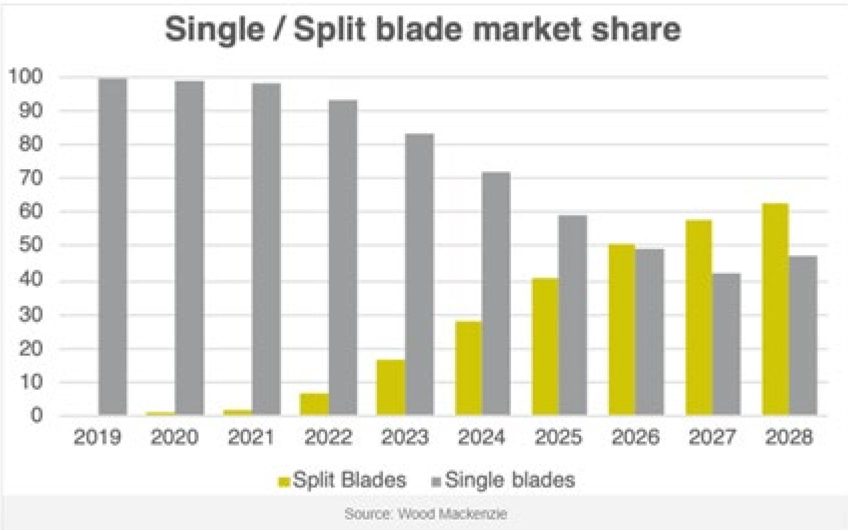


Figure 11 Single/Split blade market share [23]

With increasing size of the wind turbine generators and especially wind turbine blades, logistical and manufacturing costs and engineering challenges increase. This can be alleviated to some extent by developing blades that can be manufactured in several sections and that can be assembled at the installation site. This is also known as a split blade. It is expected that this split blade will take a larger market future, see Figure 11. Modular design for wind turbine blades will be **beneficial not only for logistics** but also in the selection of **the best materials** and most **optimal manufacturing technologies** for the different sections of the blades, or in offering a scalable blade architecture.

The logistical and manufacturing challenge would be reduced by making turbines modular as far as possible, so that a larger number of smaller, common components and subassemblies can be standardized, mass produced and assembled on site using smaller, cheaper and more available installation vessels. Standardization into smaller modules is essential for a more industrialized supply chain.

The research will also investigate modularization challenges. These challenges come in the form of:
- Additional failure modes at the joints
- Additional manufacturing cost of the joints
- Higher inspection and quality cost
- Higher overall weight
- Potential effects on rotor dynamics due to weight increase

One of the milestones in the TKI agenda focuses on the joining methods that need to be developed for a modular blade design.

There are a few different joining methods available for modular blade designs. However more research might be required to improve composite joints to make these modular designs more competitive. Detailed review of current joining methods can be found in reference [4] [24].

General Considerations for Segmentation
In order to minimize the LCoE resulting from a segmented design, which could be applied for blade, hub, and other components, the different cost components have the following considerations based on Dutton and Birkemeyer [25] [26].

Initial capital costs [24]
– manufacturing costs
– tolerance requirements
– production complexity and accuracy
– ability to use with conventional production methods
– quality control
– positioning accuracy and speed of assembly

Annual energy production
– reliability
– aerodynamics
– weight of the joint

Annual operating expenses
– requiring minimal inspection
– easy to repair during service
– possibility of disassembly for replacing segments

Cost Effectiveness of Blade Segmentation

Total cost of the blade can be separated into material costs and production costs. The material costs are largely based on the mass of glass fabric, resin, glue, core reinforcement etc. put into the blade. Some parts have to be considered by item: bushing for the connection at the root, lightning protection system, tip-brake mechanism, if needed, etc. The production costs are related to the production hours needed for building the blade, cutting and grinding, finishing, quality control, etc.

Segmenting blades is useful if this results in a reduced LCoE. Dutton [25] reported an expected increase in blade cost of approximately 19% for a large blades (60-m blade), while the transportation costs decreased only about 5% of the total price of the blade, thus overall resulting in an increasing direct LCoE.

For the standard blade, the material costs are almost equal to the production costs (49% for material costs and 51% for production costs). During the production of the prototype sectional blade, the material costs were registered. In total material costs increased in 43% and production costs for the sectional blade has been estimated at about 94%, compared to the standard blade.

However, from Dutton, it is clear that the relative added cost of segmenting a blade decreases with the size of the blades. The increase of total cost (material and production costs) for a small blade (23.3 m blade) with the T-bold connection has been estimated to be about 68%. A review of the cost of sectional blades found that for a large blade (60 m), manufacturing costs would be increase by 15-20%.

Since manufacturers see no real problems in manufacturing single, integral blades up to the size, sectional blades are only likely to be viable where there are particular problems of access to a site. However, for large rotor blades, length is a potential problem for road transportation. Segmentation of the blade might have a major advantage regarding the accessibility of isolated sites where larger blades cannot be transported.

O&M Cost

Theoretically, there are benefits in using a segmented approach during O&M costs. When wind turbine blades are severely damaged and cannot be repaired with rope access, larger maintenance or even replacement is required. For major repairs or partial/complete blade replacement, some wind farms have utilized jack-up vessels to carry out such maintenance. This maintenance costs lots of time and money. For example, a regular jack-up vessel (JUV) can cost between 100,000 to 300,000€/day.

Some examples are Princes Amalia and London Array offshore wind farm. Princess Amalia utilized MPI Resolution jack-up vessel to perform major blade repair for 29 out of 60 2MW wind turbines [27] . On the other hand, London Array utilized MPI Adventure for major blade repairs on 127 out of the 175 turbines, expanding over 500,000 manhours throughout 12-month duration [28].

If the repair or replace full blade can be avoided and only segmented sections need to be maintained, then the logistic requirement during this activity can reduce greatly. First, a smaller vessel (jack-up or floating vessel) can be employed. Second, only the segmented section needs to be replaced when replacement is required, so fewer materials are required.

4.2.2 Leading edge add-on

The idea of this innovative technology relates to a new method of manufacturing of wind turbine blades with an innovative and sustainable design of the **leading-edge add-on protection** associated with lower maintenance cost. The main aim and scope of the invention is reduction of maintenance cost of leading edges damaged by rain and hail erosion.

General idea is to come up with innovative prefabricated leading-edge add-on(s) that will:
- Reduce maintenance cost by reducing leading edge replacement time.
- Leading edge add-on can significantly reduce LCoE, while reducing the environmental impact of wind power generation.
- Be more robust, simple and accurate than leading edge tape and have better aerodynamics

The concept is represented in Figure 12.

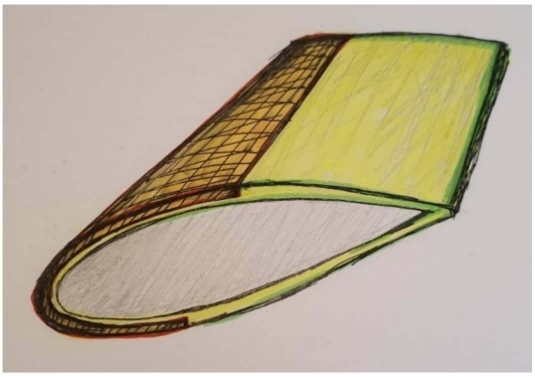


Figure 12 Leading edge add-on

LE add-on can be installed by blade maintenance technicians utilizing rope access in a rapid process that combines - Leading Edge (LE) repairs with LEP application replacement.

Materials
The leading-edge add-on must be manufactured from the recycled materials, such as fibre composites, long glass fibre reinforced thermoplastic composites or carbon fibre reinforced thermoplastic, as well as injection molded fibre reinforced thermoplastic materials. More environmentally friendly and alternative way to stellite alloys (sheets), talonite alloy or thermal spray process that commonly used in the machinery and aerospace industry to maximize combinations of wear resistance and erosion resistance. Also recycling thermoplastic material can be used to print add-on part and then attached it to the blade for leading edge protection. During the operation, the wind turbine blade can be repaired by welding. After decommissioning of the wind turbine blade, *thermoplastic* used for LE add-on protection can be melted and reused for new blades, that will make blades life cycle more sustainable.

Attachment method:
- Magnets
- Adhesion
- Welding - can be used for thermoplastic parts

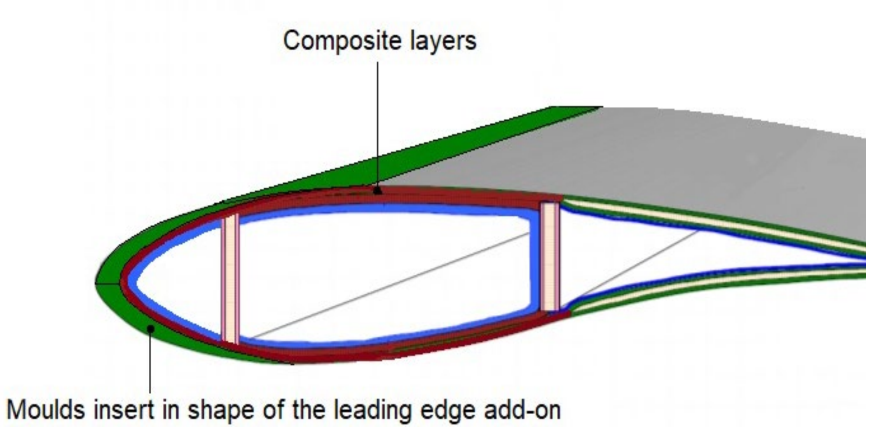


Figure 13 Mould insert in shape of the leading-edge add-on

Developments required:

1. Use insert in blade moulds to create space for leading edge add-on, see Figure 13.
2. Investigate best attachment method (e.g. inserts, bolts, screws, click-on, magnets)
3. Develop easily replaceable leading-edge add-on (3D-printing), including optimal division into parts
4. Investigate impact on leading edge maintenance cost (compared to tape and paint)
5. Investigate best material (e.g. cost, 3D printable, erosion resistance)
6. Investigate additional options (zig-zag edge, ‘shark skin’ and other aerodynamic features)

Results:

1. Prototypes for manufacturing and testing
2. Potential developments in 3D printing

5 Wind turbine blade Life Cycle Assessment

5.1 LCA description

Life Cycle Assessment (LCA) is a widely accepted tool to systematically quantify the environmental burdens related to a product or service. As indicated by the name, the focus is on the entire life cycle, including resource extraction and waste disposal and on covering a wide range of environmental impacts, such as climate change, human and ecotoxicity and resource depletion. This way, burden-shifting between life cycle stages and environmental impact categories can be avoided.

A major and decisive step in LCA is data gathering establishing an inventory of all inputs (materials and energy) and outputs (emissions, wastes, energy, and materials) related to the product or technology under investigation.

The following parts of LCA methodology (see Figure 14) are summarized below based on the ISO 14040 standard:

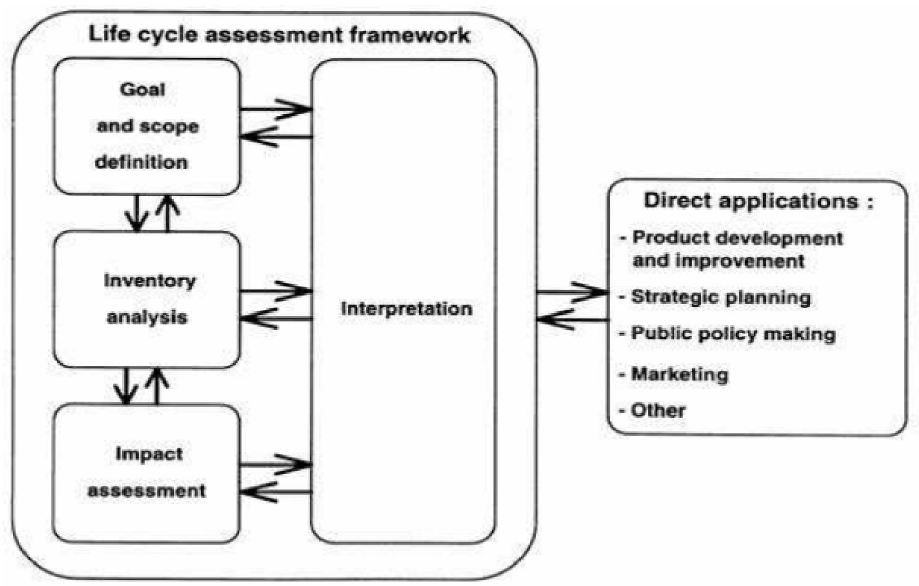


Figure 14 LCA methodology based on ISO 14040

Goal and scope definition
The goal and scope definition are the initial step of every LCA study. At this stage, the principle of the work is explained. Also, the system boundaries of the product are defined. This step is one of the most important in the LCA procedure, where the communication between the customer and analyst is crucial.

Inventory analysis
Inventory analysis engages data collection and calculations to quantify the inputs and outputs of the system described in the ‘‘goal scope and definition’’ including raw materials, waste flows, and emissions attributed to the products life cycle.

The LCI (life cycle inventory) data can be used to: understand total emissions, wastes and resource-use associated with the material or the product being studied; improve production or product performance; and be further analysed and interpreted to provide insights into the potential environmental impacts from the product system being studied (i.e. life cycle impact assessment (LCIA) and interpretation).

Life cycle impact assessment (LCIA)
LCIA describes the environmental consequences of the environmental load quantified in the inventory analysis. It interprets the environmental loads from the inventory analysis into environmental impacts such as kilogram CO_2 equivalents, acidification, biodiversity, etc.

Interpretation
The inventory calculations in a quantitative LCA are typically large and are difficult to interpret. Therefore, it is important to refine the raw results and present only a section with the most important result parameters together with initial goals.

5.2 Methodology

This study performed a detailed LCA for wind turbine blades and the processes related to their use. Figure 15 shows the relations of these processes:

- Material extraction and manufacturing,
- Logistic during transport and installation,
- O&M,
- Logistic during disassembly and decommissioning,
- End-of-life and waste treatment

Other components such as nacelles, towers, monopiles, cables, and substations are excluded in this study, as all the cases would have the same components. This study used an existing database for all materials inventory. Data has mainly been drawn from the commonly used LCA database Ecoinvent 3.4-unit processes compiled in April 2018. The LCA software SimaPro 8.5.2.0 has been used for the calculations.

The Life Cycle Impact Assessment Method used in SimaPro is the ReCiPe 2016 endpoint and mid-point, Hierarchist version for values describing such as climate change, ozone depletion, ecotoxicities, land use and damage assessment for human health, ecosystem, resources depletion, etc. The “energy cumulative demand” methodology is also used to calculate the required energy to produce the components.

For all the models, cut-off system model is used. The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. If the material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. Consequently, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. [29]

The functional unit must be defined, which provides a clear description of the function of the product, system, or service under study so that alternatives can be compared in a meaningful way. Thus, the functional unit for this LCA study is defined as 1 set of wind turbine blades (3 blade pieces), which assumes the two models considered are functionally equivalent.

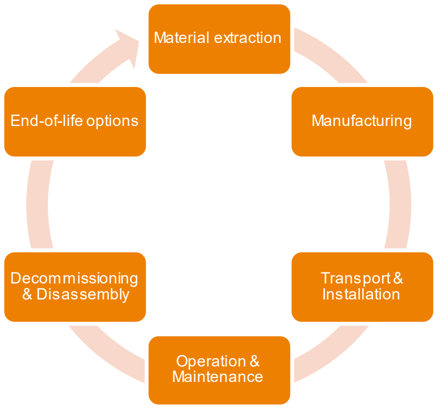


Figure 15 Wind Energy system boundary

shows the different stages that can generally be distinguished for a product, such as an offshore wind turbine in the course of its life cycle: The life cycle starts with “Material extraction and production”, where natural resources are collected or mined as the base of the material of the product. Subsequently, these materials are converted to the product (components of the wind turbine) in a “Manufacturing” stage, which typically consists of a number of separate substages for the various components. This is followed by “Transport & Installation”. Once installed the operational stage of the wind turbine follows which is associated with ”O&M” activities. After the operational stage, “Decommissioning & Disassembly” takes place before the life cycle is completed with the “End-of-life” stage. For this last stage several options exist, e.g. landfilling, waste incineration, recycling, reuse. During all life-cycle stages environmental impacts occur due to activities associated with these stages.

5.3 Data collection

Foreground data specifying the material composition of the blades were derived from an LCA study conducted by TNO in 2019 [30]. While the background data, the baseline database for avatar 10 MW blades, were obtained from the literature [31]. These data form the basis of the calculations presented in this report.

An offshore wind farm case study is investigated to calculate the impact during the offshore wind farm lifetime. A wind farm similar to the Borssele case is used to minimize the data gathering process as it is not the focus of this study. The 770 MW offshore wind farm is located in the North Sea, 60 km from the Dutch shoreline, and comprises seventy-seven 10 MW wind turbines based on the Avatar wind turbine. Various manufacturers across Europe manufacture components. Afterward, they are transported and installed in an offshore location. The distance that the components travelled, and their weight affect the LCA results significantly.

5.3.1 Modelling for material composition and manufacturing

LCI 10 MW wind turbine blades (baseline – KIP 2019)
Based on KIP 2019’s LCA work, a composition of 10 MW WTB materials is modelled. Table 1 and Figure 16 shows the material input and WTB composition in the LCA model.

Table 1 LCI 10 MW WTB (Baseline – KIP 2019)[1]

Input Name	Composition	Mass (mT)
Glass fibre {GLO}| market for | Cut-off, U	71,28%	102,90
Epoxy resin, liquid {GLO}| market for | Cut-off, U	25,91%	37,40
Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U	2,77%	3,99
Copper {GLO}| market for | Cut-off, U	0,03%	0,04
Synthetic rubber {GLO}| market for | Cut-off, U	0,01%	0,02
Nylon 6-6 {GLO}| market for | Cut-off, U	0,01%	0,01

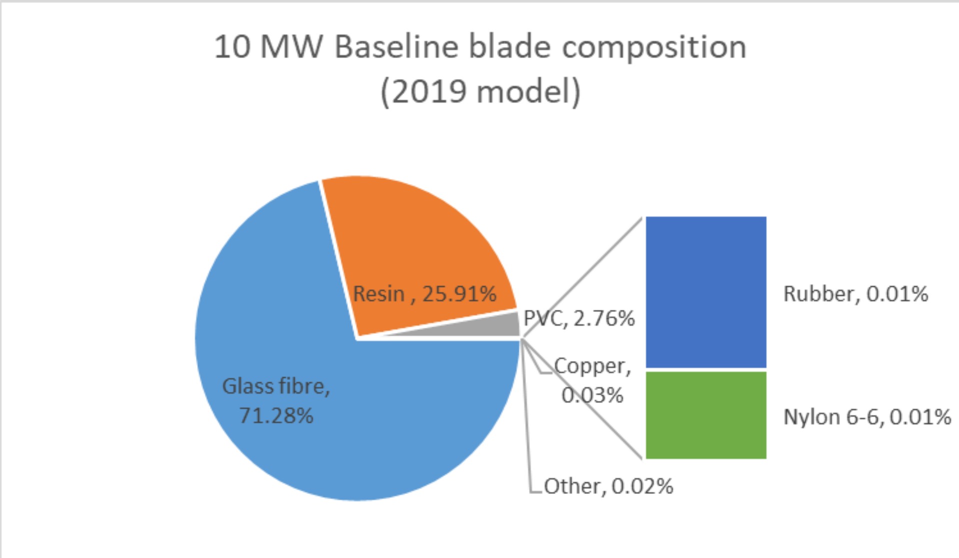


Figure 16 Material Composition WTB 10 MW (Baseline – KIP 2019)

LCI Avatar blades 10 MW and the segmented approach

For this study, an LCI based on Avatar 10 MW wind turbine is made. Avatar wind turbine blade is a mix between glass fibres and carbon fibres reinforced polymers. The resin used in this blade is epoxy. Furthermore, based on the result presented in section 4.2, a segmented blade designed is proposed. The main difference between these two compositions is there is a 5% addition in weight for (1) GFRP and (2) steel as connection. Steel is added to the composition as materials of the bolts and connection. The detailed composition of both blades are presented in Table 2 and Figure 17. Looking at the table, it is expected that the segmented approach would give higher emission during material extraction and manufacturing.

Table 2 LCI 10 MW Avatar and 10 MW Avatar Segmented Blade

Material	Short names	Avatar 10 MW Blade		Avatar Segmented 10 MW Blade	
		Composition	Mass (Tonnes/blade)	Composition	Mass (Tonnes/blade)
Glass fibre {GLO}| market for | Cut-off, U	Glass fibres	31.62%	15.22	31.59%	16.72
Epoxy resin, liquid {GLO}| market for | Cut-off, U	Resin (epoxy) for GF	18.97%	9.13	18.95%	10.03
Carbon fibre (modelled)	Carbon fibres	23.88%	11.49	21.71%	11.49
Epoxy resin, liquid {GLO}| market for | Cut-off, U	Resin (epoxy) for CF	10.28%	4.95	9.35%	4.95
Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U	PVC	7.91%	3.81	7.19%	3.81
Bundle, energy wood, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management | Cut-off, U	Balsa wood	3.36%	1.62	3.06%	1.62
Alkyd paint, white, without solvent, in 60% solution state {GLO}| market for | Cut-off, U	Glue	1.53%	0.74	1.39%	0.74
Polyurethane, flexible foam {GLO}| market for | Cut-off, U	Paint	2.22%	1.07	2.02%	1.07
Copper {GLO}| market for | Cut-off, U	Copper (i.e. ligthening system)	0.21%	0.10	0.20%	0.10
Steel, low-alloyed {GLO}| market for | Cut-off, U	Steel (connection)	-	-	4.55%	2.41
			48.12		52.93
			Addition % in weight		10%

[1] GLO: global and represents activities which are considered to be an average valid for all countries in the world

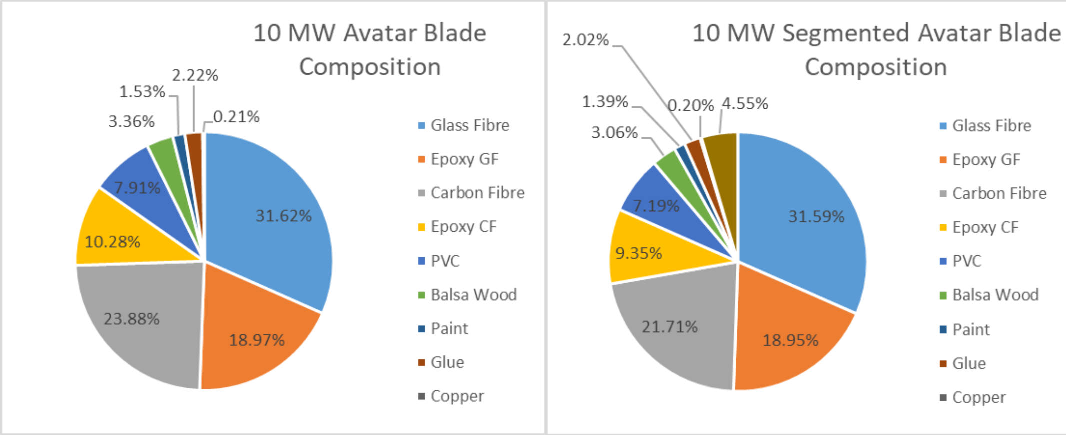


Figure 17 Material Composition WTB 10 MW Avatar and the segmented approach

For the segmented approach, two assumptions are made to determine where the connection is placed on the blades.

1. Blade mass linearly distributed along the length, at least near the tip
2. Relative distribution of material content does not change much along the blade (so same percentage for all materials e.g. CFRP vs foam vs copper etc.)

Therefore for 100 metres avatar blade, when we assumed the connection is at 10% of the tip, then the weight of this section is only 1% of the total blade mass. In this case, for 48.12 tonnes blade, the replaceable section is only 481.12 kg. In this case, the composition of the segmented blade is assumed the same as the regular Avatar blade.

5.3.2 Modelling for transport and installation and decommissioning

During the installation and decommissioning of an offshore wind farm, much transportation is required. Special vessels and equipment are required as the wind farm is located offshore, and the constructions are large and heavy. This study considers barge to transport components from their manufacturing site to the installation port and jack-up vessel to transport from installation port to wind farm. In SimaPro, this type of vessel can be categorized as "Transport, freight, sea, transoceanic ship" from the global market.

This study considers several ports for installation and O&M activity. **Error! Reference source not found.** listed the port name and usage, location, and distances (rounded up).

Table 3 Ports and its location

No	Use in the model	Distance km	Remarks
1	O&M Port	53	To wind farm
2	Installation / Marshalling port		To wind farm
3	WT Fabrication and installation port (including the blade)	550	To wind farm

To calculate the transportation impact during this phase, tkm (tonnes.km) is used as a calculation unit. A tonne-kilometre, abbreviated as tkm, is a unit of measure of freight transport which represents the transport of one tonne of goods (including packaging and tare weights of intermodal transport units) by a given transport mode (road, rail, air, sea, inland waterways, pipeline etc.) over a distance of one kilometre. The tkm includes vessel usage, fuel consumption, maintenance, port facilities, emissions, and waste and waste treatments. Weight for wind turbine blades are considered; however, the weight of different equipment used for all cases, such as sea fastening, is ignored.

5.3.3 Modelling for operation and maintenance phase

The use phase or the operation and maintenance phase is assumed to be 25 years. The phase comprises two main aspects: the vessel usage or fuel consumption and the replacement of wind turbine blade components. It is assumed that all cases produce the same annual energy production, 48,43 GWh per wind turbine.

For the cases of change of resin and specific materials (balsa wood vs PET), there is no difference in access vessel usage and large replacement. Hence this study ignores the impact of operation maintenance on these cases.

The only difference considered during operation and maintenance is vessel usage and large components replacement between avatar baseline case and segmented blade design. It is assumed instead of replacing the whole blade, we can replace only the leading-edge part. Hence it is expected the fuel usage for transporting these components is reduced as well. However, it is assumed for the inspection and small repair, both cases required the same frequency of maintenance. Hence, there are no significant difference in access vessel usage.

Based on the failure data derived from Reliawind study and summarized in ECN O&M calculator v3.0 inputs, the mean time to failure (MTTF) of wind turbine blade is 130,000 hours or 1.45% failures/turbine/year [32] [33]. The large replacement happens 10% of this time. When it translated to 25 years of 77 wind turbines, the large replacement happens in average 2.6 times with standard deviation of 1.6 times. For this study we took an extreme case, 5 sets wind turbine blades (or 15 single blades) are assumed to be replaced completely in a lifetime. In this case, these 5 sets need to be manufactured and eventually decommissioned hence assigned the EoL scenarios. For the segmented design, five scenarios are made, Table 4

Table 4 Scenarios for segmented blades

Scenarios	No. Sections	No. WT Blades (3 sections of 1 WT)
Same failure rate	15	5
½ per lifetime	117	39
1x per lifetime	231	77
Every 10 years	462	154
Every 5 years	924	308

This part of the study aims to understand if the additional weight in a segmented blade can be compensated by reducing the component weight for O&M major repair and replacement.

5.3.4 Modelling for end-of-life scenarios

The Ecoinvent database defined in the cut-off system model, there are three categories of material classification; ordinary by-product, recyclable material or waste. All the material mentioned above for the manufacturing is based on the ordinary by-product or cut-off classification. For the EoL scenario, the other two classifications are used. Some materials will be treated as recyclable and some materials will be treated as waste. The different between these two classifications are defined as:

- Recyclable: Materials with no or little economic value that can serve as the input or resource for a recycling activity. There is, therefore, an interest in their collection. Examples are scrap metals or wastepaper.
- Waste products: Materials with no economic value and no interest in their collection without compensation. Therefore, the producer must pay to dispose of these materials, so in effect, he consumes the service of disposing of these materials. Examples are wastewater, chemically polluted soil or radioactive waste.

This study assumes that not all the materials can be separated and have EoL scenarios. All the metals, copper, steel and reinforced steel, aluminium, cast iron are recyclable. Therefore, as the model used the cut off allocation, only sorting and process before recycling is considered.

While the other materials such as GFRP (glass and epoxy resin) and CFRP (carbon fibres), various types of plastics, and lubricating oil are considered to have various EoL scenarios as listed in Chapter 3. Several scenarios are developed for the blades and created in the model.

Table 5 up to Table 9 shows the EoL scenarios modelled in SimaPro.

Table 5 LCI EoL Landfill 10 MW Avatar

Short Name	Waste treatment: Landfill
Glass fibres	Waste glass {CH}| treatment of, inert material landfill | Cut-off, U
Resin (epoxy)	Waste plastic, mixture {Europe without Switzerland}| treatment of waste plastic, mixture, sanitary landfill | Cut-off, U
Carbon fibres	Inert waste {Europe without Switzerland}| treatment of inert waste, sanitary landfill | Cut-off, U
PVC	Waste polyvinylchloride {Europe without Switzerland}| treatment of waste polyvinylchloride, sanitary landfill | Cut-off, U
Balsa wood	Waste wood, untreated {Europe without Switzerland}| treatment of waste wood, untreated, sanitary landfill | Cut-off, U
Glue	Waste polyurethane {Europe without Switzerland}| treatment of waste polyurethane, sanitary landfill | Cut-off, U
Paint	Waste paint {Europe without Switzerland}| treatment of waste paint, sanitary landfill | Cut-off, U
Copper	Copper 100% primary (+avoided secondary) (modelled)

Table 6 LCI EoL Incineration 10 MW Avatar

Short Name	Waste treatment: Incineration
Glass fibres	Waste glass {NL}| treatment of waste glass, municipal incineration | Cut-off, U
Resin (epoxy)	Waste plastic, mixture {NL}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U
Carbon fibres	Waste cement-fibre slab, dismantled {NL}| treatment of waste cement-fibre slab, municipal incineration | Cut-off, U
PVC	Waste polyvinylfluoride {NL}| treatment of, municipal incineration | Cut-off, U
Balsa wood	Waste wood, untreated {NL}| treatment of, municipal incineration | Cut-off, U
Glue	Waste polyurethane {NL}| treatment of waste polyurethane, municipal incineration | Cut-off, U
Paint	Waste paint {NL}| treatment of waste paint, municipal incineration | Cut-off, U
Copper	Copper 100% primary (+avoided secondary) (modelled)

Table 7 LCI EoL Mechanical recycling 10 MW Avatar

Glass fibres Resin (epoxy) Carbon fibres PVC Balsa wood Glue Paint	Composite only Mechanical recycling (modelled) Electricity, medium voltage {RER}| market group for | Cut-off, U 5,53 MJ/kg Output: Glass fibre {RER}| production | Cut-off, U 5% Waste glass sheet {Europe without Switzerland}| treatment of waste glass sheet, sorting plant | Cut-off, U
Copper	Copper 100% primary (+avoided secondary) (modelled)

Table 8 LCI EoL Pyrolysis recycling 10 MW Avatar

Short Name	Waste treatment: Pyrolysis
GFRP	Recycling Pyrolyis 700oC GFRP (modelled)
CFRP	Recycling Pyrolyis 700oC CFRP (modelled)
PVC	Waste polyvinylfluoride {NL}| treatment of, municipal incineration | Cut-off, U
Balsa wood	Waste wood, untreated {NL}| treatment of, municipal incineration | Cut-off, U
Glue	Waste polyurethane {NL}| treatment of waste polyurethane, municipal incineration | Cut-off, U
Paint	Waste paint {NL}| treatment of waste paint, municipal incineration | Cut-off, U
Copper	Copper 100% primary (+avoided secondary) (modelled)

GFRP	Recycling Pyrolyis 700oC GFRP (modelled) Input: Nitrogen 0,646kg/kg Electricity, medium voltage {RER}| market group for | Cut-off, U (+19.5, -10.5, +0,27 MJ/kg) Output: Glass fibre {RER}| production | Cut-off, U 52,6% Waste plastic, mixture {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, U 8%
CFRP	Recycling Pyrolyis 700oC GFRP (modelled) Input: Nitrogen 0,646kg/kg Electricity, medium voltage {RER}| market group for | Cut-off, U (+19.5, -10.5, +0,27 MJ/kg) Output: Carbon fibre (modelled), U 52,6% Waste plastic, mixture {CH}| treatment of, municipal incineration with fly ash extraction | Cut-off, U 8%

Table 9 LCI EoL Solvolysis recycling 10 MW Avatar

Short Name	Waste treatment: Pyrolysis
GFRP	Recycling Solvolysis 400oC/250 bar GFRP (modelled)
CFRP	Recycling Solvolysis 400oC/250 bar CFRP (modelled)
PVC	Waste polyvinylfluoride {NL}| treatment of, municipal incineration | Cut-off, U
Balsa wood	Waste wood, untreated {NL}| treatment of, municipal incineration | Cut-off, U
Glue	Waste polyurethane {NL}| treatment of waste polyurethane, municipal incineration | Cut-off, U
Paint	Waste paint {NL}| treatment of waste paint, municipal incineration | Cut-off, U
Copper	Copper 100% primary (+avoided secondary) (modelled)

GFRP	Recycling Solvolysis 400oC/250 bar GFRP (modelled) Input: Water, unspecified natural origin, Europe without Switzerland 10L/kg Electricity, medium voltage {RER}| market group for | Cut-off, U (+24,7, -2, -22,7 MJ/kg) Output: Glass fibre {RER}| production | Cut-off, U 60% Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, U, U 10L/kg
CFRP	Recycling Solvolysis 400oC/250 bar CFRP (modelled) Input: Water, unspecified natural origin, Europe without Switzerland 10L/kg Electricity, medium voltage {RER}| market group for | Cut-off, U (+24,7, -2, -22,7 MJ/kg) Output: Carbon fibre (modelled), U 60% Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, U, U 10L/kg

5.4 Results

5.4.1 Case study baseline case including EoL scenarios

The first LCA comparison is EoL scenarios applied for the baseline model (based on KIP 2019 database). Figure 18 shows additional or reduction in damage assessment for different EoL scenarios. The material and manufacturing score are assumed at 100%. From this graph, we can conclude that incineration, landfill, and mechanical recycling with high power add 10% of human health and ecosystem damage. The recycling routes, both pyrolysis and solvolysis, reduce the damage for all categories. Solvolysis gives lower impacts due to the assumption that the glass fibres can be reused in a higher percentage compared to pyrolysis. One of the reasons why the solvolysis gives lower impacts is due to lower energy required for the recycling process as seen in Figure 7 compared to pyrolysis as seen in Figure 6. Detailed result can be also seen in Appendix Figure 1 and Appendix Table 1.

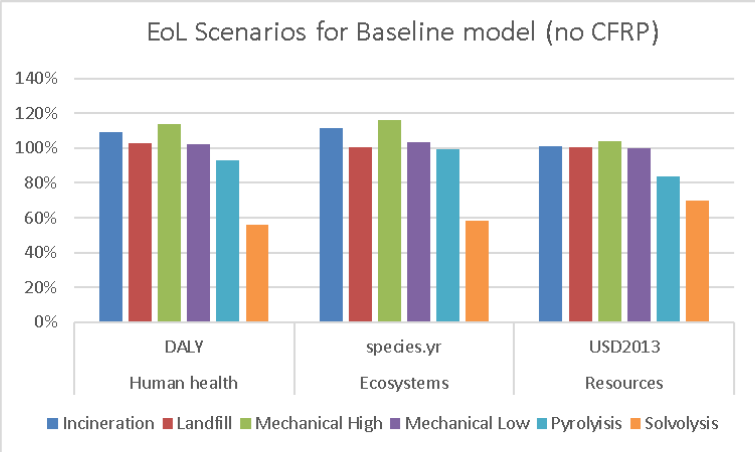


Figure 18 End Point EoL Scenarios for Baseline WTB model (without carbon fibres content)

5.4.2 *Case study balsa wood vs PET foam for Avatar blades*

The second LCA comparison is between the balsa wood and PET foam for the core (webs). Figure 19 and Figure 20 show the mid and endpoint LCA comparison. From these results, balsa wood and PET foam have no significant advantage over the land use impact. In the midpoint assessment, in almost all environmental impact categories, PET foam contributes to more impact than balsa wood. This is not significant as the score shows a higher score of 1,1% on average. The exception is in land use impact, in which PET foam shows a lower score by 21% or 2761,83- eq m2a crop. The same trend is also seen when the comparison is made with the end-point method. There is no significant difference between balsa wood and PET foam in human health, ecosystem, and resource scarcity. The detailed result is presented in Appendix Table 2.

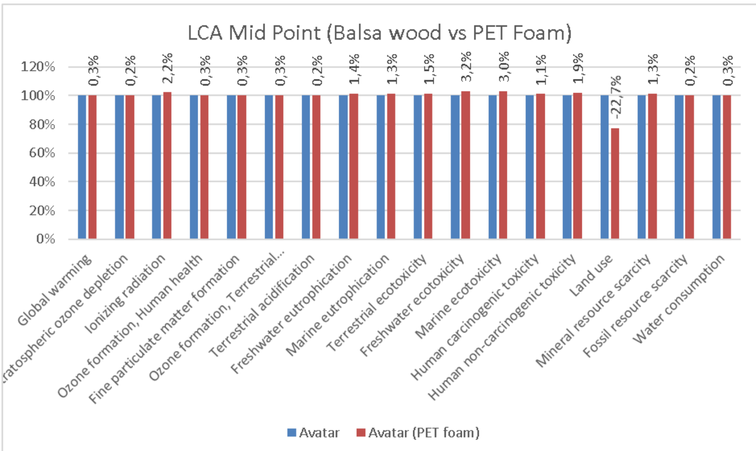


Figure 19 Mid-Point comparing balsa wood vs PET foam in Avatar 10 MW WTB

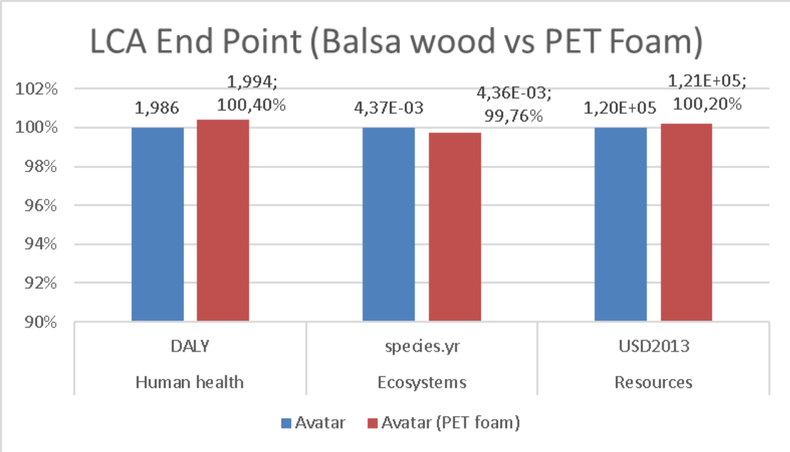


Figure 20 Endpoint comparing balsa wood vs PET foam in Avatar 10 MW WTB

5.4.3 Case study resin change for Avatar blades

Figure 21 shows the comparison between avatar blades when using different types of resin. The resins compared are epoxy, polyester, polyamide, and methyl methacrylate. It is assumed that all resins are used equally in weight except the polyester case which uses epoxy for the CFRP. The result shows that methyl methacrylate could reduce the damage potential around 8%, 5% and 1% in the material and manufacturing phase compared to the baseline epoxy based. The second-best option to reduce the damage from this phase is polyester resin.

Appendix Table 3 and Appendix Figure 2 shows the complete impact categories for the resin comparison. One specific highlighted impact is equivalent CO_2 reduction. There is a 1,56% reduction, 38.31% increase, and a 0.1% reduction when comparing the epoxy-based blades with polyester, polyamide, and methyl methacrylate. From this table, it can be concluded that methyl methacrylate has the lowest impact compared to epoxy except for the impact categories of Marine eutrophication – twice the impact.

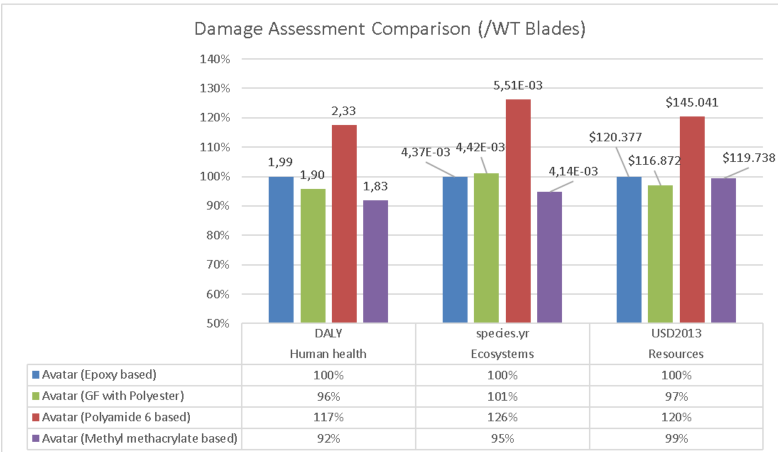


Figure 21 Endpoint comparing different thermoset and thermoplastic resin used as matrix material

5.4.4 *Case study Avatar blade including EoL scenarios*

When comparing different end of life scenarios, pyrolysis and solvolysis lower the CO_2 contribution in 770 MW offshore wind farms. Figure 22 shows that by implementing pyrolysis instead of landfill, the global warming impact can be reduced by 3.85% or equivalent to 0.24-gram CO_2-eq/kWh. A better result is observed when solvolysis is used as blades EoL scenario. The impact is reduced by 7.13%- or 0.44-gram CO_2-eq/kWh. Complete comparison for mid-point analysis is represented in Appendix Table 4. Solvolysis has the lowest impact score compare to landfill. In general, pyrolysis also has lower impacts except for ionizing radiation (10% increase) and freshwater eutrophication (3% increase). However, these scores are still lower compares to the grinding both with high and low energy.

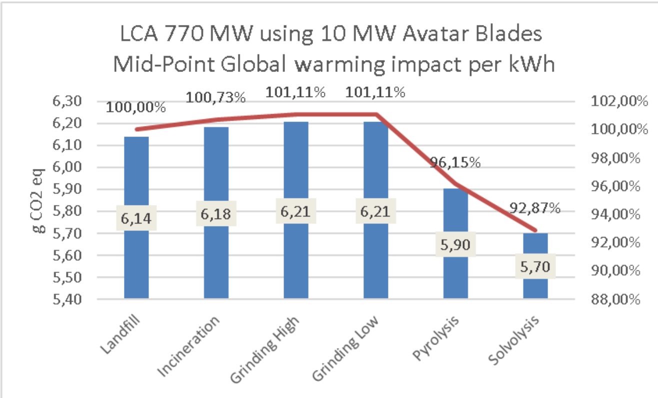
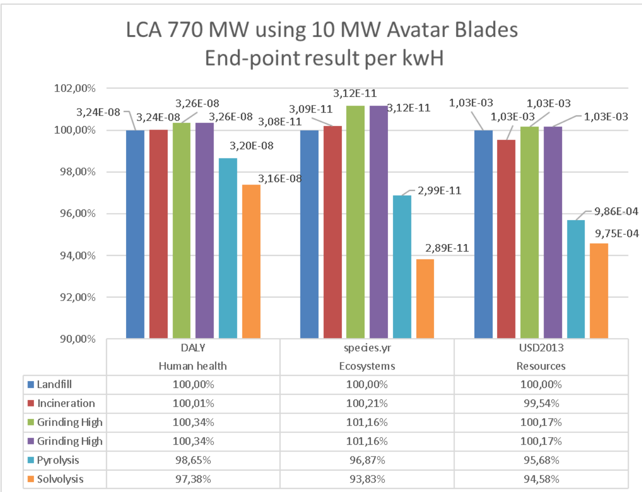


Figure 22 Global warming impact on different EoL scenarios for Avatar 10 MW WTB in 770 MW OWF

Figure 23 shows end-point result or damage assessment comparing different EoL scenarios for the avatar blade. The conclusion is similar to the figure above. Pyrolysis and solvolysis give lower impacts than other solutions, landfill, incineration, and mechanical recycling or grinding. The better score comes from the potential reuse of the glass fibres and carbon fibres in both cases. For both cases, it is worth further research on the possibility of using renewable energy as energy sources to lower the environmental impacts even more.



	DALY Human health	species.yr Ecosystems	USD2013 Resources
Landfill	100,00%	100,00%	100,00%
Incineration	100,01%	100,21%	99,54%
Grinding High	100,34%	101,16%	100,17%
Grinding High	100,34%	101,16%	100,17%
Pyrolysis	98,65%	96,87%	95,68%
Solvolysis	97,38%	93,83%	94,58%

Figure 23 End Point Assessment on different EoL scenarios for Avatar 10 MW WTB in 770 MW OWF

5.4.5 Case study segmented blade design

Material Extraction and Manufacturing

Appendix Table 5 shows the comparison between avatar baseline design with segmented blade approach proposed by this study. Since the weight of the blade increased by 10%, it is expected that all environmental impacts contribution is also increased. The highest increases are observed in human carcinogenic (+53.01%) toxicity due to additional steel in the composition and mineral resource scarcity (+71.1%) due to the additional glass fibres. Furthermore, the segmented blade increases the global warming impacts by 4.62% or 44.24 tonnes CO_2-eq for every 10 MW wind turbine. When looking at the endpoint or damage assessment results, the segmented blade increases the human health damage by 7.6%, ecosystems by 4.89% and resources by 3.56%. Table 10 shows the end-point result comparison during material extraction and manufacturing phase between 10 MW avatar blade with 10 MW avatar with a segmented approach. Two results are shown (1) comparison per wind turbine or 3 pieces of blades (2) per kWh electricity produced from 770 MW offshore wind farm.

When the blades are used in a 770 MW offshore wind farm, the impact increases by 0.48% or 0.37 CO_2-eq/kWh. This is relatively insignificant. When looking at the end-point result, a similar trend is also seen. The segmented blade increases the human health damage by 0.31%, ecosystems by 0.39% and resources by 0.7%. The result is summarized in Table 10.

Table 10 End-point life cycle assessment avatar during material extraction and manufacturing phase (regular vs segmented) – per WT and per kWh

Damage category	Unit	Material Extraction and Manufacturing phase					
		Blades 10 MW Avatar (per WT)			770 MW OWF (per kWh)		
		Baseline	Segmented	Increase	Baseline	Segmented	Increase
Human health	DALY	1,99	2,14	7,60%	4,06E-08	4,077E-08	0,31%
Ecosystems	species.yr	4,37E-03	4,58E-03	4,89%	4,53E-11	4,546E-11	0,39%
Resources	USD2013	1,20E+05	1,25E+05	3,56%	0,000506	0,0005098	0,70%

Transport (Installation and Decommissioning)

A proportional increase is expected during the installation and decommissioning phase of wind turbine blades since the blade weight of segmented approach increase by 10%. However, when seeing the overall picture of a-770 MW offshore wind farm this additional weight only accounts for an increase of 0.62% increase during the installation phase and 0.8% during the decommissioning phase. Both increases sum 14.1 tonnes CO_2-eq for whole wind farm. The mid-point results are detailed in Appendix Table 6. Looking at the end-point result, the trend is the same as shown in Table 11.

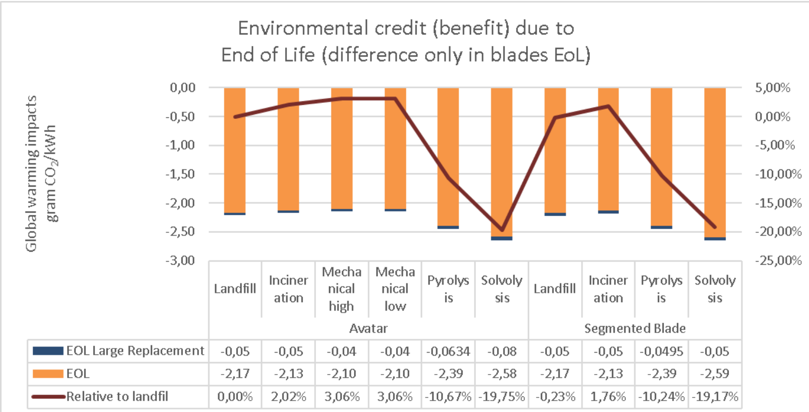
Table 11 End-point life cycle assessment avatar during installation and decommissioning phase (regular vs. segmented) – per 770 MW wind farm

Damage category	Unit	Installation 770 MW OWF			Decommissioning 770 MW OWF		
		Avatar	Segmented	Difference	Avatar	Segmented	Difference
Human health	DALY	4,99	5,02	0,63%	3,90	3,93	0,80%
Ecosystems	species.yr	9,16E-03	9,22E-03	0,63%	7,15E-03	7,21E-03	0,80%
Resources	USD2013	1,42E+05	1,43E+05	0,63%	1,11E+05	1,12E+05	0,80%

End-of-life (EoL)

Based on section 5.4.4 above, the EoL scenarios that give lower impacts are either pyrolysis or solvolysis. In this section, the segmented approach is compared with the regular blade approach regarding their contribution to the EoL impacts. The EoL impacts include the EoL for the large replacement. This section assumes that the failure rates for the wind turbine blades in regular avatar are the same as sections in the segmented approach. It means that 15 wind turbine blades need to be replaced in the lifetime. Therefore, 15 wind turbine blade sections need to be replaced as well.

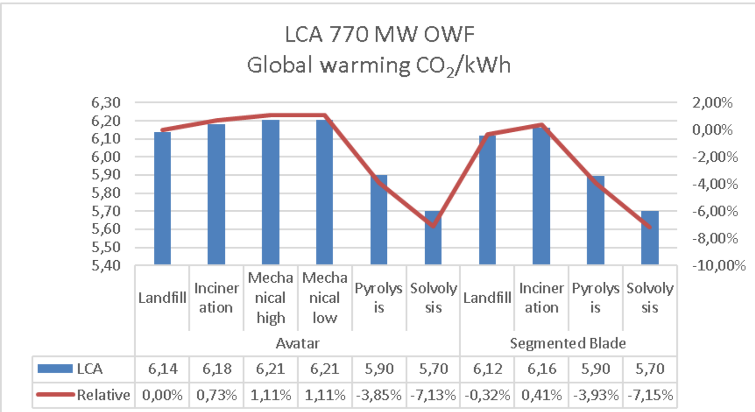
When focusing on only EoL comparison (Figure 24), the trends between different scenarios are the same. Both regular design and segmented approach results show that pyrolysis and solvolysis give significant environmental credit or benefit due to the reusability of the recyclate in the future. For the segmented blade approach, the pyrolysis gives 10,2% and solvolysis gives 19,2% environmental benefit compared to the landfill. The difference between the segmented blade and regular blade results is not significant. For all EoL scenarios, the difference is less than 0.5%. This is mainly caused by additional GFRP and steel that needs to be recycled from the large replacement (segmented blade is less) and from the EoL phase (segmented blade is more).



	Landfill	Incineration	Mechanical high	Mechanical low	Pyrolysis	Solvolysis	Landfill	Incineration	Pyrolysis	Solvolysis
	Avatar						Segmented Blade			
EOL Large Replacement	-0,05	-0,05	-0,04	-0,04	-0,0634	-0,08	-0,05	-0,05	-0,0495	-0,05
EOL	-2,17	-2,13	-2,10	-2,10	-2,39	-2,58	-2,17	-2,13	-2,39	-2,59
Relative to landfil	0,00%	2,02%	3,06%	3,06%	-10,67%	-19,75%	-0,23%	1,76%	-10,24%	-19,17%

Figure 24 Global warming impact on different EoL scenarios for Avatar and Avatar segmented approach 10 MW WTB in 770 MW OWF

When these EoL results are added to the overall LCA results, the same trends are observed. Pyrolysis and solvolysis both are beneficial to reduce the global warming impacts, as seen in Figure 22 above. The segmented blade approach benefits slightly but not as significant as the results caused by different EoL scenarios. Figure 25 and Figure 26 show this conclusion.



	Landfill	Incineration	Mechanical high	Mechanical low	Pyrolysis	Solvolysis	Landfill	Incineration	Pyrolysis	Solvolysis
	Avatar						Segmented Blade			
LCA	6,14	6,18	6,21	6,21	5,90	5,70	6,12	6,16	5,90	5,70
Relative	0,00%	0,73%	1,11%	1,11%	-3,85%	-7,13%	-0,32%	0,41%	-3,93%	-7,15%

Figure 25 Global warming impact on different EoL scenarios for Avatar and Avatar segmented approach 10 MW WTB in 770 MW OWF (II)

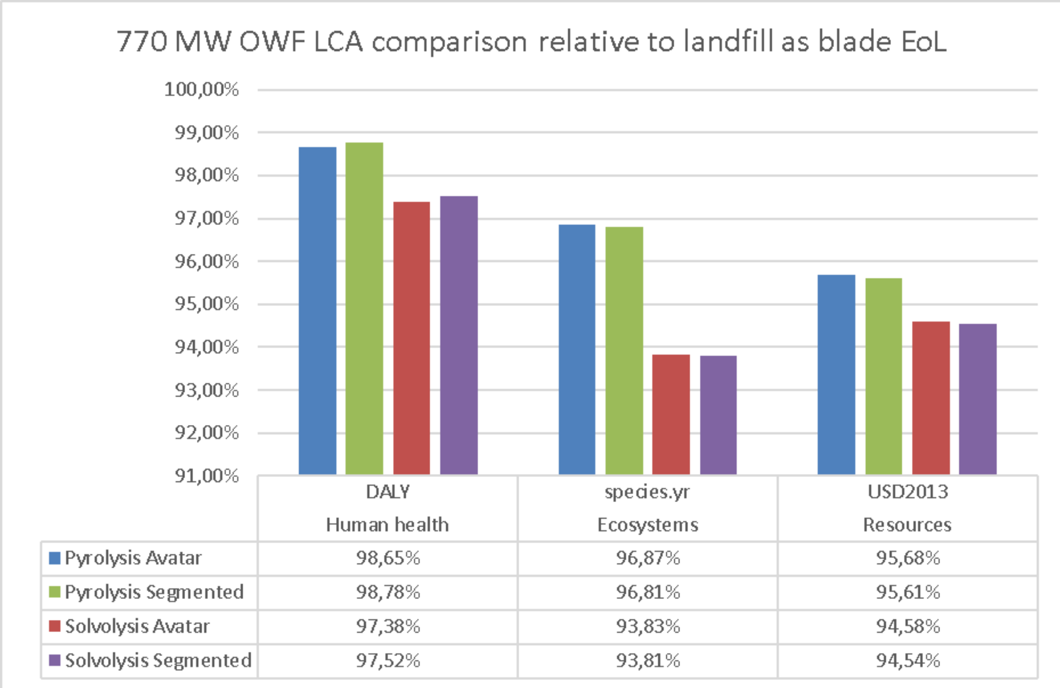


Figure 26 Damage assessment comparison between regular vs segmented approach 10 MW avatar in 770 MW OWF relative to landfill as EoL scenario for WTB

O&M (5 scenarios)

The interesting part of the segmented approach is the large replacement requirement during the O&M phase. When a blade needs to be replaced for the regular avatar blade due to leading-edge erosion damage on the tip, the replacement is done for the total 100-metres blade. With the segmented approach, this is not necessary as we only need to replace the replaceable section, which weighs only 1% of the total mass of the blade.

Three EoL scenarios, incineration, pyrolysis and solvolysis, are compared with the results from segmented approach with a sensitivity of the number of sections that need to be replaced in the lifetime. For the incineration, the segmented approach is very beneficial since it could reduce the global warming impacts even when all wind turbine blade sections need to be replaced every 10 years or in total twice (462 sections in total). The segmented approach gives environmental benefit for the pyrolysis scenario when only half sections are replaced maximum once (117 sections in total). On the other hand, for the solvolysis case, the segmented approach only adds environmental benefit when the failure rate of the sections is the same as the whole blades (15 sections in total are replaced in the lifetime). It can be concluded, as long as the wind turbine blade section has the same failure rates as the wind turbine blade, the segmented approach could give additional environmental benefit during the O&M phase. Table 12 shows these comparisons.

Table 12 O&M sensitivity study between avatar blade vs segmented approach in three EoL scenarios

Impact category	770 MW with Avatar Blade			770 MW with Segmented blade (Incineration as EoL)				
	Landfill	Incineraton		Same failure rate	1/2 per lifetime	1 per lifetime	Every 10 years	Every 5 years
Global warming (CO_2/kWh)	6,14	6,18		6,16	6,17	6,17	6,18	6,20
Relative to Landfill		0,73%		0,41%	0,47%	0,54%	0,68%	0,96%
Relative to Incineration				-0,32%	-0,26%	-0,19%	-0,05%	0,24%
Impact category	770 MW with Avatar Blade			770 MW with Segmented blade (Pyrolysis as EoL)				
	Landfill	Incineraton	Pyrolysis	Same failure rate	1/2 per lifetime	1 per lifetime	Every 10 years	Every 5 years
Global warming (CO_2/kWh)	6,14	6,18	5,90	5,90	5,90	5,90	5,91	5,92
Relative to Landfill		0,73%	-3,85%	-3,93%	-3,88%	-3,83%	-3,74%	-3,54%
Relative to Pyrolysis				-0,08%	-0,03%	0,02%	0,12%	0,33%
Impact category	770 MW with Avatar Blade			770 MW with Segmented blade (Solvolysis as EoL)				
	Landfill	Incineraton	Solvolysis	Same failure rate	1/2 per lifetime	1 per lifetime	Every 10 years	Every 5 years
Global warming (CO_2/kWh)	6,14	6,18	5,70	5,70	5,70	5,70	5,71	5,72
Relative to Landfill		0,73%	-7,13%	-7,15%	-7,12%	-7,09%	-7,02%	-6,89%
Relative to Solvolysis				-0,03%	0,01%	0,04%	0,11%	0,26%

Combination with most environmental impact reduction

Based on the results in this chapter, we made scenarios with the goal is to reduce the environmental impacts by implementing innovations in different life cycle phases. Table 13 shows a description of the scenarios.

Table 13 LCA study to find the best combination to reduce environmental impacts due to WTB in 770 MW OWF

Life cycle phase	Baseline	Scenario 1	Scenario 2
Material & Manufacturing	Epoxy based Avatar 10 MW	Thermoplastic (methyl methacrylate) Segmented approach Avatar 10 MW	
Installation	WTB is transported and installed by JUV	same as baseline (weight increased by 1%)	
O&M (replacement)	15 WT Blades	15 WT sections	
Decomissioning	WTB is decomissioned and transported by JUV	same as baseline (weight increased by 1%)	
EoL	Incineration	Pyrolysis	Solvolysis
EoL Large replacement	15 WT Blades	15 WT sections	

Figure 27 shows the mid-point results or global warming impact in gram CO_2 per kWh. The result shows by using thermoplastic resin, segmented approach, the same large replacement failure rate, then the impact can be reduced by 4.6% or 7.8% for EoL with pyrolysis and solvolysis, respectively. For scenario 1, pyrolysis case, we can reduce global warming impact by 0.28 gram-CO_2-eq /kWh or 26.10 kilotons CO_2-eq in the wind farm lifetime. For scenario 2, solvolysis case, we can reduce the impacts even more or in total 0.48 gram-eq CO_2/kWh or 44.75 kilotons CO_2-eq in the wind farm lifetime. The main contribution is the benefit from EoL then the components large replacement during O&M which compensate weight increase in segmented approach.

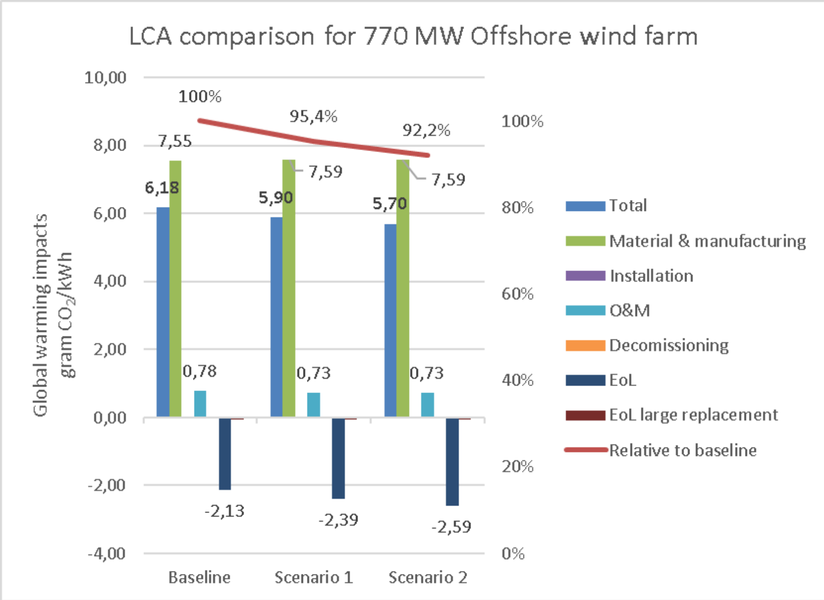


Figure 27 LCA study (mid-point) global warming impact comparison to find the best combination to reduce environmental impacts due to WTB in 770 MW OWF

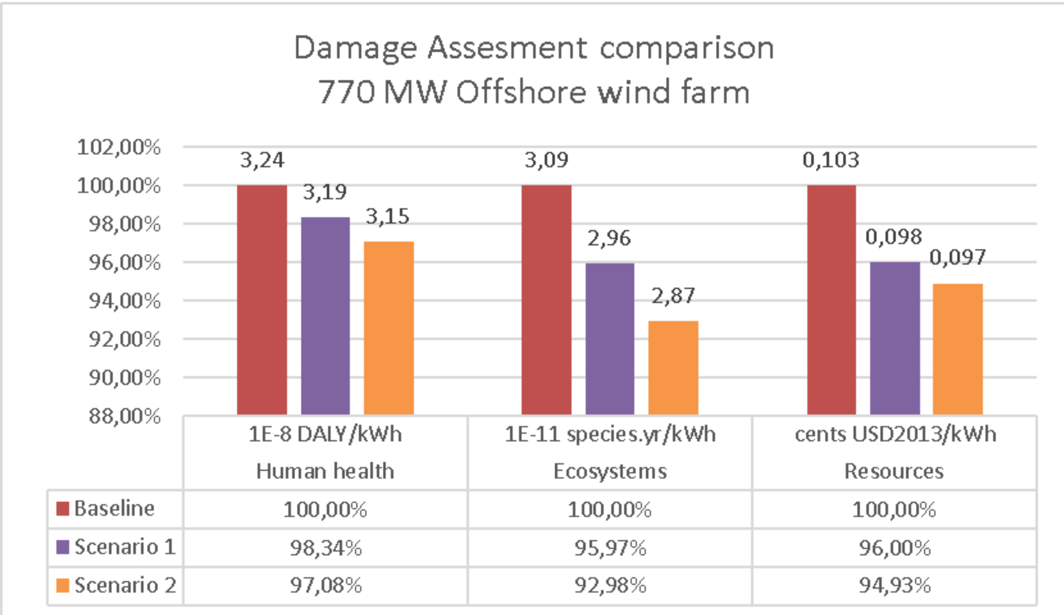


Figure 28 LCA study (endpoint) damage assessment comparison to find the best combination to reduce environmental impacts due to WTB in 770 MW OWF

Figure 28 shows the LCA comparison with the end-point method or damage assessment. The trend is similar, the first scenario could potentially reduce environmental damage in all three categories. Then the scenario two could reduce these potential damages even more as shown as in global warming (mid-point) impact. Therefore, it can be concluded that these two scenarios are worth further investigating, especially on how to implement these innovations economically.

6 Conclusion and Recommendation

This research aims to answer these research questions:

RQ 1) What are the sustainable design criteria for the next generation large wind turbine blades?

RQ 2) What is the effect of design modifications on the LCA and circularity?

RQ 3) What should be the next step for sustainable and fully circular wind turbine development?

The results of this study show:

RQ1: What are the sustainable design criteria for the next generation large wind turbine blades?

- A circular approach should already be kept in mind when designing wind turbine blades. It means materials should already have lower impacts than alternatives, the components can be transported, installed, replaced and dismantled easily when damaged or at their end of life, be less prone to damage (leading to less repair and replacement), and can be reused and recycled, preferably in the same type of product;
- Manufacturing of blades in parts (segmentation) has advantages, where modularity is a particular class of segmentation:
- Segmentation or splitting of blades would allow cheaper and more sustainable transportation and it will lead to reduced maintenance costs.
- Modularity of the blade allows tailoring the blade to different requirements by combining optimal modules for longevity and recyclability.

RQ2: What is the effect of design modifications on the LCA and circularity?

- Different core materials were investigated in a blade LCA study: The difference between PET foam or balsa wood on the environmental impacts is not significant. In almost all environmental impact categories, PET foam contributes to more impact than balsa wood (on average by 1.1%) except for the impact of land use.
- Different resin types are investigated: epoxy and polyester as thermoset resin, polyamide and methyl methacrylate as thermoplastic resin. The resin which gives the lowest impact is thermoplastic-based methyl methacrylate. There is a 1,56% reduction, 38.31% increase, and a 0.1% reduction when comparing the epoxy-based blades with polyester, polyamide, and methyl methacrylate for 10 MW wind turbine blades.
- End of life scenarios that give more environmental benefit hence reducing environmental impacts are pyrolysis and solvolysis. The reduction comes mostly from the potential reusability of the glass and carbon fibres. For a 770 MW offshore wind farm, pyrolysis and solvolysis can reduce the overall global warming impacts by 3.85% and 7.13%, respectively, compared to the landfill case.
- A changeable tip section is explored. The last 10%-length of the blade accounts to only 1%-weight of the whole blade. This part is designed to be replaceable when severe damage occurs. To manufacture this segmented blade, the total weight of the blade increases by 10%, which comes from connection materials. Segmentation of a blade can reduce the environmental impacts when the lifetime of the wind turbine blade sections is the same as that for the whole blade and recycling routes such as pyrolysis and solvolysis are used.
- The most optimised solution will be using thermoplastic (methyl methacrylate), recycling with high content of fibre reused (pyrolysis or solvolysis), segmented blade with the same lifetime expectation as the unsegmented blade. This combination can reduce global warming impacts compared to the current practice or incineration by :

- 4.6% or 0.28 gram- CO_2-eq/kWh or 26.10 kilotons CO_2-eq in the wind farm lifetime or for pyrolysis
- and 7.8% or 0.48 gram-eq CO_2/kWh or 44.75 kilotons CO_2-eq in the wind farm lifetime for solvolysis

RQ3: What should be the next step for the sustainable and fully circular wind turbine development?

- Further research to develop the End-of-Life (EoL) solution for the recycling of glass and carbon fibres from composite material wind turbine blades. The focus should be reclaiming the fibres from the recyclate, sustainable business case, and upscale ability based on the volume available.
- Further research to tailor-made reclaims fibres, glass and carbon, based on fibre size and quality for product applications
- Further research on the implementation of thermoplastic materials for wind turbine blades, including their manufacturing, O&M, EoL scenarios
- Further research to increase the circularity and sustainability of offshore wind farms. The circular economy approach needs to be adopted in every life cycle phase of the wind farm, including the project development and design. The project also needs to reduce the environmental impacts (including global warming or CO_2-eq) of the offshore wind farm.

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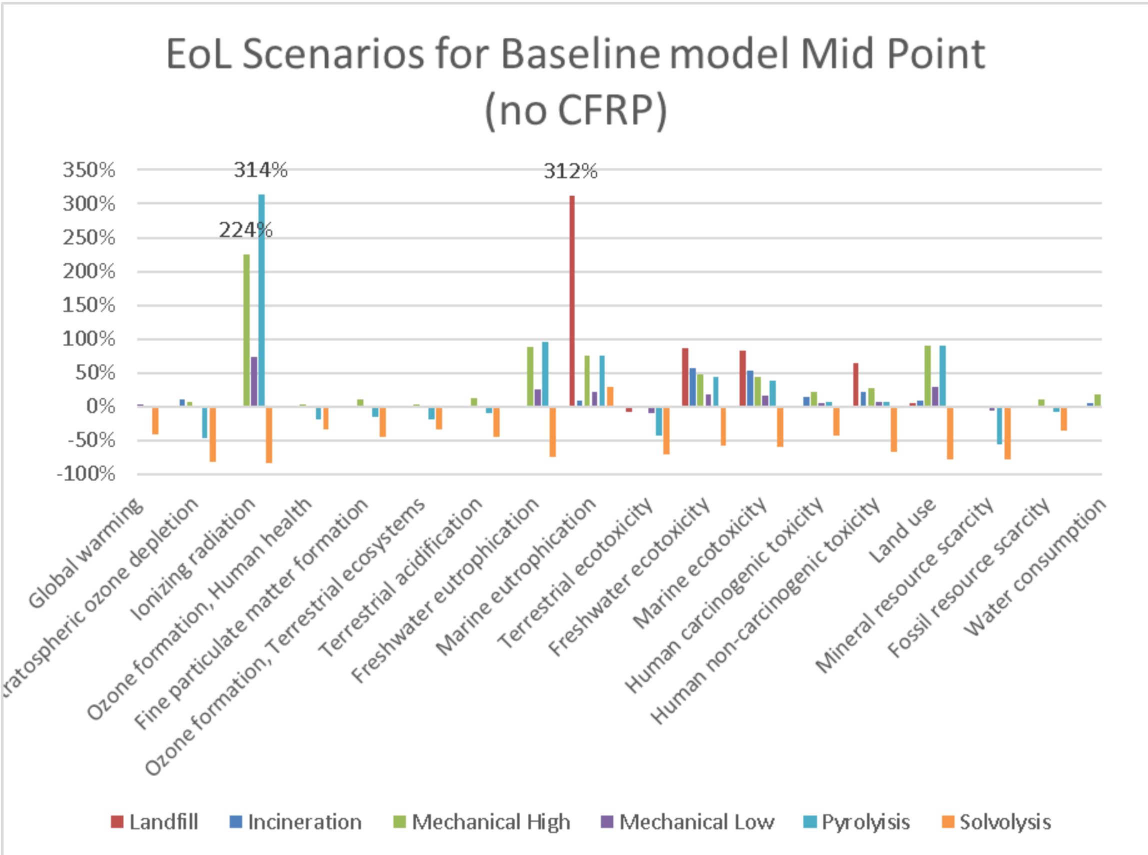
8 Appendix

8.1 Detail result for WTB LCA

8.1.1 Case study baseline case including EoL scenarios (per WT or 3 blades)

Appendix Table 1 Midpoint comparison result between EoL scenarios for 10 MW WTB baseline design

Impact category	Unit	Blades 10 MW Baseline 2019	Incineration	Landfill	Mechanical High	Mechanical Low	Pyrolyisis	Solvolysis
Global warming	kg CO2 eq	5,51E+05	9,95E+04	5,17E+03	8,23E+04	1,67E+04	-5,83E+03	-2,30E+05
Stratospheric ozone depletion	kg CFC11 eq	3,71E-01	4,10E-02	5,23E-04	2,31E-02	-8,42E-03	-1,75E-01	-3,03E-01
Ionizing radiation	kBq Co-60 eq	2,15E+04	1,40E+02	4,23E+01	4,83E+04	1,60E+04	6,75E+04	-1,79E+04
Ozone formation, Human health	kg NOx eq	2,36E+03	3,55E+01	6,51E+00	9,30E+01	-9,97E+00	-4,43E+02	-8,13E+02
Fine particulate matter formation	kg PM2.5 eq	1,08E+03	6,41E+00	-9,81E-01	1,16E+02	1,34E+01	-1,57E+02	-4,81E+02
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,40E+03	3,59E+01	6,65E+00	9,32E+01	-1,05E+01	-4,51E+02	-8,24E+02
Terrestrial acidification	kg SO2 eq	2,58E+03	1,28E+01	-4,97E+00	3,46E+02	5,50E+01	-2,52E+02	-1,14E+03
Freshwater eutrophication	kg P eq	9,72E+01	-1,50E+00	-2,23E+00	8,66E+01	2,50E+01	9,32E+01	-7,25E+01
Marine eutrophication	kg N eq	8,07E+00	6,72E-01	2,52E+01	6,04E+00	1,71E+00	6,12E+00	2,38E+00
Terrestrial ecotoxicity	kg 1,4-DCB	7,29E+05	7,38E+03	-5,95E+04	-1,01E+04	-6,64E+04	-3,07E+05	-5,20E+05
Freshwater ecotoxicity	kg 1,4-DCB	7,45E+03	4,23E+03	6,49E+03	3,56E+03	1,30E+03	3,24E+03	-4,36E+03
Marine ecotoxicity	kg 1,4-DCB	1,05E+04	5,53E+03	8,60E+03	4,70E+03	1,64E+03	3,99E+03	-6,31E+03
Human carcinogenic toxicity	kg 1,4-DCB	2,11E+04	3,16E+03	1,80E+01	4,64E+03	1,11E+03	1,38E+03	-8,92E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	2,32E+05	4,85E+04	1,48E+05	6,54E+04	1,43E+04	1,48E+04	-1,55E+05
Land use	m2a crop eq	3,74E+03	3,31E+02	2,01E+02	3,39E+03	1,09E+03	3,37E+03	-2,90E+03
Mineral resource scarcity	kg Cu eq	1,21E+03	-9,17E+00	-3,02E+01	-1,05E+01	-7,43E+01	-6,86E+02	-9,53E+02
Fossil resource scarcity	kg oil eq	1,80E+05	1,56E+03	5,65E+02	2,01E+04	3,75E+03	-1,33E+04	-6,31E+04
Water consumption	m3	8,53E+03	4,80E+02	2,73E+01	1,46E+03	4,23E+02	1,19E+03	-1,58E+03



Appendix Figure 1 Midpoint comparison result EoL between scenarios for 10 MW WTB baseline design

8.1.2 *Case study balsa wood vs PET foam for Avatar blades (per WT or 3 blades)*

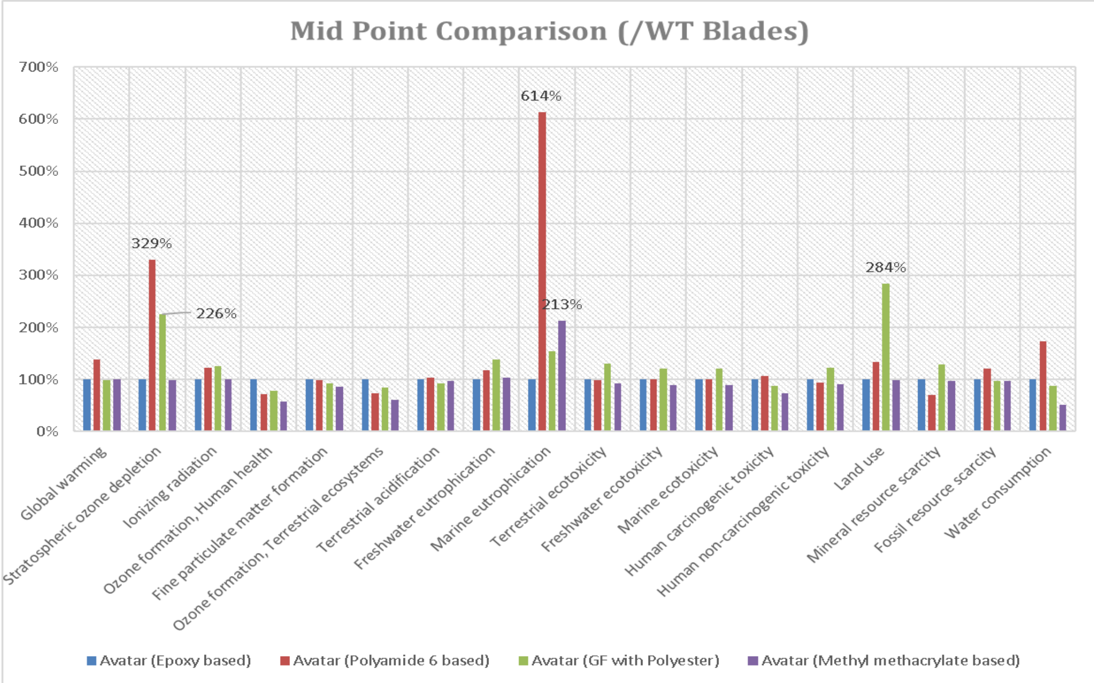
Appendix Table 2 Midpoint comparison result between balsa wood and PET foam for 10 MW Avatar blade

Impact category	Unit	Avatar (Balsa Wood)	Avatar (PET Foam)	Difference (per piece) Relative to the Balsa wood case	% Comparison
Global warming	kg CO2 eq	9,58E+05	9,62E+05	3,30E+03	0,34%
Stratospheric ozone depletion	kg CFC11 eq	7,24E-01	7,25E-01	1,42E-03	0,20%
Ionizing radiation	kBq Co-60 eq	2,80E+04	2,86E+04	6,08E+02	2,17%
Ozone formation, Human health	kg NOx eq	2,22E+03	2,23E+03	6,93E+00	0,31%
Fine particulate matter formation	kg PM2.5 eq	1,47E+03	1,48E+03	4,03E+00	0,27%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,28E+03	2,29E+03	7,06E+00	0,31%
Terrestrial acidification	kg SO2 eq	4,92E+03	4,93E+03	9,95E+00	0,20%
Freshwater eutrophication	kg P eq	1,03E+02	1,04E+02	1,48E+00	1,43%
Marine eutrophication	kg N eq	2,61E+01	2,64E+01	3,38E-01	1,30%
Terrestrial ecotoxicity	kg 1,4-DCB	1,14E+06	1,16E+06	1,72E+04	1,50%
Freshwater ecotoxicity	kg 1,4-DCB	1,03E+04	1,06E+04	3,27E+02	3,18%
Marine ecotoxicity	kg 1,4-DCB	1,48E+04	1,52E+04	4,39E+02	2,96%
Human carcinogenic toxicity	kg 1,4-DCB	2,07E+04	2,09E+04	2,29E+02	1,11%
Human non-carcinogenic toxicity	kg 1,4-DCB	3,32E+05	3,39E+05	6,28E+03	1,89%
Land use	m2a crop eq	1,22E+04	9,40E+03	-2,76E+03	-22,71%
Mineral resource scarcity	kg Cu eq	1,03E+03	1,04E+03	1,31E+01	1,27%
Fossil resource scarcity	kg oil eq	3,35E+05	3,36E+05	8,05E+02	0,24%
Water consumption	m3	1,09E+04	1,09E+04	2,84E+01	0,26%

8.1.3 *Case study resin change for Avatar blades (per WT or 3 blades)*

Appendix Table 3 Midpoint comparison result between different resin in 10 MW Avatar blade

Impact category	Unit	Blades 10 MW Avatar Epoxy		Blades 10 MW Avatar Polyester		Blades 10 MW Avatar Polyamide 6		Blades 10 MW Avatar Methyl Methacrylate	
		Score	Relative	Score	Relative	Score	Relative	Score	Relative
Global warming	kg CO2 eq	9,58E+05	100,00%	9,43E+05	98,44%	1,33E+06	138,31%	9,59E+05	100,10%
Stratospheric ozone depletion	kg CFC11 eq	7,24E-01	100,00%	1,63E+00	225,58%	2,38E+00	329,47%	7,18E-01	99,28%
Ionizing radiation	kBq Co-60 eq	2,80E+04	100,00%	3,53E+04	126,14%	3,42E+04	122,25%	2,79E+04	99,67%
Ozone formation, Human health	kg NOx eq	2,22E+03	100,00%	1,74E+03	78,45%	1,59E+03	71,85%	1,28E+03	57,78%
Fine particulate matter formation	kg PM2.5 eq	1,47E+03	100,00%	1,35E+03	91,99%	1,45E+03	98,73%	1,28E+03	86,63%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,28E+03	100,00%	1,92E+03	84,06%	1,67E+03	73,00%	1,37E+03	60,13%
Terrestrial acidification	kg SO2 eq	4,92E+03	100,00%	4,57E+03	93,02%	5,12E+03	104,06%	4,75E+03	96,54%
Freshwater eutrophication	kg P eq	1,03E+02	100,00%	1,42E+02	137,95%	1,21E+02	117,87%	1,06E+02	103,18%
Marine eutrophication	kg N eq	2,61E+01	100,00%	4,01E+01	153,75%	1,60E+02	613,57%	5,54E+01	212,51%
Terrestrial ecotoxicity	kg 1,4-DCB	1,14E+06	100,00%	1,48E+06	129,61%	1,12E+06	98,20%	1,06E+06	92,90%
Freshwater ecotoxicity	kg 1,4-DCB	1,03E+04	100,00%	1,25E+04	121,54%	1,03E+04	100,22%	9,10E+03	88,44%
Marine ecotoxicity	kg 1,4-DCB	1,48E+04	100,00%	1,80E+04	121,32%	1,48E+04	100,11%	1,32E+04	89,10%
Human carcinogenic toxicity	kg 1,4-DCB	2,07E+04	100,00%	1,81E+04	87,53%	2,22E+04	107,24%	1,50E+04	72,77%
Human non-carcinogenic toxicity	kg 1,4-DCB	3,32E+05	100,00%	4,05E+05	121,75%	3,14E+05	94,32%	3,03E+05	91,03%
Land use	m2a crop eq	1,22E+04	100,00%	3,45E+04	283,69%	1,62E+04	133,50%	1,19E+04	98,25%
Mineral resource scarcity	kg Cu eq	1,03E+03	100,00%	1,31E+03	128,09%	7,25E+02	70,68%	9,87E+02	96,28%
Fossil resource scarcity	kg oil eq	3,35E+05	100,00%	3,28E+05	97,80%	4,07E+05	121,36%	3,27E+05	97,65%
Water consumption	m3	1,09E+04	100,00%	9,46E+03	87,03%	1,87E+04	172,37%	5,60E+03	51,48%



Appendix Figure 2 Midpoint result comparison between different resin in 10 MW Avatar blade

8.1.4 Case study Avatar blade including EoL scenarios (per kWh)

Appendix Table 4 Midpoint comparison result between WTB EoL scenarios in 770 MW OWF

Impact category	Unit	Landfill		Incineration		Grinding High		Grinding Low		Pyrolysis		Solvolysis	
		Score	Relative	Score	Relative	Score	Relative	Score	Relative	Score	Relative	Score	Relative
Global warming	kg CO2 eq	6,14E-03	100%	6,18E-03	101%	6,21E-03	101%	6,21E-03	101%	5,90E-03	96%	5,70E-03	93%
Stratospheric ozone depletion	kg CFC11 eq	3,29E-09	100%	3,33E-09	101%	3,31E-09	101%	3,31E-09	101%	2,92E-09	89%	2,78E-09	85%
Ionizing radiation	kBq Co-60 eq	3,56E-04	100%	3,49E-04	98%	3,98E-04	112%	3,98E-04	112%	3,92E-04	110%	3,27E-04	92%
Ozone formation, Human health	kg NOx eq	1,60E-05	100%	1,60E-05	100%	1,61E-05	101%	1,61E-05	101%	1,59E-05	99%	1,56E-05	98%
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	100%	1,23E-05	100%	1,25E-05	101%	1,25E-05	101%	1,20E-05	97%	1,18E-05	95%
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	100%	1,67E-05	100%	1,68E-05	100%	1,68E-05	100%	1,65E-05	99%	1,63E-05	98%
Terrestrial acidification	kg SO2 eq	2,90E-05	100%	2,89E-05	100%	2,93E-05	101%	2,93E-05	101%	2,73E-05	94%	2,65E-05	91%
Freshwater eutrophication	kg P eq	2,35E-06	100%	2,32E-06	99%	2,42E-06	103%	2,42E-06	103%	2,41E-06	103%	2,29E-06	98%
Marine eutrophication	kg N eq	2,24E-07	100%	1,82E-07	81%	1,88E-07	84%	1,88E-07	84%	1,79E-07	80%	1,75E-07	78%
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	100%	5,21E-02	100%	5,21E-02	100%	5,21E-02	100%	5,20E-02	100%	5,18E-02	100%
Freshwater ecotoxicity	kg 1,4-DCB	1,32E-03	100%	1,31E-03	100%	1,31E-03	100%	1,31E-03	100%	1,31E-03	100%	1,31E-03	99%
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	100%	1,68E-03	100%	1,68E-03	100%	1,68E-03	100%	1,68E-03	100%	1,67E-03	99%
Human carcinogenic toxicity	kg 1,4-DCB	4,79E-03	100%	4,80E-03	100%	4,80E-03	100%	4,80E-03	100%	4,80E-03	100%	4,79E-03	100%
Human non-carcinogenic toxicity	kg 1,4-DCB	1,28E-02	100%	1,26E-02	99%	1,26E-02	99%	1,26E-02	99%	1,26E-02	99%	1,25E-02	98%
Land use	m2a crop eq	1,33E-04	100%	1,31E-04	99%	1,35E-04	102%	1,35E-04	102%	1,34E-04	101%	1,30E-04	98%
Mineral resource scarcity	kg Cu eq	2,80E-05	100%	2,80E-05	100%	2,81E-05	100%	2,81E-05	100%	2,78E-05	99%	2,76E-05	98%
Fossil resource scarcity	kg oil eq	2,89E-03	100%	2,87E-03	99%	2,91E-03	101%	2,91E-03	101%	2,78E-03	96%	2,73E-03	95%
Water consumption	m3	6,72E-05	100%	6,67E-05	99%	6,84E-05	102%	6,84E-05	102%	6,78E-05	101%	6,57E-05	98%

8.1.5 Case study Segmented design

Material Extraction and Manufacturing

Appendix Table 5 Midpoint comparison result between 10 MW Avatar blade and 10 MW Avatar with segmented approach, also comparison result in in 770 MW OWF

Impact category	Unit	Blades 10 MW Avatar		Blades 10 MW Avatar Segmented Blade		770 MW OWF using Avatar Blade	770 MW OWF using Avatar Segmented Blade	
		per WT (3 blades)				per kWh		
		Score	Relative	Score	Relative	Score	Score	Increase
Global warming	kg CO2 eq	9,58E+05	100%	1,00E+06	104,62%	7,55E-03	7,59E-03	0,48%
Stratospheric ozone depletion	kg CFC11 eq	7,24E-01	100%	7,43E-01	102,72%	3,00E-09	3,01E-09	0,54%
Ionizing radiation	kBq Co-60 eq	2,80E+04	100%	2,94E+04	104,94%	3,24E-04	3,25E-04	0,35%
Ozone formation, Human health	kg NOx eq	2,22E+03	100%	2,39E+03	107,87%	2,02E-05	2,04E-05	0,71%
Fine particulate matter formation	kg PM2.5 eq	1,47E+03	100%	1,57E+03	106,30%	2,13E-05	2,14E-05	0,36%
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,28E+03	100%	2,46E+03	107,83%	2,13E-05	2,14E-05	0,69%
Terrestrial acidification	kg SO2 eq	4,92E+03	100%	5,11E+03	103,93%	4,68E-05	4,70E-05	0,34%
Freshwater eutrophication	kg P eq	1,03E+02	100%	1,19E+02	115,81%	9,06E-06	9,08E-06	0,15%
Marine eutrophication	kg N eq	2,61E+01	100%	2,68E+01	102,81%	4,84E-07	4,84E-07	0,13%
Terrestrial ecotoxicity	kg 1,4-DCB	1,14E+06	100%	1,26E+06	110,36%	1,51E-01	1,51E-01	0,06%
Freshwater ecotoxicity	kg 1,4-DCB	1,03E+04	100%	1,23E+04	119,40%	1,31E-03	1,31E-03	0,13%
Marine ecotoxicity	kg 1,4-DCB	1,48E+04	100%	1,76E+04	119,05%	1,89E-03	1,89E-03	0,12%
Human carcinogenic toxicity	kg 1,4-DCB	2,07E+04	100%	3,16E+04	153,01%	2,90E-03	2,91E-03	0,31%
Human non-carcinogenic toxicity	kg 1,4-DCB	3,32E+05	100%	3,93E+05	118,09%	4,57E-02	4,58E-02	0,11%
Land use	m2a crop eq	1,22E+04	100%	1,26E+04	103,42%	1,78E-04	1,78E-04	0,19%
Mineral resource scarcity	kg Cu eq	1,03E+03	100%	1,75E+03	171,10%	3,15E-04	3,15E-04	0,19%
Fossil resource scarcity	kg oil eq	3,35E+05	100%	3,49E+05	104,02%	1,88E-03	1,89E-03	0,59%
Water consumption	m3	1,09E+04	100%	1,15E+04	105,41%	7,24E-05	7,29E-05	0,67%

Transport (Installation and Decommissioning)

Appendix Table 6 Midpoint comparison result between 10 MW Avatar blade and 10 MW Avatar with segmented approach during installation and decommissioning phase of 770 MW OWF

Impact category	Unit	Installation 770 MW OWF			Decommissioning 770 MW OWF		
		Avatar	Segmented	Difference	Avatar	Segmented	Difference
Global warming	kg CO2 eq	1,12E+06	1,13E+06	0,62%	8,76E+05	8,83E+05	0,80%
Stratospheric ozone depletion	kg CFC11 eq	5,16E-01	5,19E-01	0,62%	4,03E-01	4,06E-01	0,80%
Ionizing radiation	kBq Co-60 eq	4,35E+04	4,38E+04	0,62%	3,40E+04	3,43E+04	0,80%
Ozone formation, Human health	kg NOx eq	1,43E+04	1,43E+04	0,62%	1,11E+04	1,12E+04	0,80%
Fine particulate matter formation	kg PM2.5 eq	6,06E+03	6,10E+03	0,62%	4,74E+03	4,77E+03	0,80%
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,44E+04	1,45E+04	0,62%	1,12E+04	1,13E+04	0,80%
Terrestrial acidification	kg SO2 eq	1,85E+04	1,87E+04	0,62%	1,45E+04	1,46E+04	0,80%
Freshwater eutrophication	kg P eq	1,44E+02	1,44E+02	0,62%	1,12E+02	1,13E+02	0,80%
Marine eutrophication	kg N eq	9,90E+00	9,96E+00	0,62%	7,73E+00	7,80E+00	0,80%
Terrestrial ecotoxicity	kg 1,4-DCB	2,07E+06	2,08E+06	0,62%	1,62E+06	1,63E+06	0,80%
Freshwater ecotoxicity	kg 1,4-DCB	7,14E+03	7,18E+03	0,62%	5,58E+03	5,62E+03	0,80%
Marine ecotoxicity	kg 1,4-DCB	1,11E+04	1,12E+04	0,62%	8,70E+03	8,77E+03	0,80%
Human carcinogenic toxicity	kg 1,4-DCB	2,26E+04	2,28E+04	0,62%	1,77E+04	1,78E+04	0,80%
Human non-carcinogenic toxicity	kg 1,4-DCB	1,84E+05	1,86E+05	0,62%	1,44E+05	1,45E+05	0,80%
Land use	m2a crop eq	7,28E+03	7,33E+03	0,62%	5,69E+03	5,73E+03	0,80%
Mineral resource scarcity	kg Cu eq	1,36E+03	1,37E+03	0,62%	1,06E+03	1,07E+03	0,80%
Fossil resource scarcity	kg oil eq	3,51E+05	3,54E+05	0,62%	2,75E+05	2,77E+05	0,80%
Water consumption	m3	3,16E+03	3,18E+03	0,62%	2,47E+03	2,49E+03	0,80%

End-of-life

Appendix Table 7 Midpoint comparison result between different EoL scenarios for segmented blade approach in 770 MW OWF (focus on end of life and end of life for large replacement)

Impact category	Unit /kWh	Material Extraction	Installation	O&M	Decommissioning	Landfill		Incineration		Pyrolysis		Solvolysis	
						EoL	EoL LR	EoL	EoL LR	EoL	EoL LR	EoL	EoL LR
Global warming	kg CO2 eq	7,59E-03	1,21E-05	7,31E-04	9,47E-06	-2,17E-03	-4,94E-05	-2,13E-03	-4,94E-05	-2,39E-03	-4,95E-05	-2,59E-03	-4,97E-05
Stratospheric ozone depletion	kg CFC11 eq	3,01E-09	5,57E-12	1,05E-09	4,36E-12	-7,98E-10	-8,71E-12	-7,64E-10	-8,69E-12	-1,16E-09	-8,94E-12	-1,29E-09	-9,03E-12
Ionizing radiation	kBq Co-60 eq	3,25E-04	4,70E-07	5,88E-05	3,68E-07	-2,76E-05	-9,84E-07	-3,48E-05	-9,88E-07	8,18E-06	-9,60E-07	-5,69E-05	-1,00E-06
Ozone formation, Human health	kg NOx eq	2,04E-05	1,54E-07	2,56E-06	1,20E-07	-7,07E-06	-1,33E-07	-7,09E-06	-1,33E-07	-7,21E-06	-1,33E-07	-7,46E-06	-1,33E-07
Fine particulate matter formation	kg PM2.5 eq	2,14E-05	6,55E-08	1,99E-06	5,12E-08	-1,10E-05	-1,47E-07	-1,10E-05	-1,47E-07	-1,13E-05	-1,47E-07	-1,16E-05	-1,47E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	2,14E-05	1,55E-07	2,77E-06	1,21E-07	-7,63E-06	-1,46E-07	-7,65E-06	-1,46E-07	-7,79E-06	-1,46E-07	-8,04E-06	-1,46E-07
Terrestrial acidification	kg SO2 eq	4,70E-05	2,00E-07	5,47E-06	1,57E-07	-2,37E-05	-2,12E-07	-2,38E-05	-2,12E-07	-2,53E-05	-2,13E-07	-2,61E-05	-2,13E-07
Freshwater eutrophication	kg P eq	9,08E-06	1,55E-09	1,65E-07	1,21E-09	-6,82E-06	-7,79E-08	-6,84E-06	-7,79E-08	-6,75E-06	-7,78E-08	-6,87E-06	-7,79E-08
Marine eutrophication	kg N eq	4,84E-07	1,07E-10	1,22E-08	8,36E-11	-2,73E-07	-1,93E-09	-3,13E-07	-1,96E-09	-3,16E-07	-1,96E-09	-3,20E-07	-1,96E-09
Terrestrial ecotoxicity	kg 1,4-DCB	1,51E-01	2,23E-05	1,32E-03	1,75E-05	-1,00E-01	-1,29E-04	-1,00E-01	-1,29E-04	-1,01E-01	-1,29E-04	-1,01E-01	-1,29E-04
Freshwater ecotoxicity	kg 1,4-DCB	1,31E-03	7,71E-08	1,46E-05	6,03E-08	-1,15E-05	-1,65E-07	-1,53E-05	-1,68E-07	-1,59E-05	-1,68E-07	-2,14E-05	-1,72E-07
Marine ecotoxicity	kg 1,4-DCB	1,89E-03	1,20E-07	2,25E-05	9,41E-08	-2,27E-04	-1,89E-06	-2,33E-04	-1,89E-06	-2,34E-04	-1,89E-06	-2,41E-04	-1,90E-06
Human carcinogenic toxicity	kg 1,4-DCB	2,91E-03	2,44E-07	7,30E-05	1,91E-07	1,77E-03	4,59E-05	1,78E-03	4,59E-05	1,78E-03	4,59E-05	1,77E-03	4,59E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	4,58E-02	1,99E-06	4,28E-04	1,56E-06	-3,31E-02	-3,27E-04	-3,32E-02	-3,27E-04	-3,33E-02	-3,27E-04	-3,34E-02	-3,27E-04
Land use	m2a crop eq	1,78E-04	7,86E-08	9,78E-06	6,15E-08	-5,51E-05	-9,75E-07	-5,69E-05	-9,76E-07	-5,35E-05	-9,74E-07	-5,82E-05	-9,77E-07
Mineral resource scarcity	kg Cu eq	3,15E-04	1,47E-08	5,96E-06	1,15E-08	-2,87E-04	-5,76E-06	-2,87E-04	-5,76E-06	-2,88E-04	-5,76E-06	-2,88E-04	-5,76E-06
Fossil resource scarcity	kg oil eq	1,89E-03	3,79E-06	1,42E-03	2,97E-06	-4,23E-04	-1,01E-05	-4,44E-04	-1,01E-05	-5,25E-04	-1,02E-05	-5,74E-04	-1,02E-05
Water consumption	m3	7,29E-05	3,41E-08	8,32E-06	2,67E-08	-1,38E-05	-3,28E-07	-1,44E-05	-3,28E-07	-1,32E-05	-3,27E-07	-1,53E-05	-3,29E-07

Appendix Table 8 Midpoint comparison result between different EoL scenarios for segmented blade approach in 770 MW OWF

Impact category	Unit/kWh	Landfill	Incineration	Pyrolysis	Solvolysis	Incineration	Pyrolysis	Solvolysis
Global warming	kg CO2 eq	6,12E-03	6,16E-03	5,90E-03	5,70E-03	100,7%	96,4%	93,1%
Stratospheric ozone depletion	kg CFC11 eq	3,27E-09	3,30E-09	2,91E-09	2,78E-09	101,0%	89,0%	85,0%
Ionizing radiation	kBq Co-60 eq	3,56E-04	3,49E-04	3,92E-04	3,27E-04	98,0%	110,1%	91,8%
Ozone formation, Human health	kg NOx eq	1,60E-05	1,60E-05	1,59E-05	1,56E-05	99,9%	99,1%	97,5%
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	1,23E-05	1,20E-05	1,18E-05	99,9%	97,6%	95,5%
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	1,67E-05	1,66E-05	1,63E-05	99,9%	99,0%	97,5%
Terrestrial acidification	kg SO2 eq	2,89E-05	2,88E-05	2,73E-05	2,65E-05	99,7%	94,7%	91,7%
Freshwater eutrophication	kg P eq	2,35E-06	2,33E-06	2,42E-06	2,29E-06	99,0%	102,9%	97,6%
Marine eutrophication	kg N eq	2,22E-07	1,82E-07	1,79E-07	1,75E-07	81,8%	80,6%	78,8%
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	5,22E-02	5,20E-02	5,19E-02	100,1%	99,8%	99,6%
Freshwater ecotoxicity	kg 1,4-DCB	1,32E-03	1,31E-03	1,31E-03	1,31E-03	99,7%	99,7%	99,2%
Marine ecotoxicity	kg 1,4-DCB	1,69E-03	1,68E-03	1,68E-03	1,67E-03	99,7%	99,6%	99,2%
Human carcinogenic toxicity	kg 1,4-DCB	4,81E-03	4,81E-03	4,81E-03	4,80E-03	100,1%	100,1%	99,9%
Human non-carcinogenic toxicity	kg 1,4-DCB	1,28E-02	1,26E-02	1,26E-02	1,25E-02	98,8%	98,7%	97,8%
Land use	m2a crop eq	1,32E-04	1,30E-04	1,34E-04	1,29E-04	98,6%	101,2%	97,6%
Mineral resource scarcity	kg Cu eq	2,81E-05	2,80E-05	2,78E-05	2,76E-05	100,0%	99,0%	98,4%
Fossil resource scarcity	kg oil eq	2,88E-03	2,86E-03	2,78E-03	2,73E-03	99,3%	96,5%	94,8%
Water consumption	m3	6,71E-05	6,66E-05	6,77E-05	6,56E-05	99,2%	100,9%	97,8%

O&M (5 scenarios)

Appendix Table 9 Midpoint comparison result on different O&M large replacement for segmented approach WTB when incineration is used as EoL compared to baseline in 770 MW OWF

Impact category	Unit / kWh	Avatar 10 MW		Incineration (segmented blade)				
		Landfill	Incineraton	Same failure rate	1/2 per lifetime	1 per lifetime	Every 10 years	Every 5 years
Global warming	kg CO2 eq	6,14E-03	6,18E-03	6,16E-03	6,17E-03	6,17E-03	6,18E-03	6,20E-03
Stratospheric ozone depletion	kg CFC11 eq	3,29E-09	3,33E-09	3,30E-09	3,31E-09	3,31E-09	3,32E-09	3,33E-09
Ionizing radiation	kBq Co-60 eq	3,56E-04	3,49E-04	3,49E-04	3,49E-04	3,49E-04	3,49E-04	3,50E-04
Ozone formation, Human health	kg NOx eq	1,60E-05	1,60E-05	1,60E-05	1,60E-05	1,60E-05	1,60E-05	1,61E-05
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	1,23E-05	1,23E-05	1,23E-05	1,23E-05	1,23E-05	1,24E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	1,67E-05	1,67E-05	1,67E-05	1,67E-05	1,67E-05	1,68E-05
Terrestrial acidification	kg SO2 eq	2,90E-05	2,89E-05	2,88E-05	2,88E-05	2,88E-05	2,89E-05	2,89E-05
Freshwater eutrophication	kg P eq	2,35E-06	2,32E-06	2,33E-06	2,33E-06	2,33E-06	2,33E-06	2,33E-06
Marine eutrophication	kg N eq	2,24E-07	1,82E-07	1,82E-07	1,82E-07	1,82E-07	1,82E-07	1,82E-07
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	5,21E-02	5,22E-02	5,22E-02	5,22E-02	5,22E-02	5,22E-02
Freshwater ecotoxicity	kg 1,4-DCB	1,32E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03
Human carcinogenic toxicity	kg 1,4-DCB	4,79E-03	4,80E-03	4,81E-03	4,81E-03	4,81E-03	4,81E-03	4,81E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1,28E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02
Land use	m2a crop eq	1,33E-04	1,31E-04	1,30E-04	1,31E-04	1,31E-04	1,31E-04	1,31E-04
Mineral resource scarcity	kg Cu eq	2,80E-05	2,80E-05	2,80E-05	2,81E-05	2,81E-05	2,81E-05	2,81E-05
Fossil resource scarcity	kg oil eq	2,89E-03	2,87E-03	2,86E-03	2,86E-03	2,86E-03	2,87E-03	2,87E-03
Water consumption	m3	6,72E-05	6,67E-05	6,66E-05	6,66E-05	6,66E-05	6,67E-05	6,69E-05

Appendix Table 10 Midpoint comparison result on different O&M large replacement for segmented approach WTB when pyrolysis is used as EoL compared to baseline in 770 MW OWF

Impact category		Avatar 10 MW			Pyrolysis (segmented blade)				
	Unit / kWh	Landfill	Incineraton	Pyrolysis	Same failure rate	1/2 per lifetime	1 per lifetime	Every 10 years	Every 5 years
Global warming	kg CO2 eq	6,14E-03	6,18E-03	5,90E-03	5,90E-03	5,90E-03	5,90E-03	5,91E-03	5,92E-03
Stratospheric ozone depletion	kg CFC11 eq	3,29E-09	3,33E-09	2,92E-09	2,91E-09	2,91E-09	2,91E-09	2,92E-09	2,92E-09
Ionizing radiation	kBq Co-60 eq	3,56E-04	3,49E-04	3,92E-04	3,92E-04	3,92E-04	3,93E-04	3,93E-04	3,94E-04
Ozone formation, Human health	kg NOx eq	1,60E-05	1,60E-05	1,59E-05	1,59E-05	1,59E-05	1,59E-05	1,59E-05	1,59E-05
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	1,23E-05	1,20E-05	1,20E-05	1,20E-05	1,20E-05	1,21E-05	1,21E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	1,67E-05	1,65E-05	1,66E-05	1,66E-05	1,66E-05	1,66E-05	1,66E-05
Terrestrial acidification	kg SO2 eq	2,90E-05	2,89E-05	2,73E-05	2,73E-05	2,73E-05	2,73E-05	2,74E-05	2,74E-05
Freshwater eutrophication	kg P eq	2,35E-06	2,32E-06	2,41E-06	2,42E-06	2,42E-06	2,42E-06	2,42E-06	2,42E-06
Marine eutrophication	kg N eq	2,24E-07	1,82E-07	1,79E-07	1,79E-07	1,79E-07	1,79E-07	1,79E-07	1,80E-07
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	5,21E-02	5,20E-02	5,20E-02	5,20E-02	5,20E-02	5,21E-02	5,21E-02
Freshwater ecotoxicity	kg 1,4-DCB	1,32E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03	1,68E-03
Human carcinogenic toxicity	kg 1,4-DCB	4,79E-03	4,80E-03	4,80E-03	4,81E-03	4,81E-03	4,81E-03	4,81E-03	4,81E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1,28E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02	1,26E-02
Land use	m2a crop eq	1,33E-04	1,31E-04	1,34E-04	1,34E-04	1,34E-04	1,34E-04	1,34E-04	1,34E-04
Mineral resource scarcity	kg Cu eq	2,80E-05	2,80E-05	2,78E-05	2,78E-05	2,78E-05	2,78E-05	2,78E-05	2,78E-05
Fossil resource scarcity	kg oil eq	2,89E-03	2,87E-03	2,78E-03	2,78E-03	2,78E-03	2,78E-03	2,78E-03	2,79E-03
Water consumption	m3	6,72E-05	6,67E-05	6,78E-05	6,77E-05	6,77E-05	6,78E-05	6,79E-05	6,81E-05

Appendix Table 11 Midpoint comparison result on different O&M large replacement for segmented approach WTB when solvolysis is used as EoL compared to baseline in 770 MW OWF

Impact category		Avatar 10 MW			Solvolysis (segmented blade)				
	Unit / kWh	Landfill	Incineraton	Solvolysis	Same failure rate	1/2 per lifetime	1 per lifetime	Every 10 years	Every 5 years
Global warming	kg CO2 eq	6,14E-03	6,18E-03	5,70E-03	5,70E-03	5,70E-03	5,70E-03	5,71E-03	5,72E-03
Stratospheric ozone depletion	kg CFC11 eq	3,29E-09	3,33E-09	2,78E-09	2,78E-09	2,78E-09	2,78E-09	2,78E-09	2,79E-09
Ionizing radiation	kBq Co-60 eq	3,56E-04	3,49E-04	3,27E-04	3,27E-04	3,27E-04	3,27E-04	3,27E-04	3,27E-04
Ozone formation, Human health	kg NOx eq	1,60E-05	1,60E-05	1,56E-05	1,56E-05	1,56E-05	1,56E-05	1,57E-05	1,57E-05
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	1,23E-05	1,18E-05	1,18E-05	1,18E-05	1,18E-05	1,18E-05	1,18E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	1,67E-05	1,63E-05	1,63E-05	1,63E-05	1,63E-05	1,63E-05	1,64E-05
Terrestrial acidification	kg SO2 eq	2,90E-05	2,89E-05	2,65E-05	2,65E-05	2,65E-05	2,65E-05	2,65E-05	2,65E-05
Freshwater eutrophication	kg P eq	2,35E-06	2,32E-06	2,29E-06	2,29E-06	2,29E-06	2,29E-06	2,29E-06	2,29E-06
Marine eutrophication	kg N eq	2,24E-07	1,82E-07	1,75E-07	1,75E-07	1,75E-07	1,75E-07	1,75E-07	1,76E-07
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	5,21E-02	5,18E-02	5,19E-02	5,19E-02	5,19E-02	5,19E-02	5,19E-02
Freshwater ecotoxicity	kg 1,4-DCB	1,32E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03	1,31E-03
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	1,68E-03	1,67E-03	1,67E-03	1,67E-03	1,67E-03	1,67E-03	1,67E-03
Human carcinogenic toxicity	kg 1,4-DCB	4,79E-03	4,80E-03	4,79E-03	4,80E-03	4,80E-03	4,80E-03	4,80E-03	4,80E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1,28E-02	1,26E-02	1,25E-02	1,25E-02	1,25E-02	1,25E-02	1,25E-02	1,25E-02
Land use	m2a crop eq	1,33E-04	1,31E-04	1,30E-04	1,29E-04	1,29E-04	1,29E-04	1,29E-04	1,29E-04
Mineral resource scarcity	kg Cu eq	2,80E-05	2,80E-05	2,76E-05	2,76E-05	2,76E-05	2,76E-05	2,76E-05	2,76E-05
Fossil resource scarcity	kg oil eq	2,89E-03	2,87E-03	2,73E-03	2,73E-03	2,73E-03	2,73E-03	2,73E-03	2,74E-03
Water consumption	m3	6,72E-05	6,67E-05	6,57E-05	6,56E-05	6,56E-05	6,57E-05	6,58E-05	6,59E-05

Best Combination

Appendix Table 12 Midpoint result for 770 OWF with 10 MW avatar segmented blade (methyl methacrylate), failure rate as the avatar 10 MW baseline, and landfill as EoL

Impact category	Unit (/kWh)	Total	Material & Manufacturing	Installation	O&M	Decomissioning	EoL	EoL large replacement
Global warming	kg CO2 eq	6,14E-03	7,55E-03	1,20E-05	7,82E-04	9,40E-06	-2,17E-03	-4,90E-05
Stratospheric ozone depletion	kg CFC11 eq	3,29E-09	3,00E-09	5,54E-12	1,09E-09	4,32E-12	-7,97E-10	-8,76E-12
Ionizing radiation	kBq Co-60 eq	3,56E-04	3,24E-04	4,67E-07	6,03E-05	3,65E-07	-2,77E-05	-9,82E-07
Ozone formation, Human health	kg NOx eq	1,60E-05	2,02E-05	1,53E-07	2,68E-06	1,19E-07	-7,06E-06	-1,33E-07
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	2,13E-05	6,50E-08	2,06E-06	5,08E-08	-1,10E-05	-1,48E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	2,13E-05	1,54E-07	2,90E-06	1,20E-07	-7,61E-06	-1,46E-07
Terrestrial acidification	kg SO2 eq	2,90E-05	4,68E-05	1,99E-07	5,73E-06	1,55E-07	-2,37E-05	-2,15E-07
Freshwater eutrophication	kg P eq	2,35E-06	9,06E-06	1,54E-09	1,71E-07	1,20E-09	-6,81E-06	-7,89E-08
Marine eutrophication	kg N eq	2,24E-07	4,84E-07	1,06E-10	1,36E-08	8,30E-11	-2,74E-07	5,01E-10
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	1,51E-01	2,22E-05	1,38E-03	1,73E-05	-1,00E-01	-1,55E-04
Freshwater ecotoxicity	kg 1,4-DCB	1,32E-03	1,31E-03	7,66E-08	1,52E-05	5,98E-08	-1,09E-05	3,40E-07
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	1,89E-03	1,19E-07	2,33E-05	9,33E-08	-2,27E-04	-1,25E-06
Human carcinogenic toxicity	kg 1,4-DCB	4,79E-03	2,90E-03	2,43E-07	7,41E-05	1,90E-07	1,77E-03	4,59E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1,28E-02	4,57E-02	1,98E-06	4,46E-04	1,55E-06	-3,31E-02	-3,19E-04
Land use	m2a crop eq	1,33E-04	1,78E-04	7,81E-08	1,04E-05	6,10E-08	-5,50E-05	-9,61E-07
Mineral resource scarcity	kg Cu eq	2,80E-05	3,15E-04	1,46E-08	6,02E-06	1,14E-08	-2,87E-04	-5,77E-06
Fossil resource scarcity	kg oil eq	2,89E-03	1,88E-03	3,77E-06	1,44E-03	2,95E-06	-4,22E-04	-1,01E-05
Water consumption	m3	6,72E-05	7,24E-05	3,39E-08	8,89E-06	2,65E-08	-1,38E-05	-3,27E-07

Appendix Table 13 Midpoint result for 770 OWF with 10 MW avatar segmented blade (methyl methacrylate), failure rate as the avatar 10 MW baseline, and incineration as EoL

Impact category	Unit (/kWh)	Total	Material & Manufacturing	Installation	O&M	Decomissioning	EoL	EoL large replacement
Global warming	kg CO2 eq	6,18E-03	7,55E-03	1,20E-05	7,82E-04	9,40E-06	-2,13E-03	-4,63E-05
Stratospheric ozone depletion	kg CFC11 eq	3,33E-09	3,00E-09	5,54E-12	1,09E-09	4,32E-12	-7,64E-10	-6,63E-12
Ionizing radiation	kBq Co-60 eq	3,49E-04	3,24E-04	4,67E-07	6,03E-05	3,65E-07	-3,45E-05	-1,43E-06
Ozone formation, Human health	kg NOx eq	1,60E-05	2,02E-05	1,53E-07	2,68E-06	1,19E-07	-7,08E-06	-1,34E-07
Fine particulate matter formation	kg PM2.5 eq	1,23E-05	2,13E-05	6,50E-08	2,06E-06	5,08E-08	-1,10E-05	-1,49E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,67E-05	2,13E-05	1,54E-07	2,90E-06	1,20E-07	-7,63E-06	-1,47E-07
Terrestrial acidification	kg SO2 eq	2,89E-05	4,68E-05	1,99E-07	5,73E-06	1,55E-07	-2,38E-05	-2,20E-07
Freshwater eutrophication	kg P eq	2,32E-06	9,06E-06	1,54E-09	1,71E-07	1,20E-09	-6,83E-06	-8,03E-08
Marine eutrophication	kg N eq	1,82E-07	4,84E-07	1,06E-10	1,36E-08	8,30E-11	-3,13E-07	-2,04E-09
Terrestrial ecotoxicity	kg 1,4-DCB	5,21E-02	1,51E-01	2,22E-05	1,38E-03	1,73E-05	-1,00E-01	-1,52E-04
Freshwater ecotoxicity	kg 1,4-DCB	1,31E-03	1,31E-03	7,66E-08	1,52E-05	5,98E-08	-1,46E-05	1,01E-07
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	1,89E-03	1,19E-07	2,33E-05	9,33E-08	-2,32E-04	-1,58E-06
Human carcinogenic toxicity	kg 1,4-DCB	4,80E-03	2,90E-03	2,43E-07	7,41E-05	1,90E-07	1,77E-03	4,61E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1,26E-02	4,57E-02	1,98E-06	4,46E-04	1,55E-06	-3,32E-02	-3,29E-04
Land use	m2a crop eq	1,31E-04	1,78E-04	7,81E-08	1,04E-05	6,10E-08	-5,67E-05	-1,07E-06
Mineral resource scarcity	kg Cu eq	2,80E-05	3,15E-04	1,46E-08	6,02E-06	1,14E-08	-2,87E-04	-5,77E-06
Fossil resource scarcity	kg oil eq	2,87E-03	1,88E-03	3,77E-06	1,44E-03	2,95E-06	-4,42E-04	-1,14E-05
Water consumption	m3	6,67E-05	7,24E-05	3,39E-08	8,89E-06	2,65E-08	-1,43E-05	-3,60E-07

Appendix Table 14 Midpoint result for 770 OWF with 10 MW avatar segmented blade (methyl methacrylate), failure rate as the avatar 10 MW baseline, and incineration as EoL

Impact category	Unit (/kWh)	Total	Material & Manufacturing	Installation	O&M	Decomissioning	EoL	EoL large replacement
Global warming	kg CO2 eq	5,90E-03	7,59E-03	1,21E-05	7,31E-04	9,47E-06	-2,39E-03	-4,95E-05
Stratospheric ozone depletion	kg CFC11 eq	2,91E-09	3,01E-09	5,57E-12	1,05E-09	4,36E-12	-1,16E-09	-8,94E-12
Ionizing radiation	kBq Co-60 eq	3,92E-04	3,25E-04	4,70E-07	5,88E-05	3,68E-07	8,18E-06	-9,60E-07
Ozone formation, Human health	kg NOx eq	1,51E-05	1,96E-05	1,54E-07	2,56E-06	1,20E-07	-7,21E-06	-1,33E-07
Fine particulate matter formation	kg PM2.5 eq	1,19E-05	2,12E-05	6,55E-08	1,99E-06	5,12E-08	-1,13E-05	-1,47E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,58E-05	2,06E-05	1,55E-07	2,77E-06	1,21E-07	-7,79E-06	-1,46E-07
Terrestrial acidification	kg SO2 eq	2,72E-05	4,68E-05	2,00E-07	5,47E-06	1,57E-07	-2,53E-05	-2,13E-07
Freshwater eutrophication	kg P eq	2,42E-06	9,08E-06	1,55E-09	1,65E-07	1,21E-09	-6,75E-06	-7,78E-08
Marine eutrophication	kg N eq	2,05E-07	5,10E-07	1,07E-10	1,23E-08	8,36E-11	-3,16E-07	-1,96E-09
Terrestrial ecotoxicity	kg 1,4-DCB	5,20E-02	1,51E-01	2,23E-05	1,32E-03	1,75E-05	-1,01E-01	-1,29E-04
Freshwater ecotoxicity	kg 1,4-DCB	1,31E-03	1,31E-03	7,71E-08	1,46E-05	6,03E-08	-1,59E-05	-1,68E-07
Marine ecotoxicity	kg 1,4-DCB	1,68E-03	1,89E-03	1,20E-07	2,25E-05	9,41E-08	-2,34E-04	-1,89E-06
Human carcinogenic toxicity	kg 1,4-DCB	4,81E-03	2,91E-03	2,44E-07	7,30E-05	1,91E-07	1,78E-03	4,59E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1,26E-02	4,57E-02	1,99E-06	4,28E-04	1,56E-06	-3,33E-02	-3,27E-04
Land use	m2a crop eq	1,34E-04	1,78E-04	7,86E-08	9,78E-06	6,15E-08	-5,35E-05	-9,74E-07
Mineral resource scarcity	kg Cu eq	2,77E-05	3,15E-04	1,47E-08	5,96E-06	1,15E-08	-2,88E-04	-5,76E-06
Fossil resource scarcity	kg oil eq	2,77E-03	1,88E-03	3,79E-06	1,42E-03	2,97E-06	-5,25E-04	-1,02E-05
Water consumption	m3	6,30E-05	6,82E-05	3,41E-08	8,31E-06	2,67E-08	-1,32E-05	-3,27E-07

Appendix Table 15 Midpoint result for 770 OWF with 10 MW avatar segmented blade (methyl methacrylate), failure rate as the avatar 10 MW baseline, and incineration as EoL

Impact category	Unit (/kWh)	Total	Material & manufacturing	Installation	O&M	Decomissioning	EoL	EoL large replacement
Global warming	kg CO2 eq	5,70E-03	7,59E-03	1,21E-05	7,31E-04	9,47E-06	-2,59E-03	-4,97E-05
Stratospheric ozone depletion	kg CFC11 eq	2,78E-09	3,01E-09	5,57E-12	1,05E-09	4,36E-12	-1,29E-09	-9,03E-12
Ionizing radiation	kBq Co-60 eq	3,27E-04	3,25E-04	4,70E-07	5,88E-05	3,68E-07	-5,69E-05	-1,00E-06
Ozone formation, Human health	kg NOx eq	1,48E-05	1,96E-05	1,54E-07	2,56E-06	1,20E-07	-7,46E-06	-1,33E-07
Fine particulate matter formation	kg PM2.5 eq	1,16E-05	2,12E-05	6,55E-08	1,99E-06	5,12E-08	-1,16E-05	-1,47E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	1,55E-05	2,06E-05	1,55E-07	2,77E-06	1,21E-07	-8,04E-06	-1,46E-07
Terrestrial acidification	kg SO2 eq	2,63E-05	4,68E-05	2,00E-07	5,47E-06	1,57E-07	-2,61E-05	-2,13E-07
Freshwater eutrophication	kg P eq	2,30E-06	9,08E-06	1,55E-09	1,65E-07	1,21E-09	-6,87E-06	-7,79E-08
Marine eutrophication	kg N eq	2,01E-07	5,10E-07	1,07E-10	1,23E-08	8,36E-11	-3,20E-07	-1,96E-09
Terrestrial ecotoxicity	kg 1,4-DCB	5,18E-02	1,51E-01	2,23E-05	1,32E-03	1,75E-05	-1,01E-01	-1,29E-04
Freshwater ecotoxicity	kg 1,4-DCB	1,31E-03	1,31E-03	7,71E-08	1,46E-05	6,03E-08	-2,14E-05	-1,72E-07
Marine ecotoxicity	kg 1,4-DCB	1,67E-03	1,89E-03	1,20E-07	2,25E-05	9,41E-08	-2,41E-04	-1,90E-06
Human carcinogenic toxicity	kg 1,4-DCB	4,80E-03	2,91E-03	2,44E-07	7,30E-05	1,91E-07	1,77E-03	4,59E-05
Human non-carcinogenic toxicity	kg 1,4-DCB	1,25E-02	4,57E-02	1,99E-06	4,28E-04	1,56E-06	-3,34E-02	-3,27E-04
Land use	m2a crop eq	1,29E-04	1,78E-04	7,86E-08	9,78E-06	6,15E-08	-5,82E-05	-9,77E-07
Mineral resource scarcity	kg Cu eq	2,76E-05	3,15E-04	1,47E-08	5,96E-06	1,15E-08	-2,88E-04	-5,76E-06
Fossil resource scarcity	kg oil eq	2,72E-03	1,88E-03	3,79E-06	1,42E-03	2,97E-06	-5,74E-04	-1,02E-05
Water consumption	m3	6,10E-05	6,82E-05	3,41E-08	8,31E-06	2,67E-08	-1,53E-05	-3,29E-07