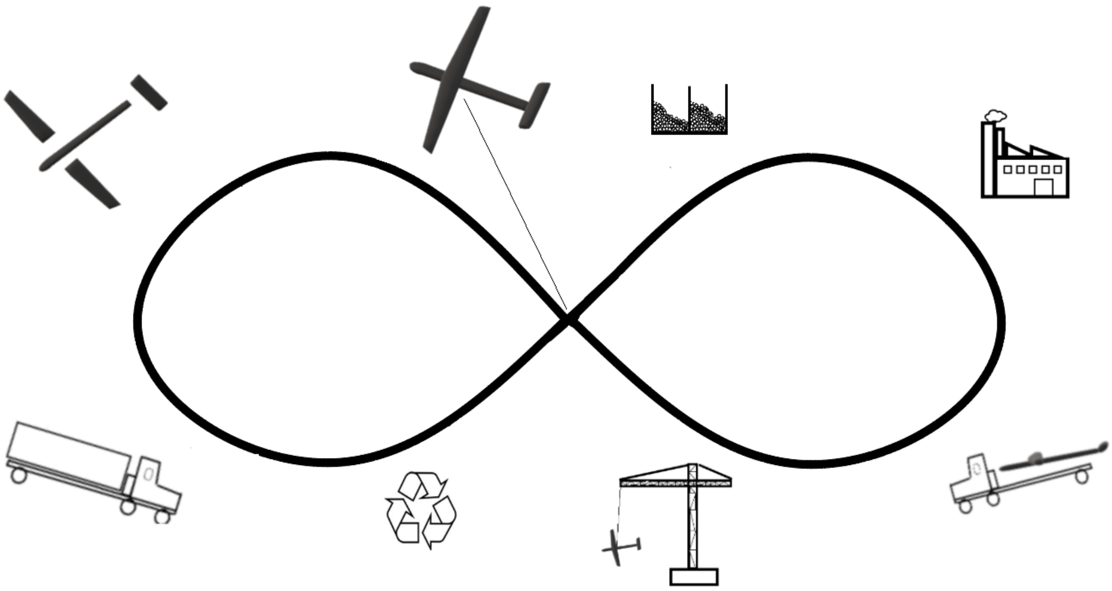
Life Cycle Assessment of Multi-Megawatt Airborne Wind Energy



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Life Cycle Assessment of Multi-Megawatt Airborne Wind Energy

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Preface

This report marks the end of a long academic journey in search of sustainability.

As a master student in Sustainable Energy Technology, my main interest has always remained the sustainability and design of mechanical systems. This LCA study performed on a new type of wind energy technology is exactly where my interests lead me over the last few years.

My interest into Airborne Wind Energy started after following a variety of courses on De-manufacturing, recycling and Circular Economy. The concept of Circular Economy introduced me to Airborne Wind Energy as an interesting RE-design for energy generation from the wind, significantly reducing the mass required in the production of renewable energy. My first goals where then also to assess AWE for its circularity.

In the end, I was provided the opportunity to perform a Life Cycle Assessment within the sector. Thereby indeed enabling me to assess the sustainability of this new technology, albeit through another method. This LCA has been performed in collaboration with industry partners; Airborne Wind Europe and Ampyx Power which significantly increased the value of my work. I would therefore sincerely like to thank Roland Schmehl, Kristian Petrick and Stefan Wilhelm for this opportunity directly connection to the industry. Covid-19 lock-downs have not made it easy to perform this project, as it required detailed understanding of a system that does not exist yet. Thank you for your continuous guidance and support over the extended project.

In addition, I would like to thank the many people that provided a variety of inspiration, insights, assistance and data. Thank you Marcello Colledani, your inspiring lectures on circular economy still drive me today. Thank you Edward Fagan and Michiel Kruijf, for your valuable input on the design of the AWE model. Thank you Joost Vogtländer and Bernhard Steubing, for your guidance into preforming an LCA. Thank you Rigo Bosman, for providing the missing data required to model the impacts of the tether. I would also like to thank everyone else who has either directly or indirectly provided valuable input to the project. Finally, I would like to thank the members of my Thesis Committee a second time. To Roland Schmehl, Joost Vogtländer, Kristian Petrick and Stefan Wilhelm, thank you for being here with me today.

Lastly, I would like to thank my family and friends. Starting with my grandpa: Thank you grandpa! The inspiring stories of your many years at the patent office are what brought me here today! To my parents: Thank you for all you support throughout my study career and thank you for raising me with an interest for sustainability. Finally, to Wouther, with whom I have studied almost every day since Covid-19 hit: Together we made it!

Luuk van Hagen
Delft, July 5, 2021

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Abstract

Airborne Wind Energy (AWE) technology provides an interesting re-design for energy generation from the wind. The value of renewable energy systems is their ability to generate electricity with reduced environmental impacts, most crucially being the Global Warming Potential.

In this project, it is assessed what the impacts of a potential Multi-Megawatt AWE system would be. Firstly to determine where its impact hot-spots are located and secondly to assess how this new technology would compare to conventional wind energy systems operating in the same farm. The location of the farm is included as a sensitivity parameter to assess the advantages and disadvantages of both systems for operation in various locations under different environmental conditions.

The technologies were assessed and compared using a Life Cycle Assessment (LCA) method. The LCA is used to assess the systems for their Global Warming Potentials (GWP) and their Cumulative Energy Demands (CED). The CED is subsequently also used to determine the Energy Payback Time (EPBT) and the Energy Return of Investment (EROI) of both systems.

The assessment of the impacts was performed on models that first had to be designed. The many unknowns and variables in both designs meant that modelling accounted for a large fraction of the project. The AWE system is modelled as a Ground-Gen, Rigid-Wing system based on the design of Ampyx Power. The HAWT system is designed to represent an accurate comparison model for the AWE system. It is fully based on various literature sources, primarily on optimisations of the NREL 5MW.

It was found that the impacts of the HAWT system greatly depends on environmental conditions at the location for which it is designed. The AWE system does however only minimally depend on the environmental conditions. Thereby, it can be evaluated where AWE would have the largest advantage over HAWT technology and where HAWT technology may be better.

The project is carried out in collaboration with Airborne Wind Europe and Ampyx Power. Data was intended to come from Ampyx Power. However, the project started too early into delayed feasibility studies which limited the availability of design data and even concept plans.

The report therefore presents the impacts of a potential future 5 MW system. Modelled to the best ability at this time, with an hydraulic drivetrain and a hub-less drum design. Additional focus is placed on the availability of improvement potentials and assessment of design variables. Thereby aiming to further improve general sustainable knowledge within the AWE sector.

The AWE system is found to use significantly less materials and to produce electricity at notably lower impacts compared to the HAWT system. AWE is found to be most advantageous for operation at unfavorable environmental conditions, where the wind speed is low, and the HAWT system requires a large hub-height.

The Land and Launch Apparatus (LLA) and the Power Generation Apparatus (PGA) subsystems are found to be the largest impact contributors within the AWE system. The largest impact component is found to be the hydraulic accumulator system in the PGA, primarily due to its large mass. Its high impacts are closely followed by the light weight tether and aircraft subsystems that require materials with high specific impacts.

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List of Abbreviations

AEP	Annual Energy Production
AWE(S)	Airborne Wind Energy (System)
CED	Cumulative Energy Demand
CFRP	Carbon Fibre Reinforced Polymers
DD	Direct Drive
DFIG	Doubly fed induction generator
EI	EcoInvent, database
EOL	End of Life
EPBT	Energy payback time
EPD	Environmental Product Declaration
EROI	Energy Return on Investment
FRP	Fibre Reinforced Polymers
GFRP	Glass Fibre Reinforced Polymers
GLO	Global
GWP	Global Warming Potential
HAWT	Horizontal Axis Wind Turbine
HMPE	High Modulus PolyEthylene
LCA	Life Cycle Assessment
LCI	Life cycle Inventory
LCIA	Life Cycle Impact Assessment
LLA	Launch and Landing Apparatus
PE	PolyEthylene
PGA	Power Generation Apparatus (also: AWE ground-station)
RER	Rest of Europe
UHMWPE	Ultra High Molar Weight PolyEthylene

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Chapter 1

Introduction

Environmental concerns are rising higher every year. We have become increasingly aware to the many different ways we impact our environment. Especially the effects of global warming are becoming more and more visible in our daily lives.

Global warming is caused by the emission of greenhouse gasses (GHG) into the atmosphere. A large portion of these GHG emissions are caused by our use of energy. Changing to more renewable energy sources is widely seen as one of the most effective solutions to reduce our environmental impacts.

One of the systems that could play a significant role in this energy transition is Airborne Wind Energy (AWE). AWE systems generate electricity from the wind by using aircraft, drone or kite-like systems tethered to the ground. The name 'Airborne Wind Energy' is an umbrella term for a large collection of design concepts with one specific design feature in common; they all capture energy from the wind with airborne elements tethered to the ground.

Figure 1.1 displays a small selection of the available AWE designs. The first 4 are variations of Ground-Gen technology; some use soft wings (kites), some use rigid wings (aircrafts) and other use soft-rigid wing mixture in between. Ground-Gen systems generate electricity on the ground; The energy captured by the aircraft it transferred to the ground in the form of a pulling force over the tether. A ground-based power station subsequently converts this force into electricity. Fly-Gen systems generate the electricity with small turbines mounted on the aircraft.

AWE has many envisioned advantages; The systems displayed in figure 1.1 all have the major advantage of (cross-wind) flight. The motion of the aircraft results in an increased relative velocity to the wind. This in term leads to a significant increase in extractable energy from the same wind resource; since the extractable energy from the wind is cubed to the wind speed.

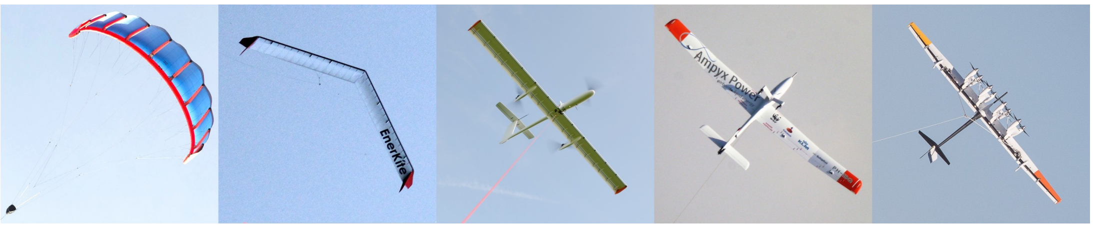


Figure 1.1: Various AWE systems (Schmehl and Tulloch, 2019).

Crosswind flight is only one of the many advantages envisioned for AWE. One of the most important advantages of this radical redesign for wind energy generation is its ability to replace heavy structural constraints through the use of control systems. Therefore, it has the ability to significantly reduces the amount of material required for the production of renewable energy.

Figure 1.2: Comparison between AWE and HAWT. Found in Vermillion et al. (2021). Originally: Left side: TwingTec pilot system (Schmehl, 2019), Right side: 2MW Ampyx concept render (Kruijff and Ruiterkamp, 2018).

Renewable energy sources are increasingly used to replace fossil energy sources in order to reduce our GHG emissions. The impacts of fossil energy sources are mainly caused in their operational lifecycle stages, through burning of fuels. The advantage of renewable energy systems is that they use clean energy sources in the production of electricity. Without the large impact emission during operation, the majority of the impacts of renewable energy systems are now emitted in manufacturing of the systems.

The impacts of different renewable energy systems can be quantified and compared through the use of a Life Cycle Assessment (LCA). An LCA is a standardised method to perform a holistic assessment of the environmental impacts of products or services. It is build up in **4 interconnected stages**; *the Goal and Scope Definition stage, the Inventory Analysis, the Impact Assessment* and finally *the Interpretation stage* (As in figure 1.3). An LCA is therefore a highly iterative process

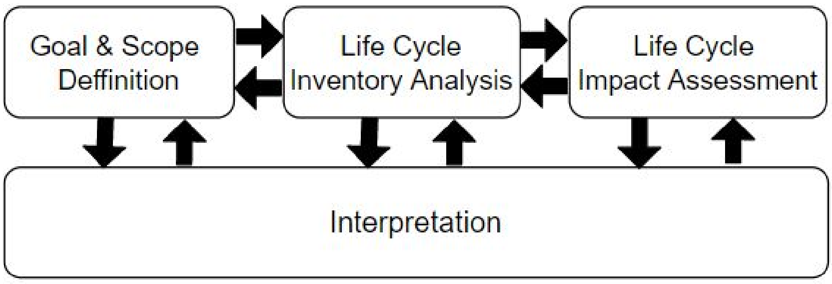


Figure 1.3: The 4 stages of an LCA.

This project assesses the environmental impact of a large scale future AWE system of 5MW; to quantify its impacts and to compare them to the impacts of HAWT technology. Comparison of the technologies is performed on hypothetical farms of 50MW each. Both technologies are designed from the ground up, modelling all materials and processes the same way for both systems. Comparison of the impacts is performed after normalisation to estimated energy outputs at a specific location; with changing environmental conditions over the height. Thereby the systems are compared as accurately as possible, under the same assumptions, for operation at the same location;

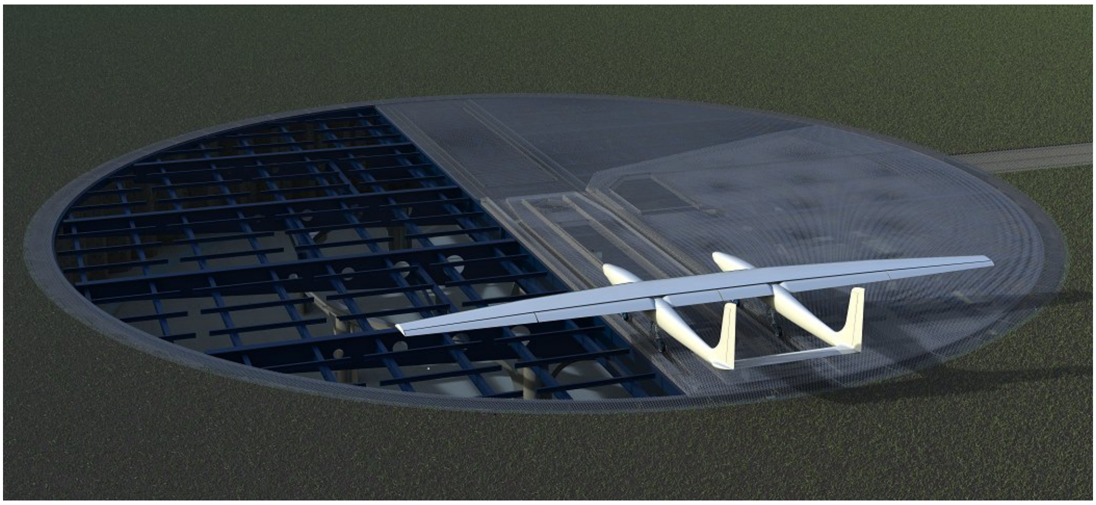


Figure 1.4: A smaller version of the Ampyx power aircraft system, on which the 5 MW is based (Ampyx, 2020).

There are many incomparable differences between the various technology types within the global term of AWE. The specific system type assessed in this work is characterised as a Ground-Gen, Rigid-Wing system, based on the design of Ampyx power. An actual design could however not be provided, the system is therefore primarily modelled based on potential future visions presented by Ampyx. The specification provided by Ampyx are subsequently further designed based on literature, expert input and assumptions.

At the time of writing this report, the largest flown Ampyx power system was the 0.15 MW AP3, which is a non-commercial test system. The largest AWE system ever flown is the the 0.6 MW Makani M600, at test flights. In contrast; the largest operating Horizontal Axis Wind Turbine are already 12 to 14 MW, the Haliade X turbines. With an even larger system of the 15MW already announced, the Vestas V236. Therefore, there is a huge differences in technological readiness between the technologies. Many components of the AWE system remain unknown, for which different options are still assessed. As a result, a choice had to be made for the model, but other options may prove better when they become better defined. In this report, the systems is modelled with an hydraulic drivetrain, and the drum is a personal design do limit the inertia losses.

The main objective of the research is to assess the environmental performance of a potential Multi-Megawatt AWE system; To quantify its impacts, to locate hot-spots and to compare its impacts to the impacts of a comparable conventional wind energy systems. The assessed impact categories are the Global Warming Potential (GWP) and the Cumulative Energy Demand (CED). The CED is also used to determine the Energy Payback Time (EPBT) and Energy Return on Investment (EROI) of both technologies.

An actual design of a large-scale AWE system does however not exist. Thus, before the impacts could be assessed, a representative model first had to be designed. Comparisons between the impacts of the AWE system and the HAWT system are performed various scenarios to assess the advantages and disadvantages of both systems for operation in different locations, and under different environmental conditions.

The research is intended to extend and improve sustainability and sustainable-knowledge within the AWE sector. Another goal is therefore to indicate areas with high impacts or large improvement potentials. Additional recommendations are provided to researches and developers on other methods that could be used to improve sustainability in more than just the LCA impacts.

Chapter 2 starts with a literature review on related background; including basic introductions into AWE technology, HAWT technology and the LCA methodology. Chapters 3 and 4 subsequently state the Goal and Scope definitions of the LCA report. The Goal definition chapter primarily states the research goals, but also the intended applications and research partners of the project. The Scope definition chapter subsequently describes the method with which the assessment is performed; it states the methodological choices, the assessed systems, the boundaries and the assumptions used. Chapter 5 follows with the actual modeling of the systems; this chapter generates a bill of materials and processes and describes how systems were designed. Chapter 6 subsequently used this bill of materials and processes to determine the impacts for the base-case scenario systems. Chapter 7 is subsequently used to assess numerous important variations to the base-case model. These variations include the sensitivity analysis, but more importantly; it includes variations to the environmental conditions to compare the technologies for their advantages in different situations. Chapter 8 finally concludes the report with conclusions and recommendations.

Chapter 2

State of the Art

This chapter provides background information on energy from the wind and the impact related to the different technologies. It starts with an general introduction into the energy in the wind, followed by sections on Airborne Wind Energy technology and Horizontal Axis Wind Turbine technology respectively. It is concluded with a section on the performance of an LCA, and previously performed LCA work on wind energy systems.

2.1 Energy From the Wind

The wind has been used to perform work for many ages, We have used it to propel our sail ships. to grind the grains for our bread, and to power the pumping stations that keep our feet dry. The wind carries an incredible amount of energy, most of which still completely out of our reach.

The first record of actual electricity generation from the wind dates back to 1887. When Scottish professor James Blyth build a turbine to provide electricity to his holiday cottage (Hardy, 2010). He used this turbine in combination with an accumulator system to guarantee electricity, even when the wind did not blow. It is this usage of an accumulator system in the first turbine that will make an interesting and important reappearance in the future of energy generation from the wind. To be used by Yo-Yo type AWE systems to stabilise their cyclic, intermittent energy production characteristic.

2.1.1 Power in the Wind

The environmental conditions as a specific location depend on a great number of factors. It is well known that the average wind speed increases with increasing altitudes. One reason why the wind speed reduces closer to earth is the earths surface roughness caused by obstacles such as buildings and trees. The further removed from these obstacles, the faster the wind blows. This is the main reason why the wind blows faster and steadier at sea, since the surface of the water only minimally reduces its power.

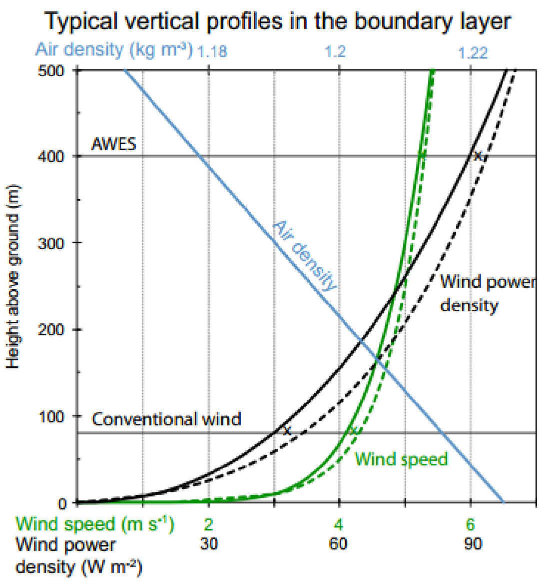


Figure 2.1: The wind power density over height (Archer, 2013).

Research states that there is much more energy to be gained at higher elevations. The increase in available power in the wind is visualised in figure 2.1. Indicating the advantages of energy generation at higher altitudes. It is this higher energy that once caught the attention of AWE pioneers.

Figure 2.1 however only includes the first 500 meters, within the atmospheric boundary layer. This is approximately the operational range predicted for the first commercial AWE systems. This height is however predicted to increase up to 1500 meters for systems further into the future (Schmehl, 2018b).

2.1.2 Airborne Wind Energy (AWE)

Being able to reach these higher heights is only one of the envisioned advantages of AWE. It has been stated that the adaptability of the operating height presents an even larger advantage (Bechtle et al., 2019). This adaptability enables AWE systems to operate in optimal environmental conditions for larger fractions of the time. Thereby increasing the capacity factor and energy output of AWE compared to HAWT.

The biggest advantage of AWE may however be its envisioned ability to generate electricity with a significantly reduced material consumption. Which is subsequently expected to result in further reduction of the impacts but also the costs of renewable energy (Wilhelm, 2015; Schmehl, 2018a).

AWE Typologies

Airborne Wind Energy (AWE) is the umbrella term for a large number of widely varying design concepts. The single common denominator between these systems is that they all capture energy from the wind with airborne elements tethered to the ground.

Most AWE concepts can be characterised by a small number of features. The system types presented in figure 2.6 represent the majority of all current AWE research. There are however also again numerous different design variations within these general system types.

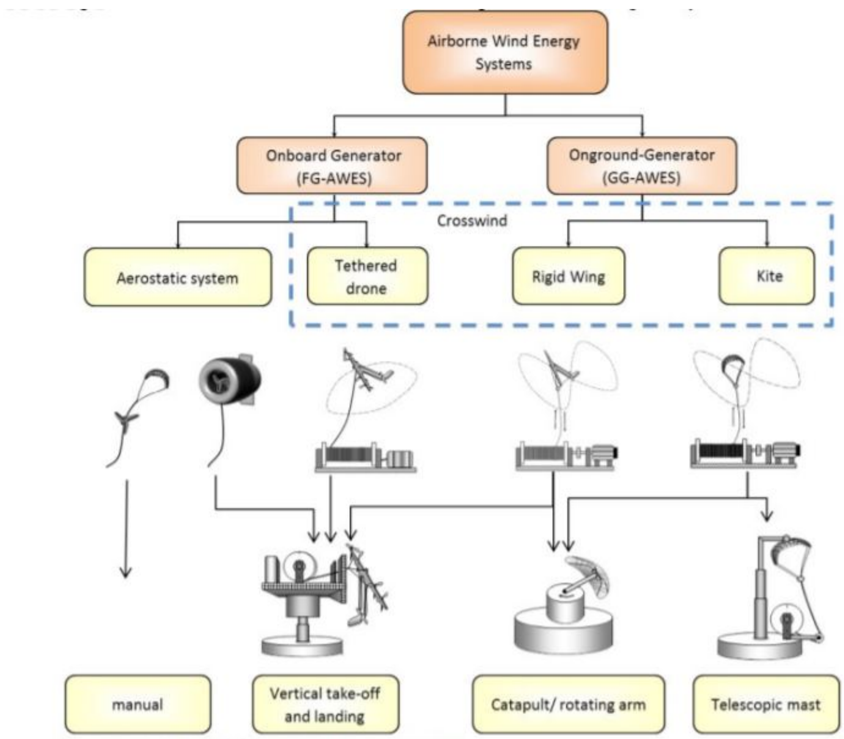


Figure 2.2: Classification and differences between AWE systems (Fraunhofer, 2014).

These systems are all classified as Airborne Wind Energy systems. However, both in operations, and especially on system levels, these designs barely have any similarities between each other. Each system type presents different advantages and disadvantages.

Aerostatic systems are furthest removed from the other AWE types. Different to the other AWE types, aerostatic systems do not make use of the 'crosswind flights' advantages that increase the relative wind speed experienced by the airborne element. Instead, these systems generally only make use of better available environmental wind speed at higher heights. E.g. by lifting wind turbine rotors higher into the air, without requiring a tower.

Figure 2.3: Example of Aerostatic system (Vermillion et al., 2013).

Crosswind, AWE types classified as 'crosswind flight systems' actually fly their aircraft, kite or drone like system through the air in order to increase the extractable energy available in the wind. Within cross-wind systems there are again several Fly-Gen and Ground-Gen system types.

Fly-Gen systems use multiple small wind turbines attached to a aircraft of drone like system. These drones are subsequently flown through the air where the wind turbines experience higher wind speeds than they would otherwise experience. Which strong increase extractable energy, as this scales cubed with the wind speed.

Figure 2.4: The Fly-Gen M600 system of Makani (Schmehl and Tulloch, 2019).

Ground-Gen (Yo-Yo type) systems also use flight to increase the amount of energy extractable from the environment. The difference is however that Ground-Gen systems convert the energy into electricity with generators on the ground.

There are 4 phases to the cyclic operation of Fly-Gen systems. Upon flight, in the traction phase, forces are generated by the flight of the aircraft or kite. These forces are transmitted by a tether that is reeled off of a drum. Electricity is generated by a generator attached to this drum. The 2nd phase is a transition phase for the flight of the aircraft. This starts when the tether is almost fully un-wound from the drum. The aircraft needs to change flight path to prepare for the 3rd stage.

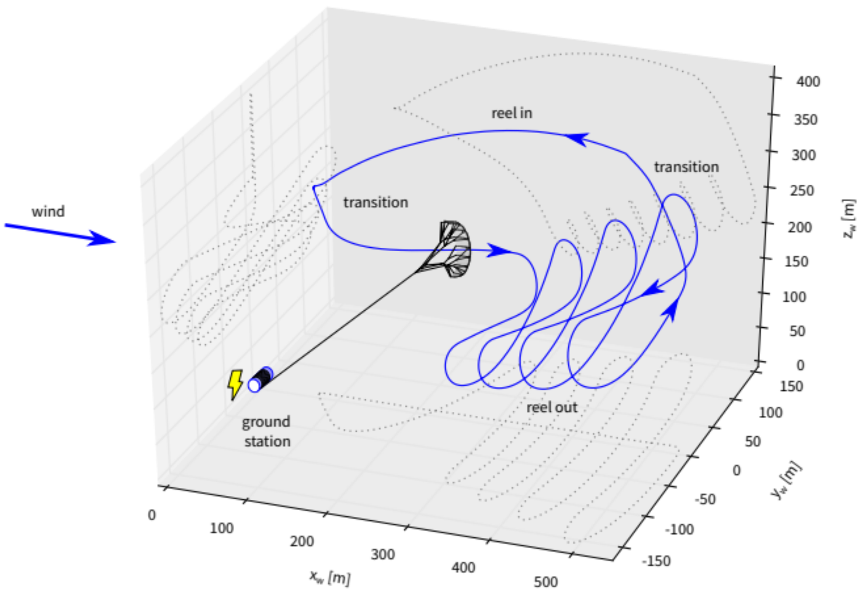


Figure 2.5: Phases of cyclic energy generation (Fechner, 2016).

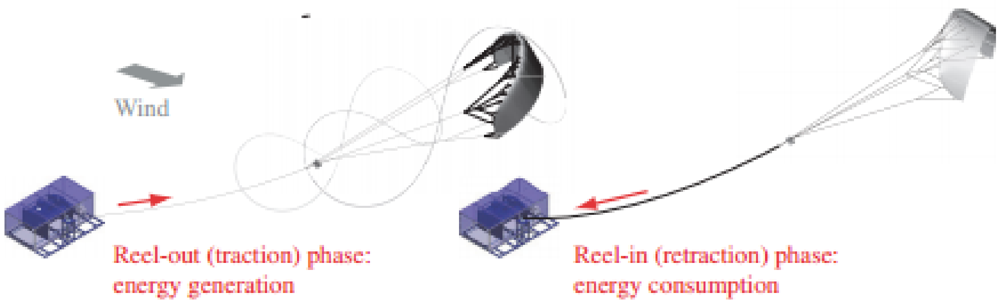


Figure 2.6: Operation of Ground-Gen (van der Vlugt et al., 2013).

The 3rd stage is the retraction phase. In this phase, the aircraft is flown back to the ground, and the tether is rewound onto the drum. A final transition phase starts the (first) traction phase again, which results in the cyclic energy output as shown in figure 2.7.

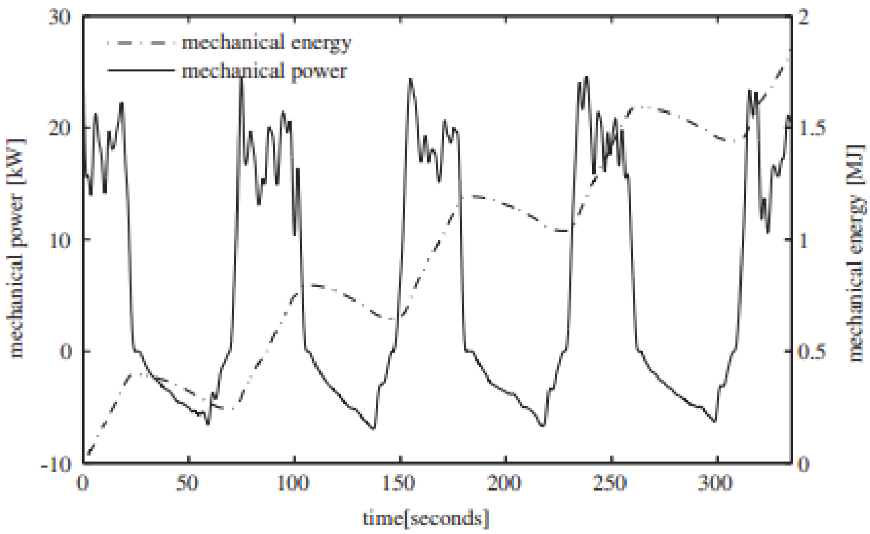


Figure 2.7: Example of cyclic behaviour in mechanical power output (van der Vlugt et al., 2013).

The airborne component of the system can either be identified as Soft-wing (kite) or Rigid-wing (aircraft), figure 2.8. (Combinations into semi-rigid-wing do also exists.)

Figure 2.8: Examples of wings (Wilhelm, 2015).

The summary above is far from an extensive summary of all AWE systems. It already indicated some of the many significant differences within the AWE system types. No clear advantage is would also result in very different Life Cycle Assessments, potentially with very different outcomes.

Useful sources of information were found to be the AWESCO website, the AWEurope website and the Airborne Wind Energy Conference documentation (AWEC2021). Equally valuable were the Airborne Wind Energy books: Schmehl et al. (2013) and Schmehl (2018a). Other valuable sources are the many papers in the industry, most notably: Cherubini et al. (2015), Watson et al. (2019) and Vermillion et al. (2021).

2.1.3 Horizontal Axis Wind Turbines (HAWT)

Horizontal Axis Wind Turbines technology is continuously changing. What started as small turbines placed steadily on solid ground has evolved to massive floating offshore structures, each able to power thousands of households. The HAWT modelled in this report is meant to function as representative systems for the assessed AWE system. Therefore, the differences in HAWT technology are important to understand.

The design of a HAWT turbine can be optimised for the location it is intended to be used in. A primary variable for optimisation is the environmental conditions in which the turbine its placed. One of the important variables is the wind class rating. HAWT turbines are rated based the IEC 61400 standards, as shown in table 2.1. Among others, these state the average wind speed experienced by the turbine at its hub height.

Wind class	Uave	Uref	1year gust	50year gust
IEC 1	10	50	52.5	70
IEC 2	8.5	42.5	44.6	59.5
IEC 3	7.5	37.5	39.4	52.5
IEC 4	6	30	31.5	42

Table 2.1: IEC standardised Wind classes.

These wind classes do however not directly relate to the wind conditions at a location. The wind speed increases over height. Therefore, at a bad wind speed location, a HAWT system would require a taller tower to reach the same wind class as it could at lower height at a location with better wind conditions.

Offshore, the wind conditions are optimal. The hub height of an HAWT turbine can be kept low, and the rotor diameter can be minimised. In worse conditions, the tower would need to be higher, and the rotor diameter larger in order to capture the same amount of energy from the wind.

The location for which the turbine is designed therefore significantly influences the material requirements and environmental impacts of the system.

HAWT Drivetrain Types

Another important design variable is the drivetrain selection. The selection of the drivetrain has a strong influence entire design of the system. There are various design options, only 2 important ones are mentioned here, these are: the Doubly Fed Induction Generator (DFIG) and the Direct Drive (DD) system.

The DFIG drivetrain is the most commonly used drivetrain type over the previous decades. It uses a gearbox to increase the low speed rotation of the rotor to high speed rotation of the generator. This gearbox is a very heavy component in the drivetrain. The efficiency and reliability of the DFIG turbine is notably lower than that of the DD drivetrain design.

The relatively recent transition towards offshore wind energy has increased the lead to an increased usage of DD drivetrains. This drivetrain type does not use a gearbox, instead; it uses a large low speed generator. This significantly increases the efficiency and reliability of the system. Which is particularly useful in offshore locations, where servicing and transport come at high costs. A downside of DD drivetrains is their usage of permanent magnets.

A fairly new concept in HAWT technology is to also use hydraulic drivetrains, which could significantly reduce the HAWT nacelle mass.

2.2 Life Cycle Assessment

The systems are evaluated for their environmental impacts by using a Life Cycle Assessment. An LCA is a standardised method used to quantify and compare the (environmental) impacts of different product or services. It is a highly iterative methodological approach that provides an holistic assessment of the impacts of a product or service.

2.2.1 Methodology

The standardised methods for performing an LCA are defined by the ISO 14040 and ISO 14044 standards. These states that an LCA is build up from 4 standardised stages: *The Goal & Scope Definition*, *The Life Cycle Inventory Analysis*, *The Life Cycle Impact Assessment* and *the Interpretation stage* (Figure 2.9). This methodological standardisation ensures the accuracy and comparability between assessments performed by different entities.

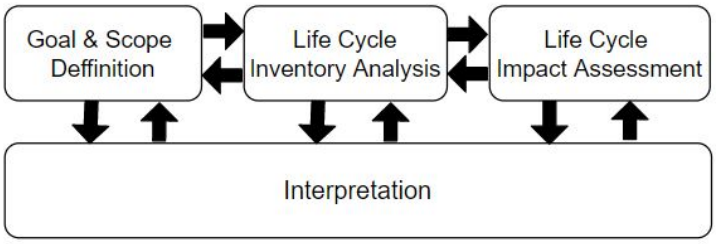


Figure 2.9: The 4 stages of an LCA

Goal and Scope Definition Stage
The Goal and Scope definition stage is defined in a collaboration between the commissioner and the practitioner of the assessment. The Goal definition primarily details the objectives of the assessment. The Scope definition subsequently defines the exact methods and assumptions used in the execution of the assessment.

These topics include the boundary conditions used in the assessment, including the cut-off criteria, the included life cycle stages and the exact design and boundaries of the assessed system. It also states additional LCA method choices, the assessed impact categories and the Functional Unit (FU) to which all impacts are normalised for comparisons between different systems. It serves as the administrative chapter, enabling comparison to other assessments.

Inventory Analysis (LCI) Stage
The LCI stage is generally the most time consuming stage of an LCA. It is used to inventory the assessed systems. The output of this stage is a bill of materials and processes which will be used as input for the impact assessment.

This bill of materials can either be from direct data, or from a data collected from literature. Different types of LCA methods require different data. An Environmental Product Declaration is an example of a LCA that states the impacts of a specific product based on known data. An LCA carried out to compare design concepts will rely more heavily on literature.

Impact Assessment (LCIA) Stage
The LCIA translates the preciously generated LCI model into impacts. All materials and processes can be appointed a representative environmental impact. The appointed impacts of a material can however significantly differ between sources. Either due to methodological differences, but also because a material or process can be made in different ways, with different fractions of renewables or in countries will lower environmental standards.

Assessments that are fully based on foreground data are able to state the impacts most accurately. Other assessments require more generalised representative impacts. These assessments are thereby more dependent on the assumptions made within the data-sources used.

Interpretation Stage
The final interpretation stage of the LCA interprets the results from the previous stages. It identifies significant issues in the design, and assessed the sensitivity of uncertainties. It also includes completeness and consistency checks. It thereby presents an indication on the level of confidence of the presented results.

Different methods and impact categories

Even-though the Life Cycle Assessment methodology is a standardised method, there are numerous variations to its execution. The outcome of the LCA also strongly deviates depending on the used methods. The most notable methodological choices are: Attributional vs Consequential, and how to deal with multi-functional processes.

Consequential assessments assess the 'changes in impacts' as a consequence of the product. This could include future changes in the market, or other consequences as a result of the product. This therefore require a detailed market research. Attributional assessments assess the impacts related to a product itself; by linking impacts to the materials and processes of the product. This method therefore assesses the current impact potentials of the assessed systems.

Multi functionality is a problem when comparing different products. The impacts of systems are compared based on functional a **functional unit**, this is a specific function that all assessed systems perform. The functions of the compared systems should be equal. There are several methods to deal with this multi functionality if one of the compared systems performs a secondary function. The function (and related impacts) either needs to be removed from this system, or added to the other systems to match the functions of the compared systems. If these methods are not possible, the multi functional process can be allocated. Allocation is for example used to allocate the impacts of a production line with 2 products, accurately over its products. The allocation of the impacts can be based on a physical relationship, a representative parameter, or an economical relationship.

Methods, Midpoints and Endpoints
The outcome on an LCA can be mitpoint indicators or endpoint indicators. Endpoint indicators are determined by weighing the importance of different midpoint indicators. Endpoint indicators are: human health, ecosystem quality, climate change and resource depletion. Midpoint indicators are more specific to specific impacts, such as: Human toxicity, ozone layed depletion, global warming potential and accidification potential.

The included midpoints and the values with which substances are normalised to these midpoints differ between available LCA methods. Thereby the GWP impact of 1kg of methane is 28 times the impact of CO_2 according to one method, but higher or lower if it was calculated with another method. Figure 2.10 presents the midpoint indicators as used in the CML method, as presented in a Vestas LCA report.

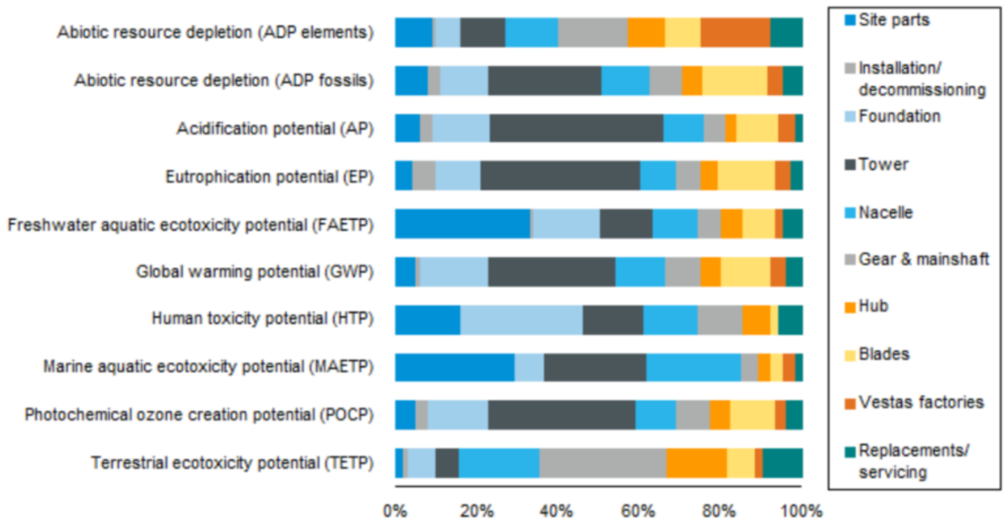


Figure 2.10: Example of LCA output for more impact categories (Vestas, 2019a).

End of Life, Recycling There are multiple ways of performing an LCA, such as cradle-to-Gate, cradle-to-grave and cradle-to-cradle. These include different selections of life cycle stages included in the assessment. These stages are: raw materials & Manufacturing, Installation, Operations&maintenance and End of Life.

Figure 2.11 shows the results over 4 life cycle stages. The method used in that assessment included credits for recycling at end of life. This is performed with an alloction method At Point Of Substitution. The EOL materials thereby substitute the requirements of vigin materials, and the saved impacts are credited to the original system as avoided impacts. another methods (allocations at Cut-Off) does not give credit for avoided impacts. This method does therefore not have negative EOL imapacts, leading to higher output impact values.

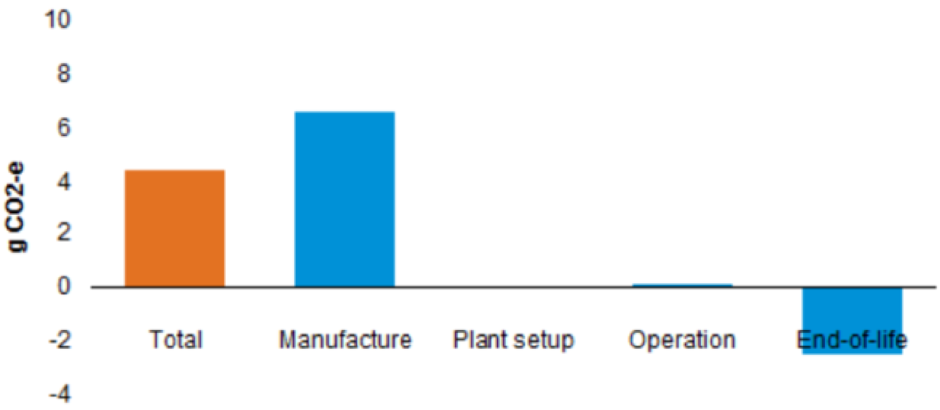


Figure 2.11: Impact distribution of a LCA that included recycling (Vestas, 2019a).

More information

This review only presented a very limited summary of all literature on performing an LCA assessment. various reports and books present much deeper insights than could be provided here. All in accordance to the ***ISO standards*** *ISO-14040:2006 and ISO-14044:2006.* Useful sources on performance of an LCA are:

- *Life Cycle Assessment, Theory and Practice* (Hauschild et al., 2018) A handbook that detailed all steps to undertake in order to perform an LCA.
- *ILCD Handbook* by the Institute for Environment and Sustainability - JRC - the European Commission
- *LCA: a practical guide for students, designers and business managers* (Vogtlander, 2012). More focused on usability the design process of a product.

2.2.2 LCA in Wind Energy

The primary advantage of renewable energy systems over fossil energy systems are their reduced impacts on the environmental. These impacts have therefore also well researched. There are numerous reports on the environmental impacts of HAWT technology. The environmental impacts within the AWE sector have however only been assessed minimally before.

AWE
The single previously performed documented LCA research on an AWE system was performed on an earlier design of the Ampyx system (Wilhelm, 2015). This paper found an GWP and CED impacts of 5.6 kgCO_2eq/MWh and 75.2 MJ/MWh for energy production using a 327 MW farm of 1.8 MW AWE systems.

This paper also determined that the Energy Payback Time (EPBT) of the AWE system would be 5 months, compared to an EPBT of 9.5 for a comparable HAWT system. It was also determined that AWE technology only uses 23% of the mass compared to HAWT system. Similarly, the GWP and CED impacts of AWE were found to be only 55% and 55% of the impacts of the modeled HAWT technology.

HAWT
The results of the numerous LCAs on HAWT systems strongly deviate between the different reports;

partly due to actual differences in assessed systems, but the differences are often also the results of differently chosen LCA methods. It is impossible to accurately compare the results of different LCA studies without detailed assessments and even alterations to match the used methods. There are however a large number of LCA studies performed in literature, some of which specifically on comparison of different assessments.

One of these comparison papers is Davidsson et al. (2012), who presented Energy Pay Back Times (EPBT) range anywhere from 1.3 to 27.6 months. Indicating the extreme variability of the impacts for different HAWT systems, under different assessment boundaries.

Other papers; Smoucha et al. (2016) and Chipindula et al. (2018) also assessed how the impacts differed for different sized rated power systems. The first paper clearly concluded that scaling up is beneficially for impact reductions, in the full assessed range from 50 kW to 3.4 MW. The second paper came to similar conclusions, this paper additionally also concluded that offshore systems have higher impacts compared to onshore systems.

Assessments performed by companies:
Vestas has published LCA reports on several of their products, Vestas. Similar reports were published by by Siemens: Gamesa (2020). These reports proved highly informative.

Chapter 3

Goal Definition

The limited prior research into the environmental impacts of AWE leaves a large range of research topics to be assessed. This chapter states the topics assessed in this project; it includes the research objectives. intended applications and target audience of this assessment. It combines the Goal definition requirements of an LCA with research objective statement as required for an academic study.

3.1 Research Goals/Objectives

The primary objective of this research is to assess the environmental impact of future Multi-Megawatt AWE technology; To quantify its impacts, to locate hot-spots and to compare its impacts to the impacts of a comparable conventional wind energy systems. Before the impacts can be defined, first, a potential future system needed to be designed.

The assessed impact categories are the Global Warming Potential (GWP) and the Cumulative Energy Demand (CED). These impact are determined using an Life Cycle Assessment method. Its results are also to be used to determine the Energy Pay Back Time (EPBT) and Energy Return on Investment (EROI).

An additional objective is to assess the advantages and disadvantages of several design choices for both AWE and HAWT technology. Most notablly, the location and environmental conditions for which the systems are designed.

A final objective is to further the knowledge of sustainability within the AWE sector; to indicate areas with valuable improvement potentials, to indicate problem materials and components within the design, and to provide recommendations that could be used to further improve sustainability within the AWE sector.

3.2 Intended Applications

This LCA is performed in collaboration between *Airborne Wind Europe (AWEurope)*, *Ampyx Power* and the *Technical University Delft*. AWEurope is the association of the European airborne wind energy industry. Their specific aim is to further the development of this novel technology (AWEurope, 2020). AWEurope intents to use outcomes of this LCA project as input in a future deliverable on the environmental performance of AWE.

3.3 Target Audience

This research is performed with the intention to improve general knowledge on material usage and sustainability topics of future large scale AWE systems. The content is intended for policy makers, researchers and developers alike.

The assessments may provide AWE companies with insights on environmental hot-spots within the presented potential future AWE system. These insights may guide research- and design-focus, potentially leading to impact reductions in future systems. The assessment also reevaluates the claim that AWE technology leads to environmental improvements over HAWT technology. The insights provided in the work may help inform policy makers in their evaluation of the technology.

3.4 Commissioner of the study and other influential actors.

This report is formed and performed as Master Thesis project for the TU Delft. Combined research interests lead to a collaboration with industry partners: Airborne Wind Europe (AWEurope) and Ampyx Power. The design of the modelled system is based on the Ampyx power system, coupled with their visions and concepts for the future. The model largely depends on direct data provided by Ampyx, other parts are modelled from literature.

The large rated power of the systems was chosen to better match the business case of Ampyx power. Ampyx did not want to compare their small systems to wind energy, as this system is primarily intended to replace off-grid diesel generators. Comparison to conventional HAWT systems is however considered of upmost importance for validation of the environmental performance of AWE technology.

3.5 Limitations of the study

The modelled 5 MW system sizes were deliberately chosen for reasons of comparability and data availability. The modeled AWE system is largely based on data provided by Ampyx power. This data is however not based on an actual design of such a large system. The data is largely based on scaling estimations from earlier designs, as well as prognoses and assumptions for future large-scale systems. The rated power of the 5 MW system is a factor 33.3 higher than that of the largest developed system by Ampyx thus far.

This early modelling results in high uncertainties for impacts of an actual system. Sensitivity studies were carried out to assess the effects of some of these variables. It proved not possible to validate the provided estimations this early before any available design, nor was it possible to provide realistic deviation ranges on the provided data. Sensitivity analysis are therefore primarily carried out to indicate the effects of various deviations from a base-case model.

As mentioned, the early modelling means that all data is based on literature, estimations and assumptions. The impacts of the manufacturing processes are modelled with averages mentioned in impact databases. The data is therefore all of low specificity to any actual future 5 MW system.

The assessment is performed using a method that cuts off the impacts of material recycling. Inclusion of recycling would benefit metallic materials most, as recycling of most other materials is still far less developed. Usage of another LCA method would significantly reduce the impacts of both the AWE as the HAWT systems, but was left outside the scope of this work.

The systems are only assessed for the GWP and CED impact categories. These are often considered the most important impact categories for energy systems. The output of the LCA is thereby however not a full environmental assessment, as it does not assess other environmental impacts.

Chapter 4

Scope Definition

The standard Scope definition of an LCA states all administrative aspects that are important for validation and comparison of the work. The scope includes: methods, assumptions and boundaries used in performance of the assessment. It also introduces the assessed systems.

4.1 Methodology

An LCA is a methodological approach for assessing the impacts of a product of service. The environmental impacts of a product can be determined with multiple different LCA methods. The assessment can be performed on detailed measured data, such as the actual energy usage of a factory, or on an early design without any further knowledge. This project does however not have access to an actual design either; no direct data is available, and reasonably defined designs for future system do not exist yet.

Therefore, this project also had to design a system that could to represent a potential future AWE system. Systems such as the landing deck and aircraft strongly depend on the design of the company, estimations of these systems were therefore provided by Ampyx. Especially the design of the launch and landing systems fully depend on the design and control procedures envisioned by the company.

Many other elements were designed personally, especially the systems in the Power Generation Apparatus (PGA). These elements were accepted, but not designed by Ampyx. The PGA consists of the drum, a hydraulic drivetrain with accumulators, generators, converters and a transformer. These components were primarily scaled from (HAWT) literature, or designed with product catalogues.

The impacts of specific products is primarily related to their materials and manufacturing processes. Every single component in the design could have been produced in numerous ways. Products could be manufactured with many different material options, and often even entirely different technologies could be used. The best options, or options on which best data was available have been chosen when required.

Data collection and processing
The masses of the systems were primarily taken from manufacturers catalogues. The mass of a specific 6250 kVA converter is thereby found to weigh approximately 5 mt. The material composition of the converter is found in an Environmental Product Declaration of another product of a different size. These sources presented the best available data when combined; using the mass of an actual system, with the material composition of another system.

The LCI stage of the LCA represents the inventory of a bill of materials and processes for all components in both the AWE and the HAWT farms, as described for the converter above. This inventory however only presents approximations, as it is not based on an actual design, and numerous variations are available for almost every component in the systems.

The impacts, calculated in the LCIA stage, are modelled in the same Excel model as the previous LCI inventory. The impacts of the systems are determined by linking specific impacts to the materials and processes unit inputs.The majority of these impact values were obtained from the Ecoinvent database

The data used in this report came from a wide variety of different data sources such as:

- Literature
- Environmental Product Declarations
- Product Spec sheets
- LCA Databases

- Product Catalogues
- Expert consultations

Average Material Processing
The majority of all impacts were found using the Ecoinvent database. Including average processing impacts for the metals. The database did however not include average processing work for all metal materials. A representative metal work process was made for cast iron. This includes the same metal work processes and scrap percentages as found in the low-alloy steel data-set, only with replaced material. Cast iron might produce less scraps, especially in larger system, but it is considered indicative enough based on data presented in a detailed LCA project on hydraulic motors (Bhander, 2001).

4.2 Functional Unit

A functional unit (FU) is an easily identifiable unit function that allows for comparison between different systems and system configurations. The chosen functional unit is:

1MWh of electricity delivered to the grid, generated from the wind.

This unit is generally used in assessments of wind energy systems. It only allows for comparison of wind energy systems and should not directly be used for comparison with continuously operating electricity generation systems such as nuclear, gas and coal.

4.3 LCA Modelling Framework

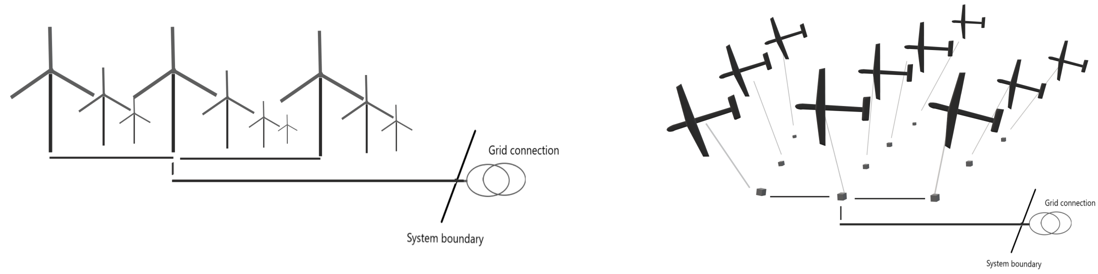
The LCA is carried out using the Cut-off allocation method. Therefore, avoided impacts related to recycling of End of Life (EOL) materials are not credited to the assessed systems. Other allocation is not required; Both evaluated systems only deliver the same Functional Unit (Electricity from the wind). Neither of the systems produces secondary functions, therefore there are no additional processes that require allocation.

Additionally; This assessment is an attributional LCA. Only the impacts related to the materials and processes of the systems are assessed. These impacts are also compared to those of HAWT technology. It is however not assessed how usage of AWE would change the market over a larger time period, as would be the case in a consequential LCA.

4.4 System Descriptions

Both the comparison between AWE and HAWT technology as the individual hot-spot analysis were carried out using modelled hypothetical farms of 50 MW. Both technologies were modelled from the ground up. Thereby, the systems were modelled with the largest consistency; with the same assumptions, boundary conditions, material and processes; ensuring the most accurate comparability.

Both systems are designed on the basis of various literature sources, product catalogues, expert input and assumptions. The AWE system is based on the system type of Ampyx Power, characterised as a rigid-wing, Ground-Gen, Cross-Wind AWE system. The HAWT system is not intended to represent any specific turbine. Instead, it is intended to function as the best comparison for the assessed AWE system. The individual AWE and HAWT systems are rated 5 MW each.



(a) HAWT farm

(b) AWE farm

Figure 4.1: Visualisations of the 50 MW farms and the considered system boundaries. Systems not to scale.

The systems are divided into logical subsystems. The BOS is assessed as a separate subsystem. Each subsystem is individually assessed for hot spots. Combined they add up to the total system impacts.

AWE System

The evaluated AWE system is a 5 MW Multi Megawatt design based on the general design of Ampyx Power. Ampyx is currently only in the early process of feasibility studies for their first commercial AWE systems of 1 MW, the AP4. The system presented in this report could therefore not be based on an actual design. Instead, a design is partly made based on a mixture of knowledge on the earlier 0.15 MW AP3 test system and minimal insights on concepts for the AP4 system. This data is coupled with a variety of predictions, assumptions and future views supported by Ampyx. The system is assessed for its 5 subsystems as presented in figure 4.2 and its main specification are presented in table 4.1.

Location	Onshore
Rated power	5 MW
Capacity factor	52.8% at 11 m/s
Lifetime:	20 years
AWE type	Ground-gen, Rigid wing
Wing span	53.7 m
Average flight height	250 m
Tether length	1200 m
Tethering:	Single tether, 2 sections
Drivetrain:	Hydraulic

Table 4.1: Main AWE specifications

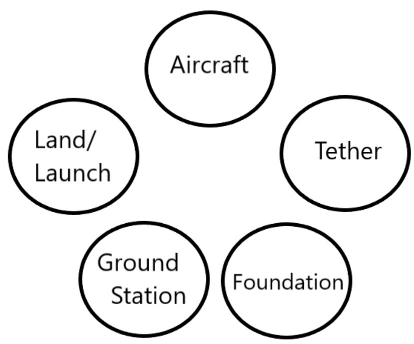


Figure 4.2: Subsystems of the AWE system

HAWT System

Selection of the comparable wind turbine can significantly influence the results of the comparison between HAWT and AWE technology. Selection within this report is primarily based on rated power and data availability. The modelled HAWT system is largely based on a NREL 5MW optimisation, coupled with data found on similar systems in literature.

The NREL 5MW is a well known standardised wind turbine design, based on the Repower M5 turbine. The Repower 5M was designed for operation at locations both onshore as offshore. The NREL 5MW is however specifically presented as a standardised model of an offshore wind turbine. Most data found on this offshore turbine is assumed representative for the presented onshore HAWT model. The system is assessed for its 5 subsystems as presented in figure 4.3, its main specification are presented in table 4.2

Location	Onshore
Rated power	5 MW
Capacity factor	46.9% at 10 m/s
Lifetime	20 years
Rotor diameter	126 m
Hub height	117 m
Wind class	IEC2 to IEC1
Generator type	DFIG
Tower type	Steel cylinder

Table 4.2: Main HAWT specifications

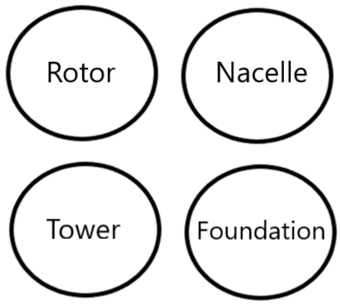


Figure 4.3: Subsystems of the HAWT system

Farm model

The technologies are compared for operation in a hypothetical farm of 50 MW. The farm is modelled onshore, with a distance to the grid of 15 km and a layout as presented in figure 4.4. The farms are modelled with operation at the same specific location. The environmental conditions experienced at a location differ over the distance from the ground. The average wind speed experienced by the AWE systems will therefore be higher than that experienced by the HAWT systems at the same locations.

Topic	Value/Description
Farm Size	50 MW
NR of Systems	10
Service Life	20 years
Location	Onshore, The Netherlands
Distance to Grid	15 km
System Distance AWE	1 × Tether length (1200 m)
System Distance HAWT	7 × Rotor diameter (882 m)

Table 4.3: Farm specifications

The location of the farm is selected based on the wind class rating of the HAWT wind turbine (IEC1). The wind speed experienced by the AWE system at higher height is estimated with the Log-law. The energy output of both systems is summarised in table 4.4. This topic is further detailed in section 5.5.1.

	Unit	AWE	HAWT
Rated Power farm	MW	50	50
Average wind speed	m/s	11	10
AEP farm	MWh/year	231264.0	205442.8

Table 4.4: Energy production summary, essential for comparability of systems.

These energy production values include a 98% availability, 3% wake losses and 6% drivetrain losses for the HAWT system. The AEP estimation of the AWE system is based on data provided by Ampyx. It includes a 95% availability and a 95% round trip energy storage efficiency. Both systems include an assumed 3.25% cable loss to the grid. It remained unknown which drivetrain losses Ampyx considered within the AWE systems, these losses are however stated to be included in the provided AEP estimation.

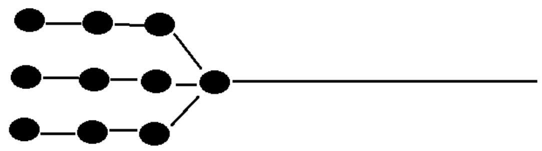


Figure 4.4: Farm layout for 10 systems, representative for inter array cabling selection.

BOS Description

The Balance of System (BOS) is modelled as a separate section in the assessment, it however only includes cabling. The usage of a transformer substation has not been included in this report, therefore all transmission takes place at 33 kV AC. Additionally, the foundations are included within the generation systems. Detailed design of the BOS (cable) system is presented in section 5.3.

Cabling Both farms require 9 inter array cables to connect the individual systems. Transmission to the grid is performed by 2 export cables. All cabling is modelled with 33 kV AC cables with aluminium conductors. The cross-sectional area of the conductors of the inter array cables are 3×240 mm^2, the export cables are 3×600 mm^2.

4.5 Boundaries

There are 3 sets of boundary conditions to be disclosed. Combined, these boundaries provide important information on the reach of the LCA study. Documentation of the system boundaries is essential for the validity of the assessment and the ability to compare this report to others. The individual topics treated in the subsections below are: The included life cycle stages, the boundaries of what is included for the systems, and the Cut-Off criteria.

Life Cycle Stages

This assessment is preformed as a 'Cradle-2-Grave' LCA. It includes the impacts over the full Life Cycle of the system, from: *Materials & Manufacturing*, *Installation*, *Operation & Maintenance* and a simplified *End-of-Life* treatment stage. The considered impact processes included in each of these stages are specified in table 4.5. The impact result will both be provided for each of these stages individually and for the full systems combined.

Life Cycle Stages			
Materials & Manufacturing	**Installation**	**Operation & Maintenance**	**End of Life**
• Materials • Processes	• Transport • Site preparations • Construction	• Replacement parts • Maintenance • Losses • Energy production	• Dismantling • EOL processing • Transport

Table 4.5: The assessed Life Cycle Stages and their included activities.

Materials and Manufacturing
The material and manufacturing stage (hence forward named; 'Manufacturing') includes all raw materials and processing steps required to manufacture the systems. This section includes design variables and assumptions for both systems.

Installation
The hypothetical farms are modelled as Onshore farms in the province of Zuid-Holland in The Netherlands. The installation stage includes transport, land transformation and installation activities at this location. This transport only includes transportation of the completed systems installed at the initial commissioning. Transport of raw materials is included in the manufacturing life cycle stage.

Land transformation and installation activities are strongly simplified. Land transformation only includes digging activities for the foundations and the cables. Installation processes are represented by crane operation.

Operation and Maintenance
Impacts over the operational life of the systems include: replacements, consumables, servicing trips and energy losses. The O&M stage also includes the generation of electricity.

End of Life
The EOL stage includes removal of the systems, transport to the EOL treatment facilities and simplifications for the EOL treatment processes. Impacts of recycling are cut-off, thereby avoided-impacts of recycling are not credited to the original systems. The usage of recycled (metal) materials is included by using market mixtures for the original input material data-sets, as taken from the Ecoinvent database.

System Boundaries

The AWE and HAWT systems are assessed in 50 MW farms. The boundaries for these farms include all systems up to the grid connection. Additionally, the differences in relative environmental conditions are included as an input difference, to compare the systems for operation at the same location.

Cutoff criteria and Completeness Requirements

Cut-Off criteria were difficult to define for this project, as the presented systems are not based on detailed data.

No more than 1% of the mass, energy or impact has knowingly been excluded unless stated specifically. Materials and processes are however often represented by other data-sets that are assumed best representative. This is stated for each material.

4.6 Representativeness of LCI Data

The presented systems should be seen as indicative for a potential 5 MW system with current knowledge. The AWE system has been modelled in accordance with current views for the future. The system sizes have been calculated, estimated and scaled based on previous designs, assumptions and concepts for future systems. It will have low representativeness to an actual future 5 MW system. The results of this report may help guide the focus for future design improvements. This is supported with sensitivity cases on some of the design variables.

Technological and Temporal coverage
This assessment is performed to assess the potential environmental impacts of (far)future large-scale AWE technology. The impacts are however presented with available data on materials and processes of recent years. Large portions of future large-scale systems are also not assessed by Ampyx yet. Data on these components is therefore designed based on currently available literature and product catalogues. Many improvements are to be expected before the actual 5 MW system becomes realised. The 5 MW HAWT system is largely based on the NREL 5MW. This is a relatively old turbine. Data of this system has been collected from recent design optimisations found in literature.

Geographical coverage
Manufacturing is all assumed to take place in Europe. The products are assumed to be manufactured in Denmark, since it already is an industry hub for wind energy manufacturers. The materials are all modeled with Global-Market data-sets. All processes are however modeled with European Production data-sets. When used specifically; 'electricity' is modelled with *Medium voltage electricity, Danish grid* and 'heat' with *'district or industrial heat, other than natural gas, Europe'*.

Electricity generation is considered to take place onshore in The Netherlands. The distance to the grid and transport distances are roughly representative for the European market. These values are based on data presented Vestas and Siemens LCA reports.

4.7 Impact Categories and Methods

The systems are assessed for 2 midpoint impacts indicators: The Global Warming Potential (GWP100) and the Cumulative Energy Demand (CED).

The GWP and CED impact categories are the most frequently used impact categories in LCAs on renewable energy systems. Additional impact categories have been evaluated in the assessment, but were excluded later in the project. The focus on just these two impact categories is considered to provide the most useful results, both for system validations as for indications for improvements potentials. More detailed information about all impact categories can be found at: EC-JRC-Institute for Environment and Sustainability (2012) and Hauschild et al. (2018).

Global Warming Potential (GWP100)

The GWP is the representative impact indicator for greenhouse gas emissions responsible for the long term warming of the climate. The value is presented as kg CO_2 equivalent.

All substances have different potential impacts on climate change. The GWP impact indicator makes it possible to compare the impacts of these substances. The GWP value of a substance presents its impact on global warming normalised to the impact of CO_2. Additionally, substances are removed from the atmosphere at different rates. The GWP indicator of CO_2 is always 1 kgCO_2eq/MWh , independent of time. The GWP factors for all other substances may however differ over time.

For example, the GWP(100) of methane is 28 kgCO_2eq/MWh . Over 100 years, methane will have 28 times more impact on the warming of the earth than CO_2 does. The GWP(20) of methane is however 84 kgCO_2eq/MWh . Meaning that it is more potent on the short time scale, but reduces over time. The time-frame considered for is the GWP100, stating the global warming potential over 100 years.

The CO2 equivalent factors of these substances differ depending on the impact method used in the assessment. The GWP impact is calculated with the CML method (CML-IA baseline, EU25). The CML method is frequently found in other assessments of energy systems, most notably in those of Vestas.

Cumulative Energy Demand (CED)

The CED states the total input energy requirements of a product, presented in MJ. It is calculated with the Cumulative Energy Demand v1.11 method.

It includes all energy requirements within the boundaries considered for the assessment. This 'cumulative' CED is subsequently normalised to the stated Functional Unit of the systems to compare different products. The CED is subsequently also used to calculate the Energy PayBack Time (EPBT) and the Energy Return on Investment (EROI) of both systems.

The Energy Payback Time (EPBT)
The EBPT states how much time passes before the input energy is fully recovered.

The Energy Return on Investment (EROI)
The EROI states how many times the input energy of the system will be recovered over the full lifetime of the system.

Chapter 5

Inventory Analysis (LCI)

The Life Cycle Inventory Analysis (LCI) is the second and by far the most time-consuming stage of the LCA. The output of the LCI is the bill of materials and processes that a system required to perform the specified functional unit of the assessment.

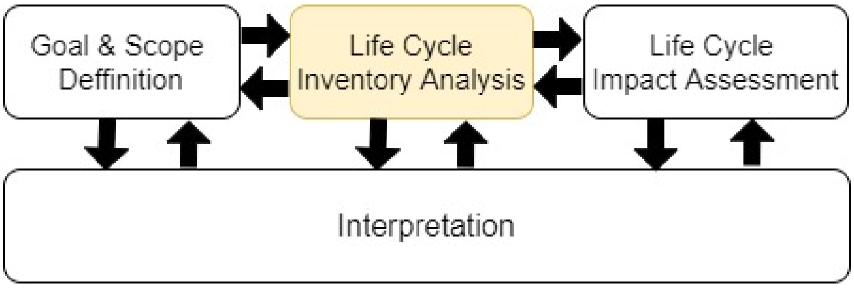


Figure 5.1: Stage 2, the LCI

There life of a product can be divided into 4 life cycle stages. These are the: *Materials & manufacturing*, *Installation*, *Operation & Maintenance* and *End of Life* stages. The boundary condition chosen for this LCA is Cradle to Grave. Therefore, the impacts over all 4 life cycle stages are included in the assessment. The elements included within each life cycle stages were stated in section 4.5.

The manufacturing life cycle stage is split into 3 sections. Section 5.1 first details the design and manufacturing of the AWE system, followed by the design of the HAWT system in 5.2 and the BOS in 5.3. The installation, O&M and EOL life cycle stages are subsequently modelled in sections 5.4, 5.5 and 5.6.

This presents the base-case system, variations are only included in the sensitivity analysis.

5.1 Manufacturing of AWE System

Manufacturing of the AWE system is divide into 5 individual subsystems. The subsystem boundaries are chosen, based on the functions performed within the AWE system. Their selected boundaries are chosen for optimal comparability to HAWT technology, but also for best relatability for other AWE system designs. Table 5.1 states the components included within each subsystem. Each subsystem is modelled individually over the following sections.

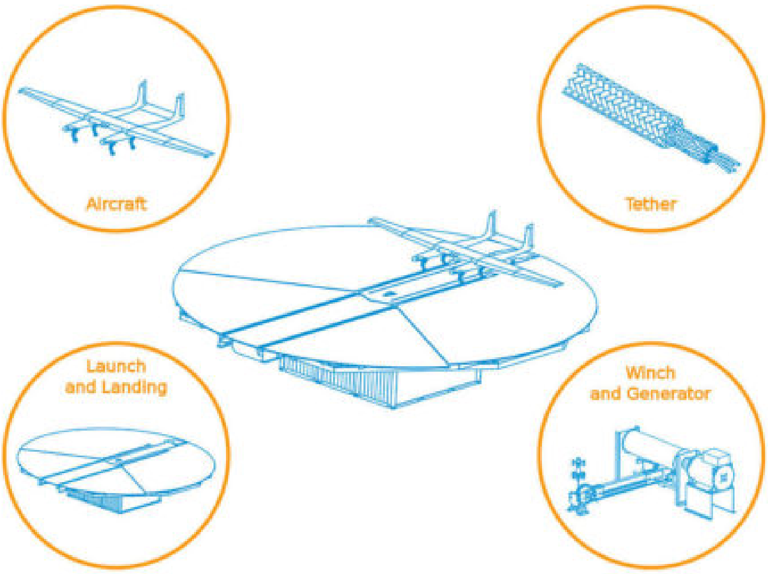


Figure 5.2: The generally considered subsections of the Ampyx system (Mission Innovation).

Aircraft	**Tether**	**Ground station**	**Land/Launch**	**Foundation**
Wing	Top Section	Drum	platform	Foundation
Fuselages	Bottom Section	hydraulic drivetrain	Yaw system	
Tale		Generators	Catapult	
		Converters	Shifter	
		Transformers		
		Control systems		

Table 5.1: AP4 System components close-up

5.1.1 Aircraft

The Aircraft is a rigid wing glider with an predicted wingspan of 53.7 m and a wing surface of 300 m^2. It is modelled according to Ampyx predictions, however the actual design of a large scale Ampyx AWE system is still entirely undefined. The presented design is therefore largely based on scaling from the AP3 model, accompanied with expected improvement potentials and prospected design changes for future larger scale systems.

The mass of the 5 MW aircraft is assumed 20 mt. This mass is the outcome of a modelling estimation provided by Ampyx, which includes significant design improvements compared to current designs. An extreme mass case can be defined by direct scaling based on the AP3 design. Scaling this pre-commercial model up to 5 MW leads to an aircraft with an approximate mass of 34 mt and a wingspan of 64 m. Reduction to a mass of 20 mt includes assumptions for significant aircraft design changes and technological improvements of materials and components.

Potential methods to further reduce the aircraft mass are: by re-design to use a fixed instead of a retracting landing gear, or by using a combustion engine instead of the currently used battery powered propulsion. Mass reductions may also be presented by the usage of improved manufacturing methods. This is especially the case for CFRP components.

The presented material composition of the aircraft is that of the scaled up version of the AP3 model. The mass reduction from the 34 mt to the 20 mt aircraft are therefore considered to be carried equally over all components of the design. Further optimisation of the design is stated to be able to reduce the mass of the aircraft even further. E.g. by replacing the heavy battery propulsion system with (hydrogen) combustion propulsion. This would however require an extreme redesign of the material composition of the aircraft and is therefore excluded from this report.

Figure 5.3: Rendered model of the AP3 aircraft design (Diehl et al., 2017).

The aircraft subsystems are assumed equal to the AP3 system design presented in figure 5.3. This is build up from 3 subsystems: The wing, the fuselages, and the (horizontal) tale. The wing and tale systems are mostly structural and aerodynamic control components. They primarily contain of CFRP and aluminium structures combined with actuator systems. The largest masses of the aircraft are located in the two fuselages which carry various heavy system such as the battery-propulsion system and the landing-gear. Global indications of the masses and materials used in the different aircraft sub systems are provided in tables 5.2 and 5.3.

	Unit	**Total**	**Wing**	**Tale**	**Fuselages**
Fraction of mass	-	100%	27.0%	7.5%	65.5%
Mass	kg	20000	5400	1500	13100

Table 5.2: Mass distribution of the aircraft, replacements not included

The materials used in the aircraft are:

Material/Component	Total	Wing	Tale	Fuselages
CFRP	48.2%	45.2%	48.8%	49.3%
Aluminium	13.63%	19.6%	1.8%	12.5%
Batteries	12.77%	0%	0%	19.5%
Motors	12.58%	14.5%	43.2%	8.4%
Titanium	2.70%	8.6%	0%	0.6%
Stainless steel	1.6%	3.9%	2.7%	0.6%
High strength steel	4.1%	4.5%	4.5%	4.5%
Low alloy steel	2.03%	0%	0%	2.0%
Additional*	2.33%	3.71%	0%	2.03%

Table 5.3: Material percentages in the aircraft. First as a total followed for each of the subsystems individually. *: Additional materials are: 1.25% electronics for control, 0.24% cables, 0.05% tire and 0.01% GFRP. 0.73% of the material mass is unknown and excluded. Replacements not included.

It should be noted that the mass fractions within the aircraft are expected to contain errors. The wing skins appear to missing in the data, their inclusion would lead to a higher fractions of FRP material wing subsystem. The total mass of the system was however provided otherwise and would not be influenced.

The motors dataset represents both the propulsion motors as the actuators for all control surfaces. The propulsion motor only represents 32.6% of the motor-related data-set. Totalling only 4.1% of the total aircraft mass. The propulsion system mass is however largely defined by its battery packs, which represent 11.7% of the total mass of the aircraft. Not including their replacement after 10 years of operation.

The CFRP material is modelled as presented in the subsection below. The motors are modelled by a data set for electric car motors. The batteries are modelled as prismatic Li-Ion rechargeable batteries, as could be used in electric cars.

5.1.1.a Fibre Composite Structures

When CFRP is mentioned in this report, it includes the fibres, epoxy, core, glue and coating of the skins and structural elements of the aircraft. Carbon Reinforced Fibre Polymers (CFRP) are exceptionally strong but low weight composite materials. Their low weight to high strength ratio makes them perfect for use in the aircraft, where the mass directly relates to the efficiency and potentially even the feasibility of AWE technology.

CFRP makes up for 48.2% of the total mass of the aircraft. This includes the carbon fibres, the epoxy resin, core materials, adhesives and all coatings on the aircraft. The exact mass and mass composition of CFRP components can strongly deviate based on design choices and the considered manufacturing method. The manufacturing method assumed in this report is that of Resin Infusion (RI).

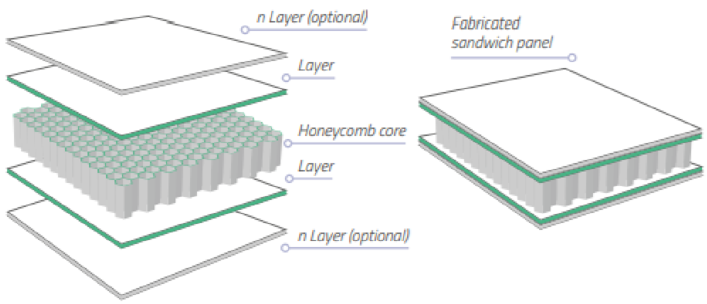


Figure 5.4: The structure of FRP laminates (EFW)

Resin Infusion is one of the most commonly used manufacturing methods for FRP materials. It uses vacuum pressure to pull liquid resin into the matrix of the fibre reinforcing mats (figure 5.5). The specific CFRP composition strongly deviates depending on the function of a component. The CFRP wing skin has a different composition than the structural elements inside the wing. The material composition of the

CFRP mixture is assumed as an average over all components in the aircraft. This average composition (presented in table 5.4) is approximated based on a previous internal study on the composition of the wing structure alone (Fagan, 2020).

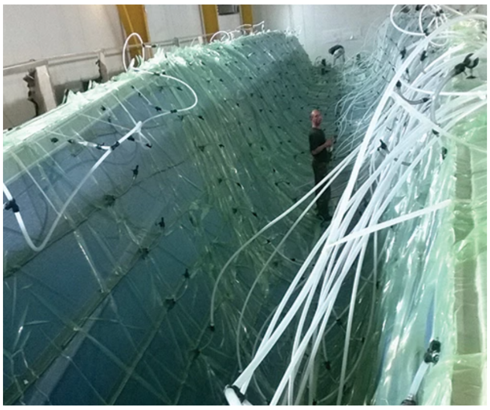


Figure 5.5: The resin infusion manufacturing process (Composites World, 2016)

Material	wt%	wt%	wt%
Fibre/Epoxy mix	85.7%	100%	-
Carbon fibres	-	60%	51.4%
Epoxy resin	-	33.9%	29.1%
Hardener	-	6.1%	5.2%
Core	4.77%	-	4.77%
Glue	5%	-	5%
Coating	4.5%	-	4.5%

Table 5.4: Material composition of the fibre composite structure materials 1: wt% of components, 2: Wt% within fibre/epoxy mix, 3: Wt% of specific material mix.

Fibres Carbon fibre production is a highly energy intensive process. Therefore it comes with significant impacts per kg of material. The fibres will represent approximately 60% of the mass in the carbon fibre-epoxy mixture. This is a reasonable indication of the ideal CFRP composition, deviations in this composition would strongly influence the properties of the material. The impacts of the fibres are the driving factor for the large impacts of the CFRP components. Apart from the fibres, CFRP mostly uses the same materials as GFRP.

The impact of 1kg of carbon fibres strongly deviates between different reports. The values used in this report were extrapolated from the Eco calculator of the European Composites Industry Association (EuCIA; Scheepens et al., 2020). Leading to a GWP of 39.2 kgCO_2eq and a CED of 789 MJ per kg of carbon fibre after conversion to the CML method.

These values represent the impacts of PAN type carbon fibres. PAN (polyacrylonitrile) based carbon fibres are the most commonly used (fossil based) fibre type. The major driver behind the impacts of the fibres is the energy requirements to produce these PAN fibres. Carbon fibres can however also be made from a lignin base. Lignin is extracted from wood-pulp and is a waste product from the biomass energy industry. The impact of these Lignin based fibres also strongly deviates per report, however recent research states that lignin based carbon fibres could potentially be produced with an impact lower that that of glass fibres (GreenLight, 2021). Whether these fibres will also suffice for usage in AWE systems is not known. Lignin based fibres (as well as recycled fibres) are short fibres, which reduces the CFRP strength (Mouritz, 2012).

Polymers The polymer mix is a 2 component mixture of a plastic and a curing agent. The most commonly used polymer type in FRP products is thermoset plastic. Recent research and announced recycling legislation are however indicating a potential shift to the usage of thermoplactic polymers. This switch would strongly improve the recyclability of FRP materials.

The polymer mix considered in this assessment is (a thermoset type) Epoxy Resin mix. The mix is a 100:18 epoxy to curing agent wt% mixture as found on product sheets (FibreGlast). The epoxy is modelled as liquid epoxy resin and is mixed with an ethylenediamine epoxy curing agent. Impacts for both materials is collected from the ecoinvent database.

End of Life The EOL treatment of the blades of wind turbines is still a major issue once the turbine is decommissioned. The recyclability of the blades could be improved if different polymer materials were used. A significant problem with recycling of FRP materials is that current processes to remove the thermoplastic polymer material also damage the fibres. This is especially the case for glass fibres, for which (new) virgin material is incredibly cheap to make. Therefore recycled glass fibres are not only weaker, they are also more expensive.

This is different with carbon fibres. These fibres are not damaged as much by the recycling process. Additionally, virgin carbon fibres are significantly more expensive than glass fibres. Therefore CFRP might be more applicable for useful recycling, given its lower function-to-value loss.

Current research is also performed on the use of thermoplastic polymers to replace the thermosets used in FRP (Froese, 2017; Wismans, 2020). The significantly improved recyclability of thermoplastic based FRP could potentially result in significant impact reductions for FRP products. It will however take a while for the HAWT industry to make this change. It has also not been assessed in this work.

Core, paint and glue The main function of the core material in fibre reinforced polymers (FRP) is to serve as a stiff spacer between the layers of high strength fibre-epoxy mix. Core materials are chosen for maximal stiffens and minimal material density. Frequently used core materials are e.g.: Plastic foams, balsa wood and geometric honeycomb structures.The density of core materials in aircraft structures generally ranges between 75 an 275 kg/m^3 (Mouritz, 2012). Weight restrictions of the AWE aircraft lead to the reasonable assumption that the core material with the lowest density will be used. In which case honeycomb structures are the preferred material. This assessment however models the core material as PVC foam with a density of 200 kg/m^3 , solely due to data availability. This may underestimate the impact of the core. The core represents 4.77% of the mass of the CFRP materials.

Paint is modelled according to the top-coat data set of the EUCIA ecocalculator. It represents 4.5% of the mass of the CFRP materials.

The glue is modelled as a polymer and curing agent mixture with the same materials as the polymer in between the fibres. It is modelled as 2/3rd liquid epoxy resin and 1/3rd ethylenediamine epoxy curing agent. It represents 5% of the mass of the CFRP materials.

Processing Resin Infusion processing impact is 1.23 kgCO_2/kg CFRP and 18.6 MJ/kg FRP material, the glue and paint has not been excluded from this mass. This processing impact is gathered from the EuCIA eco-calculator and only represents the energy consumption of production. No additional impact has been included for the machinery needed to manufacture the products. The data set is presented as an approximation independent from the fibre content.

Production of a FRP component using an RI method requires additional manufacturing consumables. These are largely different layers of fabrics to improve the equal spread of the liquid polymer, figure 5.6. Table 5.5 states all additional material losses and consumables included for both CFRP as for GFRP materials. The used 'cumulative' surface area for the consumables and length of resin tubes are related to the mass of the FRP products. these values represent an average CFRP thickness of 6.67 mm, assuming an average density of 1500 kg/m^3 .

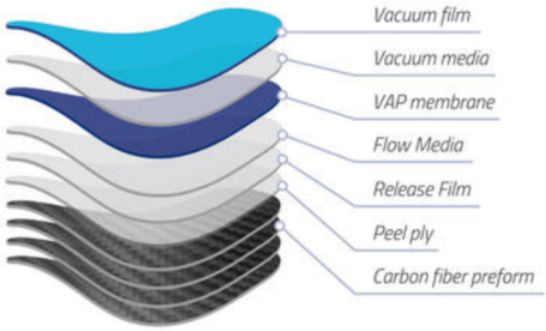


Figure 5.6: Consumables layers CFRP manufacturing (EFW)

Material	**Unit**	**Value**	**comment**	
Carbon fibres	wt% loss	25%		
Epoxy resin	wt% loss	4.6%		
Hardener	wt% loss	4.6%		
Core	wt% loss	25%		
Glue	wt% loss	5%		
Coating	wt% loss	0%		
Vacuum film	g/m^2	143.75	LDPE packing film	
Peel ply	g/m^2	181.25	Proxy by non-woven polyester textile	
Breather fabric	g/m^2	1331.25	Non-woven polyester textile	
Flow media	g/m^2	390.63	Proxy by non-woven polyester textile	
Release film	g/m^2	46.88	LDPE packing film	
Resin tubes	g/m	655	LDPE granulates, plastic pipe extrusion	
Square meter assumed	m^2/kg	0.1		
Meter assumed	m/kg	0.05		

Table 5.5: CFRP manufacturing scraps and consumables. These values are estimations presented by Fagan (2020).

Each of the manufacturing consumables is available in many different material options. The simplest available options have been used. The consumables are only used once, they are modelled with an additional waste%. This is 5% for the resin tubes and 20% for all other consumables, equal to the fraction of waste assumed for the fibres. Additionally excluded consumption materials are: sealant tape, mould release and a VAP membrane. Their masses can be neglected.

Other CFRP processing The chosen processing method for the CFRP materials is that of Resin Infusion. There are however numerous manufacturing methods, and material types that could be used. Different manufacturing methods are able to produce the CFRP components with more accuracy, and significantly less mass, Fagan (2020). These variation were not assessed further in this report. But could have a large effect on the impacts of the AWE system.

5.1.2 Tether

Only a select few materials are able to meet the material requirements essential for efficient AWE operation. The tether of a Ground-Gen AWE system is subjected to immense tension forces. Yet, heavy tethers with large diameters would provide critical problems for AWE operation. The most commonly used material for the tether is UHMWMPE, specifically that produced by Dyneema DSM, who has been a partner to the sector.

Dyneema is an Ultra High Molecular Weight PolyEthylene (UHMWPE) also known as High Modulus PE (HMPE) fibre. This is a PE type material with extra long polymer chains with high crystallinity. Its high strength to weight ratio makes it ideal for use in AWE. Tethers for Ground-Gen systems only have to transfer the force down to the ground-station, and not electricity as it would be the case for Fly-Gen systems. These tethers are made from braided strands of the UHMWPE fibres to form the ropes. This braided roping is required to prevent the rope from unraveling. This does however also halve the maximum breaking load of the fibre materials (Bosman et al., 2013).

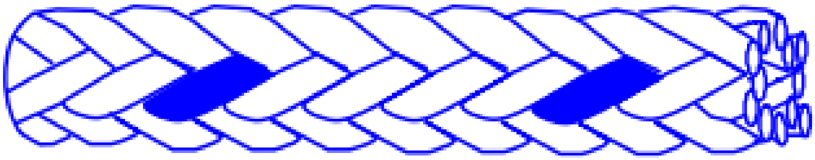


Figure 5.7: Braided tether (Bosman et al., 2013)

The Yo-Yo operation of Ground-Gen AWE systems means that the tether is cyclically wound onto a drum every few minutes. At every bend of the tether, thus also on the sheaves, the internal fibres and strands of the rope move in respect to each other. Friction coefficients within the rope, coupled with these internal movements, lead to friction forces, heat build up and wear damages within the rope. Repetitive bending of the rope leads to accumulated damages, therefore requiring frequent tether replacements. The negative effect of the tether-wear can however be minimised. Firstly; by using a coating. Tethers for AWE uses are coated with 10 to 15wt% coating in between the fibres of the rope. The function of the coating is to reduce the friction coefficient between the fibres. Thereby reducing the negative friction forces, heat build up, and damages when the fibres move around (Meuwissen et al., 2013).

Secondly; Tether wear is influenced by the drum size and the stress on the fibres (Bosman et al., 2013). Relative movement of the fibres can be reduced by reducing the angle of the bend. This results in a relation between the diameter of the tether and that of the Drum on which it is wound. For the same reason, sheaves should be minimised in number, and maximised in size. It also means that drums for future multi MW systems continue to have to grow larger.

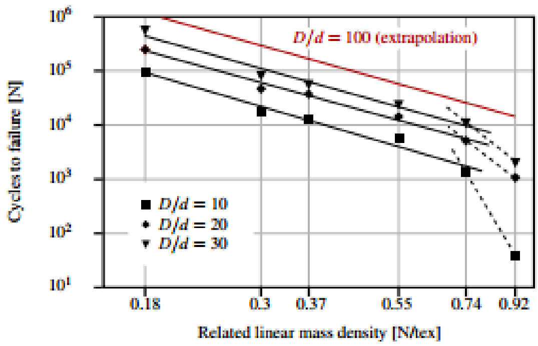


Figure 5.8: The relation between forces, D/d and nr of cycles to failure for Dyneema SK75 fibres, only indicative for the relation (Bosman et al., 2013)

A third way Ampyx minimises the impact of the tether is by sectioning the tether into a top section that stays in the air in normal traction operation and a bottom (winding) section that is cyclical wound onto the drum. Both sections need to be optimised for different failures and performances. The bottom sections will rupture from bending damages far before creep has an effect. The top section can however be much smaller in diameter, carrying higher stresses. Thereby it can be optimized to reduce the tether drag which is a serious problem when the tether gets longer and larger.

Sizing and Modelling:

The tether is modelled as 1200 m long, with a top section of 900 m long and a diameter of 5 cm. The bottom (winding) section of 300 m long and a diameter of 7.4 cm. The diameter of the top section was stated to be approximately 2 cm thinner than the diameter of the winding section. The diameter of the winding section was determined based on a provided maximum tether force of 1170 KN. The maximum stress over the tether was approximated to be 312 MPA based on values presented in Bosman et al. (2013). This tether stress equals a force of approximately 18% of the maximum break load and 0.33 N/tex.

The tether force is considered to be carried by the UHMWPE alone. This accounts for a diameter of 6.9 cm. Both sections are modelled with 12 wt% coating. The actual material of the coating is unknown, however, similar rope coatings are made from silicon polymers. The coating is modelled with a data-set representing average silicone product manufacturing, including silicone polymer materials. The linear density of both the coating as the UHMWPE are 790 kg/m^3. The feasible tether lifetimes are assumed 1 year for the winding section, and 7 years for the top section.

Component	Unit	Bottom	Top	Total
Lenght	m	300	900	1200
Diameter	cm	7.4	5.0	-
Lifetime	Years	1	7	-
Mass installed	kg	1240	1948	3188
Mass life	kg	24801	5844	30645

Table 5.6: Tether specs for the Bottom section, the Top section and the Total tether

The tether is modelled with 3 elements; the UHMWPE fibre material, the coating material, and rope making processes. The impacts of the UHMWPE fibres are acquired by personal communication with Dyneema DSM. Dyneema DSM is a partner company in the MegaAWE research group, working on realisation of large scale AWE, and a leading company in the HMPE industry. DSM produces these fibres with a large share of renewables, thereby the values used in this report are only known to represent the UHMWPE of Dyneema DSM specifically. But would not hold for generic HMPE fibres (Bosman, 2021; Dyneema).

Material/Component	GWP[kg CO_2eq/kg]	CED [MJ/kg]	Comment
Tether	8.87	287.8	-
HMPE fibres	7 to 8.5	300	Bosman (2021)
HMPE fibres biobased	2 to 3.5	-	Bosman (2021)

Table 5.7: Impacts of tether and UHMWPE materials

The most conservative value of 8.5 kgCO_2eq/kg HMPE has been used in this report. Neither the method nor the boundary conditions used in the Dyneema LCA report are known. It is however still considered to be the most accurate impact indication available at this time.

Final production into ropes is often performed by intermediate manufacturers. This processing is modelled with 2 processes: extrusion spinning to create the longer strands and weaving of synthetic fibre as a representative for braiding of the rope. An additional 3% of production losses are accounted for in the roping processes. 1.5% for each process, as is stated in the weaving of synthetic fibres dataset found in the Ecoinvent database. The impacts of the spinning process were collected from a Idemat dataset (polymer filaments 80-500dtex).

Bio-based and the energy mix
The same communication with DSM yielded that the biobased UHMWPE would have an even lower impact of only 2 to 3.5 kgCO_{2eq}/kg fibre. This same reduction of 5 kgCO_2eq was stated earlier publications by DSM (Dyneema). These bio-based values are currently considered too optimistic for usage in this LCA work, especially due to the already high uncertainties. It does however indicates that there is still significant potential for improvement.

Alternatively, it can also be approximated what the impacts of the fibres would be in a more fossil-based energy mix. Highly conservative; 300 MJ CED of the dutch medium voltage energy mix equals a GWP of 19.3 kgCO_2eq and an output energy of 110 MJ. This quick assessment does however not take into account that the CED of the UHMWPE fibres would also have been higher with a more fossil-based energy mix. This 19.3 kgCO_2eq therefore only represents an absolute minimum impact indication for generic UHMWPE fibres produced without the high fraction of renewables. DSM Dyneema confirmed this with an expectation of 25+ kgCO_{2eq}/kg UHMWPE or higher for generic UHWMPE.

5.1.3 Ground Station

The ground station (also PGA) is the collective of the components required to transform the tether forces into electrical energy at 33 kV. It includes the drum, the hydraulic system, the generators, the converters and the transformer. The ground-station sub-system boundaries are selected to be comparable to the drive-train in an HAWT system, therefore holding most elements generally found in the nacelle. It does however not include the yaw system, which is considered part of the Land and Launch system for AWE.

The drive-train of a large AWE system remains uncertainty. The drivetrain presented in this assessment used hydraulic transmissions and accumulators. This is considered one of the best options at this time. Although the hydraulic drive train is indeed one of the considered systems by Ampyx, the system presented below is a personal design based on the potential future.

All systems are modelled with an additional 0.1 wt% of paint (4.5% for the FRP materials).

5.1.3.a Drum

The drum size strongly depends on the required tether dimensions. A larger rated AWE systems need to transmit higher forces over the tether, which results in larger diameter tethers. The diameter of the drum is subsequently scaled with the diameter of the tether to minimise its wear damages. Therefore, both the forces on the drum as the diameter of the drum increase with increasing system sizes. It is expected that the mass of conventional drum systems (that would be able to handle these extreme torques and forces) would exceed feasible boundaries for AWE operations; As large drum masses lead to high mass inertia losses at every transition between the traction and the retraction phases of the operational cycle. The presented drum and PGA system described below are only a personal design for a large scale future. It is accepted, but not designed by Ampyx. The modelled drum design is not validated for feasibility.

The diameter of the drum is taken at 55× the diameter of the tether, making the drum diameter 4meters in diameter. The drum is designed to hold the entire winding section of the tether on the first level of the drum; making the width of the drum approximately 2 meters (with includes an extra 8% spacing). The maximum tether force is stated to be 1170 KN at the traction phase. At this tether force acting on the drum with a diameter of 4meters, the (static) torque on the drum axle would reach 2340 KNm. Which far exceeds the values stated on spec sheets of most similar winches and cable reeling systems (HydrauVision).

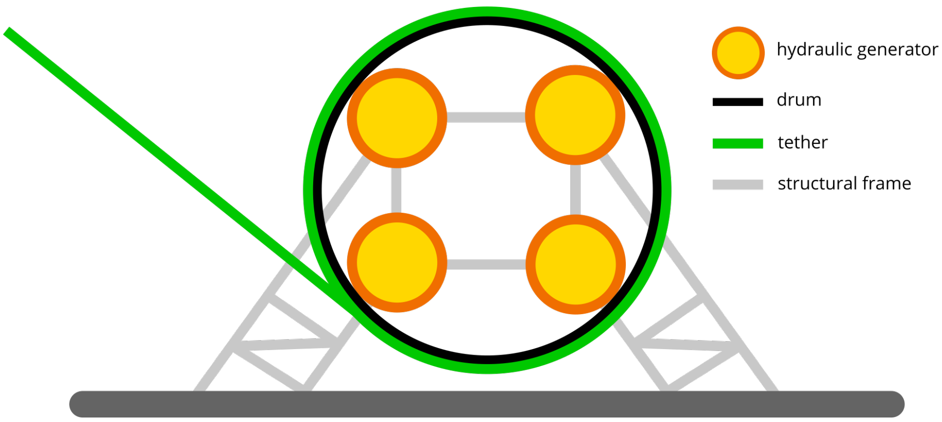


Figure 5.9: Proposed personal drum design that uses hydraulic piston motors/generators connected directly to the shell. There reducing the mass inertia of the drum by removing the heavy center (axle).

The presented drum is only a shell, without an centre axle, inspired by hub-less wheels. It rotates on 4 off-center axles, each connected to two hydraulic motors. The 4 axles are supported by a heavy steel support structure. It effectively relocates the structural mass from the rotating component to a static component to reduce inertial losses.

The shell is considered of CFRP material, with a mass of 1500 kg. It is connected to the 4 shafts through 1 or 2 gear ring(s) on the inside of the drum. These gear rings can be seen as large slew bearings with a mass of 2000 kg. Each of the axles are assumed to be cylinders of 1.5m length, with an outside diameter of 20 cm and an inside diameter of 10 cm and a weight of 275 kg. An additional mass of 200 kg of bearings is assumed. The gear ring, axles and bearings are all assumed to be made from high strength steel such as 42CrMo4, all modelled with chromium steel. The idea of this system is to reduce the mass of the rotating system. As a result, the structural loads need to be carried by an external static structural frame. This external structure is assumed 30 mt and is fully modelled as steel section beams. These masses are only personal estimations that Ampyx expects to be oversized.

5.1.3.b Hydraulic drive-train

This AWE system is considered to have an hydraulic drive-train, instead of the more common geared drive-train in HAWT systems. When the drum rotates in the traction phase, its rotation and torque drive 8 separate (low speed) hydraulic piston generators/motors. These pistons transform the axle rotation into hydraulic pressure, which in turn is stored in an accumulator system. Another set of 8 (high speed) hydraulic motors transform this hydraulic pressure back to rotational energy at the grid side. This rotation drives 4 separate (electrical) generators, with 2 hydraulic motors coupled to each. The pressure build up in the accumulator system ensures a constant pressure on the grid-side hydraulic motors. Therefore energy generation at the generator is no longer cyclic, but will produce a constant electrical power. The entire hydraulic drive train is modelled as 350 Bar.

Radial Hydraulic Pistons Motors There are 8 hydraulic pistons motors connected to the drum, operating at low speed. It is assumed that the installed hydraulic piston power needs to be 2.5x the rated electrical power of the system. This estimation was provided by Ampyx. The masses and specs for all hydraulic elements are collected from various catalogues and spec-sheets. The differences between real-out and real-in speeds are not accounted for this selection. All 8 pistons are assumed of equal power. The selected product is the CBm3000C of Boschrexroth. Which is a 1628 KW radial hydraulic piston motor, similar to figure 5.10. The mass of one single piston of this type is 5000 kg, leading to a total mass of 40 mt for all 8 pistons.

Figure 5.10: An example of a type of radial hydraulic piston motor (Bosch Rexroth)

The drum rotates at very low speed, with a diameter of 4 meter, the tether is expelled at 12.6 meter per drum revolution. The hydraulic pistons are connected to the drum with minimal gear ratio. The low speed hydraulic pistons are able to handle large torques and have a large volume displacement per revolution. These components are modelled as 50% cast iron and 50% chromium steel (plus avg chromium work).

Hydraulic pipes The use of an hydraulic system simplifies the decoupling of the rotating platform and the electrical system. The pressure is build up by the hydraulic piston motors inside the drum, which is attached to the rotating platform. The hydraulic pressure is transferred through hydraulic rubber tubes. The flexibility of these tubes makes it possible to link the rotating platform structure to the stationary hydraulic system located underneath the deck.

The selected 1.25 inch tube type has a mass of 2.6 kg per meter (Parker, 2016), of which a total length of 200 meter is assumed to be required. Hydraulic tubes are made from synthetic rubber strengthened with several layers of steel wires. They are modelled as 50% synthetic rubber with plastic pipe extrusion and 50% low alloy steel with wire drawing processing. The total mass of tubing is 520 kg. Accumulator systems would generally use steel pipes to couple the cylinders. These are however assumed to be included within the 200 meter of flexible tubing.

Accumulator system
The hydraulic energy generated at the mechanical (drum) side is partially stored in an accumulator system. By storing the energy in an accumulator system before conversion to electricity, the electrical systems do not need to be oversized, so 5000 KW generators would suffice. The energy stored in the accumulator system is released again in the re-traction phase. As a result, the electrical system is driven at constant pressure and does not need to be designed for the peaks and valleys of the intermittent (cyclic) operation of the system.

The accumulator system is a combination of hydraulic piston accumulators and additional nitrogen pressure vessels. These additional pressure vessels increase the effective volume of the accumulator system, and thereby increase the energy stored inside it. The larger volume results in lower pressure fluctuation when the accumulator releases its energy in the retraction phase. Which in turn results in a smoother energy output.

Figure 5.11: Example of hydraulic system component (Hydac).

The required working volume of the hydraulic piston accumulators is assumed to be 8000L. The additional volume of nitrogen tanks is assumed to be 21300 L. It is assumed that the pressure in the hydraulic system is 350Bar at the moment that the pressure in the accumulator system is at its maximum. This maximum pressure is achieved when the piston is fully loaded and the full working volume of the accumulator is compressed into the nitrogen cylinders. This is assumed to coincide with the exact moment that the system switches from traction to retraction.

A simple calculation of the energy stored in a hydraulic accumulator is equation 5.1, found in Leon-Quiroga et al. (2020). This method provides a slightly lower energy capacity than was found with the ideal compressed gas storage calculations.

$$E_{acc} = \frac{p_0 v_0}{n-1}\left[\left(\frac{p_0}{p_{max}}\right)^{\frac{1-n}{n}} - 1\right] \tag{5.1}$$

E_{acc} = Energy stored in accumulator in J
P_{max} = 350 Bar in Pa

n= (1.4) an ideal gas constant for isentropic processes
V_0 = Total Volume of accumulator and cylinders in m^3
P_0 = Pre-charge pressure at v_0, calculated with the ideal gas law: $P_0 = \frac{P_{max} \times V_{min}}{V_0}$ = 254 Bar in Pa
V_{min} = Volume when all working volume of the piston is compressed. (cylinder volume only) in m^3

This equation assumes adiabatic compression, thus without heat transfer and related losses. By this calculation, the maximum energy that can be stored in the accumulator of this size is 185 MJ. This energy is needed for multiple uses, firstly: to continue running the system at 5 MW during the entirety of the retraction phase (including the transition phases). Secondly: to drive the drum rotation reversal and reel the tether back in. If this energy was only used to continue running the generator, this 185 MJ of energy equals 37 seconds of 5 MW energy generation without losses. The hydraulic accumulator system of this size could therefore only work under the assumption that the retraction and transition phases are no longer than approximately 20 seconds, without safety factors included.

Piston accumulator The accumulator model is based on specs for the largest accumulator on which data was found. The total required working volume of the accumulator is 8000 liter. This is achieved by using 8×1000 L accumulators found in the accumulator catalogue of Parker. The mass of one of these accumulators is 6037 kg, leading total mass of 48.3 mt. These specific piston accumulators are the largest systems on which data was found, reaching 6 meters in height, and 0.73 m in outside diameter. The next larges piston accumulator is only 500 L large, and other accumulators no not reach much larger than 350 L. The mass of a piston accumulator like this is assumed mostly determined by the outside shell. Therefore the whole mass of the accumulator is assumed to be made of carbon steel. An additional frame of 500 kg is added for each piston, modelled as section steel with average metal work (Parker, 2018).

Gas cylinders The additional pressure vessels are taken as 284 × 75 L pressure cylinders, each with a mass of 133 kg. Similar systems to this are confirmed to be rated for 350Bar pressure operation. Additionally, these cylinders are supported by a frame weighting 284 kg per 12 cylinders (Hydac). The cylinders are modelled as carbon steel. The frames are modelled as section steels with average metal work. The numerous additional valves and other components are not included in the assessment.

The nitrogen gas The nitrogen gas volume is determined with the maximum pressure point as reference. At the maximum pressure point the pressure is 350 Bar and all nitrogen is assumed pushed out of the piston and into the gas cylinders with a total volume of 21300 L. The amount of gas is subsequently calculated using the ideal gas law and if found to be 306 kmol, assuming a temperature of 20 °c. This equals an approximate volume of 7455 m^3 at atmospheric pressure. Combined with a density of 1.25 g/liter; this equals a hydrogen mass of 9319 kg.

$$PV = nRT \tag{5.2}$$

Hydraulic motors Finally, the hydraulic pressure is converted back into rotational energy by 8 hydraulic motors. These are connected in pairs to 4 electrical generators on the grid side. These motors are selected for high speed, low torque and low volume displacement per revolution. The high rotational speed of the hydraulic motor reduces torques on the rotational systems which leads to significant mass savings of both the hydraulic motors as the electrical generators. These hydraulic motors are also selected from Boschrexroth catalogues and and have a total mass of only 2688 kg for all 8 motors. They are modelled as 50% cast iron, and 50% chromium steel. (plus avg metal work)

Figure 5.12: An example of a type of axial hydraulic motor (Bosch Rexroth)

5.1.3.c Generator

The system is designed with 4 separate generators of equal power. The generator type is considered modular induction motors, which are able to function as a generator as well as a motor. The selected generators have a power of 1625 KVA with a speed of 1500 RPM and a output voltage of 690 V, found in ABB (2020). Each generator weighs 3760 kg, for which the mass composition is interpolated for another generator from an EPD by ABB. The 1625 KVA is the apparent power that is found by multiplying the real power (Watt) with a power-factor of 0.8. In this case, the generators are modeled as 1300 KW systems, with a total power of 5.2 MW. The power-factor is taken as a reasonable value found in many sources, among which in product catalogues (ABB, 2020).

Its material composition is taken as: 57% Electrical steel, 11% hot-rolled steel plate, 11% copper wire, 11% Steel section beams, 2% cast iron and 2% fibre glass insulation. An additional 0.1% of the mass is accounted for by paint. The energy consumption during manufacturing is 13.2 MWh electricity and 6.1 MWh heat. The electrical steel is modelled with chromium steel, better assumption may be possible.

Figure 5.13: An example of the NMI modular induction motors as presented by ABB (ABB, 2020)

5.1.3.d Converter

Each generator is controlled by its own frequency converter. Each converter is rated for 1625 KVA. The converter is modelled according to the material composition presented in converter EPDs by ABB (2003a). It is modelled with 51% steel, 16% iron, 18% copper, 9% Aluminium and 2% plastics. An additional 3.6% of the mass is neglected. The total electricity and heat consumption were 6.8 MWh and 3.7 MWh, respectively. Only minimal waste is mentioned in the EPD and is therefore not included in this report. Production impacts are represented by the energy usage alone, no additional metal work is included. An additional 0.1wt% of paint is included.

5.1.3.e Transformer

The 4 individual generators have a voltage output of 690V each. However the voltages over the inter-array grid and transmission lines are assumed 33 KV. Therefore each system is equipped with an medium voltage power transformer. Transmission remains at 33 KV AC without the use of a high-voltage transformer station in this model. The transformer is modelled with the transformer data set available in Ecoinvent. The mass of the transformer is estimated using the transformer scaling equation 5.3 presented by NREL (Guo et al., 2015).

$$Transformer.Mass = 2.4445Pt + 1599 \tag{5.3}$$

Where Pt is the rated power of the transformer kVA

5.1.3.f Control systems

An additional mass of 500 kg of control systems is included with the *electronics for control* data-set found in Ecoinvent. The 500 kg is the same mass as assumed for the HAWT system. The actual amount of electronics remains unknown.

5.1.3.g Paint

Painting is not considered equal for all systems. There are 3 different paint options: A zinc coating, a powder coating, and an alkyd paint. ABB (2017) recycling instruction documentation indicates that almost all large steel plate elements are zinc coated. EPDs of ABB generators state that additional paint represents approximately 0.1 wt% of the products mass (ABB). Paint usage in this report is simplified to only include the 0.1 wt% of alkyd paint on all components other than the deck surface. It should be noted that the Alkyd paint has a much lower impact than the other paint options, likely due to different processing boundary conditions. However, neither represents significant impacts over the total system.

5.1.4 Landing and Launch apparatus

The Land and launch apparatus (LLA) represents the deck and its support structure, a catapult system for launching, a shifter system for landing and a yaw system to change the orientation of the deck. Estimations of the masses within this subsystem were provided by Ampyx but remain highly uncertain. The material compositions of the LLA components are based on literature and estimations provided by Ampyx.

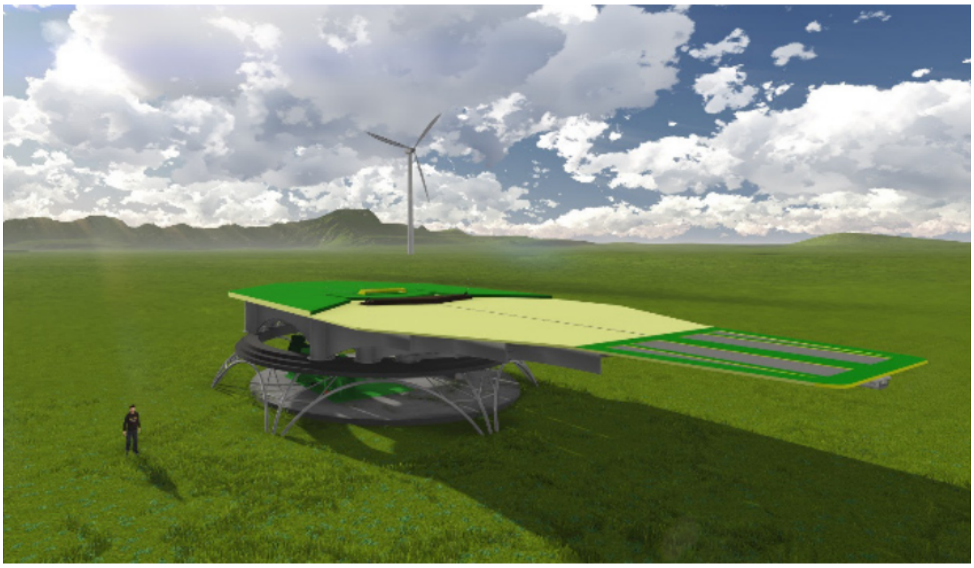


Figure 5.14: Onshore platform concept by Ampyx, presented at AWEC 2017 (Diehl et al., 2017)

An additional wt% of paint has been included on all components. The deck surface is painted based on its surface area, as is described below. All other components are modelled with an additional 0.1 wt% of paint.

5.1.4.a Platform/full deck

The length, width and mass of the landing deck/platform are roughly estimated by a platform estimator by Ampyx. The mass and length of the platform both depend on the mass of the aircraft. For the 20 mt aircraft, the deck is estimated to be 34.2 m long and 18.7 m wide. Its mass is estimated to be 128 mt which is assumed to include both the deck surface and the entire platform support-structure.

The mass is assumed 1/5th (25.6 mt) accounted for by the landing deck surface. Making the deck surface 5.2 mm thick steel plates. This deck surface is assumed to be made from standard construction steel plates of 3×12 m. A total of 251 meters arc welding is included to connect these plates into one deck. The connection between the support structure and the deck surface is not included. The deck is finished with an additional zinc and a powder coating which is assumed equal to that of a HAWT tower, described in 5.2.2.

The other 4/5th of the mass (102.4 mt) is considered the various support structures of the deck and larger platform. This is modelled as section steel (I beams) and processed with average metal work. Like all metal masses, an additional 0.1 wt% of paint is included.

5.1.4.b The yaw system

An estimation was provided for the mass of all LLA systems combined. Scaling indication were provided for the other LLA system, but not for the yaw system. The mass of the yaw system is therefore determined based on the mass that was left undefined, adding up to 22.7 mt. It has not specified which elements are included in this yaw mass. It is assumed to only include the yaw-drives, a center pivot and a large yaw ring. The structural elements underneath the yaw ring are assumed to be included in the deck structure mass. Better estimations could not be obtained.

HAWT turbines use multiple yaw motors connected to a single yaw ring to rotate the nacelle directly on the tower top. An estimation of the number of motors can be based on the rotor diameter of the system (Guo et al., 2015). This estimation can therefore not be used for the AWE system. It is simply assumed that the 5MW AWE system uses 4 motor-gearbox yaw drive sets, each with a mass of 190 kg. The composition is assumed 50% eclectic car motor, 25% cast iron and 25% chromium steel. The cast iron and chromium steel represent the gearboxes which are assumed 50% of the yaw drive sets masses. The metals are accompanied by average metal work processing.

The yaw drive systems are mounted on a central pivot, located in the rotational center of the deck structure. This central pivot is a strong structural element that supports a part of the mass of the deck structure. It is assumed to be 10mt and is modelled as 50% cast iron and 50% section steel, both with average metal work.

The yaw drives drive the rotation of the deck through a single slew bearing. This bearing is assumed with a mass of 500 kg. A basic slew bearing of this mass is approximately 2 meters in diameter. Stronger types of slew bearings would reach this mass with smaller diameters (Liebherr, 2018a). The whole mass of the bearings is modelled as high strength steel with average metal work.

Figure 5.15: Visualisation of Yaw system (Liebherr, 2018b), similar to the considered system

All additional mass of the yaw system (11.4 mt) is assumed to be the outside circle on which the outer edge of the deck rotates. It serves as a friction plate similar to a slew bearing and is modelled as an I-Beam track in which the rollers that carry the deck run in-between the flanges. The structure below this yaw circle is assumed to be represented with the deck structure mass and is thus not included in the yaw mass. This system is fully modelled as section steel with average metal work.

The yaw systems is known to contain additional components with unspecified masses. These components are however not further included in the assessment. Excluded components are for example the rollers, roller bearings, cables and cable trays. The mass of the yaw system is a very rough estimate, the mass of these 'neglected' systems can therefore be assumed to be included in the presented steel masses.

5.1.4.c Catapult

The catapult is responsible for the launching procedures of the aircraft. It is an essential component to keep the length of the deck short. The deck of the system is 34.2 m long. At this length, the 54 m wingspan aircraft would needs to accelerate to take-off speed with incredible acceleration.

Only the structural elements of the catapult are scaled with the mass of the aircraft, as larger masses equal higher forces and more energy to dissipate. This scaling is an estimation provided by Ampyx. The components in the catapult do not scale with the aircraft mass.

The catapult consists of a heavy steel structure running over a long length of the deck. It weighs a total of 32.8 mt of which 22.8 mt is structural steel, modelled as steel sections with average metal work. The other 10 mt is a mixture of hydraulic motors, shafts, ropes, drums, a motor with gearbox and general steel elements. This mixture is simplified as 40%chromium steel, 40% cast iron, 20% low alloy steel. Each with average metal work processing.

5.1.4.d Shifter

The shifter is responsible for deceleration when lading the aircraft.

Its mass is based on scaling estimations provided by Ampyx. No further redesign of the system is known for future larger scale systems. Therefore it is scaled based singularly on knowledge from the AP3 design. The mass of the shifter for a 5 MW AWE system with a 20 mt aircraft is 44.6 mt. Masses of the specific systems are shown in table 5.8.

The 16 mt steel structure of the shifter is modelled as section steel and average metal work. The damper of 8 mt is simplified to only be carbon steel. The slider of 1.6 mt is approximated with a material composition of 22% CFRP, 48% aluminium and 30% titanium. The motor mass of 2.5 mt is modelled with an eclectic car motor data-set. The 3 mt steel mass includes sheaves, wire clamps and general steel elements. This is modelled as low alloy steel with average metal work. The 4.4 mt steel wire is modelled as low alloy steel with steel wire drawing. An additional 0.1% of paint is added.

Component	**Mass kg**
Total	44465
Structural	15960
Damper	8000
Slider	1600
Motors	2500
Steel	12000
Steel wire	4400
Paint	45

Table 5.8: Masses of the shifter

5.1.5 Foundations

Not much is known about the foundation of this up scaled AWE system. The presented foundation design is therefore also not based on known research performed by Ampyx.

The LLA system as shown in figure 5.14 shows a preliminary deck design that is only connected to the ground through the center pivot and the outside yaw support ring. These 2 locations shall therefore carry the bulk of the systems mass and operational forces. Therefore the foundation is designed for localised strength at the center and outside ring. It is assumed that the area in between will suffice with lower foundation requirements.

Center foundation The center foundation is assumed 5 m in diameter and 1 m in depth. It is not known what fraction of the total system mass would be carried by this element. It will however not carry any significant overturning moments. The AWE system will only produce minimal overturning moment. The overturning moments that are generated are expected to be carried primarily by the outside foundation ring.

Outside ring foundation The deck surface is assumed to be 18.7 m in width. The support structure will however exceed further outwards for improved stability. The yaw ring is expected to connect to the ground at a diameter of 23 meter. This yaw ring will carry a large part of the platforms weight. Therefore its foundation is modelled as a 1 meter wide and 1 meter deep ring, with an outer diameter of 24 m.

The area in between The area in between these extra strengthened foundation elements is assumed as a concrete slab, roughly similar to raft (or mat) foundations used in residential constructions. The minimal thickness of the raft concrete slabs for residential buildings is 0.2 m. This thickness can be reduced further for driveways, farm building and garages. Therefore a thickness of 0.15 m is assumed sufficient for use in the middle section of the AWE foundation.

Total Under these assumptions the total concrete volume adds up to 146 m^3. All concrete is modelled 35 MPA concrete with 5 wt% rebar. This is equal strength concrete as used for the HAWT model but with a slightly lower element of rebar.

This amount of concrete far exceeds what would be required for soil bearing capacity of a static structure alone. The actual design of the foundation may strongly deviate from the designed foundation above. Change of the foundation would however not lead to the most significant environmental impact deviations; as concrete itself only has a minimal impact per m^3. Concrete can however be designed with lower impacts, this is already more standard by now, further explained in section 5.2.4.

Despite variation option for the concrete, the rebar would continue to present a much higher impact per kg than concrete does. Even at only 5 wt% rebar, the rebar exceeds the impacts of the concrete in the foundation. The 5% rebar used in the AWE foundation model is already lower than the 6.32% used in the HAWT model, but it still is above above for static buildings. Therefore it might very well be possible to further reduce the mass fraction of rebar in future AWE systems.

The impacts of the rebar steel are taken from the LCA inventory study by the World Steel Association (2017). The used dataset for the 35 MPA concrete mixture of Ecoinvent uses a mixture of 345 kg portland fly ash cement, 144 kg water, 850 kg gravel, 1045 kg sand and 3.03 kg of admixtures and a density of 2240 kg/m^3.

	Unit	**Value**	**Comment**
Digging for foundation	m^3	146	Dug by hydraulic digger
Mass of foundation	mt	338	
Wt% rebar	-	5 wt%	

Table 5.9: Foundation specifications

5.2 Manufacturing of HAWT System

Manufacturing of the HAWT system is assessed for its 4 subsystems individual. The components within each subsystem are summarised in table 5.10. This section only treats the manufacturing impacts. Impacts related to the other life cycle stages are treated in later sections.

An summary of the turbine specs can be found in section 4.4. The presented HAWT model is largely based on the NREL 5MW system, transformed to land usage. Further details on its modelling is based on a variety of literature sources, product catalogues, environmental reports and assumptions.

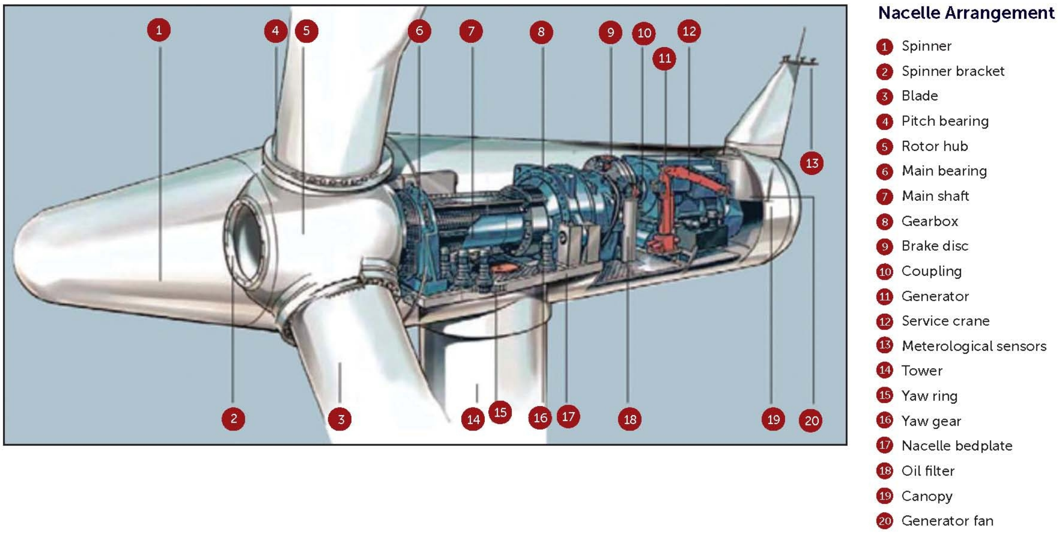


Figure 5.16: Image of components of a HAWT system (Zipp, 2010).

The components included in the sub systems are:

Rotor	Tower	Nacelle	Foundation
Blades	Tower	Yaw system	Concrete
Hub		Bedplate	Rebar
Pitch		Shafts	
Spinner		Bearings	
		Brake	
		Gearbox	
		Generator	
		Converter	
		Transformer	
		Control systems	
		Cover	
		Cable	

Table 5.10: HAWT System components close-up

5.2.1 Rotor

The rotor of a wind turbine is the collection of its blades, the pitch systems, the hub connection and the spinner covering the connections on the hub.

The rotor diameter of the NREL 5MW is 126 m. It consists of 61.5 m long blades and a 3m hub diameter. Wind turbine blades are generally made from FRP materials. Shorter blades may be produced with GFRP alone, however, larger blades frequently require CFRP structural components. The 126 m rotor diameter is designed for IEC2 to IEC1 rated wind conditions. Turbines operating in lower wind conditions would require larger rotor diameters.

Component	**unit**	**Value**
Rotor diameter	m	126
Blade length	m	61.5
Hub diameter	m	3
Tip speed	m/s	80
Masses		
Full Rotor	mt	**96.7**
Single blade	mt	16.1
Hub	mt	34.1
Pitch system	mt	14.5
Spinner	mt	1.8

Table 5.11: Rotor specs as used in the model. The masses of the rotor components are used as presented as the optimised 80 m/s tip-speed case in Dykes et al. (2014).

Blades The (three) 61.5 m long blades have a combined mass of 48.3mt. Resor (2013) presented a reference blade model which defined the blades as CFRP - GFRP combination, using CFRP structural elements. The modelled blade composition is simplified to 50% CFRP and 50% GFRP. Additional materials (such as the lightning protection) are not included.

The CFRP and GFRP are both modelled with the same manufacturing losses and consumable usages as presented for the CFRP in the AWE system. They are also both modelled with a 60 wt% fibres to 40 wt% epoxy mixture ratio. As well as the same 4.77% core material, 4.5% coating, 5% glue and an epoxy resin to curing agent wt ratio of 100:18.

Hub The hub is a heavy structural connection between the blades and the drivetrain. It has a mass of 34.1 mt and is fully modelled as cast iron with average cast iron manufacturing processes.

Pitch Pitch systems are used to control the angle of attach of the individual blades. They are primarily heavy steel slew bearings that form the connection between the blades and the hub. The pitch orientation can be controlled for each blade individually, using pitch drive systems.

Each blade is assumed to have a 190 kg pitch drive system. Modelled as 50% motor and 50% gearbox (as 25% cast iron and 25% chromium steel). Additional components are however not distinguished in detail, the remaining 14.1 mt mass is all modelled as chromium steel with average work. This largely represents the mass of the slew bearings, which are assumed to represent the largest mass of the pitch system.

Figure 5.17: pitch bearing and drive systems (Liebherr, 2018b).

Spinner The spinner (or hub cover) is a cone that protects the hub connection and blade roots from the outside. It is the rotating extension of the nacelle cover. Both covers are primarily made from GFRP material with some additional steel connections. It is modelled as 95% GFRP and 5% steel for the connections.

5.2.2 Tower

The tower of the NREL 5MW is a steel cylinder type. The mass of a steel tower type widely varies depending on a large number of design constraints. These design constraints primarily control tower vibrations to limit for fatigue stresses. The mass of an onshore NREL 5MW turbine tower was not found and a personal design of an accurate tower design was deemed too complex for this work. The tower mass has therefore been represented with the mass of another turbine tower, checked for reasonability through literature.

Component	**Value**
Hub hight	117 m
Bottom diameter	6 m
Top diameter	3.87 m
Tower mass	600 mt
Tower type	Steel cylinder with flanges
Material	Construction & Low-alloy Steel
Coating	Zinc dip and Powder coating

Table 5.12: Tower specs as used in the model

The presented tower mass for the 5WM HAWT system is based on the mass found for the old Bard 6.5 MW turbine. This onshore turbine of 6.5 MW had a rotor-nacelle mass of 450 mt and operated 90 m hub height. Its tower was a steel cylinder type with a mass of 760 mt (Bard). A slightly reduced mass of 600mt was chosen for the NREL 5MW after comparison with literature on tower optimisation: Dykes et al. (2018) and Lantz et al. (2019).

It should be noted that the actual tower mass both could become much higher or much lower than currently modelled. Lantz et al. (2019) also indicates research to reduce the mass of the tower for larger systems. The mass of the original offshore NREL 5MW is presented as only 350 mt. Further optimisation could even reduce this mass to 250 mt, Dykes et al. (2014) presented a mass of 266 mt. The mass of the onshore NREL 5MW tower is much higher than that of the offshore NREL 5MW. This is largely caused by the better wind conditions offshore, due to which the offshore hub height can be 27 m lower than the onshore hub height. Additional differences are due to the differences in transportation options between offshore and onshore locations.

10% (60 mt) of this 600 mt tower weight is considered to be from its forged flanges (BVG, 2019). The other 90% is modelled as standard steel plates, welded together and coated with 2 layers of paint. The flanges are modelled as carbon steel with avg metal work. The steel plates are modeled as standard reinforcing steel plates of 3x12 m. A total of 785 m welding is included in the production of the tower.

Paint Wind turbine towers are often spray-painted with 3 levels of paint (BVG, 2019). The first layer is a metal coating, followed by an epoxy coating layer and a final layer of Polyurethane coating. Collectively, these levels of coating provide protection against environmental impacts such as corrosion and UV radiation (Teknos, 2013). The total thickness of the coating is approximately 250um, however many variations exist.

This model simplifies the tower coating by using 2 standard painting options, neither truly appropriate for this use. The first one being a zinc coating, to protect against corrosion. The data-set used is for batch dipping of final products, whereas wind turbine towers are typically spray coated. The second layer of paint added is a powder coat layer. The data-set used is for thinner steel materials, as the energy used in this process is dependent on the thickness of the painted material. The thickness of these coating levels combined is 145um. Both these painting options are however significantly more pollutive than the alkyd paint data-set used for all other sub systems.

Tower sensitivity Tower length (hub height) is a variable determined by environmental conditions. The hub height of a 5MW turbine can be anywhere from 85 to over 150 meters high. Deviations in the hub height are evaluated in a sensitivity case.

5.2.3 Nacelle

The nacelle holds all machinery and components required to convert the rotational energy of the rotor into electrical energy at the desired 33 KV transmission voltage. Amongst others, it also includes the heavy support structure, the yaw system and the nacelle cover.

- Yaw system
- Bedplate
- Shafts
- Bearings
- Brake
- Gearbox
- Generator
- Converter
- Transformer
- Control systems
- Cover
- Cable and Switch gear*

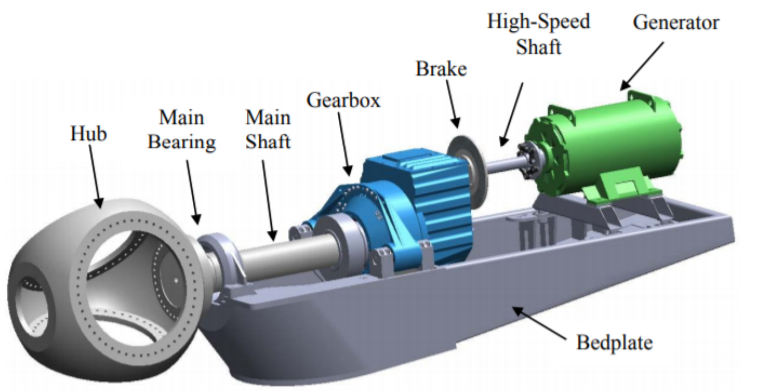


Figure 5.18: Simplified illustration of nacelle components, To indicate the shafts and other components (Oyague, 2009)

5.2.3.a Drivetrain Type

The NREL 5MW is designed with a DFIG drivetrain. The design of the nacelle and its components greatly deviates with the used drivetrain type. The DFIG has been one of the most common types over the last years and it is still most widely found in literature. DFIG drivetrains make use of high-speed induction generators, controlled by (back to back) converters. High speed generators like these are relatively lightweight in comparison to low speed generators and also do not require the use permanent magnets. They do however require a gearbox to transform the low rotational speed of the rotor to high rotational speed for the generator.

Current trends are increasingly leaning to Direct Drive (DD) drivetrains. These systems have improved efficiencies and require less maintenance. Therefore they have a large advantage for offshore wind farms. This changing trend was not included in this report. DD drivetrains use low speed generators that do not need a gearbox. The elimination of the gearbox is a large advantage for efficiency and reliability. However, the mass of the generator itself needs to be significantly higher than that of a DFIG generator. Partly because lower rotational speeds result in higher torques and therefore larger structural masses, but also due to differences in the design between a DFIG and a DD turbine. Additional mass indication were found in Sethuraman and Dykes (2017).

5.2.3.b Components

The masses of the large systems are all taken from Dykes et al. (2014). This report presents different masses for several turbine design cases. The data used in the LCA is that of an optimised 80 m/s tip-speed NREL 5MW design case. This 80 m/s tip-speed is the original spec of the non-optimised NREL 5MW defined in Jonkman et al. (2009), as are the masses of the non-optimised reference case.

Component	Mass [kg]
Total Nacelle	**207000**
Main shaft with flange	16100
Main bearing with housing	10400
Gearbox	48600
Generator	16700
Bedplate	71500
Other	**43600**
Low speed shaft	800
Cover	3021
Converter	5000
Yaw	6174
Brake	5257
Electronics	500
Transformer	16900
Cable down tower	312

Table 5.13: Nacelle specs, values copied from Dykes et al. (2014), using the optimised 80m/s design case. The components in the 'others' are acquired from a variety of scaling and data sources. The transformer is expected not to be included in the 'others' data from the Dykes et al. (2014) report.

Yaw system The yaw system is designed based on Guo et al. (2015). The yaw systems consists of yaw drives and a slew bearing. The number of yaw drives depends on the rotor diameter. The 126 m diameter turbine includes 8 yaw drives, each assumed 50% electrical motor and 50% gearbox. These small gearboxes are modelled equal to the large gearbox mentioned above (50% cast iron, 50%chromium steel). The 8 yaw drives have a total weight of 1520 kg. They drive a slew bearing/ yaw ring to rotate the nacelle on top of the tower. The mass of this slew bearing is estimated with an equation presented by Guo et al. (2015). The bearing is there assumed to be a friction plate bearing, where the mass of the friction plate is approximated based on the tower and rotor diameters. Its mass is approximately 4654 kg, assuming a top tower diameter of 3.87 m and a rotor diameter of 126 m. It is modelled as chromium steel with additional average chromium metal work.

Bedplate The bedplate is the connection between the tower and the nacelle. It rotates upon the yaw system and supports all other nacelle components. The bedplate is a strong structural element of 2 sections (figure 5.19). A front section that is assumed to be cast iron and a back section of steel I-beams. Both sections are simply assumed to represent an equal part of the mass. The bedplate is therefore modelled as 50% steel sections, and 50% cast iron, both with additional metal work.

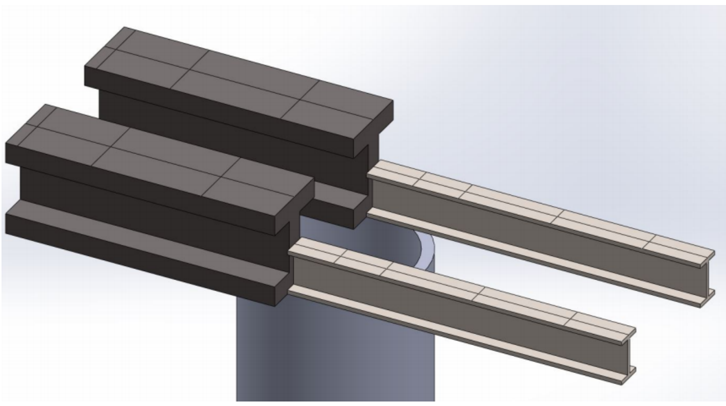


Figure 5.19: Bedplate visualisation (Guo et al., 2015)

Shafts There are 2 shafts in the nacelle of a geared wind turbine. The main (low speed) shaft that connects the rotor to the gearbox, and the coupling(high speed shaft) that connects the gearbox to the generator, figure 5.18. Both shafts are made from high strength steel types such as 42CrMo4. This has been modelled as chromium steel and additional average chromium steel processing.

The mass of the main shaft is 16100 kg (Dykes et al., 2014). The mass of the coupling is assumed 800 kg, obtained through the WindSE modelling program of NREL.

Bearings The heavy rotor is supported by a bearing system. The main-bearing supports the main shaft close to its connection to the hub. The mass of this bearing system is 10400 kg, which includes both the bearings and the bearing-housing. This mass is used as presented in Dykes et al. (2014). The different components of bearings are typically made from 42CrMo4 and 100Cr6 steels. They are fully modelled as chromium steel in this report.

Brake The brake is the collection of a carbon steel brake disk, brake pads, housing and actuators. Its mass is taken as 5257 kg, obtained using the WindSE modelling program by NREL. This is however fully modelled as low alloy steel with average metal work.

Gearbox The 3 stage gearbox is a heavy 48.6 mt component. It mainly consists of shafts and gears of high-strength steels, enclosed in a cast iron casing. The gearbox is simplified by modelling it as 50% chromium steel and 50% cast iron. Both with an included average metal work to represent all manufacturing processes.

The gearbox is the only component of the HAWT system that is considered for replacements within the lifetime of the system.

Generator The mass of the generator is used as presented in Dykes et al. (2014). It is an induction generator type, which operates at high rotational speeds. High speed generators have a relatively low weight in comparison to low speed generators which require higher structural masses. The mass of the generator is taken as 16.7 mt. Its material composition is represented by extrapolation of the material composition presented in an EPD report (ABB). This presented material composition roughly compares to composition was found though other reports (ABB, 2008). Additional usage of timber for transportation has not been excluded. Since these components missing for other components such as the blades and towers as well.

The generator is modelled with 57% electrical steel, 12.7% hot rolled steel, 11.2% copper with wire drawing, 11.3% steel profiles, 1.9% cast iron and 1.6% glass fibre for insulation. The manufacturing phase requires 43.5 MWh of electricity and 5.6 MWh of heat. This represents all manufacturing processes, therefore additional metal work has not been included. An additional 0.1% of paint is included.

Converter The 5 mt mass of the converter is estimated from masses presented in product catalogues for the ABB ACS880 wind turbine converters (ABB, 2018). Its material composition is represented by extrapolation of the material composition presented in an EPD on the ABB ACS800 frequency converter of 630 kW (ABB, 2003a). No data was found on a system with closer resemblance to the 6250 KVA converter actually required.

The converter is modelled with 51% low alloy steel, 16% cast iron, 18% copper, 9% Aluminium and 2% plastics represented by PVC. An additional 3.6% of the mass is neglected. The electricity and heat consumption for manufacturing are 4.25 MWh and 2.3 MWh, respectively. Production impacts are represented by the energy usage alone. Therefore no average metal work has been included for these materials. Only minimal waste was stated in the EPD, this is therefore excluded in this report. An additional 0.1% of paint is included.

Transformer The output voltage of the wind turbine generator is assumed the standard 690 V. This low voltage is subsequently transformed to 33 kV medium voltage by a transformer. The mass of the transformer is estimated using the same equation as used for the AWE system (Equation 5.3). The required transformer rating is assumed 6.25 kVA with a power factor of 0.8. Which leads to a mass of 16.9 mt. It is modelled using the ecoinvent data-set for high voltage transformers.

The transformer is one of the heaviest components of the turbine. It can either be located in the nacelle or in the tower base. The additional weight of nacelle based transformers do however lead to higher structural requirements for the tower and the bedplate. This report considers the transformer to be part of the nacelle machinery, regardless of its location in the NREL 5MW. Potential changes to the structural requirements of the tower and bedplate were not included.

The presented farm design does not include the usage of an additional transformer substation to increase the transmission voltage to a typical value above 120 kV. Therefore all cable transmission is assumed to be based on the 33 KV output of these system transformers.

Cover The cover of a wind turbine is generally made from steel or GFRP. It is modelled as GFRP materials with the same material composition and processing as the GFRP in the blade. The mass is assumed 3021 kg, obtained through the WindSE modelling program of NREL.

Control systems Exact data on electrical (control) systems within the turbine remains difficult to obtain. Vestas mentions the presence of over 9000 individual control components. These may control the operation of the yaw, pitch or HVAC systems, but are also stated to include the gas-insulated switch gear.

An additional mass of 500 kg of the electronics for control ecoinvent data-set is added to the system. This is intended to represent the various control elements in the nacelle. for An accurate value could not be obtained and may differ from this presented value. The Vestas (2006) LCA report presented a mass of 300 kg in the nacelle of a 1.65MW turbine. This same report however also stated a mass of 2200 kg of electronics in the tower, this is expected to be the switch gear which is excluded in this LCA work.

Cable and switch-gear Connection to the inter array grid is expected to take place at the bottom of the tower. This connection is made through use of a gas filled switch gear. These allow for safe decoupling of the systems in case a grid fault occurs. The gas used in these switch gears is often SF6, a highly potent green house gas. Both the switch gear as potential SF6 leakages have been excluded from this report, for both the AWE as the HAWT system.

The cable from the transformer down to the switch gear is assumed 117 meters long. This cable is modelled as a 3core 50 mm^2 aluminium 33 kv AC cable. The cable cross-section would need to be bigger if the transformer was located in the bottom of the tower. A cable of this type weighs approximately 3.22 kg/meter, based on catalogue data (Nexans, 2012). It has a total mass of 312 kg, of which 47.4 kg is for the aluminium cores, 137.6 kg for XPLE insulation, 28.7 kg copper wire screen and 163 kg PVC jacket. Manufacturing of cables is further detailed in section 5.3.

Excluded Various smaller components in the nacelle remain unknown and have been excluded from the assessment. Their mass fraction is however minimal compared to the elements that are included. Other elements that are known to be excluded are: a nacelle based crane and the Heating-Ventilation-and Air Conditioning (HVAC) unit.

5.2.4 Foundation

The foundation of onshore HAWT system is by far the heaviest component of the turbine. It needs to support extreme force-moments generated by the forces acting on the rotor at hub heights high above the ground.

Component	Value
Location	Onshore
Mass	1716 mt
Size	19.5×19.5×2 m
Wt% rebar	6.32%
Concrete strength	35 MPA

Table 5.14: Foundation specifications for the HAWT system

The concrete and rebar masses are extrapolated from foundation specs found in Vestas LCA reports for the V136-4.2MW (Vestas, 2019b) and the V120-2MW (Vestas, 2018). Both turbines have similar hub heights and drive train designs to the NREL 5MW. Both DFIG types with hub heights of 112 and 118 meters respectively. The hub height was deemed more important for comparison the the NREL 5MW than the wind class ratings of the turbines, both rated at IEC2, thus having a larger rotor than the NREL 5MW. Vestas uses a low groundwater level (LGWL) foundations type. The effect of less favorable (High ground water level) foundation types are not further assessed in this report.

Concrete for HAWT systems is typically of 30 to 40 MPA characteristic strength, with a 50 to 100 mm bottom layer of only 15 to 20 MPA characteristic strength concrete (Berndt, 2015). This same report also states a potential GWP impact reduction of over 11% when going from 40 MPA to 32 MPA strength concrete types. This difference is however not found within the used ecoinvent data-sets. Therefore all concrete used in this LCA report is modelled with the data-set of 35MPA concrete, as an average of typical usage.

Concrete can however be designed with lower or higher environmental friendliness. By far the most of the impacts of concrete are linked to the use of cement. A fraction of this cement can be replaced with materials such as Fly-ash and Blast furnace slag, both of which are waste products which therefore carry significantly lower impacts. Newer developments also use EOL GFRP in concrete, which is one of the most commercially viable EOL treatment methods for wind turbine blades at the moment. The dataset by ecoinvent already includes the use of a cement type with fly-ash.

5.3 Manufacturing of BOS

The Balance of System in a wind farm includes all elements required to transmit the generated electricity from the individual turbines to the grid connection. This generally includes the inter array cabling, substation(s) and export/transmission cabling. The BOS generally means 'everything but the turbines' and could therefore include the foundations as well.

Usage of a transformer substation has however been excluded in this report and the foundations were already included with the systems. Therefore the BOS only includes the inter array and transmission cables.

These cables are assumed to be buried directly in the ground. Without the addition of a cable tray, or any form of other protection like scour protection would be used offshore. Digging of the trench in which the cables are buried is included in the installation stage of the LCA.

The Cables

The 10 HAWT and AWE systems are connected with cables of the same conductor cross-section, but with different lengths depending on their assumed spacing over the farm. The conductors in power cables can either be copper or aluminium. Large power cables are more often made from aluminium for economical reasons. This conductor materials however has a lower electrical conductivity, and will therefore lead to higher losses.

All nine inter-array cables are modelled as 33 KV 3× 240 mm^2 aluminium AC cables. Export is performed by two cables of 33 KV AC with 3× 600 mm^2 conductors of aluminium. There are numerous design options within power cables. The mass per meter of cable used in this report was found in Nexans (2012) product catalogues. The mass of 1 m of the 3× 240 mm^2 cables is 6.65 kg, the mass of the 3× 600 mm^2 cables is extrapolated and found to be 12.8 kg per meter.

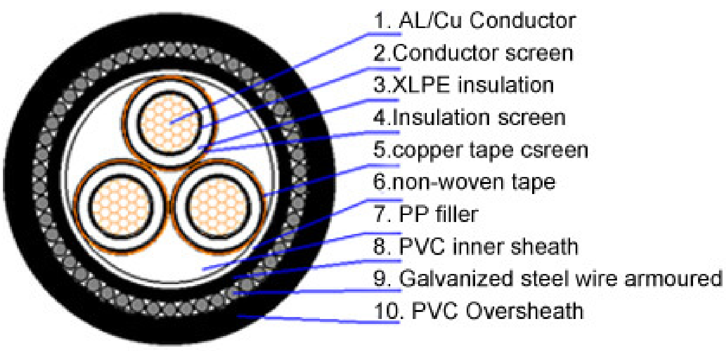


Figure 5.20: Image of a power cable similar to the designed cable. Onshore cables do not require the armouring. Image from (Huadong Cable Group)

The 3x240mm2 inter-array cable has three conductor cores of 240 mm^2, an insulator thickness of 8.5 mm and a copper wire screen of 13.1 mm^2 around the individual insulators. All additional mass is assumed PVC, either from the outer sleeve or from the material in between the three circular cable cores.

The 600mm2 export cable has three conductor cores of 600 mm^2 each, an assumed insulator thickness of 9 mm and a extrapolated wire screen area of 20mm2.

The conductor cores are modelled as aluminium wrought and copper wire drawing. Aluminium wire drawing was not available. Aluminium wrought is selected over aluminium cast for its higher material quality (MatMatch). The insulation material is assumed XPLE (PEX), a crosslinked polyethylene material with a density of 930 kg/m^3. XPLE can be made from different types of polyethylene, but is most often made from LDPE for insulation in power cables (Birkeland, 2011). XPLE is produced by 'radiating' a PE type product, thereby creating cross-links in the polymer chains of the material. These crosslinks change the originally thermoplastic PE material to the thermoset XPLE material, improving its resistance to heat as well as its dielectic resistance, (electrical insulating properties). No data was found on XPLE, therefore it is represented by LDPE alone.

The outsides of the individually insulated cores are enclosed with copper wire screens. These are modelled as copper and copper wire drawing. The size of this wire screen is approximated from the cable catalogues Manufacturing of the XPLE and PVC elements is performed by the simplified process of plastic pipe extrusion.

Cable		**AWE**	**HAWT**
Length	Inter array	1080	794
(m)	Export	3000	3000
Sizes	Inter array	240	240
(mm^2)	Export	600	600

Table 5.15: Cabling specs for the different systems. The lengths state the total cabling lengths used per single generation system. The sizes denotes the cross sectional area of a single conductor core of the 3core AC cables.

Component	**Inter array**	**Export**	**Material**
Cable Total	**6.62**	**12.81**	-
Conductor	1.94	4.86	Aluminium
Insulation	1.95	2.90	XPLE
Wire screen	0.35	0.53	Copper wire
Sheath	2.37	4.53	PVC

Table 5.16: Masses of the components of the cable, in kg/m

Manufacturing scraps Neither material losses at manufacturing nor cable cut-offs at installation are included in this report. Cable installation in offshore systems requires the cable to be cut to length before it can be installed. Cutting the cable too short would require removal of the entire cable. These lengths are therefore deliberately taken on the large side.

Additional excluded Power cables come in many different shapes and sizes. Some of the excluded elements are: steel armoring, fibre glass line and potential cable ducts. None of which are essential components for onshore cables. (Floating) offshore cables would require a large variety of additional components, such as: scour protection, dynamic cable control, and concrete anchoring.

Single cores The presented 600 mm^2 3core AC 33 KV cables are extrapolated from available data on smaller cables. It would however have been more realistic to model the export cables as separate single core cables. 3core AC cables of 600 m2 cross section cores are not found in these catalogues. The mass of a conventional 630 mm^2 single core cable is found to be 4.05 kg/m in the same catalogue (12.15 kg/m for 3 cables). The deviation is considered small enough that a recalculation is not essential.

5.4 Installation

After manufacturing the components of the wind farm, the next life cycle phase of the system is its installation. This includes all transport of final products to the location of the farm. As well as all turbine construction and site preparation activities. These include activities such as crane operation and digging activities for foundations and cabling.

5.4.1 Transport

Transport of all components excluding the foundations is considered to come from a standardised location in Denmark. Denmark is among the larges manufacturing hubs for the wind energy industry, housing large manufacturing facilities for e.g. Vestas and LM Wind Power. It is assumed that the AWE and HAWT systems are manufactured in the same area, requiring the same transport distance to the farm site. The set distances are:

Component	**Distance [km]**		**Transport type**	
	Land	**Sea**	**Land**	**Sea**
AWE				
Aircraft/ Rotor	500	2000	Heavy truck	Ferry
Tether	500	2000	Heavy truck	Ferry
PGA	500	2000	Heavy truck	Ferry
LLA	500	2000	Heavy truck	Ferry
Foundation	50	0	Heavy truck	-
HAWT				
Rotor	500	2000	Heavy truck	Ferry
Tower	500	2000	Heavy truck	Ferry
Nacelle	500	2000	Heavy truck	Ferry
Foundation	50	0	Heavy truck	-
BOS and Consumables				
Cables	500	2000	Heavy truck	Ferry
Consumables	100	0	Mid-light Truck	-

Table 5.17: Transport distances and types

Transport generally gets more efficient with higher transport masses. For example, 1 tkm of transport with a container ship is 10 times less pollutive than the same mass transported over the same distance with a ferry.

Sea transport is modelled by a freight transport ferry. Wind turbines are large and inefficient to transport. Therefore they are generally transported using specialised ships. The freight ferry is assumed to best represent the impacts of this transport.

Transport impacts of the oversized turbine components is expected to be underestimated. This is for a number of reasons. E.g.: Components such as the blades require heavy frames to keep them safe during transport. This added weight is not included. Additionally, oversized transport is most likely accompanied by support trucks. Their usage has however not been includes, nor are the detours that specialised transport would have to make to avoid bridges and tight corners.

Transport for O&M is included in section 5.5

Transport option		Dataset used
Truck 1	Light	Transport, freight, lorry 3.5 to 7.5 mt euro5, RER market
Truck 2	Mid-Light	Transport, freight, lorry 7.5 to 16 mt euro5, RER market
Truck 3	Mid-Heavy	Transport, freight, lorry 16 to 32 mt euro5, RER market
Truck 4	Heavy	Transport, freight, lorry >32 mt euro5, RER market
Container ship		Transport, freight, Container ship, GLO market
Ferry		Transport, freight, Ferry, GLO market

Table 5.18: Transport datasets by Ecoinvent

5.4.2 Land Transformation

Land transformations are limited to digging activities for foundations and the cable trenches. All digging is performed with a hydraulic digger, represented by the dataset: *Hydraulic digger, RER Processing(per m^3)*

All cable trenches are modelled as 0.8×0.8m in width and height. The length of the cable trenches differ, based on the internal spacing of the energy generating units within the farm. Table 5.19 presents the volume of dirt that needs to be dug. The power cable is assumed to be covered again by replacing the same amount of material back into the trench with the same digger. The material removed for digging the foundation is not further processed.

Activity	Unit	AWE	HAWT
Export length per system	m	1500	1500
Export cable digging	m^3	960	960
Inter array cable per system	m	1080	794
Inter array cable digging	m^3	691	508
Foundation digging	m^3	313	766
Cables burying	m^3	1651	1468

Table 5.19: Digging activities per single system. The 2 export cables share the same trench. After cable laying, the trench is filled up again with the same volume of digging; which is included as the cables burying activity.

5.4.3 Construction

Construction processes for both the HAWT as the AWE system remained uncertain. It is expected that the AWE system will require less construction activities than the HAWT system. Especially the sizes of the required construction machinery will differ greatly. HAWT cranes need to lift the components to high heights, whereas the AWE system can be constructed with smaller cranes and other ground based machinery. Table 5.20 states the included construction activities.

Activity	Unit	AWE	HAWT
Hours crane operation	h	20	40

Table 5.20: Construction activities per single system.

The accuracy of these activities can be improved significantly. The impacts of this construction will however remain limited. The impacts of crane operation are taken at 90 $kgCO_2eq/MWh$, as was presented by Smoucha et al. (2016). The CED of the crane was subsequently estimated by calculating the amount of diesel that is burned to get a GWP of 90 $kgCO_2eq/MWh$, and calculating its related CED impacts. This was based on the Ecoinvent data-set for diesel burned in construction machines.

5.5 Operation and Maintenance

The O&M stage includes all material and energy inputs and outputs over the full operational life of the system. The actual impacts of the system itself is not useful on itself. It becomes useful when the impacts of the system can be related to a useful function or output by the system. For energy generation systems, this useful output is the actual electrical energy delivered to the grid, as stated by the functional unit: ***1 MWh of electricity from the wind, delivered to the grid*** (As introduced in section 4.2).

Section 5.5.1 discusses this output energy production, including the assumed losses. Sections 5.5.2 and 5.5.2.c subsequently include all additionally required inputs over the course of the systems operational lives.

5.5.1 Operation and losses

Comparisons between AWE and HAWT systems should be performed between systems designed for usage in similar locations. The wind conditions however differ with the operating height of the systems.

The presented AWE system can operate in various wind conditions. It may only need limited design changes to the aircraft for optimal operation at different wind speeds. The masses of a HAWT system however significantly differs between systems designed for different wind conditions.

HAWT The NREL 5MW is rated for operation in the IEC2 / IEC1 wind speed classes. These have average wind speeds of 8.5 and 10 m/s at hubheight respectively. The effects of additional turbulence classes is not assessed. The onshore version of the Repower 5M, on which the NREL 5MW is based, has a hub-height of 117 m. The AEP of the modelled onshore HAWT system is determined using a variety of sources. The AEP data largely based on a Vestas LCA report on the V117-4.2MW turbine. This is an onshore turbine with a rotor diameter of 117 m, rated for wind class of IEC1. The capacity factor of this 4.2 MW HAWT system is found to be 47.3%. This includes 2.5% electrical losses, 6% wake losses and a 98% availability. The 50 MW farm of 10 HAWT systems is however assumed to have lower wake losses, this is therefore halved.

Drivetrain losses The electrical losses are stated to include all losses up to the grid, including the losses in the turbine itself. The export cables are found to be assumed to have 1% of the 2.5% loss. The additional 1.5% of all electrical losses is over the inter array and the turbine drivetrains. This assumes significantly higher efficiencies than generally stated. An overall drivetrain loss of 6% is considered in this assessment. These drivetrain losses are based on approximated efficiencies stated in Sethuraman and Dykes (2017). Amongst others, this includes a 2% generator loss. It should be noted that the considered drivetrain losses of the Ampyx system remain unknown. Their values are however included within the provided AEP estimation. The losses of the HAWT system may be over-estimated in comparison to the AWE system. Especially if Ampyx assumes similar ideal efficiencies as used by Vestas.

Cable losses The losses over the cables are not specifically calculated. Instead, indications were taken from literature. Vestas sensitivity analysis indicate assumed cable loss of 0.05% per km. Transmission without the transformer will however lead to higher losses. Therefore the transmission losses are taken at 3%, (0.2% per km). The inter array cable losses are assumed 0.25% in total.

AWE The AWE system operates at variable heights, therefore the average wind speed is stated as the average wind at an average operating height. The provided energy output of the AWE system is based on a case of 11 m/s average wind speed at an 250 m average cycle height. At these conditions the AEP of the AWE system is estimated to be 23126.4 MWh delivered to the grid per system. This includes 3.25% cable losses, an availability of 95% and a 95% round trip storage efficiency. Additional drivetrain losses are stated to be included, but remain undefined. Wake losses are not included for the AWE system. The calculated AEP translates to a Cf of 52.8% for the AWE system(including all losses upto the grid).

	Unit	AWE	HAWT
Cf	-	52.8%	46.9%
Farm AEP	MWh	231264.0	205442.8
Wind Speed	m/s	11	10
Height	m	250	117

Table 5.21: Energy production values for the farm.

5.5.1.a Wind Environment at Same Location

The NREL 5MW system is designed for the IEC2 to IEC1 wind classes. These wind classes represent average wind speeds of 8.5 to 10 m/s at hub heights. The onshore NREL 5MW hub height is 117 m. Extrapolation to the average wind speed at average AWE flight height is performed using the log law:

$$V = V_{ref} \frac{ln(\frac{Z}{Z_0})}{ln(\frac{Z_{ref}}{Z_0})} \tag{5.4}$$

For the onshore location, the surface roughness is taken as: $Z_0 = 0.1$

A location at which the average wind speed is 8.5 to 10 m/s at 117 m hub height, would have an approximate average wind speed of 9.4 to 11.1 m/s at 250 m average AWE flight height. The capacity factor of 46.9% for the HAWT system is assumed to be for the system operating in 10m/s average wind conditions. Therefore, the AEP calculation for the AWE system has been performed for an average wind speed of 11m/s at 250 m average cycle height.

5.5.1.b Self Consumption

Both the AWE as the HAWT systems are filled with control systems that require energy to operate. This self consumption is not included in the assessment. The largest energy consuming process of the AWE system (rewinding of the tether) is fed by the hydraulic system, which is charged by the system itself. Additionally, the airplane energy systems are charged with small on-board wind turbines. Other energy requiring systems such as e.g.: The yaw and HVAC systems are expected to be of small and similar energy demand.

5.5.2 Maintenance

Maintenance will be required over the 20 year service life of the systems. It includes transport trips, consumables and replacements.

5.5.2.a Lubrication and Consumables

The many rotational elements in AWE and HAWT systems require good lubrication to prevent wear and ensure long component service lives. The actual amount of required lubrication will strongly depend on the chosen system components. The amount used in this report is however simplified. The value used in this report is taken from a LCA report on a 50 MW farm (Vestas, 2015).

By this Vestas LCA report, the 50 MW farm of HAWT systems requires a total of 14000 kg of lubrication over the 20 year of operation. A large portion of this lubrication is however expected to be used in the gearbox, which is not used in the AWE design. Regardless, no difference was made between AWE and HAWT. The lubricants have been modelled with the Ecoinvent lubricant data-set.

This same Vestas LCA report states that the farm uses a total of 4000 kg of coolant over 20 years of operation. The same amount of coolant was used for both the AWE and the HAWT systems in this report. This is modelled with the ecoinvent *Ehylene Glycol* (anti freeze) data-set.

5.5.2.b Maintenance Visits

There are two types of maintenance visits: Planned maintenance visits and un-planned (emergency) visits.

Planned maintenance visits are used to check all system components for wear, perform servicing and potently replacements system replacements. The replacements are treated in the next section. Unplanned 'maintenance' such are system crashes and damages are not included in this report.

Planned maintenance is assumed to take place every 2 months, both for the HAWT systems as for the AWE systems. Offshore farms only require 2 to 4 visits a year (BVG, 2019). These systems are however build with more reliable technology to minimise the expensive offshore maintenance. The 6 visits a year include visits to all systems. It is however assumed that not all systems can be visited in one day.

HAWT systems are expected to have more problems with accessibility, whereas AWE systems are expected to require more refined fine-tuning and testing of sensors. The AWE systems will also require more small components replacements over time. It is assumed that three systems can be visited a day. Both for the AWE as the HAWT technology.

Maintenance distance is assumed to be 200 km, 6 times a year. The crew is assumed to remain on-site until all systems are visited. Thereby reducing the transport time and impact. This adds up to a total of 2400 km per year. This exceeds estimations stated by Vestas, being 1500 km transport a year to a 100 MW farm (Vestas, 2019a).

These visits are modelled by a medium sized truck (7.5 to 16 mt) loaded with 7.5 mt of maintenance equipment. This same truck also transports the additional weight for small replacement components. This includes the actuator replacements, battery replacements, tether replacements, lubrication changes and coolant replacements when they are required. Their respective masses are added to the base mass of the 7.5 mt maintenance gear.

5.5.2.c Replacements

The previous manufacturing descriptions only included the masses for the initial systems. A variety of components will however need to be replaced during the operational life of these systems. The service life of a system is determined by the shortest service life of one of its irreplaceable components. One of these limiting factors is metal fatigue in the tower of a wind turbine. Damages and wear of smaller or less critical systems can simply be replaced to prolong the service life of the system. A system replacement could be as large as a full HAWT blade, gearbox or generator.

The lifetimes of the AWE and HAWT systems are both taken at 20 years. Current HAWT systems with designed lifetimes above the 20 years are still modelled with a lifetime of 20 years. It might however be reasoned that AWE systems could potentially have larger lifetimes. The lifetimes of HAWT systems are determined by fatigue damages on system components such as the tower. When the tower has reached its maximum service life, so does the entire system. The AWE system design does not have a specific non replaceable system component. Therefore the service life of AWE could potentially be longer. This is returned as a sensitivity case.

The largest components for replacements in AWE are the tether, the batteries and the actuators on the aircraft. The HAWT system is only considered with replacement of the gearbox. Additional replacements are to be expected. This includes components such as the yaw and pitch drive systems. These and all other potential replacements are however excluded from this report.

Potential failures such as crashes of the AWE aircraft are not included in this assessment. Nor are potential failures for HAWT systems.

Component	AWE	HAWT
Tether Winding	19	-
Tether Airborne	2	-
Batteries	1-3*	0
Actuators	4	-
Gearbox	0	1
Motors (e.g. yaw)	0	0
Generators	0	0

Table 5.22: The number of replacements considered over 20 years of operation.
*: Different lifetimes for the different battery systems.

Batteries The lifetime of a battery is largely determined by its number of charge-discharge cycle, coupled with additional usage-independent factors. The number of discharges depends on the depth of discharge, the rate of discharge and its operating temperatures. The usage independent losses are not considered.

The aircraft houses 2 battery systems, one for flight controls and another for the propulsion. The flight control system is continuously used in normal operation. The propulsion system is however only used at take-off. Therefore the large propulsion battery is modelled with a longer lifetime of 10 years. The actuator batteries are continuously used, but with lower rates of discharge. They are modelled with a lifetime of 5 years.

Transport Transport of the replacement components is kept the same distance as that of the initial system. The products will still be produced at the same manufacturing location, and will still need to be transported to the same farm location. Tether, actuator and battery replacements are however not modelled with transport of a heavy >34 mt truck. Instead, they are assumed to be transported with the smaller servicing trucks. Replacements of heavier components, such as the gearbox, are modelled with the same heavy >34 mt truck as used in the initial installation.

These same transport vehicles are used for an assumed 200km transport to their respective End of Life treatment facilities.

5.6 End of Life

This LCA is performed based on the LCA CUT-OFF methods. In this method, the system is not rewarded for the recycling benefits of its End of Life (EOL) materials. All impacts related to recycling are allocated to future products.

Included in the End of Life stage are: Simplified disassembly activities, transportation, rates of EOL treatments (recycling, incineration, land-filling) and the impacts of EOL treatments.

5.6.1 Disassembly

Disassembly is modelled with the same amount of crane operation as specified for construction. Additionally, the concrete is assumed to be broken up and removed. Concrete removal is assumed to be executed for 60% with an wrecking ball mounted cable excavator and for 40% with a hydraulic excavator with tongs. The wrecking ball method removes 15 m^3 of concrete a hour with a diesel consumption of 60.8 Liter/hour. The tongs method removes 20 m^3 of concrete an hour, with a diesel consumption of 36.1 Liter/hour. These values are taken as used by NLMK Kaluga (2020). The total diesel consumption is 3.15 Liter of diesel per removed m^3 concrete.

The electrical system (cabling) is generally assumed to have a service life of 40 years. In this report it has however been assumed equal to the service life of the farm. It is assumed dug up at decommissioning of the farm. This is modelled with the same land transformation activities as used for its installation.

	Unit	**AWE**	**HAWT**
Hours crane operation	h	20	40
Volume of concrete	m^3	313	766
Diesel consumption, concrete removal	L	987	2416
Cable removal digging	m^3	1651	1468

Table 5.23: Disassembly specifications per single system,

The impact of this diesel consumption is modelled with a representative ecoinvent data-set for diesel burned in building machines. This data-set assumes that 1 kg of diesel equals 42.7 MJ of energy burned in building machines. The density of diesel is 0.85 kg/L. By these assumptions, the energy in one liter of diesel is 36.3 MJ.

Potential material and processing to fill the removed foundation holes back up has not been included in this assessment.

5.6.2 Transport at EOL

At end of life, all materials need to be transported to their respective EOL treatment facilities. Transportation to these facilities has been taken as a constant for all materials that are installed at the moment of decommissioning. Most EOL Transportation is modelled as 200 km transport with a 'heavy truck'. This distance is reduced to 50 km for the concrete. EOL transport of smaller replaced systems is transported with the maintenance truck, Lorry 7.5 to 16 mt. The heavy HAWT gearbox replacement is transported with the same truck and distance as the final system. No difference is made between transport distances towards the different land-filling, incineration or recycling facilities.

Topic	**Value**
EOL distance	200 km
EOL distance concrete	50 km
Transport type	Heavy truck
EOL replacements transport type	Lorry 7.5 to 16 mt

Table 5.24: Transport specifications for EOL

5.6.3 End of Life Rates

Recycling rates have been specified in different methods throughout literature. The recycling rates in this report are taken as an average per material alone. In reality, the metal of the tower of a wind turbine, or the deck of this AWE system are recyclable at higher rate than the same materials in the generator or other components without single homogeneous material. The actual theoretic recycling rate for steel is 100%, the losses to this recycling rate are the result of collection and separation losses.

The recycling rates for each of the materials are largely based on values used in LCAs on wind turbines. They represent the current status, but are not well designed for the future. Legislation is pushing further towards waste reduction and inclusion of recycled content. The recycling values as presented in table 5.25, will significantly have changed by the time an AWE system of this size would be feasible.

Material	**Recycling**	**Incineration**	**Land-filing**
Steel and iron	92%	-	8%
Copper	92%	-	8%
Aluminium	92%	-	8%
FRP	-	-	100%
Plastics	-	50%	50%
Electronics	50%	-	50%
Concrete	-	-	100%
Lubricants	-	100%	-
Other	-	-	100%
Motor	90%	-	10%
Transformer	85%	-	15%

Table 5.25: Recycling rates used

The EOL impacts of the different materials are used as presented by SimaPro. These EOL impacts differ per material, but is not always defined. Various materials such as the FRP composites are not presented with an EOL material type. Materials with undefined EOL materials types are modelled with data sets for averages of undefined material mixtures.

Further detail on EOL modelling can be found in appendix A.

5.6.4 Manufacturing Scraps

The average metal work data-sets in Ecoinvent include a material loss of 22.7%. These average metal work processes were not available for all metal types, such as the cast iron and titanium. Representative average processing models were made for these materials. Assuming the same manufacturing loss percentages and the same machinery usage. The large steel tower and deck elements are modelled with reduced impacts, at 50% of normal average metal work. All metal production scraps are assumed 100% collected for recycling. No additional EOL impacts are included for these metal scraps.

Manufacturing losses for the FRP materials were detailed in 5.1.1. These manufacturing losses are assumed to be disposed of at the same rates as the the EOL rates for the used materials.
The production waste for concrete is already included in the used data-set.

Chapter 6

Impact Assessment (LCIA)

The previous (LCI) chapter detailed the design and inventory of the assessed base-case systems. The current (LCIA) chapter uses these inventoried *bills of materials and processes* to determine the impacts of the modelled base-case system.

The masses of the systems are first detailed in section 6.1. The impacts of the systems are subsequently assessed in section 6.2.

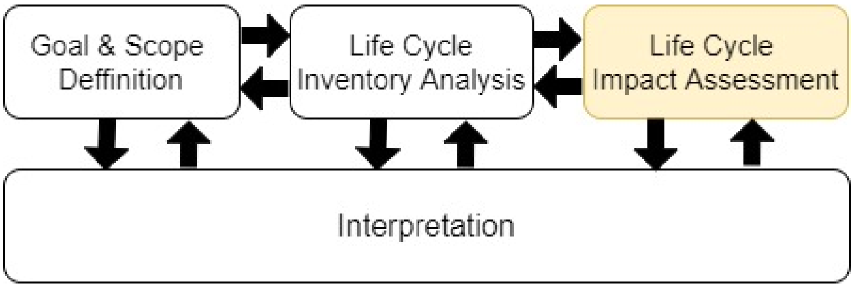


Figure 6.1: Stage 3, the LCIA

The GWP and CED impacts are presented after normalisation to the functional unit of: ***1 MWh of electricity from the wind delivered to the grid***, (described in 4.2). The energy produced over the full lifetimes of the systems is 462528.0 MWh for each AWE system and 410885.6 MWh for HAWT, these values were determined in section 5.5.1.

6.1 Mass Assessments

One of the main selling points for AWE its ability to produce the same amount of green energy with a significant reduction of material usage. This section evaluates the material usage for both systems. First in a comparison between both systems, followed by more detailed evaluations of all components within each system individually.

The AWE system requires a mass of 2.0 kg/MWh over its 20 year service life. The HAWT system requires a mass of 6.6 kg/MWh over the same time period, and at the same location. Figure 6.2 and table 6.1 present the assumed masses of the subsystems of both the AWE system and the HAWT system. The majority of the HAWT masses are presented by its tower and foundations. It is these structural elements where the lighter weight AWE technology gains it mass advantage over HAWT systems.

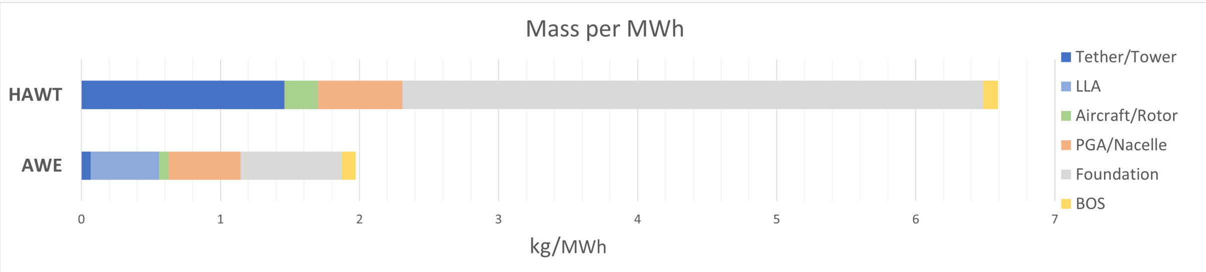


Figure 6.2: Normalised masses of both systems kg/MWh. These include the replacement masses. The actual values are stated in table 6.1.

It is important to note the numerous design variables for both technologies. Direct data on the AWE system could only minimally be obtained. Additionally, the presented HAWT model is not intended to represent any specific system. Instead, it is indented as a comparison case for the AWE system. Changes of several of these design variables is assessed in sensitivity analysis in chapter 7.

Component	kg/MWh AWE	kg/MWh HAWT	Mass mt AWE	Mass mt HAWT
Tether/Tower	0.1	1.5	30.6	600.0
Aircraft/Rotor	0.1	0.2	31.8	98.9
PGA/Nacelle	0.5	0.6	238.7	249.7
LLA	0.5	0.0	228.1	0.0
Foundation	0.7	4.2	338.2	1715.8
BOS	0.1	0.1	45.6	43.7
Total	2.0	6.6	913.0	2708.1

Table 6.1: The masses in kg/MWh and mt for each individual subsystems. These masses include the masses of the replaced components. It does not include manufacturing scraps and consumables.

Replacements
The initial tether only accounts for 10% of the stated tether mass. The other 90% of the tether mass is from the tether replacements over 20 years of operation. Only 20 mt of the 31.8 mt aircraft mass is represented by initial aircraft mass. The battery and actuator replacements account for the other 11.8 mt. The gearbox replacement of the HAWT system accounts for 48.6 mt of the nacelle mass.

6.1.1 AWE Masses

The lifetime-mass fractions between the subsystems of the modelled AWE systems are presented in figure 6.3. Each subsystem of the design represents a collection of components primarily chosen based on their collective functions and for comparability to other systems. The masses of each component in the subsystem are presented in figure 6.4.

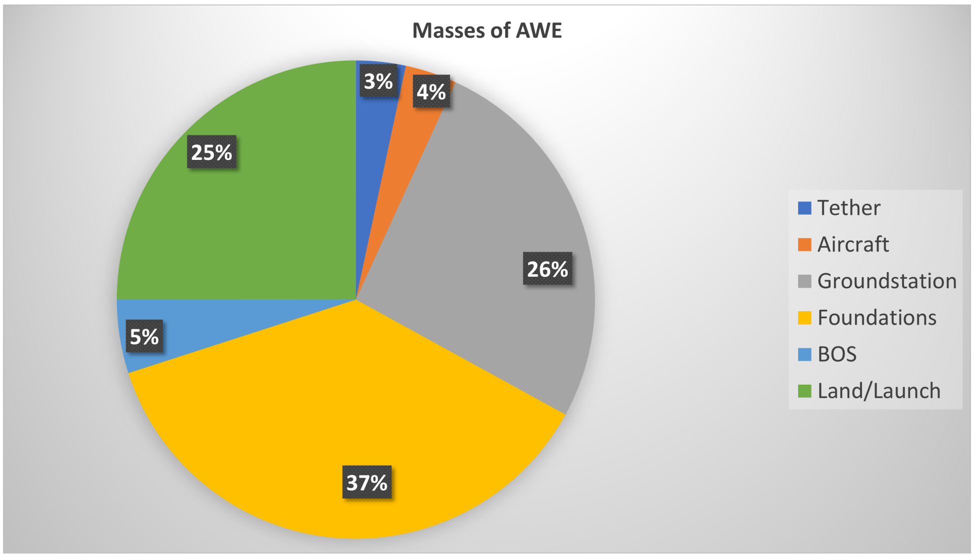


Figure 6.3: The mass fractions of the subsystems in the AWES, with the replacements included.

The graphs show that the foundations are responsible for the largest mass of the system. However, neither the size nor an indicative design of the foundation could be provided by Ampyx. An advantage of AWE technology are the near elimination of overturning moments compared to HAWT. This will most clearly be visible in strong reductions in the foundation. Even-though it is certain that AWE will suffice with a smaller foundation compared to what the HAWT system will require. An actual basic foundation design will be required before anything accurate can be stated about this subsystem.

The heaviest components in the AWE design are the LLA platform and the accumulator systems. These are both components that have not been optimised for usage in large scale future designs before.

A large portion of the mass of the LLA is presented by the platform. This platform is the combination of the deck and its supporting structures. The mass of the platform is estimated to be 128 mt. This value is obtained using an estimator model provided by Ampyx. The accuracy of this mass is however highly uncertain. The deck may have been assumed GFRP in the mass estimator provided by Ampyx. It is however modelled as steel in this assessment. This uncertainty could significantly increase the deck impacts.

The mass of the deck is so large since it needs to be both large and strong enough to land and launch the aircraft. The 5 MW Aircraft is assumed to have a wingspan of 54 m, a mass of 20 mt, and a surface area of 300 m^2. For an aircraft with these specification, the estimated deck size adds up to 18.7 m in width and 34.2 m in length.

The collective mixture of the hydraulic system components represents the largest mass after the foundation. It is the collection of the accumulators, pistons, motors and extras such as the hydraulic fluid, tubing and the nitrogen gas in the cylinders. The hydraulic system has multiple functions in the design. Apart from stabilising the energy output of the cyclically behaving system, it also functions as the connection between the drum and the generators. Allong which it also transforms the low-speed rotation of the drum into high-speed rotation of the shafts that drive the generators.

The assessed Ground-Gen AWE system generates electricity in a cycling manner. Smoothing of these peaks and valleys takes place before transformation to electricity. Therefore it also eliminates the need to oversize the generators and converters. The hydraulic system would indeed be a heavy component in

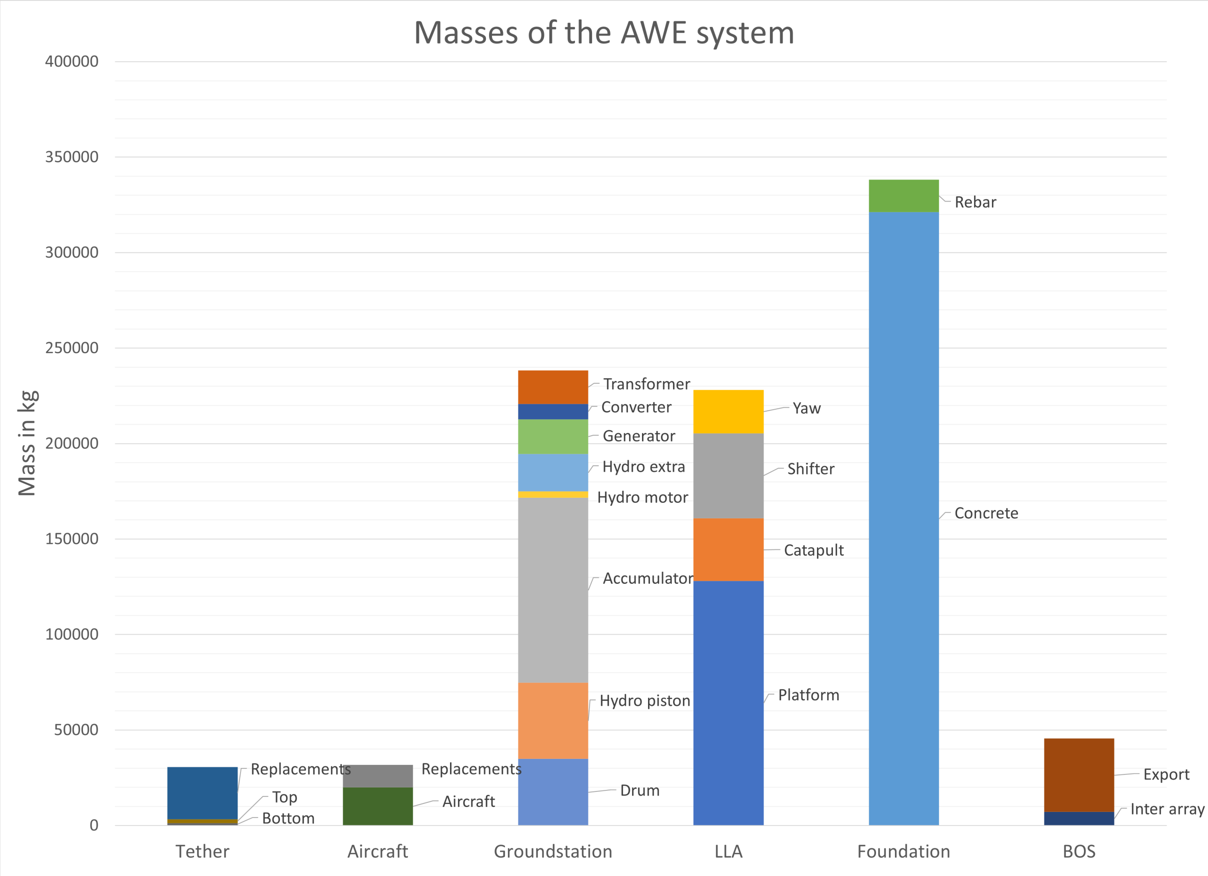


Figure 6.4: Total masses of the AWE system components, in kg.

a hydraulic drivetrain, even with potential future design improvements. Its usage however also leads to mass reductions of potential shafts, gearboxes, generators, converters and a energy stabilisation options.

The mass of an installed tether is only 3.2 mt at any time. This tether mass however builds-up significantly over the service life of the system. The yearly replacements of the 1.2 mt bottom tether section weighs a total of 23.4 mt over 20 years and the 2 replacements of the top section adds another 3.9 mt of tether material. The mass of the highly energy intensive tether materials adds up to a total of 30.6 mt over the 20 year service life of the system.

The aircraft has an initially installed weight of 20 mt. This mass is presented by Ampyx as a reasonable weight goal, which is considered achievable with significant technological and design improvements. The masses of the battery and actuator system replacements are 3.3 and 8.5 mt respectively. The installed mass of the aircraft will return in a sensitivity analysis.

6.1.2 HAWT Masses

For the HAWT system, the masses of the foundation and tower far exceed the masses of all other components. These components are however also most dependent on design choices. Under the assumption that the wind class rating of the turbine does not change, the rotor and nacelle would mostly remain constant, independent of the location where the system is built. The masses (and impacts) of the tower and foundation are however highly dependent of the location of the farm.

The masses presented in figure 6.5 present the masses of the modelled base-case on-shore HAWT system, with a hub-height of 117 m. Over 55% of its mass is from concrete alone, which represents 94% of the foundation mass. The other 6.32% of the foundation is the rebar. The tower all steel, of which 90% is standard steel plates and 10% is the flanges. The Nacelle, rotor and BOS components only account for 14% of the mass of the system. These components are displayed in further detail in figure 6.6.

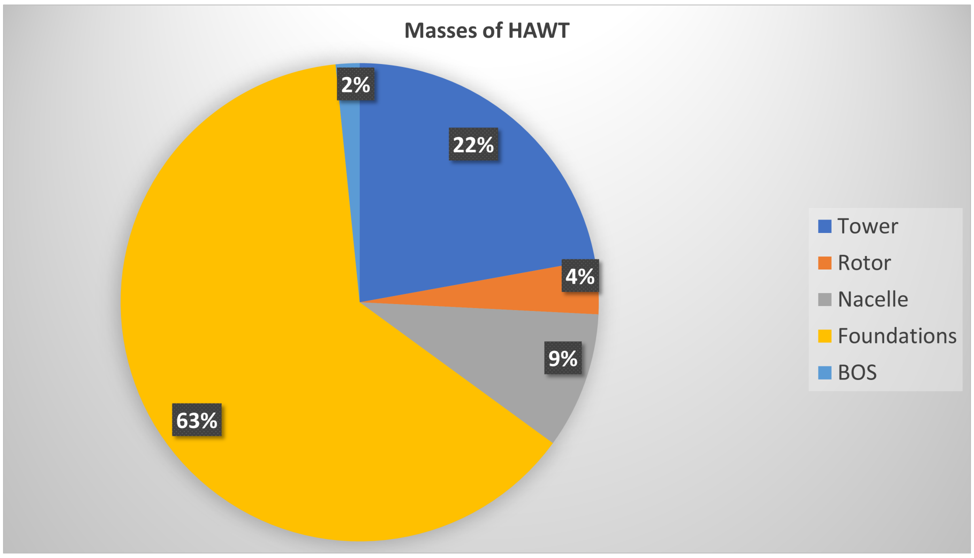


Figure 6.5: Mass fractions of the subsystems in the HAWT. Replacement masses included.

The masses in figure 6.6 include the replacement mass of the gearbox. This replacement makes the gearbox one of the heaviest components of the system after the foundation and the tower. Other heavy systems are the bedplate, hub and blades, each primarily heavy due to their structural requirements.

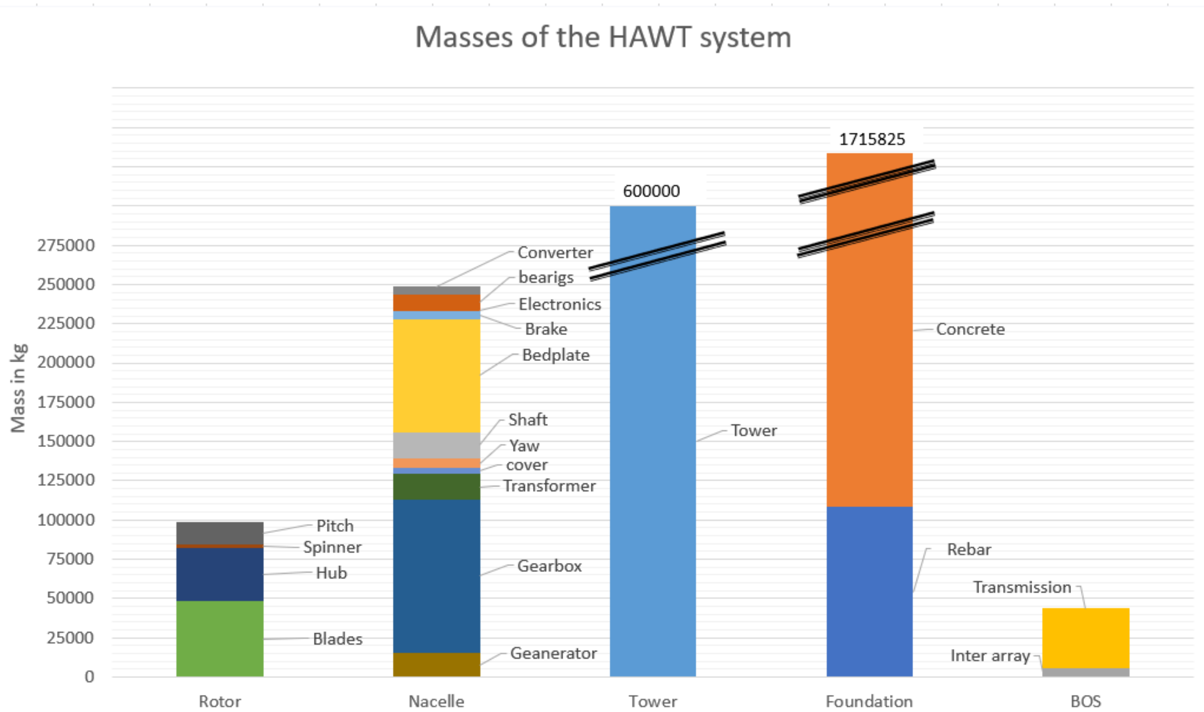


Figure 6.6: Mass build-up of the components in the HAWT system, in kg. Replacements included. Tower and concrete far exceed bounds.

6.2 Impact Assessments

The assessed impacts are the Global Warming Potential (GWP100) and the Cumulative Energy Demand (CED). The total impacts of both systems are first in an overview for total system comparisons and to indicate the hotspots. The subsequent subsections evaluate each life cycle stage and subsystem individually.

6.2.1 Full system impacts

The total GWP and CED impacts over all stages of the AWE system combined are 7.8 kgCO_2eq/MWh and 127.5 MJ/MWh respectively. The impacts of the HAWT systems are 13.0 kgCO_2eq/MWh and 195.0 MJ/MWh . In comparison, the GWP and CED impacts of the AWE are only 60.1% and 65.4% of the same impacts of the HAWT system under the base-case assumptions.

Figures 6.7 and 6.8 present the total build up of the GWP and CED impacts of both systems. The relative impacts of the different components in the systems are evaluated in detail further in this chapter.

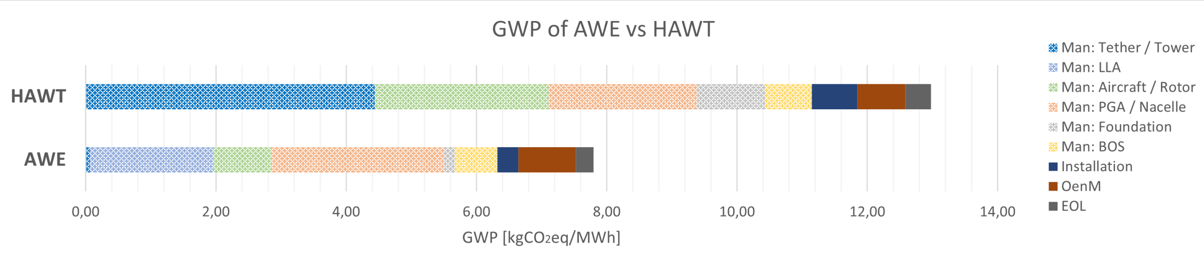


Figure 6.7: Total GWP impact results of the base-case AWE and HAWT systems. The dotted represent the materials and manufacturing stage split into the 6 subsystems. Impacts of the replacements are included in the O&M stage.

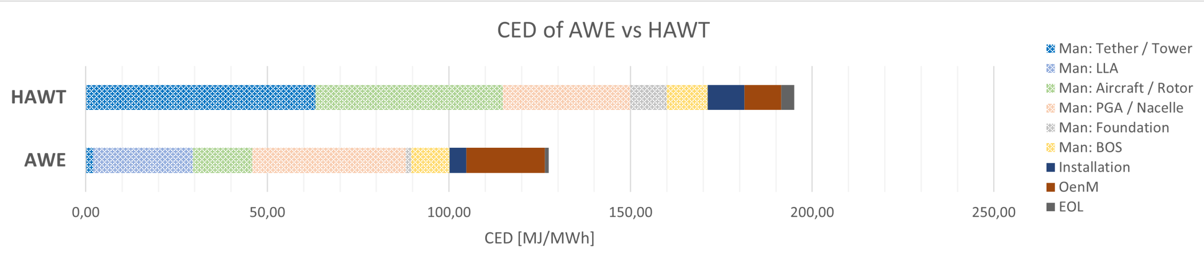


Figure 6.8: Total CED impact results of the base-case AWE and HAWT systems. The dotted represent the materials and manufacturing stage split into the 6 subsystems. Impacts of the replacements are included in the O&M stage.

Hotspots

This section only indicates the locations of hotspots, but does not assess their reasons. Detailed impacts assessments of all elements in the design are assessed within the later sections.

AWE

Figure 6.9 displays all impacts in percentages of the total impacts of the AWE system. These bars include the replacements within the component bars, but keep transport and other processes separated. The figure indicates several important hotspots in the design, each described in the following sections.

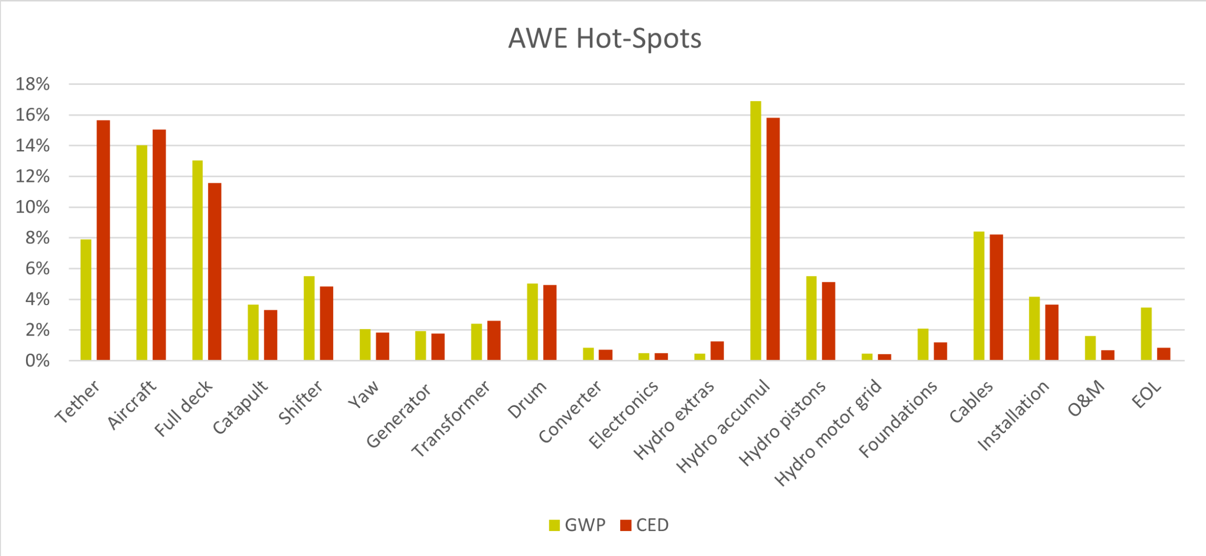


Figure 6.9: Hotspot graph of the AWE system; with replacements included in the material bars. Other O&M, transport and EOL impacts are presented separately.

HAWT

Figure 6.10 displays all impacts in percentages of the total impacts of the HAWT system. Same as for the AWE system, these bars include the replacements within the component bars, but keep transport and other processes separated. The figure indicates several important hotspots in the design.

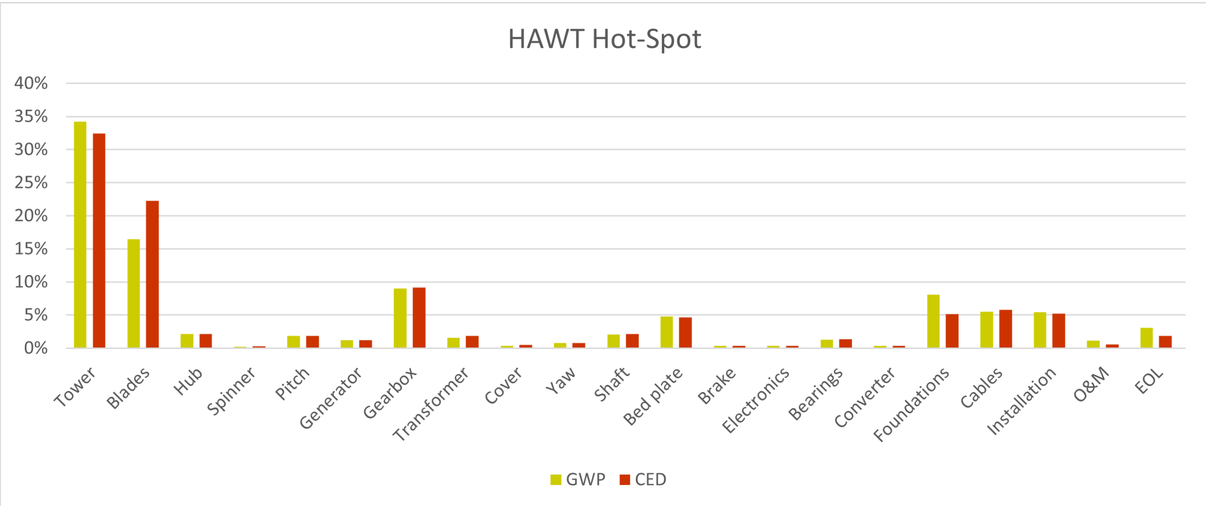
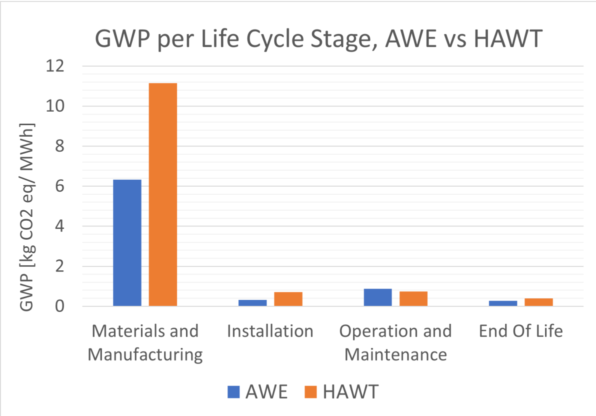


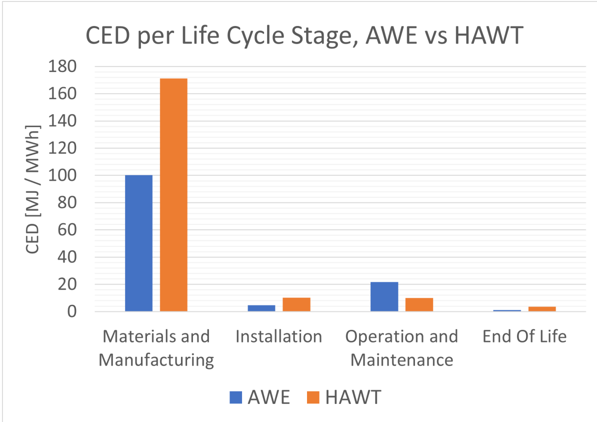
Figure 6.10: Hotspot graph of the HAWT system; with replacements included in the material bars. Other O&M, transport and EOL impacts are presented separately.

6.2.2 The Life Cycle Stages

The LCA is divided into the 4 lifecycle stages, as described in section 4.5.Impacts were calculated for each of these stages individually. The results of which are presented in figure 6.11. Each subsection is treated individually in subsections below.



(a) GWP impacts



(b) CED impacts

Figure 6.11: The impacts over the different life cycle stages.

The majority of all impacts are generated in the materials and manufacturing stages of both technologies. This stage is responsible for 81.1% and 78.5% of the the total GWP and CED impacts of the AWE system. For the HAWT system it is responsible for 85.9% and 87.8% of all GWP and CED impacts.

Life Cycle Stage	AWE				HAWT			
	GWP		CED		GWP		CED	
	GPW	%	CED	%	GWP	%	CED	%
Materials and Manufacturing	6.3	81.1	100.1	78.5	11.1	85.9	171.3	87.8
Installation	0.3	4.2	4.7	3.7	0.7	5.4	10.1	5.2
Operations and Maintenance	0.9	11.3	21.6	17.0	0.7	5.7	10.0	5.2
End of Life	0.3	3.5	1.1	0.9	0.4	3.0	3.6	1.8
Total	7.8	100.0	127.5	100.0	13.0	100.0	195.0	100.0

Table 6.2: The GWP and CED values over the different life cycle stages of both systems. CED in MJ/MWh and GWP in $kgCO_2eq/MWh$. Percentages are over all impacts.

The GWP and CED impacts generally follow similar trends. The majority of GWP impacts are caused by the exact energy usage that is indicated with the CED.

The CED impacts of the AWE replacements system presents a deviation from the other data. This CED value is notably higher than the GWP value for this same life cycle stage. This deviation is caused by the impacts of manufacturing of the UHMWPE material of the tether. Production of this tether material is a highly energy intensive process. It is however considered to be made with a large share of renewable energy. As a result, its GWP impacts remain limited in comparison to the energy usage. This effect presents itself well in the replacements, as the replacements of the tether represents a large portion of all replacements.

6.2.2.a Materials and Manufacturing

The majority of all GWP and CED impacts are located in the materials and manufacturing stages for both technologies. Its GWP and CED impacts for the AWE system are 6.3 $kgCO_2eq/MWh$ and 100.1 MJ/MWh respectively. These impacts are assessed for each individual subsystem of the design, figure

6.12. These impact only include the materials and manufacturing processes for the initially installed systems. The impacts of the replacements are accounted for in the Operations & Maintenance stage.

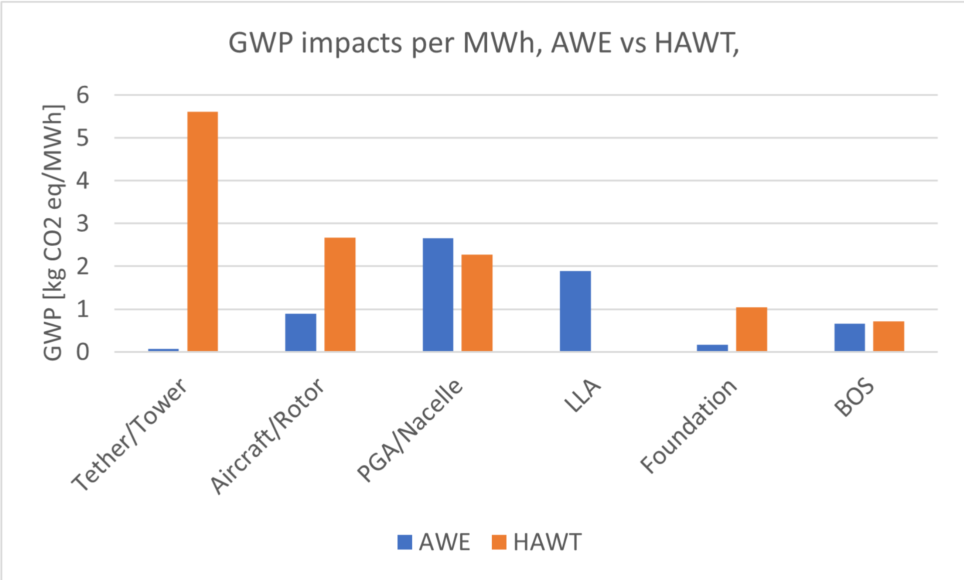


Figure 6.12: The GWP impacts of the different subsystems in the manufacturing stage. CED impacts are not shown, but follow the same trend. Exact values are presented in table 6.3. These do not include the replacements.

The results clearly indicate that the reduced structural requirements lead to significantly reduced impacts for AWE. The largest reductions are made by elimination or reduction of the tower, rotor and foundations with regards to the HAWT system. This advantage appears extra large when only assessing the manufacturing of the initial system, as presented in figure 6.12. These results do however not include the replacements.

	GWP			CED		
Subsystem	**kgCO$_2$eq/MWh**	**% of stage**	**% of all**	**MJ/MWh**	**% of stage**	**% of all**
Total AWE	6.3	100.0	81.1	100.1	100.0	78.5
Tether	0.1	1.0	0.8	2.1	2.1	1.6
Aircraft	0.9	14.1	11.4	16.3	16.3	12.8
PGA	2.7	42.0	34.0	42.3	42.2	33.2
LLA	1.9	29.9	24.3	27.4	27.4	21.5
Foundation	0.2	2.6	2.1	1.5	1.5	1.2
BOS	0.7	10.4	8.4	10.5	10.5	8.2
Total HAWT	11.1	100.0	85.9	171.3	100.0	87.8
Tower	4.4	39.8	34.2	63.2	36.9	32.4
Rotor	2.7	24.0	20.6	51.6	30.1	26.5
Nacelle	2.3	20.4	17.5	35.1	20.5	18.0
foundation	1.0	9.4	8.1	10.0	5.8	5.1
BOS	0.7	6.4	5.5	11.3	6.6	5.8

Table 6.3: The *Materials and Manufacturing* impacts for the different subsystems. Replacements not included.

The largest impacts of the AWE system are caused by the PGA and the LLA systems, representing 42.2% and 27.4% of the the Materials and manufacturing GWP impacts, and 33.2% and 21.5% of the total GWP impacts over all life cycle stages of the AWE design.

Tether/Tower

At the first installation, the GWP and CED impacts of the tether are only 0.1 kgCO_2eq/MWh and 2.1 MJ/MWh . These impacts however add up to a total of 7.9% of all GWP and 15.7% of all CED impacts of the AWE system over the 20 year service life. The UHMWPE is is responsible for the majority of these impacts. The relative impacts within the tether are displayed in figure 6.13.

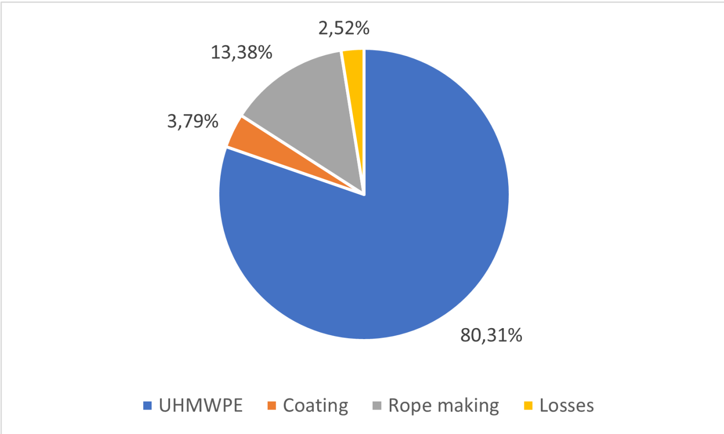


Figure 6.13: GWP impacts within the tether.

The tower of the onshore turbine is an exceptionally heavy component. It significantly heavier than the tower mass of the offshore NREL 5MW, primarily due to the higher hub height of the onshore system. Manufacturing of the tower is responsible for 34.2% of all GWP impacts and 32.4% of all CED impacts of the HAWT system. The size of this component is however strongly influenced by design choices. The tower is assessed in detail in a sensitivity analysis.

Aircraft/Rotor

The initial mass of the AWE aircraft is only 20% to the mass the HAWT rotor. A large mass advantage of AWE is the removal of the heavy structural elements of the hub, the pitch system and the structures in the blades of HAWT technology. The materials required for AWE are however still significantly less friendly that the structural elements it may replace within the blades. The mass of the aircraft has an important effect on the total impacts of the system. The mass does not only effect the impacts of the aircraft itself. It also has a significant effect on the sizes and masses of the LLA systems. The aircraft mass is therefore assessed in a sensitivity case.

The mass of the aircraft may potentially have an even larger influence on the impacts of the AWE technology with its effect on the flight behaviour of the aircraft. The effect that the mass has on the flight behaviour has not been evaluated in this report. The impacts of energy generation systems is however always related to their output energy, and not their rated power. EPDs of generators and transformers state that over 95% of their impacts are related to losses over their operational lives. Simplified variations of the capacity factor are assessed in a sensitivity case.

The aircraft represents 14.0% of all GWP and 15.0% of all CED impacts of the AWE system with the manufacturing impacts of the replacements included. Most of these impacts are the results of the CFRP material used. The used CFRP materials represents 63.6% and 73.1% of the impacts of the aircraft.

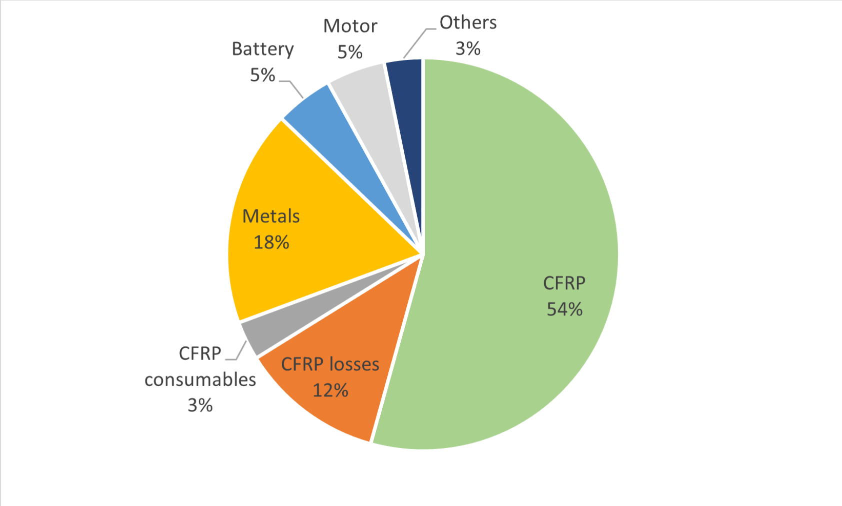


Figure 6.14: GWP impacts within the initial aircraft. CFRP here represents the mixture of carbon fibres, epoxy, core material, glue and the coating.

The HAWT rotor is modelled with 50% CFRP and 50% GFRP materials. The correct material composition of the blade differs per design. The usage of 50% CFRP in the blade is however an unfavorable material when it come the impact of the rotor. The manufacturing stage of the HAWT rotor represents 20.6% of all HAWT GWP impacts and 26.5% of all CED impacts. The CFRP materials represent 66.4% and 69.4% of these GWP and CED impacts. Whiles the same mass of GFRP only represents 13.6% and 14.6% of these impacts. Usage of a full GFRP blade is therefore included as a sensitivity.

Ground-station (PGA) /Nacelle

The absolute impacts of the AWE PGA are higher than the impacts for the HAWT Nacelle. This is primarily the result of the added functions performed by the PGA. The PGA of the AWE system represents 34.0% of all GWP and 33.2% of all CED impacts of the AWE system. The nacelle of the HAWT system represents 17.5% and 18.0% of these impacts for the HAWT system. This difference can be explained by the additional tasks required of the AWE PGA. AWE is able to reduce on structural masses, but will require energy stabilisation and/or system over-sizing in its place.

	GWP			CED		
Subsystem	**kgCO_2eq/MWh**	**% of stage**	**% of all**	**MJ/MWh**	**% of stage**	**% of all**
Drum	0,39	14,74	5,02	6,27	14,83	4,92
Hydraulic pistons	0,43	16,15	5,50	6,55	15,49	5,14
Hydaulic accumulator	1,32	49,62	16,89	20,16	47,70	15,81
Hydraulic extras	0,04	1,36	0,46	1,61	3,81	1,26
Hydraulic motors	0,04	1,37	0,46	0,55	1,31	0,43
Generator	0,15	5,70	1,94	2,27	5,38	1,78
Converter	0,06	2,44	0,83	0,90	2,13	0,71
Transformer	0,19	7,13	2,42	3,34	7,89	2,62
Electronics	0,04	1,49	0,51	0,62	1,46	0,48
Total	2,65	100,00	34,03	42,26	100,00	33,15

Table 6.4: Manufacturing impacts of the PGA for AWE.

AWE

A closer look at the components in the AWE PGA shows that a large portion of the impacts are linked to the hydraulic system, figure 6.15. The hydraulic accumulator system is responsible for 16.9% of all GWP impacts and 15.8% of all CED impacts of the AWE system. It is thereby one of largest impact components of the system, primarily due to its large mass. It represents the combination of all piston accumulators, gas cylinders and the frames with which they are supported.

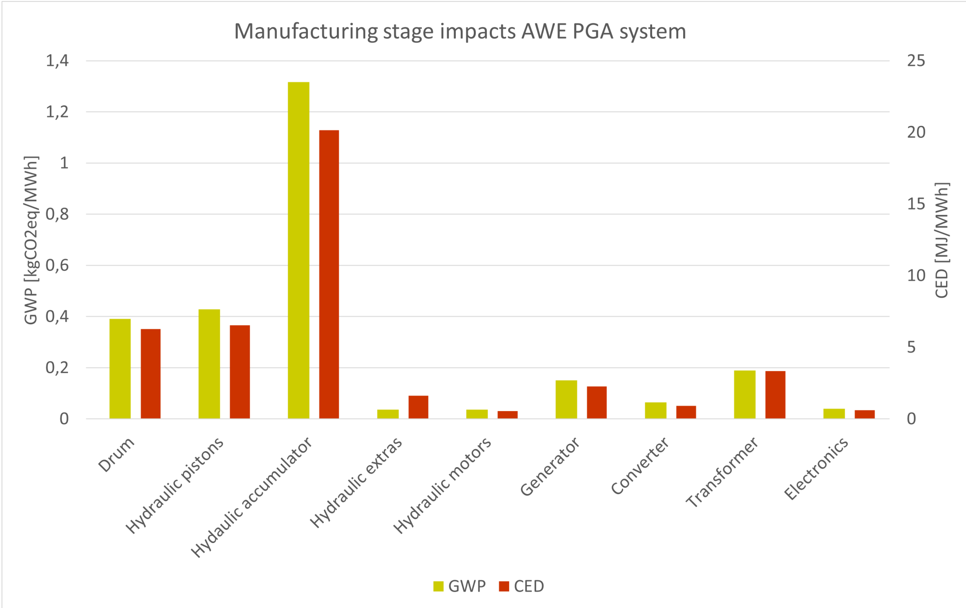


Figure 6.15: GPA manufacturing stage impacts for AWE system.

Usage of this hydraulic accumulator is only one potential option for future AWE systems. Other methods were also briefly assessed, primarily a 'electrical storage' option with a gearbox. The downside to this is the cyclic behaviour of Ground-Gen systems. In the HAWT system, the gearbox already represents 9.0% of all GWP and 9.2% of all CED impacts (including the replacement). The gearbox of the AWE system would however need to be oversized, currently assumed by a factor of 2.5 for the hydraulic system.

It is not known how the gearbox of an AWE system would relate to the gearbox of a HAWT system. It can however be stated with high certainty that the gearbox of an AWE system would at-least be equal or larger to that of a similar rated HAWT system. In which case, the impacts of an hypothetical gearbox would already outweigh the impacts of the modelled accumulator system. While the mechanical drivetrain would still require additional over-sizing of the converters and generators. Nor does it include a system for output stabilisation, most likely super-caps in this design. Which have a high impact themselves as well.

The potential usage of some sort of a flywheel system has not been assessed in this assessment.

HAWT

The largest impacts in the Nacelle of the HAWT system are the gearbox and the bed-plate, these are the heaviest components in the nacelle. Both components only use metal materials. The impact of the gearbox presented in figure 6.12 only includes the initial gearbox. This impact is later doubled due to its replacement.

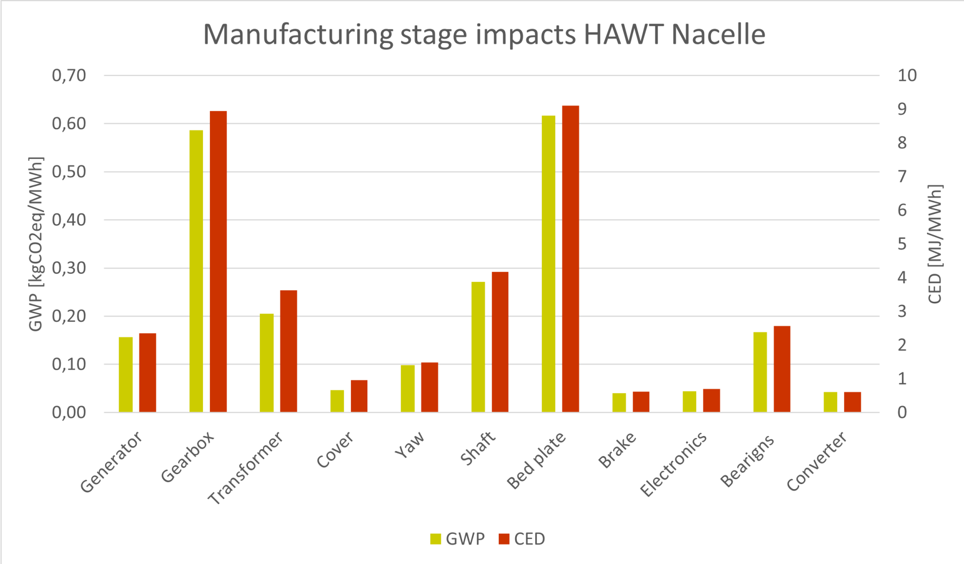


Figure 6.16: Impacts of the manufacturing stage for the Nacelle of the HAWT, these do not include any replacements.

Land and launch system (LLA)

The Land and Launch Apparatus is responsible for 24.3% of the GWP and 21.5% of the CED impacts of the AWE system. This subsystem is modeled least accurate of all subsystems. It strongly depends on the design of Ampyx, whom was not yet able to provide the required information to accurately model it. The results are therefore primarily informative for the importance of optimising the subsystem.

If the deck can be limited to a mass of 128 mt, fully made of steel, it would be responsible for 13.0% and 11.6% of all GWP and CED impacts of the AWE system.

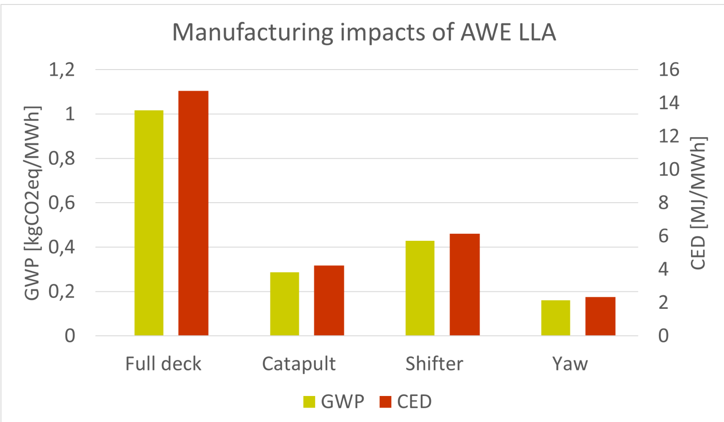


Figure 6.17: Impacts of the manufacturing stage for the LLA of the AWE.

Foundations

The foundations represent the majority of the masses for both systems. 37.0% for the AWE system and 63.4% for the HAWT system. It however only represent 2.1% and 1.2% of the GWP and CED impacts of the AWE system. For the HAWT system it accounted for 8.1% and 5.1% of the GWP and CED impacts. The foundation is one of the elements on which AWE has significant advantage over HAWT. This reduction of foundation mass does however not lead to the highest impact reductions.

Even though the foundation masses of both the HAWT and the AWE systems far exceed their other masses, their impacts remain minimal. Concrete is largely made of gravel, which does not have a large impact. The 6.32% and 5% of rebar in the HAWT and AWE foundations respectively account for more than halve of the impacts of this subsystem. (51.3% of the GWP and 60.1% of the CED impacts of the AWE foundation materials)

BOS

The BOS subsystem only included inter array and transmission cabling. The materials and manufacturing stage impacts of the cables are responsible for 8.4% of all GWP impacts and 8.4% of all CED impacts of the AWE system.

The manufacturing processes for these cables were modelled with standard wire drawing processes. High voltage cables would in reality however require higher quality processes. These impacts may therefore be underestimated. Birkeland (2011) indicated that the manufacturing processes and systems could add up to 30% of the total impacts for offshore cabling. Another 42% of the impacts are related to installation, servicing and EOL. Only 27.5% is the materials themselves. In this AWE LCA, the cable manufacturing activities only account for 6% of the impacts, and the materials for 94%, installation is otherwise included. This may indicate a large under-sizing of the impacts. It also indicates the large impacts of Installation, maintenance and EOL vessels for offshore cables.

6.2.2.b Installation

The installation phase is only responsible for small percentages of the impacts for both technologies. It represents 4.2% of all GWP impacts and 3.7% of all CED impacts of the AWE system. For the HAWT technology is represents 5.4% and 5.2% of all GWP and CED impacts.

	GWP			CED		
Subsystem	**kgCO$_2$eq/MWh**	**% of stage**	**% of all**	**MJ/MWh**	**% of stage**	**% of all**
AWE installation	0.3	100.0	4.2	4.7	100.0	3.7
Transport	0.3	97.6	4.1	4.5	97.5	3.6
Digging	0.0	1.2	0.1	0.1	1.2	0.0
Crane operation	0.0	1.2	0.0	0.1	1.2	0.0
HAWT installation	0.7	100.0	5.4	10.1	100.0	5.2
Transport	0.7	98.1	5.3	9.9	98.0	5.1
Digging	0.0	0.7	0.0	0.1	0.7	0.0
Crane operation	0.0	1.2	0.1	0.1	1.3	0.1

Table 6.5: The impacts of the installation stages.

Transport The primary impact of the installation is the transport to the site. This is modelled with 2000 km shipping with a freight ferry and 500 km trucking with a >34 mt freight transport truck. There are large differences in the impacts between different transportation options. Shipping of wind turbines is assumed best represented with a freight ferry. Heavier container ships are able to transport products more efficiently, at lower impacts per tkm transported.

The AWE system is modelled with the same transport type as the HAWT system. This system may however be able to be transported more efficiently. The average impact of transport with a container ship is a factor 10 lower than the transport with the freight ferry. This is an potential advantage of AWE that is under-represented in this report.

Transport over the road is also modelled with the same trucks for both HAWT as AWE. This too presents a potential under-represented advantage for AWE. Most components of a wind turbine will require specialised transport. This oversized type transport is not accounted for in this report. Oversized transport is bound to stricter rules and more route limitations, potentially requiring large detours to the construction site. Most components of the AWE system have the potential to be transported more efficiently. In the end, this will lead to a slight additional improvement for AWE technology.

Other installation The additional installation processes remained highly uncertain. Only crane operation and digging activities are included. The 20 h crane operation assumed for AWE and 40 h for HAWT, only represent a minute fraction of impact over the total systems. It is more than likely that these impacts are underestimated. However, they will remain minimal compared to other impacts. This statement is confirmed with results from other LCA reports on onshore systems. Offshore, the high impacts of cable installation would result in a higher impact fraction over the installation stage.

6.2.2.c Operation and Maintenance

The O&M stage includes the replacements, consumables and transportation for servicing visits as well as the replacements. In total, the O&M stage represents 11.3% and 17.0% of the GWP and CED impacts of the AWE system. For the HAWT system it represents 5.7% and 5.2% of the impacts.

The impacts of the O&M stage are dominated by the manufacturing impacts of the replacement components. The AWE system replaced the tower with a tether. However, this tether will require frequent replacements where the tower does not. The impacts of the tether replacements are approximately 9 times higher than the impacts of originally installed tether.

Replacements of both systems are highly simplified. It only includes tether, battery and aircraft actuator replacements for the AWE system. For the HAWT system it only included the replacement of the gearbox. Intermediate replacements of worn out components like rubber seals etc are not included.

	GWP			CED		
Subsystem	**kgCO_2eq/MWh**	**% of O&M**	**% of all**	**MJ/MWh**	**% of O&M**	**% of all**
AWE O&M	0.9	100.0	11.3	21.6	100.0	17.0
Replacements	0.8	85.6	9.7	20.8	96.0	16.3
Tether	0.6	62.8	7.1	17.9	82.8	14.0
Battery	0.1	6.3	0.7	0.9	4.1	0.7
Actuators	0.1	16.6	1.9	2.0	9.2	1.6
Consumables	0.0	0.6	0.1	0.3	1.2	0.2
Transport	0.1	13.8	1.6	0.6	2.8	0.5
HAWT O&M	0.7	100.0	5.7	10.0	100.0	5.2
Replaceents	0.6	79.7	4.5	9.0	89.1	4.6
Gearbox	0.6	79.7	4.5	9.0	89.1	4.6
Consumables	0.0	0.9	0.1	0.3	3.1	0.2
Transport	0.1	19.4	1.1	0.8	7.8	0.4

Table 6.6: The impacts of the O&M stages.

Under the presented O&M assumptions, the AWE system will require slightly larger impacts over the operations and maintenance life cycle stage. This is particularly visible for the CED, since the tether represents the majority of the AWE replacement mass; and the tether is modelled with a high CED impact compared to its GWP.

6.2.2.d End of Life

The final EOL life cycle stage represents 3.5% of the GWP and 0.9% of the CED impacts of the AWE system. The same stage represents 3.0% and 1.8% of the impacts for the HAWT system. The impacts of the considered processes within the EOL are detailed in table 6.7. Transport includes the transportation of all materials to their respective EOL processing plant. The treatment impacts are the impacts related to land-filling and incineration processes. Disassembly indicates the impacts of crane operation and cable removal.

	GWP			CED		
Subsystem	**$kgCO_2eq/MWh$**	**% of EOL**	**% of all**	**MJ/MWh**	**% of EOL**	**% of all**
AWE EOL	0.3	100.0	3.5	1.1	100.0	0.9
Transport	0.0	12.5	0.4	0.5	50.1	0.4
Treatment	0.2	83.4	2.9	0.4	34.8	0.3
Disassembly	0.0	4.1	0.1	0.2	15.1	0.1
HAWT EOL	0.4	100.0	3.0	3.6	100.0	1.8
Transport	0.1	30.2	0.9	2.0	55.2	1.0
Treatment	0.2	61.4	1.9	1.1	31.1	0.6
Disassembly	0.0	8.4	0.3	0.5	13.7	0.3

Table 6.7: The impacts of the EOL stages.

Impact method The impacts of the EOL stage are completely different depending on the method chosen for the assessment. The method used in this assessment was by Cut-off allocation method. This method cuts-off all impacts of recycling at end of life. It therefore also cuts-off all potential avoided impacts of recycling and reuse at end of life.

There are advantages to each method. Allocating the benefits of recycling to the primary product provides higher incentives to make sure a product is recyclable. A downside is however that this negatively criticized newer products for which recycling is not possible or perfected yet.

Additionally, even if steel is 100% recyclable at EOL, the material used to manufacture the product will still require a large portion of virgin materials. The demand for metals is much higher than can be supplied with recycled materials. This 'Allocation at the point of substitution' (APOS) method might incentify manufacturers to focus on recycling. It however does not punish for the usage of large masses.

The deck An example of the different incentives provided by the different allocation methods can be seen in the evaluation for the material to use for the deck. The deck of the Ampyx system is still completely undefined, including its material selection. The Cut-off method used in this report primarily incentives material reductions to reduce the impacts of the system. Through this method, the usage of GFRP for the deck would appear more beneficial than it should.

At the time of writing this report, the recycling options for FRP materials remain highly limited. However, even if recycling options for FRP materials improve greatly, it would never be able to match the near perfect recyclability of metals.

Energy Payback Time (EPBT)

The energy payback time (EPBT) states how long it takes for the system to return the energy that it takes to make and run it. The input energy includes all energy over the full service life of the system. Including the maintenance and EOL impacts which both occur well after their energy is already 'payed back'. The EPBT is calculated with equation 6.1 and is expressed in months. The EPBT of the AWE system is 8.5 months, for the HAWT systems it takes 13.0 months to pay back all input energy.

$$EPBT = 12\frac{Life\ Cycle\ Input\ Energy}{AEP} \tag{6.1}$$

Energy Return on investment (EROI)

The Energy Return on Investment states how many times the invested input energy is returned as output over the service life of a system. It is calculated according to equation 6.2. The AWE system will generate 28.2 times its input energy. This is only 18.5 times for the HAWT system.

$$EROI = \frac{Total\ Lifetime\ Energy\ Produced}{Total\ Lifetime\ Energy\ Required} = \frac{AEP \cdot Service\ Life}{Life\ Cycle\ Input\ Energy} \tag{6.2}$$

	Unit	AWE	HAWT
AEP (farm)	MWh	4625280.0	4108856.1
Full energy input (farm)	MWh	163772.9	222579.5
Energy Payback time	Months	8.5	13.0
Energy rate of return	-	28.2	18.5

Table 6.8: Energy Payback Time and Energy Rate Of Return

Chapter 7

Interpretation

The interpretation stage is the final stage of the 4 LCA stages. It is generally used to indicate the confidence of the presented results. It is here however also used to specifically indicate the large variability between design choices. AWE and HAWT technology are two completely different technologies to perform the same function. The comparison presented above only represented a base-case scenario. The different technologies will however have different advantages at different operating scenarios. Amongst others, the sensitivity analysis is used to assess some of these different scenarios. It also assessed the impact variations resulting from deviations from the presented base-case.

This chapter starts with a section on significant issues in the design. This is followed by various sensitivity studies. After which the chapter is finishes with a 'completeness and consistency check' section.

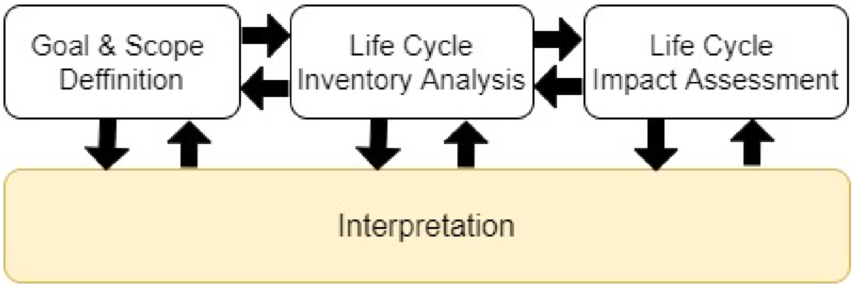


Figure 7.1: Stage 4, the Interpretation

7.1 Significant Impacts

The most significant impact materials of the AWE system are the UHMWPE in the tether, and the CFRP in the aircraft. These have high impacts, despite the low masses. The largest impacts are however created by heavy steel components in the design.

The AWE and HAWT systems largely rely on the exact same materials. Both require large amounts of metal, concrete and FRP components. AWE is however a new development. Therefore it also requires the usage of additional newer, less documented and less optimised materials. Particularly in the tether and the aircraft. The UHMWPE in the tether and the carbon fibres in the CFRP both require highly energy intensive production processes.

Combinations of improved production efficiencies, renewable energy usage, technological improvements and complete product changes have the ability to significantly reduce the impacts of materials, especially younger materials. AWE manufacturers can have a significant influence on the impact of their product by selection of the greener supplier. This may be the case for UHMWPE, but it certainly will be the case for metals and other materials as well.

7.2 Sensitivity Study

Sensitivity studies were carried out on a variety of design choices and variables. Neither the AWE nor the HAWT models could be based on exact data. The AWE system is modelled far into the future, for which a design does not exist yet. While the HAWT system is intended to represent a decent comparison to the AWE system. It is therefore of high interest to assess the effects of potential design fluctuations within the modelled systems.

7.2.1 Aircraft Mass

The mass of the aircraft presents a large uncertainty. The 20 mt mass is presented by the Ampyx as a both required as a feasible goal weight. However, both significant technological improvements as design improvements will be required reach this goal. Direct scaling according the the AP3 model would have resulted in much higher masses, this design was however not yet optimised for mass reduction, but primarily for system validation. It is indeed expected to have enough room for improvements to realise these large mass reductions.

Deviations in the mass of the aircraft would however lead to significant changes in the impacts of the systems since the aircraft does not only influence its impacts, but it also influenced the masses of the LLA systems. The Deck, Catapult and Shifter all scale based on the forces and kinetic energy of landing and launching the aircraft. Therefore the a sensitivity is included with a fluctuation of ±10% and ±20% of the aircraft mass.

	-20 wt%	**-10 wt%**	**Base Mass**	**+10 wt%**	**+20 wt%**
Aircraft mass	16	18	20	22	24
LLA mass	192.3 (-15.6%)	209.8 (-8.0%)	228.0	246.8 (+8.3%)	266.4 (+16.8%)
GWP AWE	7.3 (-7.0%)	7.5 (-3.5%)	7.8	8.1 (+3.6%)	8.4 (+7.3%)
CED AWE	119.0 (-6.7%)	123.2 (-3.4%)	127.5	131.8 (+3.4%)	136.3 (+6.9%)

Table 7.1: Sensitivity case: Aircraft masses. Masses in mt, GWP in $kgCO_2eq/MWh$ and CED in MJ/MWh

7.2.2 Variation in HAWT Comparison

The impacts of the HAWT system significantly differs with specific design choices. The base-case HAWT design has a hub height of 117 m high. Its blades are assumed 50% CFRP based structure. And its AEP equals an capacity factor of 46.9%. Each of these choices are evaluated through sensitivity analysis.

7.2.2.a Hub height and Tower Mass

This assessment was was carried out on a onshore HAWT system that matched the NREL 5MW turbine. The 117 m hub height was the original hub height of the onshore REpower 5M. The offshore NREL 5MW is however designed with a hub height of 90m, and current onshore GE systems in the range of 5MW are stated to be available with hub heights of 101, 121, 151 and 161 meters high (GE).

The hub height of HAWT systems varies based on the location for which they are designed. Good environmental locations could present the required wind environments at lower hub-heights. This is especially the case when comparing offshore and onshore locations. This is also why the offshore NREL 5MW is designed with a lower height than its onshore version.

The mass of the tower depends on several factors important variables and choices. The first is the stiffness range for which the tower is designed. Specific stiffness ranges are defined to avoid fatigue damages and resonant tower vibrations. The differences of tower masses between these ranges are extreme.

Another major factor in the mass of a tower are the different tower design options. Dykes et al. (2018) and Lantz et al. (2019) presented different idealised tower designs for a 3.3 MW reference turbine. The mass presented in the base case is that for a transportable tower, which is the conventional, but heaviest tower type. Changes in tower design could significantly reduce its mass, especially for higher hub-heights, as show in figure 7.2. It was not assessed how this mass changes with rated power. The idealised NREL 5MW tower mass presented a similar mass to the soft-stiff value presented for the 3.3 MW case.

The 600 mt base-case tower mass is an average in between the mass of transportable soft-soft and soft-stiff tower (figure 7.2 only shows the soft-stiff). The extreme mass of a stiff-stiff tower design is not assessed. The mass of the shorter standard NREL 5MW offshore tower is however only 347.5 mt; about which it is stated that could even be optimised further, to only 250 mt. A sensitivity assessment was considered of upmost important, given these large variations and the high impact of the base-case tower.

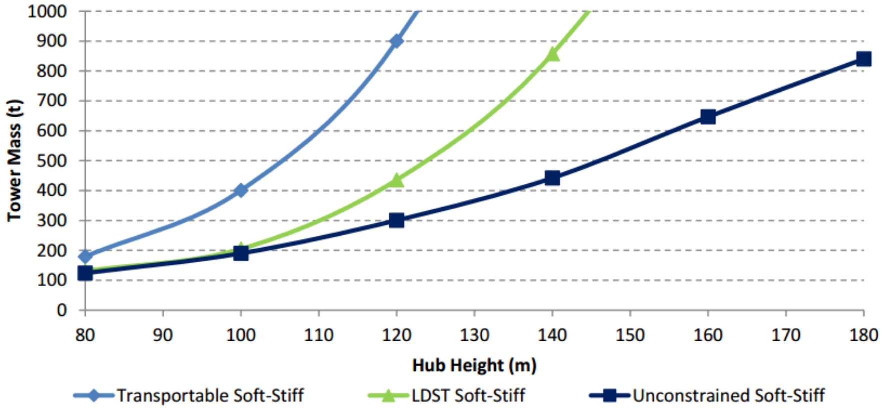


Figure 7.2: Presented mass optimization results for soft-stiff tower design cases for a 3.3MW reference turbine (Lantz et al., 2019).

Sensitivity analysis were carried out for: A tower with the base-case hub-height, but a mass of the transportable tower as presented in figure 7.2. Another one for the same height, but with the mass of the 3.3 MW LDST case presented in the same figure. Followed by 2 cases for lower hub heights. One with the standard NREL 5MW mass, and another with a reduced mass. The foundation is not changed in any of these cases.

A change in the hub-height of the comparative HAWT system would result in a change in wind speed conditions experienced for the AWE system, since the relative difference in height has changed. The average wind speed experienced by an AWE system at a location where the wind speed is 10 m/s at 90 m is again calculated with the log law equation 5.4. At an average flight height of 250 m, the experienced average wind spreed would be approximately 11.6 m/s. Which is an 0.5 m/s average wind speed increase compared to the base-case. This higher wind speed increases the AEP of the AWE farm to 238005 MWh, an energy output increase of 3%.

	Base case	Heavy	Light	Short	Short&Light
Hub height	117,0	117,0	117,0	90,0	90,0
Tower mass	600,0	800,0	400,0	347,5	250,0
AWE avg wind	11,0	11,0	11,0	11,5	11,5
AWE farm AEP	23126.4	23126.4	23126.4	238005,0	238005,0
HAWT					
GWP	13.0	14,6 (+12,4%)	11,4 (-12,4%)	11,0 (-15,6%)	10,2 (-21,6%)
CED	195.0	217,9 (+11,7%)	172,2 (-11,7%)	166,2 (-14,8%)	155,0 (-20,5%)
AWE					
GWP	7.8	7.8	7.8	7,6 (-2,8%)	7,6 (-2,8%)
CED	127.5	127.5	127.5	123,9 (-2,8%)	123,9 (-2,8%)

Table 7.2: Sensitivity case: HAWT hub-height. GWP in $kgCO_2eq/MWh$, CED in MJ/MWh and AWP in MWh

It shows that the impact of the HAWT system is highly influenced by the location at which it is placed. The impacts for the short tower indicate that the changes in the tower due to better environmental conditions would significantly reduce the impacts of the HAWT system. While the difference in experienced average wind speed would only minimally reduce the impacts of AWE. Differences in the type of tower used have similarly significant differences in the HAWT impacts. However, for these onshore locations, the impacts of AWE would remain lower than the impacts of optimised HAWT options. Offshore is assessed in a later sensitivity case.

7.2.2.b GFRP blade

Blades of the large scale HAWT systems are always made from FRP materials. Shorter blades may suffice with GFRP alone, but larger blades for higher rated systems require higher strength materials in the form of CFRP structures. It is however uncertain whether this would already be a logical choice for blades of 61.5 m. The original NREL 5MW rotor is stated to weigh 110 mt. This is calculated from other research. This mass is stated to deviate from the original REpower 5M rotor mass. The HAWT blade presented in this report is assumed 50% CFRP and 50% GFRP. The original REpower 5M is however stated as a GFRP blade, no mention of CFRP. The mass of a full GFRP blade would exceed that of a CFRP/GFRP composite.

The original NREL 5MW blade was presented with a mass of 17.7 mt, but did not specify its material composition (Jonkman et al., 2009). Resor (2013) later presented a more detailed blade design which included CFRP structural elements. The mass used in this LCA was presented by Dykes et al. (2014), which presented an optimisation of the NREL 5MW, based on the specifications of the previous papers. The 50% GFRP and 50% CFRP were only approximation of the presented mass fractions. It is also stated that the HAWT blade would use a larger fraction of core material compared to what is expected for the AWE system. These differences have not been accounted for in this report, the CFRP and GFRP material compositions are modeled equal for the HAWT and AWE technologies.

A blade of 61.5m could however also be made from GFRP alone (Griffith et al., 2011). This would significantly reduce the impacts of the rotor. If the HAWT blades are full GFRP the GWP and CED impacts of the entire HAWT system would reduce by 10.9% and 14.5% to 11.6 kgCO_2eq/MWh and 166.7 MJ/MWh , respectively.

7.2.3 Offshore

One of the most significant advantages of AWE is its reduced overturning moment compared to HAWT. This presents its largest advantages for offshore locations. Offshore could only be assessed minimally in this report, this preliminary offshore assessment only presents indications based on a specific system comparison, Numerous other floating system options were not assessed. The assessed systems show a significant advantage when comparing floating AWE and HAWT systems. These advantages however appear minimal for locations where AWE would use a floating systems, and HAWT a monopile.

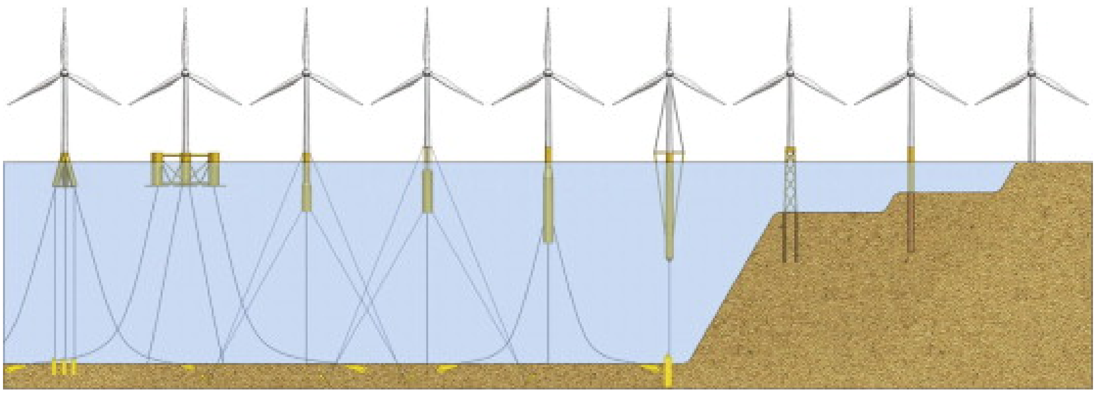


Figure 7.3: Available foundation options, the center image is the Hywind farm (Myhr et al., 2014).

A downside for offshore is that there is only minimal difference in environmental conditions over changing heights. The average wind speed experienced by the AWE system at average operating height of 250 m is again calculated with the log-law (equation 5.4), assuming a surface roughness of 0.0002 m for open sea. A location with an average wind speed of 10 m/s at 90 m hub-height, would have an average wind speed of approximately 10.8 m/s at 250 m average flight height of the AWE system.

Note that this sensitivity is only performed extremely limited depth. It does not present accurate values for comparison between On-shore and Off-shore locations. Cables are not changed, nor are any changes included for the installation and O&M stages. The impacts of these stages are relatively small for the onshore location, but known to be larger for Off-shore locations. Other than the experienced average wind speed, this sensitivity only includes the changes in the materials and manufacturing processes of the HAWT tower and both foundations. Results are presented in a table 7.3.

7.2.3.a Shallow Offshore HAWT

There are several shallow offshore foundation options for HAWT systems. Over the last decades, the monopile type foundation has been the most commonly used. Monopiles can be used in a wide range of sea depths, generally up to approximately 40 m. This range however further expands for increasingly higher rated turbines (Nordenham, 2019). The maximum sea depth of a monopile for a 5 MW rated systems is taken as 40 m, which is a bad case scenario for HAWT. Another case with reasonable low sea depth of 12.8 m is added for comparison.

A monopile is just a steel cylinder, similar to the tower. The mass of the substructure of a NREL 5MW turbine at this location weights approximately 1457 mt (Damiani et al., 2016), which includes the foundation and the tower. This assumes a hub height of 90 m, a platform height at 16 m above mean sea level, and a penetration depths of 24.5 m into the sea-bed. The impacts of the monopile would be much lower for locations with shallower sea depths. Additional scour protection is not included in the assessment.

7.2.3.b Floating HAWT

Floating foundations are still a recent development. The design of these foundations remains filled with even more uncertainties and a large improvement potential than there already were for the onshore case. Only one specific floating foundation option is assessed; the spar buoy type used in the Hywind farm. This farm is a 30 MW pilot wind park of 6 MW floating turbines. The Hywind spar buoys are stated to have a structural mass of 1700 mt and an additional 8000 mt of ballast weight to keep the turbine vertically stabilised. This ballast is split in a solid (concrete) part and a part water (Eldøy, 2017). The correct fraction of concrete is however not stated, it is simply assumed 50% in this LCA.

Additionally, floating systems also require heavy mooring lines and anchors to keep the turbine stable. The Hywind farm required 3 mooring lines of approximately 800m length each (Eldøy, 2017). This original Hywind report approximated the mass of the chains in a range 200 to 550 kg/meter. Other literature however states significantly different values, in which the mooring line is split in chains and wires.; an LCOE study approximated a mass of 126.5 kg/m for the chains and 29 kg/m for the wire (Myhr et al., 2014). By assuming a fairly low constant mass of 150 kg/m, the total mass of the mooring lines adds up to another 360 mt of steel, this mass could however be much higher. The Hywind park uses 3 steel anchors of 17 mt each. Other potential anchoring options could however also have weight much as 3×4 0mt or 1×140 mt (with only one mooring line) per turbine (Myhr et al., 2014).

Myhr et al. (2014) also states various other floating foundations, some of which would require a notably lower steel mass than the floating AWE foundation presented below. These systems are stated to use huge amounts of concrete, some even over 10,000 mt (Sclavounos et al., 2008). The mass of these systems would therefore far outweigh the mass of the Floating AWE system. The impacts of concrete are however much lower than those of steel, especially if recycling is not included. A reasonable model of this system could unfortunately not be modelled anymore, it is therefore not further included in the report.

7.2.3.c Floating AWE

Not much is known about the foundation for the AWE system. The largest advantage of AWE is its lower overturning moment. This is also why the industry is said to focus on this market, where its advantage compared to HAWT would be greatest.

A more specific design of a floating AWE foundation was researched in the Sea-Air-Farm Project (Ampyx, 2018). This paper presented a design of a 'three-column semi submersible'-type floating structure, figure 7.4 Its structural mass is stated to weigh 491 mt for a 2 MW AWE system of Ampyx. It is not certain what this system requires for additional ballast mass. It is however stated to have a free floating water displacement of 1259mt. This is interpreted as the total mass of the floater, resulting in a ballast mass of 768 mt. The ballast of the AWE system is modelled with the same fraction of the mass as assumed for the HAWT system, taken at 50%. The accuracy of this estimation is however not known.

The platform size of this presented 2 MW floating foundation is designed with a length of 30 m and a width of 20 m, similar to the sizes envisioned for the 5MW system. The mass of the 5 MW LLA and PGA systems would however be significantly larger than those of the 2 MW system. The mass of this 2 MW floating foundation is simply doubled as an indication for the 5MW system, this may significantly vary. Fully loaded, the floater has a draught is 16 m.

The additional mooring systems are subjected to far lower forces, these could be designed smaller than the HAWT system. The design of the mooring system is assumed similar to the HAWT case, as was used in Ampyx (2018). The masses of the lines are simply taken as halve those required for the HAWT system.

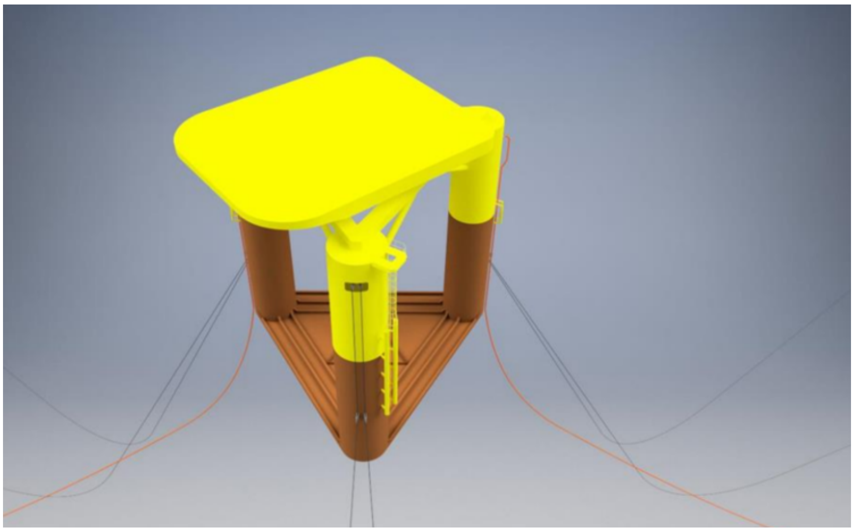


Figure 7.4: The floating foundation for the 2MW Ampyx system (Ampyx, 2018).

Offshore Discussion

	HAWT Monopile	**HAWT Monopile**	**HAWT Floating**	**AWE Floating**
Water depth m	40.0	12.8	deep	25+
Operating height	90.0	90.0	90.0	250.0
Avg wind	10.0	10.0	10.0	10.8
Farm AEP	205442.8	205442.8	205442.8	227360.0
Masses mt				
Tower	302.0	315.0	302.0	-
Structural steel	1155.0	600.0	1700.0	982.0
Ballast concrete	-	-	4000.0	768.0
Mooring lines	-	-	360.0	180.0
Anchors	-	-	51.0	51.0
Total system mass	1849.3	1307.3	6805.3	2555.8
System impacts				
GWP	18.0	14.0	26.9	16.3
CED	268.5	212.2	392.0	247.8

Table 7.3: Sensitivity case: offshore. The floating systems are only rough designs, these technologies are still developing, and better options may be available for both technologies. GWP in $kgCO_2eq/MWh$ and CED in MJ/MWh .

The monopiles are modelled with structural steel alone, these are generally not painted, An additional 50% of average metal work was added. The mooring lines and the anchors are modelled with low alloy steel, and average metal work. The concrete is taken as the same concrete as used onshore, this would more likely be of lower strength in reality. Paint is not included in any of the components other than the tower, which is simply a smaller version of the base-case tower.

The majority of these impacts are the results of the large masses of steel in the floaters and the chains. The concrete only has a small impact in comparison to its mass, as was the case at the onshore locations.

The presented floating systems are only to be seen as indicative, more accurate data could not be obtained. The monopile cases are however accurate estimations of a technology that has already been well explored. These assessments do not include accurate installation and O&M processes; the masses for transport changed automatically, but all other processes remain what was determined for the onshore case.

The impacts of the HAWT system significantly increase with increasing sea depths. This is visible with reasonably accurately modelled monopile systems. Offshore, the foundations present much larger fractions of the impacts than they do Onshore. This is primarily related to the material of the foundations. Onshore, the 5 wt% of rebar in the reinforced concrete foundations, already accounted for more than halve the impacts. A fully steel foundation therefore simply used a more pollutive material.

Note that the metal impact would have been reduced with an LCA method that includes recycling, and that the installation impacts (that are not included) would be significantly higher than for the Onshore case, particularly for the cable installation.

7.2.4 Distance to Grid

The distance to the grid is a variable that will depend on the location. The 15 km used in this report is presented by Siemens as a representative distance based on experiences in the European market. The BOS (including the inter array cables) account for 8.4% of all GWP impacts of the AWE system in the base-case scenario, This does not include the additional 3% cable (electricity) loss over the export cable. This is a large impact, therefore sensitivity cases are assessed for distances of 15 km ± 5 km. An additional case without cables is also assessed.

The choice for a farm without a transformer substation only holds for smaller farms with limited distance to the grid. Therefore it is debatable whether a sensitivity case for larger grid distance is indeed reasonable.

	Unit	20 km	Base case	10 km	0 km
HAWT					
Farm AEP	MWh/year	203570,1	205690,7	207811,2	212052,2
GWP	$kgCO_2eq/MWh$	13,3	13,0	12,6	11,9
CED	MJ/MWh	200,4	194,8	189,3	178,7
AWE					
Farm AEP	MWh/year	228892,8	231277,1	233661,4	238430,0
GWP	$kgCO_2eq/MWh$	8,1	7,8	7,5	6,9
CED	MJ/MWh	132,0	127,5	123,1	114,5

Table 7.4: Sensitivity case: Distance to grid

The large differences in environmental impacts are the results not only the result of material reductions. The losses over the cables also differed. They are assumed 0.2% per km for the 33kv transmission. Transmission at 33KV is highly unfavourable, its losses are high and the conductor cross-sections need to be large. It would only be used over relatively short distances, for relatively small farms.

The usage of a transformer substation did not make it into this report. It could have been modeled with data presented in an EPD on a ABB high voltage transformer (ABB, 2003b). This same method was found to be used in Vestas reports, such as Vestas (2019b).

7.2.5 Capacity Factors

The capacity factors (Cf) of both the AWE system as the HAWT system present significant uncertainties. The HAWT cf is taken at 46.9% in this report. This is assumed to include all losses up to the grid connection. The Cf of HAWT turbines however greatly differs between turbines. A recent LCA by Siemens used 49.2% for their 5MW DFIG turbine (Gamesa, 2020). Vestas uses a Cf of 47.3% for their V117 4.2MW IEC1 turbine (Vestas, 2019a), but only a Cf of 43% for their V136 4.2MW IEC2 turbine (Vestas, 2019b). These capacity factors are presented as AEP values for specific average wind speeds that differ significantly between the reports.

The average Cf of all operational onshore HAWT systems in Europe was only 24% over 2019 (WindEurope, 2020). This however includes smaller and older systems, while the recent 12 to 14 MW (IEC1 Off-shore) Haliade-X turbines are stated to have capacity factors between 60-64% (GE).

A sensitivity is carried out for capacity factors fluctuating 46.9% ± 5% and 10% for HAWT, and 52.8% ± 5% and 10% for the AWE system.

	Unit	-10%	-5%	Base case	+5%	+10%
AWE						
Cf	%	42.8	47.8	52.8	57.8	62.8
AEP system	MWh/year	18746.4	20936.4	23126.4	25316.4	27506.4
GWP	$kgCO_2eq/MWh$	9.6	8.6	7.8	7.1	6.6
CED	MJ/MWh	157.3	140.8	127.5	116.4	107.2
HAWT						
Cf	%	36.9	41.9	46.9	51.9	56.9
AEP system	MWh/year	16164.3	18354.3	20544.3	22734.3	24924.3
GWP	$kgCO_2eq/MWh$	16.5	14.5	13.0	11.7	10.7
CED	MJ/MWh	247.9	218.3	195.0	176.2	160.7

Table 7.5: Sensitivity case: capacity factor variations

7.2.6 Lifetimes

Both the AWE and the HAWT systems are modelled with a lifetime of 20 years. Newer HAWT systems are already stated to have longer lifetimes, reaching 25 to maybe 30 years. LCA studies by manufacturers on these systems are however still primarily performed with an assumed lifetime of 20 years, also recent ones. The lifetime of HAWT systems is determined by the shortest life of one of its crucial system. It is often limited by fatigue stresses of the tower. Smaller components with shorter lifetimes can be replaced within the service life of the turbine. These are for instance the gearbox and yaw drive systems.

AWE systems may not contain such an 'irreplaceable' component. Therefore AWE may actually be able to reach longer system lifetimes than HAWT systems do. An accurate lifetime estimation can not be provided at this time. Ampyx does however expect their AWE system to be able to reach at least an equal lifetime to the extended lifetimes of the newer HAWT turbines.

Extended lifetimes require additional O&M activities. The following sensitivity assessment states potential lifetime deviation for lifetimes of the base-case 20 years ± 5 and one for 30 years. the 20 years ± 5 cases do not include changes to the replaced HAWT gearbox, the 30 years case does include an additional gearbox replacement. The AWE replacements are recalculated according to lifetimes stated in section 5.5.2.c. The other O&M impacts (from consumables and servicing trips) are scaled with the service life. Potential decreases in efficiencies are not accounted for.

	15 years	Base case	25 years	30 years
AWE				
GWP	9.8 (+29.6%)	7.6	6.3 (-16.9%)	5.4 (-28.5%)
CED	158.6 (+28.3%)	123.6	104.1 (-15.8%)	90.2 (-27.0%)
HAWT				
GWP	16.7 (+33.0%)	12.6	10.1 (-19.8%)	8.8 (-29.8%)
CED	251.7 (+33.2%)	188.9	151.3 (-19.9%)	132.2 (-30.0%)

Table 7.6: Sensitivity case: Lifetime deviations. GWP in $kgCO_2eq/MWh$ and CED in MJ/MWh

Lifetime extension would lead to significant environmental improvements, as the majority of all impacts are made in the manufacturing of the initial systems. Extended lifetimes directly increases the energy output over the products service lives. While only the O&M impacts will deviate with service life changes.

The O&M stage of the AWE system represents only 11.3% of the systems GWP and 17.0% of the systems CED impacts over 2 year operation. In the base case 20 year scenario, the replacements are responsible for a GWP of 0.9 $kgCO_2eq/MWh$ and a CED of 21.6 MJ/MWh after normalisation to the produced energy. The O&M impact are directly proportional to the service life of the system. Increased O&M impacts over aging systems has not been accounted for in this assessment. Therefore this normalised impact of the O&M stage remains steady with lifetime deviations. All other life cycle stages are however independent of this service life. Their normalised impacts will reduce with the increased energy output resulting from lifetime extension.

Under the assumed replacements, AWE would have slightly smaller impact reductions compared to the reductions of the HAWT system. This is directly related to the larger replacement requirements for the AWE system. The high impacts of the tether replacements over the O&M stage result in reduced impact reductions. This is particularly visible in the comparison between the CED and the GWP impacts over the changing service lives of the AWE system. Which indicates lower improvements for the CED due to the UHMWPE in the tether being produced with a high fraction of renewables that keep the GWP lower. This does not take away from the advantage gained if lifetime of AWE can be assumed larger than that of HAWT.

7.2.7 Tether replacements

The lifetime of the tether may significantly improve with future technological improvements. It however also strongly depends on a variety of design choices for which positive choices for the tether would negatively effect the performance of the system. This sensitivity assesses the impacts of changes in the frequency with which the tether is replaced. It assesses 2 cases; one where the tether lifetimes are halved, and another where the tether lifetime is doubled.

	Halved Lifetimes	Base case	Doubled lifetimes
GWP	8.3 (+9.4%)	7.6	7.2 (-4.2%)
CED	143.3 (+15.9%)	123.6	114.8 (-7.2%)

Table 7.7: Sensitivity case: Tether lifetimes. Masses in mt, GWP in $kgCO_2eq/MWh$ and CED in MJ/MWh

The halved lifetimes assume lifetimes of 6 months for the winding tether section and a lifetime of 3.3 years for the top section. The doubled lifetime case assumes lifetimes of 2 years for the winding section of the tether, and 10 years for the top section (1 replacement).

7.2.8 AWE System Size

The assessed AWE system is rated at 5 MW. AWE is however still a very young technology. In time, systems of different sizes will become available. As more systems become available, systems of different rated power may be produced at the same time, under the same technological status. Thereby it can be assessed how the choice to model a 5 MW sized AWE system affected the outcome, and how higher or lower rated systems would perform if build according to the model presented in this report.

The impacts of scaling under constant technological status was not specifically quantified in this research. It can however be evaluated based on scaling assumptions and insights gathered over the course of the project. An important side note is that this indication only holds for scaling of a system as presented in this report. Based on current knowledge, with the used assumptions, with an hydraulic drivetrain and for onshore.

Scaling relations for the subsystems of the AWE model indicate that the masses of most components scale faster than the rated power of the system. This is the case for the aircraft, the LLA, and the tether. The PGA mainly consists of components that more or less scale directly with the rated power; such as the hydraulic accumulators, the generators and the the hydraulic pistons at the drum. For systems like the one modelled in this report, the impacts per MWh electricity delivered to the grid would increase with increasing rated power, and decrease with lower rated power.

This means that a 2 MW or 3 MW rated AWE systems of this design would have further reduced impacts compared to the 5 MW system. The impacts of HAWT systems strongly differ between literature sources sources. However, several comparative reports indicate that the impacts of HAWT systems reduce with increasing system sizes (Smoucha et al., 2016; Chipindula et al., 2018). Based on these observations, it can be stated that the AWE system would likely have performed even better if the comparison had been performed on lower rated systems.

7.3 Completeness and Consistency Check

Both technologies are only modelled by their largest components. Smaller elements such as fire prevention and radio control are not included for either technology.

Additionally, the data availability differed significantly between the different components in both drivetrains. The generators and converters are modelled with more detailed data based on available Environmental Product Declarations found online. Other systems had to be modelled with a more generalised approach, presenting a larger uncertainty. These known inconsistencies are however modeled the same in both systems, it therefore does not affect the comparison.

A larger inconsistency is caused by the large difference in product readiness. The HAWT system is based on much more accurate data, of a system that already experienced optimisations over time. The AWE system is however a completely new product on which much less data is available, and for which technological optimisations based on experiences are much less advanced. This could not be avoided.

Chapter 8

Conclusion and Recommendations

The goal of this research was to assess the environmental performance of a future Multi-Megawatt AWE system. Firstly, to quantify the impacts of AWE and to assess the system for impact hotspots. Secondly, to compare the impacts of AWE to the impacts of conventional Horizontal Axis Wind Turbine (HAWT) technology. The technologies were modelled for operation in hypothetical farms of 50 MW. Assessment is performed using an Life Cycle Assessment. The technologies were assessed and compared for their Global Warming Potential (GWP) and their Cumulative Energy Demand (CED). The CED is also used to determine the Energy Pay Back Time (EPBT) and the Energy Return on Investment (EROI).

The assessed AWE and HAWT systems both have a rated power of 5 MW. However, an actual design of a large scale AWE system remained unavailable at this point in time. The AWE system is therefore a personal design, largely based on the system by Ampyx Power. A part of the design for this Ground-Gen, Rigid-Wing AWE system is based on estimations provided by Ampyx. These estimations were however primarily based on knowledge gained on the much smaller 0.15 MW AP3 system. The many other elements that remained undefined had to be designed based on expert input, literature and various assumptions.

One of the important variables for future systems is selection of the drivetrain type. The system considered in this assessment used a hydraulic drivetrain type that uses hydraulic piston motors, a hub-less drum design and hydraulic accumulators to even-out otherwise the intermittent energy production of this cyclically operating system. The HAWT turbine is largely based on a recent optimisation of the NREL 5MW. It is however build for comparability to the AWE system and is therefore altered to operate onshore by changing its hub-height, tower mass and foundation type. The HAWT system does therefore not specifically represent the impacts of the NREL 5MW.

AWE and HAWT technologies both have numerous design variables. Most notably depending on the location and environmental conditions for which the systems are designed; table 8.1 states the assessed base-case scenario. Variations to this base-case scenario were subsequently evaluated in several sensitivity analysis to assess the different advantages of both technologies under different conditions. Additional sensitivity studies were performed on uncertainties and other important considerations.

Specification	**AWE**	**HAWT**
Location	Onshore	
Farm size	50 MW, 10 Units	
Service life	20 years	
Capacity factor	52.8%	46.9%
At avg wind speed of	11 m/s	10 m/s
At (avg) operating height	250 m	117 m
System type	Ground-Gen, Rigid-Wing	IEC1 rated
Drivetrain	Hydraulic	DFIG
Wing span / Rotor diameter	53.7 m	126 m
Tether length	1200 m	-
Tether / Tower specs	Single, 2 sections	Steel cylinder

Table 8.1: Summary of most important base-case specifications

An LCA is a structured method to assess and compare the environmental impacts of different systems or products. The outcome of an LCA is strongly influenced by the boundaries and methods used in the assessment. It is therefore not possible to simply compare the outcomes of different reports. In this project, both the AWE and HAWT systems were modelled from the ground up to ensure the most accurate comparison possible. Data for this was primarily collected from literature sources. This is a Cradle-to-Grave assessment, using a Cut-Off allocation method. Therefore, it does not include the (avoided) impacts for recycling at End of Life (EOL).

An LCA determines the impacts of a system based on unit inputs of materials and processes such as welding and transport. These inputs are collected in the Inventory (LCI) stage of an LCA. AWE technology is however still in very early development. Defining a representative model for a potential Multi-Megawatt AWE system therefore became an important and time consuming part of this project. This however also means that the presented models and impact-results should primarily be seen as informative for a potential future system. The results indicate advantages and disadvantages of AWE and may guide research to important topics.

8.1 Conclusion

The relative material requirements and impacts between AWE and HAWT systems significantly differ based on the location and wind conditions for which the systems are designed.

This was primarily assessed for onshore locations. The HAWT system requires higher hub-heights and larger rotor diameters to function equally in worse environmental conditions. On the other hand, the impacts of AWE remain largely constant, independent of the location. The AWE impacts mostly only change with respect to changes in energy output under different wind conditions.

One of the biggest advantage of AWE is its ability to produce energy with a significantly reduced material consumption compared to HAWT.

The masses of the modelled base-case AWE and HAWT systems are normalised to the energy produced over their lifetime, their values are displayed in table 8.2. In the base-case scenario, the AWE system produces electricity at only 28.3% of the mass required for the HAWT system.

	Unit	AWE	HAWT
Normalised Mass	kg/MWh	2.0	6.6
Total Mass	mt	913.0	2708.1

Table 8.2: Total masses of both systems including replacements. Normalisation is performed to amount of energy produced.

The majority of these mass reductions are achieved by reduction- or elimination- of heavy structural constraints such as the tower and the foundation.

The foundation of the HAWT system weighs approximately 1715.8 mt, thereby it accounts for 63.4% of the total HAWT system mass. This large mass is required to prevent the system from falling over due to the high overturning moments. In comparison, the foundation of the AWE systems is estimated to weigh only 338.2 mt. The large fractions are displayed in figure 8.1.

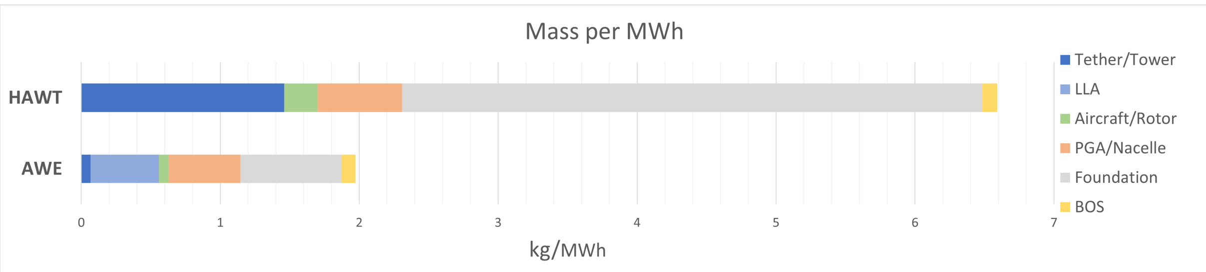


Figure 8.1: Repeated; Masses of both systems normalised to their energy output. All components over 20 years included.

The two other large masses in the AWE system are the Power Generation Apparatus (PGA, 238.7 mt) and the Launch and Land Apparatus (LLA, 228.1 mt). The LLA mass and the total lifetime tether mass of 30.6 mt combined effectively replace the 600.0 mt tower of the HAWT system. Indicating a mass reduction of 57% in the presented base-case scenario. This mass relation could however significantly change with changing environmental conditions. Even so much that the mass difference would only be minimal under the best environmental conditions, when the HAWT system has the lowest hub height. The difference could however also easily be double or even triple the base case values in the worst environmental condition, where a large hub height or a heavy tower design may be required. For onshore, it is these locations where AWE would have the most significant environmental advantage over HAWT systems.

The PGA of a AWE system with a hydraulic drivetrain is of similar mass to the nacelle of a HAWT system. The majority of this mass is represented by the hydraulic accumulator system, required to stabilise the energy output of the cyclically operating system. These systems are however also responsible for a large number of functions in the design. Most importantly, functioning as gearbox, transmission and for power output stabilisation.

The AWE has significantly lower impacts compared to HAWT technology.

The GWP and CED impacts of the AWE and HAWT systems are presented in table 8.3 under the base case assumptions. The determined impacts indicate that the AWE system would generates electricity at only 60.1% and 65.4% the GWP and CED impacts of the HAWT system operating at the same location. A similar reduction in payback time, and increase in EROI is observed.

	Unit	AWE	HAWT
GWP	$kgCO_2eq/MWh$	7.8	13.0
CED	MJ/MWh	127.5	195.0
EPBT	Months	8.5	13.0
EROI	-	28.2	18.5

Table 8.3: Base-case impact results

The presented impacts are notably higher compared to the impacts presented in the earlier LCA report on AWE.

Wilhelm (2015) presented an EPBT of 5.01 months, an EROI of 47.9 times the input energy, a GWP impact of 5.6 $kgCO_2eq/MWh$ and a CED of 75 MJ/MWh. These values differ significantly from the results found in this new report, caused by a large variety of differences. The capacity factor and the tether material impact are significantly more favorable in this new assessment. Primarily due to material, design and data improvements. The tether, foundation and aircraft are however significantly heavier. Partly due to increased experience at Ampyx, partly due to different modelling of systems for which nothing is known at the time, such as the foundation. The largest difference is however caused by the accumulator systems. This was excluded from the previous work, as no data could be found at that time. This element is found to be the largest impacts component of the AWE system in this current assessment.

The manufacturing stages of the initially installed systems represent the majority of all impacts for both technologies.

This stage represents 81.1% of all GWP and 78.5% of all CED impacts of the AWE system. The impacts of both systems are presented in figure 8.2.

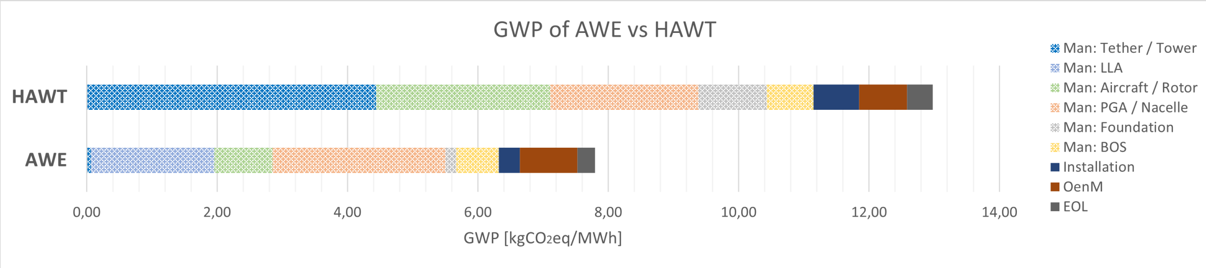


Figure 8.2: Repeated; Image of GWP impacts over the base-case model. The dotted elements represent the materials and manufacturing stage split into the 6 subsystems. Impacts of the replacements are included in the O&M stage.

The larges impact of the AWE system is found to be the PGA.

The high impacts of the PGA are primarily related to the large masses of the hydraulic accumulators. The hydraulic pistons and the personal design of a hub-less CFRP drum represent 2 other major impacts within the PGA. The second larges impacts component is the LLA. In the presented design, this will require a large mass, which is the main reason for its large fraction of the impacts. AWE effectively replaces the tower with the tether and the LLA. When comparing the technologies, only the PGA of the AWE system presents a larger impact than the similar component in the HAWT system, the nacelle. The LLA only comes close to the mass of an highly optimised HAWT system in optimal environmental conditions.

The tether and aircraft represent high impacts compared to their low mass fractions.

Major impacts materials in these subsystems are the UHMWPE in the tether and the carbon fibres in the aircraft. These materials require highly energy intensive manufacturing processes. Values for their impacts vary significantly over literature. The presented UHMWPE impacts are already significantly reduced in impacts, as they are assumed to be made with a manufacturing process with a large share of renewable. These materials are however also still less developed compared to the metals and concrete that represent the majority of all other materials. Significant technological improvements are most likely for these materials. For instance by usage of bio-based or recycled fibre types. These options could significantly reduce the impacts of these components. But would require further research, as is elaborated on in the recommendations.

Offshore

Data for offshore assessments remained largely unknown. It has therefore only been included minimally in this assessment. A sensitivity analysis on offshore elements indicates that the impacts of both HAWT and AWE technology significantly increase. There is too much uncertainty to make any conclusions about offshore operations. But HAWT systems certainly have advantage to the better wind conditions at shallow shore locations. Mover further into deep offshore remained too uncertain, different floating HAWT foundations could also deviate the impacts by as much as the entire base case impacts.

Sensitivity

The base-case HAWT blades were assumed 50% CFRP and 50% GFRP. A HAWT of this size may however also suffice with only GFRP in its blades. A sensitivity study showed that this would reduce the GWP and CED impacts of the HAWT system by 10.9% and 14.5%.

Important variables with large uncertainties are the capacity factors. These are taken at 52.8% and 46.9% for the AWE and the HAWT system, respectively. The Cf of the HAWT system was not varied in the assessment, even though it may differ between onshore and offshore. It has been kept at 46.9% for 10 m/s average wind speeds at hub height, regardless of the location of hub-height. The Cf of the AWE system is varied based on the average wind speed at average operating height of 250 m. This wind speed is varied based on the location and was determined in relation to the average wind speed at the different hub heights of the HAWT comparison. These capacity factors of the AWE system were provided by Ampyx, but may deviate from a system that is 33 times larger than their largest current system. An increased capacity factor to 57.8% would result in a GWP reduction of 9%. A capacity factor decrease to 47.8 would result in a GWP impact increase of 10% for the AWE system.

Another important variable is the lifetime of the systems. The AWE system is assumed to have the same lifetime as the HAWT system, both taken at 20 years. The newest HAWT turbines are however stated to have higher lifetimes, of over 25 years. Increasing the lifetime of the systems significantly reduces their impacts. The lifetime of a system is determined by the shortest lifetime of one of its irreplaceable components. AWE does not appear to have any such irreplaceable systems. This could therefore significantly further reduce the impacts of AWE relative to HAWT technology.

A final variable is the system size used in the comparison. The impacts of scaling were not quantified in this report, but an assessment based on scaling relation indicates that the impacts of the modeled system would have been lower for a system of 2 or 3 MW. The choice for the 5 MW was therefore unfavorable for the AWE system. Especially since the impacts of HAWT system generally reduce with increasing size. This indication does however not claim to know how another design would scale, especially for offshore.

The presented 5 MW AWE system is more than 33 times as large as the largest rated system by Ampyx thus far. Numerous design changes and improvements are to be expected for an actual Multi-Megawatt system. Assessments performed on actual design considerations along the way could be a valuable tool to get come to an optimal system, with lowest environmental impacts and largest advantages compared to HAWT systems.

8.2 Recommendations

The 3rd goal of this project was to Present (actionable) recommendations on improvement potentials. Large uncertainties and limited data availability have lead to limitations in the scope of this assessment, leaving numerous recommendations for later work.

The project eventually evolved into an assessment of a number of variables on which AWE and HAWT technology were compared. These variables were assessed with sensitivity analysis on base-case assumptions. There are however a number of recommendations that could be used to improve this assessment. There are also several recommendations for other methods that could potentially improve the environmental performance and knowledge of the AWE sector. The topics are:

- Re-perform LCA with actual design
- Usage of an LCA in selection processes
- Compare different AWE system types
- Other boundary conditions, Recycling
- Circular Economy
- Research of better materials

Re-perform an LCA once an actual design is available.

This assessment was intended to be carried out on early design options for the first commercial AWE system by Ampyx. Unfortunately, it proved too early in the feasibility studies to be able to assess and compare actual design concepts.

Over the course of the project, it became clear that these uncertainties would significantly effect the outcome of the study. This study should therefore be seen as indicative, to assess a potential future and to improve sustainable knowledge. Intermediate results of this study have already lead to a variety of insights that may lead to improvements of future systems by Ampyx. But the actually presented values will be of low specificity to an actual design.

An assessment based on actual design options would present a more detailed and more accurate understanding of the impacts of AWE. Ampyx was not interested in an assessment of the earlier AP3 system, as this 150kW system was designed with redundancy in mind. An assessment of the near future 1MW AP4 system could however provide valuable knowledge.

An even more detailed assessment can be carried out one measured data becomes available. This will require first hand data and experiences. The more detailed the direct data of e.g. energy usage, the fewer assumptions will be required and the higher the specificity to the impacts of the assessed product.

Usage of an LCA in selection processes

This 1MW AP4 system is currently in early feasibility studies. The impacts of this future system can be minimised by inclusion of Life Cycle Assessment steps within the concept design stages. An LCA can be a large, expensive and time consuming process; it does however not need to be when using it to compare concepts in the design phase of a project.

A good option to consider using in the design phase of a project is the usage of streamlined (also known as fast-track) LCA (Vogtlander, 2012). The assessment presented in this LCA on AWE did not start with an actual design to assess, therefore, data-collection and designing this system became the most time consuming part of this project. This same data would already have been available in an actual project design phase, which therefore significantly cuts down on time intensiveness of an assessment

LCA reports typically get their material impact data from expensive databases such as Ecoinvent and Gabi. Impacts of materials can also be found in free databases. The impacts specified differs significantly between databases. Like the LCA, these impacts also depend on boundary conditions and assumptions. An example of such a databases is Idemat (Ecocostvalue).

Large LCA reports also generally use specialised LCA software (SimaPro, Gabi, OpenLCA, Humberto). Such software could be very useful when the input data is already reasonably known, it is however not a requirement. An LCA could very well be performed in excel, as has been the case in this project.

Comparing different AWE system types

The different AWE technologies (Ground-Gen v/s Fly-Gen, Rigid-wing v/s Soft-wing) all have their own advantages and disadvantages. This report presented the impacts of a Ground-Gen, Rigid-Wing system. The impacts of this system were individually determined for its subsystems. These subsystems were specifically chosen for comparability to HAWT and to provide insight for other AWE typologies. The significant differences between the designs and subsystems of different AWE typologies are however not further assessed. It could be valuable to compare these technologies, for different sizes and locations.

A large part of the impacts of the Ampyx system are located in the PGA and LLA subsystems. These subsystems would be far smaller in Fly-Gen systems. Fly-Gen systems would however require a heavier aircraft which is made from materials with very high specific impacts.

This assessment was carried out on a 5 MW system. It was found that scaling of this model is unfavorable for larger system. Thus: a lower rated system would have resulted in lower impacts that presented for the 5MW case. If, after design improvements, scaling of the Ampyx aircraft indeed remains unfavorable for the mass, as stated in this report, it would be reasonable to presume that the same would hold for a similar Fly-Gen aircraft such as that of Makani. A comparison of different sizes and location could be used to assess the environmental advantages disadvantages of each technology in different locations, similar to the comparison to the HAWT system in this project.

Different boundary conditions, Recycling

This report is carried out with Cradle to Grave boundaries, using the (LCA) 'Cut-Off' allocation method. This means that the (avoided) impacts of recycling are not credited to the assessed systems, but rather to the next product that uses the recycled materials. Recycling and usage of recycled materials present large modelling uncertainties. For example; the GFRP blades from a HAWT system could be 'recycled' to be used in concrete or asphalt. The avoided impact that can be subtracted for this recycling is only the avoided impacts of the material that is replaced. Even-though this type of 'down-cycling' is still considered recycling, it is one of the worst option, and can only be done once, it is not circular. New and improved recycling options will become available in the near future. Including potential options to actually recycle materials for reuse in similar usages as the blades.

At this point in time, inclusion of recycling would primarily benefit metal materials, for which recycling is already well developed. In Vestas reports, the EOL stage represents an GWP impact reduction of approximately 35% of the other stages. A roughly similar reduction can be expected for AWE. Inclusion of recycling will therefore be more meaningful when recycling options for other materials are also better developed and the materials usage for an actual system is more accurately defined.

Research other materials

The impacts of materials significantly change with technological improvements. Overall, AWE and HAWT largely uses the exact same materials; primarily metals, concrete and plastics. There are however also differences, especially in the tether and the aircraft.

The lifetime impacts of the tether are responsible for 7.9% of all GWP impacts and 15.7% of all CED of the AWE system. The impacts of the UHMWPE were obtained from Dyneema DSM, with a GWP of 8.5 $kgCO_2/kg$. This already assumes the use of a large share of renewable energy in the production of the fibres. The GWP impact of the tether could easily be tripled if a more fossil based energy mix was used. The impacts could however also significantly be reduced with the usage of bio-based UHMWPE. These fibres are stated to have a GWP impact of 2 to 3.5 $kgCO_2/kg$. Usage of these Bio-based fibres could therefore reduce the GWP impact of of the tether by approximately 60%. The CED would likely reduce even more.

The lifetime impacts of the aircraft are responsible for 14.0% of all GWP impacts and 15.0% of all CED of the AWE system. A major impact in the aircraft is caused by the carbon fibres in the CFRP. The impacts of CFRP are highly variable within literature, the values of 39.2 $kgCO_2eq/MWh$ and 789 MJ/MWh as used in this report are reasonably average within literature. At these impacts, the carbon fibres are more than 15 $\times$ as impact-full as steel, responsible for approximately 50% of all aircraft impacts. Commonly used carbon fibres are (fossil based) PAN type, these fibres require highly energy intensive production processes. Usage of other fibres such as recycled fibres or (bio based)lignin carbon fibres could greatly reduces the impacts of CFRP in the future, even below the impacts of GFRP. Both these fibre variations are however short length fibres. It would therefore first need to be researched whether these fibres could provide sufficiently strength the meet the requirements for usage in the AWE aircraft.

There are numerous other material factors that play a role here. Usage of more optimised manufacturing methods could significantly reduce the mass of the aircraft. Since the mass of the aircraft also influences the requirements of the LLA system, the better manufacturing method would lead to larger impact reductions then only its own impacts. CFRP manufacturing scraps are another notable consideration, responsible for approximately 10% of the impacts in this assessment.

Circular Economy

Sustainability is a very wide topic, not fully assessable with an LCA alone. An important sustainable development for AWE is the increasingly important concept of 'circular economy', especially with the upcoming land-filling bans. Circular Economy and 'Cradle to Cradle' thinking aim to reduce the usage of (virgin) materials and the production of waste. An important level of circular economy is designing for recyclability of products and materials. Recycling is however still one of the least favorable options presented by the circular economy pyramid.

The recyclability of materials is an global industry topic and is not specific to AWE. Circular economy can however also be used specifically in the AWE sector. More specific to AWE are the higher levels of the Circular economy pyramid, especially that of RE-design for material reduction. AWE can be seen as an extreme Re-design of conventional wind energy generation. By that mind-set, onshore AWE presents a material reduction of 71.3% compared to HAWT technology. Making AWE very interesting from the perspective of Circular Economy.

Other mind-sets for this are: RE-powering of old HAWT foundations. The foundation of (off-shore) HAWT turbines are often not sufficient to support new (larger) turbines. AWE would however require much less from its foundation. The offshore foundation represents a major impact for both AWE and HAWT technology; RE-powering would not only reduce material consumption, it would also significantly reduce the impacts of shallow shore wind energy production.

A new, but growing concept is the inclusion of a circular economic indicator within LCA studies. A primary driver behind this is the Ellen MacArthur Foundation (2015). This 'Material Circularity Indicator (MCI)' is already found to be used in recent LCA studies by Vestas. It has not been assessed in detail in this project, but could also be performed outside of an LCA study.

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Appendix A

EOL

EOL Rates

The EOL rates are chosen based on various literature sources.

Metals recycling is generally taken between 90 and 98% due to separation and collection losses. Separated metal material flows that make it to the recycling plant are said to be 100% recyclable by the industry (Worldsteel). Therefore it is easier to recycle large mono-material metal components such as the tower. Vestas accounts for that by stating different recycling rates for the different wind turbine components: 98% for the tower and 95% for the generator, gearbox and cables etc. smaller items are recycled at 92% (Vestas, 2019a).

Siemens Gamesa (2020) handles it differently. They state the EOL methods much more specifically per component. The general tents are however similar over most literature.

These differentiations have not been included in this research. All metal recycling is set at 92%, without deviations for different recovery rates.

Datasets

A large portion of incinerated and land-filled materials were modelled with the average *municipal solid waste, sanitary landfill* data-set. This is an average data-set that is used when the base materials of a product, or the actual impacts of a material are unknown within SimaPro. The data-sets used for incineration and landfill EOL impacts:

Data-set	**Materials**
Scrap steel CH treatment of, inert material landfill	low alloy steel, steel plates, chromium steel, structural steel, rebar
Municipal solid waste CH sanitary land fill	Copper, titanium, transformer, electric motors, lubricant, electronics, FRP and all others
Municipal solid waste, treatment of, incineration	FRP, lubricants
Waste aluminium, treatment of, CH, sanitary landfill	Aluminium
Waste polyethylene sanitary landfill, CH	XPLE, UHMWPE, PE
Waste poly ethylene municipal incineration CH	XPLE, UHMWPE, PE
Waste PVC CH treatment of, sanitary landfill	PVC
Waste PVC CH treatment of, municipal incineration	PVC
Waste plastic mix sanitary landfill, CH	Tether coating,
Waste plastics mix municipal incineration CH	Tether coating,
Waste concrete, EU without CH, inert material landfill	Concrete
Waste paint, Treatment of waste paint	Paint

Table A.1: EOL datasets