Master thesis aerospace engineering

Life cycle assessment of a soft-wing airborne wind energy system and its application within a hybrid power plant configuration

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TU Delft

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by

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Cover: Kitepower setup during operation [1]

TU Delft

Preface

This master thesis marks the culmination of my academic journey in aerospace engineering, a field I have passionately explored for nearly six years. During my master's program, I focused on power and propulsion systems, deepening my knowledge in these areas within the aerospace sector. Simultaneously, I developed a strong interest in sustainability, which ultimately guided me towards pursuing research in renewable energy technologies and their environmental impacts.

This thesis, conducted within the Wind Energy Master's program, allowed me to step beyond my primary track and immerse myself in the exciting realm of airborne wind energy (AWE). Through this experience, I encountered new perspectives and met many remarkable individuals. I am particularly grateful to Roland, who introduced me to the innovative world of AWE and provided numerous opportunities to engage with this emerging technology. My sincere thanks also go to Rishi, whose guidance was invaluable whenever I faced challenges or sought to refine my report. Special recognition goes to Lavinia and Prapti; your support was instrumental in my rapid understanding of Life Cycle Assessment (LCA), significantly enhancing the quality of this thesis. The supervisory team's expertise and encouragement were crucial to the successful completion of this research.

I would also like to extend my gratitude to those who were not directly involved in this thesis but played a significant role in my academic journey. My family, despite being on another continent, provided unwavering emotional and financial support, enabling me to pursue my dreams. My friends, whose camaraderie and laughter made these years unforgettable, and my girlfriend, whose encouragement and companionship made this thesis enjoyable and helped me grow as a person both academically and personally.

Completing this thesis is just the beginning. I am excited to see what the future holds and to apply the knowledge and skills I have acquired to make meaningful contributions to the field of renewable energy and beyond. I look forward to doing 'cool' things with the expertise I've gained and continuing to explore new frontiers in sustainability and technology.

Kirsten Coutinho
Delft, August 2024

Abstract

The European Commission's roadmap for transitioning towards a fully renewable energy system includes ambitious goals to install 60 GW of offshore wind energy by 2030 and 300 GW by 2050. This accelerated capacity scale-up will entail a massive consumption of raw materials to manufacture the required wind turbines, including the foundations and installation infrastructure. Airborne wind energy (AWE) is a relatively novel technology that uses higher windspeeds at higher altitudes to theoretically produce more energy than conventional wind turbines. One of the key advantages of airborne wind energy is the low material demand of the technology, which should not only lead to a reduced carbon footprint of renewable electricity but also to a reduced environmental impact.

The work done within this report aims to quantify the overall environmental impact of a commercially developed 100 kW soft-kite AWE system through the use of a life cycle assessment (LCA). The presently pursued target market for soft-wing AWE systems in the 100-500kW range is for off-grid remote areas – coupled with a solar component and batteries, primarily for displacing diesel generators. Thus, a comparative LCA study of a hybrid power plant (HPP) configuration with and without AWE will also be performed. The site data used for this study was from a military base in Marseille, France.

The LCA uses the methodology as provided in ISO 14040 and 14044. The life cycle inventory (LCI) modelling framework used is an attributional LCA with system boundaries from cradle-to-grave. The functional unit is: 'Annual electricity production of 450 MWh, generated by an airborne wind energy system'. Activity browser and ecoinvent are used as the LCA modelling software and database respectively. The impact indicators used to assess the system are the global warming potential (GWP) and cumulative energy demand (CED). These indicators have been chosen as they are most common for LCAs conducted on renewable energy technologies.

The study finds that AWE systems do indeed have a lower environmental impact compared to other technologies. Specifically, the Falcon AWE system has a GWP and CED of 8.6 [kg CO2 eq/ MWh] and 144.1 MJ/ MWh] respectively. The greatest impact of the system comes from the ground station. The source of this is the housing of the system. The second and third most impactful sub-components are the frame and generator of the ground station. The kite and tether materials are the most frequently replaced over the operational lifetime. The KCU is the least impactful component.

For the comparative study, it was found that it was most beneficial to use all components within a configuration in a HPP. This is because including the diesel generator and battery components results in a lower oversizing of the renewable components. The less the components were oversized, the better the configuration performed from a sustainability point of view. The diesel generator is the most impactful of the components followed by the solar plant. The majority of the environmental impact from a diesel generator is attributed to the burning of diesel fuel during operations.

It is recommended to build a database specific to AWE systems for the future to have improved accuracy. It is also recommended to evaluate more impact indicators to have a broader environmental impact perspective. As LCA is an important tool for sustainable design, it is recommended to append the LCA modelling to a larger holistic model capable of evaluating the technical and economical performance of the system.

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Nomenclature

Abbreviations

Abbreviation	Definition
AEP	Annual Electricity Production
AWE	Airborne Wind Energy
BESS	Battery Energy Storage System
BLDC	Brush-Less Direct Current
CAD	Compute Aided Drawing
CAPEX	CAPital EXpenditures
CED	Cumulative Energy Demand
DGO	Diesel Generation Optimization
EMPA	Swiss Federal Laboratories for Materials Testing and Research
EOL	End Of Life
EPBT	Energy Payback Time
EROI	Energy Return On Investment
FRP	Fibre Reinforced Polymer
GWP	Global Warming Potential
HPP	Hybrid Power Plant
IDEMAT	Industrial Design & Engineering MATerial database
IEA	International Energy Agency
ISO	International Organization for Standardization
KCU	Kite Control Unit
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
LCI	Life Cycle Inventory
LCI	Life Cycle Impact Assessment
LCoE	Levelized Cost of Electricity
LEI	Leading Edge Inflatable
MDO	Multi-Disciplinary Optimization
NDA	Non-Disclosure Agreement
PEPBT	Primary Energy Payback Time
PEROI	Primary Energy Return On Investment
PV	Photo Voltaic
PVC	Polyvinyl chloride
REPA	Resource and Environmental Profile Analysis
SETAC	Society of Environmental Toxicology and Chemistry

Symbols

Symbol	Definition	Unit
C_{diesel}	Diesel generator size	[W]
CED_{P}	CED of a specific product	[J]
$\text{CED}_{\text{total}}$	CED of a specific product	[J]
ced_{material}	CED of a specific material	[J]
F_P	Production factor of production processes	[-]

Symbol	Definition	Unit
f_{burned}	Diesel fuel burned	[gal/hr]
m_{material}	Mass of a specific material	[J]

1 Introduction

Relatively a novel technology, Airborne wind energy (AWE) is a growing concept in the renewable energy industry that uses tethered flying devices to utilize wind energy at higher altitudes than conventional wind turbines. Within the realm of AWE, there exists several different promising concepts; this thesis will be centered around the concept of a soft-wing ground generation wind energy system developed by Kitepower B.V. One of the key advantages of AWE systems relative to conventional wind turbines is the reduced material usage despite both systems producing similar energy outputs [2]. The reduced material usage could result in a lower environmental impact and therefore a more desirable characteristic of the system as society strides towards a more sustainable future. Therefore, the life cycle assessment (LCA) of such a system becomes a helpful procedure to quantify the environmental benefits of AWE. LCA on fixed-wing AWE systems have already shown the benefits, however an LCA of a soft-wing system is yet to be done [3].

The goal of this report is to quantify and evaluate the overall environmental impact of a 100 kW soft-wing ground gen AWE system over its entire operational lifetime. After having acquired knowledge on the relevant topics, work to answer the research questions can be executed. This is initiated with a detailed LCA on the AWE system. The methodology used for this is done according to the ISO 14040 and 14044 guidelines [4], [5]. The life cycle stages that have been documented are: materials and manufacturing, installation and logistics, operation and maintenance, and end of life and waste treatment. The modelling of the LCA is done using the Activity Browser GUI(Graphical User Interface) for Brightway and the ecoinvent database.

After a detailed LCA of the AWE system, streamlined LCAs of the other components within the Hybrid power plant (HPP) have been documented; these are the diesel generator, PV modules and battery energy storage system. The environmental impacts of these were compared for different optimal configurations that were determined in an earlier sizing study of the HPP [6].

Before starting the technical part of the report, a literature study has been conducted in chapter 2. The literature study presents and critically assesses state-of-the-art literature from four areas of interest: airborne wind energy systems, hybrid power plants, life cycle assessment and LCA tools & software. The research focus uses the literature to present the research questions and objectives at the end of the literature study. The detailed life cycle assessment of the AWE system is conducted within the entirety of chapter 3. The LCA follows the structure as provided by the guidelines in ISO 14040 and 14044: goal & scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. To supplement the comparative study for an off-grid HPP, the streamlined LCAs of the solar, battery and diesel generator components have been conducted and presented within chapter 4. With all the data from the required LCAs generated and documented, the comparative study with results and analysis has been presented in chapter 5. Lastly, the conclusions and recommendations for future work are presented in chapter 6.

2

Literature study

2.1. Airborne wind energy systems

In order to provide a foundation for understanding the system to be assessed, this chapter will conduct a literature study on airborne wind energy systems, more specifically, the soft-wing ground generation energy system. First, a general overview of the three main concepts within AWE is presented in subsection 2.1.1. This section also provides information on fixed-wing and soft-wing aircraft in AWE as these are areas of interest. This chapter ends with a presentation on the importance of quantifying the environmental impact of AWE and wind energy technologies in subsection 2.1.2.

With the onset of the energy transition and countries moving to promote the use of more carbon-free energy sources, it is becoming crucial to innovate and apply such energy sources in order to reach the sustainability goals such as those set out by the IEA (International Energy Association)[7]. Among the renewable energy resources, wind is one of the most popular and widespread. However, though deemed renewable, conventional wind energy such as wind turbines still have an impact on society and wildlife [8].

On the other hand, in the last decade, some researchers and companies have increased interest in the field of airborne wind energy. Windspeed at higher altitudes is typically higher and therefore more energy can be extracted [2]. Windspeed closer to the surface of the Earth is lower due to friction and the zero-velocity boundary condition at the surface (using a simplified approach).

Overall, wind is a very promising energy resource that is expected to be capable of meeting the global energy demand even in a worse case scenario. Hence, research that supports and promotes the use of wind energy in any form is crucial for the advancement of civilization and will be a significant contributor to executing the energy transition and preventing climate change.

2.1.1. Overview of AWE systems

The three primary AWE concepts in development to date are ground-gen pumping systems, fly gen systems and ground-gen rotory systems. This section will provide a brief overview of these systems. Furthermore, as it is the focus of the research, the ground-gen systems will be elaborated on by presenting the soft-wing and fixed wing configurations.

Ground-gen pumping systems

Ground-gen pumping systems are the most common AWE concept within the industry. The components usually consist of the kite, a tether and a generator on the ground. The generator is the key component that converts mechanical energy into electrical energy when the kite is driven by the kinetic energy in the wind, moving the tether in generally figure 8 shapes [2]. The operation of these systems typically consists of an energy-producing phase and a recovery phase. The energy-producing phase is when the kite will generate energy while some of this generated energy must be consumed in order to reel in the aircraft during the recovery phase.

Fly gen systems

Fly gen systems will produce electricity via rotors or other components fitted to the aircraft. The aircraft, onboard rotors and generators, a tether and a base station are components that generally make up this system. The kinetic energy from the wind drives these rotors and the conversion from the mechanical energy to electrical energy also occurs onboard via the generators. The Electricity will then travel back to a station on the ground through a conductible tether [9].

Ground-gen rotary

A ground-gen rotary system will usually consist of a lifter kite, multiple airfoils connected through tethers and a ground station generator. The lifter kite will provide stability to the system in the air, while the forces produced by the airfoils will cause them to rotate with the tethers and as a consequence rotate a drum in the generator that converts the mechanical energy to electrical energy [10].

To better visualize these systems, they have been presented in Figures 2.1 to 2.3.

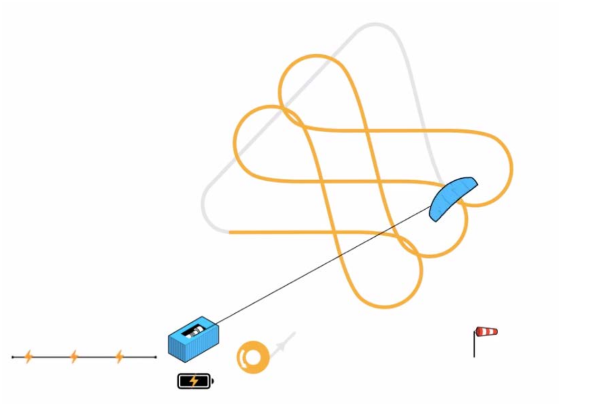

Figure 2.1: Ground gen pump AWE system in operation [10]

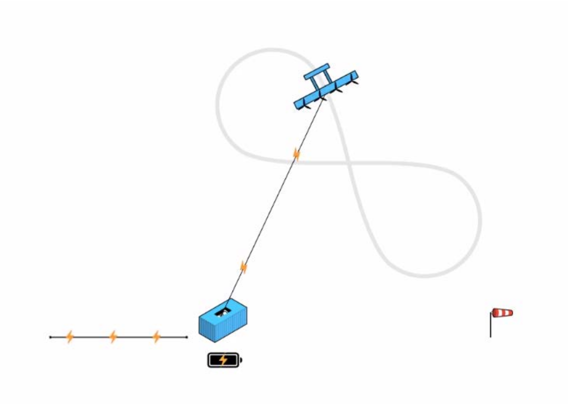

Figure 2.2: Fly gen AWE system in operation [10]

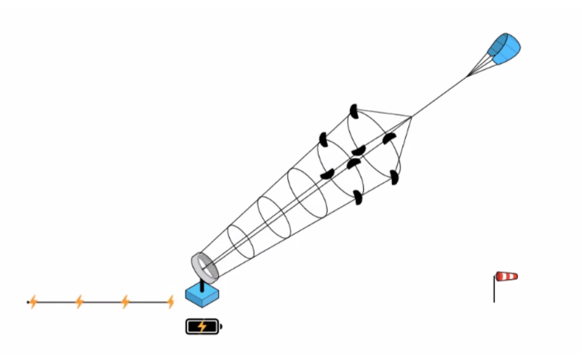

Figure 2.3: Ground gen rotary AWE system in operation [10]

The research to be done will be centred around a ground gen system that uses a soft wing. It is important to distinguish between fixed-wing and soft-wing aircraft. This will be done in Figure 2.1.1. In the context of the research, which is to execute an LCA, it is important to mention the discrepancies between these as the structure and therefore materials along with the operation and maintenance of the aircraft are quite different. Therefore, modelling them in an LCA will also be quite different.

Fixed-wing and soft-wing

Fixed-wing systems are those that typically have a stiff air-frame structure that will maintain its shape during operation. Given their structure, rigid wind systems require aerodynamic systems to control their wings and keep their shape. While this characteristic leads to an additional weight it also means that rigid wings have a higher aerodynamic efficiency relative to soft-wing systems and can therefore generate higher power. Due to their aircraft design, rigid wings tend to weigh more than soft wing aircraft. This leads to a different operating methodology and also a higher CAPEX. In addition to a higher CAPEX, a crash landing of a fixed wing system leads to the discarding of the entire system whereas this is not the case for a soft-wing [2].

Soft-wing systems are typically kite-like. The primarily researched soft wing types are Leading Edge Inflatable (LEI) kites and Foil kites. While it was previously mentioned that the rigid wing aircraft have higher CAPEX and higher replacement costs, the durability of soft-wing systems are lower and therefore compromise the performance of the kite during operation and require replacement around every six months. These total replacement costs can accumulate and exceed the higher CAPEX and replacement costs of fixed wing due to the higher replacement frequency. From an environmental impact point of view this would also mean that, unless recycled, soft-wing systems produce more waste material than rigid wing [11]. Soft wing and fixed wing systems have been presented in

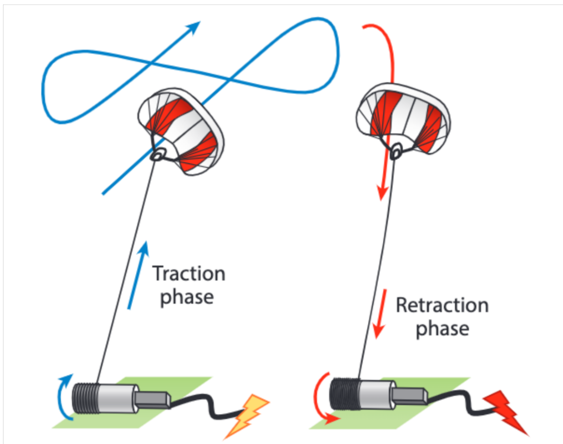

Figure 2.4: Soft-wing ground gen system showing traction and retraction phase [9]

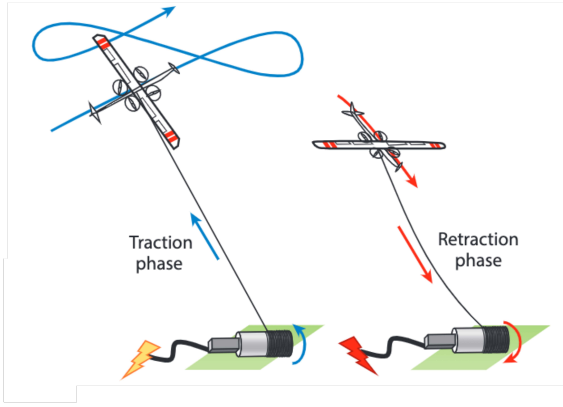

Figure 2.5: Fixed-wing ground gen system showing traction and retraction phase [9]

At the current moment, it is still unclear which of the two: fixed(rigid)-wing or soft wing systems are desirable. One paper that evaluated the two wing-types using the Best Worst Method (BWM) concluded that the more desired system depends on a scenario-to-scenario basis. For instance, in terms of flexibility, if a wind energy source is required in a remote and isolated area that is difficult to reach, then a rigid wing system could be used as less maintenance and replacement is required. On the other hand, technology superiority was identified as the most significant factor in the decision. In this regard, soft-wing systems are more advanced due to the ease of development. [12]

An overview of the different AWE concepts taken from [13] has been edited and is presented in Figure 2.6. The AWE concept that will be assessed within this project is a soft-wing (fixed ground station) ground gen system that is to be offered by the company Kitepower.

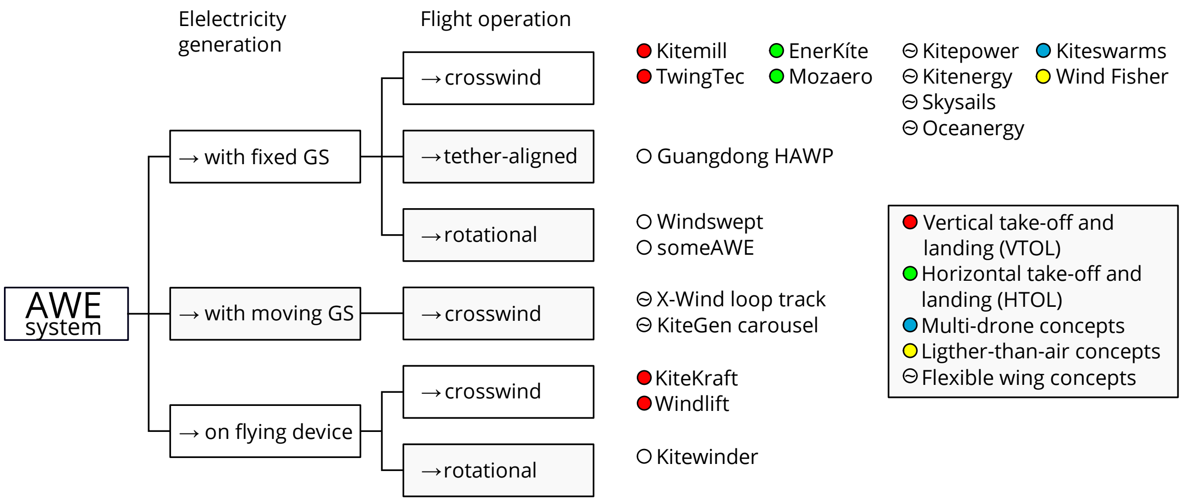

Figure 2.6: An overview of the different AWE technologies with relevant companies developing these [13].

Crosswind kite power is a very important concept in airborne wind energy as it forms the basis for the idea of kites generating power from high speed winds at higher altitude. This concept was first introduced by Miles Loyd [2]. The importance of the crosswind can be better explained when comparing the AWE system to a conventional wind turbine system. It is reported that for a wind turbine, the outer third of the blade produced over half of the total power. The other two thirds of the blade will therefore have a very low power density (W/ kg) as the inner region of the wind turbine blades will be thicker and therefore much heavier while only producing less than half the total power.

AWE systems design for this by essentially substituting the inner part of the turbine with a tether (a much lighter component). This means that AWE systems can theoretically have a much higher power density than conventional turbines in addition to using faster windspeeds at higher altitudes [2]. The theoretical power output of AWE per wing area is expected to be 40 kWm^{-2} which is a magnitude higher than expected for even optimized wind farms using wind turbines [14].This means that AWE systems stand to have two primary advantages in that they use less materials, are easier to install and could potentially have a lower environmental impact while also having a higher power output density. The lower environmental impact effects of AWE and why they are important for the future of wind energy technologies is elaborated on in subsection 2.1.2.

However, the trade-off that comes with this high theoretical power output is the instability and unpredictability of the AWE system. Conventional wind turbines are easy to operate and switch-off immediately when required. On the other hand, control of AWE systems is not so straightforward; the aircraft needs to continue to fly and failure of a component is probable to lead to a total system failure. A sophisticated automatic flight control system is therefore required to operate the aircraft while in use. Such a component both lowers the power density of the system as well as increases its negative impact on the environment [3], [9]. Therefore, a thorough investigation that maps out the life-cycle of an AWE system as well as a relevant system for comparison is required to prove whether the technology is a viable pursuit in the transition to more sustainable technologies.

2.1.2. Environmental impact of AWE

Wind turbines are often cited as promising renewable energy technologies that will accelerate the energy transition and prosper humanity immensely. While this is true, there is usually minimum attention to the environmental impact of the technology as this is generally automatically assumed to be 'good' for the environment [15]. Materials used to construct wind turbines for example will inevitably have some environmental impact, and it is important not to overlook these. If these environmental impacts are not quantified and used to design for more sustainability, this could eventually lead to negative impacts later. For instance, as can be seen in Figure 2.7, the blades of wind turbines typically end up in landfill at the end of their life cycles

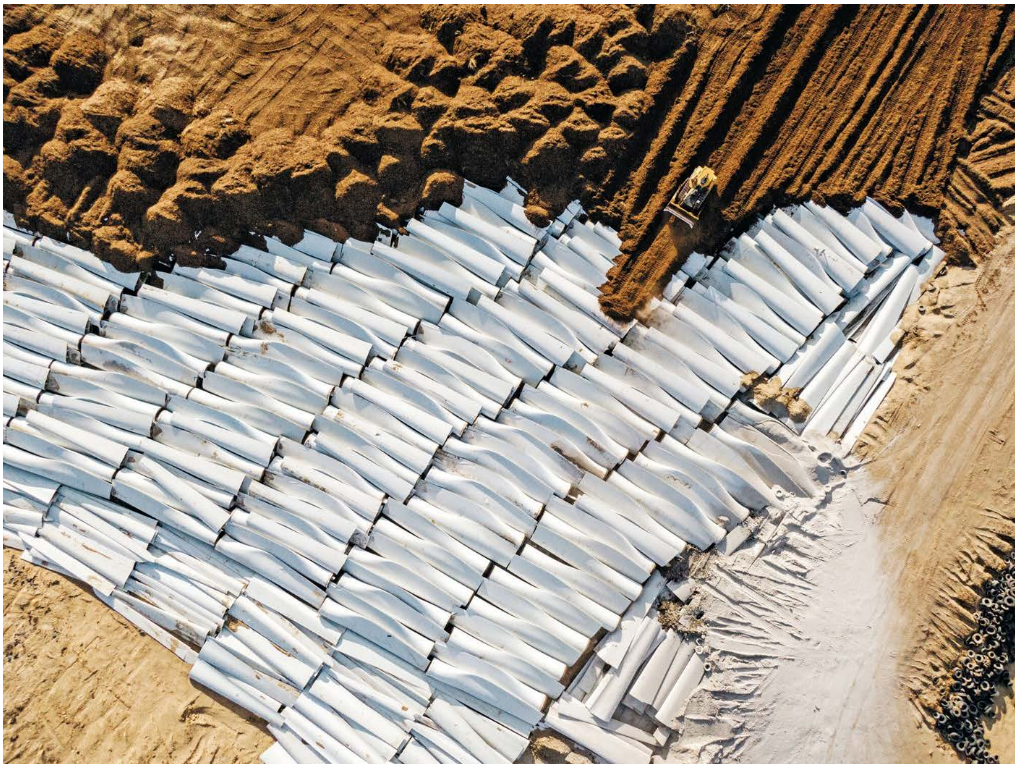

Figure 2.7: Wind turbine blades in landfill [16]

Executing studies like LCA and applying them to new energy technologies is essential as it allows for sustainable design and scientific based identification of hot-spots within a product system that is not as sustainable as initially hypothesized. Quantifying material and energy requirements of these new energy technologies is also important for policy and decision makers when discussing both large-scale and small-scale future development. In the case of the wind turbine blades, some companies have identified the problem of landfill and have started recycling the blades by using them to produce cement[16]. With both the increase of interest in renewable technologies and LCA, there have been a substantial amount of LCA on wind turbine technologies, as will be explained in subsection 2.3.5.

2.2. Hybrid power plants

Within the study, a comparative case to be assessed will be that of an off-grid hybrid power plant (HPP) with and without AWE. This chapter presents some general information on hybrid power plants, and provides reasoning on executing the comparative study for off-grid HPPs.

Typically, a HPP is a combination of different energy systems such as a diesel generator, solar panels, etc. that work together to provide energy both in on and off-grid scenarios. In an on-grid application, the HPP can also supply the grid with electricity when the energy generating systems it consists of produce excess power. Alternatively, HPPs are most useful in off-grid remote applications such as islands and rural areas, where the costs of long distance transmission is too expensive.

Hybrid energy systems are beneficial as together with different energy sources and energy storage devices, the supply of electricity can be optimised (using a control system) to suit the availability of its own energy sources [17]. This can be especially important when making a HPP of solar and wind energy due to the intermittency of these renewable energy sources. Given that electricity is required when needed and that there is no controllability in solar and wind energy for instance, a hybrid energy system using a renewable energy source needs either a viable energy storage device or a (typically controllable) energy source such as a diesel generator. It is important to note that in the context of LCA, more systems would most probably lead to a higher negative environmental impact especially if the mass of the HPP is more than a single power system.

Off-grid hybrid power plant

HPPs possesses greatest strength for off-grid applications. While the diesel generators were the preferred system for generation of electricity, the use of renewable energy sources has become more prominent recently due to increasing energy prices and lower costs offered by other sources such as renewable HPPs [17]. As explained previously, a diesel generator is still required as a back-up energy system due to the intermittency of solar and wind energy, along with a battery for energy storage during periods of over-production.

It is hypothesized that AWE with a battery energy storage system (BESS) could replace diesel generators in HPPs as a more sustainable alternative. Kitepower has recently released the Hawk AWE system to do this [18]. This system claims to be easy to set up, more efficient and using less material as conventional wind turbine systems. To validate this hypothesis, it is important and worthwhile to conduct a comparative LCA study of an off-grid hybrid power plant where the diesel generator is replaced with the soft-wing ground gen AWE system. A simplified block diagram has been used in Figure 2.8 to better visualize this. The arrows represent power transmission cables. The balance of plant will contain all power auxiliaries including the controller that manages the power distribution within the plant, and also the power converters.

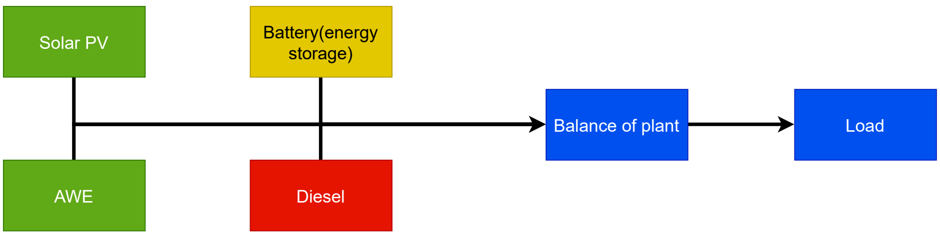

Figure 2.8: Simplified block diagram of a typical HPP

The concept of an AWE in a micro-grid system does exist and is presented in [1] - one of the main conclusions from this study highlighted the importance of sizing the energy storage system within the micro-grid. Again, energy storage systems such as batteries usually consist of rare earth metals that negatively impact the environment.

Additionally, the use of AWE in an HPP consisting of solar, diesel generator and battery has been studied in [6]. This report optimised the sizing of components within the system with the objective function to minimise the levelized cost of electricity (LCoE). It concluded that the greatest minimisation of LcoE occured when all energy systems were used to generate and store electricity. Without a diesel generator, the renewable systems and battery would be drastically oversized. This means that, at current time, the integration of non-renewable energy sources such as diesel generators are still essential to minimising LcoE.

2.3. Life cycle assessment

This chapter provides an analysis on Life cycle assessment. First, relevant background information is provided in subsection 2.3.1. Following this, the importance of executing LCA is presented in subsection 2.3.2. The methodology using the four stages of LCA is provided in subsection 2.3.3. As these will be important for both the Life cycle impact assessment and interpretation stage, common impact indicators for LCA when evaluating renewable energy technologies are presented in subsection 2.3.4. A brief analysis on some LCA executing within the wind energy industry is provided insubsection 2.3.5. Lastly, as it will be important for the research to be conducted and is also a developing topic in LCA, some common implementation methods for recycling in LCA are given in subsection 2.3.6

2.3.1. Background information

Sustainability is a holistic concept that encompasses the harmonious integration of environmental responsibility, economic viability, and societal well-being to meet the needs of the present without compromising the ability of future generations to meet their own needs. A Life Cycle Assessment (LCA) solely quantifies environmental impact through a rigorous evaluation of a product's entire life cycle. It aims to examine the resource use, energy consumption, and emissions associated with a product from raw material extraction to disposal. By comprehensively analyzing environmental aspects such as carbon footprint, water usage, and toxicity, LCA contributes to the environmental pillar of sustainability.

The analysis from "cradle to grave" and the "functional unit" are two distinctive characteristics that set a LCA apart from other environmental assessment methodologies [19]. When combined, these properties make it possible to compare product systems that serve the same or very comparable purposes.

A cradle-to-grave LCA analysis would investigate the environmental impact of all components making up the system. For a wind energy system for instance, this would include all stages: manufacturing, installation, operation and maintenance, and end of life. Cradle-to-cradle is another term commonly used as a boundary definition in LCA. This is a more sustainable definition that would encompass the entire life cycle of a product by using a more bio-mimetic approach. What this means is that in a cradle-to-cradle analysis, the product is considered to be part of a larger ecosystem where, rather than a complete stop at the end of life of the product, it is used again in another application- thus mimicking a natural ecosystem [20].

In the context of an LCA, the products that eventually make the system being assessed are viewed as product systems. This means that each product comprises of other sub-products and sub-processes contributing to the generation of that specific product itself.

One of LCAs strengths as a tool are its broad range of applicability to different products and the ability to compare different products. When doing such comparisons, certain minor non-impactful influences can be neglected in a way that allows the two products being compared to be modelled for in a similar manner. The functional unit is then quantitatively defined as the foundation of comparison between two systems that must fulfill the same or similar function. The use of a functional unit allows for comparison of completely different products in terms of material composition provided they produce the same function. Such is the case for the comparison of airborne wind energy in a hybrid energy system consisting of solar panels, battery and diesel generator.

The concept of LCA came to fruition through the desire to compare two similar products for their environmental impact. For instance, how does one determine whether glass, aluminium or paper bottles are better for use despite all being recycleable? The environmental impact of such cases is often more prominent in the production, transportation and end-of-life phases than the actual use phase of the product itself. Therefore, an LCA becomes a useful tool to quantify such impacts. In its early stages of conception, LCA came about due to rising concerns on matters such as resource efficiency, pollution control, and waste management. One of the notable early works in LCA (at the time referred to as a Resource and Environmental Profile Analysis (REPA)) was conducted by the Midwest Research Institute for the Coca Cola company in 1969. LCA studies initially focused on energy analyses but expanded to include resource requirements, emissions, and waste generation [21].

After a period of diminishing interest in the concept, LCA studies received a revival that was realised when an extensive list of the data required for LCA investigations was supplied in a study by the Swiss Federal Laboratories for Materials Testing and Research (EMPA), which led to a wider use of LCA. The study also provided the first impact assessment approach, which aggregated airborne and waterborne emissions into so-called "critical volumes" of air and "critical volumes" of water, respectively, using the relevant semi-politicalstandards for those emissions. While the use of LCA became prevalent, many parties executed these assessments using different concepts where the LCA of the same product had different results. The standardization of LCA was spearheaded by organizations like the Society of

Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) [20]. SETAC played the role of coordinator while ISO standardized activities. The work of these organizations led to notable pieces of work such as SETAC's 'Code of Practice' and ISO 14040 and ISO 14044 which introduce standardized LCA principles and guidelines. In Figure 2.9, the general methodology from ISO is presented [21].

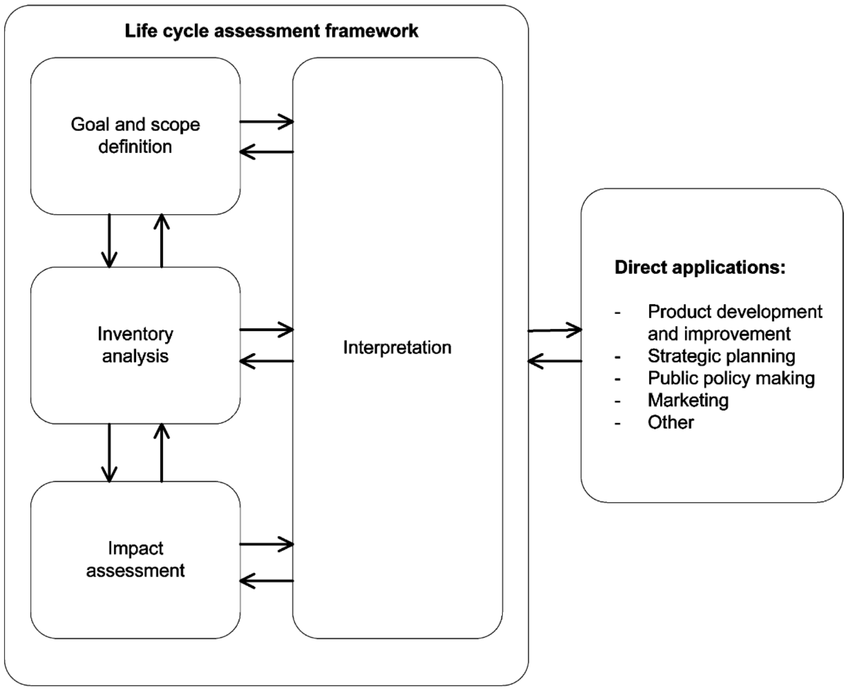

Figure 2.9: General framework presented by ISO [4]

In the modern day, the concept of Life Cycle Sustainability Assessment (LCSA) is gaining prominence. It expands the scope of traditional LCA by including economic and societal impact. The work to be done only consists of environmental impact and will not consider these. However, it is recommended to extend the work with an LCSA when possible. While an LCSA will be more tedious due to its tran-disciplinary nature, it would be helpful to execute as it can broaden the focus from product-related questions to sector and economy-wide levels.

2.3.2. Importance of an LCA

LCA as a concept can be very useful in product design and decisions making, whether political or environmental. Alternatively, some institutions caution its use due to the ability to exploit and manipulate data to make one product look environmentally more 'beneficial' in so called greenwashing campaigns [22]. An example of this exploitation with relevance to AWE could potentially be setting the system boundaries between a comparative LCA of fixed-wing and soft-wing; the results of the LCA with neglect of recycling in a soft-wing could significantly differ than if the boundaries were extended to include recycling. As assumptions used can differ between methods, this can also impact the validity of LCA results [23].

Nevertheless, in terms of an environmental impact assessment method, LCA is regarded as a 'front-runner' compared to alternative methods. More importantly, if used as part of a more comprehensive decision-making framework, LCA becomes very useful in informing, designers, architects, engineers and all involved stakeholders on product and process development [24]. Comparitive LCA studies can also be important to avoid scrutiny from competing parties and further expand on the quality of the work done during the LCA. With the widespread emergence of development for renewable energy technologies, LCA becomes an important tool in providing an overall quantification of different environmental indicators for policy-makers and designers to make informed decisions on legislation to be established for the future.

2.3.3. Methodology

As previously explained in subsection 2.3.1, the ISO has standardised the methodology to perform an LCA by breaking down the study to four main stages:

1. Goal & scope definition
2. Life cycle inventory analysis (LCIA)
3. Life cycle impact assessment
4. Interpretation

In the following subsections, these different stages will be further elaborated on, along with the importance of their use:

Goal definition

Before beginning any LCA study, the goal definition must be established. This is done so that the LCA practitioner and all involved parties/ stakeholders are aware of the application of conducting the study along with what decisions can be made moving forward based on the study itself. Identifying a goal first in the study ensures that the results of both the LCIA and LCA are kept within the boundaries defined by the goal and scope. According to the ISO14044[5], the goal definition should consist of six aspects:

1. The applications for which the study is intended for should be identified.
2. The limitations of the method, along with assumptions and the impact coverage should be specified.
3. The motivation for executing the study.
4. The target audience should be identified.
5. The type of comparisons that will be involved - in the case of this project, this would be the performance of the system in a hybrid energy system.
6. The party that commissions the study along with other relevant stakeholders.

Scope definition

During the scope definition stage, the product system to be assessed must be exhaustively identified along with the assumptions and system boundaries that are to be applied. The scope definition follows from the goal definition phase in that it establishes the deliverables, system boundaries, LCIA impact categories and methods, and appropriate reporting of results that are to be expected from achieving the goal of the project. The scope definition should ensure that the work to be done is consistent in methodology and reproducible. If an inconsistency is present, then this is to be documented and proven for its insignificance to the overall LCIA. The functional unit is also defined at this stage. Regarding the work to be done, an important aspect of the scope definition will be determining the system boundaries; in the case of a soft-wing AWE, the kite is generally replaced every 6-months[18], therefore whether recycling is to be included or not (and to what extent) in the study can have significant implications on the environmental impact of the product along with the results of the comparison in a hybrid energy system.

The functional unit can be determined on both a qualitative and quantitative scale. The quantitative determination of the functional unit usually involves choosing the relevant technical function that is to be fulfilled and also the period of time over which the function is to be provided. A qualitative definition of the functional unit can be important for cases where the function that the product provides is not sufficiently straightforward. For instance, in the case of a fashionable product, this metric often relies more on perception rather than a quantifiable number. However, it is important to note that for the case of the study on the soft-wing AWE in the context of a hybrid energy system , the function of providing power is more straightforward and therefore a qualitative functional unit may not be necessary. Nevertheless, in the industry of wind energy an often significant factor that generates resistance towards the large-scale implementation of systems is the 'unaesthetic' look of wind turbines [25][26]. Therefore, a qualitative approach may be more important for future recommendation when AWE is more well established and can be compared to wind turbines.

Life cycle inventory analysis

Life Cycle Inventory Analysis (LCI) is a fundamental phase within the broader framework of Life Cycle Assessment (LCA). It involves the systematic collection, quantification, and organization of data on all material and energy inputs, emissions, and environmental releases associated with a product, process, or system throughout its entire life cycle (elementary, product and waste flows). The LCI phase hence consists of the exhaustive accounting of all data required to execute the LCA. Additionally, a planning for where the data required to assess such processes is also to be obtained. The primary constraint when conducting such an analysis is that the entirety of the system is to be modelled such that the functional unit is met. LCI plays a crucial role in understanding the environmental performance of a subject of interest, and it serves as the basis for subsequent phases of LCA, including Impact Assessment and Interpretation.

Within the life cycle inventory analysis, the choice of whether to conduct an attributional or consequential LCA must also be completed. These are two of the main LCI modelling frameworks; this choice is important as it impacts the type of input used in the LCA to follow. An attributional LCA looks at the current state of the environment and system to be assessed and attributes the environmental impact from a product and processes used to create that product during its lifetime. Whereas a consequential LCA would generate an estimate on what the environmental impact that the existence of a product would have on the environment. The primary distinction between these two methodologies would be that attributional LCA only look at the environment at the time while consequential LCA provides an assessment if the product is added to the environment and what impact this would have after this addition. Therefore, it can be said that an estimate of the product's share of the global environmental impact is provided by an attributional LCA. A consequential LCA provides an assessment of how the product's production and consumption affect the environment globally [27].

Overall, the choice between the different LCA methods is non-trivial and depend on various criteria on a case-by-case basis. The decision also depends on the use of the LCA. In the case of decision-making, one could say that a consequential LCA is more accurate in determining the steps to reduce environmental impact. On the other hand, an attributional LCA is more straightforward and has more data availability, and it can therefore be said that an attributional LCA is more detailed relative to its counterpart.

In Figure 2.10, a framework for the LCI phase can be found. This shows that the first step to be made in the LCI is to obtain all relevant data from different sources such as through literature, internal communication etc. This data must then be categorized and organized. This involves breaking down the collected data into specific categories, such as materials, energy, water, emissions, and waste, for a structured analysis. The data collected can then be normalized with respect to the functional unit such that it be be used in a comparative analysis. The midpoint and endpoint characterisation factors can then be determined and applied to the collected data in the next step. Midpoint indicators are those associated with specific impacts such as human toxicity, climate change, etc. While endpoint indicators are typically quantifying damage at typically three areas of protection: human health, natural environment and natural resources. There are different methods used to measure the same midpoint or endpoint indicators such as CML and ReCiPe [28], [29]. The absolute values of these differ per method and therefore once a method is chosen, it should be applied to all other relevant points of the assessment such that the results are consistent. The decision on which method is to be used is dependent on the goal of the LCA that had previously been defined.

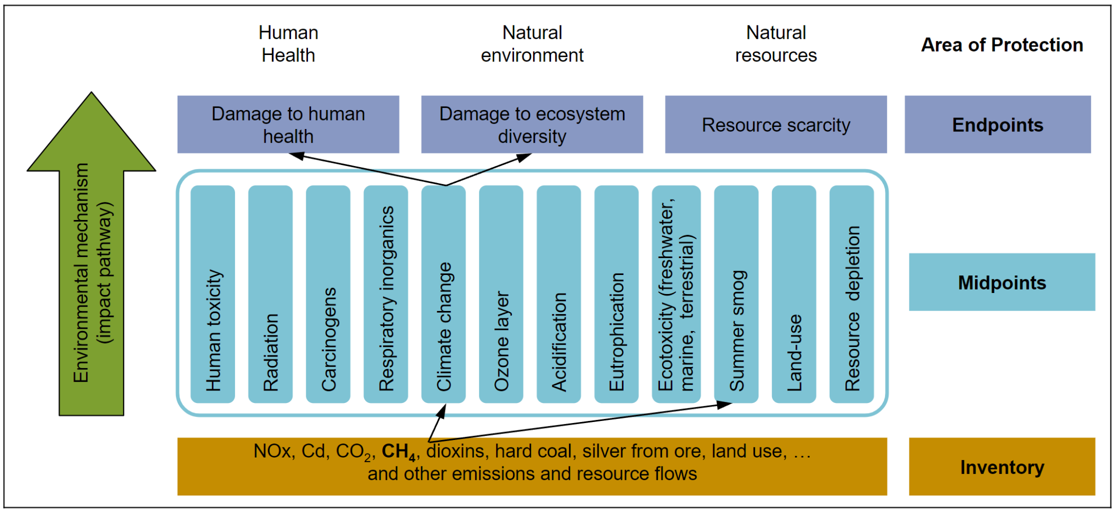

Figure 2.10: Framework presenting steps of a LCI [30]

At the end of the LCI analysis, a bill of materials should be produced of which the data has been meticulously evaluated and documented along with the processes that the materials undergo. This will set the foundation for the Life cycle impact assessment.

Life cycle impact assessment

In the next step of Life cycle impact assessment, the LCI generated previously is translated into the chosen impact indicator results. It is crucial to remember that life cycle assessment (LCA) and impact assessment (IA) analyze possible environmental effects of actions that affect humans and the natural environment beyond the boundaries of technosphere and ecosphere, frequently only after fate and exposure processes. Rather than serving as forecasts of actual environmental consequences, the LCIA data should be viewed as environmentally relevant impact potential indicators. As data from the LCI can be acquired through various sources, the LCA practitioner must ensure that elementary flows from the LCI are appropriately linked with the chosen LCIA factors. It is important to verify that all elementary flows have a characterisation factor assigned in the LCIA methods. If this is not the case, the life cycle impact assessment can be considered incomplete. Furthermore, in some cases, the unassigned characterisation factors can have significant implications on the results and conclusions of the study.

In addition to quantifying the environmental impact of the life cycle inventory, an LCIA can also be used iteratively in a sensitivity analysis where the influence of different materials can be assessed by varying them and analysing the LCIA results.

An optional step in the LCIA is the normalisation and weighting of the impact categories. The decision to do this must be done during the scope definition stage.

Interpretation

The life cycle interpretation phase has two objectives: By iteratively conducting the LCA, the life cycle inventory model can be improved to better meet the goals of the study. Once the iteration is complete, conclusions and recommendations from the LCA in its entirety can be derived. All aspects of all phases are evaluated and conclusions and recommendations are derived while adhering to the aims and constraints set during the goal and scope definition. With this evaluation, the identification of significant issue in the modelling must take place and a sensitivity analysis on uncertainties in the model must also be conducted. A flow diagram of the interpretation and its link to the other phases has been presented in Figure 2.11 [4]:

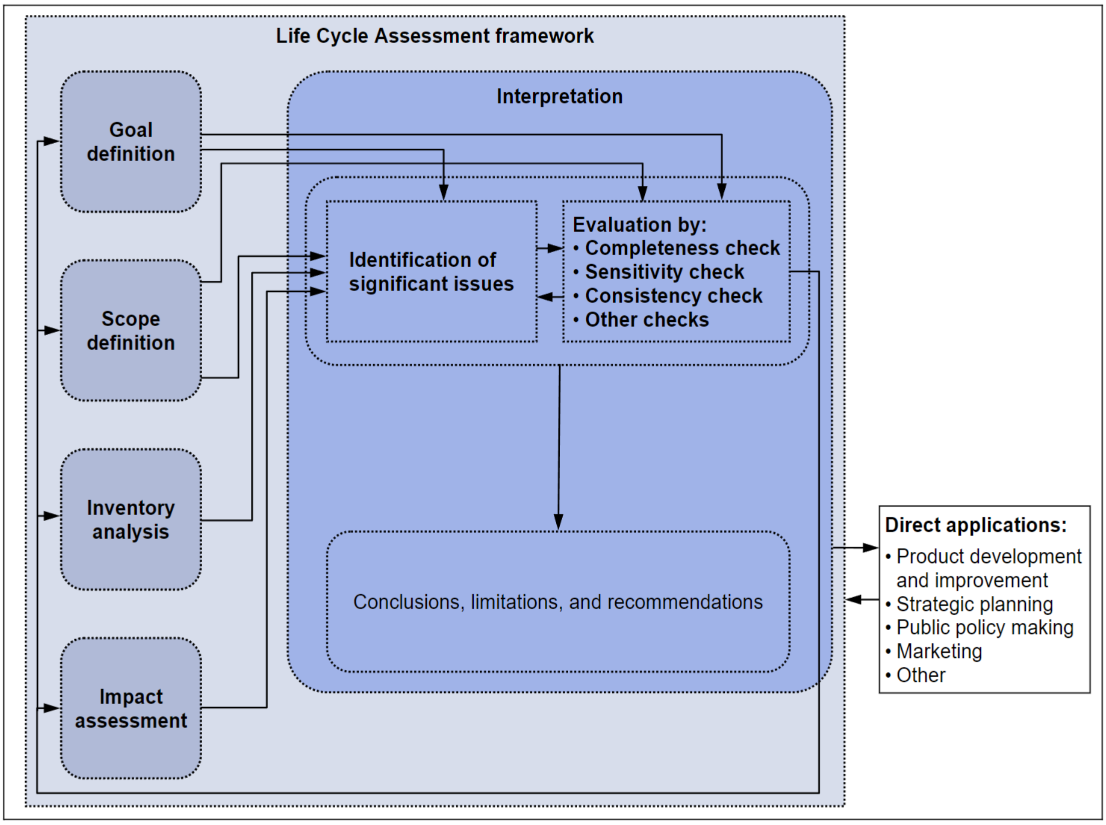

Figure 2.11: Elements of interpretation phase along with links to other LCA phases [19]

To summarize, Table 2.1 presents an overview of the discussed LCA phases, along with typical steps and results to be expected from them.

Table 2.1: Overview of LCA phases with typical deliverables expected[20]

Phase	Steps	Main result
Goal & scope definition	Procedure Goal defintion Scope definition Function, functional unit, alternative and reference flows	Functional unit, alternatives compared
Inventory analysis	Procedure Economy-environmental system boundary Flow diagram Format and data categories Data quality Data colleciton and relating data to unit processes Data validation Cutoff and data estimation Multifunctionality and allocation Calculation method	Inventory table, other indication (e.g., missing flows)
Impact assessment	Procedures Selection of impact categories Selection of characterization methods: category indicators, characterization models Classification Characterization Normalization Grouping Weighting	Environmental profile Normalized environmental profile Weighting profile
Interpretation	Procedure Consistency check Completeness check Contribution analysis Perturbation analysis Sensitivity and uncertainty analysis Conclusions and recommendations	Well-balanced conclusion and recommendations

2.3.4. Impact category indicators

Previously, the use of impact category indicators was briefly touched upon in item 2.3.3. In Life Cycle Assessment (LCA), a plethora of impact categories can be used to quantify and evaluate the environmental impacts associated with products, processes, or systems. Some commonly used impact categories include Global Warming Potential (GWP), Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, Human Toxicity Potential, and Ecotoxicity Potential. Each impact category focuses on specific environmental issues, allowing for a comprehensive assessment of a product's environmental performance. Furthermore different institutions develop these impact category indicators and measure them differently [31].

For example, Global Warming Potential (GWP) measures the potential for a substance to contribute to global warming over a specified time horizon, usually 100 years. It is often used to assess greenhouse gas emissions, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O), which are major contributors to climate change. Acidification Potential evaluates the potential for emissions to acidify the environment, leading to detrimental effects on ecosystems and biodiversity. Eutrophication Potential assesses the potential for nutrient pollution to cause excessive growth of algae in water bodies, leading to oxygen depletion and harm to aquatic life.

When conducting the LCA of renewable energy technologies, such as wind or solar power systems, Global Warming Potential (GWP) and Cumulative Energy Demand (CED) are two of the most important impact category indicators to consider. This is because renewable energy technologies aim to mitigate greenhouse gas emissions and reduce reliance on non-renewable energy sources, thereby addressing climate change and energy sustainability concerns. By focusing on GWP and CED, LCA practitioners can effectively evaluate the environmental performance of renewable energy technologies and identify opportunities for improvement in their life cycle energy and carbon footprints.

This section presents some of the commonly used impact category indicators associated with evaluating renewable energy technologies.

Eco costs
Eco costs are a single issue indicator that aim to quantify the costs that a product has on the environmental burden of the planet. They are essentially the costs that would be required to prevent an environmental burden and therefore keep the relevant sustainability parameter(CO2 emissions, acidification, eutrophication, etc.) stable with what the Earth is capable of sustaining. In reality, these costs do not apply when procuring and designing products, however, the estimation of eco-costs could be relevant in the context of regulations set by governments in the future. For the project itself, estimating the eco-costs of the AWE model could be beneficial given the novel nature of the technology itself along with part of the company's business case [1]. Eco costs can be useful indicators due to the ease of comprehension when monetary values are involved. However, there is difficulty in applying such an indicator to LCA with system boundaries for cradle-to-cradle calculations, and the consequences of other pollutants is not accounted for [32].

GWP
Global Warming Potential (GWP) is one of the most common indicator metric for CO2 equivalence. It is described by the overall change in radiative forcing over a given time-period. Where the radiative forcing is the warming of the Earth given by the perturbation of the Earth's atmosphere caused by the emission of a climate pollutant. This effect is then 'normalized' with respect to an equivalent quantity of CO2. The time period commonly used is a 100 years (adopted in Paris agreement and Kyoto Protocol for instance[33], [34]). Such a metric is useful as it can encompass the environmental impact in terms of global warming for different pollutants and asses them both on their innate heat-trapping ability along with their effective 'lifetime' within the atmosphere. It is noteworthy to mention that this metric also gets critiqued due to the 100 year time period. The reason for this is threefold: it can be unfair when evaluating different pollutants as the connection between emissions and climate change contribution. It can also be inefficient as different pollutants impact the environment differently over a time period - short-term reduction of emissions may be beneficial despite low radiative forcing long term effects being more impactful. Lastly, as it is normalised by CO2 equivalence, the need to reach net-zero carbon emissions may be understated for other pollutants, effectively promoting the emission of pollutants that may not have as high of a CO2 emission. The reason for this is further elaborated in [35].

CED
The cumulative energy demand (CED), in the context of LCA, is essentially a measure of a system's total primary energy consumption over its entire lifetime. The unit typically used to quantify the CED is MJ or MWh. In addition to the direct energy used in production and consumption, it also accounts for the energy contained in raw materials, the energy used in transportation, and any energy needed for recycling or waste management [36]. The CED of a specific product, for instance a hybrid power plant, can be computed by first breaking down the plant (system) into its respective components ($CED_{P.Components}$), sub-components and fundamental materials. If a database is used that possesses the data for the materials identified in the system components (ced_{material} , one can find the cumulative energy demand (of production) for this power plant (CED_P) to be found by Equation 2.1 [36]. Where (m_{material}) is the mass of the relevant material and F_P is a production-factor, used to account for the energy demand of production processes [37].

$$CED_P = \sum_{\text{Components}} CED_{P.Components} \tag{2.1}$$

$$CED_{P,\text{ Component}} = \sum_{\text{Material}} [ced_{\text{material}} \cdot m_{\text{material}}] \cdot F_P \tag{2.2}$$

Note, that the total CED for a system's life cycle can then be similarly found by identifying and analysing the CED for all energy consuming processes and activities. The system boundaries are important in deciding what is to be considered in the computation of this impact category indicator. Due to the complexity of large systems and their energy demand, there are multiple different approaches to calculating the CED. Approached can differ because of how they collect energy. For instance, whethere the approach considers the total energy harvested from a resource or the maximum energy that is harvestable. Another example in different approaches would be using the lower or higher heating values of fossil fuels when assessing the energy demand from this resource [38], [39].

While the computation of CED is typically concerned with energy consumptions, the CED can indirectly be used to assess the 'energy efficiency' of the system. For example, in the case that the functional unit used in the LCA is to produce a certain amount of energy over a certain time period, the CED of the system being evaluated can be normalized by the value of energy production in the functional unit. In this way, a low efficiency system would be one where the CED is greater than the energy produced by the system, resulting in a higher normalized CED. A method like this could be used in the competitive study for the hybrid power plant scenario with and without AWE, to be done within this research [38]. CED can also be useful in optimizing the upstream processes of an energy technology. one paper investigated this through the use of a MATLAB simultaion. Through the use of optimization integrated with an LCA where the CED was used as an impact category indicator, the optimized configuration for the sizing of plant components led to a lower CED and therefore a decreased environmental impact [40].

2.3.5. LCA in wind energy

Within the renewable energy and even the wind energy industry, there have now been a plethora of LCA studies executed on the relevant technologies, especially wind turbines. [15] presents a complete comparative analysis of twelve studies on wind energy systems. It found that, despite the high number of LCAs on wind turbines, the results of the studies still differed from each other. The common reasons for these discrepancies were the TRL(technology readiness level) of the technology assessed, location and site-specific data. It was also found that the uncertainty analysis performed during the interpretation phase of these studies showed higher uncertainties for lower capacity energy systems, relative to the larger systems.

Additionally, the methodology used to perform all LCAs were different in the metrics used to generate results as well as the impact assessment. Notably, there is no consensus on what are the exact categories that define environmental impact-this can lead to varied results. For instance, even when the same wind turbine model, with the same case study uses different impact methodologies, the results significantly differ.

For example, Table 2.2 presents the energy return on investment (EROI), Primary energy return on investment (PEROI), energy payback time (EPBT), primary energy payback time (PEPBT). retrieved from the twelve studies evaluated in [15]. The size of turbines ranged from 0.3 - 5 MW. The parameters presented in Table 2.2 quantify the energy performance of the systems. Such a varied spread of results exists between studies due to the different aspects of the methodology used. These ranged from how the capacity factor for each system was defined as well as what time period was used to assess the systems despite some systems being very similar.

Table 2.2: Energy performance results from the twelve LCA studies assessed in [15]

Study	EROI	PEROI	EPBT (months)	PEPBT (months)
Ardente et al. (2008)	-	40-80	-	3-6
Crawford (2009)	-	21(850 kW) 23(3.0MW)	-	11.4 10.4
Guezuraga et al. (2012)	8.7-33.3	-	7.2-27.6	-
Lee et al. (2006); Lee and Tzeng (2008)	185	-	1.3	-
Martinez et al. (2009a, b)	50 34.4	-	4.8 7.0	- 4.7 (offshore)
Schleisner (2000)	-	51.3 onshore 76.9(offshore)	-	3.2(onshore)
Tremeac and Meunier (2009)	11.8(4.5 MW) 3.1(250 W)	34.5(4.5 MW) 8.7(250 W)	20.4(4.5 MW) 78(250 W)	7.0(4.5 MW) 27.5(250 W)
Vestas (2011)	30	68.6-109.1	8	2.2-3.5
Weinzettel et al. (2009)	18.5	46.2	13	5.2
White (2006)	11,24,28	-	21.8,10.2,8.6	-

LCA in Airborne Wind Energy

To date, there have been a limited amount of LCA studies on AWE published. One study assessed a conceptually designed 1.8 MW fixed wing ground gen AWE system [41]. It also featured a comparative study with an equivalently sized conventional wind turbine. Impact category indicators used were the CED and GWP. The study computed an overall system impact of 5.611 gCO2 eq/ kWh and 75.2 kJ eq/kWh for the GWP and CED respectively.

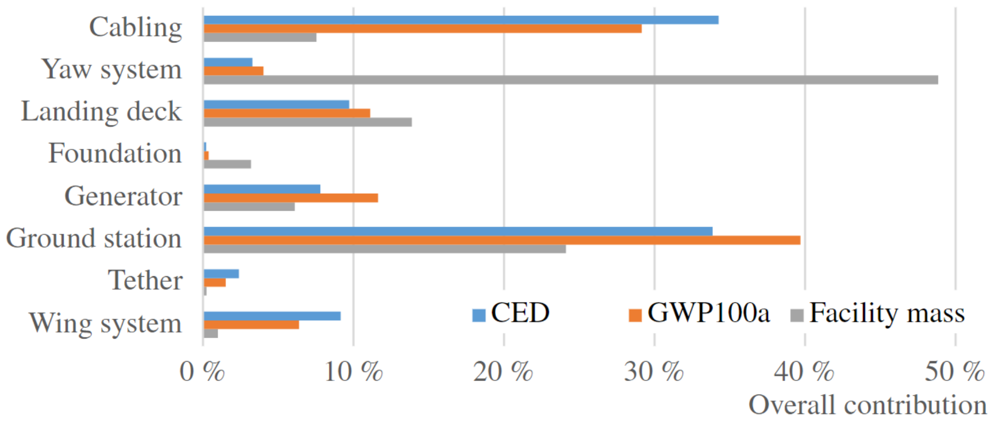

Figure 2.12: Plot showing the environmental hot-spots for the LCA done in [41]

Another study, executed the LCA of a 50 MW hypothetical AWE farm [3]. Similarly to the previous study, the comparative study was also done on an equivalently sized conventional wind turbine farm, with CED and GWP as the primary impact indicators. This study computed an overall impact of 7.8 kg CO2 eq/MWh and 127.5 MJ/MWh for the GWP and CED respectively.

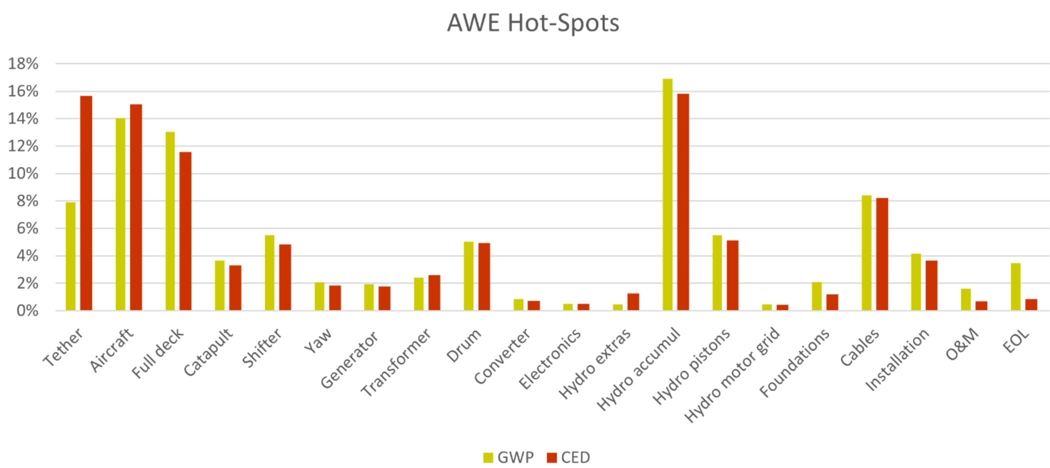

Figure 2.13: Plot showing the environmental hot-spots for the LCA done in [3]

Lastly, a comparative LCA of AWE and HAWT in Turkey was documented in [42]. The AWE system in this study was theoretical and its environmental impact results were compared to those ofa traditional HAWT system. This study also found that AWE had a relatively lower environmental impact and attributed this to low material usage; the foundation and tower components require the most mass in a HAWT system. The data for this was mostly derived from [3] using the fixed-wing system from Ampyx power. However, as the application and location for this study changed, it resulted in a GWP and CED of 8.9 kg CO2eq/MWh and 73.7 MJ/MWh respectively.

Figures 2.12 and 2.13 show the impact indicator results for [41] and [3] respectively. For Figure 2.12, the ground station and cabling have the most environmental impact. Despite having the greatest mass, the yaw system has a much lower CED and GWP compared to other components. The environmental hot-spots from [3] are the ground station (hydraulic accumulator), tether and aircraft.

All of the aforementioned LCA studies on AWE were based on fictitious AWE systems. However, the research to be done will be based on the Kitepower Falcon model that already has a prototype built. Hence, this may lead to less uncertainties and limitations in the study. Additionally, at the time of publications, it is expected that more LCA studies may be published on AWEs thus adding to the literature available.

2.3.6. Recycling in LCA

The kite material used in the soft-wing kite must be replaced every six months [18]. For a renewable energy technology, this frequency of replacement is quite high. Of the two LCA studies on AWE technologies, none of them considered recycling as a whole and neither of them were based on a soft-wing AWE system, hence this did not seem significant in this study. Therefore, one aspect that could be important to consider in the research project is to explore the integration of recycling in LCA. One of the significant hurdles for integration of recycling is how to attribute the environmental impact of a product that has several life cycles due to recycling - this problem has yet to be resolved by any ISO standards. Additionally, there are minimal attempts to standardise integration of (open-loop) recycling.

In Figure 2.14, various methods along with a qualitative assessment done by T. Ekvall et al [43] have been presented.

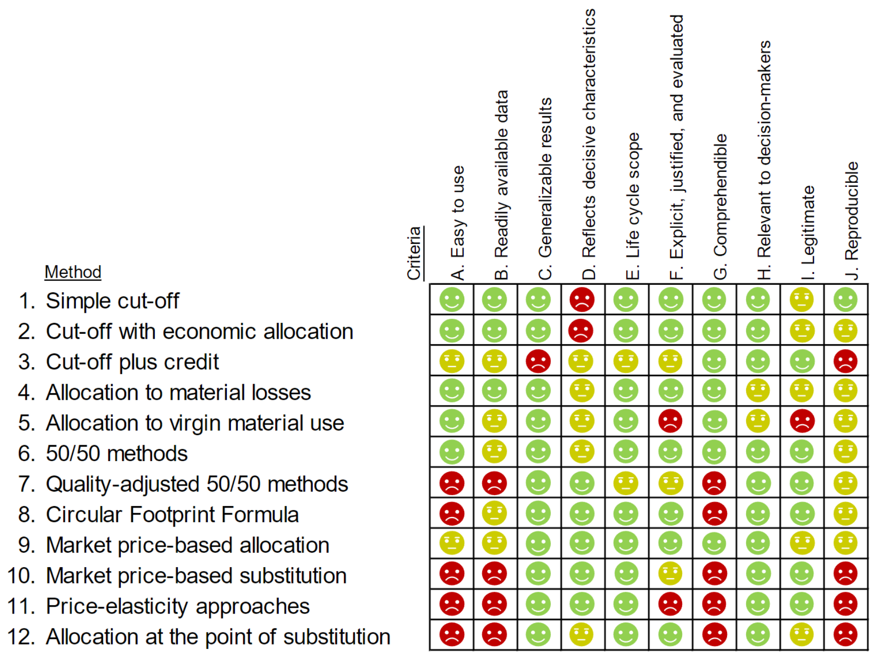

Figure 2.14: Qualitative evaluation of recycling methods as done by T. Ekvall et al [43]

From Figure 2.14, three of the main procedures that can be deduced are the 'cut-off', 'waste-valuation' and 'system expansion' approaches:

- **Simple cut-off:** The cut-off method assigns the environmental impact of a product to only what is associated during its life cycle. Hence any additional change that could be done to increase or decrease the environmental impact is 'cut-off' at the end of life of the product. For instance, if material from the kite of an AWE system is recycled and used as clothing, the kite and clothing will have their own life cycles and therefore, the environmental impact of the kite will not be connected to the impact of the clothes. This method is easy to integrate in LCA and is the most widespread use method to do so. The method is also known as the 100/0 method as 100% of the virgin material that is produced is allocated to the product that uses the virgin material itself.

- **Waste-valuation:** One of the cut-off method's caveats was that the product's first life environmental impact was not considered in the system boundary. This means that the waste that forms was not assigned any value despite waste material often being used in some industries; plastic bottles being recycled, aluminium cans being recycled, etc. The wast valuation method distributed the environmental impact between its first life as the primary product and also its second life as a recycled product [30]. The waste is valued in this way by using the recycled material mass or economic value. Therefore, the environmental burden using the waste-valuation approach is quantified by adding the environmental impact contribution from the waste that could be allocated to have 'value' to the environmental burden of the product using the cut-off method. It should be noted that one of the pitfalls of this method is that the value of the waste is determined by market prices at the time of LCA and can therefore fluctuate in reality which can bring uncertainty to the assessment. Some methods that use this procedure from Figure 2.14 include market price-based allocsation, cut-off with economic allocation, cut-off plus credit, etc.
- **System expansion:** Shen et al [30] propose a method of system expansion to overcome the problems of the two previously discussed recycling methods. While not easy to apply, this method models the actual cradle-to-grave life cycle of the product system at hand and therefore does not simply allocate environmental burden to a specific stage of a product's life cycle but rather accounts for what is being done with the material from the product in reality over the course of its lifetime. Hence, this method is exhaustive and can be difficult to apply, especially in the absence of data. Therefore, for the research that is to be done, it may not fall within the scope of the study due to time constraints. Some examples of the methods from Figure 2.14 that use this procedure are 50/50 methods and allocation at the pont of substitution.

The approach that is to be used must be relevant for the product being assessed, and the goal & scope defined for the study. Additionally, the appropriateness of the recycling method used is also dependent on the system boundaries and data available. While the cut-off and waste valuation methods are quite common and useful for business cases, the system expansion method accounts for what is actually being done to the materials being used for the product. Studies often delve more into a form of waste management when dealing with recycling rather than production of recycled products [44]. Recycling is very dependent on the material being recycled, recycling process and allocation method implemented in the LCA and/ or the system boundaries used in the study [30]. Regardless of these effects, even recycling of plastic should be beneficial in reducing the overall environmental impact of a product system. Therefore, it is worthwhile to explore the implementation of this and analysing the results of this.

2.4. LCA tools & software

With the increasing adoption of technology in all industries, life cycle assessment tools have also seen widespread interest by researchers and industry. At present time, there exist a plethora of LCA tools both commercial and opensource such as SimaPro, OpenLCA, Brightway2, Gabi to name a few. Despite all being capable of conducting the same function, that is to conduct an LCA, the methodology and results, regardless of the nature of the study being performed, that can be obtained using each software can vary. This chapter will provide a general overview of LCA software and some of the software that have been analyzed.

While initially focused on production processes, LCA software can now encompass other processes of the product's life cycle such as waste management. LCA software are useful as they support LCA practitioners to efficiently model and track the various data used to conduct the LCA. Additionally, as the system boundaries of LCA and processes involved are often not straightforward and need to be modified or applied with relevant assumptions, LCA software help practitioners to edit and keep track of large and complex models. Additionally, modelling LCA using software is also helpful for comparative studies; once models are built, they can be edited to evaluate different scenarios.

2.4.1. LCA software framework

The two main elements that form a complete LCA software are the modelling and database modules. This section will mainly focus on the modelling module. The modelling module is responsible for connecting all processes associated with the product using material and energy flows. Each process will then have its own inputs and outputs. For more complex modelling, a hierarchical approach can be adopted where the primary identified processes can be broken down to sub-processes. An example of how a hierarchical structure would look is presented in Figure 2.15. A good LCA software is capable of providing the output oriented data such as those defined by the impact categories but can also easily edit processes that could be more input-oriented such as recycling. The software should also allow users to evaluate multiple outputs along the process chain.

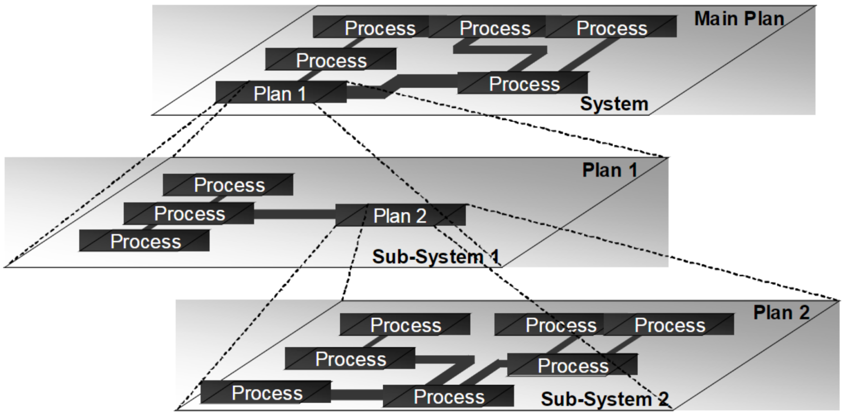

Figure 2.15: Example of hierarchical structure of processes in LCA software [45]

As is common with other softwares, a useful LCA software is one that is also transparent in its calculation structure. Ideally, rather than being a blackbox, a user would want to trace back any ambiguous results in the modelling of the LCA. This could be especially important during the interpretation phase. A good software is also one that is intuitive to use; it seems that most LCA softwares that accomplish this incorporate a graphical user interface where the user can make use of features such as drag-and-drop, visualizing the hierarchical process chains if applicable, 'go to' feature, etc. As explained in section 2.3, LCA can be useful to multiple parties involved in decision making such as architects, engineers, researchers, etc. Therefore, a good software tool also has a variety of presentation formats in its presentation toolbox. These presentation formats should also be standard as used in the relevant industry to have maximum effect. Lastly, different availabel LCA software could be generated for specific purposes. Therefore, the LCA practitioner should also pay attention to the detail required from their own research in relation to the detail provided by the LCA software of choice.

In the context of LCA calculations, an LCA is essentially a mass and energy balance. This is especially the case in an attributional LCA. Typically, LCA software use linear equation systems to model processes, however, some software also offer increased functionality in that they can use paramterization to model non-linear systems too. As stated previously, one of the activities to do during the interpretation phase is the sensitivty and uncertainty analysis. To aid the user in this, some software also offer Monte Carlo simulations and other probabalistic simultations to conduct these analyses. Some LCA software also offer cost consideration in the form Life cycle cost analysis and also other valuable resource assessments such as working time.

To summarize, when evaluating LCA software for their use in research, once can identify the following criteria:

- **Structure and display of processes:** This refers to how processes are displayed to the user and how easy it is to intuitively follow the product system being modelled in the LCA software.
- **Transparency, flexibility and user-friendliness:** As all LCA software will perform an LCA using

a mass and energy balance of some sort, user-friendliness is a significant criteria. This refers to how easy it is for the user to navigate through the user, and edit and modify as is required.

- **Database:** Some software come pre-installed with databases while others do not. This can be an important criteria, as the purchasing or construction of new databases if required would consume resources during the research or even constrain it.
- **Calculation methods and analyses:** While LCA software are sometimes seen as blackboxes [46], it is important for the LCA practitioner to understand the calculations used in the LCA software. This could be especially important in the interpretation stage of the LCA, if an error has been found in the output and needs to be traced to be resolved.
- **Service and support:** This criteria is practical and could apply to any software. During research, problems with the software itself could arise and must be addressed by a developer such that the research is not bottle-necked and can continue.

Three different LCA analysis tools will be presented in the following section, and they will be assessed according to the criteria previously defined.

2.4.2. LCA software

2.4.3. Activity browser

Activity browser is an open source software tool that acts as a graphical user interface for the open-source LCA software brightway written in Python programming language. Through the GUI, Activity browser provides easier accessibility for users to brightway's functions [47]. The software is quite flexible as it can be used both in parallel to brightway and without. The fact that the software is open-source and python based means that it could prove very useful for future research if one is to export the results and use them for other related research. The software makes use of its GUI by offering users the ability to breakdown complex processes and supply chains into their fundamental processes and materials, as well as offers a drag and drop function. The software offer a comprehensive presentation toolbox as well as uncertainty and sensitivity analysis. The software only comes with simple databases for the biosphere materials, more larger databases need to be added manually.

SimaPro

SimaPro is a well established commercial software that is suitable for function-based LCA, screening and accounting LCAs, and for cradle to gate, end of life studies and other partial LCA.The tool is intended for LCA experts, design engineer and environmental engineers. The software has a user-friendly interface that breaks down the LCA data into the different stages of LCA as mentioned in section 2.3. This makes it especially easier for newcomers to adapt to the software. The software also provides a professional presentation toolbox that will be important for the interpretation stage of LCA. As a commercial software, the Ecoinvent and IDEmat databases are included. These databases are very extensive especially when dealing with chemicals and engineering materials. More information will be provided on these databases in subsection 2.4.4. Different scenarios can also be modelled through the software. This could be important when integrating the disposal of materials and recycling. An important feature of the software is the ability to trace back results during any stage of the LCA. This is important for the calculation methods criteria[48], [49].

OpenLCA

OpenLCA is another open-source software that is established within the realm of LCA [50]. The user interface is quite friendly and extensive. The presentation toolbox offered is good, however, both Activity browser and SimaPro have been found to use better visuals to present data. As with Activity Browser, the strength of being an open-source software allows for easily shareable data and allows the continuation of research in other projects if necessary [51].

Trade-off

After conducting research and testing the functionality of all three aforementioned software over a period of time, a trade-off has been performed and is presented in Figure 2.16.

Software	Structure and display of processes	Transparency, flexibility and user-friendliness	Database	Calculation methods, uncertainty and variability analyses	Methodological properties	Service and support
SimaPro	4	3	4	4	4	4
Activity Browser	4	5	4	3	4	4
OpenLCA	3	3	3	3	4	4

Figure 2.16: Trade-off table for the evaluated LCA software

From Figure 2.16, it can be seen that Activity Browser is rated the highest and is very close in rating to SimaPro. The open-source characteristic of Activity Browser means that the calculation methods are transparent. Along with this, the user-friendliness of the GUI provided was found to be superior to the other software. Data can be easily exported via brightway to python and be used for other research. This is not possible in SimaPro. As Activity Browser is a GUI for brightway, there is sufficient support for the software. Note that the grading has been done based on both research and personal experience, and is especially tailored to the specific case of the research to be performed. In reality, the choice of software can be complex and is dependent on the scope of the research to be done and user preference.

2.4.4. LCA databases

In this section, the databases available will be explained and their relevance presented.

Ecoinvent

LCA requires large amounts of data. This is especially evident during the life cycle inventory analysis stage of the LCA. To prevent time consuming exercises of acquiring data for general processes and materials, many organizations have documented and now offer comprehensive online databases to aid LCA practitioners. Ecoinvent is a popular database, developed and managed by the Swiss Center for Life Cycle Inventories [52].

IDEmat

The Industrial Design & Engineering MATerials (IDEMAT) database is a collection of ICI data that has been developed by the Sustainable Impact Metrics Foundation (SIMF). The motivation for the databases' conception comes from the need to teach Industrial design engineering students at TU Delft [53]. This database has also been developed to improve on data that ecoinvent was found to lack. The data used is based on Ecoinvent, peer reviewed literature and measured data. It is also claimed that the data is more transparent compared to ecoinvent. With this said, Ecoinvent is still more useful with respect to data on chemicals and chemical processes while IDEMAT is more useful for product design and engineering. The strength of both databases in types of electricity within different countries is similar[32].

2.5. Research focus

Having completed the literature review, a framework for the research focus can be developed. Firstly, some of the research objectives are identified after which the the research gaps can be identified. The culmination of these two activities leads to the generation of the research questions and sub-research questions.

The research objectives for the proposed project have been established as below:

- Execute (evaluate the environmental performance), using LCA, the detailed life cycle assessment of a 100 kW soft-wing ground generation airborne wind energy system.
- Provide a foundation for stakeholders in the product and AWE industry to assess the environmental impact of the AWE system.
- Quantify the impacts, identify highly impactful components and/or processes during the life cycle of the AWE system.
- Identify areas where components and/or processes could be optimized for minimum environmental impact using the LCA model and results from the research.

- Identify components that could be made more sustainable in the AWE/ renewable energy technology industry.
- Compare the impacts of different configurations for a hybrid power plant with and without AWE.
- Expand on knowledge of sustainability within AWE sector.
- Provide an indication on the benefit of recycling AWE components.
- Provide information for policy/ decision makers in the AWE/ renewable energy sector.

From the literature study discussed, several knowledge gaps have been identified. These are:

- LCA within the realm of AWE is minimal.
- There are no known published LCA studies on soft-wing ground gen AWE systems.
- The energy intensive processes and material resource intensive components of a soft wing AWE are not documented.
- There is no set methodology for the integration of recycling in LCA for AWE.

By considering the identified knowledge gaps, the main research question has been determined as follows:

'**What is the overall environmental impact, from cradle-to-grave, of a 100 kW soft-wing ground gen AWE system?**'

The sub-questions used to help in answering the main research question are also listed as follows:

- '*What are the resource requirements of a soft-wing ground gen 100 kW system?*'
- '*What are the most energy and emission intensive components and/or processes for a soft-wing ground gen 100 kW AWE system?*'
- '*How is the environmental impact effected with varying the size of components/ processes?*'
- '*What are the environmental impacts of decommissioning and disposing of renewable energy components at the end of their life cycle for a soft-wing AWE system?*'

As mentioned earlier, a comparative study on the environmental impacts of different configurations both with and without AWE will be included in the project. Therefore, the study will also be extended by answering the following sub-questions:

- '*How does a soft-wing ground gen 100 kW system perform in the place of a diesel generator in a pre-designed off-grid hybrid power plant?*'
- '*What are the trade-offs/ benefits from an environmental impact standpoint, of different energy technologies in a hybrid power plant?*'

3

Life cycle assessment of a soft-wing airborne wind energy system

3.1. Methodology

Firstly, a methodology can be determined that will enable the successful completion of the research project. The research work to be conducted is centered around the detailed life cycle assessment of the 'Falcon' airborne wind energy system offered by Kitepower. Additionally, to investigate its application in an off-grid hybrid power plant, a comparative study will be conducted to evaluate the environmental impact of different configurations both with and without AWE. Figure 3.1 presents a flow chart to depict the framework to be used. The data to be used is acquired from literature, Kitepower and ecoinvent. The methodology for LCA follows the guidelines of ISO 14040 and ISO 14044 as explained in section 2.3. Activity browser will be used as it was determined as the preferable LCA software in section 2.4.

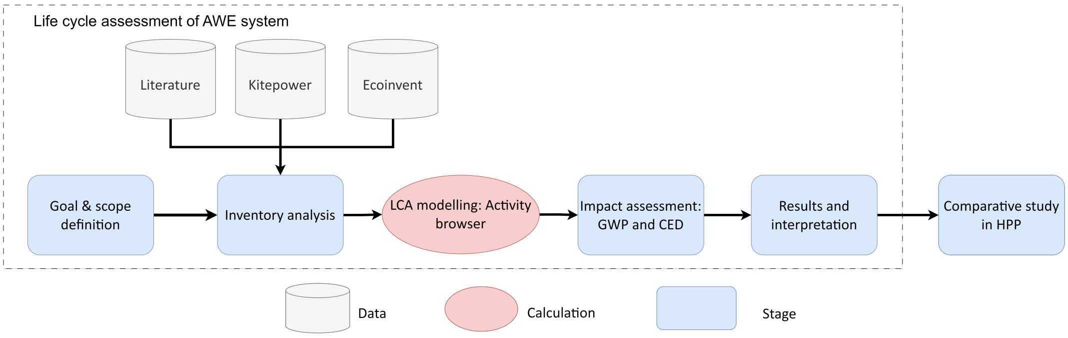

Figure 3.1: Methodology used to execute research project

3.2. Goal & scope definition

This chapter commences the first phase of the LCA study: the goal & scope definition. The goal definition, presented in subsection 3.2.1, is the starting point of any LCA that defines the work that is to be done along with its intended purpose and audiences. This is then followed by the scope definition in subsection 3.2.2, which provides detailed information on the study such as the system description, functional unit and basis of impact assessment. The goal and scope definition should encompass all the deliverables of the study and leave no room for ambiguity, especially when analysing results in the interpretation phase.

3.2.1. Goal definition

As the first stage of the LCA, the goal definition will identify the research objectives, assumptions and target audience for the study, among other things. The commissioner of the study along with its intended applications are presented within the goal definition. The method, assumptions and impact limitations are then discussed. These are followed by the identification of the database and tools used. Lastly, the target audience along with reasons for carrying out this study are provided.

Commissioner of the study and its intended applications

The research is conducted and documented as a master thesis at the TU Delft. TU Delft, Kitepower B.V. and AWEurope collaborate on this project through the NEON research program. This study used data directly obtained through Kitepower, and is conducted under the supervision of AWEurope. The study will aid kitepower in identifying their product's environmental weak points and also provide advice on the components that require most attention with regards to recycling.

For AWEurope, this study will help further knowledge on sustainability of the novel technology that is Airborne Wind Energy. Furthermore, the results of this study will be used to help achieve their deliverable of social acceptance in Work package 4 (WP4) of the International Energy Agency (IEA) wind task 48 [54]. The study will also be used to support the comparative assertion that AWE systems can replace diesel generators in off-grid HPPs.

Method, assumption and impact limitations

The method used during the study implements the four stages of LCA as specified by ISO 14044 and ISO 14040: goal & scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. Throughout the duration of this study, the LCA has been conducted in an iterative manner. The most iterations occur during the life cycle inventory analysis phase. At the start of the study, minimal data and knowledge are available for the AWE system. However, after further research has been conducted and data modelled, the goal & scope definition can be revised appropriately and the LCI updated where necessary.

The updation of data is always executed in consultation with Kitepower using both data from Kitepower and available literature. As the study is done in cooperation with Kitepower, the data gathered for each of the components of the system can be done to a reasonably high resolution. However, as some components are manufactured by third parties (for example the sub-components in the ground station), the masses of these must be estimated using available literature.

Additionally, as AWE technologies are new and innovative technologies, the impact category data for specific materials and components need to be estimated or assumed similar to what is available in the Ecoinvent database. For instance, the data for the tether (made of dyneema) was derived from literature [2] where the environmental impact data was provided by the manufacturers of the material themselves rather than the Ecoinvent database. Furthermore, data for generators, capacitors, etc. were acquired by retrieving the most similar components in terms of power rating and function from the Ecoinvent database. Therefore, there may be slight deviations in the materials used in Ecoinvent and those used in reality.

The recycling methods used are also primarily theoretical. As a new technology, many AWE systems are yet to reach their end of life and therefore, the end-of-life operations are yet to be implemented on a large-scale where the impact is significant. Where necessary, these assumptions and estimations are documented throughout the report.

As the main goal of this study is to conduct the LCA for the AWE system, the documentation and modelling for this has been presented in detail. For the comparative study involving the system's implementation in a configuration for an off-grid HPP, less detailed LCAs have been conducted and documented for the other components of the HPP. The 'streamlined' LCAs for these components are documented in chapter 4.

Various impact categories exist for quantifying the environmental impact of a system. The indicators used in this study (GWP and CED) are most commonly used to analyze the impact of renewable energy systems. Nevertheless, other impact category indicators could be important in developing a better understanding of the environmental impact of an AWE system. For instance, resource depletion could be especially important in understanding the significance of replacing components such as the kite and tether frequently over the system lifetime. Therefore, after establishing a detailed life cycle inventory within this study, a more detailed results analysis and interpretation could be conducted for a multitude of impact category indicators in the future.

Data and tools

An LCA software will be used to perform the LCA calculations. The chosen software, based on the trade-off conducted in Figure 2.16, is Activity Browser/ Brightway2. Furthermore, majority of the general data for materials and activities for the LCA study will be taken from the Ecoinvent 3 database. Materials and activities that are specific to the AWE system itself will be approximated and modelled appropriately.

Target audience and reasons for carrying out the study

The intended audience that the study may interest consists of engineers, researchers, designers, policy-makers and AWE enthusiasts. Being one of the few known LCA studies on soft-wing systems at the time, this study will help the stakeholders involved in the development of AWE (especially soft-wing ground gen AWE). The outcome of the work (especially the comparative study) could also be used to develop policy to replace or strictly regulate systems such as diesel generators that are hypothesized to have a lower environmental performance. Lastly, the components in AWE that require recycling can be identified and this information used by the intended audience as motivation to implement the relevant recycling programs.

3.2.2. Scope definition

The scope definition is derived from the goal definition and presents the focus of the LCA study in more detail. The scope definition accomplishes this by identifying the system(s) being assessed along with system boundaries, the impact categories used for the assessment, and establishing the requirements on the methodology, reporting and data quality. Firstly, the function, functional unit and reference flows are determined. The modelling framework to be used for the LCI phase is also established within the scope definition. The basis of impact to be used during the life cycle impact assessment phase and an evaluation on the quality of data that will be used have been presented in this subsection.

Function, functional unit and reference flows

The functional unit is a metric that can heavily influence the results and interpretation of the study. The functional unit should be relevant to the system being assessed, as well as use an appropriate metric to fairly compare entirely different systems that produce the same function (such is the case for the different systems in a HPP). Using the function description for the AWE system along with the aggregated information derived from the literature review, the functional unit must quantify electricity produced by any system. It is defined as follows[18]:

'Annual electricity production of 450 MWh, generated by an airborne wind energy system'

As the main goal of this study is to execute the detailed LCA of a soft-wing ground gen AWE system, only one reference flow is required for this. The reference flow is as follows:

'One soft-wing ground gen 100kW AWE system with a lifetime of 25 years'

It is important to specify the lifetime of 25 years in the reference flows as otherwise, important factors that dictate the LCI and LCIA such as component replacements will not be accounted for.

LCI modelling framework

The system is modelled from cradle-to-grave with open-loop recycling. Open-loop recycling is considered because the materials typically used in the AWE system such as the kite material and tether do not maintain their mechanical properties over their lifetime and these can't be restored by recycling. Therefore, these materials must be recycled for other functions in different system life cycles.

The study is an attributional LCA. This decision was made as an attributional LCA would be more relevant when presenting a more granular examination of the system's environmental impacts at a detailed level [55]. The cut-off approach will be used as a reference case to model the system. Where the benefit of recycling is to be quantified, this has been done using an avoided burden approach and extending the system boundaries. The methodology of this has been explicated in Figure 3.5.3.

System description

The system to be assessed for the LCA is the Kitepower 100kW Falcon model. This is a soft-wing ground-gen AWE system. With a rated power of 100 kW, the Falcon succeeds at providing energy to off-grid locations such as remote communities and islands. The market segment for small-scale off-grid energy production for the aforementioned use-cases are generally dominated by diesel generators. The falcon AWE system offers enhanced mobility, low material usage and offers robust energy production relative to other known renewable options. Figure 3.2 presents a breakdown of the main components for the AWE system along with a short explanation for each of these components.

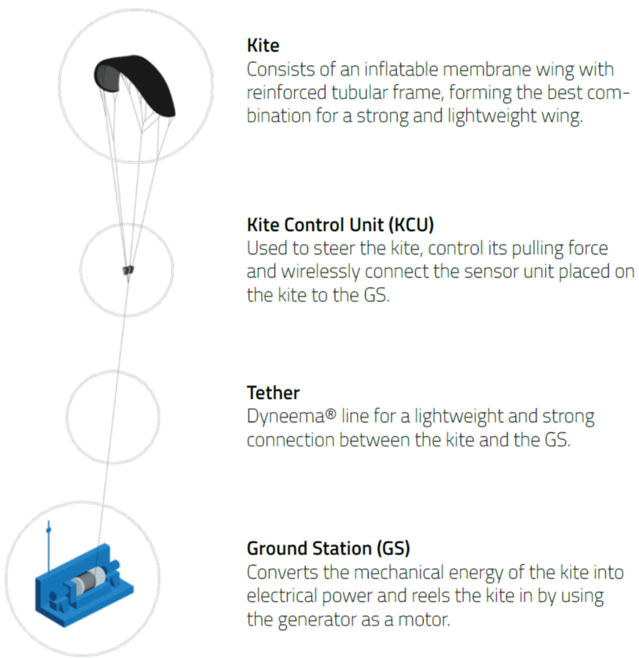

Figure 3.2: Diagram of Kitepower Falcon system with breakdown of main components [18]

As is common in soft-wing ground gen systems , the falcon cycles through periods of energy production and consumption; these are the reel-out and reel-in phases respectively. Each cycle is completed within 100 seconds. The energy difference is net-positive with a production of 130 kW for 80% of the time during reel-out and a consumption of 20 kW for the remainder of the time during the reel-in phase. More technical specifications on the system can be found in Appendix A

System boundaries and cut-off criteria

The system boundaries can be defined in multiple dimensions: temporal, geographical, between technosphere and biosphere etc. It is important to define the relevant boundaries in the scope definition as these can have significant impacts on the LCI phase and therefore the results and interpretation of the LCA study.

The system boundary of this study will be from cradle-to-grave. This means that all stages of the system's life cycle are modelled in the LCA. These different stages are elaborated on in section 3.3. where recycling has been implemented, the system is considered to use open-loop recycling. This is because the materials typically do not maintain their desired properties after use and must therefore be used in a different system's life cycle when recycled [56].

Basis of impact assessment

The systems being assessed in this study are energy producing or storing technologies. The impact categories that are most useful in conducting an assessment on such technologies are the GWP and CED. These impact category indicators are also most commonly used when quantifying the environmental impact of energy technologies.

Global warming potential (GWP)

The GWP provides a quantitative metric to measure the contribution of all greenhouse gas emissions to global warming by aggregating all GHG emissions and converting them to an equivalent measure of carbon dioxide. Having this metric defined by the unit: [kg of CO2 equivalent] provides interested stakeholders a simplified and easily interpretable metric to assess a system's impact on climate change. This impact metric can be especially important for policy-makers and industry as carbon dioxide emissions are commonly used to develop regulations and plans for energy transition [7].

Cumulative energy demand (CED)

The CED provides the total primary energy consumption during the entirety of a system's life cycle. The CED is a useful impact metric as it can also allow stakeholders to investigate the energy consumed versus the energy produced. Energy-intensive hotspots can also be easily identified using this metric and recommendations for improvement on energy efficiency can be provided.

Furthermore, the energy payback time and energy return on investment can also be computed to provide valuable insights in the energy performance and sustainability of the energy technologies. They can aid in decision-making when analysing the feasibility of projects using these technologies and configurations. Both impact category indicators can also be normalized by the functional unit. This allows for an equal comparison of the different energy producing and storing components in the HPP application.

Evaluation on quality of data

As is typical in LCAs on technologies with a lifespan greater than 10 years, the net present values are used for the LCA modelling with an applied discount rate. These values can never accurately reflect reality and are only an estimate. This is because values used in the datasets for different materials are subject to change in the future.

The electricity production for all components considered within this study are assumed to perform the same over all years of the operational lifetime. In reality, this varies for both solar and wind energy technologies. Nevertheless, it is difficult and complex to predict accurate wind and solar data. Furthermore, the focus of the study is the environmental impacts of the energy systems and the energy systems are compared while consistently using this assumption. Therefore this assumption shouldn't impact the results of this study.

3.3. Life cycle inventory analysis

The life cycle inventory analysis phase will detail the data collection and system modelling of the LCA study. The outcome of the LCI will be used in the LCIA stage to generate data for the interpretation stage of the LCA. The boundaries for this phase are dictated by the scope definition. This phase typically requires the most effort out of any because all materials and processes are identified and analysed over the life cycle of the product. Majority of the details on the constituents of the inventories have been acquired through correspondence with Kitepower. However, in some cases, it is challenging to obtain data on the composition of relatively novel components; the methodology used to model these uncertain cases has been documented in this chapter where necessary [57].

4 separate stages have been included in this study to encompass the entire life cycle of the system. These are:

- **Materials and manufacturing:** This stage includes the materials and manufacturing activities leading to the generation of the components making up the final product. Hence, the starting point of this stage would be extraction of raw materials to production of sub-components and final assembly of sub-components to components. This has been documented in subsection 3.3.1.
- **Transport and installation:** Installation refers to any energy intensive processes that occur during this process as well as land use. For instance, transport of personnel to complete the set-up of the system should also be included in this. The transport can vary depending on the application that the system is being used. In this research, the specific case is off-grid energy generation. The contents of this can be found in subsection 3.3.2.

- **Operation and Maintenance:** Operation and maintenance include activities during the use phase of the system. This could vary from replacement of kite material and tether, to maintenance checks. These activities have been presented in subsection 3.3.3.
- **End of Life and recycling:** The disposal of the system along with any waste-treatment activities are to be included in the modelling of this stage. This has been discussed in subsection 3.3.4.

Furthermore, the AWE system is broken down into four main components: the kite, tether, KCU and ground station. Lastly, the modelling approach of the system using software, and the data gathered within this chapter can be found in subsection 3.3.5.

3.3.1. Materials and manufacturing

The materials and manufacturing stage should encompass all stages that lead up to the production of the final product. In this case, this would be the Kitepower 100 kW Falcon AWE system.

Kite

The kite is a 60 [m2] hybrid structure made using Dacron as the inflatable kite material, and glass fiber for the skeleton that maintains the structure and shape of the kite. The kite, along with other scaled versions of itself, has been presented in Figure 3.3. Dacron is the brand name of a polyester (polyethylene terephthalate (PET) fabric made by DuPont [58]. Dacron is used due to its high strength, resistance to abrasion and durability. It has a wide variety of uses ranging from the textile to even the medical industry. The wide range of uses could be significant for the waste-treatment of kite material as it could be upcycled to produce clothes, for example.

An important note regarding this is that the kite material is not re-used in the kite itself once it is replaced. This is because the kite material does not maintain the desired properties for its function in an AWE system after its use-cycle [57] . Therefore, any form of recycling for this material must be done in open-loop recycling rather than closed-loop. This possibility will be further analyzed in subsection 2.1.4. The exact environmental details for Dacron are not available within the Ecoinvent database, therefore a proxy must be used to overcome this. Given that Dacron is a polyester fibre, the Ecoinvent activity ‘polyester fibre production, finished’ has been used to model the material. As a proxy, the actual impact of Dacron may vary depending on the discrepancies in production methods between the two materials.

Figure 3.3: The kite component scaled to different sizes [57]

The kite textile material also contains Polyethylene(PE) which is used as packaging film for the kite material to keep it intact. In consultation with Kitepower, it was discussed that the kite textile material arrives and is cut to shape using a machine. This means that there will be material loss before the final kite shape is produced. Therefore, to account for this, a ‘loss factor’ to represent the conversion rate of kite material to final kite shape must be implemented in the LCA modelling. A loss factor of 5% is used as this was estimated by Kitepower. Lastly, an area of improvement that has been identified in discussion with Kitepower is that the kite material used is over-designed [57]. Therefore, if the kite material is found to be a hotspot for the environmental impact, then this material could be made thinner while still meeting the design requirements.

The kite’s skeleton is made from glass-fibre. The skeleton of a soft-wing AWE system primarily serves two functions: it must maintain the shape of the kite to uphold its aerodynamic performance during reel-out phase so that the maximum energy can be extracted from the wind. It must also be load-bearing and capable of withstanding all loads that are encountered during operation [5]. In simple terms, the lightweight characteristic of glass-fiber means that it will perform sufficiently in the discipline of aerodynamics. The flexibility, durability and high strength-to-weight ratio of glass fiber are also very beneficial from a structural and load-bearing point of view.

The glass fiber skeleton primarily consists of rod shapes. The glass-fiber must go through two processes to arrive at this desired shape: injection moulding and resin coating. Injection moulding is a process where the glass-fiber pellets are melted and then injected into a mould (in this case, a rod-shaped mould). Resin coating is then applied to the glass-fibre rods to form a fibre-reinforced polymer. This process improves the strength and durability of the material. A material breakdown of the kite is presented with their respective mass percentages in Table 3.1

Table 3.1: Material breakdown used to model the kite

Constituent	Material	Mass %
Kite material	Dacron	70.99%
Kite material	PE	17.75%
Exoskeleton	Glassfiber	11.27%
Total mass		100.00%

Tether

The tether is used to connect the kite, KCU and ground station. It is an essential component of the system as it is responsible for generating torque during reel-out. It is made of an ultra-high-molecularweight polyethylene (UHMWPE) called Dyneema®. Dyneema is an innovative polymer that has characteristics of high strength and low density. It is also reported to have 90% lower carbon footprint than generic HMPE fiber [59]. These are requirements for the material that makes up the tether as it will encounter many loads, especially tensile, that occur during reel-in and reel-out phase. The material must also be light as it is connected to the KCU and kite, and must not impact aerodynamic performance of the kite as this will negatively impact its energy generation. As the tether can be greater than 100m long, drag is produced even with a small amount of rope thickness. A single tether is used in the Falcon to minimize anything that produces drag. Other companies such as Enerkite use multiple tethers resulting in more aerodynamic drag as the tethers are hundreds of meters long.

Multiple strands of Dyneema are used to make the tether. The Falcon specifically uses SK78 Dyneema which consists of 12 strands wound together. The presence of multiple strands can result in high friction forces between each other during operation. Therefore, shearing of tether strands can result in damage and high replacement frequency. This problem can be partly overcome by covering the strands in a coating that reduces the friction forces between the strands of the tether, The coating for the strands is typically between 10% to 15% by weight of the rope material.

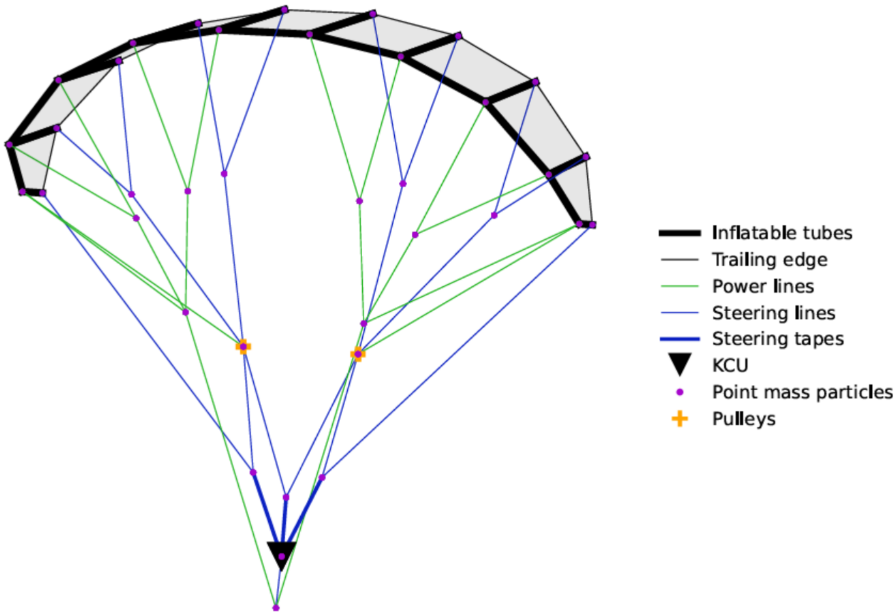

Figure 3.4: Kite schematic [60]

The tether is also modelled to include the bridal system of the kite. The bridal system refers to the multiple thinner tethers that connect the kite to the KCU. The bridal system maintains the structure of the kite during operation and also enables the KCU to deform and effectively steer the kite as required.The front bridal system carries about 70% of the aerodynamic forces. A simple schematic vizualising how these tethers can be attached from the KCU to the kite, to form the bridal system is depicted in Figure 3.4.

Forces can be controlled based on the reeling speed cause by the drum in the ground station. The two main phases of a ground-gen pumping AWE system are the traction phase and retraction phase. In the traction phase, the kite is allowed to fly due to the wind and reels the tether out. Eventually, the kite will fly in figure eight shapes causing the generator in the ground station to produce electricity. A plot showing this trajectory can be found in Figure 3.5 [61].

Once the tether has been completely reeled out, the tether and kite must be reeled back in a retraction phase. The retraction phase consumes electricity. The electricity is consumed from the ultracapacitor in the ground station that is used as an energy storage component. A reel-out and reel-in phase is considered one pumping cycle. The AWE system will produce energy by completing multiple cycles during operation.

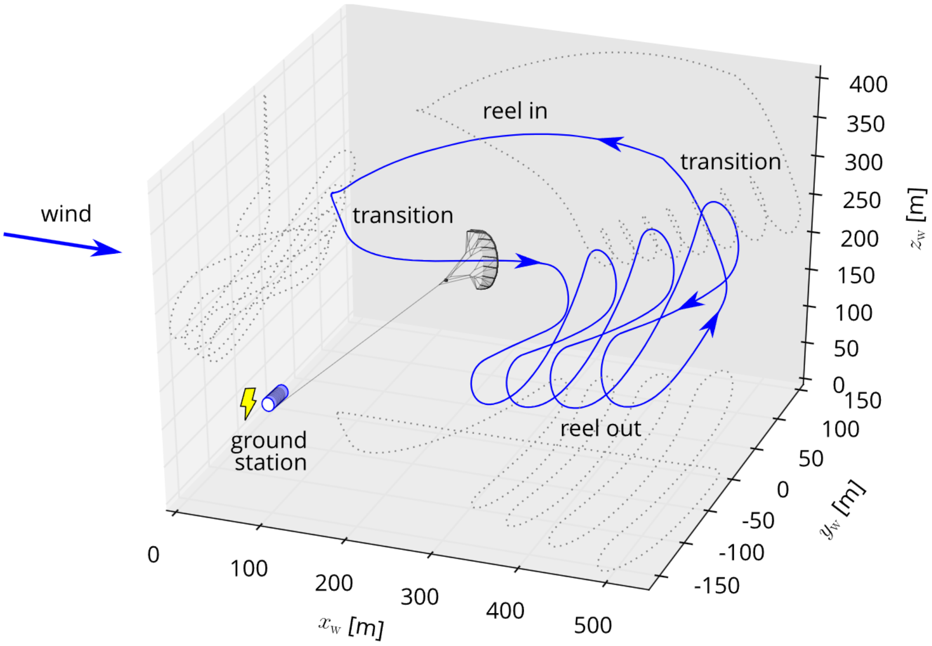

Figure 3.5: Plot showing the trajectory of the AWE system [61]

The Kitepower Falcon system specifically has a cycle duration of 100 seconds. 130 kW of power are produced during the reel-out phase which lasts for 80 seconds. 20 kW of power are consumed during the reel-in phase which lasts for the remaining 20 seconds of the cycle. A plot of this power cycle where the production phase and recovery phase correspond to the reel-out and reel-in phase respectively is depicted in Figure 3.6 [62]. There is a limit to wind speed for power generation because maximum capacity is reached at a certain altitude and it becomes more costly to reel in the kite because more power is required to be consumed. A computational model finds that this limit is reached at 6 m/s wind speed and wind turbines produce much less power at this point [13].

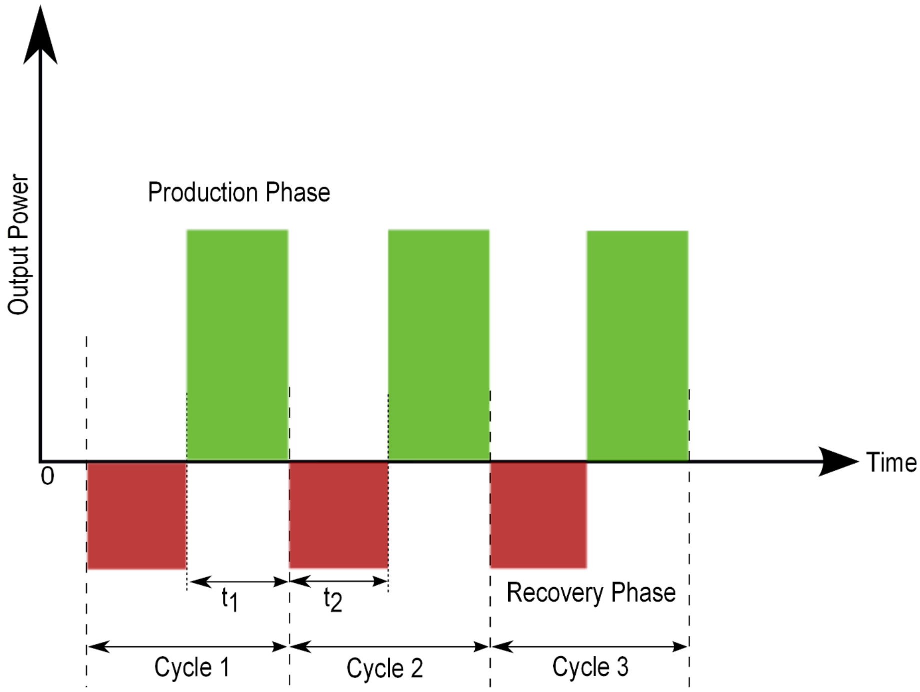

Figure 3.6: Plot of the power cycle for an AWE system [62]

Table 3.2 presents the material breakdown used to model the tether component of the AWE system.

Table 3.2: Material breakdown used to model the tether

Constituent	Material	Mass %
Rope	SK78-Dyneema	88.00%
Rope coating	Polymer coating	12.00%
Total mass		100.00%

Kite Control Unit (KCU)

The Kite Control Unit is a unique and sophisticated component capable of steering the kite and maintaining steady flight during the power generation phase. To do this, it makes use of a controller that can execute the changes required to keep the kite in steady flight or perform manoeuvres [13]. The controller is able to do this through a motor and system of pulleys that pull on the kite and steer it in the desired directions. The motor is powered by a lithium-ion battery in the KCU.

It also contains the control system which comprises of sensors, electronics, circuit boards and other equipment that can measure the data required to provide feedback to the controller on what actions to execute next. The KCU is placed as close to the kite as possible to minimize drag.

At the end of the reel-in phase, the kite system lands on the ground. As the KCU comprises of delicate electronic systems, it is protected from damage by a layer of polyvinyl chloride (PVC) foam padding about three times the size of the KCU itself. PVC foam is not available in the Ecoinvent database. Therefore, polyurethane foam is used as a proxy to model the protective padding. In addition to the protective padding, a cover for the KCU itself is also modelled as polyurethane foam. This polyurethane foam was chosen as a proxy because it is used in similar applications as protective padding and coverings.

As visualized in Figure 3.4, tape guides are attached close to the KCU. The components of the KCU can vary the lengths of these tapes to steer the kite. Depowering tapes are also attached close to the KCU, the length of these tapes is varied to change the angle-of-attack as desired during kite operation[63]. Tapes are utilized as opposed to the tether lines because of their superior reeling behaviour and reduction in layer buildup on the drums that wind the tape within the KCU [64]. The tape is modelled as stainless steel. This information was obtained through discussion with Kitepower [57].

A mounting structure is used to mount all sub-components within the KCU. This is solely modelled using processed aluminium as this is the primary material that the structure consists of [18]. This assumption shouldn't cause too much deviation as the mass contribution of the structure is relatively small. Therefore, it is expected that a high-resolution bill of materials for this structure wouldn't result in a high variation of the results. The drive train of the KCU consists of pulleys. These are powered by motors that generate a torque force to steer the kite. The Ecoinvent database does not include a pulley. Therefore, similarly to the mounting structure, processed steel is used to model the pulleys.

The KCU is composed of multiple additional subsystems that cohesively work together to perform its main function. Figure 3.7 displays these multiple subsystems in a Computer Aided Drawing (CAD) model [65].

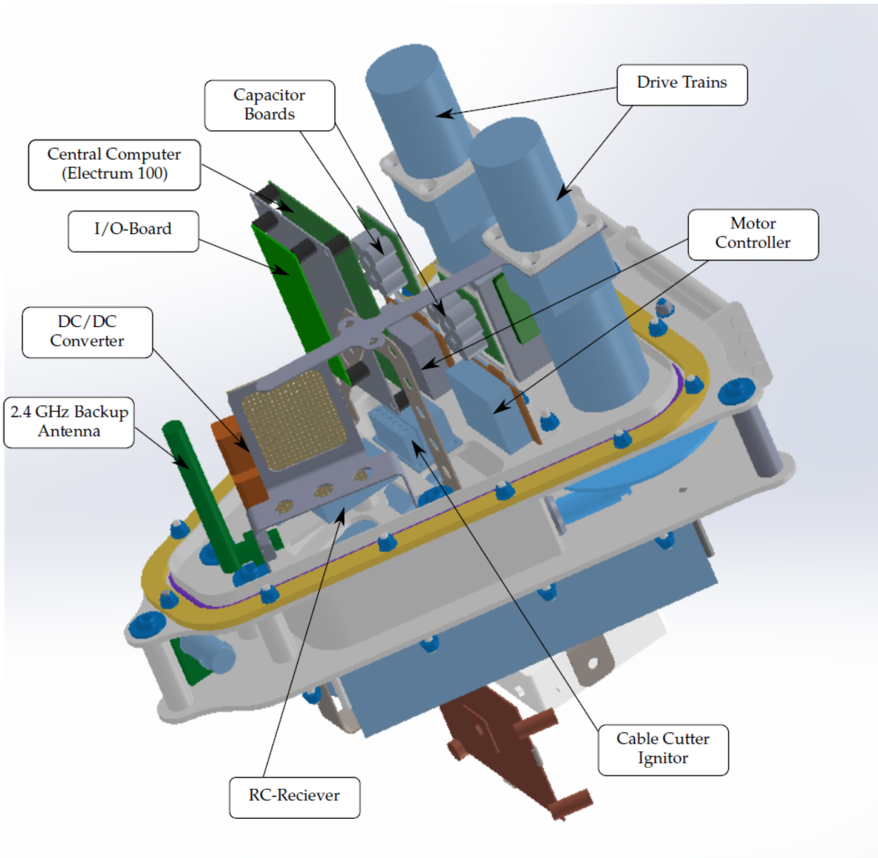

Figure 3.7: A CAD model showing different components within the KCU [65]

Onboard turbine

The KCU uses energy to control and navigate the kite during operation. In addition to lithium-ion batteries, a small wind turbine is used onboard the KCU to supply it electricity. Despite being a novel method to provide power to the KCU, the turbine itself functions as any other turbine would. The blades of the turbine convert the kinetic energy of oncoming wind to torque due to the tangential of the resultant force generated by the pressure distribution over the blade and the length of the blade itself.

The torque rotates a shaft that produces power using a generator. The rotation of the shaft within a magnetic field maintained by the generator results in an electric current running through the coils of the generator. A brush-less DC (BLDC) machine is used due to its inexpensiveness, durability and efficiency. While complex, the component only weighs 8 % of the total mass of the KCU. The turbine blades and structure are made using polymer powder 3D printing. The generator of the turbine is primarily made of steel. These are modelled accordingly by using nylon 6 and hot rolled, low-alloyed steel. Nylon 6 is a common polymer used in additive manufacturing for different powder printing techniques.

Lastly, the KCU contains a small percentage of electronics and circuit boards. These are modelled using the 'electronics, unspecified' database from Ecoinvent. A final breakdown of the components and sub-components of the KCU system has been presented in Table 3.3.

Table 3.3: Material breakdown used to model the KCU

Constituent	**Material**	**Mass %**
Casing/ protection	PVC foam	7%
Tape guide	Steel	23%
Mounting structure	Aluminium	7%
Cover, foam	PE foam	33%
Pulleys and drivetrain	Steel	15%
Batteries	Lithium-ion battery cells	5%
Electronic boards, etc.	Electronics	1%
Airborne wind turbine	Plastic & steel	8%
Total mass		100%

Ground Station

The ground station is the component that functions as both the mechanical-electricity converting system and the foundation of the system. It contains a 160 kW generator, coupled to a winch, to generate electricity during the reel-out phase. A gearbox is used between the winch and generator for tuning the speed of the winch to match the ideal operating conditions of the generator. An ultracapacitor is used to store energy when required and to provide energy to the system during the reel-in phase. Cabling and other components contributing to balance of system are also included within this component. The ground station is similar to the drive-train of a wind turbine. In the case of the Falcon, the Launch and Landing Apparatus is not treated as a separate component as it is already integrated into the ground station structure. The components of the ground station are housed within a large standardized shipping container.

The ground station also consists of other sub-components that help it perform its function. The drum is a sub-component of the ground station over which the tether wraps around and is unwound from during operation. The exact material composition is challenging to obtain, however, the mass of the drum is obtained through consultation with Kitepower. As this sub-component makes up a significant mass percentage of the ground station, a viable material breakdown must be identified and modelled. This breakdown is adapted from a previous LCA report on AWE [3]. The material breakdown with mass as a percentage of the total weight of the drum is presented in Table 3.4.

Table 3.4: Material breakdown used to model the drum of the ground station [3]

Constituent	Material	Mass %
Shell	CFRP	2.11%
	Scraps	2.11%
	Consumables	2.11%
Bearings	High strength steel	0.35%
Large ring	High strength steel	2.81%
Axles	High strength steel	1.54%
Structure	Section	42.11%
Paint	Paint	0.05%
Total mass		100.00%

A brake chopper is also included in the LCA modelling. This apparatus is crucial in the functioning of the ground station as it enables the ground station to switch between reel-in (energy generation) and reel-out (energy consumption).

The frame and housing of the ground station act as the primary structural elements of the system. These elements also act as the foundation of the ground station. Hence, land modification and a separate foundation are not required to install the AWE system. These two elements majorly contribute to the mass of the station. The modelling of the housing is based off a shipping container. The housing most closely represents this dataset. The frame of the ground station is modelled using high-strength chromium steel.

Energy storage device

An ultracapacitor is also included in the ground station to allow for short-term energy storage. This ultracapacitor has a capacity of 375 Wh. During the reel-in phase, the generator functions as a motor and drives the drum to wind the tether, hence reeling in the kite at the end of its operation cycle. The energy stored by the ultracapacitor is consumed during this phase.

Alternatively, batteries are also commonly used for energy storage within the ground station. Therefore, the option to use a battery rather than an ultracapacitor will also be explored in section 3.5. This is a point of interest as both devices use different materials and also require different masses to perform a similar function. For the option where the battery is used, a lithium ion battery bank of 120 kWh is used.

Lastly, power converters must be accounted for within the electrical drivetrain of the ground station. A rectifier with a rating of twice the rated power is used before the ultracapacitor to convert alternating current to direct current. This is because the ultracapacitor is a DC device. After this, the current is converted from alternating current to direct current using an inverter sized equivalently to the 100 kW rated power of the system [66]. A flow diagram of the ground station's drivetrain is presented in Figure 3.8.

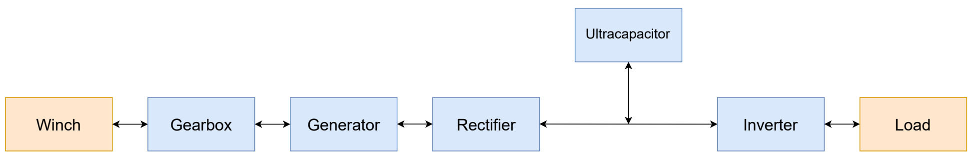

Figure 3.8: Block diagram showing the electrical drivetrain of the ground station using an ultracapacitor [66]

A table with all modelled constituents and their mass as a percentage of the total mass of the ground station is presented in Table 3.5

Table 3.5: Material breakdown used to model the ground station

Constituent	Material	Mass %
Drum	Steel	7.62%
Inverter and cabling	Electronics	2.69%
Brake chopper	Electronics	1.43%
Housing	Steel	18.83%
Frame	Steel	53.05%
Generator+gearbox	200 kW generator	15.02%
Energy storage device	Ultracapacitor	1.35%
Total mass		100.00%

3.3.2. Transport & installation

The installation and logistics phase consists of all the activities associated with transporting components to the desired site and installing them. The data for the sources for the materials used in the AWE system have been provided by Kitepower and their distances estimated using the Searates website [67]. An overview of this data has been presented below in Table 3.6.

Table 3.6: Overview of material and component transport data

Component	Mode(s) of transport	From	To	Distance (km)
	Kite			
Kite-Dacron	Ship	India	Rotterdam, NL	12183
	Lorry	Rotterdam, NL	Delft, NL	15
Kite-Glassfibre	Lorry	Germany	Delft, NL	408
Kite-PE	Ship	India	Rotterdam, NL	12183
	Lorry	Rotterdam, NL	Delft, NL	15
	Tether			
Tether	lorry	EU	Delft, NL	130
	train			240
	ship			270
	KCU			
KCU	Lorry	Germany	Delft, NL	408
	Ground station			
Remainder of sub-components	lorry	EU	Delft, NL	130
	train			240
	ship			270
Housing	Lorry	Netherlands	Delft, NL	59
Generator	Lorry	Italy	Delft, NL	1346

For this study, all AWE components can be transported from Delft to Marseille by lorry. Assuming that the lorry's are efficient and conform to the EURO6 emission standard for vehicles, this transportation of components can be modelled using the 'transport, freight, lorry >32 metric ton, EURO6 for Europe (RER) dataset from Ecoinvent. The transport of replacements will be modelled similarly in subsection 3.3.3.

Installation of the AWE system is relatively simple and doesn't require extensive modelling as it isn't expected to significantly contribute to the overall environmental impact of the system. The installation activities are modelled using the ’electricity, low voltage’ dataset for Europe. The time taken for installation is provided by Kitepower. It is assumed that the electricity consumed during installation is equivalent to a crane with a load capacity of 15 t.

The land does not need to be modified to build a foundation for the AWE system, the kite can be launched using the launch and landing apparatus integrated in the ground station. Therefore, land is only required to be sectioned out so that the kite can operate within its operational radius and land safely. The land use of a single system is 10000 m^2 as provided by Kitepower. This area only accounts for the restricted zone. The operational zone that will include the area for the kite’s flight zone, launching and landing zone are greater than the previously mentioned value. However, the land that the kite uses for its flight zone can also be used for other activities while the kite is deployed. Therefore, this larger area is not modelled for land use specifically by the AWE system. The operational zones of the Falcon system are presented in Figure 3.9 along with a legend indicating the different operational zones.

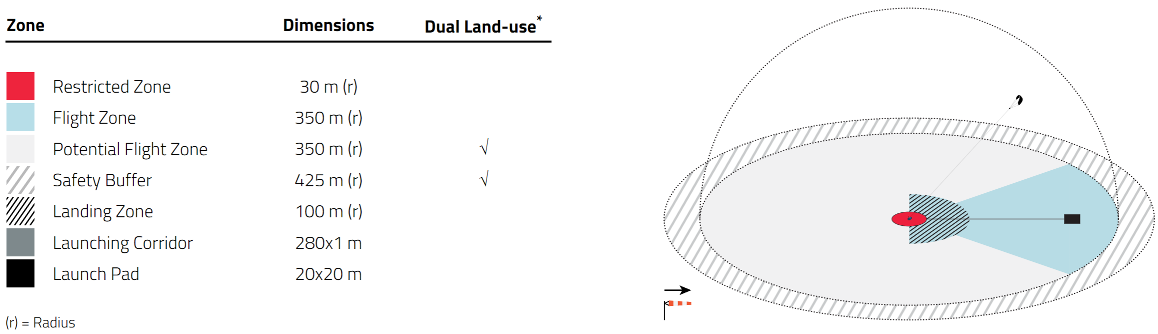

Figure 3.9: Operational zones of the Falcon system with legend [18]
Land can be used for alternative activities while Kitepower is deployed. During operation untrained people are not allowed in the flight zone.

Lastly, as the application for which the LCA is conducted is for an off-grid setting. There is no cabling required for a connection to the grid. The connection to be modelled is only for the load that the system provides power to in the applicable scenario. In the comparative study for the implementation of the AWE system in an off-grid HPP, the system boundary will be extended to include a balance of plant system that accounts for cabling to connect and manage all the components. This information can be found in chapter 5.

3.3.3. Operation and maintenance

The operation and maintenance phase consists of all activities and processes required during the use phase of the system. The use phase is in line with the reference flow previously defined:

’One soft-wing ground gen 100kW AWE system with a lifetime of 25 years’.

The location for AWE systems can have significant impact on performance [68]. As the windspeed distribution at the site impacts the energy produced by the system and therefore the functional unit set for this LCA study, it is assumed that the wind speed distribution is the same for each year of the 25 years of operation. The system requires maintenance over the 25 year period. This maintenance will be carried out by two people at a frequency of one day every quarter. The crew responsible for this maintenance is assumed to be available within the country of the site at a distance of 100 km. Transport of the crew to the site is via automobile transport.

In terms of LCA modelling, the operation and maintenance phase primarily consists of the replacement of components as they reach the end of their lifetime. A breakdown of the replacements that are applied over the 25 year service time are presented in Table 3.7. The transport of the components to the site is modelled with the same modelling as the first components before installation and logistics. The mode of transport for different materials is dependent on the mass of the materials being replaced. It is assumed that the AWE system does not comprise of any critical components of which failure could result in a replacement of the entire system.

Consumables such as lubricants and coolants could also be relevant to the environmental impact of the system. These have been modelled using lubricating oil and ethylene glycol. The sizing of these fluids has been determined from studies for wind turbines of comparable rated power. Other consumables have not been included within this study as they are not expected to account for greater than 5% of the overall environmental impact. Hence, these have been cut-off from the modelling due to lack of data and influence on the results.

Table 3.7: Breakdown of the replacements that are implemented in the LCA modelling for operation & maintenance over the operational period of 25 years

Component	Sub-component	Number of replacements
Kite	Kite material-textile	22
	Kite material-packaging film	22
	Exoskeleton	4
Tether	Rope	11
	Rope coating	11
KCU	Casing/ protection	4
	Tape guide	4
	Mounting structure	4
	Cover, foam	4
	Pulleys	4
	Batteries	4
	Electronic boards, etc.	4

Kite

The kite is under constant aerodynamic forces during operation. Additionally, it is also pulled and steered by the KCU to help it maintain power generating flight. The kite lands on the ground after each cycle; this can fatigue the properties of the kite material and exoskeleton due to the high frequencies at which pumping cycles occur. As the kite experiences fatigue, its properties may no longer be suited for safe and constant power generating flight and are required to be replaced.

For the Falcon system, the entire kite material or exoskeleton must be replaced when the material reaches the end of its lifetime. The replacement of the kite materials is more frequent relative to the glass fiber exoskeleton. As a soft-wing kite is less complex in design than a fixed-wing kite, failure of the components of the kite will only result in replacement of that specific component and not the entire kite [13].

Tether

The tether also experiences tensile forces during operation. This results in fatigue and eventually could lead to failure of the tether itself. Therefore, the tether must be replaced before failure occurs. The length of the tether means that different forces occur at different intensities at different locations on the tether. Some locations will experience more wear than other and will thus require replacement more frequently. Kitepower does not need to replace the entire tether when one part is at the end of its lifetime. The tether can be sectioned by length and replaced. Through consultation with Kitepower, this results in the frequency of replacement material reducing to a third of the mass than if the entire tether was replaced.

KCU

All the KCU's constituents, as provided in Table 3.3 are modelled with the same lifetime. This information was provided by Kitepower. This means that the entire KCU is replaced once it reaches the end of its life cycle. The replacements are modelled the same way as they were modelled in the materials and manufacturing phase.

Ground station

The ground station does not have any significant replacements as the primary sub-components such as the generator, housing and ultracapacitor have long lifetimes. Thus, maintenance activities such as oil changes, coolant replacement, etc are modelled for this component. This is modelled by implementing an energy consumption to represent the maintenance activities. It is important to note that the materials or consumables required during the maintenance activities are assumed to be negligible. This assumption was used due to lack of information. Therefore, deviations of the results from reality could occur if replacement materials account for a significant mass percentage of the ground station.

3.3.4. End of Life and waste treatment

The contribution of recycling to the environmental impact of the AWE system is an important aspect within this study. This is especially the case for soft-wing AWE because of the frequent replacement of the kite, among the other components. The cut-off method is most commonly used in LCA and relatively easy to implement. The potential benefits of recycling will be quantified separately using a substitution approach. This method will 'cut-off' the impacts at end of life waste treatment and credit the system by subtracting the impact of the raw materials that are avoided for production.

Figure 3.10 and Figure 3.11 present the impacts accounted for in the LCA of the AWE system using the cut-off and substitution approach respectively. Another end-of-life should be used to quanifty the benefit of recycling because the cut-off method does not include the benefit of recycling in the assessment of the first system but rather the life cycle of the second system. Thus, all impacts of treatments for waste up to the start of the life cycle of the second product system would be allocated to the AWE system. Nevertheless, The cut-off method is useful and applicable to various LCA studies as it promotes recycling of materials due to the lower environmental impact of the second product system [43].

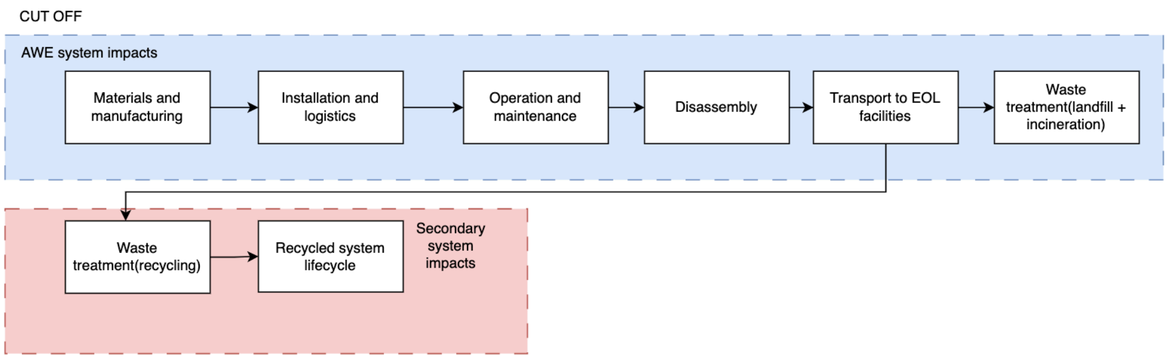

Figure 3.10: Flow diagram showing the impacts accounted for in the LCA of an AWE and secondary recycled product using the cut-off approach.

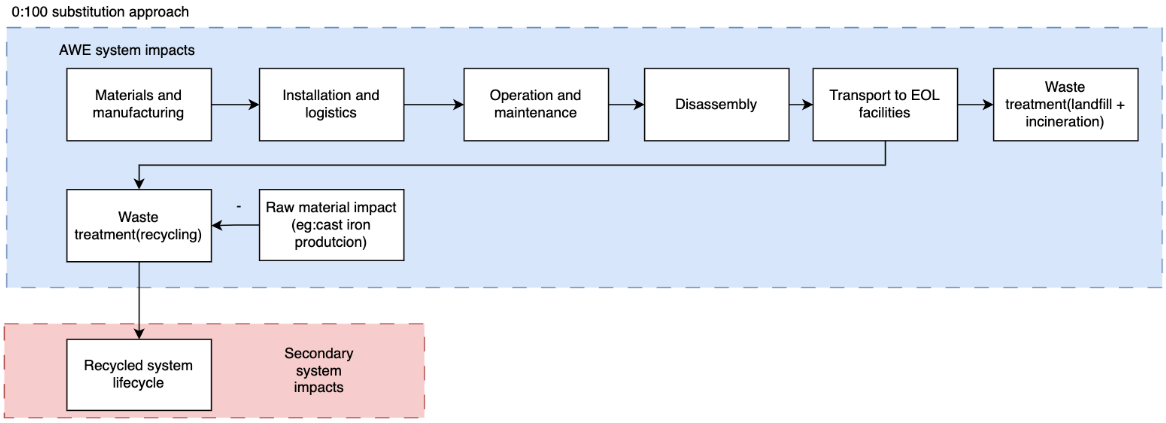

Figure 3.11: Flow diagram showing the impacts accounted for in the LCA of an AWE and secondary recycled product using the substitution approach.

Disassembly and transport

At the EOL, the system must first be disassembled, and the different materials sorted. Firstly, it is assumed that the entire AWE system is disassembled on-site. The energy consumed to perform this activity is modelled using the same method used for the assembly during installation in subsection 3.3.2. The disassembled components must then be transported to their relevant wast treatment facility. It is assumed that all waste treatment facilities are within a maximum radius of 200 km from the site. Hence, transport to waste treatment is conservatively modelled using a lorry. The transport of waste material also accounts for the waste material accumulated from replacements that occur during the operation and maintenance phase. An overview of the activities used to model the disassembly and transport at EOL has been presented in Table 3.8

Table 3.8: Overview of disassembly and transport activities modelled.

Process	Value	Unit	Ecoinvent activity used
Disassembly	550	kWh	market for electricity, low voltage
Transport to EOL facility	3552	tkm	market for transport, freight, lorry > 32 metric ton, EURO6

Waste treatment

Waste treatment is divided into three different categories:

- **Recycling:** involves collection of materials and recycling them. This is represented by a recycling rate.
- **Incineration:** incineration refers to the process of collecting and burning material to get rid of waste. In some cases, incineration is used with heat recovery. Heat recovery is beneficial for the environment as the heat for recovery plants does not need to be produced by other energy sources, thereby avoiding additional emissions and energy consumption.
- **Landfill:** modelling includes all impacts associated with the terminal disposal of waste materials. This includes the impact of emissions and lecheate production due to waste disposal.

Firstly, the waste treatment rates must be identified to find the share of materials attributed to each waste treatment facility. Table 3.9 presents the rates used for the materials that compose the AWE system. Note that in some cases, material breakdowns had to be generalized to one specific material. This is due to lack of information and simplification of modelling.

Table 3.9: Overview of waste treatment rates used in the modelling for the most prominent materials

Material	Recycling	Incineration	Landfill
Steel	0.9	0	0.1
Copper	0.9	0	0.1
PE	0.905	0	0.095
Fiber-glass	0	0.6	0.4
Capacitors	0	1	0
Aluminium	0.76	0	0.24
Li-ion Battery	0.48	0	0.52
Electronics	0.42	0.08	0.5
Plastic	0.12	0.38	0.44

Upon inspection of Table 3.9, the materials can be categorized into the following:

- Metals
- Plastics
- Fibre reinforced polymers (FRPs)
- Electronics
- Batteries

Metals

Metals are applied in many industries. The resources required to produce virgin metals is very high. The use phases of these materials can be on both extremes. However as virgin materials get more scarce, and energy and cost intensive, the benefit of recycling metals is more apparent. The high use of metals means that there is a correlation to the economic growth of the EU. This demand also means that scrap metals can be viewed as a commodity in the global market [69].

Theoretically, metals can be infinitely recycled. The loss of 10% shown in Table 3.9 accounts for the loss of materials during collection. There are multiple treatments that can be used to recycle metals. The recycling of metals is beneficial both environmentally and economically. This is because it is less energy intensive to recycle metals than to produce them. It is also less resource intensive and doesn't contribute to material ending up in landfill and polluting the Earth.

The process of recycling metals typically consists of collection and sorting. Metals are sorted into recyclable and non-recyclable categories. They can also be divided into ferrous and non-ferrous categories. Once sorted, the recyclable materials are shredded, purified and melted. This results in a pure molten cast metal that is ready to be transported and used again in industry.

Plastics

Similarly to metals, plastics must also be collected and sorted before processing. The collected plastics then undergo mechanical or chemical processes to convert them into materials that can be re-used in other plastic products. For example, plastics can be melted to remove impurities and then solidified to plastic pellets. These pellets can be sold to companies in various industries for different functions. Increasing the collection rate of plastics is essential to increasing the used plastic feedstock for recycling, thus reducing virgin plastic materials entering the market [70].

Fibre reinforced polymers (FRPs)

Recycling of FRP materials are generally uncommon to practice. This is indicated in Table 3.9. Nevertheless, given their use in multiple industries, technologies are present and are also being developed to aid in the recycling of these materials. While expensive and limited, mechanical and chemical recycling are possible [71]. Therefore, while recycling of FRPs are not accounted in this study, it could be possible once recycling methods for FRPs are in practice and databases for these have been updated.

Electronics

Electronic waste or E-waste accounts for a significant share of the global solid waste stream. Caution must be used when collecting and processing e-waste as they can be hazardous to environmental and human health. E-waste recycling is important as majority of electronics use printed circuit boards (PCBs) that consist of precious metals and toxic substances. Precious metals can be recovered from e-waste using various hydrometallurgical, pyrometallurgical or biohydrometallurgical techniques [72]. The avoided burden of the raw precious metals from e-waste have been modelled using a material breakdown from literature.

Batteries

Recycling of (lithium ion) batteries is becoming increasingly important as they are rapidly being used in different sectors, especially the automobile industry. After being collected and sorted, lithium-ion batteries are mechanically processed and separated into three final materials: cobalt & lithium salt concentrate, stainless steel, copper, aluminium and plastic. In this way, majority of the battery is recycled.

This categorization is used for further modelling of the EOL as Ecoinvent generally lacks data on the treatment of specific materials. Therefore, the breakdown of waste materials to be treated at end of life is presented in Table 3.10.

Table 3.10: Breakdown of lifetime waste materials to be treated at end of life.

Material category	recycled [kg]	incinerated [kg]	landfill [kg]	Total waste [kg]
Metals	9500	0	1000	10600
plastics	3000	150	500	3700
FRPs	0	200	200	400
electronics	250	50	305	615
batteries	4	0	4	8

After establishing the amounts of each material category, the activities used to model the treatments of these need to be determined. These have been identified and presented in Table 3.11.

Table 3.11: Breakdown of activities used to model the EOL treatments

Material category	EOL treatment	Activity used
Metals	**Incineration**	treatment of scrap steel, municipal incineration
	Landfill	treatment of scrap steel, inert material landfill
	Recycling	treatment of metal scrap, mixed, for recycling, unsorted, sorting
Plastics	**Incineration**	treatment of waste polyethylene, municipal incineration
	Landfill	treatment of waste plastic, mixture, sanitary landfill
	Recycling	treatment of waste polyethylene, for recycling, unsorted, sorting
FRPs	**Incineration**	treatment of hazardous waste, hazardous waste incineration
	Landfill	treatment of waste plastic, mixture, sanitary landfill
	Recycling	treatment of waste polyethylene, for recycling, unsorted, sorting
Electronics	**Incineration**	market for electronics scrap from control units
	Landfill	treatment of municipal solid waste, sanitary landfill
	Recycling	market for electronics scrap from control units
Batteries	**Incineration**	treatment of hazardous waste, hazardous waste incineration
	Landfill	treatment of municipal solid waste, sanitary landfill
	Recycling	treatment of used Li-ion battery, hydrometallurgical treatment
		treatment of used Li-ion battery, pyrometallurgical treatment

Avoided production of raw materials

To allocate the benefit of recycling to the system, the raw materials of which virgin production is avoided must be determined and modelled in the system as negative inputs. An overview of the materials used for each of the previously determined recycled material categories have been presented in Table 3.12

Table 3.12: Activites used to model the avoided production of raw materials from recycling

Material category	Ecoinvent activity used
Metals	Cast iron production
Plastics	Plastic pellets
FRPs	Plastic pellets
Electronics	Copper production (from precious metals recovered)
Batteries	Cobalt production (from precious metals recovered)

3.3.5. Modelling of the system

In this section, the overall set-up of the modelling and flow of data is presented to provide clarity on the methodology used for the LCA modelling.

As stated previously, details on the inventory for the system have beem provided by Kitepower [57]. Additionally, some data needs to be computed using sizing calculations where appropriate. These data and computations are stored and executed in an excel workbook. The outputs are stored in separate inventory tables for each of the components: kite, tether, KCU and ground station. The information within these tables is then converted in a separate excel sheet to a format that is readable by the Activity Browser software. Activity browser stores the data for the system as its own database. In LCA modelling, this is typically referred to as the foreground data. The environmental impact data for this database is linked to the Ecoinvent database:the background database. Once in Activity Browser, the data can be used to perform the LCA calculations and generate the impacts from the chosen impact category indicators.

In an LCA, the life cycle inventory is generally iterated to improve the accuracy in the modelling of the system. When this happens, the paremeters from the sizing calculations and data from kitepower must be edited as necessary and the inventory tables updated. The updated inventory tables are then translated to the readable format for Activity Browser if applicable. An overview to visualize the flow of data used in the modelling of the system is presented in Figure 3.12.

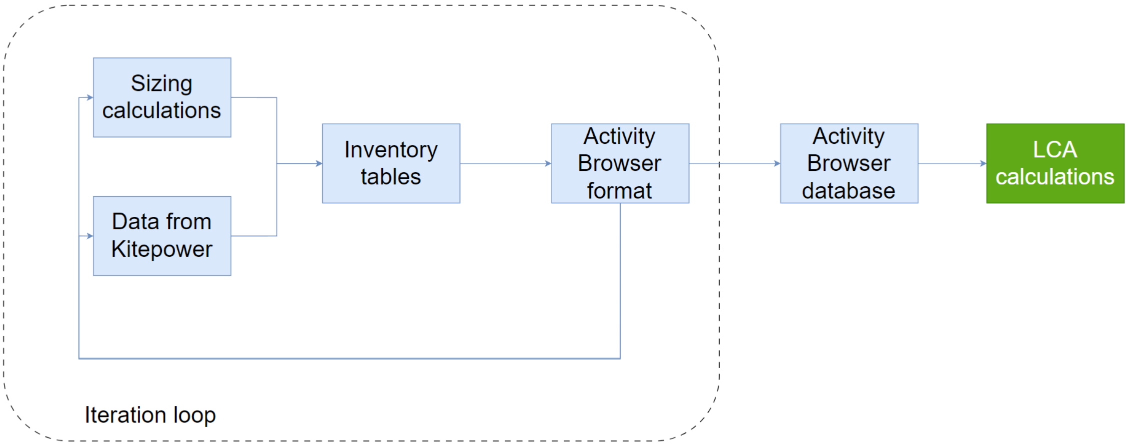

Figure 3.12: Mapping of data flows used to execute the LCA modelling

3.4. Life cycle impact assessment

After documenting and modelling the inventory for the AWE system, the results of the impact category indicators identified in subsection 3.2.2 can be evaluated. Firstly, the mass of the system and its components over its entire lifetime are evaluated in subsection 3.4.1. Then, an assessment of the impact category indicators are presented in subsection 3.4.2.

3.4.1. Mass

Firstly, Table 3.13 shows the mass % breakdown of the total system's mass for both the mass of 1 system and with the mass of replacements accounted. While initially, the ground station contributes to almost all the mass of the system without replacements, this contribution varies over the lifetime of the system. This is especially the case for the kite and tether components, as these components are the most replaced over the operational life. This was previously indicated in Table 3.7. At the end of the system's operational life, the kite and tether contribution to mass has risen from a total of only 2% up to almost 24% of the total system mass with replacements. The disparity between the mass composition of 1 system and the system over the operational lifetime have been depicted in Figure 3.13 and Figure 3.14.

Nevertheless, the ground station component is a significant contributor to the overall mass for both cases. The KCU has the least contribution to mass of the system in both cases. This is expected given the function of the KCU; it's mass must be minimized to not impact the aerodynamic performance of the kite. It does not contribute to the lift generation of the kite during operation but only in navigating and maneuvering.

Table 3.13: Mass assessment for both the initial system and with replacements over its lifetime

Component	Mass % of 1 system	Mass % of system w/ replacements
Kite	0.78	12.60
Tether	1.22	11.34
KCU	0.26	0.61
Ground station	97.74	75.46
Total mass of system(s)	100	100

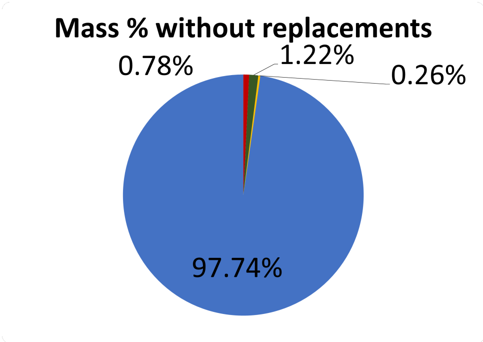

Figure 3.13: Pi chart showing mass share of components of 1 system

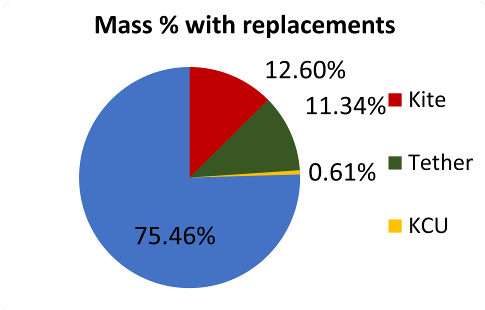

Figure 3.14: Pi chart showing mass share of components over the operational lifetime

A more detailed stacked bar chart showing the mass breakdown of the components is presented in Figure 3.15 to identify the mass hotspots within the system. This plot includes the masses for both the initial system and the replacements during operation. The masses are given as a percentage of the total system mass with replacements. The ground station accounts for majority of the system's lifetime weight despite never being replaced. The replacements of the kite material and tether material contribute significantly to the mass of the system's lifetime weight. Altogether, replacements of components and their individual lifetime could be interesting points of improvements in the system's design as they account for almost a quarter of the lifetime mass.

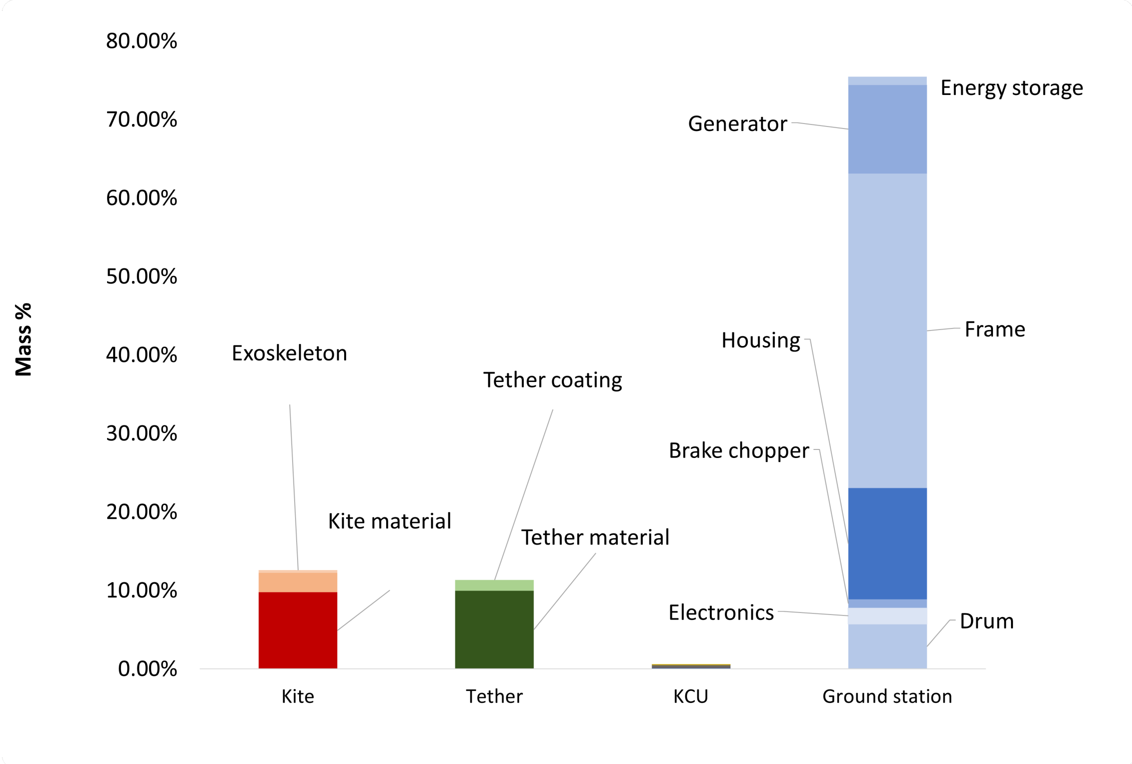

Figure 3.15: Plot showing the detailed mass % contribution of the AWE system

The kite material is the major contributor to the mass of the kite. This is expected as the material is of a significant area and is required to produce lift. The rope material mass contribution follows the modelling that used the ratio of rope material to rope coating documented in section 3.3. The KCU and ground station were modelled using eight and seven sub-components respectively. The largest contributor to the mass in the KCU is the foam cover followed by the tape guides and the drive-train with pulleys. The steel frame of the ground station accounts for 53.05 % of its total mass. The housing and generator make up 18.83 % and 15.02 % of the station's total mass respectively. This result could be of interest in the context of recycling; all three of these sub-components are made of metals which a highly recyclable. An assessment on the benefit of this recycling will be conducted in section 3.5.

3.4.2. Impact category indicators

An assessment of the chosen impact category indicator results is conducted within this section. This is then followed by a more detailed breakdown and evaluation of the contribution for all sub-components to the GWP and CED. The lifetime impacts are also presented and evaluated within this section. The overall GWP and CED of the system are 8.6 kg CO2 eq per MWh and 141.1 MJ eq per MWh, respectively.

The contribution of the components to the overall impact follows a similar trend to the mass contributions: the ground station has the highest impact followed by the kite and tether, and lastly the KCU. This correlation between mass and environmental impact is maintained for both impact category indicators. This could be explained by the fact that components with high masses require more resources resulting in more emissions (GWP) and energy consumption (CED). This correlation will be explicated in section 3.5.

GWP

In this subsection, a detailed assessment of the GWP is conducted to identify the impact hotspots of the system. Figure 3.16 presents a plot of the absolute values of the GWP from each component with a stacked bar showing the GWP contribution of the relevant sub-component that was modelled in the LCA software.

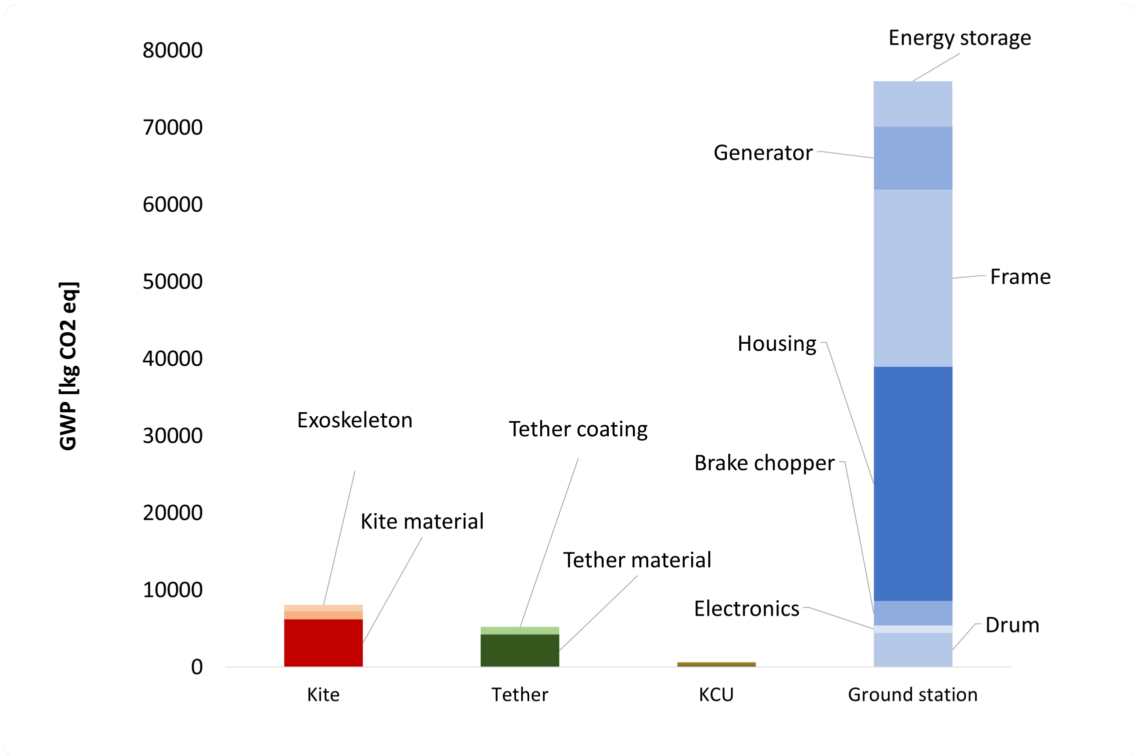

Figure 3.16: Plot showing the detailed GWP contribution of the AWE system

By far, the greatest contributor to the GWP is the housing of the ground station. The housing alone contributes more than each of the other components of the system. The next greatest impacts for the GWP are the ground station frame, generator and energy storage device. The kite and tether materials are replaced the most amount of times over the operational lifetime. Lastly, while the KCU was modelled using the most sub-components, it's environmental impact with respect to the GWP is minuscule compared to the other components. This suggests that it would not be worthwhile to improve the design of the KCU from an environmental standpoint.

Despite having more mass, the frame has a lower GWP than the housing. This is because the frame is modelled using processed stainless steel while the housing of the ground station is modelled using a shipping container. Therefore, the higher impact could be due to a more detailed inventory being available in Ecoinvent. Additionally, shipping containers are made of various other materials such as plywood and rubber which could contribute to the higher impact. The influence of varying the dataset used to model the housing will be evaluated in section 3.5

CED

The CED of the system is further evaluated within this subsection. A detailed breakdown of the contribution for each component and sub-component to the CED of the system is displayed in Figure 3.17. The CED contributions follow a similar trend to that observed for the GWP in subsection 3.4.2. This also holds true for the impact category contributions of the sub-components for each component. While this proportionality between GWP and CED is usually expected, a detailed inspection of this relationship will be conducted in section 3.5

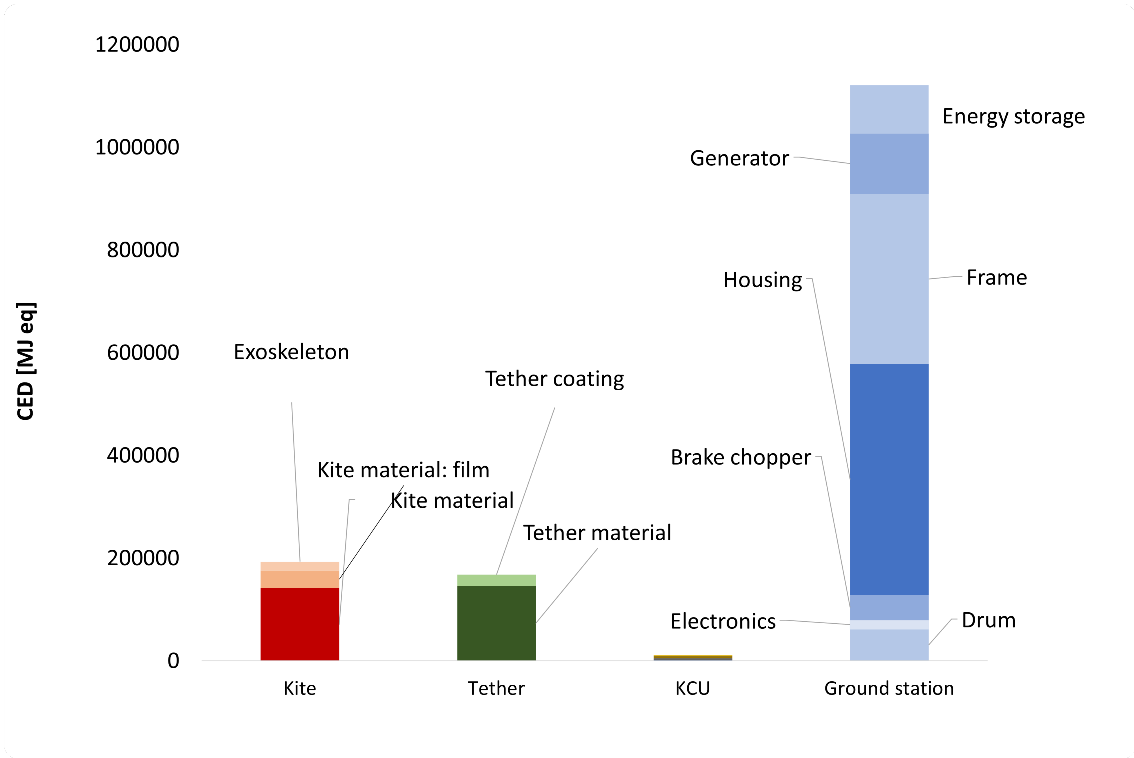

Figure 3.17: Plot showing the detailed CED contribution of the AWE system

Energy payback time

Energy payback time of the system is computed by dividing the total CED by the total energy produced by the system. Using Equation 3.1, the EPBT is 11.8 months

$$\text{EPBT} = \frac{\text{CED}_{total}}{\text{AEP}} \tag{3.1}$$

Energy return on Investment

EROI is computed using Equation 3.2

$$\text{EROI} = \frac{\text{AEP} \cdot \text{operational lifetime}}{\text{CED}_{total}} \tag{3.2}$$

EROI using cut-off is 25.5 times

Lifetime impacts

The contribution of the four lifetime stages for GWP and CED are presented in Figure 3.18 and Figure 3.19 respectively. The greatest contributor to the overall impact of the system is the materials and manufacturing stage. The reason for this could be because virgin materials typically require more energy and materials, leading to more emissions. This stage also includes the ground station, which contributes to majority of the environmental impact despite requiring no replacements over the operational lifetime. The impact of replacements is included in the O&M stage. This shows that the replacements of sub-components that the system incurs over the operational lifetime are significant and are a parameter of interest to investigate in the context of eco-design. The impact for the EOL phase in Figure 3.18 and Figure 3.19 was modelled using the cut-off method, the potential benefit from recycling using the substitution approach will be presented later.

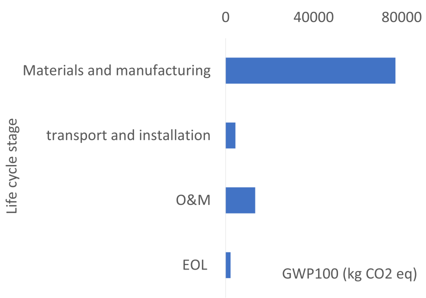

Figure 3.18: GWP impacts over lifetime

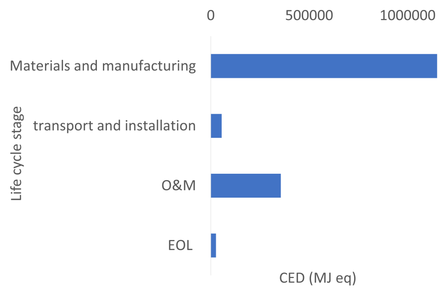

Figure 3.19: CED impacts over lifetime

Materials & manufacturing

The GWP and CED impacts that account for the materials and manufacturing stage of the system have been presented in Figure 3.20 and Figure 3.21 respectively. The housing and frame of the ground station are by far the greatest contributors for both GWP and CED. The generator with gearbox and energy storage device (ultracapacitor) also contribute to the impacts. The ground station sub-components have the greatest environmental impacts. Thus, it is recommended to focus future research and development on the eco-design of these sub-components. The kite and tether materials could also be points of focus for more environmentally friendly design. As seen before, the KCU impacts are almost negligible to the overall impact of materials and manufacturing. Thus, it has not been broken down into its sub-components in the graphs presented:

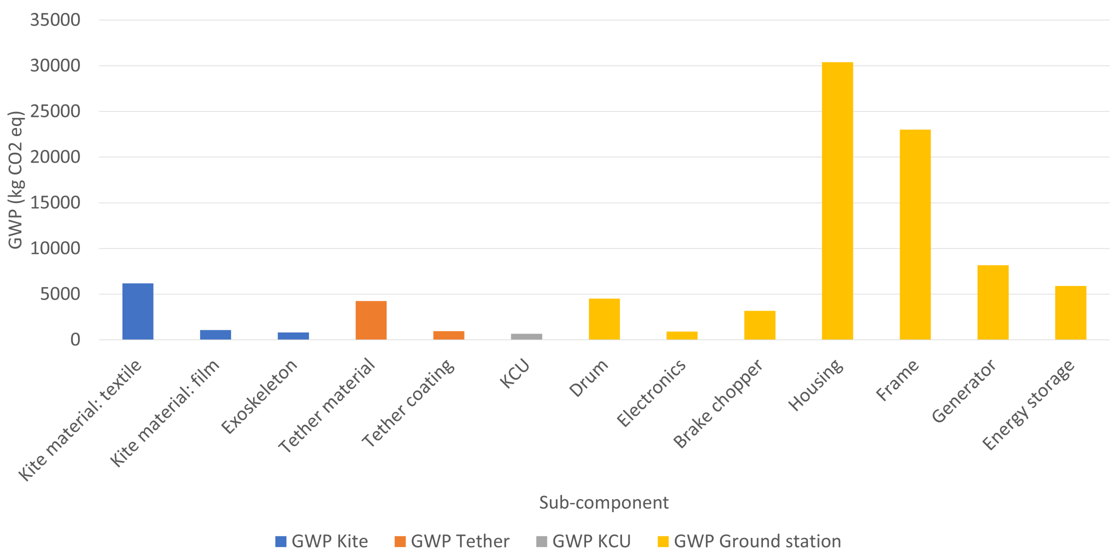

Figure 3.20: Plot of the GWP impacts for the sub-components

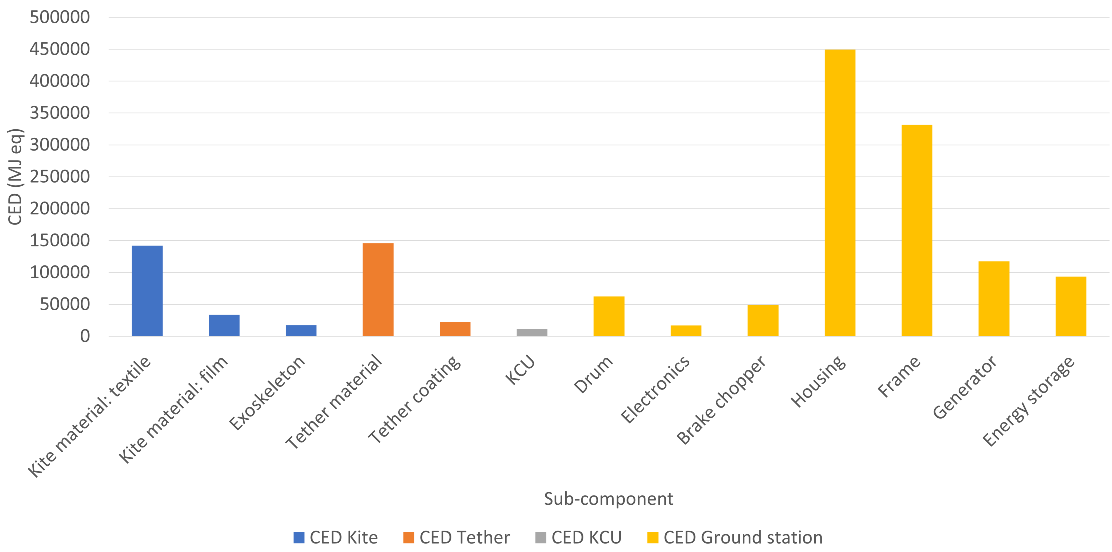

Figure 3.21: Plot of the GWP impacts for the sub-components

Transport & installation

An overview of the transport & installation activity contributions is presented in Table 3.14. It can clearly be seen that the correlation between GWP and CED of these activities are not entirely linear. For instance, the transport of the initial system consumes most energy but does not produce as many emissions as the land use of the system. This could indicate that while emissions from lorries are relevant when transporting components, land use is also relevant. Transport of replacements also has significance for both impact category indicators. The assembly of the system on site is least impactful overall. Lastly, while these impacts are relevant, their overall impact is still minuscule.

Table 3.14: Impact overview of the transport & installation stage

Stage activity	CED stage impact	GWP stage impact	CED total impact	GWP total impact
Transport - materials	28%	23%	1%	1%
Transport-initial system	41%	31%	1%	1%
Transport-replacements	12%	9%	0%	0%
Installation-assembly	0%	0%	0%	0%
Installation-land use	19%	37%	1%	2%
Total	100%	100%	3%	5%

Operation & maintenance

Operation & maintenance is the second most impactful life cycle stage of the system. This is in large part due to the materials and their production incurred through replacements. Maintenance activities are almost negligible in the overall impact. While replacements account for a significant share of the system's total lifetime impact, the impact of the initial system contributes to majority of the impact. This is due to the ground station having the largest impact. An overview of this stage's impacts can be found in Table 3.15

Table 3.15: Impact overview of operation & maintenance phase

Stage activity	CED stage impact	GWP stage impact	CED total impact	GWP total impact
Replacements	97%	96%	22%	13%
Maintenance	3%	4%	1%	1%
Total	100%	100%	23%	14%

EOL & waste treatment

Transport of waste to their respective EOL treatment facilities contribute to the majority of the EOL stage impact. There is also some disparity between the results of the GWP and CED in the EOL and waste treatment phase. Disassembly of the system consumes more energy than producing emissions. On the other hand, incineration at EOL contributes to a larger share of the EOL emissions realtive to the CED. In this way, landfill could be seen as a more sustainable option for EOL treatment. However, it should be noted that incineration treatment doesn't account for heat from incineration that could be used for power generation. Nevertheless, relative to the overall impacts of the system, the EOL activities do not contribute significantly.

Table 3.16: Impact overview of EOL & waste treatment phase using cut-off approach

Stage activity	CED stage impact	GWP stage impact	CED total impact	GWP total impact
EOL-disassembly	1%	0%	0%	0%
EOL-transport	92%	67%	2%	2%
EOL-incineration	6%	25%	0%	1%
EOL-landfill	1%	8%	0%	0%
Total	100%	100%	2%	2%

3.5. Interpretation

This chapter will execute the interpretation phase of the detailed LCA of the AWE system. The primary objectives and questions posed in subsection 3.2.1 will be addressed within this chapter. Firstly, the completeness and consistency of the LCA is evaluated in subsection 3.5.1. After this, subsection 3.5.2 analyzes the impacts of the components and sub-components of the system. Lastly. a sensitivity analysis will be conducted in subsection 3.5.3. It should be noted that all analyses conducted within this section are done with respect to the cut-off approach as a reference case.

3.5.1. Completeness and consistency check

The AWE system was broken down into four main components: kite, tether, KCU and ground station. Sizing data for modelling these components was acquired through continuous consultations with Kitepower. The background data was modelled using the Ecoinvent 3.9 cut-off database. Nevertheless, some inconsistencies were inevitable during modelling. For instance, for sub-components that are procured from external parties such as the generator, shipping container, etc. a best approximation was identified from the Ecoinvent database.

The exact model and therefore exact specifications and materials were not always identical to reality. These sub-components were modelled using allocation based on the sub-component's function or mass. Some systems such as the airborne wind turbine were not available in the Ecoinvent database. Therefore, in such cases, the component was broken down into their primary components and relevant manufacturing processes for these materials were applied.

All sub-components were modelled to account for the total mass of their respective components. This means that no materials have been unknowingly left out of the modelling, provided they do not impact the mass of the system by more than 5 %. Market mixes were used when exact processes or locations of materials and components were not available. A 'best approximation' was consistently used where data was limited.

3.5.2. Contribution analysis

The contribution analysis will evaluate the relative significance of the components on the overall system impacts. Executing this analysis will identify the hotspots of the AWE system with respect to the environmental impact. In Figure 3.22, the impact contribution of each sub-component is presented and normalized by the total impact for the respective impact category. This method of normalization is used so that both the impact hotspots and relationship between impact categories can be evaluated.

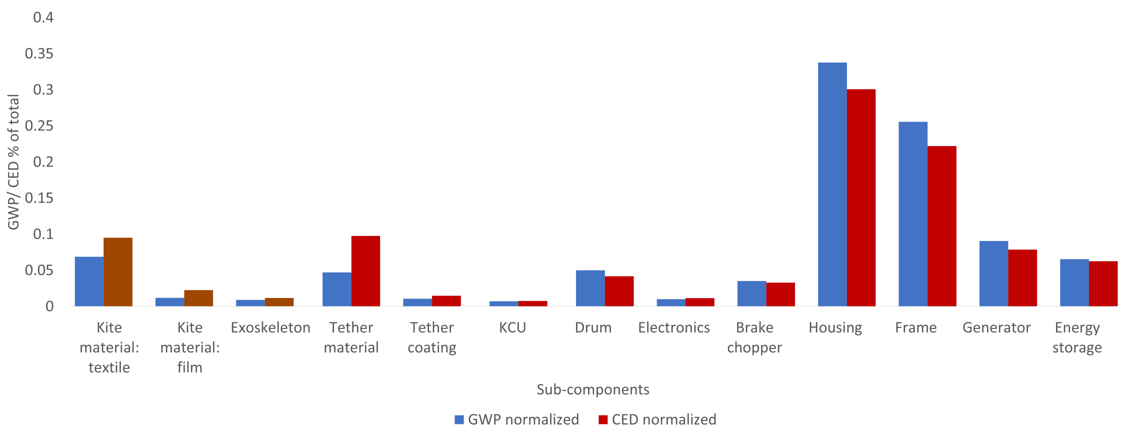

Figure 3.22: GWP and CED of system sub-components normalized by the total impact for the respective impact category

From subsection 3.5.2 it can be concluded that the greatest contributors to the system impact are the housing of the ground station, followed by the frame and generator. The ground station used by Kitepower is a 20 ft shipping container. In the LCA model, the mass of a similar sized shipping container from Ecoinvent does not have the same mass as the container specifications provided. Therefore, the mass of the shipping container dataset used in Ecoinvent was multiplied by an appropriate factor to account for this mass.

The shipping container model from Ecoinvent is scaled to match the mass provided by Kitepower. More energy and materials may be required to make multiple containers rather than one large container that matches the size and mass required by Kitepower. This high impact may come from the various materials and processes used to build a shipping container; multiple materials require different processing techniques leading to more emissions and energy consumption. For example, the frame of the ground station, while heavier was solely made of steel and used metal working for steel. This in turn led to a lower specific GWP and CED. A list of the materials and processes used to model the shipping container have been presented below:

- building, hall
- chromium steel pipe
- metal working, average for chromium steel product manufacturing
- metal working, average for steel product manufacturing
- plywood
- steel, low-alloyed, hot rolled
- synthetic rubber
- welding, arc, steel
- zinc coat, pieces

Both the kite and tether materials have a relatively higher CED than the GWP. This means that more energy is consumed to produce these sub-components than emissions. Both materials are made from plastics, however, both materials require processing to produce the final product. The kite material is modelled using polyester which requires water, oil and energy in addtion to plastic granules. These have high impacts on the environment.

Similarly, while the tether material is modelled using data for Dyneema which is produced from clean energy, it still requires processes such as extrusion and weaving of the fibres to form the tether. This consumes energy resulting in a relatively higher CED.

The KCU has the least environmental impact from all components. This is in large part due to the low mass of the component. Therefore, further development of this component with respect to sustainability is not as important as that of the ground station, kite and tether.

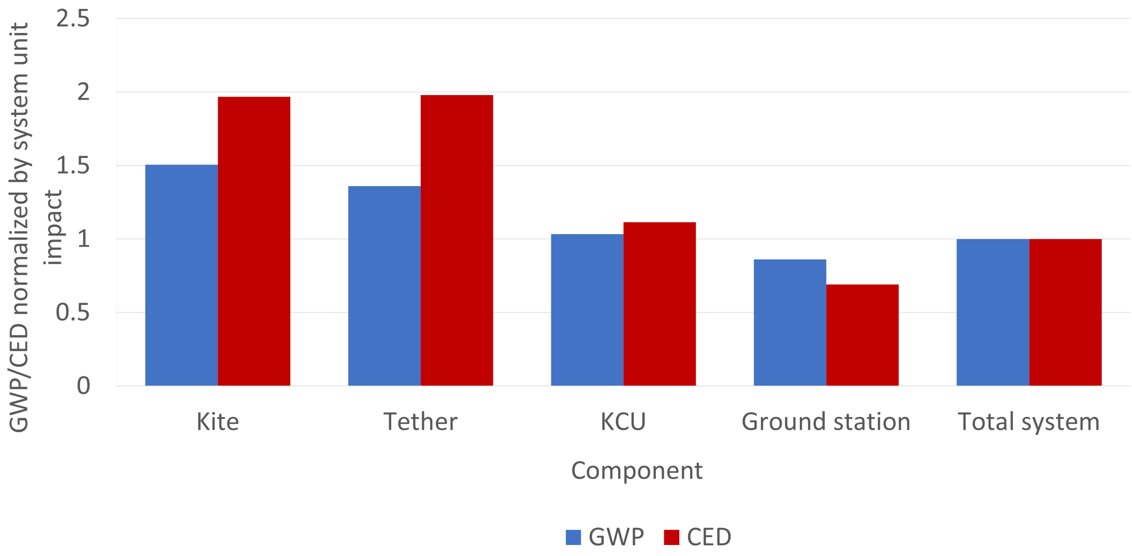

Figure 3.23: Mass specific impact of GWP and CED normalized by their respective specific system impact

In Figure 3.23, the impacts of the system components have been normalized with respect to their mass. By using this normalization method, the most impactful components can be identified by their mass. While the ground station was the most impactful by absolute terms. When looking at specific impact by mass of each component, relative to the impact of the total system, presented in Figure 3.23, the ground station is least impactful per kg. The kite and tether contribute the highest, followed by the KCU. Additionally, the specific CED for the Kite and tether is higher than their specific GWP. This confirms that it requires relatively more energy than emissions to produce the kite and tether. Therefore, it can be concluded that the kite and tether use the most impactful materials and processes and can be considered environmental impact hotspots for the AWE system.

3.5.3. Sensitivity analysis

The sensitivity analysis will be conducted by varying parameters of interest within ranges to determine the effect on the overall environmental impact of the system. In this study, the results of the analysis are consistently compared to the overall impacts using the cut-off approach as the reference case. Sensitivity analysis are usually conducted to estimate the impact on the results by changing parameters with high uncertainty. For this study, as AWE is a novel concept, the results of the sensitivity analysis have also been interpreted for improvements that could occur in future developments of the product.

Ground station: housing

The ground station had the greatest mass and environmental impact among all system components. In subsection 3.4.2, it was seen that the housing of the ground station in particular had the greatest environmental impact despite the frame of the ground station accounting for a significant share of the total mass. The housing only accounted for 14% of the lifetime system mass compared to the frame which contributed 40% of the lifetime system mass.

The housing of the ground station was modelled using the 'intermodal shipping container, 20-foot' dataset from ecoinvent and scaling its mass linearly to match the mass data provided by Kitepower. This was determined to be a best approximation to model the housing given that no specific dataset was available. Since the housing had the highest impact, the influence of this parameter's mass has been investigated. Figure 3.24 presents the influence that a change in the mass of housing imposes on the overall environmental impact results.

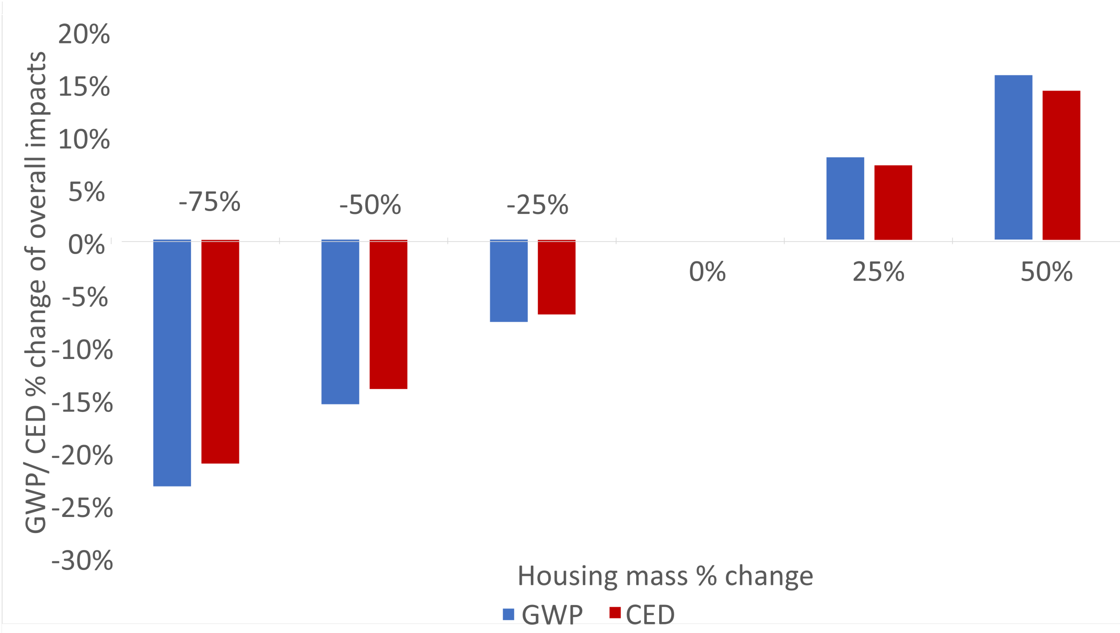

Figure 3.24: % change of overall system impacts with varying mass of housing

From Figure 3.24, it is evident that the housing has a significant influence on the overall system impact. Additionally, this variation in impact follows an almost completely linear relationship with the number of container datasets used to model the housing. Therefore, it is recommended to minimize the mass of the housing. Additionally, it is also recommended to create a unique dataset to accurately model the container Kitepower uses for the falcon. Implementing these could be beneficial to the environmental impact of the system as reducing the mass of the housing by 25% could result in over 5% decrease.

Frequency of replacements and component lifetimes

In subsection 3.4.2 it was clear that the replacements of the kite and tether over the operational lifetime have a significant effect on the mass and environmental impact of the system. This was because of their relatively lower lifetimes and material composition.

In the future, as materials progress, their properties and therefore lifetimes could be improved. This could have an impact on components that are replaced frequently over the operational lifetime. The lifetimes of the kite and tether are investigated in this sensitivity analysis as they were most frequently replaced.

The kite material was the most replaced sub-component of the system over its lifetime. Figure 3.25 presents the impact that varying the lifetime has on the overall system impacts for GWP and CED.

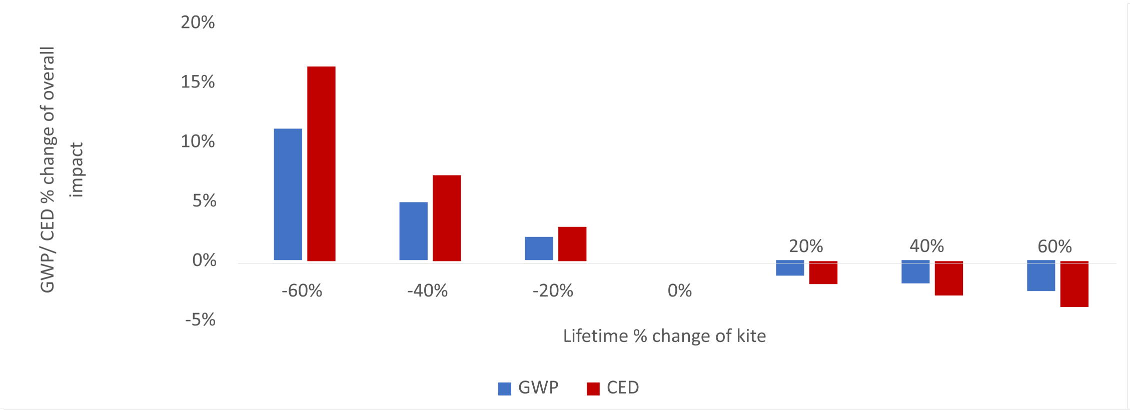

Figure 3.25: % change of overall system impact with increasing lifetime of kite material

The tether material was the second most replaced sub-component over the operational lifetime. Figure 3.25 presents the impact that varying the lifetime of kite material influences has on the overall system impacts for GWP and CED.

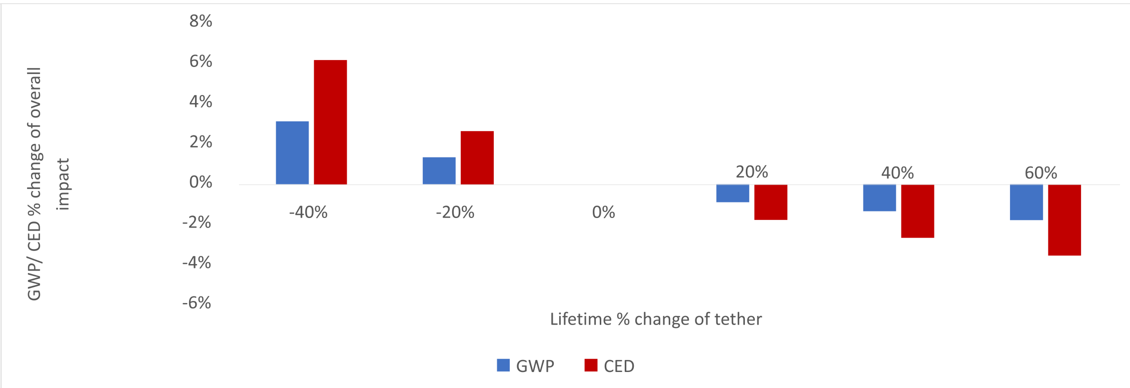

Figure 3.26: % change of overall system impact with increasing lifetime of tether

Both sub-components follow a similar trend with increasing lifetime. The relationship followed is close to exponential decay. This is because the operational lifetime constraints the minimum number of replacements as lifetime increases- after a certain lifetime is reached, only one replacement is required. Whereas the number of replacements can continue to increase until the lowest possible lifetime of the component is reached. The CED varies more than GWP when increasing or decreasing the lifetimes of both components. A 20 % increase in kite lifetime leads to a 2% decrease in GWP and 4% decrease in CED while a 10% increase in tether lifetime leads to a 1% decrease in GWP and 3% decrease in CED. Therefore, it could be concluded that improving the lifetime of the materials used for the kite and tether could be beneficial to further develop soft-wing AWEs in the future. On the other hand, it is important to note that drastic improvements in material lifetimes is not possible unless significant design changes or new materials are implemented.

Lifetime of energy storage device

It was assumed that all the sub-components in the ground station do not get replaced over the operational lifetime. This assumption has some uncertainty, especially because AWE is a nascent technology and newly operating systems are yet to reach their end of life. One sub-component with high uncertainty in its lifetime is the energy storage device (ultracapacitor). Figure 3.27 presents the percentage change in overall system impact with decreasing lifetime of the ultracapacitor. Both a 20% and 40% decrease in the lifetime lead to the same impact on the results. This is because the number of required replacements is rounded up. While a significant decrease in ultracapacitor lifetime leads to a significant increase in the environmental impact, it is expected that the lifetime used shouldn't differ substantially from what is used in the modelling. Therefore, as even a 40% decrease in the lifetime leads to only a 5% increase in the overall impact, it can be concluded that the uncertainty in the lifetime of the energy storage device doesn't have too much influence.

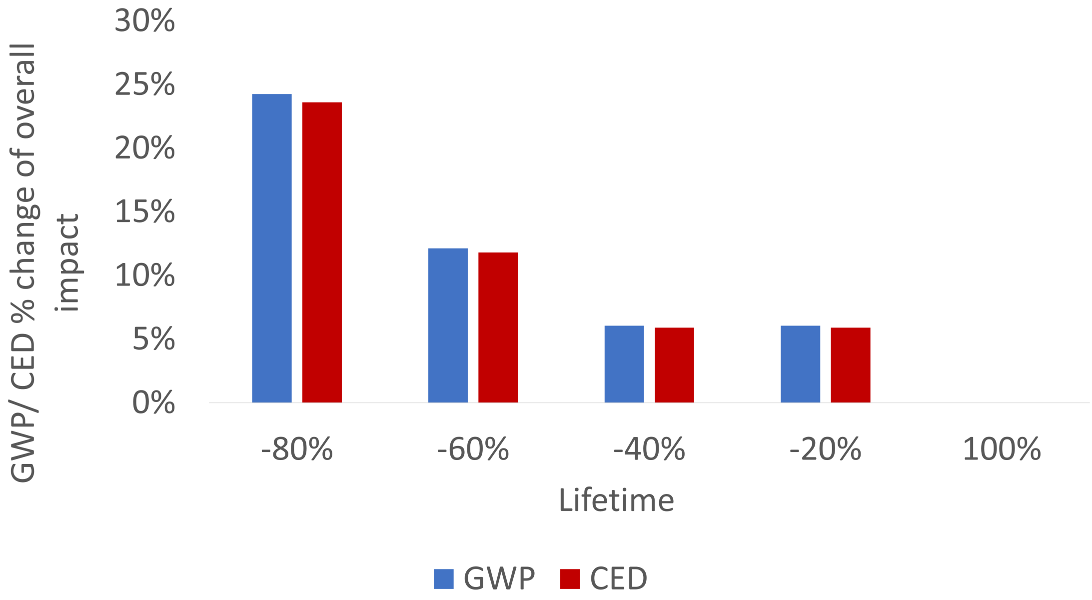

Figure 3.27: % change of overall system impact with decreasing lifetime of energy storage device

In addition to the lifetime of the ultracapacitor, the option of replacing the ultracapacitor with a battery is also evaluated here. For the functional unit, using a battery increases the mass of the energy storage device by 590%, the GWP by 58% and CED by 54%. Therefore, from both a mass and sustainability point of view, it is much more beneficial to use an ultracapacitor as the energy storage device whenever possible. While ultracapacitors have a higher impact per kg compared to a battery, they are mass-efficient at carrying out their function. Requiring nearly 6 times less mass results in the ultracapacitor being the more environmentally friendly option.

Capacity factor

As AWE is a novel concept with novel technologies, the annual electricity production and capacity factors of these systems could increase over time as more knowledge and optimization of the system takes place. This could effect the environmental impact of the system. Figure 3.28 presents the influence that the capacity factor of the system has on the overall impact. The capacity factor is varied up to a maximum increase of 30% from the base case. This is because it is not viable to constantly operate an AWE system at its full power rating. The results in Figure 3.28 show that operating the system at its rated power for as long as possible would be beneficial from a sustainability point of view. Even a 10% increase in capacity factor leads to an almost 10% decrease in both GWP and CED. This result shows that operating the system at its rated power more often would have a significant effect on the overall environmental impact.

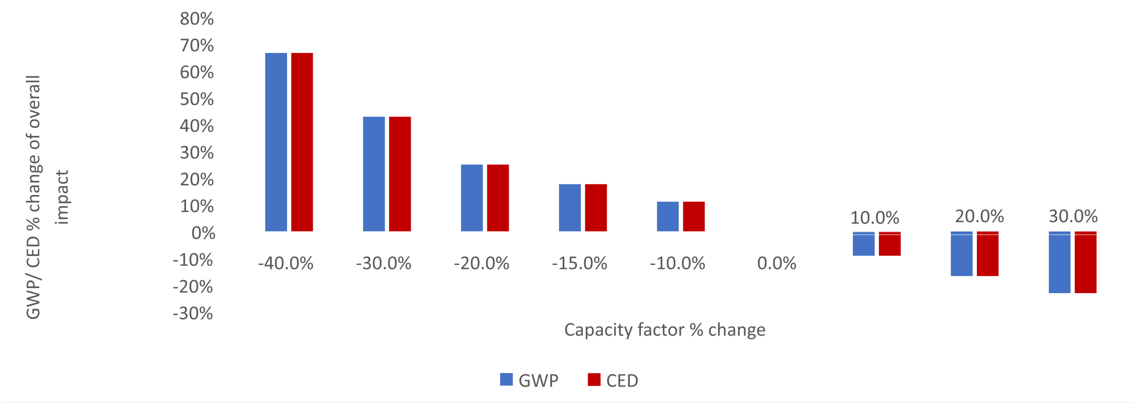

Figure 3.28: % change of overall system impact with increasing capacity factor up to the theoretical limit

Operational lifetime

Figure 3.29 presents the influence of the operational lifetime on the overall environmental impact for GWP and CED. The results are shown as a percentage difference from the base case, which is the 25 year operational lifetime. Furthermore, the values are for the GWP and CED normalized by the energy production over the lifetime. This is done to account for the fact that the system will produce more energy over a longer lifetime while incurring additional replacements during operation and maintenance. Figure 3.29 also shows that the absolute variation by increasing the operational lifetime is not as much as the variation experienced by decreasing the operational lifetime. Nevertheless, increasing the lifetime by 10% still yields about an 8% reduction in environmental impact, showing that research and development into more durable materials and sub-systems could be very beneficial for the environmental impact of an AWE.

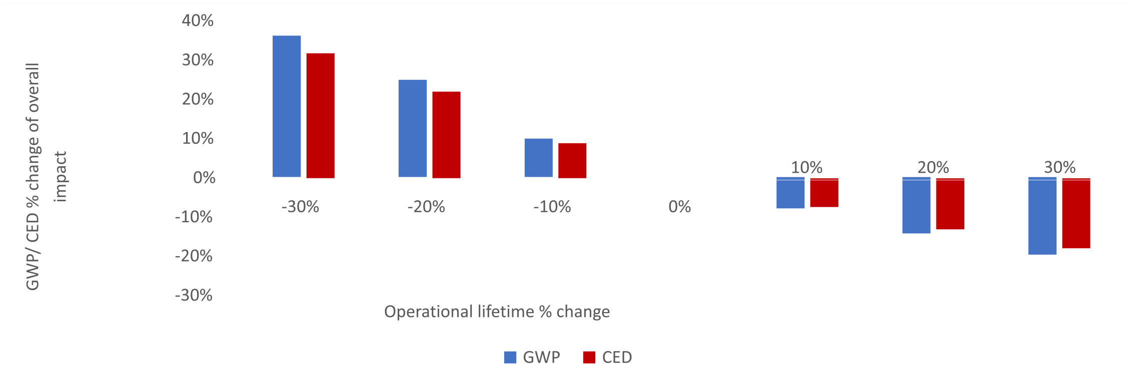

Figure 3.29: % change of overall system impact with varying operational lifetime.

Recycling

Cut-off vs avoided burden

The cut-off approach was used as a reference case for this study. Now, the potential benefit of recycling will be quantified by using the substitution approach. The method for modelling this has been previously explained in section 3.3. The results for the lifetime impacts using the avoided burden approach for GWP and CED have been presented in Figure 3.30 and Figure 3.31 respectively.

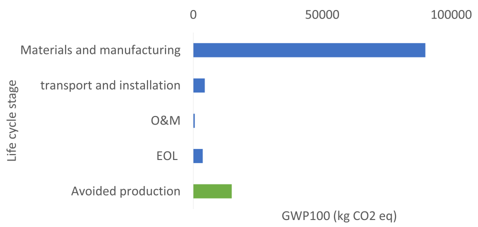

Figure 3.30: GWP impacts over lifetime using the avoided burden approach

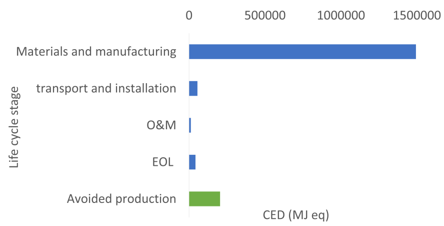

Figure 3.31: CED impacts over lifetime using the avoided burden approach

The green bar in both figures represents the impact for avoided production. This bar represents the ideal scenario where all waste material is treated appropriately and recycled to useful raw materials. All produced recycled materials are also used in other applications thus avoiding the burden of producing virgin materials. The avoided burden from the production of raw materials is then completely allocated to the AWE system. Thus, the bar representing avoided burden can be subtracted from the overall environmental impact of the system. When including the avoided burden approach and attributing all the benefit to the AWE system, the normalized GWP and CED are 7.4 (kg CO2eq/MWh) and 124.3 (MJ eq/MWh). This means that if all the benefit of recycling is allocated to the AWE system, the emissions and energy consumption effectively decrease by 14% and 12%, respectively. Such a reduction is quite significant. Therefore, it would be both beneficial and important to develop appropriate waste treatment policies for the development and application of AWE systems in the future.

4

Life cycle assessment of the hybrid power plant components

This chapter details the 'streamlined' LCA for the other components of the off-grid HPP that will be used in different configurations both with and without AWE in chapter 5. The ISO 14040 and 14044 is adapted and the LCA is done in a streamlined manner using the standard stages: Goal & scope definition and life cycle inventory analysis [4][5]. The impact assessment and interpretation stages are not included as these are implemented in chapter 5. The goal & scope definition is presented in section 4.1. Following this, the inventory used is detailed in section 4.2. The inventory encompasses the same stages as those in section 3.3: materials & manufacturing, transport & installation, operation & maintenance and eol & waste treatment.

4.1. Goal & scope definition

The goal and scope definition is the same as that discussed in subsection 3.2.1 and subsection 3.2.2. An additional research objective is to compare the impacts in a comparative study for different configurations in an off-grid hybrid power plant derived from a previous sizing study [6]. Therefore, only a system description of the HPP components are presented within this section.

4.1.1. Functional unit

The functional unit will now be with respect to the greater system, the HPP. This follows from the load analysis in [6]: **'An annual electric production of 4383 MWh, from a configuration within an off-grid hybrid power plant.'**

Similarly, the reference flow of the study is now: **' One 500 kW hybrid power plant with a lifetime of 25 years.'**

4.1.2. System description

HPP study system description

The components to be modelled within this section are the diesel generator, solar power plant and battery energy storage system (BESS). The environmental impact from the AWE was previously determined from the detailed LCA in chapter 3 . The results of this will be scaled to match the appropriate configuration taken from the paper by S. Reuchlin et al: 'Sizing of Hybrid Power Systems for Off-Grid Applications Using Airborne Wind Energy' [73].

In this paper, the components in an off-grid HPP are sized and optimized with the objective to minimize the Levelized Cost of Energy (LCoE). The LCoE is a parameter of interest to minimize as it means that energy is made more affordable, systems are more cost competitive and therefore economically viable. Some of the variables in the optimization were the tilt and azimuth angle of the solar modules, number of kites for AWE.

The main conclusion of this paper was that the optimum configuration to minimize LCoE was to have a HPP comprising of a combination of all components. While this may be beneficial for the LCoE of the system, the environmental impact of using multiple components rather than one for energy generation is not accounted for in this optimisation. This study will determine this and evaluate how beneficial it is to replace diesel generators in a HPP with an AWE system for an off-grid setting. A visual for how such a HPP could look is presented in Figure 4.1[18]. Note that the system boundaries for this study will be from cradle-to-grave and use the cut-off approach.

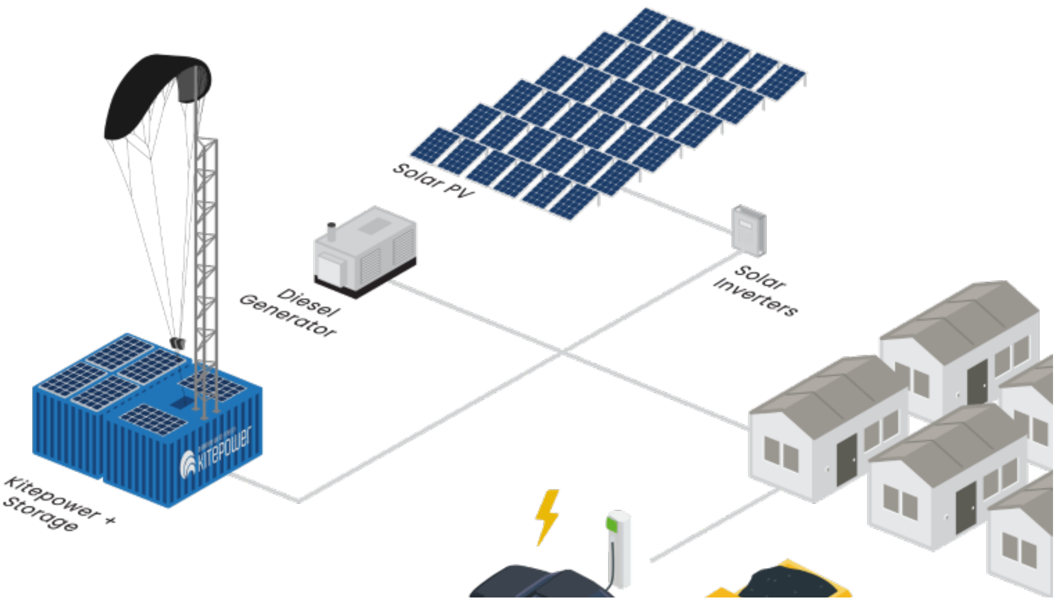

Figure 4.1: Figure visualizing what a HPP in this study could look like [18]

The setting for the HPP is on an off-grid military training camp in Marseille, France. The details of the energy consumption of this base are presented in Table 4.1. The data for the camp are taken from the year 2019 [6].

Table 4.1: Technical details of the hypothetical off-grid military base in Marseille, France [6]

Property	Value	Unit
Average hourly demand	0.5	MW
Peak hourly demand	0.7	MW
Average wind speed at 320 m	7.2	m/s
Equivalent sun hours	4.0	kWh/m^2/day
Diesel price	1.37	€/L
Carbon tax	0.125	€/kg

The final table with different configurations along with their LCoE from the sizing study [6] is presented in Table 4.2. The data from this table will be used for sizing the different components in each configuration when doing the LCA modelling.

Table 4.2: Optimum sizing details for different configurations in the HPP [6]

HPS Configuration	Solar PV (MWp)	AWE (MW)	Battery (MWh)	Diesel (%)	LCoE (€/MWh)
Diesel	0	0	0	100	720
AWE + Diesel	0	2	92	0	900
AWE + Battery + Diesel	0	0.7	0	40	410
Solar + Battery	30	0	36	0	670
Solar + Battery + Diesel	10	0	8.3	27	410
Solar + AWE + Battery	10	0.5	25	0	390
Solar + AWE + Diesel	2.7	0.6	0	24	330
Solar + AWE + Battery + Diesel	5	0.6	7.2	7	280

4.2. LCI of HPP components

This section entails the life cycleinventory of the remaining HPP components: diesel generator, solar power plant and BESS. Similarly to section 3.3, the four life cyclestages are presented for each of the components: materials & manufacturing, installation & logistics, operation & maintenance, and end of life & waste treatment.

4.2.1. Materials & manufacturing

This subsection will entail the manufacturing phase for all components other than the AWE system. Similar assumptions as for AWE are used in the modelling of the components.

Solar power plant

The solar modules used in [6] are based on the Panasonic HIT N340.N335 photovoltaic (PV) modules. The efficiency of these modules decrease to 86.2% of its original value after 25 years. All assumptions used to size the modules are carried on from the sizing report. For example, it is assumed that no shade will be present on the modules during operation; this may not be representative of what is observed in reality. However, while this scenario is hypothetical and this case study is primarily used to determine the environmental impact and not model the performance of the modules, it is expected that the impact of this assumption shouldn't be too significant. The sizing of the physical modules is more important to have a viable assessment. This methodology will consistently be applied to all other components of the HPP to ensure an equal comparison of the technologies.

The dataset: 'photovoltaic plant, 570kWp, multi-Si, on open ground' from EcoInvent is used to model these modules. This dataset includes all components for the solar plant to provide electricity to the load. It includes the PV panels, mounting system, electric installation and inverter. Additionally, this dataset includes energy and diesel fuel required to install the plant. However, as this dataset is quite old, it has been updated by replacing the default modules with inventory data from [74]. The number of datasets required to model the PV module are determined by simply dividing the power required for the relevant configuration from Table 4.2 by the rating of one photovoltaic plant from the ecoinvent dataset.

Similar to the AWE system, it is assumed that the solar irradiance data for the 25 years of operation are constant resulting in a constant AEP. This assumption simplifies the modelling and ensures that the primary focus is on the environmental impact of the system.

Battery Energy Storage System

In an off-grid scenario, constant power must be provided to the load to ensure seamless operation of the facility. This is not achievable using purely intermittent energy resources like wind and solar. Therefore, the BESS acts as a form of short-term energy storage within the HPP. The sizing report that this case study is based on considered Lithium-ion batteries with properties projected to the year 2030.

A simplified approach has been used to model the BESS: it is firstly considered that the BESS primarily consists of the Lithium-ion battery cells and the battery management system. The battery cells in a BESS typically compose between 65% to 75% of the total BESS mass. The remainder of this mass is made up of the battery management systems, thermal systems, casing, cables, etc [75]. For ease of modelling, it is assumed that the BMS contains similar materials to other systems and sub-components within the BESS . Therefore the dataset can be used appropriately to model these aforementioned systems. For future work, it is recommended to execute detailed LCAs for all components of the HPP that use a similar goal and scope definition.

Both the lithium-ion battery cells and the BMS datasets used to model the system can be found in the ecoinvent database. The battery capacity from Table 4.2 is used to compute the number of cells required. The energy capacity for the cell is specified in ecoinvent and is used to compute the mass of the battery cells required. The ratio of 0.7 to 0.3 is used for the battery cell to BMS mass.

In [6], the battery is sized according to the absolute highest value required from the energy mismatch between supply and demand. This means that even if the battery capacity required is very high for a small duration of the year, the battery size is equivalent to this. Additionally, compared to the other technologies within the HPP, the battery is used as a means of energy storage and **not** for energy production. Therefore, when evaluating the results of the normalized environmental impact, it is important to evaluate the results of the BESS with this difference in function in mind.

Diesel generator

The primary energy production systems available for the off-grid hybrid power plant are the solar power plant and airborne wind energy system. Both of these use intermittent sources of energy. This means that their availability is uncertain and there can be periods of no power generation from these sources. This is especially the case because a load loss factor is applied to have a reduction in the oversizing of the energy generation components and battery. The trade-off for implementing the loss of load is that the size of the battery is reduced but the power plant can't meet the load at specific points in time, resulting in a power outage.

To overcome this, a reliable source of energy such as a diesel generator is used. The diesel generator uses a diesel generation optimization (DGO) where electricity is only generated when both the renewable energy sources and battery are unable to meet the load required by the military base. It only functions to supply electricity to the load and does not charge the battery [6].

Diesel generators compose of a vast array of metals and other materials. An example list of materials for such a system is presented in Table 4.3 [76].

Table 4.3: List of materials that are generally used to produce a diesel generator

Materials		
Aluminium Alloy	Ferosillicon	PCB
Cast Aluminium	Lead	Stainless Steel
Cast Iron	Low Alloy Steel	Steel, Bar & Rod
Copper	Low Carbon Steel	Tin
Epoxies	Molybedenum	Titanium Alloys
Ferromanganese	Nickel	Zinc

The energy that the diesel generator should supply when used in a configuration varies from 7-100 % of the demand, corresponding to a peak power supplied between 49-700 kW. The most representative dataset available in Ecoinvent is used to model the generator. This is the 15- 18.5 kW diesel-electric generating set. The generator will be linearly scaled to meet the power requirement of the appropriate configuration. It is assumed that the diesel generator can be scaled linearly with no performance loss or gain. In reality, if a larger (power rating) diesel generator is required, less materials should be used and therefore there would be a lower environmental impact for the manufacturing phase of the diesel generator.

This assumption shouldn't have a significant effect on the environmental impact of the diesel generator as a majority of the impact typically comes from the burning of diesel fuel to produce electricity during the operation & maintenance phase [76]. More details on the manufacturing and materials phase of the chosen diesel generator can be found through the ecoinvent database [52].

Balance of plant

Lastly, the balance of plant for the power plant needs to be accounted for in the inventory. In the case of the off-grid HPP, the balance of plant refers to the auxiliary systems and supporting parts that are required to deliver electricity, aside from the producing units themselves. For example, these could include cabling, inverters, transformers, protective equipment, switching and control equipment, power conditioners, supporting structures, etc.

Inverters are already included within the datasets used to model the Solar plant and AWE system. The diesel generator already produces AC current. A transformer is included to change the voltage from the HPP to match that of the load. The mass of the transformer required is determined by using a power factor of 0.8 for the 500 kW plant. Therefore, a transformer of 625 kVa is required. Such a transformer weighs around 2000 kg [77]. The Ecoinvent dataset 'transformer production, high voltage' is used to model this.

Next, the SCADA system and cabling for the HPP is modelled. This system is modelled using the environmental product declaration (EPD) from Col Group [78]. The product functions to monitor and remotely control the electricity distribution within the HPP. The EPD also includes the wiring required for such a system.

4.2.2. Installation and logistics

It is assumed that all components are delivered to Kitepower HQ in Delft and then transported to the military camp in Marseille, France over a distance of 1200 km. Transport impacts for the sub-components are included by using the 'market' activities from ecoinvent. As this assumption is also used to model the AWE system, it will ensure a fair comparison between the technologies in the interpretation phase.

The land use of solar panels is dependent on the number of solar cells and therefore the configuration used in the HPP. This land use is modelled by scaling to the number of solar modules (1.67 $m^2/module$) using the activity 'land use change'. The land use of the diesel generator and battery are assumed to be negligible. This assumption shouldn't impact the results too much as these components use relatively much less land than the solar and AWE components.

The assembly of the components and the HPP must also be modelled. This is done using the 'assembly of a heat and power co-generation unit' activity from ecoinvent. The number of datasets is scaled to match the rated power of the HPP (0.5 MW). While the dataset may not be the most representative for the assembly of a HPP, implementing this enables a more complete LCA of the HPP.

4.2.3. Operation and maintenance

Solar power plant

Solar power plant manufacturers typically offer a guaranteed lifetime of the modules for about 25 years. This would mean that no large-scale replacement of the modules are incurred throughout the operational lifetime. Note that the description of the ecoinvent dataset used to model the solar power plant indicates a lifetime of 30 years.

The maintenance of solar modules consists of two forms: preventive or scheduled maintenance and corrective maintenance. Preventive maintenance encapsulates the consistent maintenance activities performed to optimize the PV module lifetime and system efficiency. The frequency of this type of maintenance is determined by parameters such as the system design itself and also the economics of the project using the modules. This maintenance mainly includes activities like monitoring the plant, and cleaning and maintaining the modules [79].

Corrective maintenance includes the activities performed when the modules require repairing due to failure. The Ecoinvent activity dataset used to model the solar plant already includes energy demands and consumables required for maintenance. Therefore, it is assumed that the aforementioned maintenance have been accounted for within this dataset. It is expected that maintenance activities for solar will not contribute significantly to the overall environmental impact of the system

BESS

Lithium ion batteries have a projected lifetime of 10,000 charge and discharge cycles. However, the battery gradually deteriorates, especially over the use period. Cells are usually replaced after reaching 80-60% of their initial capacity. This range depends on what the minimum amount of deterioration is acceptable to meet the demand of the load required. It is assumed that the entire BESS is disposed once the battery cells reach the end of their lifetime. Therefore the BESS is replaced three times during the 25 year operational period. Other methods of maintenance are assumed to have negligible influence on the overall impact of the system.

Diesel generator

The burning (and transport) of diesel fuel accounts for majority of the environmental impact of a diesel-electric generator. This is usually greater than 90 % [76]. Therefore, the bulk of the LCA modelling for this system will be from the burning of diesel fuel and its transport to the site. To determine this, a fuel burning rate for the generators' power rating must be established. This is done by first taking data [80] for both the diesel burn rate and power rating at different loads, that has been presented in Figure 4.2.

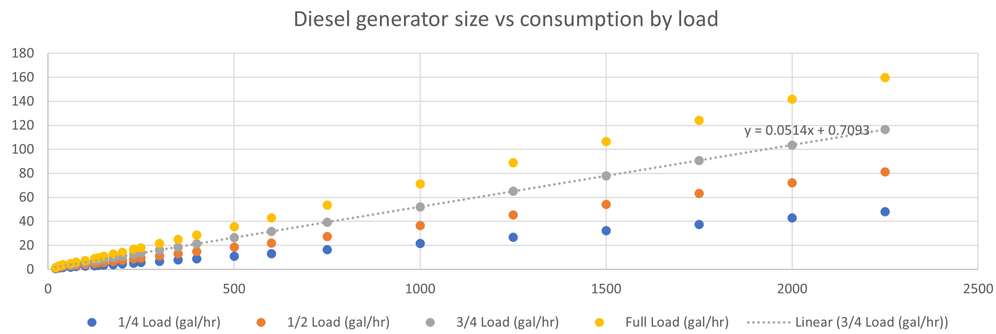

Figure 4.2: Plot of diesel fuel consumption against the generator size for different loads [80]

Upon inspection of Figure 4.2, there is a clear linear correlation between the two parameters for the given size range: the diesel generator size C_{diesel} and the diesel fuel burned f_{burned}. The relation for the 3/4 of capacity is used as diesel generators generally operate at this load.

$$f_{burned} = 0.0514C_{diesel} + 0.7093 \tag{4.1}$$

Regarding the modelling of maintenance, diesel generators are generally required to be twice every year. The maintenance is modelled using a 'best approximation' in the form of the 'maintenance for heat and power co-generation unit' of similar power rating. The transport of the diesel fuel is modelled to be within a 100 km radius.

4.2.4. End of life and waste treatment

The EOL phase is modelled using the cut-off approach. Hence, similarly to the AWE, the activities included in assessing the impact of the system are disassembly and transport to EOL facilities. Additionally, the impact from landfill and incineration are also modelled within the system boundaries.

Disassembly and transport

The disassembly of the system is modelled using the same dataset used to model its assembly during the installation phase. Transport to EOL facilities is modelled using a semi-truck and assuming these facilities are within a 200 [km] radius from the site. This approach is consistent with what was used for the detailed LCA of the AWE system.

EOL treatments

The materials to be treated by their appropriate EOL treatment are determined by using the EOL rates found in Table 3.9. This is applied to the material breakdowns found in the activities used to model each of the HPP components. Once the masses have been determined, the materials can be categorized and modelled for their EOL treatments using the activities presented in Table 4.4.

Table 4.4: Breakdown of activities used to model the EOL treatments

Material category	EOL treatment	Activity used
PV modules	**incineration**	treatment of hazardous waste, hazardous waste incineration
	landfill	treatment of municipal solid waste, sanitary landfill
Metals	**incineration**	treatment of scrap steel, municipal incineration
	landfill	treatment of scrap steel, inert material landfill
Batteries	**incineration**	treatment of hazardous waste, hazardous waste incineration
	landfill	treatment of municipal solid waste, sanitary landfill
Electronics	**incineration**	treatment of hazardous waste, hazardous waste incineration
	landfill	treatment of municipal solid waste, sanitary landfill

5

Comparative study: Airborne wind energy in an off-grid hybrid power plant setting

The results along with the comparison of the environmental impact from the different technologies within the HPP will be presented within this chapter. This is done using the different configurations identified in Table 4.2. Having completed the detailed LCA of the AWE system and the streamlined LCAs of the other components in previous chapters, the inventories for these technologies can be scaled to match the configurations and evaluated. Table 4.2 has now been extended to include the normalized environmental impacts of each configuration. The results are normalized by the total energy production of the HPP over its operational lifetime. This is presented in Table 5.1, alongside the previously determined LCOEs. Firstly, an impact assessment of the different configurations is presented in section 5.1. These results are then interpreted and analyzed in section 5.2.

Table 5.1: Extended table of HPP configurations from [6], extended to include the environmental impacts normalized by the total lifetime energy production.

HPS configuration	Components used	LCOE	GWP normalized	CED normalized
1	Diesel	720	1430	19725
2	AWE + Diesel	900	776	10823
3	AWE + Battery + Diesel	410	580	8021
4	Solar + Battery	670	945	14214
5	Solar + Battery + Diesel	410	676	9716
6	Solar + AWE + Battery	390	436	6396
7	Solar + AWE + Diesel	330	411	5788
8	Solar + AWE + Battery + Diesel	280	280	4058

Table 5.1 seems to have a correlation with the number of components. This shows that more components results in less oversizing of the renewables. This results in less materials and therefore lower emissions and energy intensity. Additionally, configuration 8 which includes all components, and has the lowest LCOE, also has the lowest environmental impact. This is a desired result as it shows stakeholders that the cheapest configuration is also the most environmentally friendly.

5.1. Impact assessment of HPP configurations

The Falcon AWE system could be implemented in off-grid HPPs. It is especially targeted towards replacing diesel generators within these HPPs. Diesel generators dominate the market for off-grid microgrids. Configuration 1, will be used as a reference case for comparison. Configuration 6 is chosen for further analysis as it would present the impacts of removing the diesel component from the HPP. Configuration 7 will also be analaysed to investigate the impact of not including energy storage in the HPP. Lastly, configuration 8 which includes all components and has the lowest overall impact will also be analysed.

5.1.1. Configuration 1: Diesel

Mass assessment

The results for the analysis of configuration 1 have been presented in Table 5.2. The mass of diesel fuel makes up most of the mass of the diesel component over the plant lifetime.

Table 5.2: Mass breakdown of diesel component in configuration 1

Parameter	Mass [kg]	% share
Mass of system	27200	0.08
Mass of fuel	34800000	99.92
Total mass	34827200	100

Impact assessment

The GWP and CED, normalized by the total energy production are 1430 and 19725 respectively. The contributions of each life cycle stage to these impacts have been presented in Table 5.3. For a diesel generator, nearly all of the environmental impact comes from the burning of diesel fuel. This result is expected as the fuel had the highest mass share in Table 5.2, and burning of diesel fuel is emission and energy intensive. The results show that use of diesel generators needs to be minimized in order to minimize environmental impacts. Furthermore, while the use of diesel generators in hybrid power plants is advised due to it being a reliable power source, it must still be minimized to ensure the least environmental impact possible.

Table 5.3: Environmental impact breakdown of diesel component in configuration 1

life cycle stage	GWP % share	CED % share
Diesel - materials	0.178	0.160
Diesel - transport	0.002	0.003
Diesel - installation	0.002	0.003
Diesel - fuel burn	99.593	99.565
Diesel - fuel transport	0.225	0.269

5.1.2. Configuration 8: Solar + BESS + diesel + AWE

Mass assessment

As it had the lowest impacts and LCOE, configuration 8 is of interest and will be evaluated. Figure 5.1 presents the absolute masses for each technology implemented in configuration 8. The mass of the diesel compnent is the highest, followed by the solar and battery components. The AWE system(s) are the components with the lowest masses when evaluating the mass of materials required to manufacture the systems. Note that the mass of diesel fuel accounts for majority of this component.

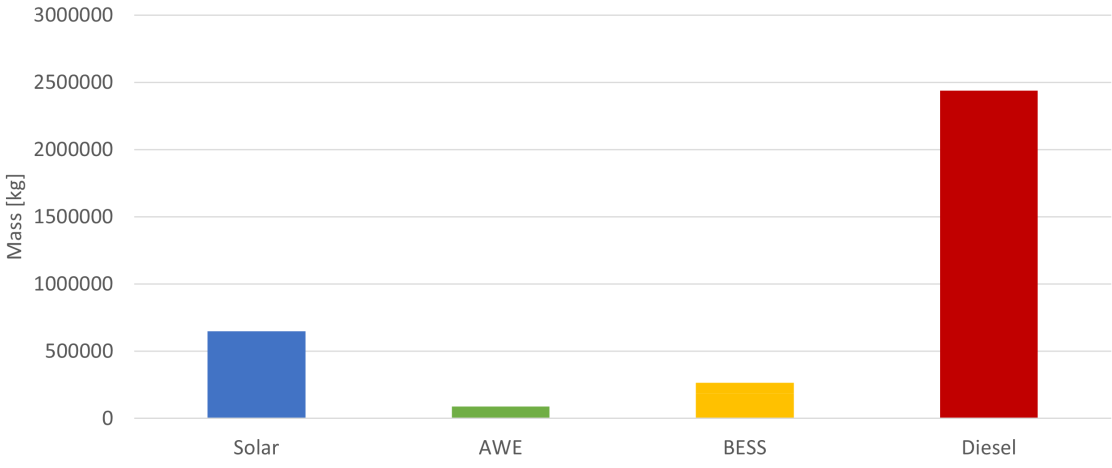

Figure 5.1: Mass of HPP components for configuration 8

Next, the mass per energy generated from the components is presented in Figure 5.2. Note that the BESS is not included as it acts as energy storage rather than an energy generating component. The diesel generator requires the most mass to produce a specific amount of energy.

The diesel generator requires the most mass to produce the same amount of energy. This is followed by the solar plant and AWE system. The diesel generator component has a higher value due to the high mass of fuel required, compared to solar and wind. This result highlights the benefit of using renewable energy technologies both from a sustainability point of view but also for logistics; high fuel mass requirements will require greater transportation capacities. This benefit could be of particular interest in off-grid scenarios where it may be harder to transport fuel to the site.

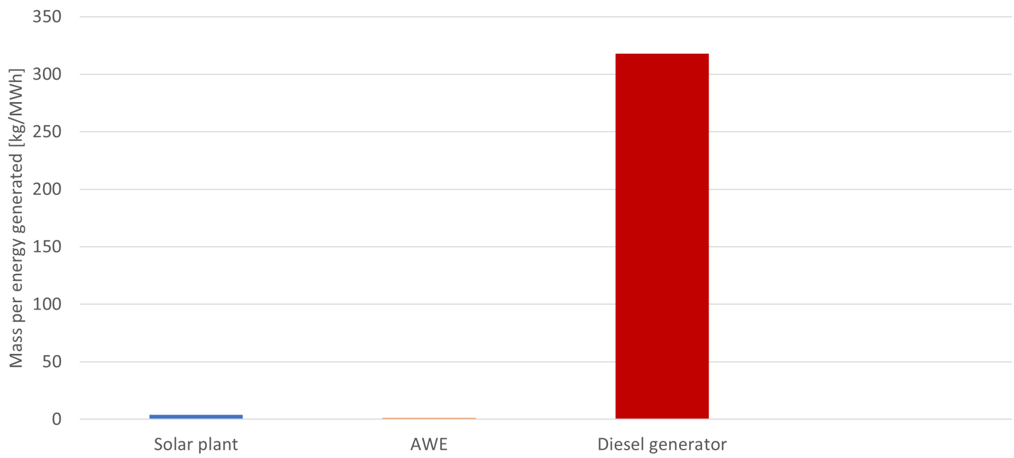

Figure 5.2: Mass per energy generated of HPP components for configuration 8

Impact assessment

Next, configuration 8 is evaluated for its environmental impact using the GWP and CED impact indicators. The results of this have been presented in Figure 5.3 and Figure 5.4, respectively. As expected, both the GWP and CED impact category indicators follow similar trends:

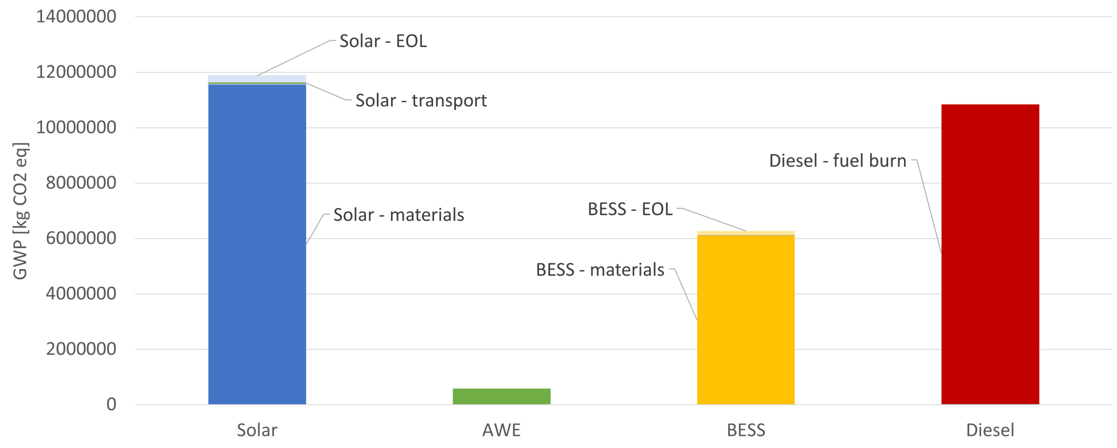

Figure 5.3: GWP of HPP components for configuration 8

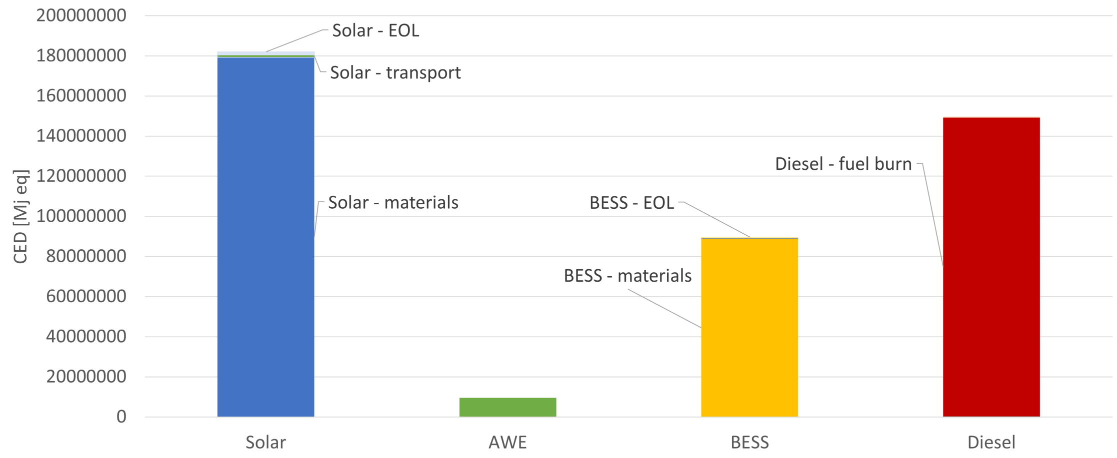

Figure 5.4: CED of HPP components for configuration 8

Configuration 8 employed all components and resulted in the lowest, LCOE, GWP and CED. Within the configuration, The solar component accounts for the highest impact and is closely followed by the diesel generator which only provides 7% of the energy demand. The materials for all components except the diesel generator contribute to majority of the impacts. For the diesel generator, almost all of the impact is attributed to burning of fuel. The AWE component is least impactful by several factors.

5.1.3. Configuration 6: Solar + BESS + AWE

Mass assessment

Configuration 6 represents the HPP without a diesel generator. The mass of the battery now rises significantly. This is because the two sources of energy generation are intermittent energy sources and require a form of energy storage to compensate periods of low or no energy production (no sun or wind resources). Therefore, the battery requires a battery capacity about three times greater than in configuration 8. The higher capacity means a higher mass is required within the configuration.

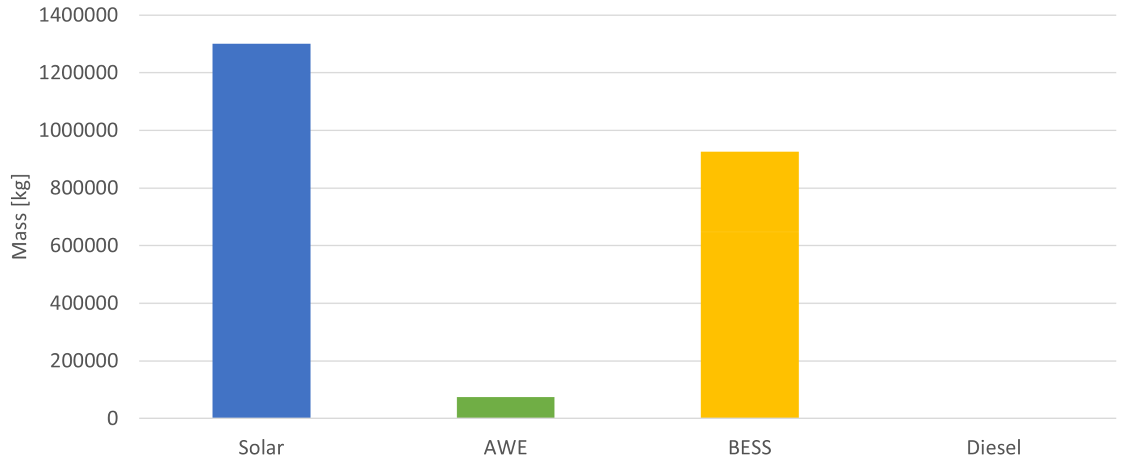

Figure 5.5: Mass of HPP components for configuration 6

Impact assessment

The GWP and CED of the components used in configuration 6 are presented in Figure 5.6 and Figure 5.7, respectively. As the battery capacity is much higher in this configuration, more cells are required leading to a much greater environmental impact with respect to both the GWP and CED. The BESS has the second most impact.

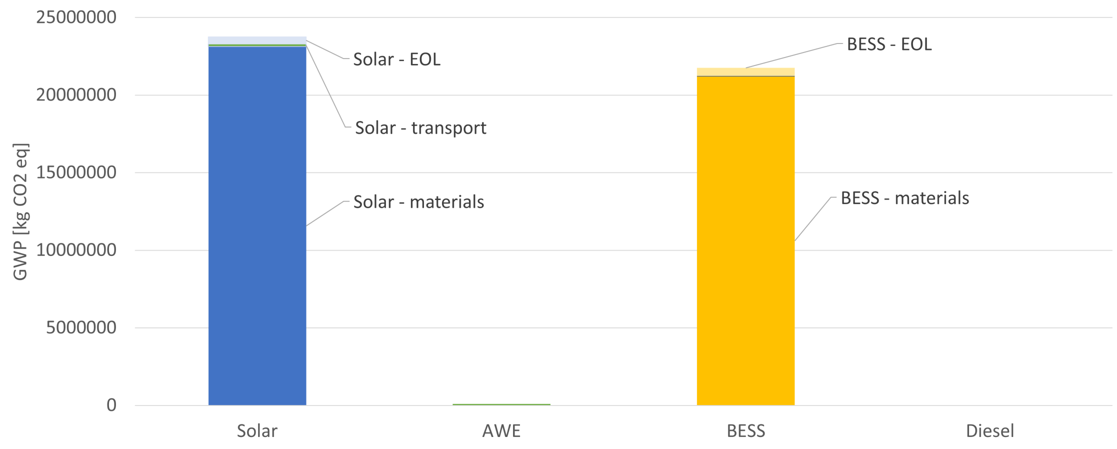

Figure 5.6: GWP of HPP components for configuration 6

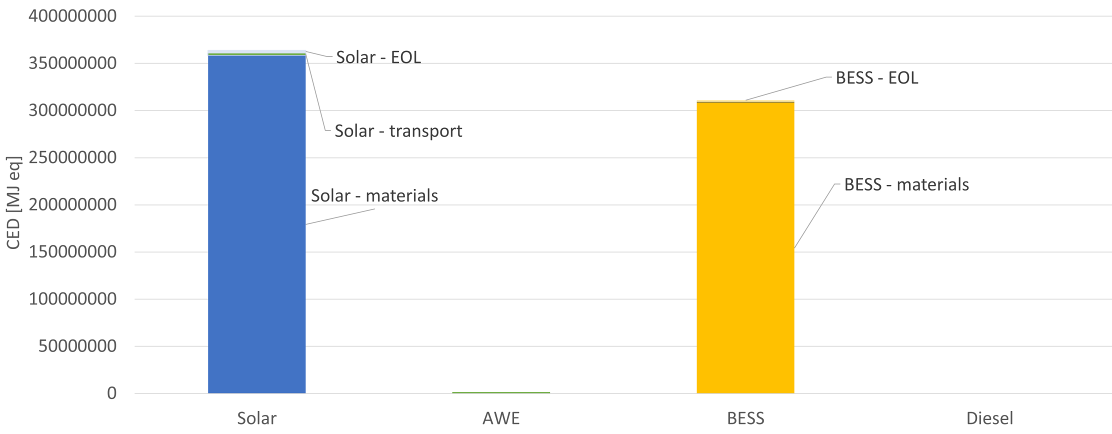

Figure 5.7: CED of HPP components for configuration 6

In general, the solar component must be oversized due to it being a renewable energy source and also its low capacity factor. Nevertheless, solar is used in these configurations as it reduces the LCOE significantly. Over time, the LCOE of the components assessed within this study are subject to change. Being a nascent technology, AWE has potential to reduce its LCOE. Therefore, a study that determines the optimum HPP configuration for both a minimum LCOE and environmental impact in a future scenerio may be of interest to stakeholders in understanding the economic and environmental potential of AWE.

5.1.4. Configuration 7: Solar + AWE + diesel

Mass assessment

Lastly, configuration 7 removes the need for energy storage (BESS) and makes use of the diesel component as a reliable and consistent energy source that can meet the demand. The mass breakdown of the components has been presented in Figure 5.8. As expected, the mass of the diesel component is the greatest because it now provides 24% of the total energy demand resulting in a high mass of diesel fuel. This is followed by the solar and AWE components.

Figure 5.8: Mass of HPP components for configuration 7

Impact assessment

The GWP and CED results have been presented in Figure 5.9 and Figure 5.10, respectively. The trend followed by the environmental impact indicators is the same as that of the mass. The only discrepancy is that the diesel component takes up a higher share of the total result for the mass when compared to the share it takes up for the environmental impact.

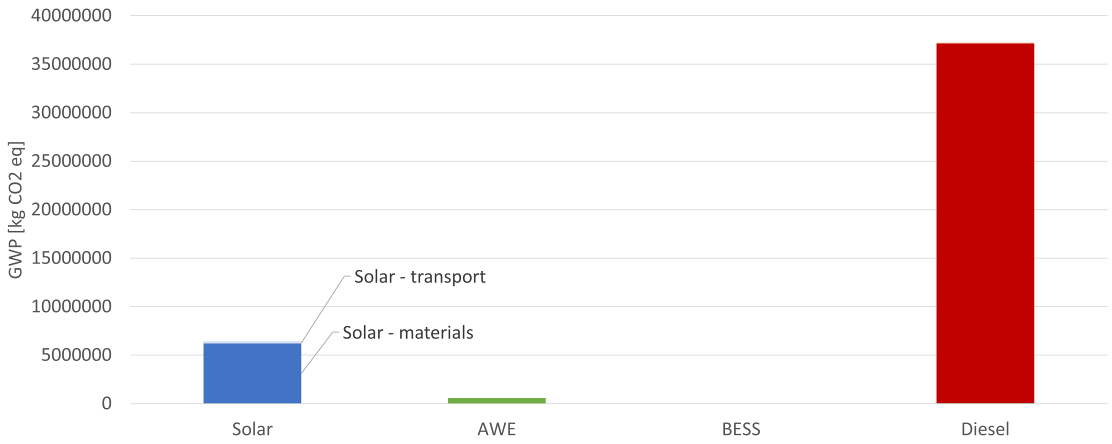

Figure 5.9: GWP of HPP components for configuration 7

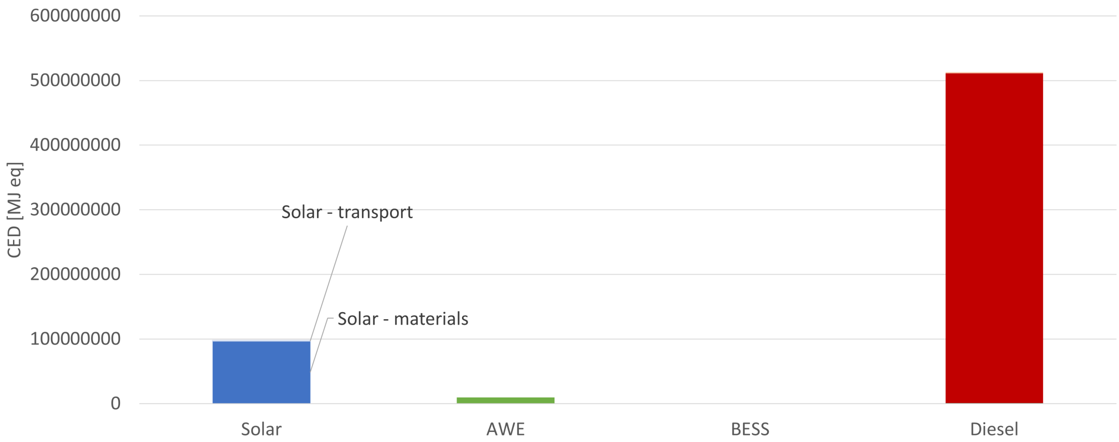

Figure 5.10: CED of HPP components for configuration 7

The impact of the diesel generator is several factors greater than the other components used within the HPP. This result shows clear motivation to minimize the use of diesel generators to reduce environmental impact.

5.2. Interpretation

After completing the impact assessment of the configurations of interest in section 5.1, an interpretation of the results can be executed. Firstly, the mass per energy generated for the diesel generator is the highest, followed by the solar power plant, battery system and AWE. The mass assessment on the configurations consistently shows that AWE requires less mass to produce the same amount of energy. This proves the potential of AWE to be beneficial in off-grid applications where transporting larger masses may not be feasible.

The AWE component within a HPP also has significantly lower environmental in general. This is because of the lower requirement on resources for manufacturing and operation. The manufacturing of the solar component is the most impactful stage within its lifetime. While the manufacturing of a diesel generator is relatively negligible compared to other technologies, the burning of diesel fuel during operation has an overwhelming impact on the environment. Additionally, the high masses of diesel fuel are also required to be transported to the site. While this activity is not significant in terms of environmental impact, it is an important consideration for the convenience of operation for future implementation of off-grid HPPs. The BESS can also have a relatively high impact if a high capacity is required. This occurs in configuration 6 when there is no diesel generator to provide constant energy to the base load. The impact per kg for each HPP component in configuration 8 is presented in Figure 5.11.

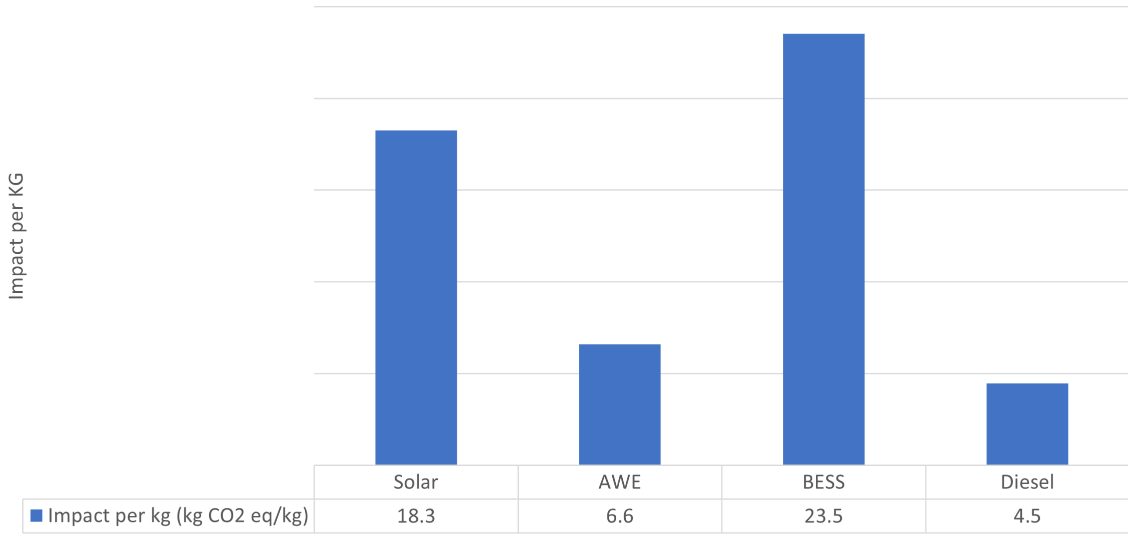

Figure 5.11: Impact per mass for the different components in configuration 8

Figure 5.11 shows that the BESS is the most impactful component by mass within the system. This could be because of the precious metals and hazardous electronic materials that are used to make lithium battery cells. The solar component is also impactful despite being a renewable energy technology. Lastly, AWE and diesel are close in terms of this impact. However, the mass per kg of diesel includes the mass of diesel fuel required over the operational lifetime. If this mass is not included in the calculation, then the mass specific impact of diesel results in a specific impact of 5693 kg CO2 eq per kg.

Therefore, it can be concluded that AWE is a promising technology to be used in off-grid HPPs due to its lower material use and environmental impact compared to other energy technologies. Nevertheless, it would be beneficial to include a constant power source in the form of a diesel generator to not oversize the renewables and battery. Incorporating all components in the HPP leads to the lowest overall environmental impact.

Table 5.4: Environmental impacts normalized by component energy share

Component	Normalized GWP (kg CO2 eq/MWh)	Normalized CED (MJ eq/MWh)
Solar	70.2	1075.9
AWE	8.6	144.1
Diesel	1416.0	19506.4

Table 5.1 shows the impacts of each configuration normalized by the total energy production of the plant. This table is useful to determine which configuration has the best environmental performance but it does not clearly show the environmental performance of each component within the configuration. To do this, the environmental impacts of a component must be normalized by the energy produced by the component itself. These results have been presented in Table 5.4. The BESS component is not included as it functions as an energy storage rather than an energy source. Therefore, normalization by its capacity would not be a comparable metric with the other components.

The AWE component performs the best, being a magnitude(s) smaller than solar and diesel. This result shows why AWE systems could be crucial in making the energy transition a reality. These systems not only perform efficiently by generating the most useful energy per kilogram of system but they also generate the most electricity with significantly less emissions and energy consumption. Even other renewable energy sources such as solar modules end up having a greater environmental impact due to the higher surface area and material requirements to produce the same amount of energy. Therefore, such a result is powerful for stakeholders in the technology to inform policy and decision makers within the renewable energy industry and government to enable more funding and improve legislation for this technology.

Table 5.4 also shows that while the diesel component has the lowest mass specific impact, its impact per energy generated is much higher meaning that it has a low environmental performance. Therefore, while it is beneficial to include a diesel generator in an off-grid plant to avoid power outage and maintain a reliable source of energy, it is an objective to minimize the size of this generator within the plant as much as possible to improve the environmental performance of the overall configuration. For future work, it is recommended to combine this LCA with the optimization model in [6], and perform a multi-disciplinary optimization that minimizes both LCoE and the environmental impact indicators to obtain the optimum sizing parameters for the HPP configuration.

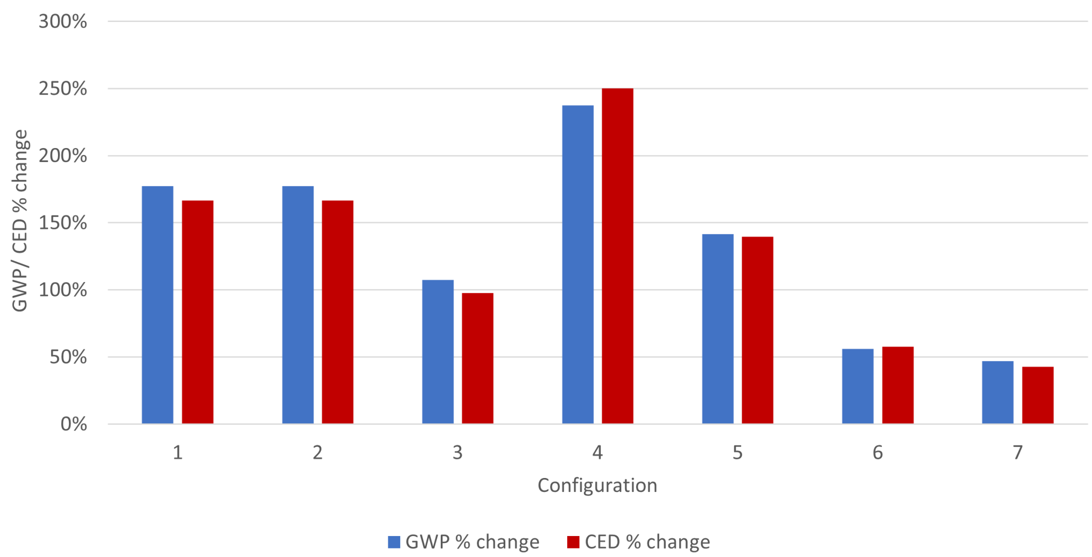

Figure 5.12: Percentage changes in impact with respect to configuration 8 in the HPP

The percentage change relative to the impacts for configuration 8 have been presented in Figure 5.12. The worst performing configuration with respect to environmental impact is configuration 4, which uses only solar for energy generation and BESS for energy storage. This result is in line with Figure 5.11 which shows that these components are the most impactful. In a case where it may not be possible to use solar in the off-grid HPP, for instance, the land requirement may not be possible, the environmental impact for this is relatively better than other configurations. This is supported by the result for configuration 3. If it is not possible to use all technologies within the HPP, the next best choice would be to either use no diesel generator or no battery. This is represented by configurations 6 and 7 respectively. However, these configurations still under-preform in terms of environmental impact by around 50%.

Therefore, it is most beneficial to include all technologies within an off-grid HPP.

6 Conclusions & recommendations

The goal of this research was to perform the detailed life cycle assessment of a 100 kW soft-wing ground-gen airborne wind energy system. This analysis aimed to evaluate the environmental impact of the system and provide valuable insights to stakeholders and policymakers in the renewable energy industry. The LCA included all lifecycle stages of the system: from cradle-to-grave. The environmental impact was assessed using the GWP and CED. The methodology for the study was derived from the ISO 14040 and ISO 14044 guidelines and documents the following LCA stages: goal & scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. Additionally, the application of the AWE system in off-grid hybrid power plant configurations was also studied and the environmental impacts assessed.

6.1. Detailed life cycle assessment of the AWE system

For the detailed life cycle assessment of the AWE system, the functional unit used was: 'Annual electricity production of 450 MWh, generated by an airborne wind energy system' with reference flow: 'One soft-wing ground gen 100kW AWE system with a lifetime of 25 years'. After completing the life cycle assessment of the system, the GWP and CED are 8.6 kg CO2 eq per MWh and 144.1 Mj eq per MWh respectively.

- **The ground station was identified as the component with the greatest environmental impact in a soft-wing AWE system.**

The ground station is the heaviest component of the system. As a consequence, it uses the most materials and therefore outputs the most emissions and consumes the most energy. The next most impactful sub-components also belonged to the ground station; these were the housing, frame and generator. The housing of the ground station was identified as the greatest environmental impact contributor, primarily due to its high mass. It had a greater impact than the metallic frame of the ground station despite having a lower mass. The materials and manufacturing stage of the system life cycle is attributed with the most environmental impact followed by the operations & maintenance phase when the replacement of materials are factored in. Transport & installation and EOL activities had relatively insignificant impacts. This is a typical trend followed for renewable systems; alternatively, diesel generators have most impacts attributed to the operations & maintenance phase due to diesel fuel burning and fuel transport.

- **The kite and tether are the most impactful components by mass**

The kite and tether materials also had significant impacts due to their high mass-specific impacts and replacement frequency. This result showed that the kite and tether are made from materials of relatively high environmental intensity. For instance, an analysis on the environmental impact per kilogram of each component showed that the ground station had the least impact. Conversely, the Kite Control Unit (KCU), despite having many sub-components, had a smaller overall impact. Therefore, it is recommended to focus research and development on the sustainability of the ground station sub-components, and the kite and tether materials.

A sensitivity analysis revealed that variations in the datasets used to model the ground station housing could influence the results. Developing an AWE-specific dataset to accurately model the shipping container used in the housing is recommended. Additionally, extending the lifetimes of kite and tether materials would significantly reduce the overall environmental impacts. Doubling the system's operational lifetime could decrease environmental impacts by almost 50 %, highlighting the importance of building systems and projects with long lifetimes.

The lifetime of the kite and tether materials could also have significant effects on the overall results. This is especially the case if the lifetimes of these sub-components were reduced. This could show that while research and development on the lifetime of the materials used in the kite and tether is beneficial, it could also be more beneficial to optimize the mass of material used in these components.

- **It could be worthwhile to develop appropriate waste treatment policies and recycling programs to improve the environmental performance of AWE systems in the future.**

The benefit of recycling was also quantified by extending the system boundary and using the avoided burden approach. In this approach, the impact of recycling along with the theoretical benefit of avoiding the production of virgin raw materials was presented. Using the avoided burden approach, the normalized GWP and CED decreased to 14% and 12% respectively.

6.2. Comparative study on airborne wind energy in an off-grid hybrid power plant setting

After completing the detailed life cycle assessment of the AWE system, a comparative study of its application in configurations within an off-grid hybrid power plant could be analyzed. The location data and sizing of the components were adapted from a previous sizing study for a HPP using combinations of a solar plant, AWE system(s), BESS and diesel generator to provide power to a military base located in Marseille, France. The functional unit for this study was: 'An annual electric production of 4383 MWh, from a configuration within an off-grid hybrid power plant.' The reference flow also changes to: 'One 500 kW hybrid power plant with a lifetime of 25 years.'

Before evaluating the environmental performance of the different configurations, streamlined LCAs for the remaining components of the HPP were executed and documented. The methodology for this was similar to the detailed LCA on the AWE system, and majority of the data used was taken from datasets for these components already available in ecoinvent.

- **The AWE component consistently performed well for mass and environmental impact.**

Configurations 5, 6 and 8 were further assessed to evaluate the impact of AWE systems replacing diesel generators in an off-grid setting. The diesel generator had the highest mass, majority of this was attributed to the mass of fuel burned. This was followed by the Solar, BESS and AWE components. The low impact from the AWE component was due to a lower demand on resources during manufacturing and operations. The sizing of the diesel generator and BESS can have significant influence on the results. The majority of the environmental impact for a diesel generator is attributed to the burning of fuel during operation, while the impact of the BESS comes from the materials used. Using solely diesel generators in off-grid applications could also be inconvenient from a logistics point of view due to the high masses of fuel required during the operations and maintenance phase.

- **Incorporating all components in the HPP performed the best for both LCoE and environmental impact.**

This is because the oversizing of the renewables is decreased due to the presence of a constant energy source such as a diesel generator, and an energy storage device. This is an interesting result for stakeholders and policy makers as it shows that the most economic configuration is also the most sustainable.

6.3. Recommendations

The findings of the research lead to several key recommendations that could be used to both improve the environmental performance of AWE systems and the quality of this study. These have been listed below:

- **Generate AWE-specific datasets for components and sub-components**

The study made use of proxies for materials and processes due to the unavailability of specific data. Some examples of these include the housing of the ground station and the kite textile material. Developing detailed datasets that are specific to AWE components will improve the accuracy of the study and also facilitate these studies for other AWE systems. This will also help further development in the AWE industry from a sustainability point of view.

- **Minimize the mass and environmental impacts of the ground station**

The ground station was identified as a hotspot for both mass and environmental impact. Research and development of this component to minimize its mass and environmental impact should be conducted to lower the overall environmental impact of the system. This could be done by avoiding the overdesigning of the ground station sub-components and investigating the use of less impactful materials and processes during manufacturing. The development of a unique housing rather than the use of standardised shipping containers could also be beneficial to the eco-design of the system.

- **Improve lifetimes of kite and tether**

The kite and tether were the most replaced components, resulting in a significant increase in their mass shares over the system lifetime. Additionally, both of these components had the highest specific impacts. Therefore, it would be beneficial to research and design solutions to increase the lifetimes of these components.

- **Expand assessment by using a multitude of impact category indicators**

While this study primarily used GWP and CED as impact indicators, a more detailed analysis using a broader range of impact categories could provide a more holistic understanding of the environmental impacts. Therefore, the scope of the study could be expanded to include an extensive set of impact indicators to capture all potential environmental effects. Examples of the indicators that could be used are: resource depletion, ozone formation and ecotoxicity.

- **Integrate LCA model into holistic assessments**

LCA's are useful to evaluate the environmental impact of a system. Implementing the LCA model within a broader techno-economic framework could provide a more complete assessment of AWE systems. Given that this work could be used as a base for soft-wing AWE systems, the model developed could be extended to an LCSA. This approach would help stakeholder in evaluating not only its environmental impacts, such as global warming potential (GWP) and cumulative energy demand (CED), but also its economic viability and social implications. Additionally, this would enable more informed decisions for policy makers.

The implementation of these recommendations could not only improve the current sustainability of AWE systems but also ensure their long-term viability and acceptance as a key component in renewable energy solutions.

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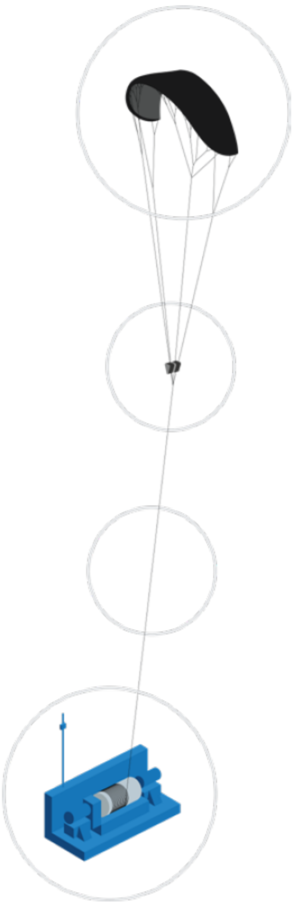
A

Kitepower product specifications

More detailed specifications on the Kitepower ’Falcon’ AWE system can be found in the following pages:

System Components & Space Requirements

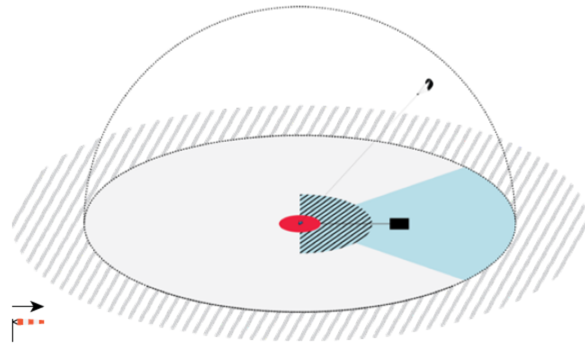


Kite
Consists of an inflatable membrane wing with reinforced tubular frame, forming the best combination for a strong and lightweight wing.

Kite Control Unit (KCU)
Used to steer the kite, control its pulling force and wirelessly connect the sensor unit placed on the kite to the GS.

Tether
Dyneema® line for a lightweight and strong connection between the kite and the GS.

Ground Station (GS)
Converts the mechanical energy of the kite into electrical power and reels the kite in by using the generator as a motor.



Zone	Dimensions	Dual Land-use[1]
Restricted Zone	30 m (r)	
Flight Zone	300 m (r)	√
Potential Flight Zone	300 m (r)	√
Safety Buffer	400 m (r)	√
Landing Zone	100 m (r)	
Launching Corridor	150x2 m	
Launch Pad	24x12 m	

Obstacles' height within operational envelope:
1m allowance every 10m of distance from the GS

[1] Land can be used for alternative activities while Kitepower is deployed.
(r) = Radius

The Kitepower Falcon

Technical Summary

General Information

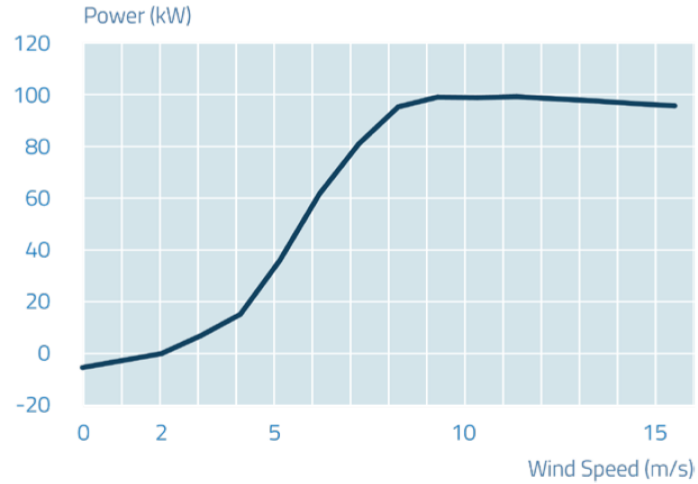
Nominal Power Output[1]	100 kW
Yearly Power Output	450 MWh/year
Rated Wind Speed	7 m/s
Cut-in wind Speed	2 m/s
Max Operating Wind Speed	15 m/s
Min Launching Speed	5 m/s
Airborne Wind Range	0-25 m/s
Max Flight Altitude	300 m
Ground Space Required[2] (radius)	300 m

[1] Power output potential might differ depending on the kite variant
[2] The ground space must be free of obstacles

Kite

Variant	V9.60
Size flat (m^2)	60 m^2
Size projected (m^2)	47 m^2
Force (t)	3,5 t
Lifetime (hours)	4000h
Avg. Flight Speed (km/h)	110 km/h
Air Traffic Lights	√
Airborne Pump	√
Field Pump	√
Sensor Unit	√
Kite Bags	√
Safety Line	√
Landing Protection	√
Safety Attachment Points	√
Parachute Landing	√

Power Curves



KCU

Weight	23 kg
IP Rating	IP65
Wireless communication link	2 km
Built-in Alarm	90 dB
Airborne Power Supply	√
Protective Cover	√
Air Traffic Lights	√
Airborne Wind Turbine	√
Protection Cover	√
Safety Release	√
Health Supervisor	√

Ground Station

Main Dimensions	W: 2,44 m H: 2,60 m L: 6,06 m
Weight	9.6 t
IP Rating	IP64
Lifetime	25 years
AC Power output	400V AC 3 phase
DC power output	550-700 V
Nominal Power	100kW
Peak Power	120 kW AC / 250 kW DC
Connection mode	Power lock or screw terminals
Built-in Alarm	90 dB
Launch Unit	√
Safety Emergency Stop	√
Health Supervisor	√

Tether

Type	UHMWPE Dyneema®
Length (default)	450 m
Passive Safety Release	√

+ More information can be found within *The Kitepower Falcon 100kW Technical Specification Document.*