Department of Mechanical and Aerospace Engineering

A Comparative Life Cycle Assessment of various End of Life Decisions on Onshore Wind Turbines.

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A thesis submitted in partial fulfilment for the requirement of degree in
Master of Science in Sustainable Engineering: Renewable Energy Systems and the
Environment

August 2021

Copyright Declaration

Abstract

Advancements in recent years within the wind industry has seen a shift in the trend of installation of new wind projects from onshore to offshore. However, in the past the installed capacity of wind was largely onshore and therefore due to the 20 – 25 year lifespan of wind turbines, 32% of the UKs installed onshore wind capacity is coming to the end of its life. When facing end of life; there are three options, firstly Scenario 1; to decommission, in which case the turbines will be disassembled, disposed of and the site will be restored to a natural state. Secondly, lifetime extension is possible through Scenario 2; Refurbishment of wind turbine components, where faulty or low functioning components may be treated and restored to factory standard. Finally, there is the option of Scenario 3; Repower, where the original turbine will be decommissioned and a new, usually larger turbine will be installed in its place. Scenarios 2 and 3 both provide technically feasible options for lifetime extension, however the climate crisis requires improved sustainability, across all energy infrastructure; including renewables. In order to compare and deduce which EoL options provide the least potential impacts to the environment, Life Cycle Assessment (LCA) is performed. Data is gathered to provide inputs for the LCA software used; openLCA in conjunction with the ecoinvent database. Two case studies are used within the project; Stranoch 2 Wind Farm, a proposed 20 turbine onshore wind farm in the South West of Scotland to gain inputs on transport and turbine specifications associated with the manufacturing and installation of turbines. A second case study; an industry interview with Renewable Parts LTD provides data on the process of refurbishment for Scenario 2. Environmental Impact Assessment methods ReCiPe mid and end point are used, as well as Green House Gas Protocol to identify the potential impacts of the options. Results of the LCA show that the production and manufacturing stages consistently pose the greatest environmental impact, particularly that of the foundations. Manufacturing of the foundations accounts for 62% of carbon emissions from manufacturing and transporting the entire wind turbine. Transportation closely follows behind, resulting in large contributions of Fossil CO2eq into the atmosphere. Scenario 3; Repowering is found to be the least Sustainable option, due to the second full production and manufacturing process. Refurbishment is found to only produce a small amount of emissions over Decommissioning, with decommissioning producing the least emissions. In instances when recirculated parts are used within Refurbishment, the only additional emissions come from the transport of parts to and from the Refurbishment facility.

Acknowledgements

I would like to thank Dr David Butler, for the invaluable advice and academic support throughout the writing of this thesis.

I would also like to thank my classmates, friends and family for the emotional and wellbeing support throughout the duration of this project. I could not have completed it without such supportive people in my life.

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Nomenclature

Symbol	Description
EoL	End of Life
LCA	Life Cycle Assessment
EIA	Environmental Impact Assessment
SNH	Scottish National Heritage
GIS	Geographic Information Systems
GHG	Greenhouse Gas
RDP	Restoration and Decommissioning Plan
GWP	Global Warming Potential
RPL	Renewable Parts LTD
O&M	Operations and Maintenance

1.0 Introduction

This project aims to assess the potential environmental impacts of various end of life decisions on onshore wind turbines. A comparative Life Cycle Assessment (LCA) of the options of decommissioning, remanufacturing and repowering is undertaken to assess the potential impacts and determine the option which is best for the environment. This chapter will provide a background to the project and area of study; an introduction to renewable wind technology in 1.1, the generation of wind power in sections 1.2 and 1.3 End of Life (EOL) options. Section 1.4 will provide an introduction to the analysis method used within the project: LCA and the objectives and scope of the project and will be detailed in section 1.5. Finally, the structure of the thesis and all remaining sections of the thesis will be summarised in section 1.6.

1.1 Introduction to Renewable Wind Technology

The need for Renewable Energy is well established, with climate change occurring at an alarming rate, one of the main contributing factors is the use of finite resources for Energy. Oil and gas have predominantly fuelled all sectors; heating, electricity and transport, for decades. With the depletion of finite resources and the damage caused to the Ozone, an increasingly inherent need for the transition to an alternative production of energy is apparent. Wind power generation is one of the most established renewable energy sources in Europe (WindEurope, 2020). Wind turbines operate by the energy of the wind propelling 3 turbine blades, these blades are connected to a shaft which spins a generator to create electricity (Energy.gov, 2020). The structure of a wind turbine is illustrated as in figure 1.

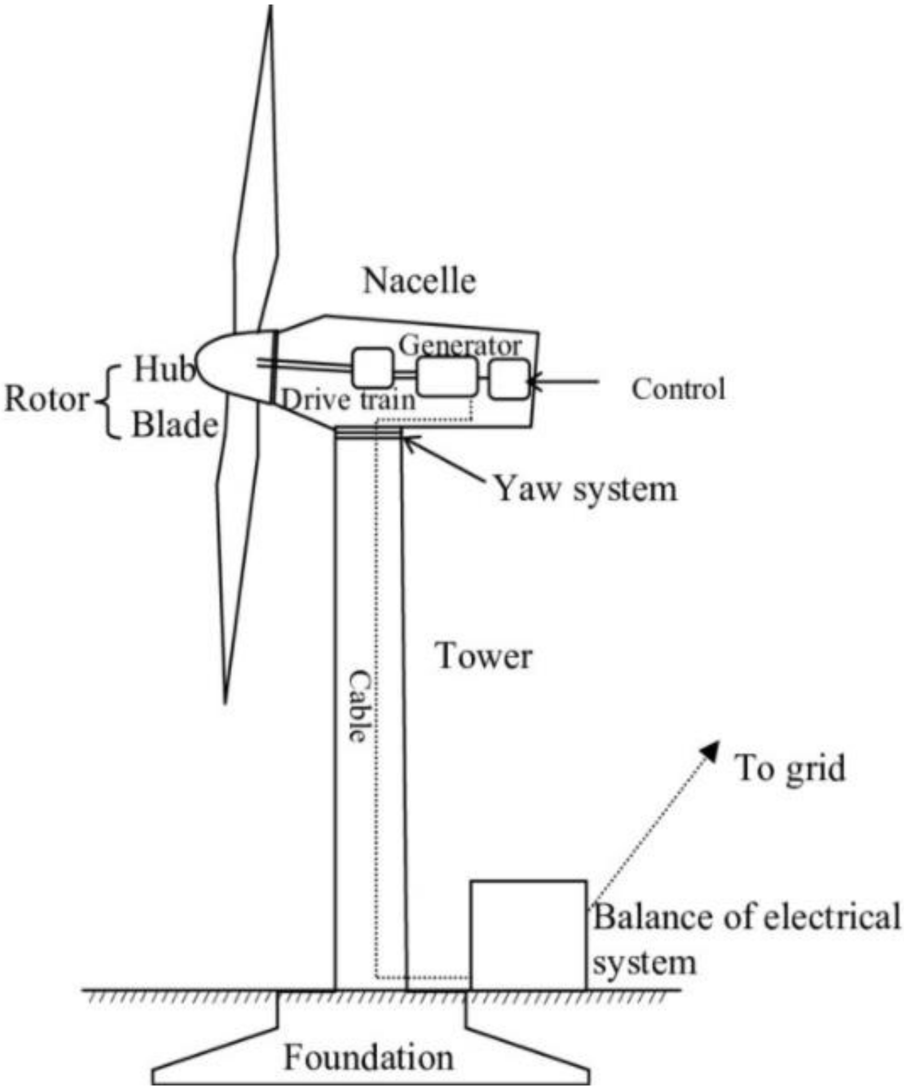

Figure 1- Structure and components of a typical onshore wind turbine (Albadi, 2010).

1.2 The Generation of Wind Power

The generation of power for the heating and electricity networks is increasingly done so by renewable technology. Solar, hydro, tidal, wave and biomass all contribute towards renewable generation in Scotland, however the installed capacity of wind power far exceeds that of these technologies combined, as illustrated in figure 2 (Scottish Renewables, 2020). As Scotland is one of the windiest countries in the UK, further implementation of wind power boasts large generation potential (Met Office, 2020).

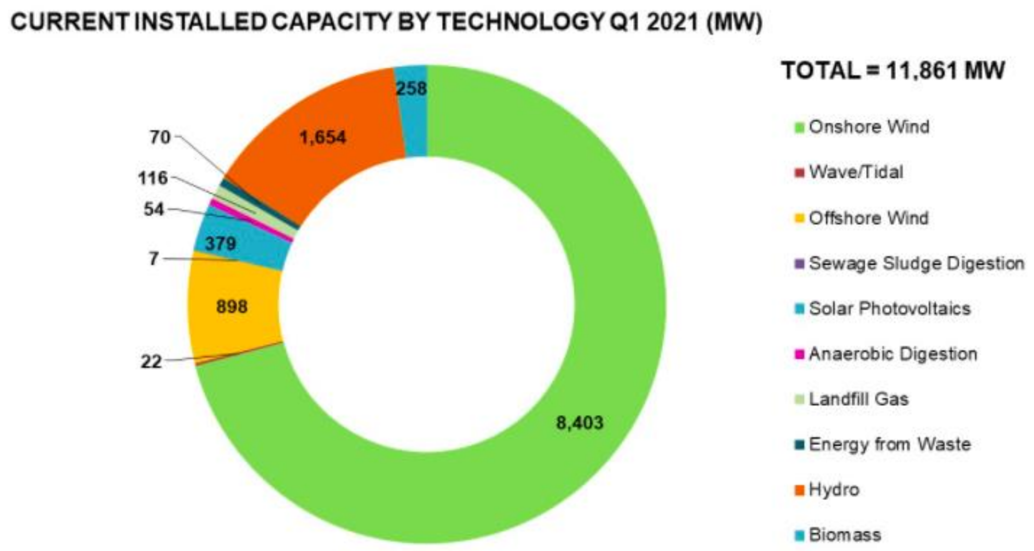

Figure 2- The current installed capacity by renewable technology in quarter 1 of 2021 in MW. Onshore wind generation provides the largest installed capacity (Scottish Renewables, 2020).

Figure 2 illustrates the current installed capacities of renewable technologies in Scotland, highlighting that onshore wind provides 70.8% of the installed renewable generation capacity for Scotland, resulting in the electricity, heating and more recently transport sectors all incredibly reliant on the capacity of onshore wind generation. Within the installed capacity of wind generation, onshore wind generation attributes 90.3%, with offshore attributing 9.7%, however trends are displaying a shift in new installed wind projects from onshore to offshore. Figure 3 illustrates the trends of renewable electricity generation, from installed onshore vs offshore wind in Scotland from the years 2010 to 2019. Although the generation from onshore wind contributes a far larger percentage of total capacity in 2019 – 40% - than in 2010- 20%. Onshore wind capacity still attributes the largest proportion.

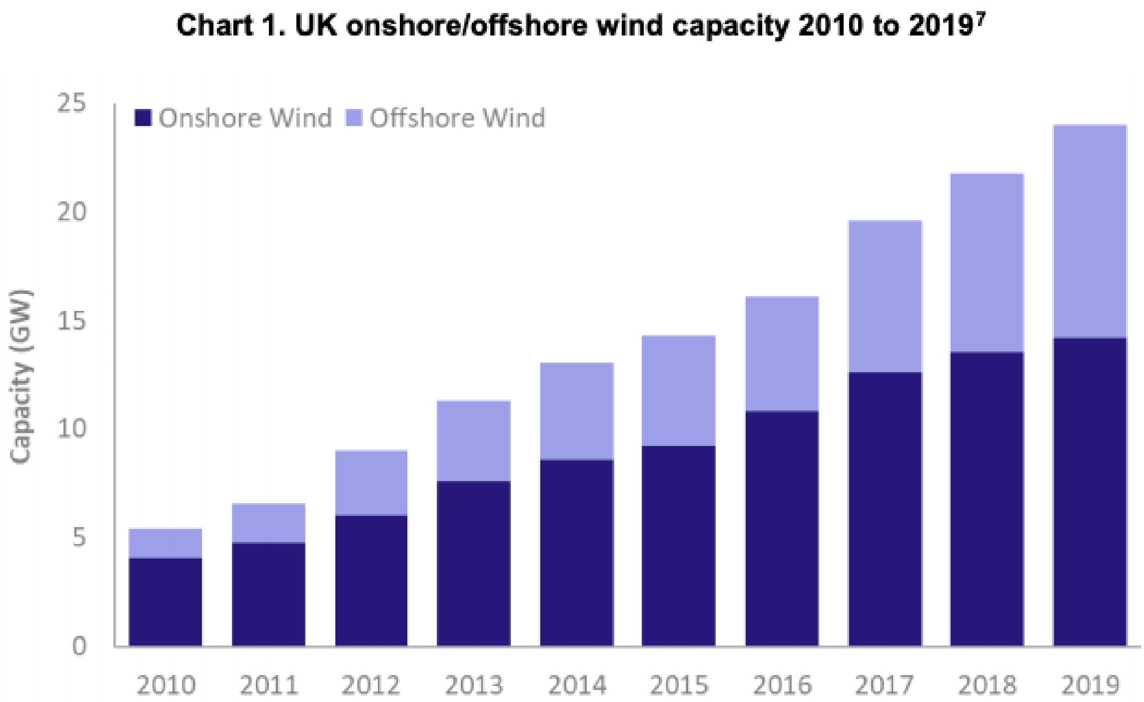

Figure 3- Onshore vs offshore installed capacity in GW from the year 2010, to the year 2019. Installed capacity of both increased throughout the years, however onshore wind still contributes the largest percentage of total capacity (Gov, 2020).

Typically, wind turbines have a lifetime of 20-25 years, meaning that a large percentage of the current installed capacity of onshore wind in Scotland is soon approaching the end of its life. Due to the reliance of the electricity, heating and transport sectors on the onshore wind installed capacity, this is potentially detrimental. Figure 4 provides insight into the ageing population of installed onshore wind turbines throughout seven countries in Europe, with the majority of the ageing population in Denmark, Spain and Germany. However, 32% of the UKs installed onshore wind capacity is already at, or will be coming to the end of its life within the next 5 to 10 years.

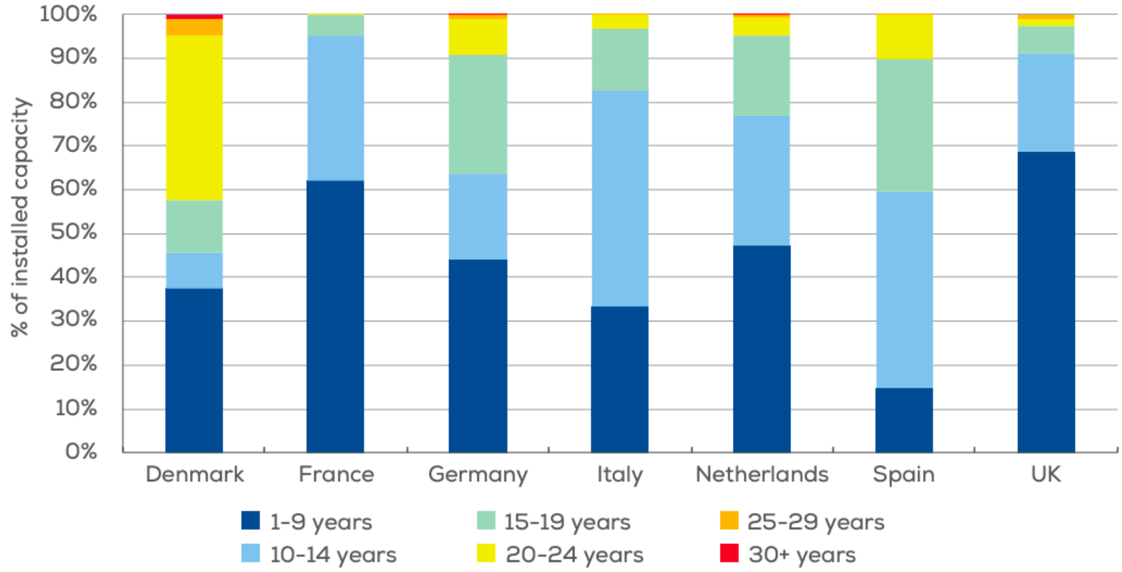

Figure 4- The percentage of installed onshore wind capacity by age through-out seven countries within Europe- Denmark, France, Germany, Italy, Netherlands, Spain and the UK (WindEurope, 2020).

Additionally, the intermittent nature of renewable generation, means with a growing demand for a renewable supply, there must be a growing installed capacity and storage to meet it. The Scottish government pledged to reach 100% of electricity generation by renewables in 2020, and ambitiously pledge to achieve 50% of generation from all sectors to be renewable by 2030 (Scottish Government, 2016). As onshore wind power contributes so largely to the renewable generation, onshore wind technology is crucial in achieving, maintaining or even surpassing such generation pledges. Future roadmaps for the green transition include plans to expand and integrate renewable technology, with increased electric vehicle use and charging ports, a growing green hydrogen (commonly produced by wind power) economy and renewable reliable smart grids (IRENA, 2020). Therefore, with EoL approaching for much of the onshore fleet, in order to not deplete the overall capacity of onshore wind generation, actions must be taken to extend the lifetime of the turbines. As a turbine reaches EoL, there are numerous options of action to take; firstly to decommission, secondly to remanufacture or finally, to repower.

1.3 End-of-Life Options

Once a turbine, or fleet of turbines within a wind farm reach the end of their 20 – 25 year lifespan, there are numerous routes of action. Turbines can either be decommissioned, remanufactured or repowered as illustrated in figure 5, with the options providing varied extension periods.

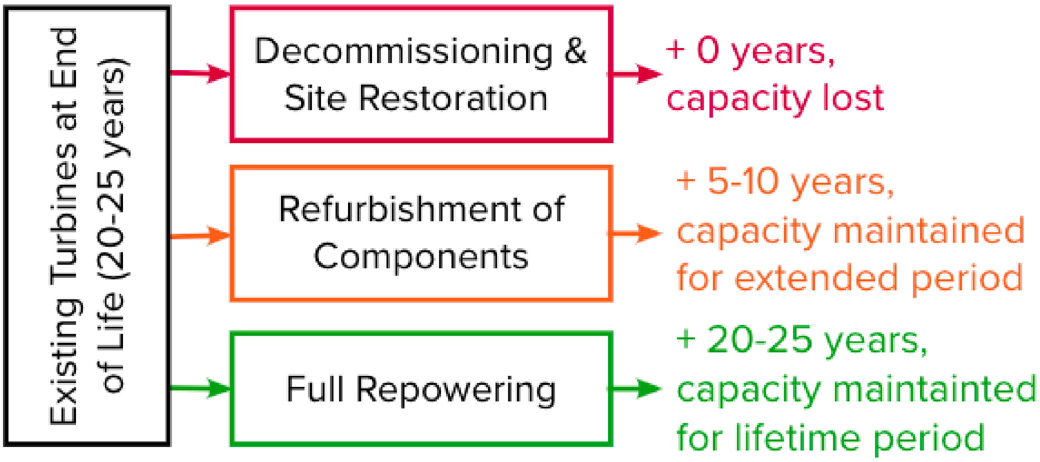

Figure 5-Flow chart of End of Life pathways for Turbines after 20-25 years of operation. With full repowering providing the greatest extension period, remanufacturing providing a shorter extension period and decommissioning providing to period of extension (Jensen, 2021).

Firstly, in the case where a wind farm may choose to decommission, all turbines will be dismantled and foundations, cabling and all other infrastructure at the site will be removed and transported to waste management facilities. In most cases, the land of the wind farm will be restored completely back to a natural state, however in some cases where it may be deemed too detrimental to remove all structures, partial decommissioning will occur, whereby parts of the structures will be left in place. Upon dismantling, the components of the turbine may either be repurposed, recycled where possible or sent to landfill. Decommissioning plans will be included in the initial Environmental Impact Assessment (EIA) reports conducted when new wind farm projects are being proposed, with an outline of the processes necessary to restore the specific site back to a natural state (Hall, João and Knapp, 2020). Responsible disposal of turbine parts will be dependent on each country and the framework set out for recycling of metals, plastics and concrete components.

A secondary option is to remanufacture certain components of the wind turbines, to restore the operation of the turbine back to the original manufactured capacity. Many different components of the turbine can be remanufactured, commonly the turbine blades are refurbished to restore the turbine to factory state. However, components within the nacelle of a wind turbine are more likely to cause system failure, such as the hydraulics system, electrical system or gearbox (Local Energy Scotland, 2016). Remanufacturing these components within the turbine can provide a lifetime extension of 5-10 years, with regular maintenance of the turbines. It is important to note that the process of remanufacturing will coincide with features of the decommissioning process, whereby it will first require the dismantling of the turbine, and then components replaced within the remanufacturing process must be disposed of or recycled responsibly.

Finally, and most commonly there is the option to repower. Repowering entails the dismantling and disposal of the original turbine, to be replaced with a newer, usually bigger and higher capacity turbine. This results in wind farms with a fleet of larger turbines, therefore a site with a greater output. This option requires the dismantling and disposal of the original turbine, however the site infrastructure may be re used, such as parts of the foundations, electrical connections and the battery storage.

Currently, the industry is lacking a "best practise" pathway set to address the EoL of wind turbines, concern is consistently placed upon the need to meet the demand of capacity, however there is little no thought or consideration of how the steps taken to meet the growing demand may impact the environment. Although remanufacturing and repowering are desirable lifetime extension options, it is important to note there will inevitably be the time when decommissioning will have to occur. This is why it is essential to assess the environmental impacts of the different options, from the cradle to the grave.

1.4 Introduction to Life Cycle Assessment

LCA is an effective tool to assess the environmental impacts as it takes into consideration all stages of the life cycle of turbines, LCA follows the creation of a product, to the use and eventually disposal of said product. In doing so it takes into consideration the energy, labour, materials input to manufacturing of products, any energy, labours or materials used throughout operation, the emissions produced from the processes within manufacturing and the processes of transport, from material extraction, to product delivery. LCA will also encompass the final stages of product life, with the end of use disposal or recycling also taken into consideration, and the emissions and waste associated with the energy taken to recycle or send to landfill. A typical system boundary for a LCA is shown in figure 6, where inputs and outputs of the product system can be seen on the left and right, respectively.

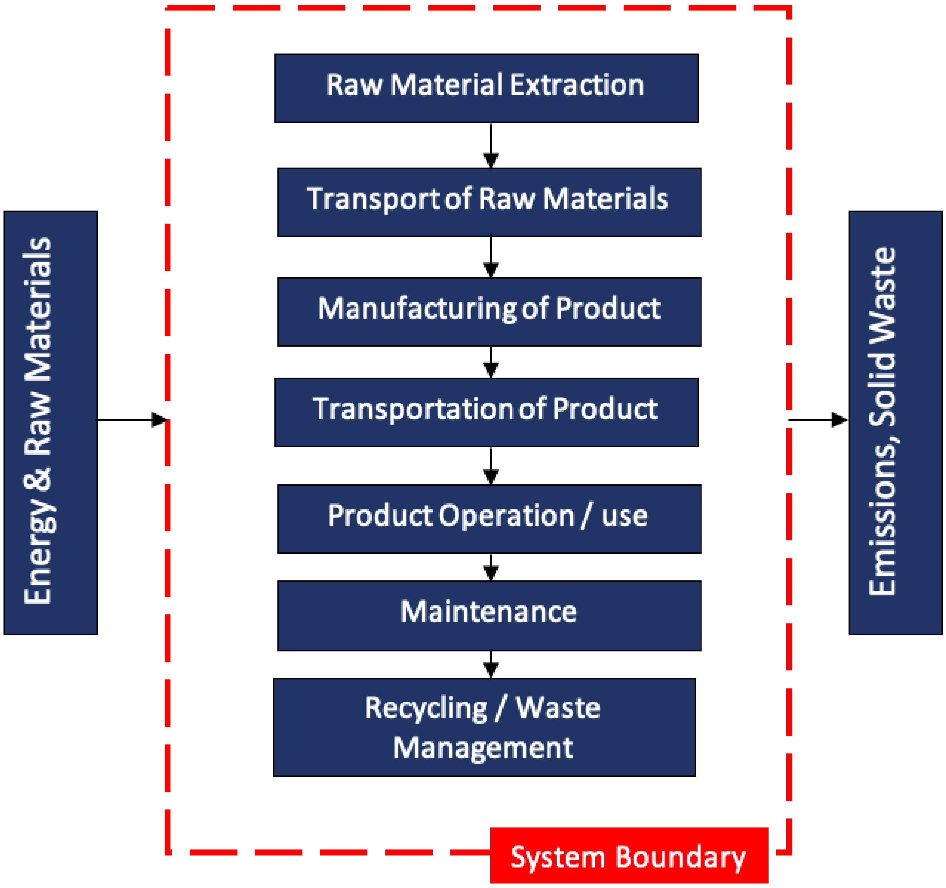

Figure 6- Typical System Boundary for a product for Life Cycle Assessment, where inputs of energy and raw materials allow for the processes within the system boundary. Emissions and solid waste are the resultant outputs.

Once all processes within a products life cycle are taken into consideration, it is possible to assess the environmental impacts of a product. This may be done by looking at the energy consumed throughout life cycle, the carbon emissions of a product and its production or an assessment of the solid, non-recyclable waste produced at the end. LCA will be used throughout this project to assess and compare the environmental impacts of the various pathways of wind turbines at EoL.

1.5 Project Aim, Objectives and Scope

This project aims to assess the environmental impacts of various EoL decisions by a comparative LCA of the options. The objectives of the project are to deduce the most carbon intensive stages throughout the lifecycle and conclude the EoL option best for the environment. The scope of the LCA will include the raw material extraction, transport, manufacturing, construction and operation of a base turbine model, with a lifespan of 25 years. Turbine components considered within scope are the foundations, tower, nacelle and rotor. Components considered out of scope for the sake of the project are cabling and electrical connections and battery storage. Processes and construction involved to prepare a wind farm site for turbine installation, such as levelling of ground or site infrastructure have been deemed out of scope. The cost and socio-economic factors are out of scope of the project, with only environmental factors taken into scope. To allow for an accurate comparison of the three EoL options, the eventual EoL of the extended lifetimes of remanufactured or repowered turbines has been deemed out of scope and the system boundaries of the remanufactured and repowered options will end at erection of the extended life turbine.

1.6 Thesis Structure

As outlined throughout Chapter 1, an introduction to the project and project background is detailed. Chapter 2 of the thesis encompasses a literature review of the literature currently on all three EoL options, as well as the use of LCA to assess environmental impacts of wind turbines and the various EoL decisions. Chapter 3 will recount the methodology of the project, with consideration of two case studies used; A- EDF Renewables Stranoch 2 wind farm, a case study of an existing wind farm within Scotland, to provide accurate, exemplar account of wind turbine sizes, capacities, manufacturing location and transport routes from manufacturing, to site. The secondary case study used B- Renewable Parts Limited Industry Data, is a case study of the remanufacturing process, with particular focus of data as to the parts and process of remanufacturing mechanical components within the nacelle of the turbine. A site visit to the Renewable Parts Ltd. is also used to gain understanding of the process within remanufacturing of turbine components. The methodology section provides detailed system boundaries for the LCA of each option and an account of the software used to carry out the LCA; open source software openLCA, in conjunction with the EcoInvent database. The results of the LCA of all three EoL options are detailed in Chapter 4. Chapter 5 provides a discussion of the results from the LCA with validation of results from literature. Finally, chapter 6 provides conclusion of the project and suggested future work.

2.0 Literature Review

Throughout this chapter, published literature is reviewed to illustrate understanding within the trends of wind power generation, the challenges faced within this Sector and the potential solutions to combat them. This chapter will review literature discussing the options faced at EoL for onshore wind turbines; decommissioning, refurbishment and repowering in sections 2.1, 2.2 and 2.3 respectively. Literature drawing comparison of all three options will be reviewed in section 2.4, exhibiting the current gap in the industry of a "best practise" approach, with environmental consideration to treatment of EoL wind turbines, particularly within Scotland. Finally, the current use of LCA within wind power will be assessed and the advantages of the use of LCA to address the question of which EoL options pose the least potential impact to the environment will be highlighted in section 2.5.

2.1 Decommissioning of Wind Turbines at EoL

The first option often brought to mind in EoL discussions of onshore wind is decommissioning; the de-energising and removal of wind power generation infrastructure. Surveys also show that, members of public are also often more accepting of or favourable towards decommissioning wind farms, with respect to the visual impacts on landscape (Szumilas-Kowalczyk, Pevzner, and Giedych, 2020). During the initial EIA and scoping stages in recent projects, EoL consideration in the form of decommissioning is commonly assessed and plans made. Often, project consent towards new wind farms is granted upon the basis that eventually, sites will be decommissioned and returned to natural state. However, this has not always been the case, earlier commissioned wind farms often do not have a set plan for EoL, meaning that commonly there is no consideration of the disposal and recycling processes resultant of decommissioning. Although wind energy does not produce any direct CO_2 emissions from operation, it is important not to overlook the indirect emissions and environmental impacts from the manufacturing, assembly, disassembly and eventual waste management of the technology. It is well understood that the dismantling, recycling and disposal of wind turbines poses to become a major challenge (Tota-Maharaj and McMahon, 2020),(Lightenegger et al, 2020),(Jensen and Skelton, 2018),(Hall, João and Knapp, 2020). Therefore, the necessity to provide an environmentally safe disposal solution for the ageing fleet of onshore turbines is of priority (Invernizzi et al, 2020).

A study by Tota-Maharaj and McMahon has applied waste data analytics for the UK, to determine the decommissioning waste in the UK up until the year 2039. The study also analysed current EoL practises in respect to waste management procedures in order to create baseline procedures, with the aim of providing more environmentally safe solutions, compared to the current waste management practises in place(Tota-Maharaj and McMahon, 2020). The recycling of the main components of the turbines; steel towers, steel foundation and mechanical parts prove relatively easy, however composite blades are not so straightforward. Assessment of current practise in the UK found that the material components of turbines that are commonly found to be 90-100% recycled are steel, aluminium, iron and copper with minor losses to landfill. However, components such as the concrete used in foundations, plastics used within electronics and composite materials such as fibre reinforced plastics (FRP) all have rates of 95-100% landfill (Tota-Maharaj and McMahon, 2020). Results of the study conclude that waste management options where efforts are made towards recovery, particularly of components such as concrete foundations and FRP result in a greater sustainability. Reuse, refurbishment and recycling with waste to heat recovery result in a maximised sustainability for the wind industry, through the reduction of waste to landfill and Greenhouse Gas (GHG) emissions.

Most commonly, literature published has a focus on the recycling of wind turbine blades upon decommissioning. Due to the size and composition of blades, recyclability is very difficult to achieve (Sakellariou, 2018). The inability to recycle turbine blades causes an engineering dilemma, for there are many depending factors; the blade specific composition, the availability of recycling technology, country specific legislation and logistical issues due to the sheer size and mass (Sakellariou, 2018). Another challenging dynamic within the blade recycling dilemma is that no company wants to claim responsibility to recycle; manufacturers and energy operators often ascribe it to one another (Sakellariou, 2018). To quantify the level of concern surrounding this dilemma; from the year 2033, across the world there will be 200,000 tons of blade waste alone every year (Deeny et al, 2021). Further blade waste quantifying studies highlight Germany, Spain, France and the UK as the top four countries with the most incoming blade waste in Europe up until the year 2050 (Lichtenegger et al, 2020). Advice published throughout the study by Lichtenegger et al, shows the future potentials of integration of decommissioned blade waste into circular economy principles, with blade waste providing great potentials for civil building materials. Figure 7 highlights the trends of incoming blade waste in the UK up to the year 2020, showing a projected yearly increase of blade waste across the next 10 years.

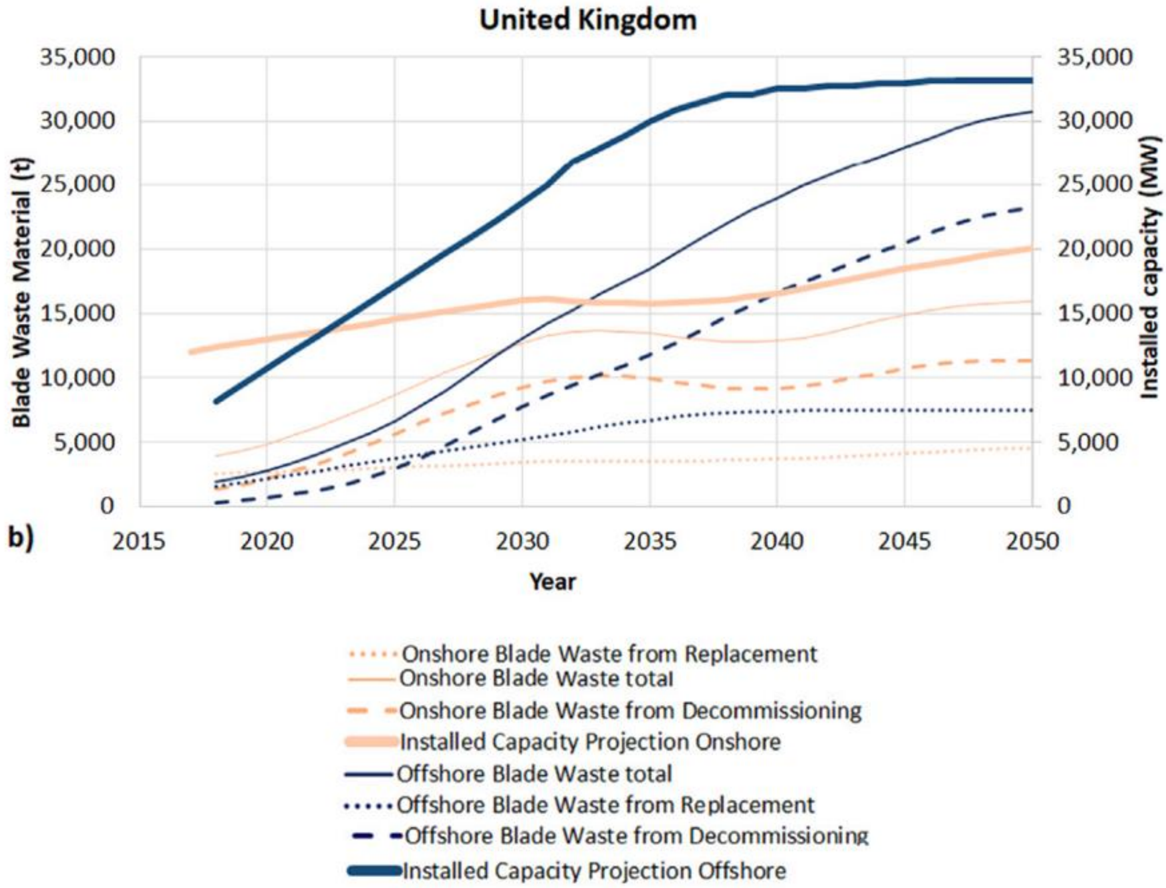

Figure 7- The projected wind turbine blade waste in the UK in tons, for both onshore and offshore installed capacity (Lichtenegger et al, 2020).

Analysis throughout Lichtenegger, et al's study also highlights that the UK, in particular South West Scotland will become a hot spot across Europe for blade turbine waste generation in the year 2030 – see figure 8 -, this trend will then continue to be projected into 2040 and 2050.

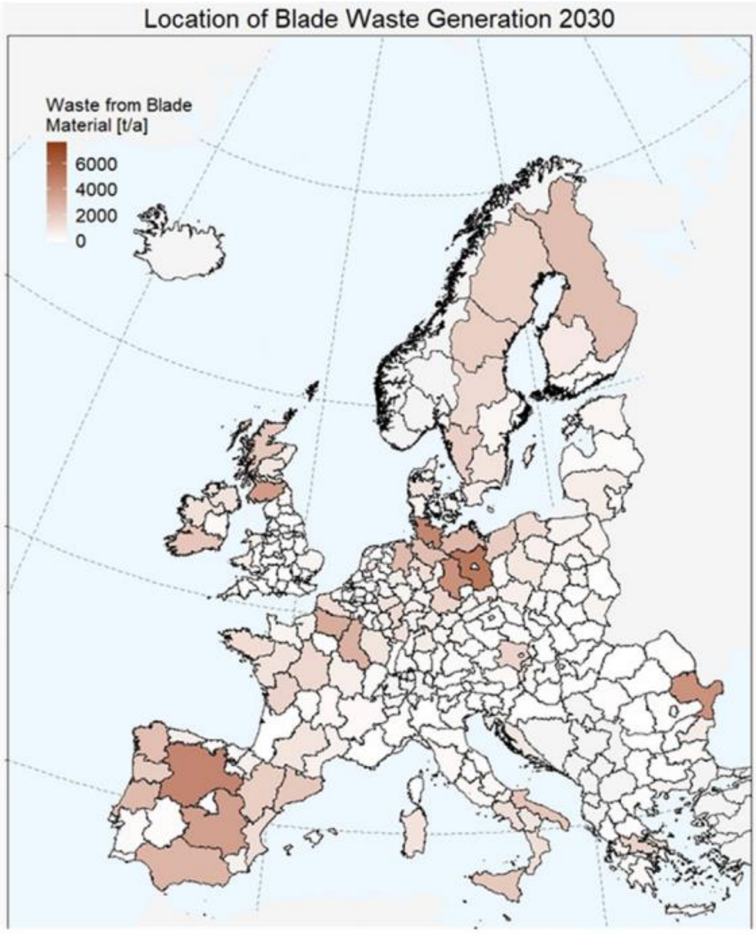

Figure 8- Location of Blade Waste Generation across Europe in the year 2030, by waste from blade material in tonns per area. South West Scotland, France and Germany are highlighted as hot spots (Lightenegger et al, 2020).

Waste management options for blades include landfill, or high energy processes such as incineration, co-processing or repurposing of blades into furniture or infrastructure; by way of small projects such as bus stops or large scale projects such as bridge fabrication (Deeny et al, 2021). This study by Deeny, et al combines the use of LCA, GIS and sensus data to conclude that bridge fabrication provides the most sustainable option for the decommissioned turbine blades, closely followed by other repurposing methods; into furniture or small infrastructure. Waste management options which do not include some form of recirculation of the blades or composite materials rank the lowest in sustainability potential (Deeny et al, 2021). These trends are prominent from the practises within circular economy and the waste hierarchy followed within this concept, whereby Refusal, Reuse and Recycle in order of decreasing desirability all are preferential to disposal- in the case of blades incineration or landfill (Pires and Martinho, 2019) (Jensen, 2018).

To slow the need for reactive solutions to wind turbine blades, waste preventative EoL consideration should be implemented within design of new blades (Mishnaevsky, 2021). The future of wind turbine blades with the use of new, bio-based or biodegradable materials may allow for easier refurbishment, and resultant extension of life. Most importantly, it may lessen the need for recycling and disposal of the composite blades due to a reduction in waste. Therefore, creating an environmentally desirable product model for wind turbine blades which incorporates the pinnacle of the waste hierarchy; reduction of waste (Mishnaevsky, 2021).

The Scottish National Heritage (SNH) published a commissioned Report, providing advice on the decommissioning of wind farms and the consequent restoration of sites to their natural state (Welstead et al, 2013). The report produced by SNH is a follow up to the 2010 published 'Good Practise During Wind Farm Construction Guidance' aimed at wind development, whereby environmental legislation and pollution prevention are now to be considered during the project consenting stages (Welstead et al, 2013). The advice laid out within the report is designed for easy integration with existing environmental protection processes, such as Habitat Management Plans. Recommendations for decommissioned sites include that the site should provide restoration of the site, to the standard of or even better than the baseline state. In order to demonstrate the 'reversibility' of the wind farms, efforts must be made to remove all infrastructure, both sub and above surface level (Welstead et al, 2013). After doing so, components which may be repurposed or recirculated must do so, and those that cannot must be recycled. Site specific decisions must be made with consideration of the soil, specifically in terms of peat disturbance and ensure that restoration will allow biodiversity to return to site as habitat. Assessment upon decommissioning of each site must take into consideration the carbon balance of site vehicle, transport throughout the decommissioning process and provide solutions which require the least amount of transport, where possible. Figure 9 illustrates the process involved in creating a Restoration and Decommissioning Plan (RDP) for onshore wind farms.

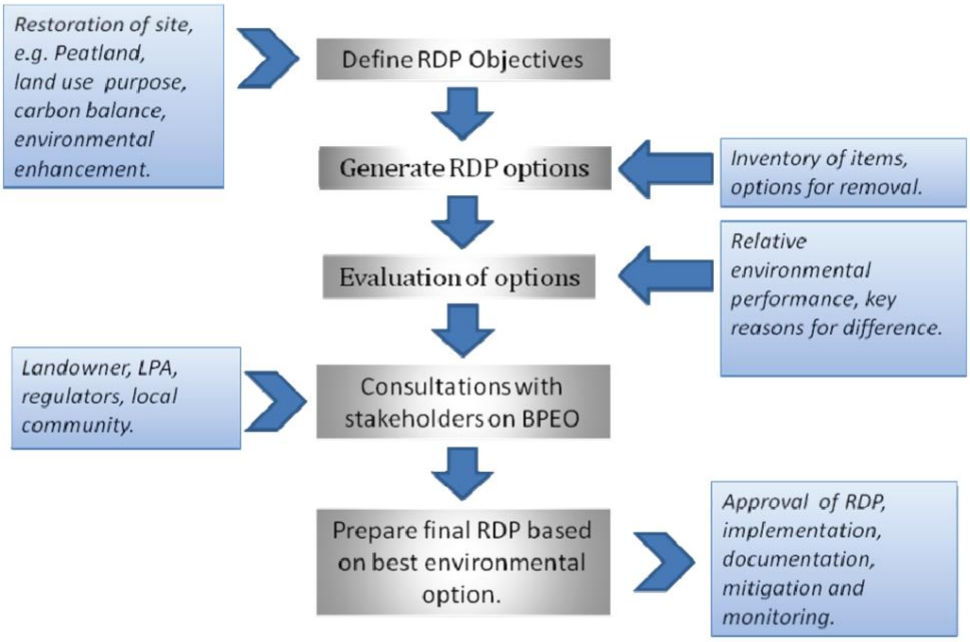

Figure 9- A flow chart illustration of the process involved in producing a Restoration and Decommissioning Plan for Onshore Wind Farms, as written by the Scottish National Heritage (Welstead et al, 2013).

Future planning for wind turbines should include the production of an RDP, to minimize environmental impacts at decommissioning. A prior consideration for waste reduction in design is one of the most Sustainable practises to include within infrastructure planning.

To summarise, the process within decommissioning is well documented throughout literature, with a great focus on the challenges and potential solutions to waste management of turbine parts, including foundations and blades. It is concluded that the reuse, repurpose or recycling of turbine components at EoL, particularly blades is critical to optimise the sustainability of the wind industry (Jensen, 2018). It is however, also known that the EoL of wind turbines, even throughout LCA is rarely assessed in enough detail (Andersen et al, 2018). It is assumed that the majority of the generation of turbines reaching EoL within the next 10 years do not have set RDP in place to allow for environmentally friendly decommissioning, so further research into what it means, environmentally to decommission this particular ageing fleet would mean is necessary.

2.2 Refurbishment of Wind Turbines at EoL

As the focus shifts towards offshore wind, the financial desirability of choosing to extend onshore wind assets through refurbishment of parts or remanufacturing is becoming increasingly popular (Amiri et al, 2019). Refurbishment is the process where components of the turbines are restored, repaired or replaced to return the turbine to a factory standard performance and functionality. Costs of doing so, are far lesser than that of repowering a full fleet, more importantly the opportunity for circular economy and increased sustainability is the draw to deciding to refurbish over decommissioning or repowering (Jensen et al, 2019). Despite these characteristics of the option, there is a lack of industry surrounding the process of remanufacturing or refurbishment and it is believed there is still reservations surrounding the use of recirculated parts and the warranty of them (Jensen et al, 2019).

A study undertaken by Jensen et al, investigates the value chain design, management and sustainability of integrating remanufacturing of wind turbines into a circular economy model. Results of the study highlight that the driver of the remanufacturing and refurbishment industries is the potential to close loops within the industry, subsequently allowing for low cost and high efficiency supply chains. Often, mechanical components of wind turbines require maintenance and replacement regularly throughout the guaranteed 20-25 year lifespan, posing a need for refurbishment of components (Jensen et al, 2019). The necessity of this may steer more investment into refurbishment, as it is unlikely that operators of wind farms will chose to repower, before a return investment has been made on the original lifetime of the wind farm. This paper highlights extremely well the potential positive environmental impacts through reduction of waste via refurbishment, and a particularly in depth insight to the economic benefits that a circular integrated business approach could provide the wind industry. However, the paper fails to address many other environmental aspects, and does not provide a comparison to any other EoL options for wind turbines.

Hao et al, approached the business model of remanufacturing in a similar way, with a lesser focus on the business and economic potential and a stronger focus on the waste and material savings. The core principal of Circular Economy is the regenerative and restorative nature by design, where the elimination of waste is striven for through the use of circular design and repurposing, refurbishing or recycling (Hao et al, 2020). The potential for refurbishment not only covers wind turbine blades, but components within the nacelle; which often are the cause of premature deterioration of turbine performance (Michaud, Sroka and Benson, 2010). In the case of wind turbine blade refurbishment, it is structural defects that need tending to, such as surface erosion, flaking and cracking (Wraith, 2013). The temptation for operators to opt to immediately re blade, in circumstances where perhaps refurbishment would provide a better solution regardless of the longer timescale highlights that the need for Environmental best practise within these circumstances is a necessity (Wraith, 2013).

The scepticism present surrounding the use of refurbished or remanufactured parts is easing, with the evolution of research and industry (Michaud, Sroka and Benson, 2010). An evidence based study by Michaud, Sroka and Benson shows that the refurbishment process produce excellent results, with proven restored functionality of components. In a case study of the refurbishment of over 2300 planet and hollow gears, all of the refurbished gears have remained within the required tolerance (Michaud, Sroka and Benson, 2010). Figure 10 illustrates the superfinishing process as part of the refurbishment of the gears, where surface damage from operation is successfully reversed.

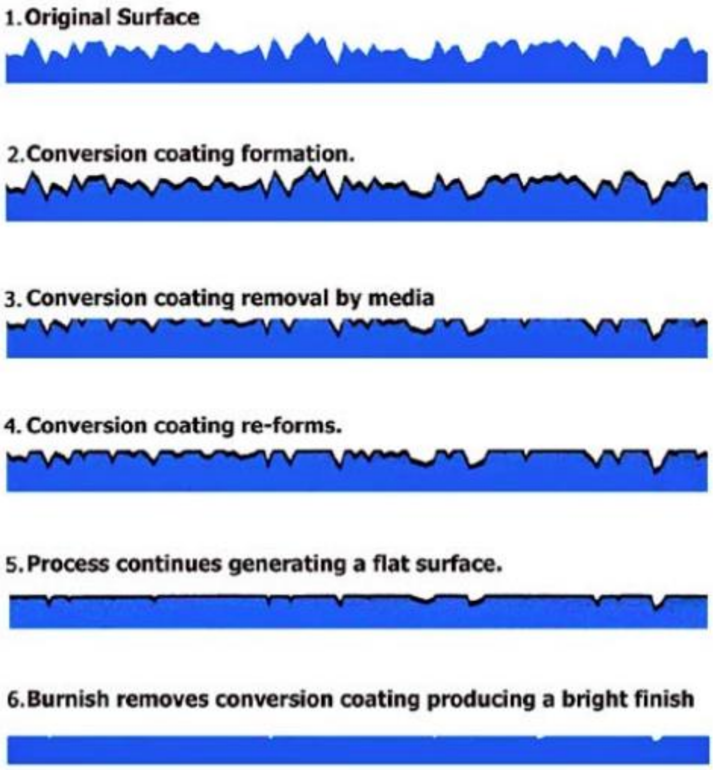

Figure 10- A visual representation of the superfinishing process of a ground gear surface (Michaud, Sroka and Benson, 2010).

Where it is clearly evident that the recirculation and refurbishment of existing materials and parts produces the necessary and desirable outcome, with warranty, it seems as though it would be obvious with increasing environmental concern that industry should all take strides to partake in refurbishment, rather than replacement of parts or entire units (Michaud, Sroka and Benson, 2010).

A study from Mishnaevsky, 2021 produces similar results and conclusions, however with respect to the refurbishment of turbine blade components. Figure 11 illustrates various different refurbishment approaches of blades, with the motivations behind each method illustrated in flow.

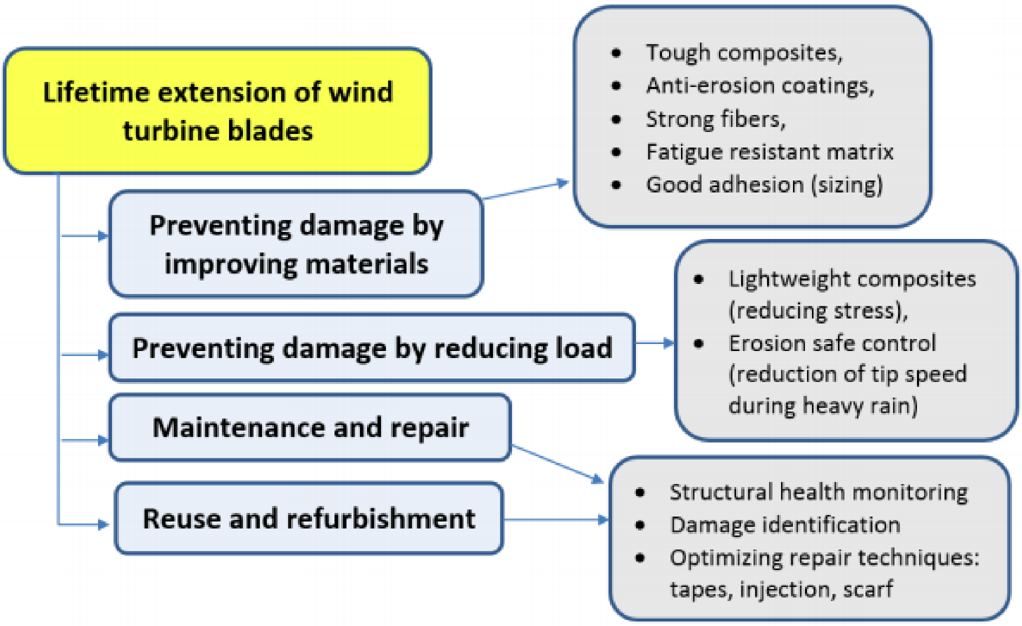

Figure 11- The process of lifetime extension of wind turbine blades and the outputs of the process (Mishnaevsky, 2021).

Once the blade damage is analysed, there are multiple approaches to refurbish the blades, dependant on the damage, including filling, shaping, coating and patching (Mishnaevsky, 2021).

Ultimately, the green potential of the wind industry is reliant on further growth of the refurbishment industries, and the continuous recirculation of parts and materials within the industry, reducing waste and environmental impact. Further studies, which quantify the positive environmental impacts of remanufacturing, with comparison to repowering would help carve a clear environmental pathway towards such practises.

2.3 Repowering of Wind Turbines at EoL

Frequently, the EoL option appearing is the Repowering of wind farms. With the vast advancements in wind technology since the ageing fleet were first installed, wind power operators are opting to install an entirely new fleet of usually larger turbines, with higher generation capacities. The operation of the ageing fleet may be quite depleted, however the farm asset still has the elementary potential for a very high power generation (Martínez et al, 2018). Particularly with the trend towards new developments offshore, there may be a lack of availability of suitable onshore wind farm sites left, particularly in densely populated turbine countries such as Scotland (Rio, Silvosa and Gomez, 2011). This may drive the EoL decision away from decommissioning an ageing fleet, to prolonging the asset via full repowering. Assessment of the suitability of dismantling and disposing of an entire fleet of turbines at a time is necessary to understand whether the renewable energy production potential outweighs the environmental impacts of the decommissioning, manufacturing and installation processes.

Alternatively, another option is to only partially repower, offering a more affordable approach that still results in the increase of generation capacity (Martínez et al, 2018). Rio, Silvosa and Gomez assess the socio-environmental aspects and policies surrounding repowering. Certain barriers that may be faced with repowering, particularly onshore, is the opposing of larger turbines within society as an eyesore, the need for grid updates to sustain such increased renewable generation, financial challenges and licensing procedures (Rio, Silvosa and Gomez, 2011). However, though full repowering may appear a quite aggressive approach, it does offer many social benefits; generation of jobs, increased renewable generation capacity, thus positive strides towards net zero. The use of repowering may also prove to have positive environmental impacts, due to the increased efficiency of energy generation per square meter of rotor area. There are potential policies and feed in tariff’s that could prove advantageous for the planning and permission of repowering.

The feasibility of repowering will be different from case to case, dependant on repowered turbine spacing regulations; in some cases, the larger turbines have the potential to in fact, not sustainably increase the overall generation of a site (Grau, Jung and Schindler, 2021). Quantifying the potential renewable energy generation and emission savings of a repowered farm with comparison to the emissions associated with the installation of the repowered fleet would provide valuable insight into the time period until, or feasibility of the generation potential outweighing the initial impacts of decommissioning and installation of new units.

Evidence based studies have also shown that there is room for a small introduction of circularity with regards to the feasibility of reuse of original foundations (Waldron et al, 2018). This is essential to reduce the environmental footprint of the repowering process.

2.4 Comparison of EoL options

The growing concern for a solution to address the ageing fleet of onshore wind turbines is well documented, with a highlight drawn to the number of turbines coming to EoL in particular in Germany, Denmark and the UK (Ortegon, Nies and Sutherland, 2013) (Piel et al, 2019) (Ziegler et al, 2018). However, research which considers the entire picture of the turbines at EoL is limited.

Piel et al, draw particular focus on the case within Germany and aimed to provide support to answer the question of which route is the best option; decommissioning, lifetime extension or repowering with the use of Geographic Information System (GIS). The aim of the analyses is to asses an optimal strategy for EoL care of wind farms, over a variety of scale from total farm to single turbine (Piel et al, 2019). Throughout the research, consideration of economic, spatial, wind and turbine data has been combined through various simulations to assess the potential of a uniform EoL option for all wind farms. It is important to note that lifetime extension within this study refers to refurbishment of turbine components to prolong the lifecycle of the original turbines in place. Piel et al, recognise that the three options available for EoL care are decommissioning, refurbishment or repowering, however recognises that decommissioning is the option chosen whereby refurbishment or repowering are not feasible.

The GIS approach to assess the potentials of refurbishment or repower is particularly useful for macro-scale analysis, as undertaken within this study. Figure 12 illustrates the system architecture of the GIS, highlighting the key considerations of the analysis as spatial and economic considerations.

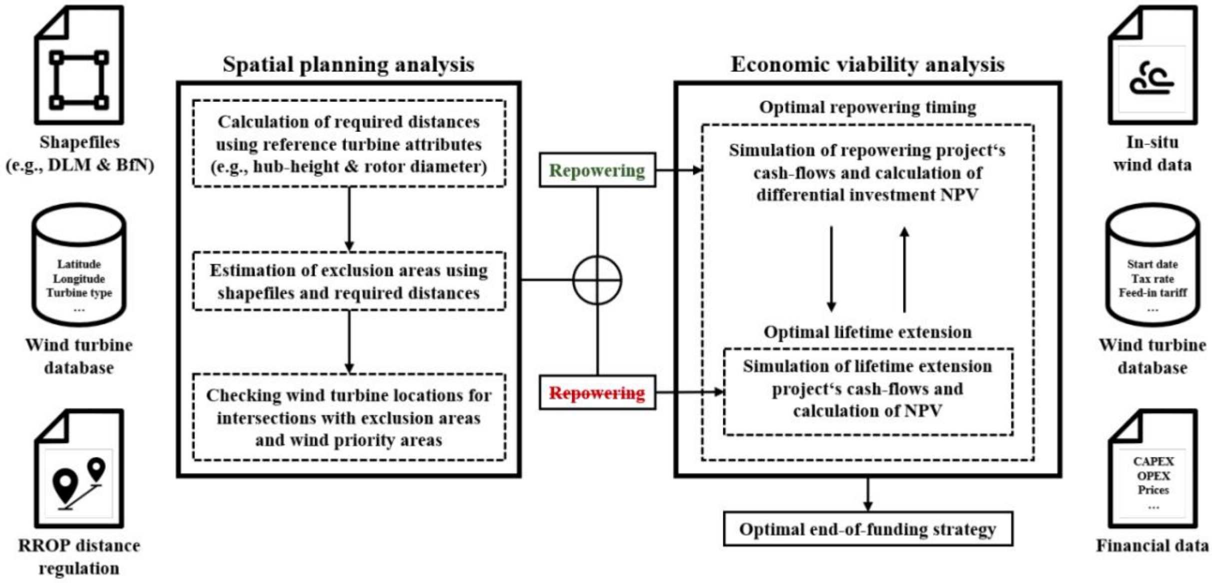

Figure 12- System architecture of the decision support system and required data inputs (Piel et al, 2019).

Firstly, spatial analysis is considered, to determine where feasible; repowering or refurbishment may occur. Upon completion of spatial analysis, a dependant economic assessment is undertaken. The economic assessment is particularly useful to determine an optimal extension timeframe. Results from Piel et al research are shown, by optimal EoL decision colour coded in figure 13. Results of the study conclude that both refurbishment of old turbines and repowering prove to be economically feasible options for EoL extension of wind turbines, however that the spatial feasibility of repowering is dependant and varied from site to site. Trends throughout Germany show that most commonly, the desirable option would be to repower immediately, followed closely by turbine decommissioning and finally, the least desirable option to only refurbish. Further understanding of the spatial constraints of repowering could be understood with a larger scoped study, including other countries such as the UK within the inputs of the GIS. Research of the paper therefore concludes that no uniform practise can be applied to EoL treatment of wind turbines, with a need to be assessed case by case.

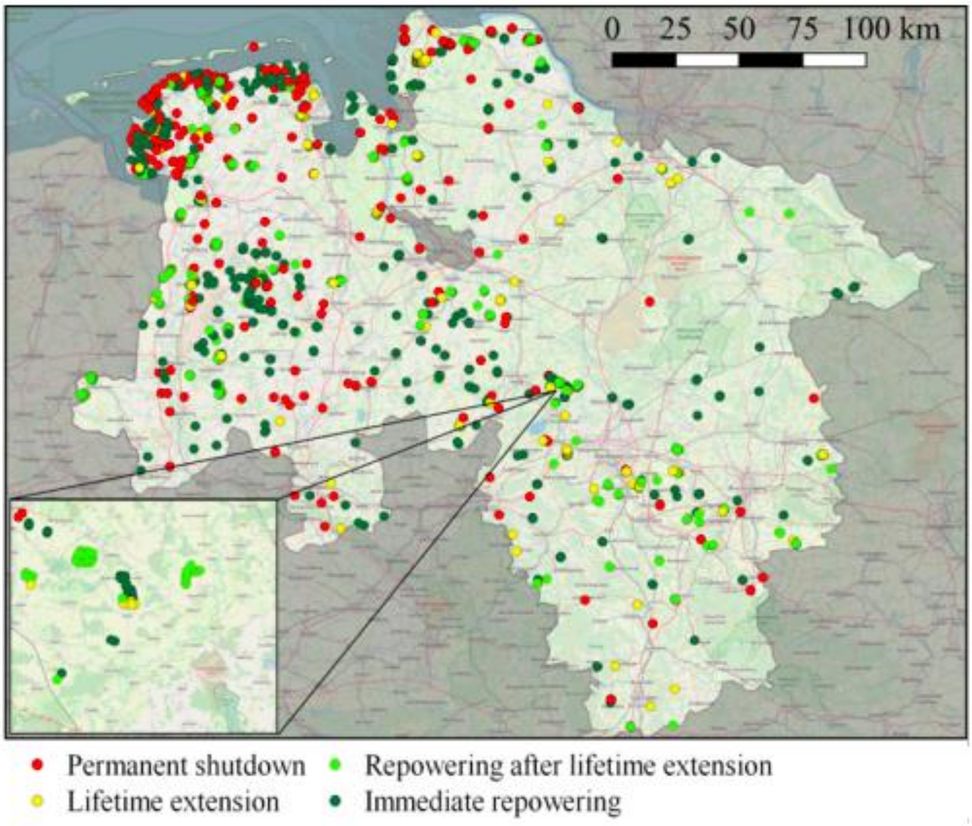

Figure 13- Optimal End of Life option for wind turbines approaching end of life across Germany. With decommissioning in red, refurbishment in yellow and immediate repowering in blue (piel et al, 2019).

The paper is written well, with effective use of GIS analysis to produce a non-biased conclusion, however there are limitations to the study. Whilst this paper provides excellent decision support with regards to the economic and spatial feasibility of EoL extension or repowering, it fails to take into consideration the environmental impacts of either options. This becomes a recurring theme throughout the literature, whereby the potential detriment to the environment by lifetime extension or decommissioning are ignored.

Although evidence throughout published literature shows the economic, mechanical and spatial feasibilities of various EoL options for wind turbines, to the thesis authors knowledge; there is a lack of research synthesising all potential options with a comparison of the potential impacts to the Environment. The use of GIS does not have the functionality to produce the insight needed to quantify environmental impacts, thus an alternative method of assessment must be considered.

2.5 LCA of Wind Turbines

In recent years, there has been a frequent emergence of studies using LCA to assess the environmental impacts of wind turbines, globally; (Vélez-Henao and Vivanco, 2021), (Teffera et al, 2021), (Li, Li and Wu, 2020), (Wang, Wang and Lui, 2019). With the current climate crisis the push to decarbonise even renewable energy systems is becoming more and more pressing, particularly with the increasing trend in consenting of future renewable assets, including many onshore wind (Li, Li and Wu, 2020).

LCA's are consistently being used to assess the carbon footprint, with the aim of highlighting areas within the Life Cycle of onshore wind generation technology that can be improved, increasing the overall sustainability of the technology. The study undertaken by Li, Li and Wu encompasses a carbon comparison of two EoL options; repowering and decommissioning. Turbines at EoL that are dissembled for either option, have the opportunity to be sold to small community scale projects, or scrapped for metal and components and recirculated, reducing the carbon footprint (Li, Li and Wu, 2020). The carbon emissions per stage of life cycle for a 49.5 MW wind project are illustrated in figure 14.

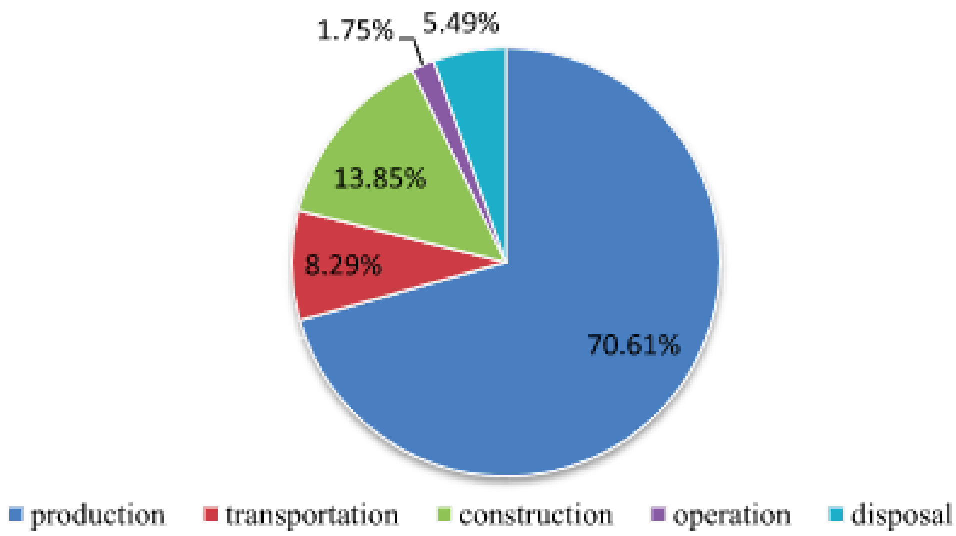

Figure 14- The carbon intensity of each stage, as a percentage of total carbon emissions (Li, Li and Wu, 2020).

Conclusions of the study show that, when compared to thermal generation technologies, the carbon intensity of wind generation is much lower. This paper provides an incredibly detailed breakdown of the carbon intensity of every material within each component of every life cycle stage, and also includes considerations for recycling and recirculation of turbine components. An example of the carbon emission breakdown for the construction phase are detailed in table 1;

Table 1- Carbon Emission Factor, by material from the construction phase of a wind turbine (Li, Li and Wu 2020)

LCA data inventory of carbon emissions during the construction phase.

Material	Carbon emission factor		Quantity	
	Value	Unit	Value	Unit
Concrete	0.283	kg/m^3	18317.6	m^3
Steel	1	kg/kg	1377140	kg
Sand	0.00234	kg/kg	13563000	kg
Stone	0.0131	kg/kg	24100000	kg
Diesel	3.246	kg/kg	65297.32	kg
Gasoline	3.136	kg/kg	4256.95	kg
Electricity	0.0136	kg/kWh	71589.6	kWh
Water resources	0.00619	kg/L	36500000	L

Such in depth analysis is essential to identifying points where changes can effectively be made to reduce the carbon intensity of the Life Cycle.

Similarly, Wang, Wang ad Lui completed a study published in 2019 quantifying the greenhouse gas emissions of each component within the turbine, for the purpose of a comparison of onshore to offshore wind turbines. Results showed that the offshore wind turbine of the same output were proven to have greater carbon intensity throughout lifecycle, namely due to the production of additional infrastructure and the intensity of the transport associated with construction (Wang, Wang and Lui, 2019).

Teffera et al, use LCA to quantify the average midpoint environmental impacts of a wind power generation system where human toxicity, metal depletion, fossil depletion, terrestrial acidification, photochemical ozone formation and freshwater eutrophication are the indicators of environmental impact considered. The potential scope of LCA within EIA is tremendous, with such varying outputs LCA can be applied to any EIA assessment.

A case study of an onshore wind farm in Guajira, Colombia undertook a Hybrid LCA to quantify whether direct, or indirect carbon emissions account for the greatest contribution to the carbon footprint. Hybrid LCA take into consideration additional to environmental impacts, socio-economic impacts too (Vélez-Henao and Vivanco, 2021). Results of the study found that indirect services account for a greater deal of the Carbon intensity, particularly those within the manufacturing stage of life. Velez-Henao and Vivanco also included an assessment of the use of LCA as an assessment tool itself, concluding that sensitivity analysis and vast data gathering and research are key to a successful and accurate LCA.

Evidence throughout literature shows that there is great consideration of the processes' and environmental impacts within each EoL option, however there is a lack of a synthesis of information to compare the options. An assessment of 72 available LCAs of onshore wind turbines showed that only 11 of those studies included considerations for the treatment at EoL (Ortegon, Nies and Sutherland, 2012). Although more recently, there has been a better consideration of EoL care, to the authors knowledge, there is no published literature which provides a direct comparison of the potential environmental impacts of EoL options for onshore wind turbines, with the UK or worldwide. It is key to understand such potential impacts respective to each other, in order to pave a best practise approach or at the least, gain a full understanding of the options. LCA, throughout the literature review chapter has been demonstrated as an extremely useful tool within EIA. With the completion of an LCA, many different environmental impacts can be deduced, isolated and understood. Therefore, it is deduced that the use of LCA to compare the environmental impacts of EoL decisions on Onshore wind turbines will provide the most suitable analysis.

3.0 Methodology

This chapter will review the methodology undertaken throughout the study of LCA of EoL decisions on wind turbines. Firstly, an overview of the methodology is illustrated in the flow chart in figure 15. Section 3.1 will describe the LCA software openLCA in collision with the ecoinvent database used throughout the assessment. The case studies used within the assessment will be described in sections 3.2; Stranoch 2 Wind Farm and 3.3 Renewable Parts Limited; a refurbishment company specialising in wind turbine component refurbishment. The Life Cycle boundaries that are defined for each EoL scenario are defined in section 3.4. Section 3.5 detailed the methodology for scaling the mass of turbine components and a summary of the openLCA inputs are detailed in section 3.6. Finally the Environmental Impact Assessment method used in openLCA; ReCiPe midpoint and endpoint and GHG protocol are described in section 3.7.

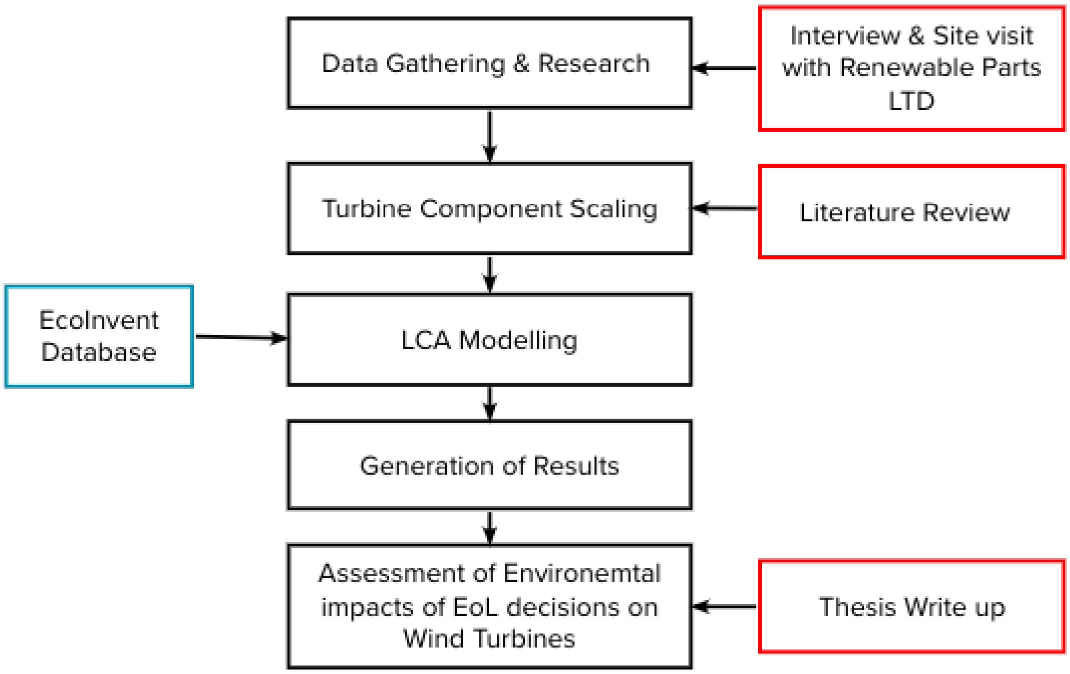

Figure 15- Visual flow representation of steps within methodology shown in black, with inputs from author in red and external inputs in blue.

Data gather, literature review, and industry data collection via the site visit to RPL for Refurbishment specific information encompassed the first steps within the project, where industry or real life data was attempted to be found where possible, minimising the need for assumptions throughout the assessment. Combined with the inputs for turbine components, transport and operation, the ecoinvent database provides environmental profiles for all inputs, allowing for the generation of results within openLCA to assess the ReCiPe midpoint environmental impacts.

3.1 Open LCA and Ecoinvent Database Selection

In order to assess the environmental impacts of EoL decisions on Wind Turbines, the open source, Life Cycle and Sustainability Assessment tool openLCA was selected to use for analysis. This software is selected due to the vast features provided; including a variety of 15 different Environmental Impact Assessment methods, including ReCiPe, GHG protocol, CO_2 quantification, Global Warming Potential (GWP) and socio-economic factors (OpenLCA, 2021). OpenLCA also provides the feature of self-data Quality Assessment, with database specific data quality systems and the option to regionalize the impact assessment, specific to study area.

In conjunction with OpenLCA, the ecoinvent database was used to provide Environmental Profiles. The database provides a wide selection of profiles on materials including metals, plastics and composite materials. It also has profiles for processes within construction, transport and waste management and processing (ecoinvent, 2021). The database also provides elementary flows, for emission quantifying of waste products/pollutants directly to, or from the environment.

Data gathering of all turbine specs and materials must be gathered as inputs for openLCA by user, materials and process' then have environmental impact characteristics associated, which are scaled dependant on material mass, volume or operation. Product Flows and governing processes are created by user, to then combine into a product system. For example, a flow and governing process are created, for the manufacturing stage of life, the steel, concrete and gravel components of a turbine foundation are created individually, then brought together in one process to create the flow of the manufacturing of a turbine foundation. A product system is the complete wind turbine, with all processes throughout lifecycle.

3.2 Case Study 1: Stranoch 2 Wind Farm

In order to increase robustness of study, real life data was used where found. Stranoch 2 proposed windfarm is used as a case study to have accurate specs for the expected size of turbine, transport within construction period, including routes and type of transport and number of loads, expected construction time periods and operation and maintenance checks. Stranoch 2 is a proposed wind farm development in the South West of Scotland, in the area surrounding Glenwhilly, see appendix A for site layout, with the planned HGV route from port used to calculate shipping distance laid out. This wind turbine farm is a further development of the edf asset (Wood, 2018). Stranoch 1 wind farm development proposed plan is to have 20 wind turbines, with varying turbine size and hub height. For the sake of the report, a smaller, turbine with lower hub height and smaller rotor diameter was considered to be the standing, base model of turbine. Throughout the study the "base model" turbine, is the turbine with the original full lifecycle, before EoL decisions must be made. All three options include the base turbine model, within their extended or decommissioned lifetime. The turbine design spoke of in the licensing design with the largest rotor diameter and hub height is chosen as the 'Repowered' model. The refurbished model follows the same specifications as the base model, with a period of lifetime extension assumed to be 7 years (Jensen, 2021). Figures 16 and 17 illustrate the Scenario 1 Base/Refurbished model size and the Scenario 2 Repowered model size respectively.

Table 2- Turbine size specifications taken from case study: Stranoch 2 wind farm (Wood, 2018).

Turbine Specification	**Base Model**	**Refurbished Model**	**Repowered Model**
Blade Tip Height (m)	149.9	149.9	175
Rotor Diameter (m)	136	136	152
Hub height (m	80.4	80.4	99
Clearance to ground (m)	10.9	10.9	23
Blade Length (m)	4.2	4.2	75
Rotor Radius (m)	69.5	69.5	76
Swept Area (m^2)	14526.72	14526.72	18145.84
Rating	4.2	4.2	4.6
Lifespan	25	7 (+25 of base model)	25 (+25 of base model)

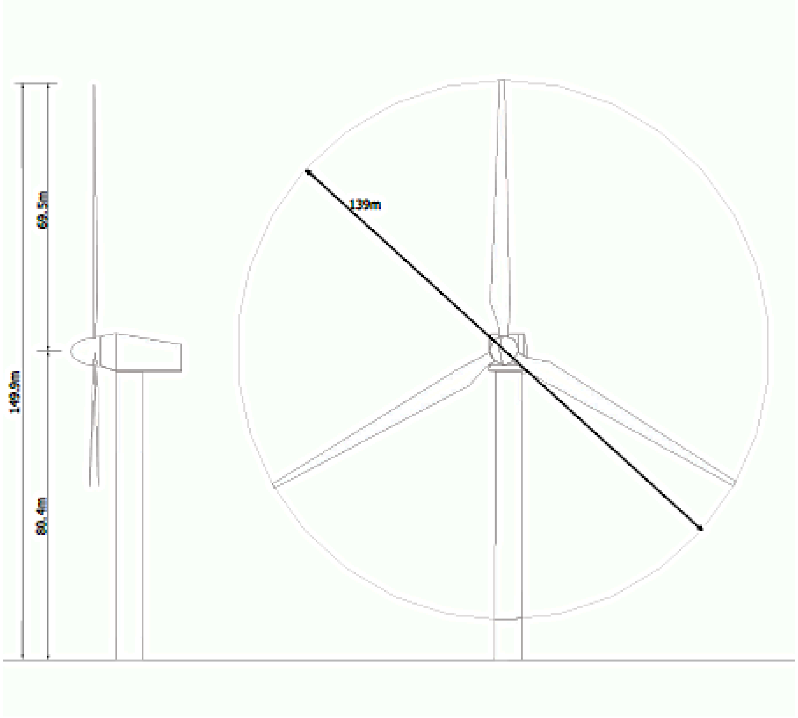

Figure 16- Plan drawing of the Base Turbine and Refurbished Turbine Model (Wood, 2018).

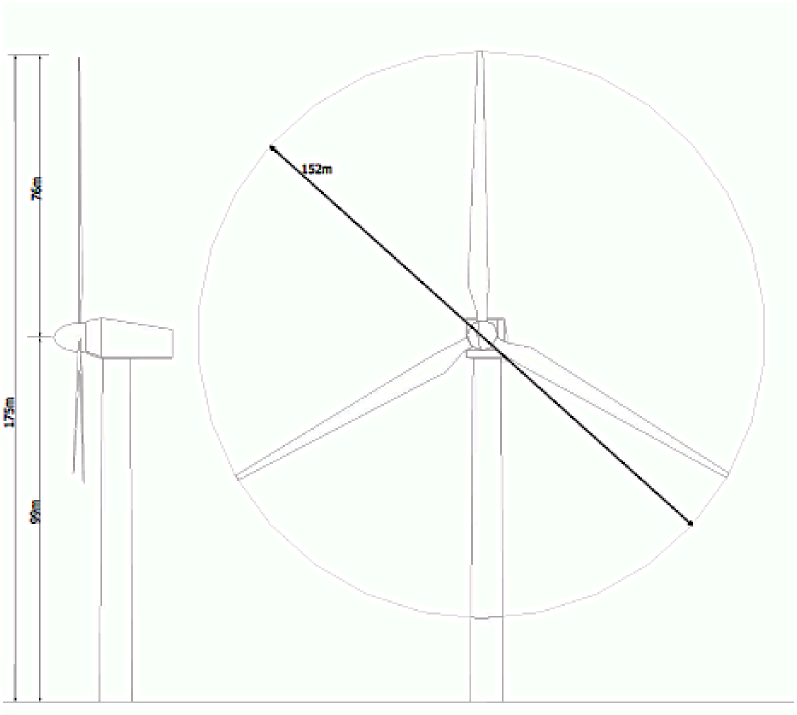

Figure 17- Plan drawing of the Repowered model, with higher hub height, larger rotor diameter and blade length compared to Base Turbine (Wood, 2018).

The two models both follow the same type of turbine; three bladed, variable speed, with the rotor and nacelle mounted on a cylindrical tubular steel tower, with a gravity based steel reinforced concrete foundations (Wood, 2018).

Table 3- Transport specs for the delivery of the components of one turbine; parameters for inputs of openLCA taken from case study, Stranoch 2 wind farm.(Wood, 2018)

Turbine Component	Number of Vehicle Trips	Mode of Transport	Distance travelled (km/trip)
Blades	3	HGV	29
Tower	3	Articulated lorry	29
Nacelle	1	Articulated lorry	29
Blade Hub	1	HGV	29
Generator Controller	2	Articulated lorry	29
Concrete (foundation)	80	HGV	17.7
Steel (foundation)	4	20t HGV delivery vehicle	17.7

All turbine components with transportation distance of 17.7km per trip are components sourced locally, with the foundation materials sourced in Glenluce (Wood, 2018). Components with delivery distance of 29km per trip are those items imported overseas, where 29km is the distance from the port at Cairnryan; the assumed port of delivery of turbine components, to a midpoint within the area of the Stranoch 2 wind farm site; Glenwhilly. As this proposed farm contains the assumption of wind turbine manufacturing out-with the UK, that assumption is applied to this project. Assumptions for fuel usage from vehicle trips and trips of workforce to site are quantified based upon distance and mode of transport (Department of Transport , 2018).

While the turbines described in the EIA for Stranoch 2 do not specify a particular turbine model or brand, the rated power output of one turbine is assumed to be 4.2MW, this number is calculated as an average of the stated output of the entire farm; 84MW (wood, 2018) per turbine, within a 20 turbine fleet. Based upon the 4.2MW output and the rotor radius provided within the case study, a 4.2MW, 136m rotor radius Vestas model is considered; the V136 model

(Vestas, 2021). Therefore, overseas shipping is assumed to be from Vestas Denmark Manufacturing facility (Vestas, 2021). The calculated shipping route and distance for the shipment of parts, based upon a route from Aarhus → Skagens Odde → Aberdeen → Cairnryan is a total of 740 Nautical Miles (National Geospatial intelligence agency, 2011).

In the EIA proposal for Stranoch 2, details of construction time, and vehicles used throughout the construction process are detailed, table 4 provides details of the period of use of each construction vehicle. These values have been scaled down for suitability of one turbine, from data given for entire proposal.

Table 4- The type of construction vehicle used during turbine installation and the period of use (wood, 2018).

Construction Vehicle	Period of Use (days)
100t crane	8
1000t crane	8
Support vehicle	8
Cement mixer	2
Low loaders	8

The period of use was calculated as a division of the total time predicted to install the fleet of turbines on the farm by 20, to account for scaling from 20 turbines to 1; giving 8 days of installation time per single turbine. The period of use of cement mixer was set at 2 days based on the assumption that the cement mixer is only used during the process of installation of foundations. Similarly, the number of workmen commuting to the site by car to work on the installation of the turbine was scaled down from the assumed workforce for the entirety of the wind farm. It was therefore assumed that 4 work personnel would be commuting to the wind farm per day to work on the installation of one turbine, for a period of 8 days.

Stranoch 2 wind farm EIA report was also used to quantify the labour throughout the operation and maintenance of 25 years lifespan. Table 5 highlights the maintenance expected in hours per year, and lifetime based on the scope of frequency of major and minor maintenance published in the EIA report (Wood, 2018). Assumptions; Minor maintenance personnel would make routine visits, one day per month. Major maintenance will occur periodically throughout the year assumed to be one day of major maintenance, every 3 months. For both cases, a day of work is assumed to be 8 hrs.

Table 5- The total labour in hrs per year, and lifetime of routine and major maintenance, over an assumed lifetime of 25 years.

Maintenance Type	Labour (Hours per year)	Labour (Hours per Lifetime)
Routine	96	2400
Major	32	800

3.3 Case Study 2: Industry site visit Renewable Parts LTD

On the 4th of August, 2021 a site visit for interview, inspection and data collection was undertaken at Renewable Parts LTD (RPL) Refurbishment warehouse in Lochgilphead, Scotland.

Specific distances for the transport of parts within the refurbishment process were able to be calculated, with the distance from the location of the Refurbishment office in Lochgilphead, Scotland to the midpoint of the wind turbine site of Stranoch 2 wind farm; Glenwhilly. Distance taken as 160 miles / 257km. See appendix B for transport route. The assumption was set that this distance would be travelled twice, once on the way to refurbishment, and once upon completion and return to the farm site.

Industry data gathered by RPL is used to understand the Refurbishment process and conclude the components of a turbine most commonly required to refurbish, it is important to note that RPL do not offer services on the refurbishment of wind turbine blades, so therefore they are not included within the RPL case study of Refurbishment. Table 6 provides a summary of the number of the number of times a turbine part was replaced, across all models of turbine that RPL refurbish, within the year 2020. The cumulated data shows that Yaw Gears are the most commonly refurbished part, with 233 yaw gears refurbished in 2020. Other components within the yaw system are also commonly refurbished, including callipers and gears. Components within the pitch system also frequently require refurbishment, particularly pitch cylinder and pitch slip rings. Anemometer and brake callipers also consistently required refurbishment.

Table 6- Summary of number of times turbine component is refurbished by RPL, in the year 2020. Cumulative data for all turbine manufacturers and models. (RPL, 2020).

Turbine Component	Number of Times Refurbished in 2020
Yaw Gear	233
Anemometer	120
Brake Calliper	43
Yaw Calliper	32
Clutched Yaw Top Moto	31
Calliper Light Touch	24
Pitch Cylinder	24
Pitch Slip Ring	21
Generator Slip Ring	12
Yaw Gear Motor	11
Pitch Motor	8
Wind Vane	5
Pump / Motor Assay	4
Synch Carrier	3
Yaw Top Moto	1
Proportional Valve	1
Inline Filter	1
Offline Filter	1

The visual difference between a yaw gear upon arrival to the refurbishment factory, prior to refurbishment can be seen in figure 18, after refurbishment and sanding in figure 19 and finally after painting and packing in figure 20.

Figure 18- Two Yaw Gears upon delivery to RPL Refurbishment factory, prior to any work. Photographed by the author at the refurbishment factory in Lochgilphead on 04/08/2021.

Figure 19- Two Yaw Gears after refurbishment and sanding.. Photographed by the author at the refurbishment factory in Lochgilphead on 04/08/2021.

Figure 20- Four fully refurbished and painted Yaw Gears, packaged to return to turbine customer site. Photographed by the author at the refurbishment factory in Lochgilphead on 04/08/2021.

Based upon the data from RPL a case study scenario where all 4 yaw gears within the turbine, the brake calliper and all components of the pitch system are to be refurbished to produce the refurbished model in EoL Scenario 2.

RPL also have a large focus on the recirculation of components and materials within their business, minimising waste as much as possible, wherever possible. Figure 21 highlights the steel recirculated vs landfill, and savings for the year 2020 (Renewable Parts LTD, 2020).

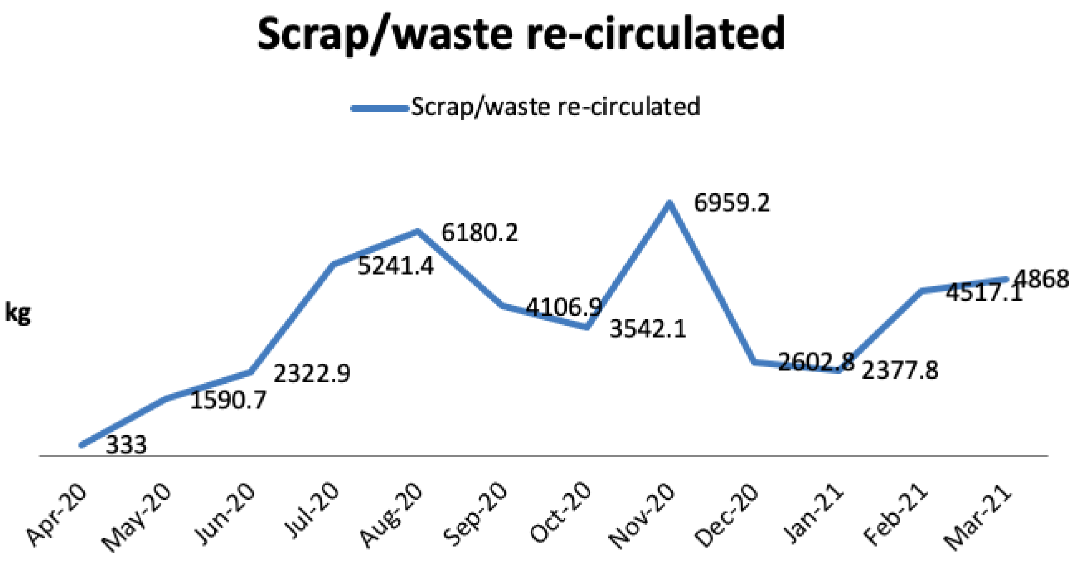

Figure 21- The mass of scrap/waste recirculated within the refurbishment factory, in kg, per month of the year 2020 (Renewable Parts LTD, 2020).

These values are the equivalent of the steel components used within refurbishment process month to month (RPL, 2020), based upon this; the assumption is made for the study that steel components within refurbishment are made from recirculated or recycled materials, only plastic components can be considered virgin materials, and replaced plastic parts not recycled throughout the process.

3.4 Defining Life Cycle System Boundaries

When undertaking a life cycle assessment, it is crucial to define the boundary of the system, including all inputs, processes and stages within the life cycle and outputs of the life cycle. The system boundaries created for each EoL scenario; 1- Decommissioning, 2- Refurbishment and 3- Repowering, are defined throughout this section. For all system boundaries, as per the scope described in section 1.5, cabling, battery storage, wind farm site prep, social and economic factors are deemed out of scope and not included within the system boundary. For EoL scenarios 2 and 3, the extended life cycle, beyond the installation of the refurbished or repowered turbine model is not considered within the system boundary, as this will not allow for an accurate comparison between all three EoL options.

The defined system boundary for scenario 1; Decommissioning is illustrated in figure 22, where inputs to the system can be seen on the left in blue, and outputs on the right in red. Elemental inflows are an input provided from the ecoinvent database within openLCA.

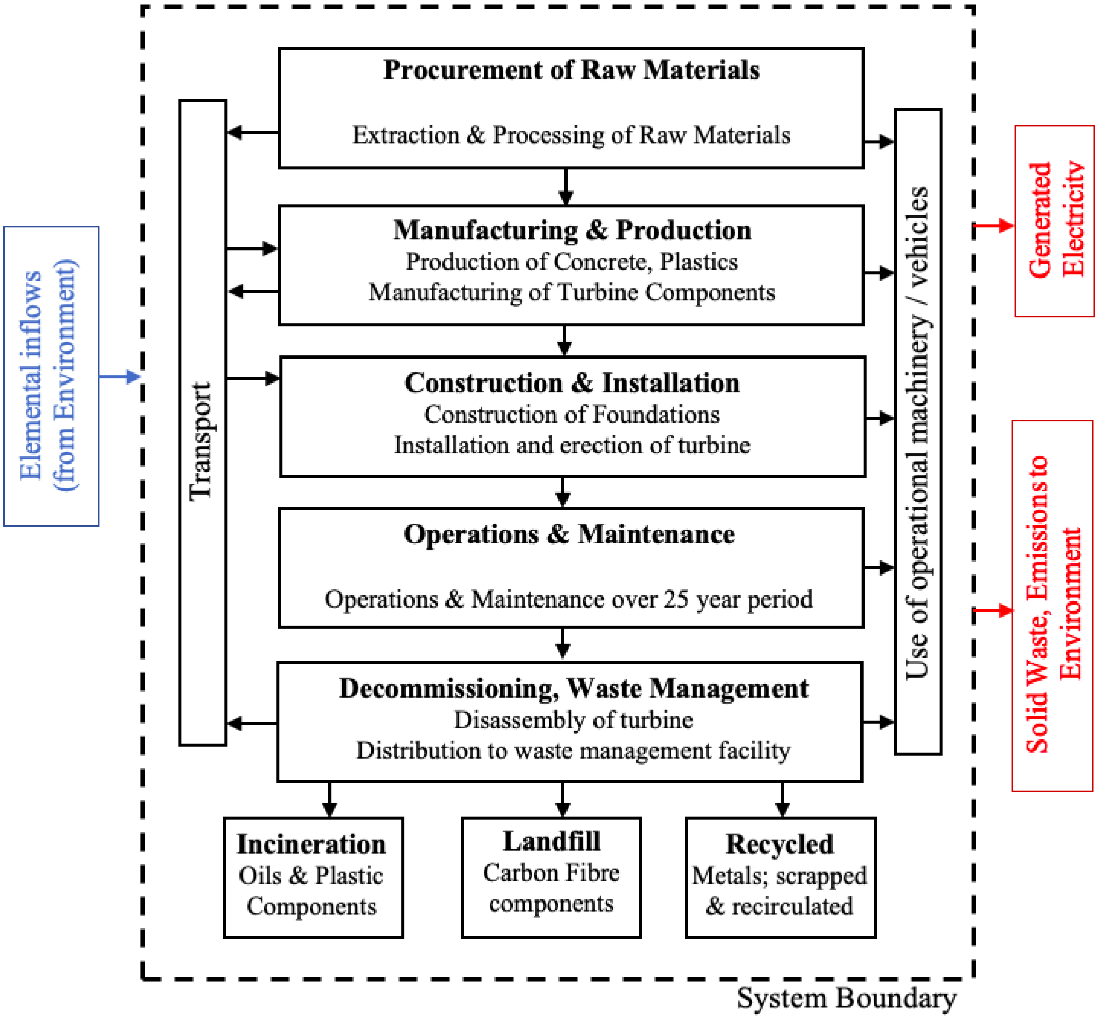

Figure 22- System Boundary for EoL Scenario 1; Decommissioning. System Boundary depicted by black dotted line.

The Recycled components within waste management are assumed to be 100% recirculated. Transport is used to deliver raw materials from extraction point to site of manufacturing, from manufacturing factory to wind farm site and also from wind farm site to waste management facility upon decommissioning.

Figure 23 illustrates the system boundary for EoL scenario 2; Refurbishment. An assumption is applied to this scenario that all metal components used within the refurbishment process are recirculated (recycled) parts and similarly that all metal components produced as waste from the refurbishment process will also be recirculated.

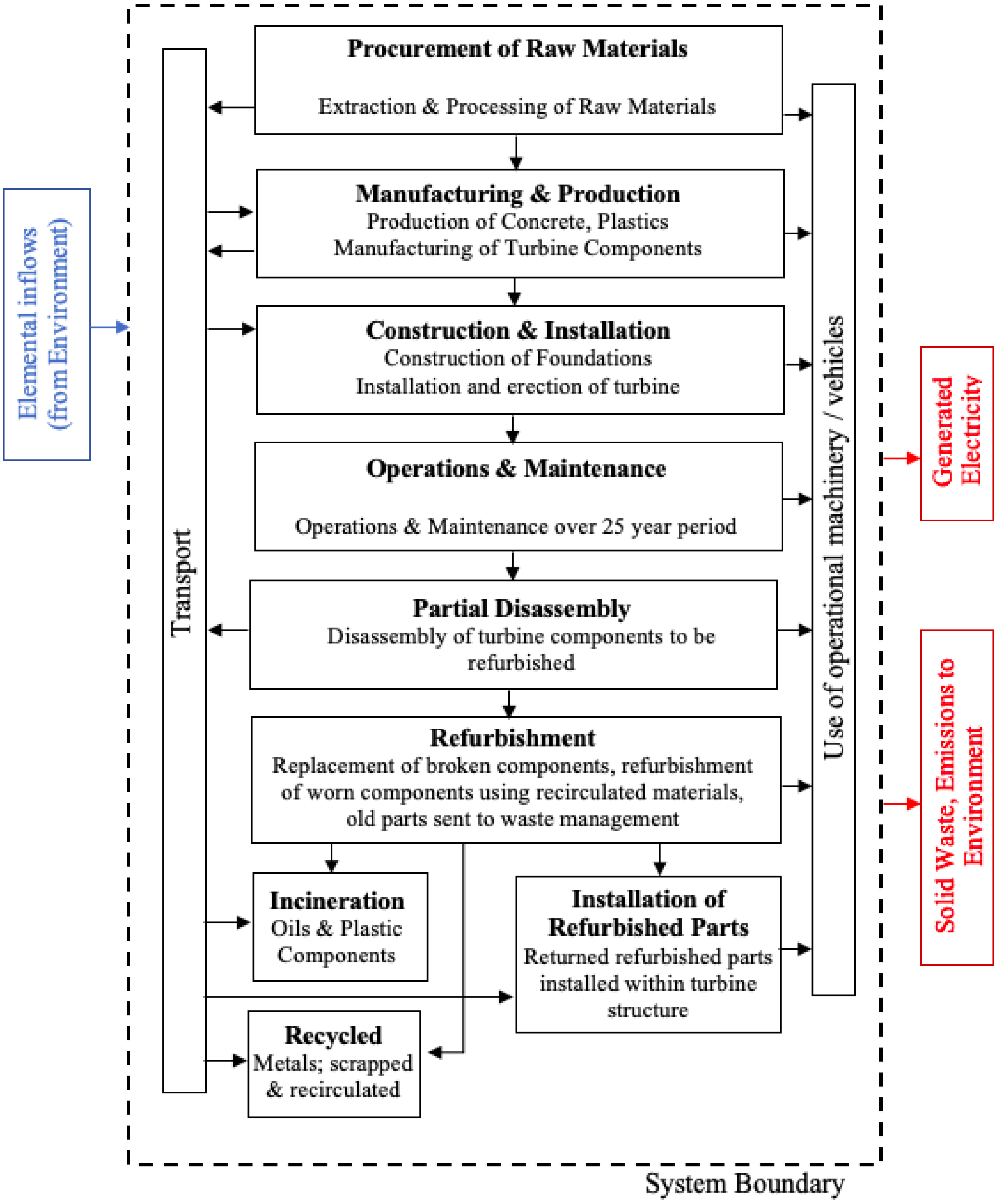

Figure 23- System boundary for EoL scenario 2: Refurbishment. System Boundary depicted by black dotted line.

Finally, the system boundary for EoL scenario 3 is illustrated in figure 24. The total system is the sum of the system for the base turbine model, plus the repowered turbine model.

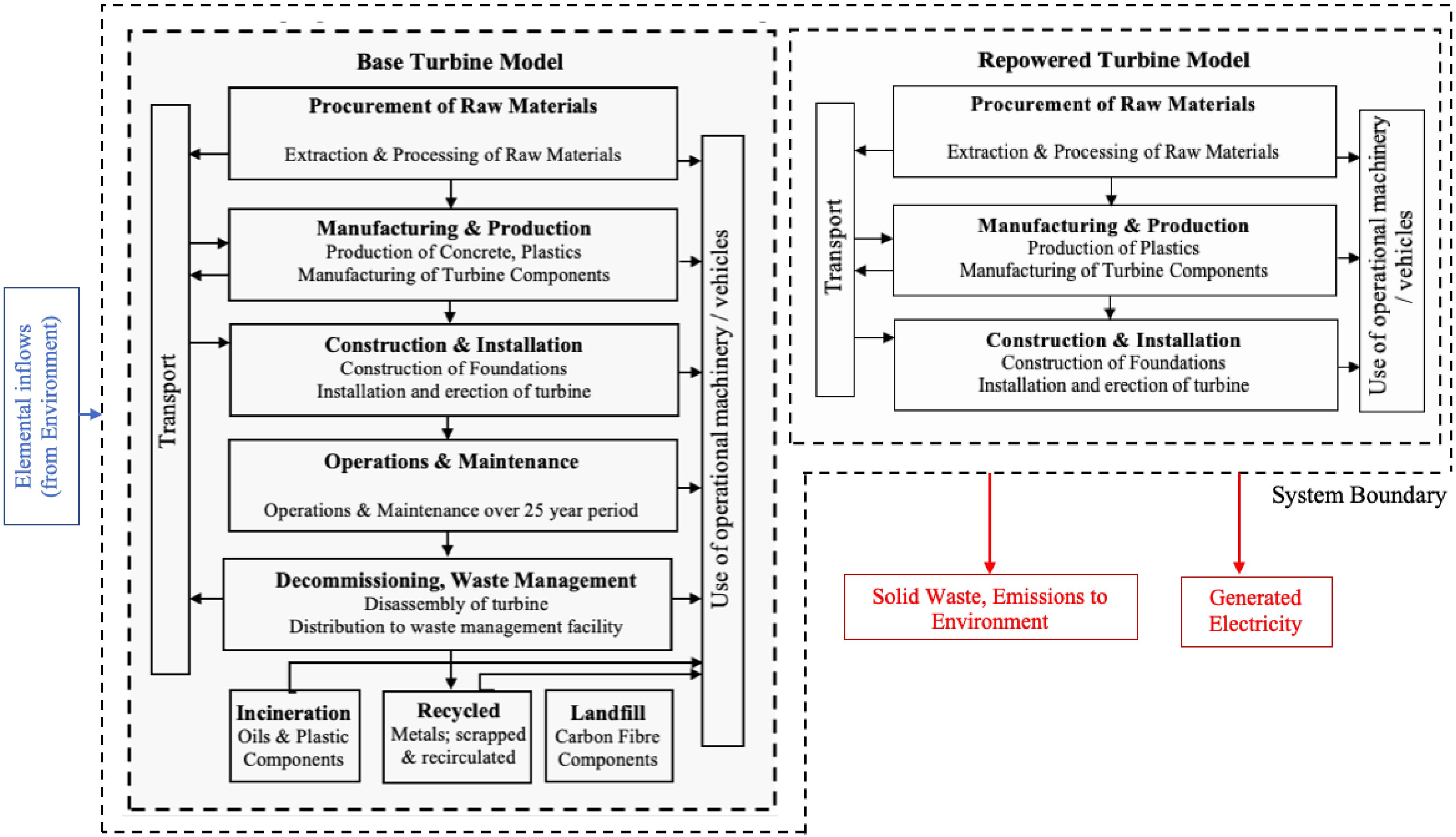

Figure 24- System Boundary for EoL Scenario 3; Repowering. System Boundary can be denoted by black dotted line, overall system compromises of system for base model + system for repowered model.

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3.5 Turbine Component Scaling

In order to quantify the mass of materials used within each component to the specifications of the turbine rotor radius and hub heights for Scenario 1, 2 and 3 as defined within section 3.2 the NREL turbine component scaling methodology was followed (Fingersh, Hand and Laxson, 2006). The mass of the components was then used to produce inputs for openLCA with regards to mass of materials manufactured. The equations used to scale each turbine component -excluding the foundations-, as a function of the rotor radius or machine rating detailed in table 2, section 3.2 are illustrated throughout this section:

Firstly, the swept area, in m^2 was calculated as a function of the Rotor Radius in m;

$$Swept\ Area = \pi r^2 \quad [1]$$

Turbine Tower Mass in kg Scaling as a function of hub height in m and swept area in m^2 (Fingersh, Hand and Laxson, 2006);

$$Tower\ Mass = 0.2694 * Swept\ Area * hub\ height + 1779 \quad [2]$$

Turbine Blade Mass Scaling Relationship, where mass in kg is a function of rotor radius R in m (Fingersh, Hand and Laxson, 2006);

$$Blade\ Mass = 0.1452 * R^{2.9158} \quad [3]$$

Turbine Hub mass scaling, where hub mass in kg is dependent upon blade mass in kg (Fingersh, Hand and Laxson, 2006);

$$Hub\ mass = 0.954 * (single\ blade\ mass) + 5680.3 \quad [4]$$

Pitch Mechanisms and bearings Scaling relationship, pitch bearing [5] and system [6] mass in kg calculated as a function of the blade mass for all three blades in kg (Fingersh, Hand and Laxson, 2006);

$$Total\ Pitch\ Bearing\ Mass = 0.1295 * total\ blade\ mass + 491.31 \quad [5]$$

$$Total\ Pitch\ System\ Mass = (Total\ Pitch\ Bearing\ Mass * 1.328) + 555 \quad [6]$$

Nose cone mass, in kg is calculated as a function of rotor diameter in m (Fingersh, Hand and Laxson, 2006);

$$Nose\ Cone\ Mass = 18.5 * rotor\ diameter - 520.5 \quad [7]$$

Main Shaft mass, in kg is calculated as a function of the rotor diameter (Fingersh, Hand and Laxson, 2006);

$$Main\ Shaft\ Mass = 0.0142 * rotor\ diameter^{2.888} \quad [8]$$

Main Bearings mass, in kg is calculated as a function of the rotor diameter (Fingersh, Hand and Laxson, 2006);

$$Main\ Bearings\ Mass = \left(rotor\ diameter * \frac{8}{600} - 0.033\right) * 0.0092 * rotor\ diameter^{2.5} \quad [9]$$

Mechanical Brake mass, in kg is calculated as a function of the machine rating (Fingersh, Hand and Laxson, 2006);

$$Mechanical\ Brake\ Mass = (1.9894 * machine\ rating\ in\ kw - 0.1141 \quad [10]$$

Nacelle mainframe mass, in kg is calculated as a function of the rotor diameter (Fingersh, Hand and Laxson, 2006);

$$Mainframe\ mass = 1.295 * rotor\ diameter^{1.953} \quad [11]$$

The nacelle cover mass, in kg is calculated as a function of the machine rating (Fingersh, Hand and Laxson, 2006);

$$Nacelle\ cover\ mass = (11.537 * machine\ rating(in\ kw) + 3849.7) / 10 \qquad [12]$$

The hydraulics / cooling system mass, in kg is calculated as a function of the machine rating (Fingersh, Hand and Laxson, 2006);

$$hydraulic\ system\ mass = 0.08 * machine\ rating\ (in\ kw) \qquad [13]$$

Generator mass in kg is calculated as a function of the machine rating (Fingersh, Hand and Laxson, 2006);

$$Generator\ Mass = 6.47 * \ machine\ rating^{0.9223} \qquad [14]$$

To scale the mass of components within the foundations, the dimensions of the foundations were recorded as illustrated in the Stranoch 2 wind farm EIA report (Wood, 2018). See appendix C for the sketch detailing foundation dimensions.

All other turbine component masses, including the gearbox (offshore wind industry, 2016), plastic components, coolant, electronics, lubricants and magnets (Razdan and Garrett, 2019) were calculated and scaled as assumptions based upon literature.

3.6 Defining OpenLCA inputs

Based upon the data gathered from case studies 1 and 2 defined in sections 3.2 and with use of the equations presented in section 3.5, the inputs for openLCA are defined throughout this section in table 7.

Throughout all product sources for the processes of manufacturing, or transport within openLCA the “Market for” selection has been preferentially made where possible, as this therefore includes the extraction of the raw materials. Where possible, the source has also been selected as within Europe, for accuracy of manufacturing specifications defined in the project.

Table 7- Material and Mass inputs to openLCA, broken down by turbine component and turbine model.

Turbine Component	Base Model		Refurbished Model		Repowered Model	
	Material	Mass	Material	Mass	Material	Mass
Foundation	Concrete	1996.58 t	Reused from Base		Reused from Base	
	Gravel	3510.35 t				
	Steel	70 t				
Tower	Steel	316.42 t	Reused from Base		Steel	485.74 t
Blade (one blade)	Carbon Fibre	19.20 t	Reused from Base		Carbon fibre	26.56 t
	Plastic Resin	11.84t	Reused from Base		Plastic Resin	16.38 t
	Iron fasteners	0.96 t	Reused from Base		Iron Fasteners	1.33 t
Hub	Cast Iron	5.71	Reused from Base		Cast Iron	5.722 t
Pitch System	Aluminium	1.22 t	Repurposed aluminium	1.22 t	Aluminium	1.23 t
Nose Cone	Steel	2.0 t	Reused from Base		Steel	2.29 t
Main Shaft	Steel	20.60t	Reused from Base		Steel	28.41 t
Main Bearings	Cast Iron	3.53 t	Reused from Base		Cast Iron	5.22 t
Mechanical Brake	Steel	0.84 t	Repurposed Steel	0.84 t	Steel	0.92 t
Mainframe	Steel	18.92 t	Reused from Base		Steel	23.51 t
Nacelle Cover	Steel	52.31 t	Reused from Base		Steel	56.92 t
Hydraulic system	Steel	0.34 t	Reused from Base		Steel	0.37 t
Generator	Steel	14.21 t	Reused from Base		Steel	15.45 t
Gearbox	Steel	62 t	Reused from Base		Steel	62 t
Yaw Gear	Steel	32 t	Repurposed Steel 32 t		Steel	32 t

Turbine Component	Base Model		Refurbished Model		Repowered Model	
	Material	Mass	Material	Mass	Material	Mass
Plastic components	rubber	18.5 t	rubber	18.5 t	Assumption; same as base	
Coolant	Hydraulic fluid	0.29 t	Reused from Base		Assumption; same as base	
Lubricant	Lubricating oil	1.2 t	Reused from Base		Assumption; same as base	
Magnets	Neodymium Oxide	3.79 t	Reused from Base		Assumption; same as base	
Electronics	copper	3.75 t	Reused from Base		Assumption; same as base	

Type of component materials for the mass inputs calculated were sourced from literature (Li, Li and Wu, 2020). There is an assumption that all weights and materials of the refurbished components in EoL scenario 2 are the same as those of the original base turbine model. However where parts have been repurposed; with EoL scenario 2; the yaw gears, mechanical brake and pitch system; these are assumed to be completely recirculated and thus the mass of manufacturing is not included.

It is important to note that Reused from Base and Assumption; same as base are not the same; reused from base defines components repurposed in further models, however same as base refers to the same material and mass as the base turbine model.

3.7 OpenLCA Environmental Assessment Method

The impact assessment methods used within openLCA for this project are the ReCiPe midpoint and endpoint (Acero, Rodriguez and Ciroth, 2015). The ReCiPe midpoint factors focus on sole environmental problems, table 8 highlights the environmental impact category group within openLCA. Key for the table can be found in figure 25.

Key:
E= Egalitarian / H= Hierarchist / I= Individualist
HH= Human Health / EQ = Ecosystem / RD= Resources

Figure 25- Key for tables 7 and 8 (Acern, Rodriguez and Ciroth, 2015).

Table 8- The ReCiPe midpoint impact category groups, and method used in openLCA (Acero, Rodriguez and Ciroth, 2015).

Method: **ReCiPe midpoint (E, H & I)**				
Impact category group	**Name of the impact category in the method**	**E**	**H**	**I**
Acidification	Terrestrial acidification	TAP500-E	TAP100-H	TAP20-I
Climate change	Climate Change	GWP500-E	GWP100-H	GWP20-I
Depletion of abiotic resources	Fossil depletion	FDPinf-E	FDP100-H	FDP20-I
	Metal depletion	MDPinf-E	MDP100-H	MDP20-I
	Water depletion	WDPinf-E	WDP100-H	WDP20-I
Ecotoxicity	Freshwater ecotoxicity	FETPinf-E	FETP100-H	FETP20-I
	Marine ecotoxicity	METPinf-E	METP100-H	METP20-I
	Terrestrial ecotoxicity	TETPinf-E	TETP100-H	TETP20-I
Eutrophication	Freshwater eutrophication	FEPinf-E	FEP100-H	FEP20-I
	Marine eutrophication	MEPinf-E	MEP100-H	MEP20-I
Human toxicity	Human toxicity	HTPinf-E	HTP100-H	HTP20-I
Ionising Radiation	Ionising radiation	IRPinf-E	IRP100-H	IRP20-I
Land use	Agricultural land occupation	ALOPinf-E LOP-E	ALOP100-H LOP-H	ALOP20-I LOP-I
	Natural land transformation	LTPinf-E LTP-E	LTP100-H LTP-H	LTP20-I LTP-I
	Urban land occupation	ULOPinf-E	ULOP100-H	ULOP20-I
Ozone layer depletion	Ozone depletion	ODPinf-E M2E-E	ODP100-H M2E-H	ODP20-I M2E-I
Particulate matter	Particulate matter formation	PMFPinf-E	PMFP100-H	PMFP20-I
Photochemical oxidation	Photochemical oxidant formation	POFPinf-E	POFP100-H	POFP20-I

ReCiPe endpoint factors focus on the environmental impacts on a higher level, where environmental impacts are grouped into concerns to human health, biodiversity and resource scarcity (RIVM, 2018). Table 9 illustrates the impact category group and method within openLCA for the ReCiPe endpoint factors, key to read table presented in figure 25.

Table 9- The ReCiPe endpoint impact category groups and methods with openLCA (Acern, Rodriguez and Ciroth, 2015).

Method: **ReCiPe endpoint (E, H & I)**				
Impact category group	**Name of the impact category in the method**	**E**	**H**	**I**
Acidification	Terrestrial acidification	TAPinf EQ-E	TAP100 EQ-H	TAP20 EQ-I
Climate change	Climate change	GWPinf HH-E GWPinf EQ-E	GWP100 HH-H GWP100 EQ-H	GWP20 HH-I GWP20 EQ-I
Depletion of abiotic resources	Metal depletion	MDPinf RD-E	MDP100 RD-H	MDP20 RD-I
	Fossil depletion	FDPinf RD-E	FDP100 RD-H	FDP20 RD-I
Ecotoxicity	Freshwater ecotoxicity	FETPinf EQ-E	FETP100 EQ-H	FETP20 EQ-I
	Marine ecotoxicity	METPinf EQ-E	METP100 EQ-H	METP20 EQ-I
	Terrestrial ecotoxicity	TETPinf EQ-E	TETP100 EQ-H	TETP20 EQ-I
Eutrophication	Freshwater	FEPinf EQ-E	FEP100 EQ-H	FEP20 EQ-I
Human toxicity	Human toxicity	HTPinf HH-E	HTP100 HH-H	HTP20 HH-I
Ionising radiation	Ionising radiation	IRPinf HH-E	IRP100 HH-H	IRP20 HH-I
Land use	Agricultural land occupation	ALOPinf EQ-E	ALOP100 EQ-H	ALOP20 EQ-I
	Urban land occupation	ULOPinf EQ-E	ULOP100 EQ-H	ULOP20 EQ-I
	Natural land transformation	LTPinf EQ-E	LTP100 EQ-H	LTP20 EQ-I
Ozone layer depletion	Ozone depletion	ODPinf HH-E	ODP100 HH-H	ODP20 HH-I
Particulate matter	Particulate matter formation	PMFPinf HH-E	PMFP100 HH-H	PMFP20 HH-I
Photochemical oxidation	Photochemical oxidant formation	POFPinf HH-E	POFP100 HH-H	POFP20 HH-I

Upon completion of creation of the lifecycle product system with openLCA, environmental impact assessment results are ran with the use of ReCiPe midpoint and endpoint assessment methods to produce the results of this study. Figure 26 shows the relationship between the ReCiPe midpoint factors and the resulting ReCiPe endpoint areas of protection.

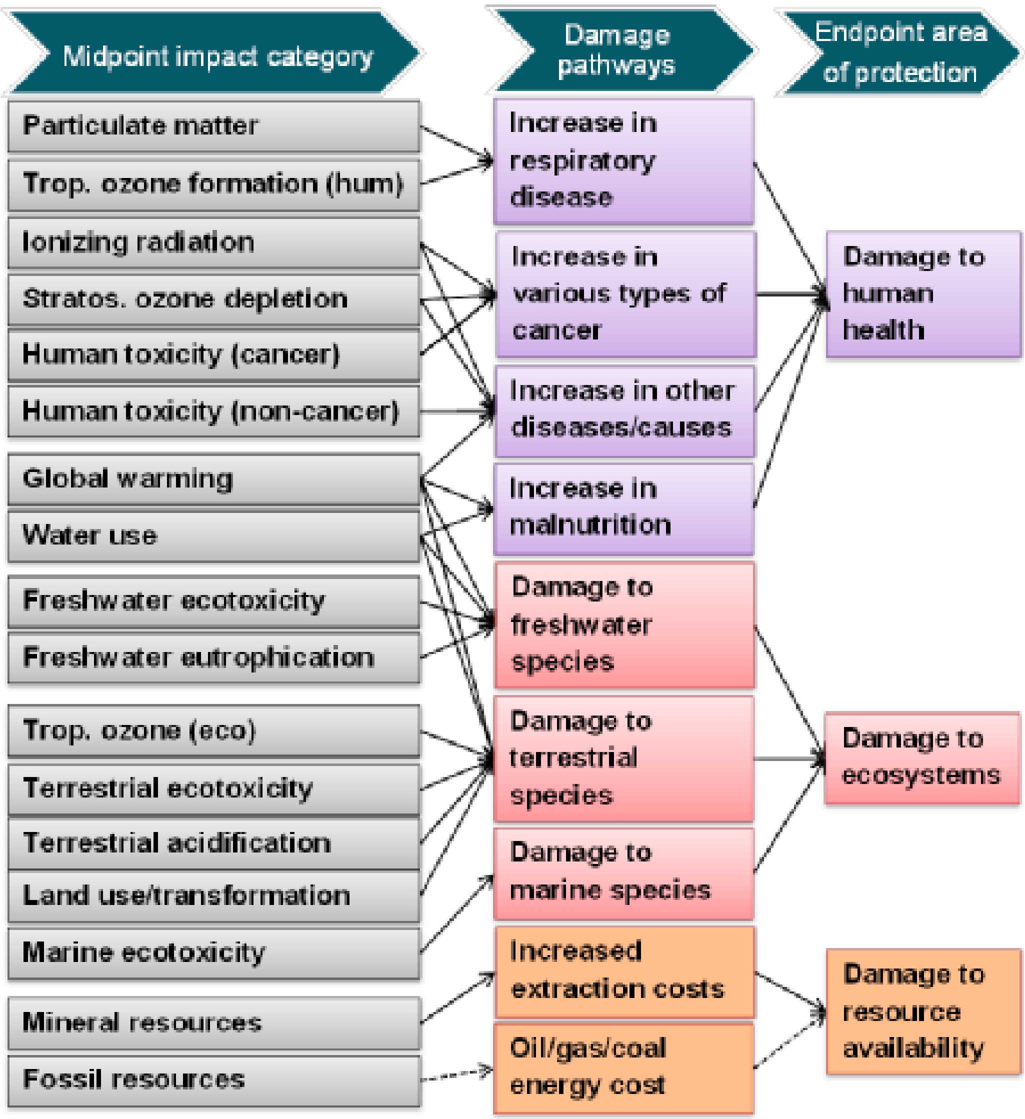

Figure 26- The relationship between ReCiPe midpoint impact categories and ReCiPe Endpoint protection areas, linked by damage pathways (RIVM, 2018).

Also considered throughout analysis is the GHG protocol environmental impact assessment, whereby the breakdown of CO_2 emissions is assessed.

4.0 Results

The results of the LCA with openLCA are detailed throughout this chapter, firstly with the results of the ReCiPe midpoint analysis in section 4.1 and the results of the ReCiPe endpoint analysis in section 4.2. The GHG protocol outputs are detailed in section 4.3. All data within this section has been exported from the LCA made using software openLCA.

4.1 ReCiPe Midpoint Environmental Impact Assessment

4.1.1 Scenario 1; Decommissioning

The ReCiPe midpoint impact categories and results, with relevant reference unit for the entire system boundary (as defined in figure 22) of Scenario 1 are presented in table 10.

Table 10- ReCiPe midpoint environmental impact assessment results for Scenario 1: Decommissioning. Exported from openLCA.

Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	7936.612221
Fossil resource scarcity	kg oil eq	1139272.964
Freshwater ecotoxicity	kg 1,4-DCB	370794.1231
Freshwater eutrophication	kg P eq	1313.344603
Global warming	kg CO2 eq	4764040.89
Human carcinogenic toxicity	kg 1,4-DCB	254793099.6
Human non-carcinogenic toxicity	kg 1,4-DCB	1203573301
Ionizing radiation	kBq Co-60 eq	602134.0331
Land use	m2a crop eq	244997.7996
Marine ecotoxicity	kg 1,4-DCB	1746030658
Marine eutrophication	kg N eq	3001.226378
Mineral resource scarcity	kg Cu eq	202004.6287
Ozone formation, Human health	kg NOx eq	18157.90773
Ozone formation, Terrestrial ecosystems	kg NOx eq	18552.49776
Stratospheric ozone depletion	kg CFC11 eq	2.801963003
Terrestrial acidification	kg SO2 eq	16479.04822
Terrestrial ecotoxicity	kg 1,4-DCB	33275247.75
Water consumption	m3	41657.86247

4.1.2 Scenario 2; Refurbishment

The ReCiPe midpoint impact categories and results, with relevant reference unit for the entire system boundary (as defined in figure 23) of Scenario 2 are presented in table 11.

Table 11- ReCiPe midpoint environmental impact assessment results for Scenario 2: Refurbishment. Exported from openLCA.

Impact Category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	8787.106334
Fossil resource scarcity	kg oil eq	1152793.653
Freshwater ecotoxicity	kg 1,4-DCB	399791.1531
Freshwater eutrophication	kg P eq	1388.662626
Global warming	kg CO2 eq	4888496.22
Human carcinogenic toxicity	kg 1,4-DCB	307219890.7
Human non-carcinogenic toxicity	kg 1,4-DCB	1231279865
Ionizing radiation	kBq Co-60 eq	617754.949
Land use	m2a crop eq	235413.0276
Marine ecotoxicity	kg 1,4-DCB	1826816490
Marine eutrophication	kg N eq	3009.787134
Mineral resource scarcity	kg Cu eq	233261.184
Ozone formation, Human health	kg NOx eq	17832.882
Ozone formation, Terrestrial ecosystems	kg NOx eq	18217.34203
Stratospheric ozone depletion	kg CFC11 eq	2.847940269
Terrestrial acidification	kg SO2 eq	17125.53311
Terrestrial ecotoxicity	kg 1,4-DCB	36580632.47
Water consumption	m3	43863.86032

4.1.3 Scenario 3; Repowering

The ReCiPe midpoint impact categories and results, with relevant reference unit for the entire system boundary (as defined in figure 24) of Scenario 3 are presented in table 12.

Table 12- ReCiPe midpoint environmental impact assessment results for Scenario 3: Repowering. Exported from openLCA.

Impact category	Reference unit	Result
Fine particulate matter formation	kg PM2.5 eq	8787.106334
Fossil resource scarcity	kg oil eq	1152793.653
Freshwater ecotoxicity	kg 1,4-DCB	399791.1531
Freshwater eutrophication	kg P eq	1388.662626
Global warming	kg CO2 eq	4888496.22
Human carcinogenic toxicity	kg 1,4-DCB	307219890.7
Human non-carcinogenic toxicity	kg 1,4-DCB	1231279865
Ionizing radiation	kBq Co-60 eq	617754.949
Land use	m2a crop eq	235413.0276
Marine ecotoxicity	kg 1,4-DCB	1826816490
Marine eutrophication	kg N eq	3009.787134
Mineral resource scarcity	kg Cu eq	233261.184
Ozone formation, Human health	kg NOx eq	17832.882
Ozone formation, Terrestrial ecosystems	kg NOx eq	18217.34203
Stratospheric ozone depletion	kg CFC11 eq	2.847940269
Terrestrial acidification	kg SO2 eq	17125.53311
Terrestrial ecotoxicity	kg 1,4-DCB	36580632.47
Water consumption	m3	43863.86032

4.1.4 Comparison of Scenarios

A comparison of the ReCiPe midpoint categories and results across all three EoL scenarios is illustrated in figure 27. Some impact results may not appear visible on the comparison chart, refer to tables 10, 11 and 12 to provide exact data for Impact Categories with very small resultant quantities. Note that referral of Reference unit must be made to tables 10, 11 and 12 when reading quantity of impact category result from figure 27.

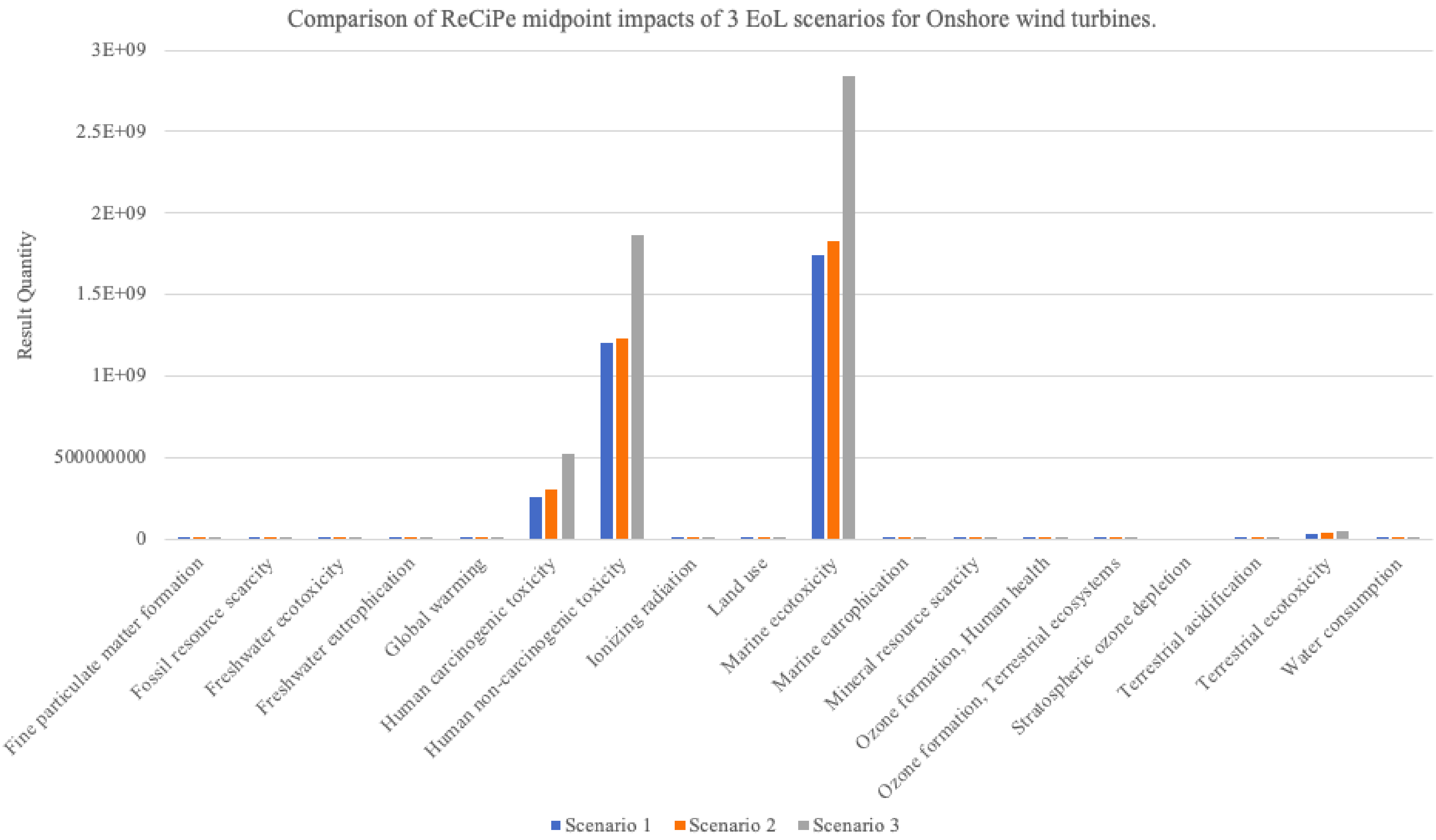

Figure 27- Comparison of ReCiPe midpoint impact results, for 3 EoL decisions of onshore wind turbines. Results exported from openLCA. The reference unit for result quantity of each impact category can be found in tables 10, 11 and 12.

4.1.5 Focus on Global Warming; Carbon Dioxide Emissions

A focus assessment was undertaken using the ReCiPe midpoint impact category 'Global Warming' , where the carbon dioxide emissions (kgCO2eq) are quantified. Figure 28 illustrates the Carbon Dioxide Emissions from each life cycle stage, with a magnified focus on the stages after production and manufacturing illustrated in figure 29.

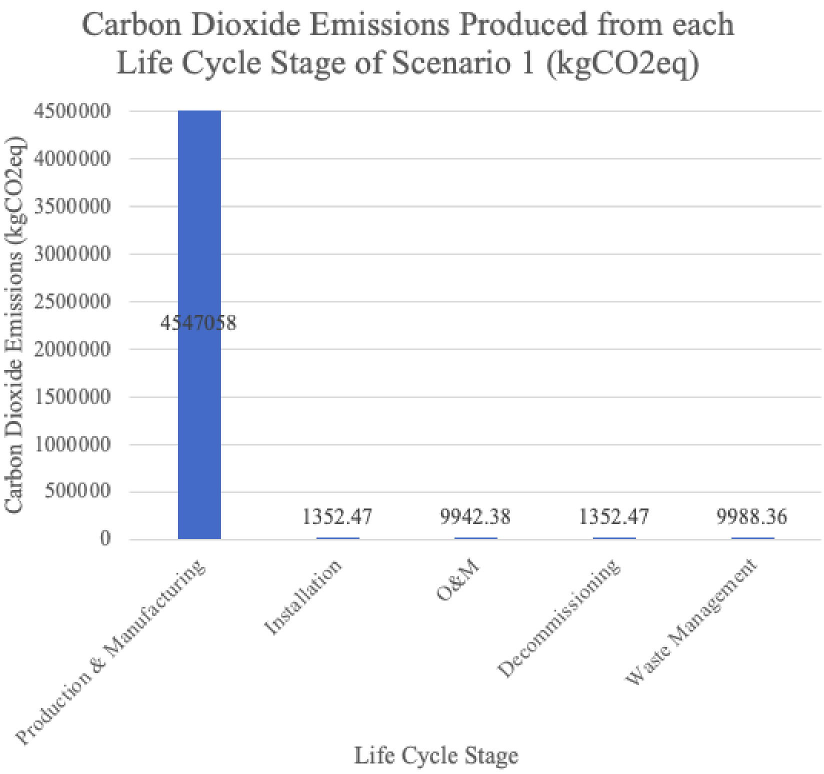

Figure 28- Carbon Dioxide Emissions Produced from each Life Cycle Stage of Scenario 1 (kgCO2eq).

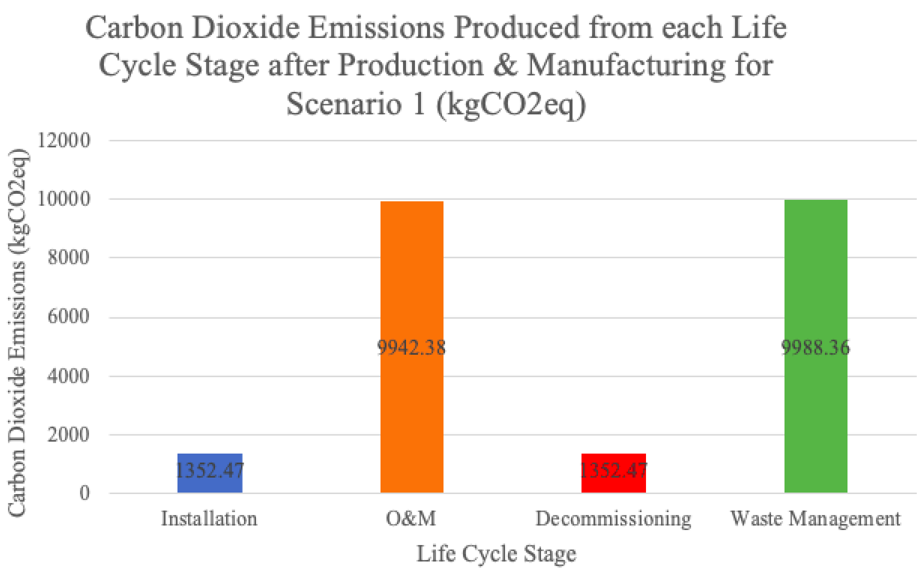

Figure 29- Comparison of the carbon dioxide emissions produced from each life cycle stage, after production & manufacturing in kgCO2eq.

The percentage breakdown of carbon emissions associated with the production & manufacturing of each turbine component is shown in figure 30. The quantity of carbon emissions associated with the production and manufacturing of each turbine component can be found in appendix D.

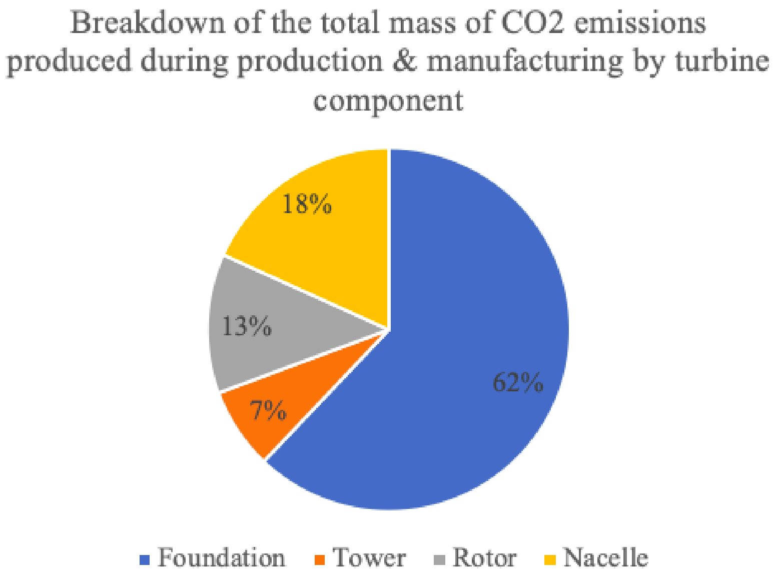

Figure 30- Percentage breakdown of the mass of CO_2 emissions produced per turbine component production and manufacturing.

The carbon dioxide emissions per life cycle stage after production and manufacturing of original turbine for scenario 2 are illustrated in figure 31. The carbon emissions of the production and manufacturing stage are equal to those illustrated in figure 28.

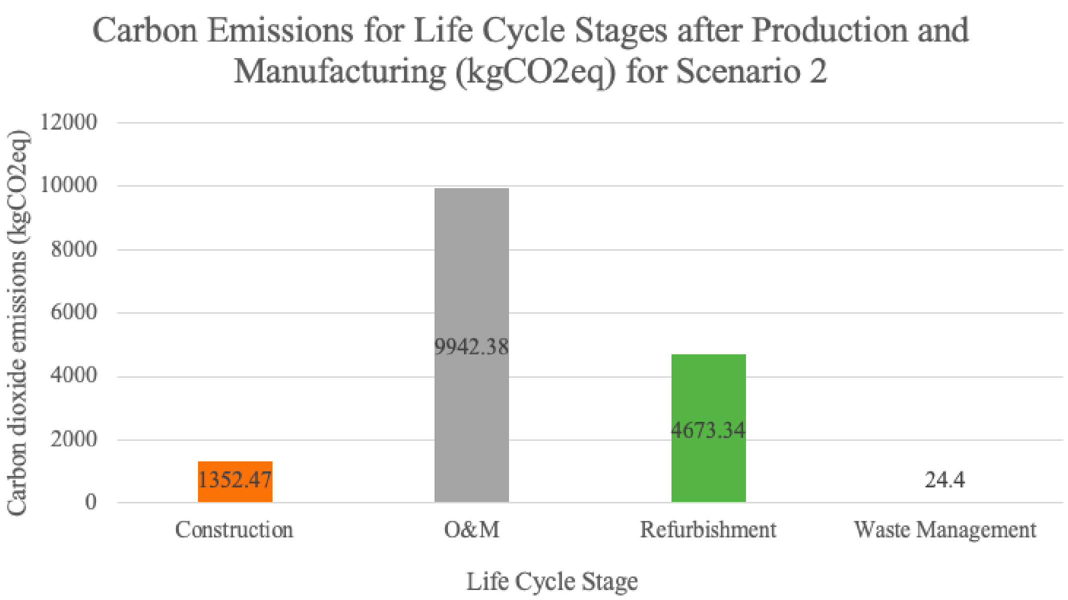

Figure 31- Carbon emissions ($kgCO_2eq$) per life cycle stage (after production & manufacturing) for scenario 2.

Figure 32 depicts the breakdown of the contribution of carbon emissions associated with each part of the refurbishment process.

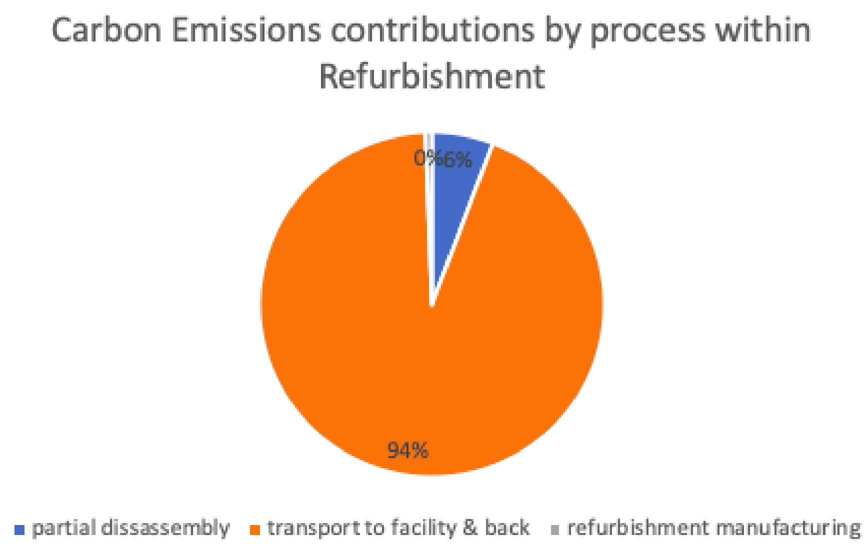

Figure 32- Breakdown of Carbon emission contributions by process within refurbishment process.

Finally, the breakdown of carbon emissions per life cycle stage of Scenario 3 are depicted in figure 33. See appendix E for detailed carbon emissions of processes within repowering; including the manufacturing and transport of the repowered turbine.

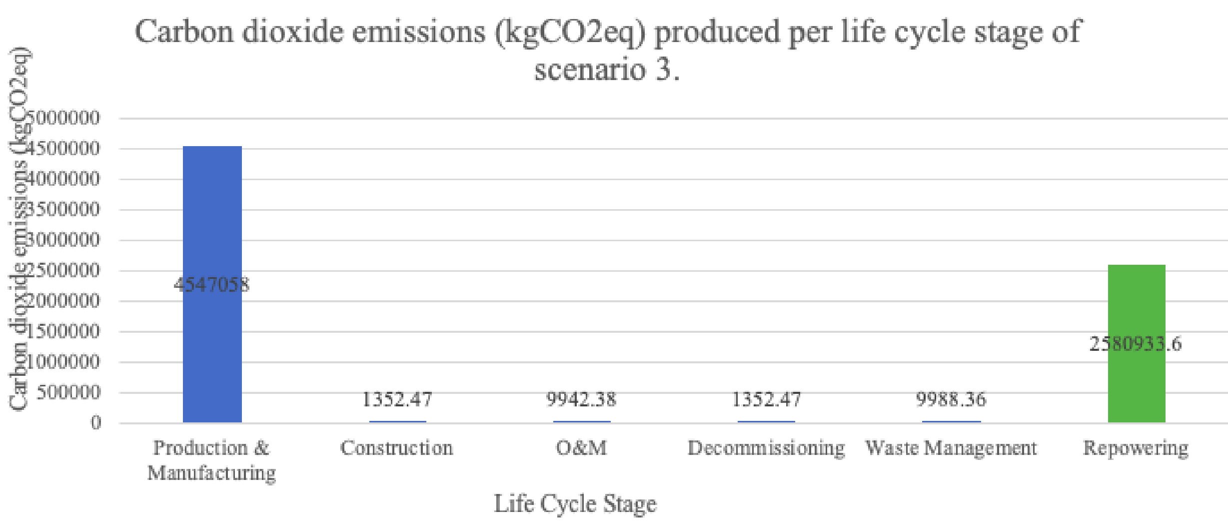

Figure 33- Carbon dioxide emissions (kgCO2eq) produced per life cycle stage for scenario 3.

4.2 ReCiPe Endpoint Environmental Impact Assessment

Table 13 presents the endpoint environmental impacts of each EoL option scenario, as a result of the highest impacted ReCiPe midpoint categories. Midpoint Impact Categories are ranked within each scenario in descending order of magnitude of impact. Resultant Damage pathways and endpoint area of protection derived from literature (RIVM, 2018).

Table 13- ReCiPe Endpoint Impact Assessment, for all 3 EoL scenarios.

	Midpoint Impact Category	Damage Pathway	Endpoint area of protection
Scenario 1	Fossil Resource Scarcity	Increase in oil/gas/energy costs	Damage to resource availability
	Global warming	Damage to terrestrial species, freshwater species and increase in malnutrition and disease	Damage to human health, damage to ecosystems
	Human Carcinogenic toxicity	Increase in various types of cancer	Damage to human health
	Mineral Resource Scarcity	Increased extraction costs	Damage to resource availability
	Human – non carcinogenic toxicity	Increase in other diseases	Damage to human health
Scenario 2	Fossil Resource Scarcity	Increase in oil/gas/energy costs	Damage to resource availability
	Mineral Resource Scarcity	Increased extraction costs	Damage to resource availability
	Global Warming	Damage to terrestrial species, freshwater species and increase in malnutrition and disease	Damage to human health, damage to ecosystems
	Marine Ecotoxicity	Damage to marine species	Damage to ecosystems
	Fine Particulate	Increase in respiratory disease	Damage to human health
Scenario 3	Fossil Resource Scarcity	Increase in oil/gas/energy costs	Damage to resource availability
	Mineral Resource Scarcity	Increased extraction costs	Damage to resource availability
	Global Warming	Damage to terrestrial species, freshwater species and increase in malnutrition and disease	Damage to human health, damage to ecosystems
	Fine Particulate	Increase in respiratory disease	Damage to human health
	Human Carcinogenic Toxicity	Increase in various types of cancer	Damage to human health

4.3 GHG Protocol Environmental Impact Assessment

The outputs generated from the GHG protocol impact assessment method are illustrated in figure 34 as a comparison of Fossil CO2, CO2 uptake, CO2 from land transformation and biogenic CO2 (all in kgCO2eq) against EoL scenario. The amount of CO2 equivalent form the lifecycle of each Scenario can be seen.

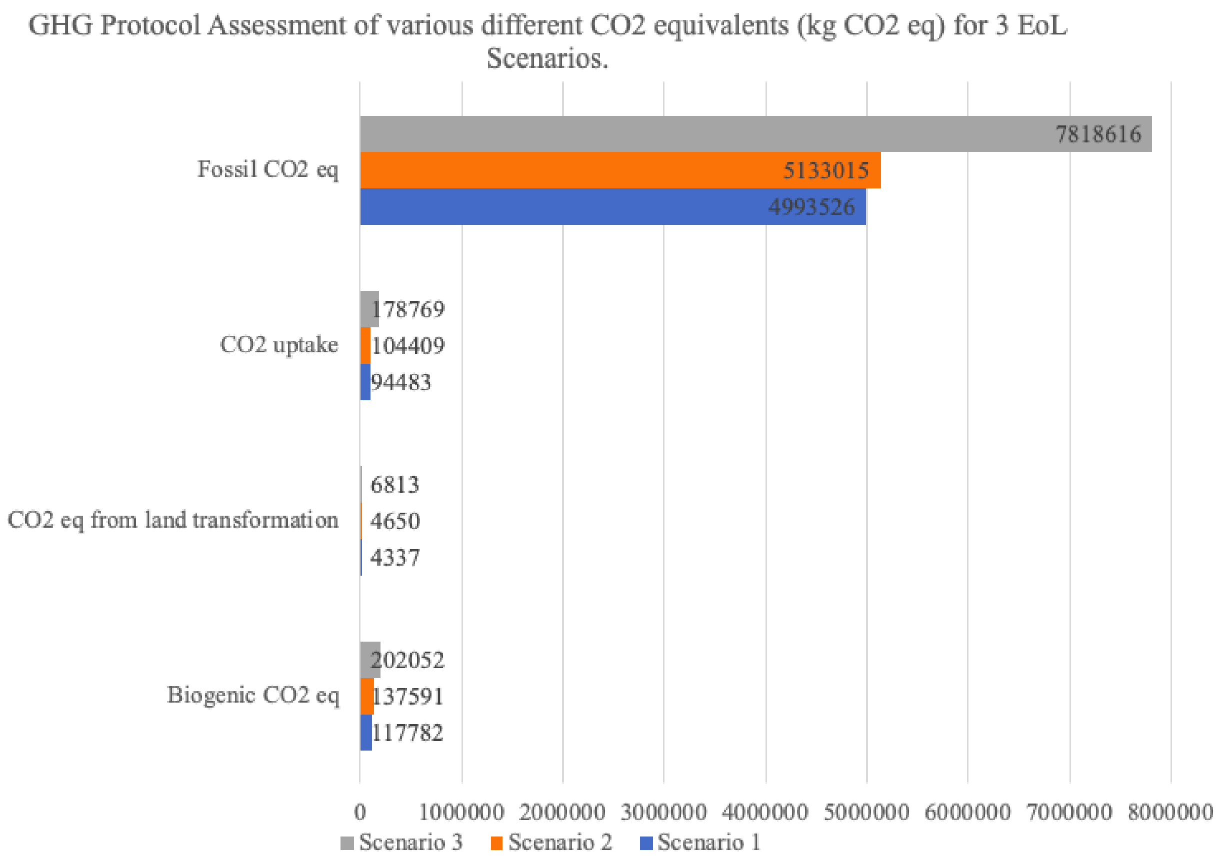

Figure 34- The GHG Protocol Environmental Impact Assessment, a comparison of the carbon dioxide outputs of three EoL options, where all categories of CO2 are measured in kg CO2 eq.

5.0 Discussion

The results from the ReCiPe midpoint environmental impact assessment show that all three options produce results and emissions associated to every midpoint category. Across all three EoL options the same environmental impacts are of the highest concern. Human Carcinogenic, Human non-carcinogenic and marine ecotoxicity all present as the three quite significantly highest impacting categories in figure 27. Terrestrial ecotoxicity and global warming also rank within the 5 highest impacting categories. To understand the source of the pollutants, and at which stage within the life cycle it is important to break it down and gain a more detailed view.

Throughout section 4.1.5 the ReCiPe midpoint assessment is dissected and the global warming environmental impact is focused upon, with the assessment of carbon dioxide produced, per stage of the life cycle. Figure 28, highlights that the carbon emissions associated with the production and manufacturing stage significantly outweigh those of the stages of installation, O&M and waste management. Figure 29 highlights that the carbon emissions for the O&M and the waste management are very similar at around 9900kgCO2eq per stage for Scenario 1.

It can be seen in figure 30, that the construction and production of the foundations component of the wind turbine is the most carbon intensive, responsible for contributing 62% of the carbon emissions for the production and manufacturing of the turbine components. This is further seen in figure 33, where the Repowering stage is almost half that of production and manufacturing of the original turbine model. The repowering production and manufacturing is so low as in the repowered model it is assumed that the original foundations would be re used, cutting out the need to remanufacture them. Partially, the vast contributions to the carbon dioxide emissions associated with the manufacturing of the foundations is as a result of the high number of trips via truck taken to deliver the cement, 80 trips for enough for one turbine alone (shown in table 3). The re-use of existing foundations is essential to increase the sustainability of lifetime extended turbine models, whether it is the refurbished or remanufactured models. Where the foundations are primarily being built, sourcing the concrete from as close to the turbine site as possible will vastly help reduce the emissions associated with transporting the materials.

Manufacturing and production of the nacelle accounts for the next largest percentage at 18% of total carbon emissions from manufacturing and production; as the majority of the components within the nacelle are made of steel- the opportunity to reduce the carbon footprint of nacelle production is there, and should be done with the use of waste / scrap steel and recirculated parts- even in the initial manufacturing.

Consistently, with a breakdown of the manufacturing and production stage, as seen in figure 32 for the production of the repowered model, the most carbon intensive contribution is consistently the transport associated with moving materials and parts.

The ReCiPe end point analysis shows that across all scenarios, fossil resource scarcity and mineral resource scarcity are of concern, potentially resulting in permanent damage to resource availability by driving costs up too high. The emissions associated with the life cycle of turbines, across all three scenarios produce carcinogenic and non-carcinogenic human toxicity, these result in the increased spread of disease and cancers, endangering human health. The GWP associated with carbon dioxide emissions throughout all stages of all three EoL options, results in a large concern for damage to terrestrial species, freshwater species and an increase to human disease; resulting in the potential damage to human health and the worlds ecosystems.

The GHG protocol environmental impact assessment as shown in figure 34 highlights which kind of carbon dioxide emissions contribute larges towards the emissions of the turbine life cycles. Fossil CO2 is significantly ahead of the other forms of CO2, in particular for the contributions of scenario 3. This is a direct result of the fuel used within transporting turbine components and within manufacturing and construction machinery. The only slight difference in carbon emissions from refurbishment, compared to decommissioning proves that refurbishment is an environmentally desirable lifetime extension option, where the impacts of the extension are minimal, resulting in up to another 10 years of life producing green energy.

Repowering consistently proves to be the highest contributor to all emissions throughout the environmental categories presented in table 12, and within the GHG protocol assessment. Refurbishment does not produce a great deal more emissions than the option to decommission, with additional emissions as a result of the transport to and from the refurbishment facility. Decommissioning does remain the lowest environmentally impactful option, across all assessments.

6.0 Conclusion

The current climate crisis requires there to be sustainability assessment within all areas of infrastructure, particularly with increased pressures on renewable technology to achieve net zero goals the assessment of the environmental impacts of all aspects of said technology is essential. LCA is a very useful tool to assess Sustainability as it not only provides insight into numerous environmental impacts of the system, it also identifies the key stages within a product lifecycle that are the highest pollutant producing, providing an insight into things that may need to change and enabling an accurate assessment of how to do so.

While decommissioning does offer the lowest environmental impacts of the three end of life options, considerations must be made as to whether beyond EoL care, in the bigger picture of things if reducing the green energy supply is more or less environmentally friendly. The outputs for decommissioning all show lower numbers than the other two options, this is a direct result of only one stage of production and manufacturing within the lifecycle. Where installed wind capacity is no longer a requirement, the decommissioning of turbines will provide a low carbon, low environmental option at EoL. There is also opportunity for wind turbines, once decommissioning has occurred that a supply chain from the parts and materials within disassembled turbines could be recirculated throughout the industry, improving circularity and sustainability.

Repowering provides a desirable option from the aspect of producing a greater generation of electricity, however the sustainability of total repowering wind farm sites is in question. The stage within the life cycle of an onshore wind turbine that produces the highest number of emissions is the production and manufacturing stage, particularly due to the necessity to transport large items, usually at such long distances.

Refurbishment as a method of EoL extension proves to be environmentally effective, particularly in cases where the components used in the refurbishment process are recirculated parts or waste to scrap materials. Through the reuse of the majority of the original turbine model and the foundations; the extra emissions associated with the refurbishment process generally only tend to come from the transportation of the parts to and from the refurbishment centre. This option provides a way of extending life that is sustainable.

In conclusion, there is no best practise option at the EoL, as not only the environmental impacts can be taken into consideration; cost, social issues, energy demand and time constraints may all play a huge influence into any decisions made. However, from a strictly environmental standpoint, refurbishment proves the best option, where lifetime of the turbine is extended and the power generation output is not lost, without causing the production of more emissions through a full second manufacturing process, such as is within the Repowering option.

6.1 Limitations to the Study

Due to the nature of the breadth of the scope of the study with the comparison of three life cycles, a large limitation was the inability to provide a greater detailed assessment of the breakdown of materials within the turbine components, resulting in an LCA with less accurate materials input than if a smaller scope had been assessed. An improvement to the study would be a specific, full, detailed turbine spec sheet with component material and mass to use as inputs for the LCA.

Infrastructure associated with installed wind turbines that was left out of scope for this study, including electrical cables, storage and the process surrounding preparation of wind farm sites create a limitation to the results of the study as they do not offer a full insight to the environmental impacts or emissions of what an entire wind farm may produce.

Limitations of openLCA and the ecoinvent database meant that while the market provider allowed for accurate resourcing of materials globally, further investigation into the each areas of material extraction and then application of these within openLCA and the ecoinvent database.

6.2 Recommendations for future work

Future work within this project is suggested to look at sensitivity analysis of the results, producing multiple similar life cycles, with alterations to transport, or manufacturing country. The results of the variations within manufacturing location, reduced transport may provide great insights into ways to reduce the carbon footprint and increase sustainability of wind turbine life cycles.

A key recommendation for future work would encompass using the knowledge gained of the most carbon intensive process and stages within the wind turbine life cycle, and developing lower carbon / more sustainable solutions, with particular attention to the production and manufacturing stage of the life cycle; potentially through an increase of use of locally sourced and manufactured components; reducing transport emissions.

Further investigation into the energy production of the wind farm, by scaling the environmental impacts assessed for the life cycle of one turbine to the life cycle of an entire fleet of turbines, alongside analysis of the green energy production and the resultant energy payback time, would be very insightful to understand how soon the energy used to refurbish or manufacture repowered turbines is earned back through the production of green energy from the turbines.

Cost analysis of the various EoL options assessed in this study would strengthen any best practise routes trying to be implemented.

Spatial and feasibility of a combination of all three end of life options may provide an optimised solution to ageing turbines, whereby some are repowered to retain the power output of the wind farm, and perhaps some are decommissioned to be used for parts within refurbishing others.

The opportunity investigate the feasibility of creating a circular business model, by creating a supply chain of the parts from those of the ageing fleet of turbines that choose to decommission, for repurpose within the refurbishment and / or repowering processes. If circularity is not possible, the research into which parts of the supply chain, or components of turbines could become circular should be undertaken.

The concept of sustainability by design would also be insightful, to see if turbines that are built with purpose to be refurbished / scraped / redistributed at the end of their life, result in significantly lower associated emissions and environmental impacts of the life cycle and EoL extensions.

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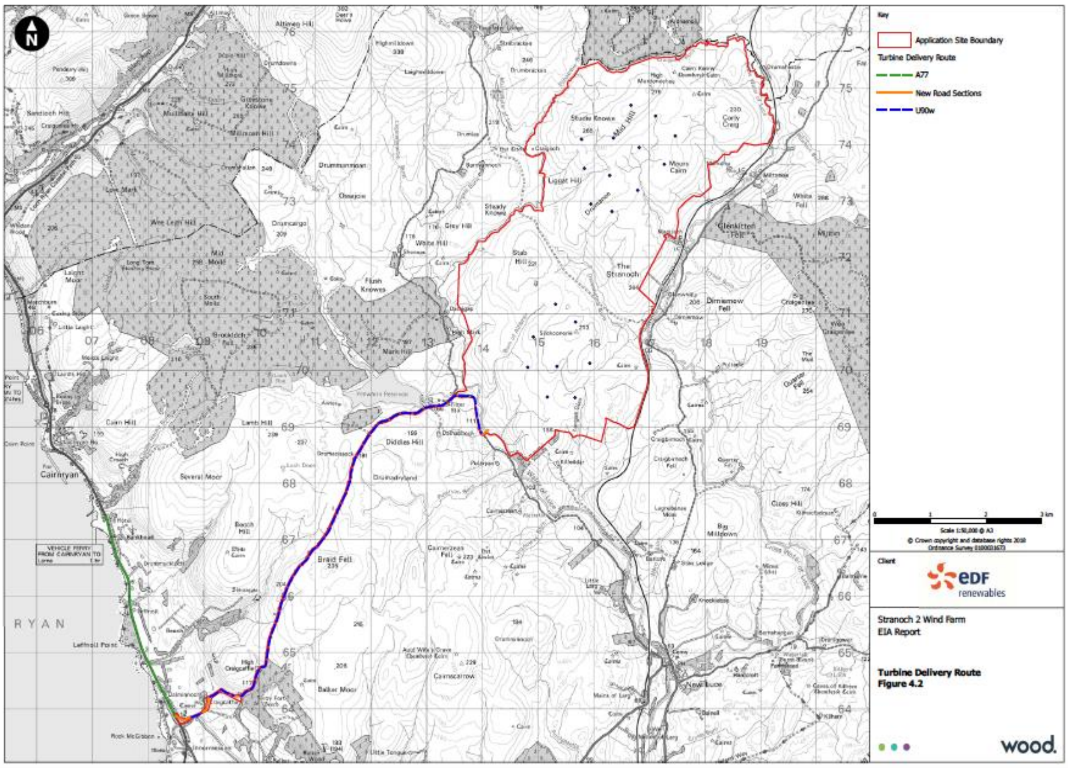
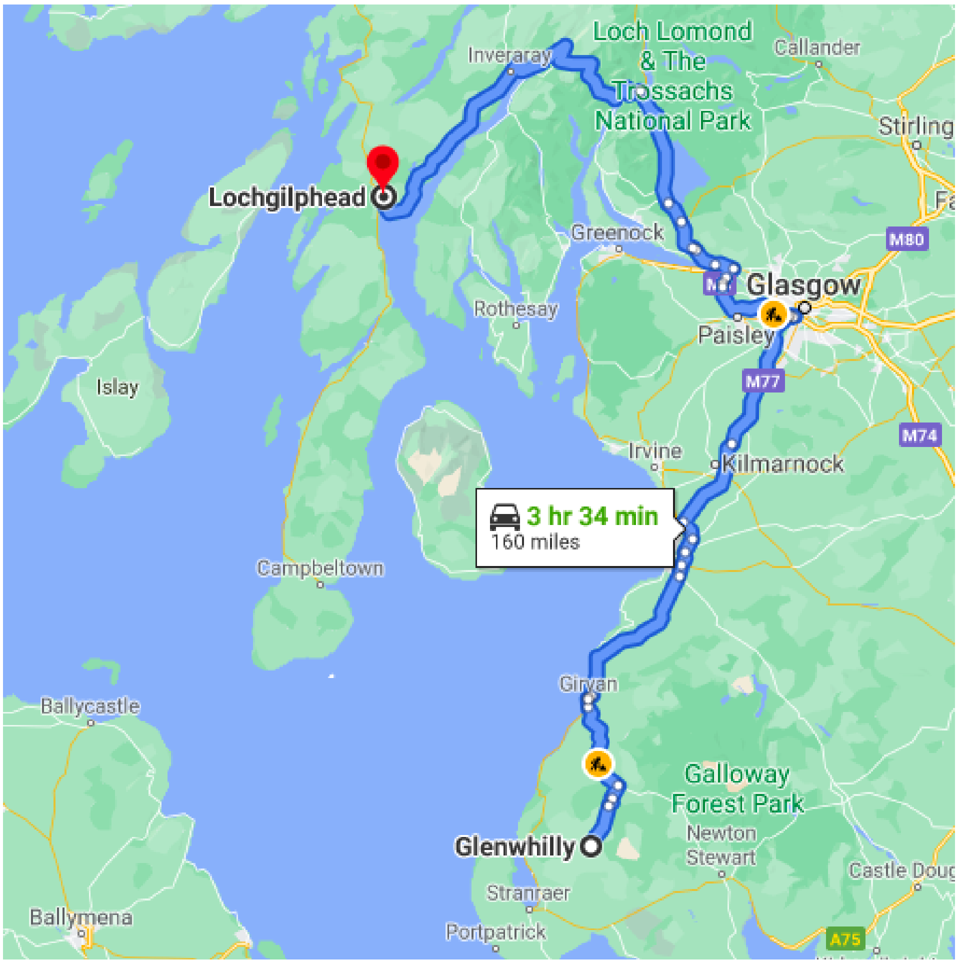
Appendix A- Site Location of Stranoch 2 Wind Farm

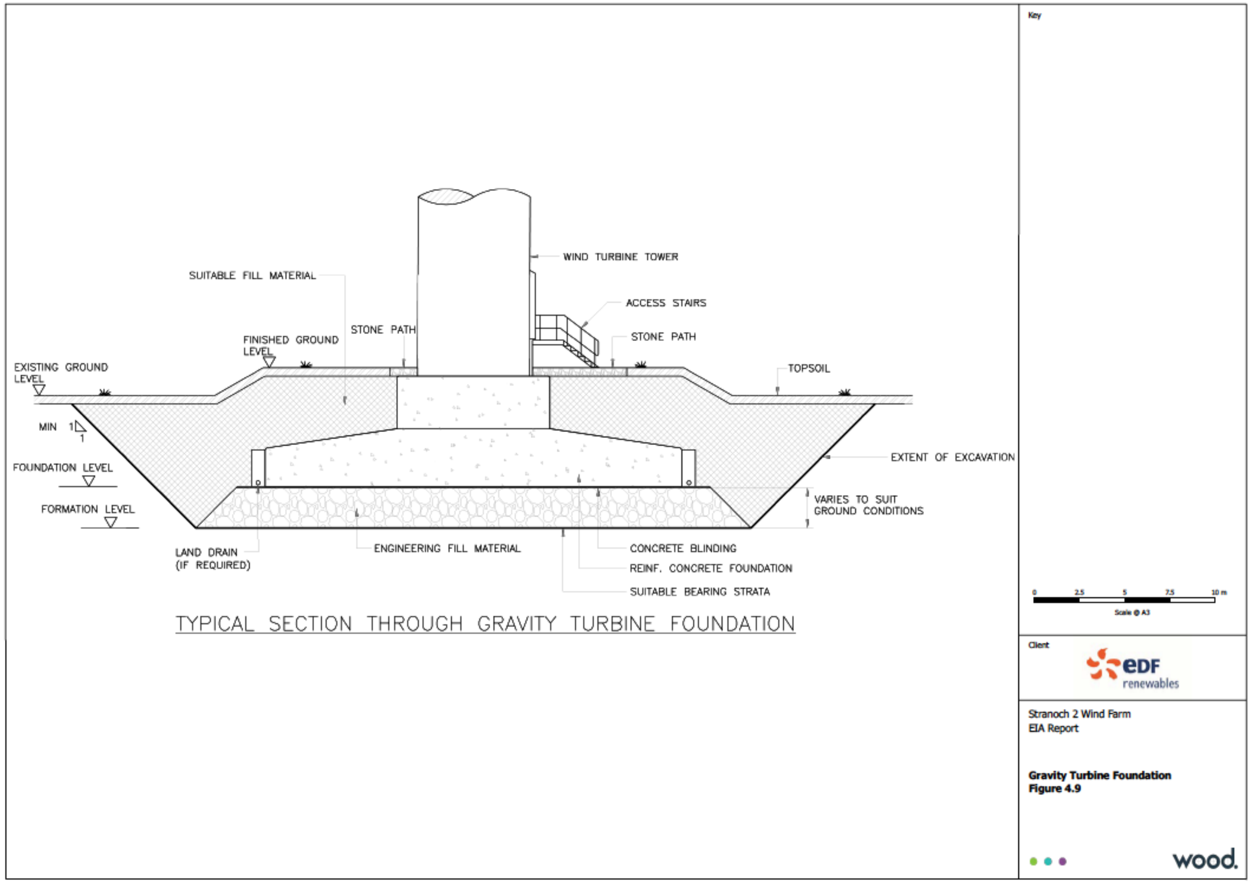


Appendix B- Transport Route to Refurbishment Factory



Appendix C- Gravity Based Foundation Sketch

Wood, 2018. Volume 2 Environmental Impact Assessment Report, *Stranoch 2 Wind Farm*. EDF



Appendix D- Carbon Dioxide Emissions associated with the Production & Manufacturing of Each Turbine Component

Raw material acquisition, manufacturing and transport	
Turbine Component	**Carbon Dioxide Emissions (kgCO2eq)**
Foundation	2823160
Tower	329894
Rotor	564417
Nacelle	829587
TOTAL	4547058

Appendix E- Carbon dioxide emissions per process within Repowering

Production & Manufacturing	Carbon Dioxide Emissions (kgco2eq)
repowered nacelle (including transport; land)	999586
repowered tower (including transport; land)	505102
repowered rotor (including transport; land)	1062930
transport (ship)	13315.6