Department of Mechanical and Aerospace Engineering

An Analysis into the Embodied Carbon Associated with the Early Life of a Wind Turbine Blade

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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 & the Environment*

2022

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Abstract

Amidst the surge of the offshore wind industry, many life cycle assessment papers have addressed several topics such as cost, energy payback or various possibilities of post-life options for wind turbines. However, an underlying issue among these papers is the lack of depth regarding the early stages of the supply chain, especially in emissions associated with materials. This study aims to quantify the embodied carbon associated with the materials and its transportation for a wind turbine blade. From this, the carbon emissions from each material should be differentiated, along with establishing the best transportation options to reduce emissions through theoretical scenarios. The results from this study should establish a baseline to be applied to realistic and justifiable cases. Little has been researched and published in this particular field and a study into the supply chain would serve useful to the industry to highlight the embodied emissions within the early stages. A Life Cycle Assessment (LCA) was performed on the early stages featuring a reference 15 MW offshore wind turbine blade, starting from its ore to the transportation to the assembly site. The results obtained from this study indicates that the chemical boron contains the highest carbon emissions associated with E-glass at $16.20\, kgCO2e/kg$. Furthermore, the findings from the wind turbine blade found that polyurethane adhesive contains the highest emissions per kg at $5.30\, kgCO2e/kg$, however only makes at 4% of the blade. Though, epoxy resin was found to hold the most emissions, making up 30% of the total blade at $4.31\, kgCO2e/kg$. Analysis into the transportation finds that long distance freighting by cargo ship is not necessarily bad if the majority of travel is performed on sea, as opposed to land travel from a heavy goods vehicle (HGV). It was also found that if land travel is necessary then the incorporation of freight railway is essential in reduction carbon emissions. Overall, the findings and analysis from this study should establish recommendations on what aspects of the material consumed in the manufacturing of a wind turbine blade should be analysed if the embodied emissions were to be reduced. Moreover, the study should also establish the ideal scenarios regarding freighting and highlight areas in which carbon emissions can be reduced in the current and future supply chain.

Acknowledgements

I would first like to express my deepest appreciation towards my project supervisor Dr. Stephanie Sánchez, for her intellectual guidance, unconditional support, and patience through my MSc thesis despite losing weeks due to illness.

Thanks, should also go to Dr. Paul Tuohy, my academic supervisor and all my lecturers during my MSc for their availability and friendliness, always ensuring a comfortable environment.

I would like to acknowledge the support granted from my family and friends who were always available for a chat despite the stress.

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Nomenclature

Symbol	Description	Units
LCA	Life Cycle Assessment	
CO_2	Carbon Dioxide	KgCO_2eq
HGV	Heavy Goods Vehicle	
GHG	Greenhouse	
PVC	Polyvinyl Chloride	
LCIA	Life Cycle Impact Assessment	
Wt%	Weight Percentage	

1. Introduction

Amidst these strange and turbulent times in today's economical and consequently political landscape, there is even greater pressure upon the green transition and net-zero pledges. Amongst this, offshore wind is one of the fastest-growing sectors in the renewable energy sector, especially in the UK. It is estimated that this sector will increase by 235 GW in the next decade across the globe, resulting in a total capacity of 270 GW (Xu et al., 2022). With such growth, other implications that may not be so obvious need to be considered, such as the impact of supply chains. To evaluate this, a prospective LCA will be performed to study the materials used in the early life cycle of a turbine blade, from resource extraction up until the transportation of the blade itself. This is necessary to quantify and differentiate the embodied carbon (carbon footprint) associated with wind turbine blades in the cradle stages. This paper will compare data found through the utilisation of the ecoinvent database and literature to compile comparative scenarios to highlight key areas which contain substantial emissions.

2. Literature Review

This section of the paper fulfils background knowledge required to support the methodological approach used to achieve the pursued aims as previously mentioned in the section before. Section 2.1. provides the tools used in this study and their importance within an LCA, along with a description. Section 2.2. explains the reason and desire to reduce carbon emissions and explains the role of the wind industry in this regard. Section 2.3. describes the current and forecasting trends of offshore wind. Section 2.4. provides the findings from available LCA literature regarding wind turbines and highlights flaws within those. Section 2.5. discusses literature which provides data regarding embodied carbon and utilises it as a baseline

2.1. Ecoinvent and OpenLCA

Based in Switzerland with over 20 years of experience in life cycle inventory data management and life cycle methodology, amongst other data related matters, the ecoinvent Association is a well trusted partner for organisations that require high-quality data. The ecoinvent database is an annually updated data database which holds over 19,000 reliable life cycle inventory datasets. As well as this, it supports environmental assessments such as carbon foot printing and LCA all around the globe, allowing the user to gain a rich insight regarding the environmental impact of products, services, and the supply chain (ecoinvent, 2022). OpenLCA is a high-performance open-source life cycle assessment software, which enables the ecoinvent database to be accessed. It offers reliable calculations on both life cycle and sustainability assessments and allows for the identification of main drivers through the life cycle (openLCA, 2022).

2.2. Net Zero and the Wind Industry

Adopted by 196 parties at COP21, the Paris Agreement is a legally binding international treaty on climate change. The aim of this treaty is to keep global temperatures well below $2^{\circ}C$ and came into fruition in 2016. To achieve this, the parties agreed on 5-year cycle which increases upon ambition to reduce greenhouse gas emission (GHG) (UNFCCC, 2015). Moreover, the UK has set the greatest target to combat climate change in pursuing the goal Net Zero by 2050 in 2019. This means reducing GHG to a minimum, and the closest value to zero with the intention that the remainder will be absorbed by the atmosphere through oceans and forests. This sector has been active, with several wind generation records being broken in 2020, peaking at 59.9% of the total electricity mix in August.

In our ever-shifting world, and in post coronavirus, the UK has announced that a key factor in the nation's recovery will be upon the surge of renewable energy (Nationalgrid, 2022). This boost is further enhanced with the Ukraine conflict, shifting the tides of the political stability into uncertainty which consequently influences the energy sphere. Russia being the 2nd largest gas producer (17% of global output), this will have an impact on the UK as they still are heavily dependent on gas for electricity generation and heating for homes (Ralston, 2022).

Although natural gas combustion emits approximately 55% less carbon emissions than coal or oil, there are still many issues regarding this source ranging from hydraulic fracking and direct by-product production of hazardous air pollutants (Ucsusa, 2014). Electrification is believed to be the path forward, particularly evident in transport and heat. Renewable energy combined with green hydrogen is anticipated to fulfil this rising demand (Climate Change Committee, 2022). Due to the geographical location of the UK and its experience in onshore wind, it is foreseeable that the next trend shift in renewables is offshore wind generation. Currently, the UK are the world leaders in offshore wind with an installed capacity just over 10 GW, this industry is ever-growing with the UK aiming to achieve 50 GW by 2030, assisting in Net Zero ambitions (Great.gov.uk, 2022).

As the mid-2020s approach, the first batch of offshore wind turbine farms are starting to enter their decommissioning phase (Pakenham, Ermakova and Mehmanparast, 2021). At present, this is a widely discussed topic and many publications have written about the post-life options. From the total mass of a wind turbine, 85 to 90% can be recycled or reused, such as metal, copper wiring or electronic components (Evwind, 2020). Nevertheless, the blades, which primarily consist of composite materials like fibreglass are difficult to decommission. These are essentially the combination of two or more materials with different properties. In detail, a matrix (type of material) encased by fibres or fragments (reinforcement). When combined, the materials are still differentiable and don't dissolve in one another. The main driver for composites is for their characteristics such as high strength-to-weight ratio. Developed in the late 1940s, fibreglass still remains as the most common composite, making up 65% of all composites manufactured today. In general, it is plastic that has been reinforced by fibres or filaments of glass and can be arranged in various methods dependant on the requirement such as bundling or woven (Mischa, 2015).

With these complex materials, standard protocol of decommissioning the blades is to put them into landfill or burn them through pyrolysis, however a lot of innovation is happening in this particular field. Global Fibreglass Solutions founded in 2009 along with Washington State University have managed to recycle the non-degradable fiberglass. They do this by grinding up large pieces of material into small pellets which can be used in other industries such as, construction or manufacturing (GFS, 2022). Another company in the USA, Caron Fiber Recycling has developed a successful method to recycle carbon fibre waste by separating the fibre and epoxy resin – a type of substance combined with a fibre to create a composite. This is vital as it allows 100% of the waste materials to be reused, meaning nothing goes into landfill. The chopped carbon fibre can be used in a plethora of applications whilst the epoxy resin can be turned into fuel to generate power (Windpower Engineering & Development, 2022). Veolia, a company who specialises in resource management such as waste have the capacity to recycle blades into raw material which can be used in cement manufacturing. The results from this are expected to reduce the CO_2 emissions by 27% and water consumption by 13% (WMW, 2022). Repurposing is also an option that has been considered, through architectural design of bike shelters, bridges or even children playground structures as shown in figure 1. WTG Offshore, an Irata wind turbine blade inspection and integrity management company have started a new venture into repurposing blades as shown in the figure 2. This is interesting concept as companies would normally have to pay a fee to dispose of these, but in these scenarios', companies may take the blades for a smaller fee or even for free if they provide their own transportation.

Figure 1. A children's park in the Netherlands which used repurposed decommissioned wind turbine blades.

Figure 2. Repurposed wind turbine blade, source: picture taken at front desk of Global Offshore Wind 2022

This raises the question of why organisations favour landfill opposed to a circular economy approach and this is simply down to cost, as it is cheaper to go along with the landfill method. This is because repurposing will require addition transportation, machinery work, skilled labour among other factors extending the process. Quite ironic that a renewable organisation may take a an "non-environmentally viable" approach, but it is important to remember that it is still a business at its core. However, the industry is changing with WindEurope, an association in Brussels who are heavily involved within European wind are pushing a ban on the use of landfill by 2025. This initiative pushes the commitment of the European wind industry to recycle, reuse and reclaim all decommissioned blades (Downtoearth.org.in, 2022).

2.3. Trends in the Offshore Wind Market

According to the Offshore Wind Market Report: 2023, the continuous falling prices of offshore wind has sparked interest in many countries as the global installation in 2021 amounted to 17,398 MW, compared to the previous year of 5,519 MW. This pushed the global installed capacity over 50 GW with 257 operating projects. This year also saw the erection of three floating offshore wind projects at a capacity of 57.1 MW total, which includes the largest, 50 MW Kincardine Offshore Wind Farm in Scotland. As this industry continues to grow, this will consequently lead to the development and continuous increasing size of turbine capacity, and thus their blades. Figure 3 from the offshore wind market report 2022, illustrates the trend of the average offshore wind turbine capacities from 2000 up until 2022 to 2027 where announced future commercial turbines will be functional. From the figure, it can be identified that the general trend is that the capacities are steadily increasing. As well as this, the trend suggests that the 15 MW rated wind turbine will become more common in the industry by 2027 (Offshore Wind Market Report: 2022 Edition, 2022).

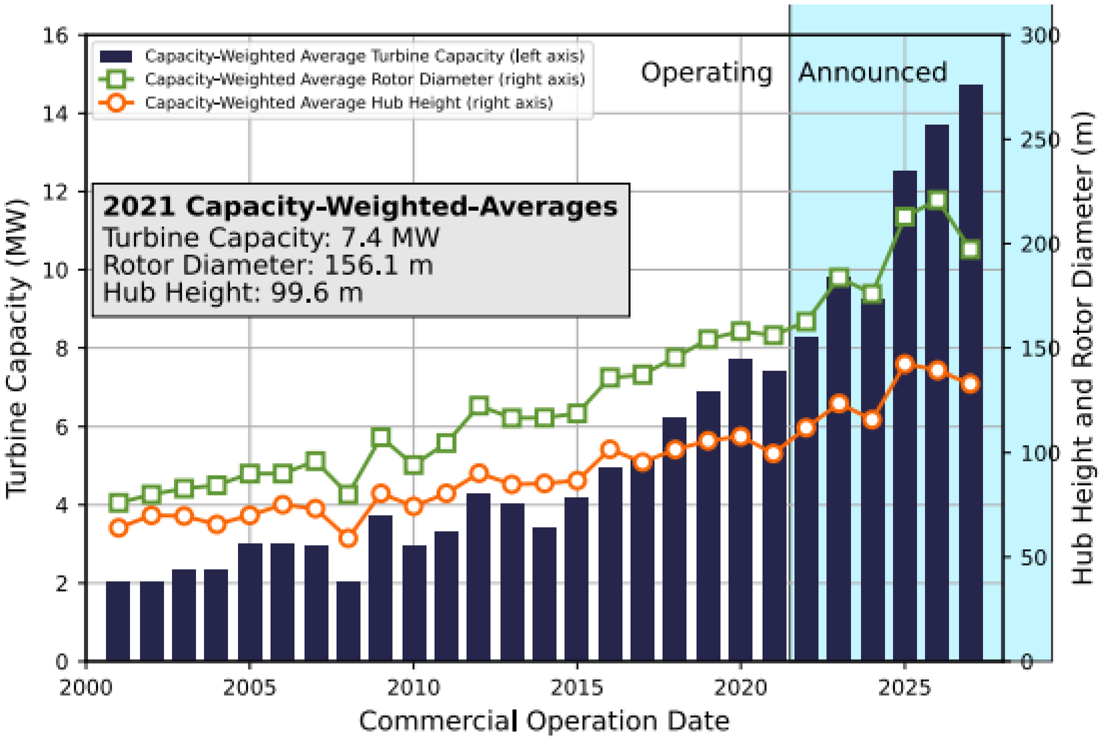


Figure 3. Historical and forecast trend of offshore wind turbine capacity upsizing using market averages, source: (Offshore Wind Market Report: 2022 Edition, 2022)

This is important as developers will favour the utilisation of the largest turbine for a project as it will maximise energy capture and will reduce the total number of turbines which subsequently benefits operation and maintenance costs on a per-kilowatt basis. As well as this, upscaling of capacity is more easily possible offshore as the barriers to deploy the turbines are not as difficult compared to onshore (Offshore Wind Market Report: 2022 Edition, 2022). Since areas that require floating wind turbines are generally located on harsher weather conditions, they often as a result have greater potential for wind generation, such as the coast of Hawaii where planning has been ongoing (4coffshore.com, 2021). With offshore floating sites now established commercially, it will only open more opportunities for the development and proposal of future wind turbine site locations along with non-floating. In line with all of this, the major European manufacturers of turbines are now in development of 15-MW wind turbines and have plans to commercialise the production between 2022 and 2024. Future global projections predict that there will be more than 260 GW by 2030. This is amplification of renewable is great for the industry, but however the amplification of the supply chain such as manufacturing and transportation should be considered (Offshore Wind Market Report: 2022 Edition, 2022).

2.4. LCA Application to Offshore Wind

A LCA is a framework for measuring and identifying the environmental impacts for a product throughout its life cycle. Dependant on the study, some may also include the upstream of the life cycle such as raw materials or suppliers and downstream which would include waste management. Due to the complexity of the supply chain and its everlasting possibilities – as it can go into the equipment used to extract the raw materials and vice versa. This means that there are various variants of a life cycle assessment as illustrated in figure 4 (Liebsch, 2019). Figure 5 illustrates a simplified scope for the life cycle of a wind turbine.

The four phases of a LCA study are defined in the ISO (international organisation for standardisation) standards of 14040 and 14044:

1. The goal and scope definition phase
2. The inventory analysis phase
3. The impact assessment phase
4. The interpretation phase

(ISO, 2014), (ISO, 2014)

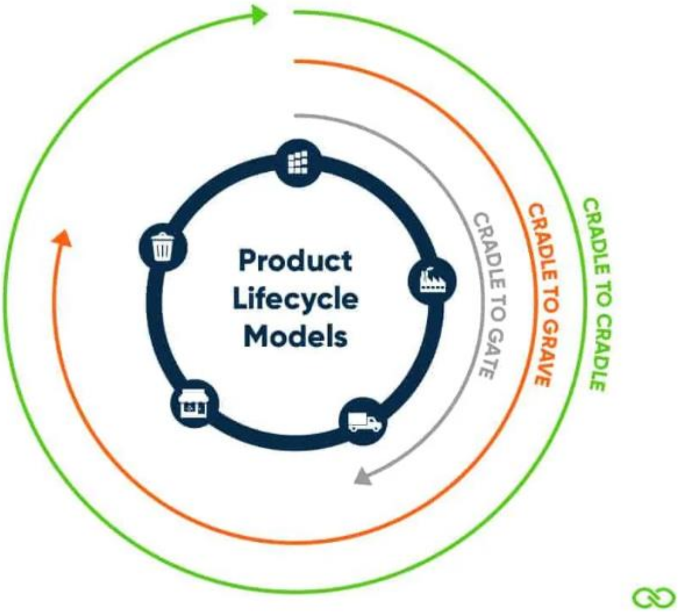


Figure 4. The possible Variants of an LCA, source: (Liebsch, 2019)

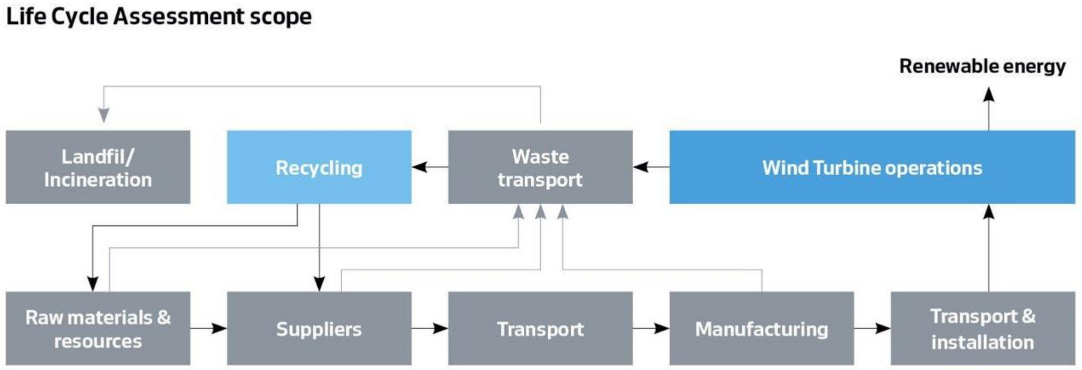


Figure 5. Simplified LCA for a wind turbine, source: (Vestas.com, 2022)

2.5. Available Literature

As previously mentioned in section 2.2., the post life options are a well mentioned and discussed topic. But, on the other hand, the studied LCA literature regarding wind turbines fail to go in-depth on the breakdown components and consequently, their materials (Weinzettel et al., 2009) (Schleisner, 2000) (Guezuraga, Zauner and Pölz, 2012) (Martínez et al., 2009). Since all literature was based on the whole wind turbine, it was found that much literature allocated their analysis between components despite composites (which are primarily in the blade) being the most complex and subsequently hold the most intricate supply chain. Thus, leaving a gap in knowledge. When analysing a product or process, it is vital to not just study the surface but understand the complexity of the supply chain, and the number of processes it may consume.

Since LCA literature did not provide much information in terms of carbon emissions, other types of literature were evaluated. A paper by Antonio Augusto Morini, evaluated the environmental impact of a 63 m wind turbine blade and the carbon equivalents are provided in table 1. This dataset was originally sourced from the Granta Selector 2020 database. These findings can be used as a baseline to compare with the results from this project (Morini, Ribeiro and Hotza, 2021).

Table 1. Carbon equivalent baseline sourced from literature, source: (Morini, Ribeiro and Hotza, 2021)

Material	**KgCO_2e**
Glass Fibre	3
Resin	6.59
PVC	2.47

3. Methodology

3.1. Goals, function unit and system boundaries

The goal of the LCA in this study is to analyse and quantify the embodied CO_2 emissions involved within the early stages of the life cycle of a wind turbine blade, in particular the materials. This includes emissions starting from the extraction and refinement process of raw resources, as well as the manufacturing and transportation of the blade itself to the site where it will be assembled. This will be achieved through the utilisation of the ecoinvent version 3.8 database, OpenLCA and literature for all the processes. The transportation from emissions will be calculated by using the UK government GHG conversion factors 2022, despite the location to maintain consistency through scenarios. The baseline established from this study should be used to highlight the areas which could be further studied to reduce the overall embodied emissions of a wind turbine blade and consequently reduce their contribution towards climate change.

For the processes and embodied emissions of refined materials, kgCO_2eq was selected and for the transportation, kgCO_2e/km.tonne. These units are industry recognised in their respective sectors and allows for a credible comparison.

The system boundaries for this study will focus on the raw ore extraction of E-glass to the transportation of the wind turbine blade product to the site, this is illustrated in the red box in figure 6. In this study, the refiner of the raw material is assumed to also supply the material. Factors such as the paint and capital goods (machinery and equipment used by factories) were excluded from this study due to difficulties in data procurement. In regards of ecoinvent and OpenLCA, the life cycle impact assessment (LCIA) method used was BEES+ (Building for Environmental and Economic Sustainability) as it provides environmental and economic performance data in line with ISO14040.

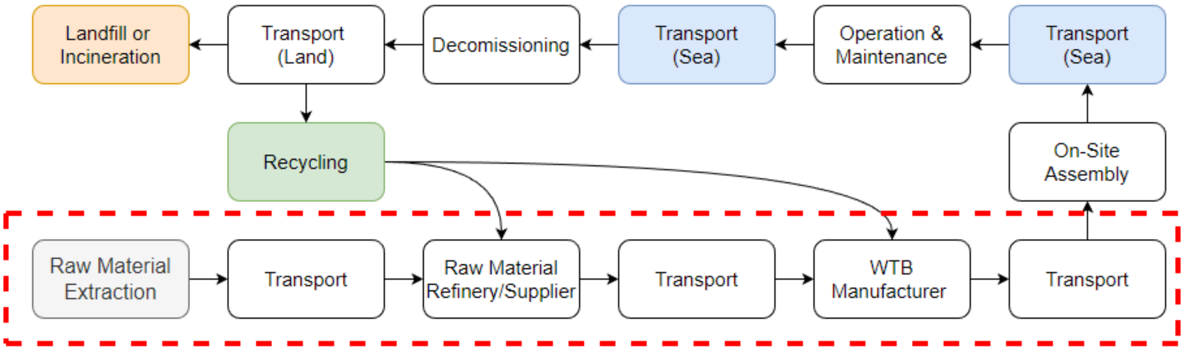


Figure 6. System boundaries of the project's LCA

For this study, the ScotWind 1 GW Cluaran Ear-Thauth site was chosen. This site is illustrated in figure 7 and is located in the North Sea approximately 33km off the coast of Orkney. Since the site has a bathymetry greater than 60m, this site will require the deployment of floating offshore wind turbines, opposed to traditional offshore turbines which are fixed bottom. This requires the assembly of the turbine to be in the port and for a tug vessel to pull it onto site. The website searates.com was used to identify all possible seaports for this opportunity. The findings from this were that the majority of these ports were small and unable to host such a large expedition, other than the Port of Scrabster which has already hosted some renewable activity (Digital, 2022).

Figure 7. Map of the Scottish Highlands, Cluaran Ear-Thauth site and local seaports, source: (SeaRates, 2021)

3.2 Inventory Analysis

As described in ISO 14040 and 14044, the inventory analysis is the 3rd part of an LCA. In this section, the inputs and outputs of a product must be analysed. Much of the data is gathered from available literature or the ecoinvent dataset.

3.2.1. Wind Turbine Blade Structure

A decision has not been made in regards of turbine selection for the Cluaran Ear-Thauth site, and thus this value must be estimated. Currently, the largest floating offshore wind turbine farm in Scotland is the 50 MW Kincardine Project which utilises 9.5 MW turbines (Principlepower.com, 2022). With Cluaran Ear-Thauth still in development, the assumption that 15 MW floating turbines will be normalised by the time this project begins planning has been assumed. The main factor for choosing this rating would be to optimise the energy captured through the use of bigger turbines which will minimise the number of total turbines on site to help with the operation and maintenance of the wind farm. In detail, variables such as turbine visits, repair time, time-based availability, and met-ocean conditions.

With the turbine rating in mind, the composition and structure of the turbine blade must be defined. However, due to the difficulties in direct data procurement of the breakdown of specific wind turbine models, this data must be gathered from literature. Although there are many manufacturers and manufacturing techniques, wind turbine blades typically tend to follow a similar composition. Typically, they consist of two shells bonded together by a girder (shear webs) (Iberdrola, 2022). In figure 8, the girder is illustrated by the shear webs which are made of core foam material (balsa wood or PVC) sandwiched between a composite outer layer. This composite layer is normally a form of glass fibre impregnated with epoxy resin. The shell of the structure follows this similar construction (J. Nagle et al., 2020).

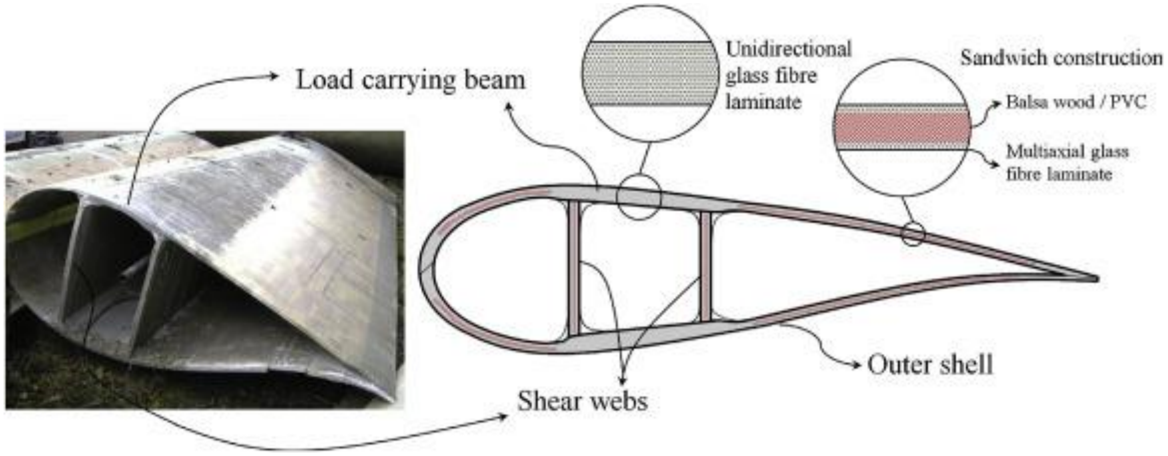


Figure 8. Structural design of wind turbine blade, demonstrating shear web layouts and sandwich construction, source: (J. Nagle et al., 2020)

Moreover, the weight percentage breakdown of materials gluttonised must be analysed to calculate the embodied emissions accordingly. Due to difficulties of data procurement, as this is classed as sensitive information, this must be found through literature. Cited from literature, the breakdown of a 5,700 kg blade was found and upscaled to 65,205 kg for this study. This weight was sourced from a technical report by International Energy Agency Wind (IEA Wind), in regards of a 15 MW offshore wind turbine blade mass. Despite this, it is important to acknowledge that this value will differ from model to model (IEA, 2020). Figure 9 illustrates all the required studied material for a wind turbine blade. Although most materials are self-explanatory, the aluminium may not seem so obvious for all. This material is used for components such as metal bolts to connect different parts of the blade to the hub among other structurally vital components, as seen in figure 10.

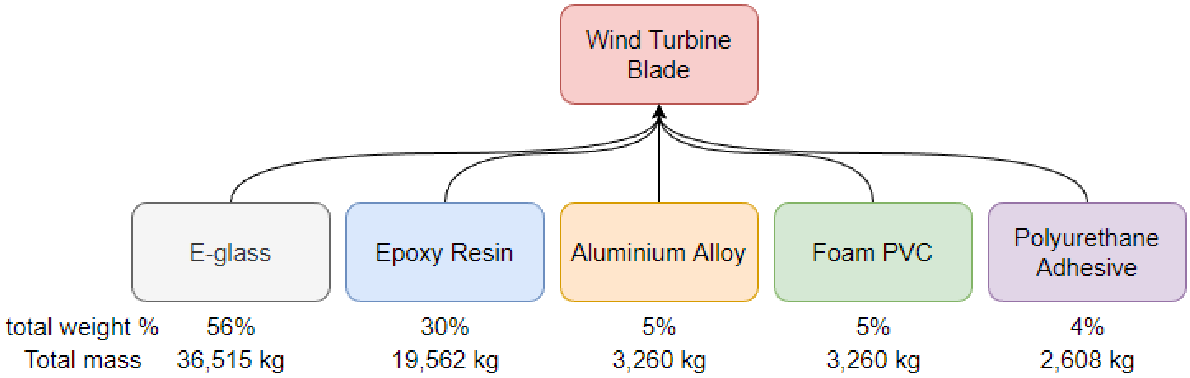


Figure 9. Materials consumed for a wind turbine blade, data source: (J. Nagle et al., 2020)

Figure 10. Picture taken at visitor centre of Whitelee Wind Farm, demonstrating the utilisation of metal bolts

3.2.2. E-Glass Structure

From the previous figure, it can be identified that E-glass makes up the majority of composition for a wind turbine blade at 56%, whilst the matrix consisting of epoxy resin follows with 30%. This combination of glass fibre and resin forms a composite material, these fibres are synthetic and among the most used in the wind industry. The composite industry is constantly involved with development as they take up most of the market when it comes to high performance applications such as aerospace, healthcare, and wind turbine blades (Formlabs, 2022). For this reason, a study was performed on E-glass and its breakdown.

Unlike carbon fibre, which is directly processed from crude oil, E-glass (a form of glass fibre) is composed of five primary chemical elements as illustrated in figure 11. Like the wind turbine blade, there might be further trace materials ranging between 0-20 weight percentage (wt%) dependant on the manufacturer, but these have been excluded due to the limitless depth and possibilities (Q. Dai et al., 2015).

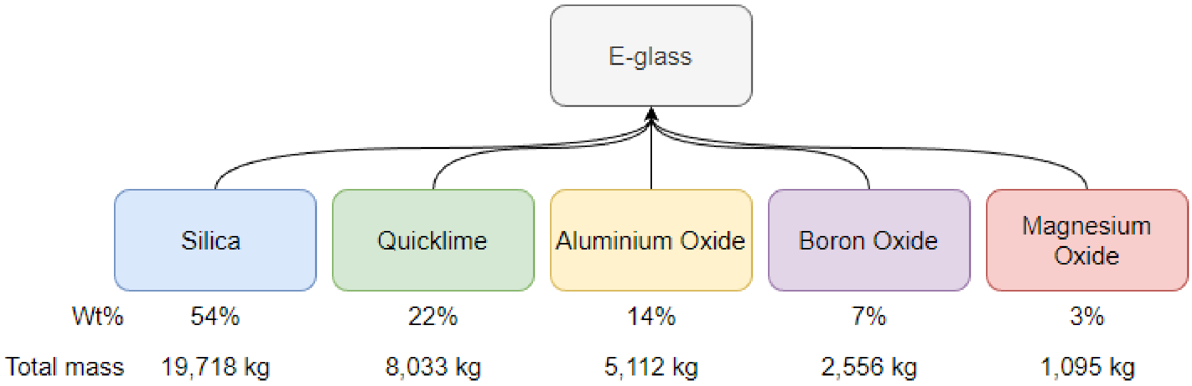


Figure 11. Chemical elements consumed for E-glass, data source: (Q. Dai et al., 2015)

Moreover, the comparison of material between various turbine ratings have been studied. The parameters of these can be seen in table 2:

Table 2. Wind turbine power ratings and their equivalent blade masses, data source: (IEA, 2020)(Desmond et al., 2016)

Wind Turbine Power Rating (MW)	Blade Mass (kg)
15	65,205
10	41,716
8	35,000
5	17,740

3.2.3. Freighting

Due to manufacturers not disclosing their exact supply chain, estimations have been made to study this topic. As well as this, some of the chemical elements can be obtained, extracted, and sourced from various countries, thus the most common or largest market share locations and suppliers were selected for the study. The locations selected for this study for the suppliers can be found in table 3.

Table 3. Locations of supplier of required materials for E-glass, data source: (Smartsand, 2022) (Super Cement, 2022) (consolidatedchem, 2022) (alkimpetrokimya, 2022) (listofcompaniesin.com, 2022)

E-glass Materials	Manufacturer/Supplier Location
Silica	Waynesburg, United States of America
Quicklime	Musaffah, Uunited Arab Emirates
Aluminium Oxide	Arndell Park, Australia
Boron Oxide	Melek Aras Bulvarı, Turkey
Magnesium Oxide	Liaoning, China

From The Observatory of Economic Complexity, they state the top exporters of Glass fibres to be China, United States of America (USA), and Germany (OEC, 2022). The USA was selected for this study and the manufacturer was selected to be a supplier in Charlotte, USA (Trelleborg, 2022). The remainder of materials required for the assembly of a wind turbine blade can be shown in table 4, and like the materials of E-glass, can be sourced from various countries.

Table 4. Locations of supplier of required materials for a wind turbine blade (Verified Market Research, 2021) (Europages, 2022) (Dnb, 2022) (Jindal, 2021)

Wind Turbine Blade Materials/Components	Manufacturer/Supplier Location
E-glass	Charlotte, United States of America
Epoxy Resin	Calgary, Canada
Polyurethane Adhesive	Haguenau, France
Aluminium Alloy	Melbourne, Australia
Foam PVC	Beijing, China

The scope covered in this study for transportation is illustrated in figure 12 and figure 13. Figure 12 illustrates the scope for the E-glass materials and begins at the refiner/manufacturer of the materials required for E-glass. In this scenario, the HGVs would transport the materials to the closest container terminal port to the E-glass material manufacturer/supplier then shipped to the terminal in Norfolk, USA and then onto another HGV to E-glass manufacturer in charlotte. Port Norfolk was selected as it was the closest terminal to Charlotte. However, the export of E-glass was decided to be located at the terminal in Newport, Providence, USA as it was the closest terminal to the UK. Subsequently, the terminal at the port of Southampton, UK was chosen as it was the closest to LM Wind Power's factory in Eastleigh – the selected wind turbine blade manufacturer for this study (Lmwindpower, 2022). Then the assembled wind turbine blade will be transported up to Scrabster by HGV.

The reason why the study starts from the manufacturer/supplier of the material is because the ecoinvent database incorporates the average regional market data of the materials used in this study, including all transportation data until refinement of the raw material. Thus, the transportation of raw materials to refiner has been covered as the emissions have already been considered. Moreover, figure 13 illustrates the scope for the remainder of the wind turbine blade materials, other than E-glass to the UK for wind turbine assembly. In this scenario, the HGVs would transport the materials to the closest container terminal port to the material manufacturer/supplier then shipped to the container terminal in Southampton and then onto another HGV to the wind turbine blade manufacturer. The distances for land transportation were measured using Google Maps, and nautical miles of cargo ships were measured through shiptraffic.net.

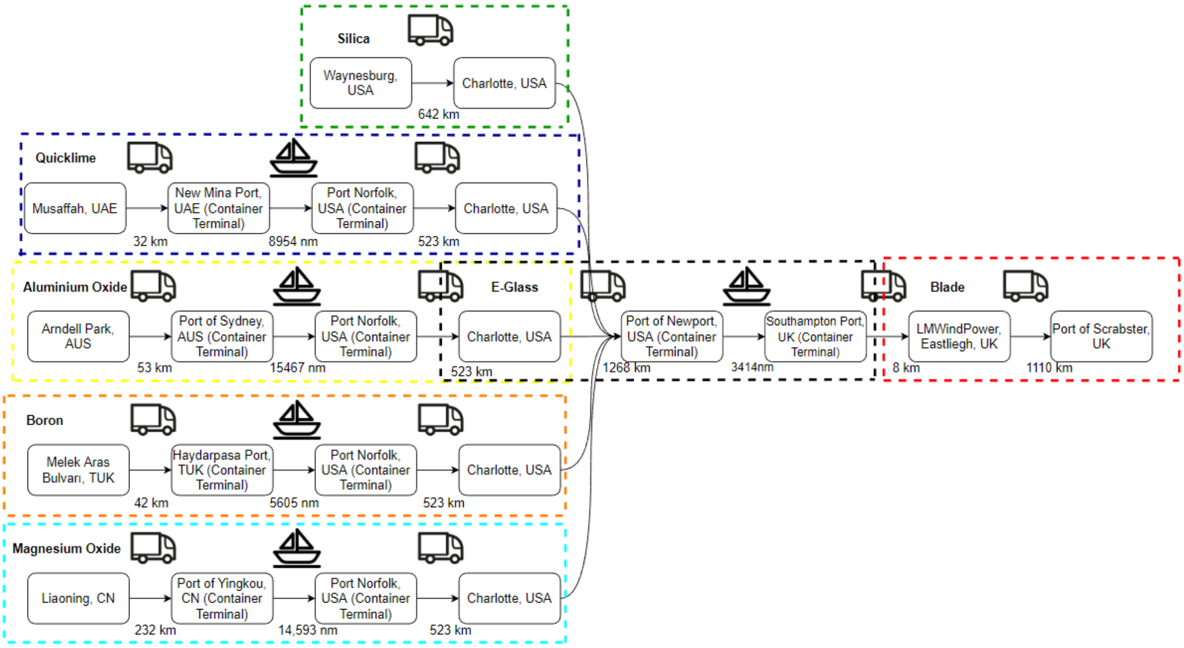


Figure 12. Scope of E-glass materials, E-glass itself and the wind turbine blade to site

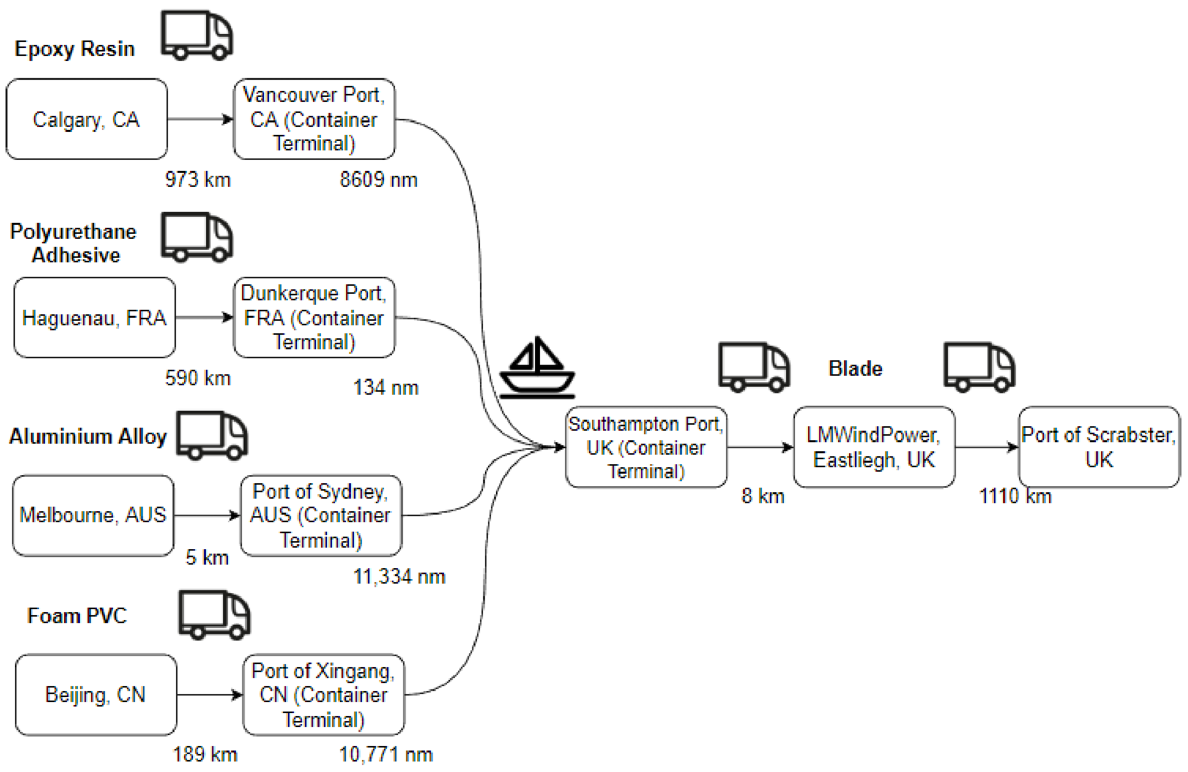


Figure 13. Scope of wind turbine materials to wind turbine manufacturer/supplier

To analyse the processes accordingly, the study has been complied into three separate stages:

- Stage 1: E-glass materials from various locations to E-glass manufacturer/supplier in the USA.
- Stage 2: E-glass manufacturer/supplier in USA to wind turbine blade manufacturer/supplier in UK.
- Stage 3: Reminder of wind turbine materials from various locations to wind turbine manufacturer/supplier in UK.
- Stage 4: Blade manufacturer/supplier in Eastleigh (south of England) to wind turbine assembly port in Scrabster (north of Scotland)

To calculate the kgCO_2e, in regards of the transport, the following equation was applied, in which the UK government GHG conversion factor is represented as “CF”:

$$kgCO2e = CF * (weight) * distance(km)$$

Each form of transport and transport type has its own conversion factor and the ones used in this study are as follows:

- Average cargo ship = 0.01614 kgCO_2e/tonne.km
- Average diesel HGV (average laden) = 0.89061 kgCO_2e/tonne.km

A further study was done in regards of an alternative form of freighting on land. In this study the implementation of the UK freight railway was compared to the original method of just a lone HGV. This new scenario is illustrated in figure 14, where the HGV transports the blade to the closest freight rail container terminal in which the railway ends at Grangemouth (the rail lines highest point), west of Edinburgh – this map can be viewed in appendix I. The UK government conversion factor for the railway is provided below:

- Average freight rail = 0.02782 kgCO_2e/tonne.km

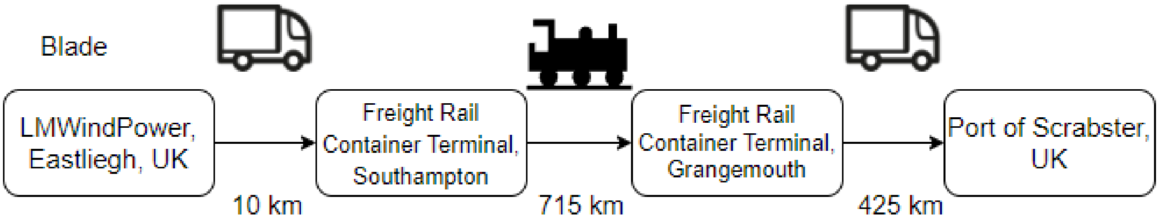


Figure 14. Alternative scenario for stage 4, freight railway included

4. Results and Analysis

4.1 Materials

Figure 15 illustrates the embodied emissions of materials associated with the amount of E-glass required for a single 15 MW blade. The standout result from this graph is that the boron contains the majority of the emissions when compared to the other chemical elements, despite the weight percentage of it being the second smallest quantity at 7%. Between boron and quicklime, there was a decrease of emissions by 78.34%. For aluminium oxide it was 91.93%, magnesium oxide was 97.31% and 98.02% for silica.

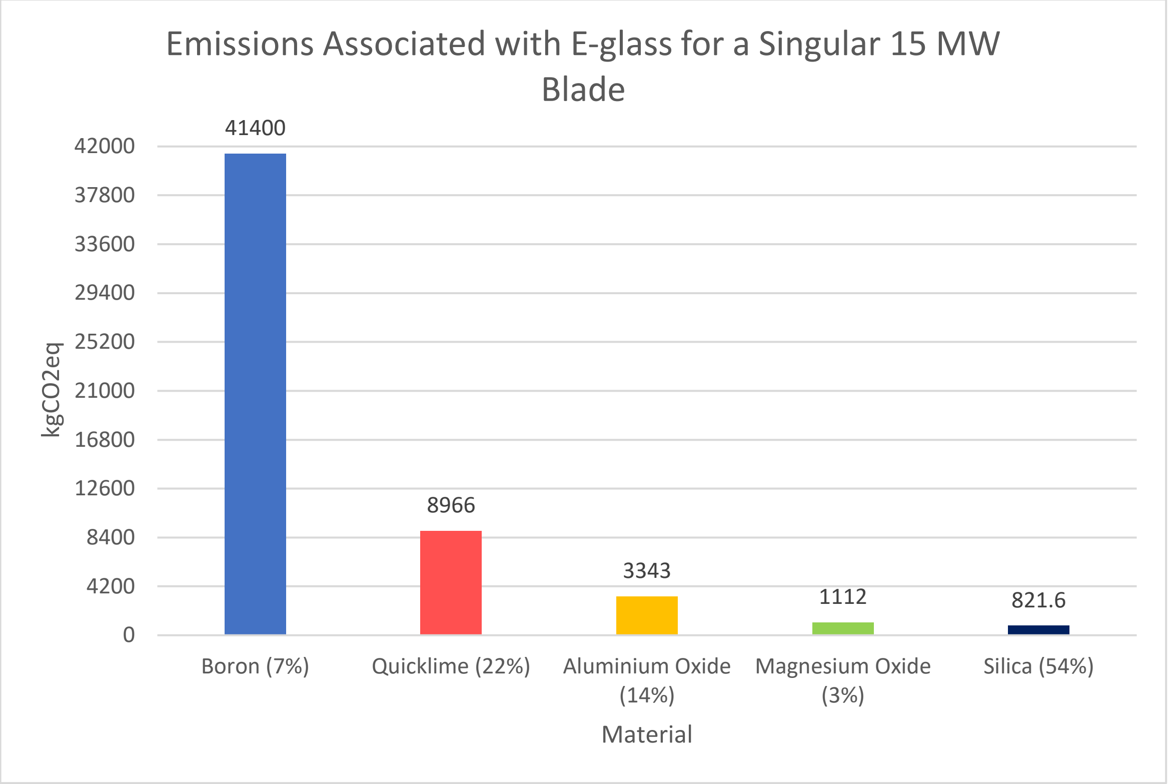


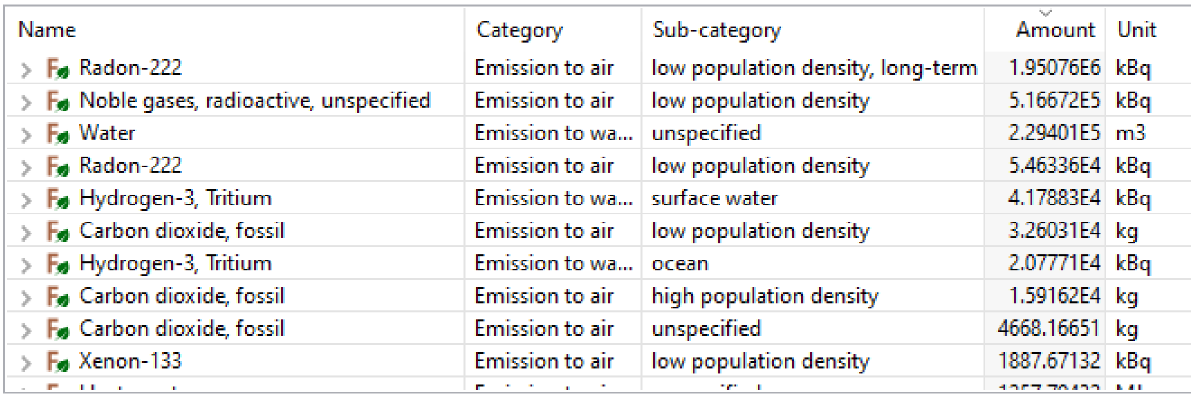
Figure 15. Total kgCO2e of embodied emissions from a single 15 MW blade

From graph, the per $kgCO2e$ can be calculated and the results from these are shown in table 5. From this table, it is clear that boron has a high embodied carbon factor as it is valued at $16.20kgCO2e/kg$, which is around 14 times greater than the second highest valued element of quicklime at $1.12kgCO2e/kg$. Silica has the smallest $kgCO2e$ at $0.04kgCO2e/kg$, this is expected as it is sourced from filtering from sand which is both plentiful and not much energy intensive compared to the others. If E-glass was to be decarbonised, the piority would be to look for a manufacturing alternative or a replacement material with a lower embodied carbon value.

Table 5. Per kgCO2e of materials used in E-glass and the weight values for a 15 MW blade

Material	$1kgCO2e$	Weight (%)	Weight (kg)
Boron	16.20	7	2,556
Quicklime	1.12	22	8,033
Aluminium Oxide	0.65	14	5,112
Magnesium Oxide	1.02	3	1,095
Silica	0.04	54	19,718

Figure 16 is directly from OpenLCA and is another feature which presents the general outputs in order of decreasing amounts from the E-glass materials. From the figure, the most noticeable factor would be the amount of radioactive by-product elements such as Radon-222, noble gases and hydrogen-3 which all have their own corresponding half-life and embodied emissions. Despite this, it is important to mention that not all the outputs are presented, and some may play a larger role.



Name	Category	Sub-category	Amount	Unit
Radon-222	Emission to air	low population density, long-term	1.95076E6	kBq
Noble gases, radioactive, unspecified	Emission to air	low population density	5.16672E5	kBq
Water	Emission to wa...	unspecified	2.29401E5	m3
Radon-222	Emission to air	low population density	5.46336E4	kBq
Hydrogen-3, Tritium	Emission to wa...	surface water	4.17883E4	kBq
Carbon dioxide, fossil	Emission to air	low population density	3.26031E4	kg
Hydrogen-3, Tritium	Emission to wa...	ocean	2.07771E4	kBq
Carbon dioxide, fossil	Emission to air	high population density	1.59162E4	kg
Carbon dioxide, fossil	Emission to air	unspecified	4668.16651	kg
Xenon-133	Emission to air	low population density	1887.67132	kBq

Figure 16. Outputs from E-glass material production from decreasing amounts

Figure 17 Illustrates the emissions associated with a 15MW blade by its materials where it shows epoxy resin containing the majority of emissions at 84,290 $kgCO2e$. Between the epoxy resign and E-glass, there was a decrease of emissions by 33.99 %. For Aluminium Alloy it was 90.90 %, PVC was 90.67 %, and 84.64% for Polyurethane Adhesive.

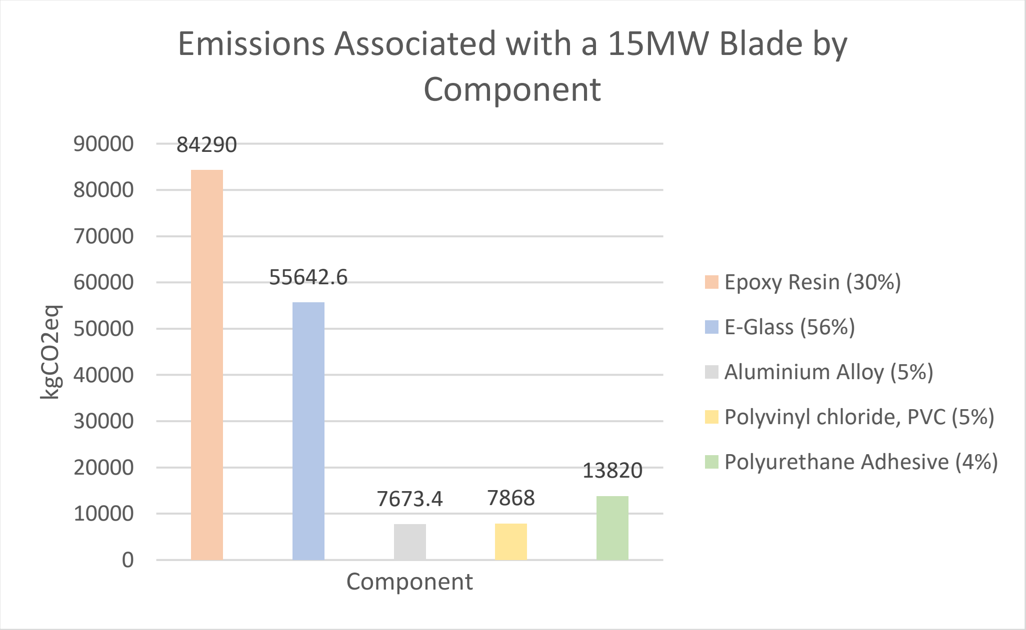


Figure 17. Total emissions associated with a 15 MW blade, including E-glass

Like the section before, the per $kgCO2e$ can be calculated from the graphs and the results from these calculations are shown in table 6. The standout value from this table would be that polyurethane adhesive actually has the highest per $kgCO2e$ at $5.30kgCO2e/kg$, larger than epoxy resin which was found to be at $4.31kgCO2e/kg$, meaning that the epoxy only stands out on the graph due to its sheer volume in the wind turbine blade. Not surprisingly, E-glass contains the least at $1.52kgCO2e/kg$ but due to the volume of 56%, in total, E-glass makes up the second largest $kgCO2eq$. If decarbonising the wind turbine were a piority, despite E-glass holding such a small $kgCO2e$ value, it would still be worthwhile targeting this material as a wind turbine blade still has to consume a weighting percentage of 56%. As well as this, it is a well used material in general, so the snowball effect of the research would prove useful.

When referencing to the paper by Antonio Augusto Morini in table 1, it can be compared that the glass fibre of $3\ kgCO2e/kg$ is vastly different from the value obtained from this study at $1.52\ kgCO2e/kg$ (Morini, Ribeiro and Hotza, 2021). A big difference can be seen between the epoxy resins where their value is $6.59\,kgCO2e/kg$, whilst the findings are $4.31\ kgCO2e/kg$ for this paper. However, both the PVC results are relatively similar with the values are $2.47\ kgCO2e/kg$ and $2.41\ kgCO2e/kg$ from this study. The differences of the embodied emissions are most likely derived from the difference in supply chain, from the method of extraction or ore processing, stressing the complexity of the supply chain.

Table 6. Per kgCO2e of materials used in a wind turbine blade and the weight values for a 15 MW blade

Material	$1kgCO2e$	Weight (%)	Weight (kg)
Epoxy Resin	4.31	30	19,562
Polyurethane Adhesive	5.30	4	2,608
Polyvinyl Chloride, PVC	2.41	5	3,260
Aluminium Alloy	2.35	5	3,260
E-glass	1.52	56	36,515

Figure 18 Illustrates the emissions associated with a 15MW blade by its materials but with E-glass broken down into its respective materials, displaying the emissions associated with each. From the figure, it can be identified that the boron from E-glass is still predominantly large when compared to the other materials as expected. However, the material with the largest embodied emissions is epoxy resin. Between epoxy resin and boron, there was a decrease of emissions by 50.88 %. For polyurethane adhesive it was 83.60 %, quicklime was 89.36 %,

PVC was 90.67% and 84.64% for other (which includes aluminium oxide, magnesium oxide, silica, and aluminium oxide).

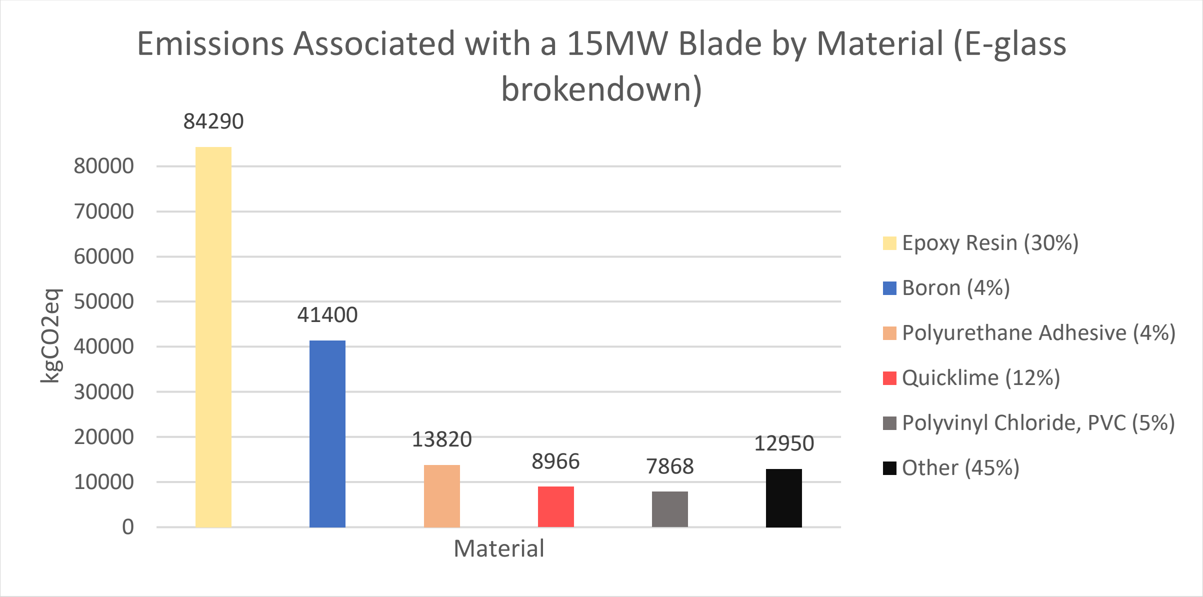


Figure 18. Total emissions associated with a 15 MW blade with E-glass materials broken down

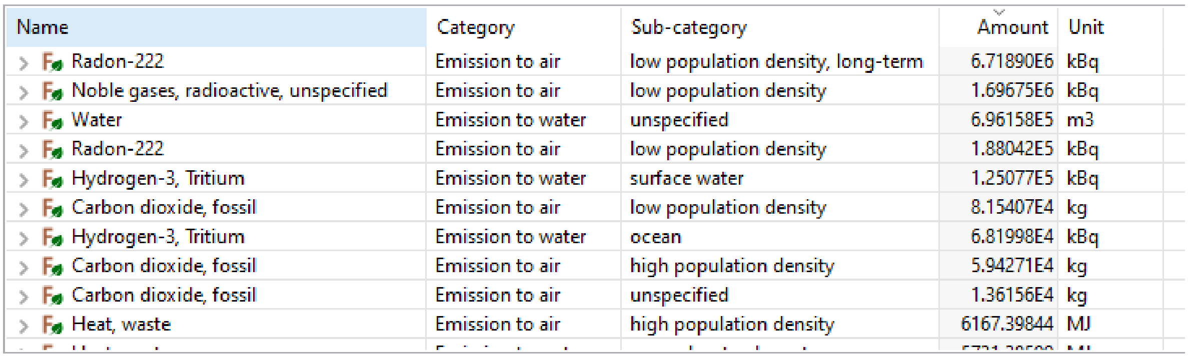
Table 7 summarises the weight percentage and kg value of each material in the wind turbine blade. In terms of kg where epoxy and silica each hold 30% of total equity. Although silica has a large weight percentage, the emissions resulting from this material is low when compared to the epoxy resin. A visible error is apparent in the silica where the weight in kg is a lot larger despite them sharing the same weight percentage, this is derived from rounding the value of E-glass from the whole blade to 36,515 kg from 36,514.8kg. Despite epoxy at 30%, the emissions associated with synthetic materials such as PVC at 5%, boron and polyurethane adhesive at 4%, these hold the majority of the emissions which coincidently have a long and complex life cycle, regardless of their comparatively small stake.

Table 7. Summarised weight percentages and weight kg of materials

Material	Weight (%)	Weight (kg)
Epoxy Resin	30	19,562
Silica	30	19,718
Quicklime	12	8,033
Aluminium Oxide	8	5,112
Polyvinyl Chloride, PVC	5	3,260
Aluminium Alloy	5	3,260

Polyurethane Adhesive	4	2,608
Boron	4	2,556
Magnesium Oxide	2	1,095

Figure 19 represents the outputs from the 15 MW wind turbine blade in order of decreasing amounts. Similar to the E-glass outputs but in this case all the factors have increased in value. Despite this, the 10th variable has changed to 6,167 MJ of heat waste, this could be derived from the addition of processing required for epoxy resin baking and heavy industry of aluminium alloy.



Name	Category	Sub-category	Amount	Unit
Radon-222	Emission to air	low population density, long-term	6.71890E6	kBq
Noble gases, radioactive, unspecified	Emission to air	low population density	1.69675E6	kBq
Water	Emission to water	unspecified	6.96158E5	m3
Radon-222	Emission to air	low population density	1.88042E5	kBq
Hydrogen-3, Tritium	Emission to water	surface water	1.25077E5	kBq
Carbon dioxide, fossil	Emission to air	low population density	8.15407E4	kg
Hydrogen-3, Tritium	Emission to water	ocean	6.81998E4	kBq
Carbon dioxide, fossil	Emission to air	high population density	5.94271E4	kg
Carbon dioxide, fossil	Emission to air	unspecified	1.36156E4	kg
Heat, waste	Emission to air	high population density	6167.39844	MJ

Figure 19. Outputs from wind turbine material production from decreasing amounts

Figure 20 illustrates the comparison of emissions for turbine blades of differing power ratings as mentioned in section 3.2.2. E-Glass Structure. A power trendline was added to this graph to demonstrate the decreasing rate of emissions in line with the decrease in blade mass.

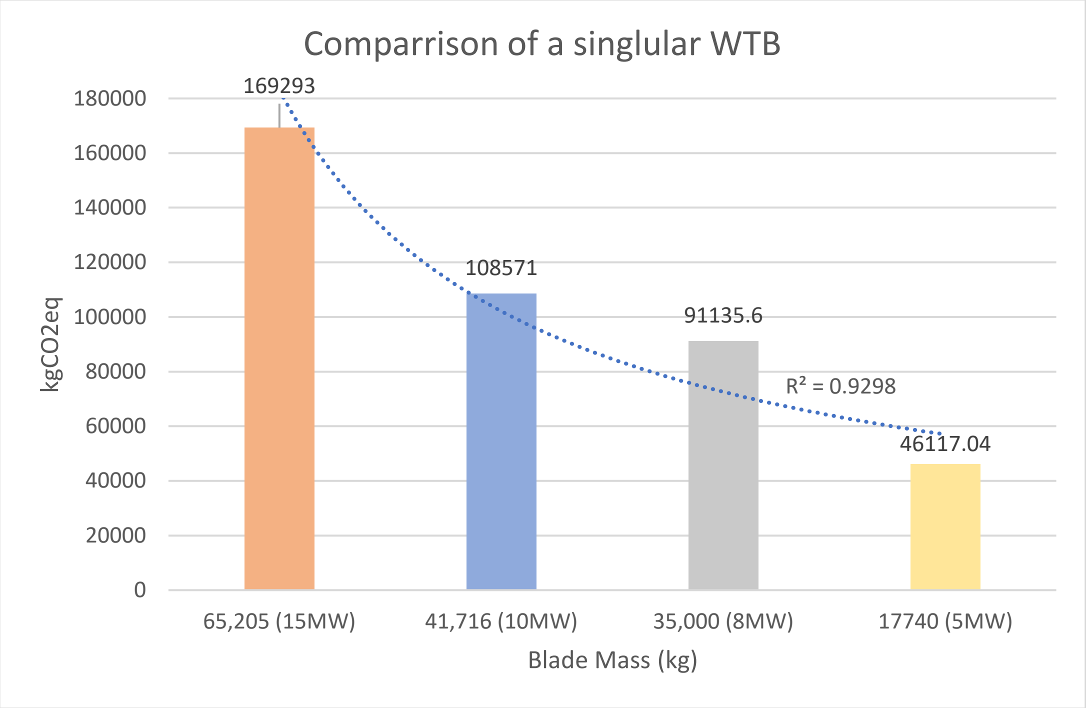


Figure 20. Comparison of emissions associated with differing blade mass

Table 8 displays the emission and mass percentage difference between the 15 MW blade from the 10MW, 8MW and 5MW blade. From this table it can be identified that these values correlate with each another meaning the amount of mass decreased equates to the number of emissions saved. Demonstrating that manufacturers can estimate savings in emissions through the mass when manufacturing a wind turbine blade. Though, it is vital to mention that this is a very simplified study, and more datasets are required to ensure validity and robustness.

Table 8. Emission and mass percentage difference against 15 MW wind turbine blade

Percentage Difference	**10 MW**	**8 MW**	**5 MW**
Emission % difference	35.87%	46.17%	72.76%
Mass % difference	36.02%	46.32%	72.79%

Figure 21 illustrates the comparison of the emissions associated with E-glass for a 15 MW blade against the whole 10 MW, 8 MW and 5 MW blade. Instantly, it can be viewed that the E-glass alone has more emissions than a whole 5 MW blade by 17.12%. Between the E-glass from the 15 MW blade and 10 MW blade, there is a 48.75% increase of emissions and a 38.94% for the 8 MW. Although companies may instantly favour larger turbines due to optimising energy capture or reducing operation and maintenance cost, the consideration of the increased material usage should be considered when upsizing turbine capacity.

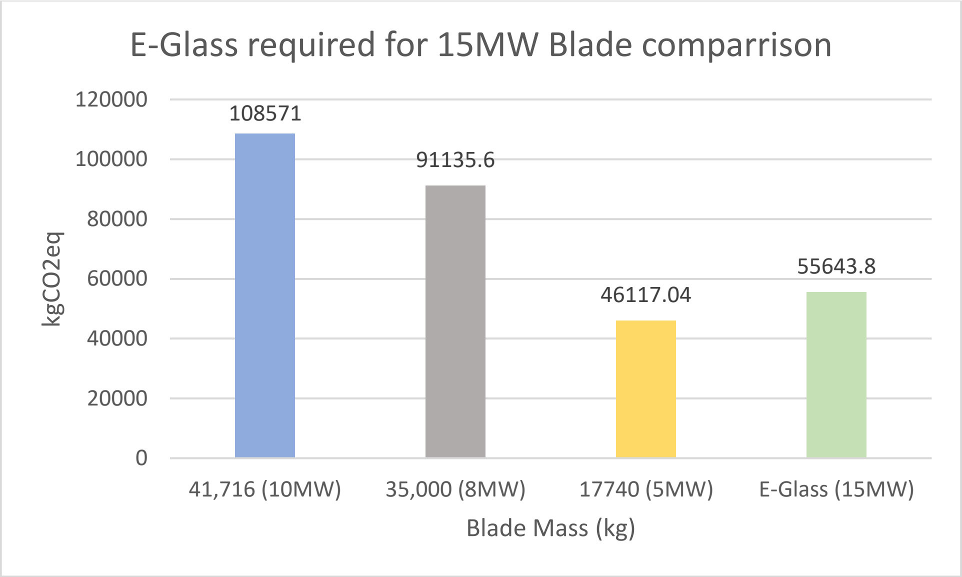


Figure 21. Comparison of E-glass used in 15 MW against 10 MW, 8 MW, and 5 MW blade

4.2. Freight

- Stage 1: E-glass materials from various locations to E-glass manufacturer/supplier in the USA.
- Stage 2: E-glass manufacturer/supplier in USA to wind turbine blade manufacturer/supplier in UK.
- Stage 3: Reminder of wind turbine materials from various locations to wind turbine manufacturer/supplier in UK.
- Stage 4: Blade manufacturer/supplier in Eastleigh (south of England) to wind turbine assembly port in Scrabster (north of Scotland)

Study 1 represents the freighting of E-glass materials from various locations to the E-glass manufacturer/supplier in USA. An interesting and unnoticed finding from research would be that many of the suppliers and manufacturers are in fact located close to container ports and freight options, reducing the amount of travel time and distance. Figure 22 demonstrates this and illustrates the emissions from stage 1 as previously mentioned in section 3.2.3. Despite the substantial distanced travelled on sea versus land (appendix II), the production of emissions is far greater on land due to the conversion factors between HGV and cargo ships.

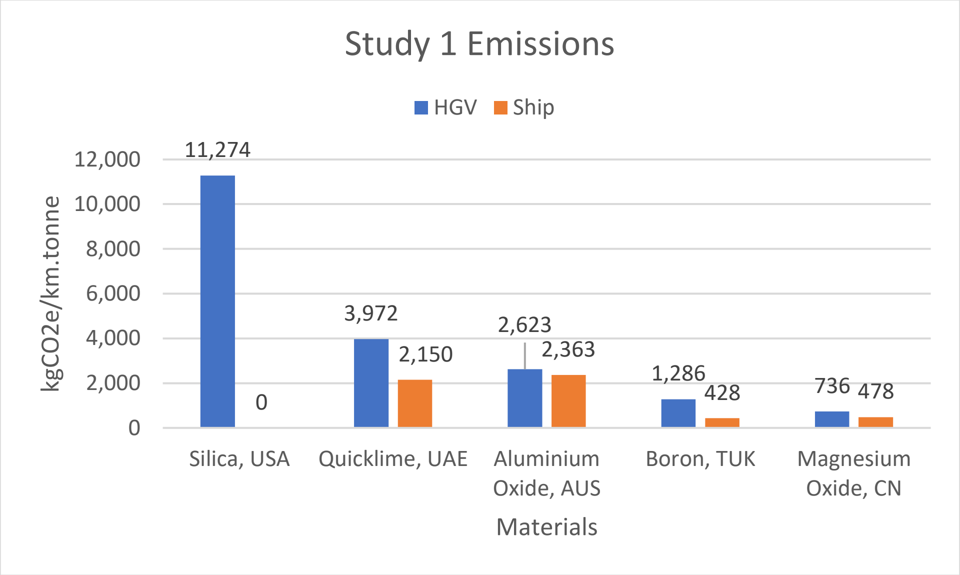


Figure 22. Emission results from study 1

Figure 23 illustrates the results from study 3, where the freighting emissions of materials (other than the E-glass) needed for the wind turbine are shown. The majority of the emissions resulting from this is from the epoxy resin in Canada. This is because the location of the manufacturer/supplier for this material is based in Calgary which is far from the coast and therefore requires a long distance (973 km) to reach the closest container terminal at Vancouver. The calculations for this study can be seen in Appendix III.

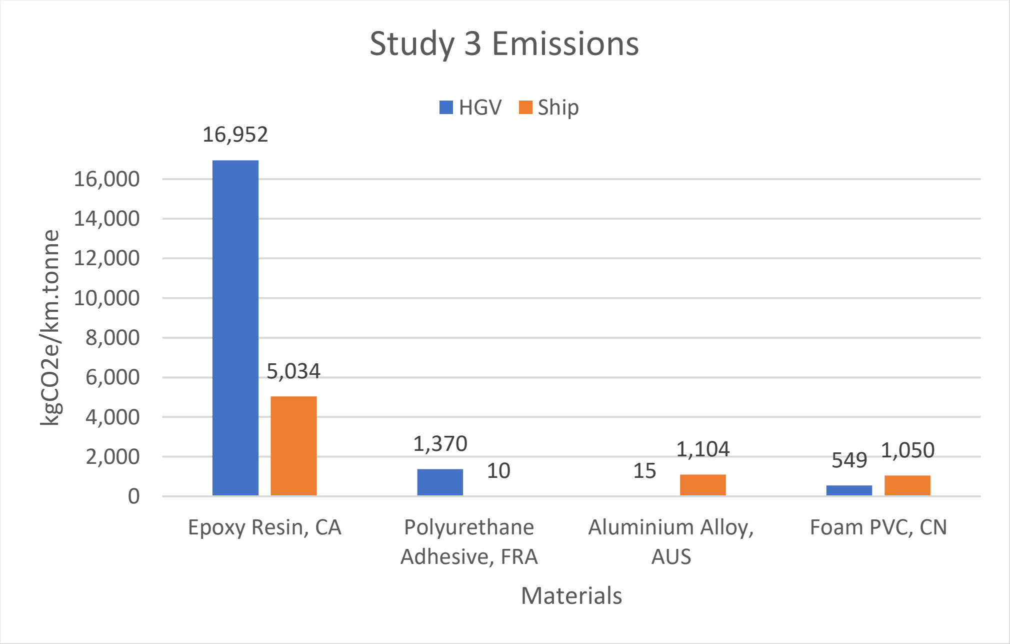


Figure 23. Emission results from study 3

Figure 24 illustrates all the stages compiled into one graph. Stage 1, despite having the largest total distance travelled, it contains the least emissions as suppliers are located close to container ports, whilst the majority of travel occurs on sea. Stage 2 contains a fair amount of land travel as the E-glass supplier here does not travel to the closest port to Charlotte, USA but instead the closest port to the UK, resulting in more land travel and consequently more emissions. This result means that if the supplier were to just travel to the closest container port, a save in emissions would occur, as land travel would swap with sea travel. Stage 3 just has a slightly larger $kgCO2e/km.tonne$ than stage 1. Stage 2 travelled a cumulative distance of 7,599 km, whilst Stage 3 only travelled 1,118 km, there was an increase of 30.37% due to the larger distance travelled on land. The calculations for study 2 and 4 can be seen in appendix IV & appendix V respectively. Overall, the studies have demonstrated that cargo ships emit the lesser emissions when compared to the HGV and shows that importing materials abroad may be more beneficial granted that the majority of travel is over sea than land.

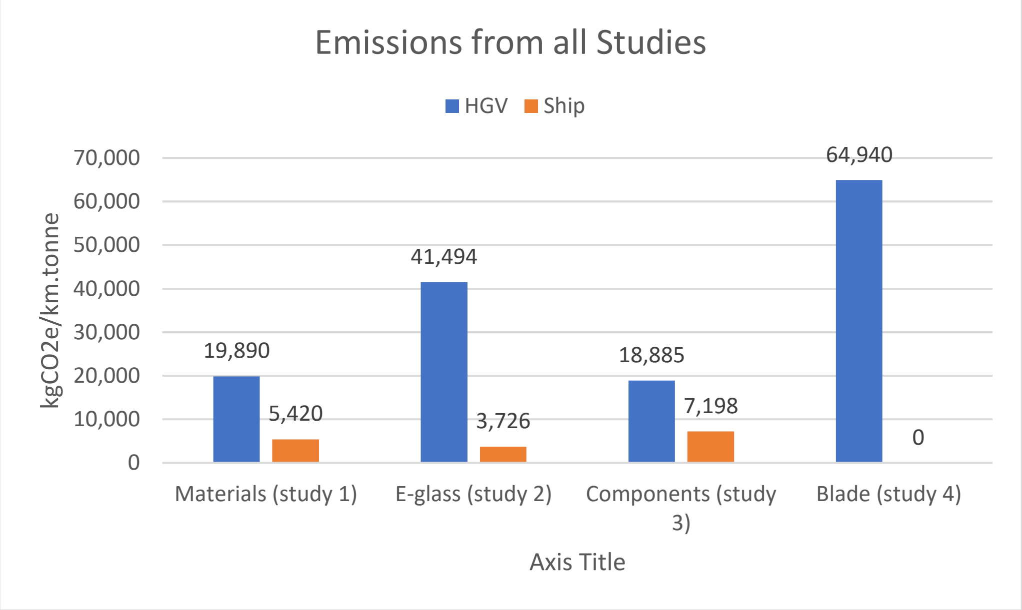


Figure 24. Emission results from all studies

Figure 25 illustrates the findings from utilising the freight railway system in the UK. Despite a diversion to the terminal and the rail line itself re-routing (seen on appendix I), a decrease of 59.91% in emissions from the original study was found when incorporating the freight railway system.

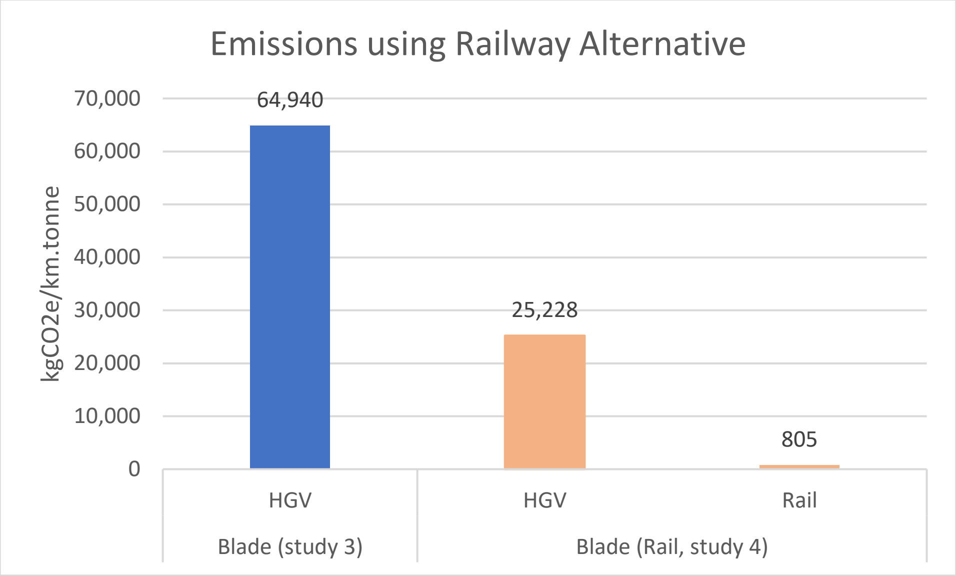


Figure 25. Emission results from the alternative study 4

5. Conclusion and Further Work

In summary, the study was successful in quantifying the embodied emissions of the materials within a wind turbine blade utilising the combination of ecoinvent and literature data. From the results it was identified that the material with the largest embodied carbon within the E-glass material was $41{,}400 kgCO2e$ of boron for a 15 MW turbine blade, whilst epoxy held the biggest value at $84{,}290 kgCO2e$ when compared overall with all materials in the wind turbine blade. Additionally, the findings from the turbine blade mass study identified that the emission and mass percentage differences correlated, meaning manufacturers can estimate emission savings when manufacturing a wind turbine blade. It was also found that the amount of E-glass required for the 15 MW trumps the total emissions from a 5 MW blade by approximately 17%. suggesting that despite the increasing trends in upsizing, it may not be as straight forward as it will consequently require a surge in input materials. Furthermore, cargo ships surpass HGV in emission savings and thus meaning suppliers should locate closer to the sea to minimise HGV travel and consequently carbon emissions. From the study it was found that emissions from HGV were far greater than cargo ships and in order to reach Net Zero ambition, incorporation of a more developed and expanded freight railway system would aid in this endeavour, either being an addition to transportation or substituting for land travel.

Suggestions for further research would include looking into an alternative for boron and epoxy resin, or possibly the manufacturing method. As well as this, a common alternative to foam is balsa wood, a comparison of emissions would be interesting. If there was more time, additional datasets in regards of comparing emission and mass differences would ensure robustness and validity to the study.

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Appendix I – Map of the UK showing freight railway line

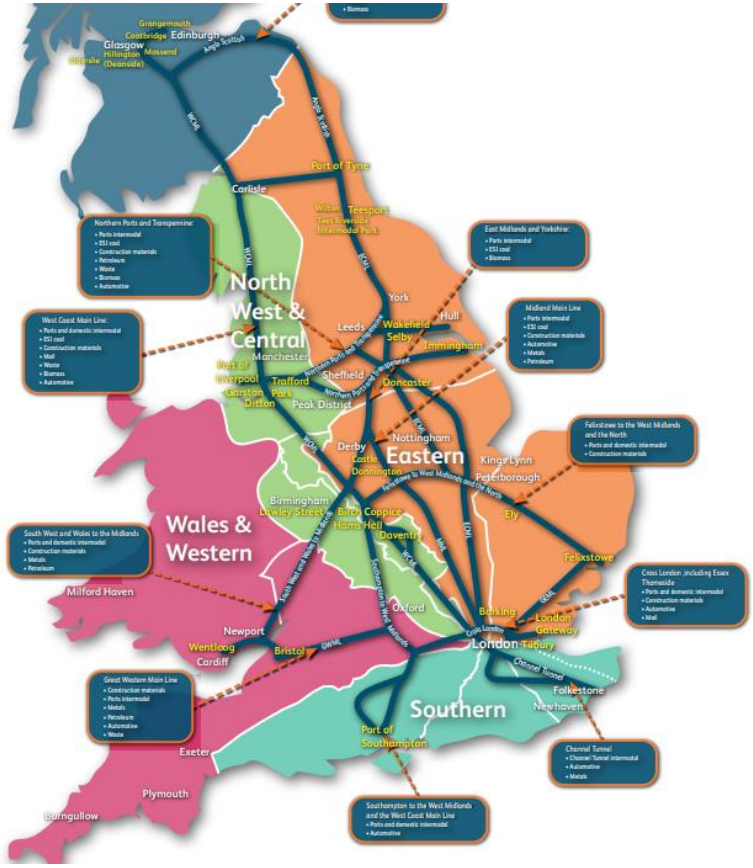
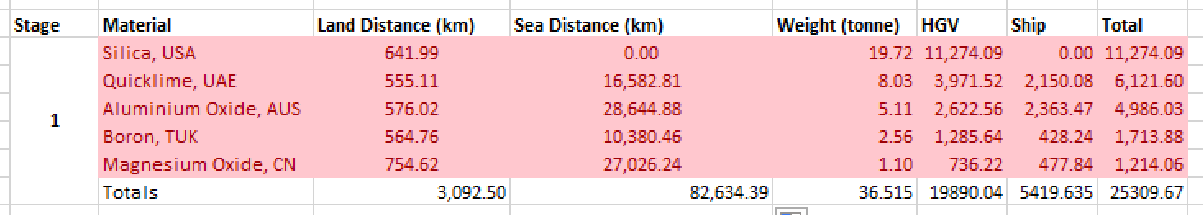


Figure 26. Map of the UK showing freight railway line

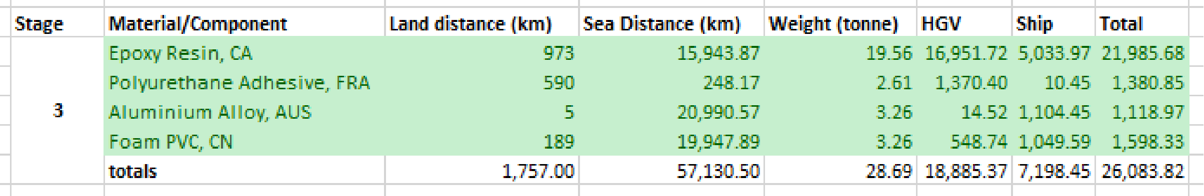
Appendix II – Calculations done for study 1



Stage	Material	Land Distance (km)	Sea Distance (km)	Weight (tonne)	HGV	Ship	Total
1	Silica, USA	641.99	0.00	19.72	11,274.09	0.00	11,274.09
	Quicklime, UAE	555.11	16,582.81	8.03	3,971.52	2,150.08	6,121.60
	Aluminium Oxide, AUS	576.02	28,644.88	5.11	2,622.56	2,363.47	4,986.03
	Boron, TUK	564.76	10,380.46	2.56	1,285.64	428.24	1,713.88
	Magnesium Oxide, CN	754.62	27,026.24	1.10	736.22	477.84	1,214.06
	Totals	3,092.50	82,634.39	36.515	19890.04	5419.635	25309.67

Figure 27. Calculations from study 1

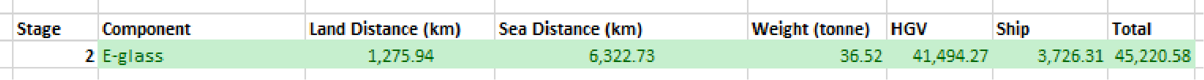
Appendix III – Calculations done for study 3



Stage	Material/Component	Land distance (km)	Sea Distance (km)	Weight (tonne)	HGV	Ship	Total
3	Epoxy Resin, CA	973	15,943.87	19.56	16,951.72	5,033.97	21,985.68
	Polyurethane Adhesive, FRA	590	248.17	2.61	1,370.40	10.45	1,380.85
	Aluminium Alloy, AUS	5	20,990.57	3.26	14.52	1,104.45	1,118.97
	Foam PVC, CN	189	19,947.89	3.26	548.74	1,049.59	1,598.33
	totals	1,757.00	57,130.50	28.69	18,885.37	7,198.45	26,083.82

Figure 28. Calculations from study 3

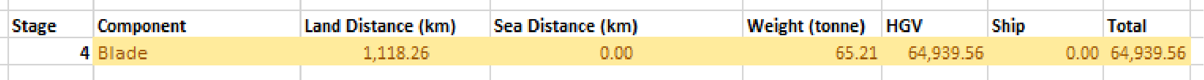
Appendix IV – Calculations done study 2



Stage	Component	Land Distance (km)	Sea Distance (km)	Weight (tonne)	HGV	Ship	Total
2	E-glass	1,275.94	6,322.73	36.52	41,494.27	3,726.31	45,220.58

Figure 29. Calculations from study 2

Appendix V – Calculations done for study 4



Stage	Component	Land Distance (km)	Sea Distance (km)	Weight (tonne)	HGV	Ship	Total
4	Blade	1,118.26	0.00	65.21	64,939.56	0.00	64,939.56

Figure 30. Calculations from study 4

Student No.