PN000463 – Cornwall Flow Accelerator

WP4 Task 2 – Reducing Carbon Emissions from Towers

GENERIC REPORT

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EXECUTIVE SUMMARY

In early 2022 The Crown Estate announced an ambition to host 4GW for floating wind capacity in the Celtic Sea alone by 2035, the leasing round of which is expected to being in 2023 followed by a further 20GW by 2045. This will bring a significant boost to the local supply chain. However, as floating offshore wind turbines become larger and more commonplace so too does the need to reduce harmful CO_2 emissions across each wind turbine component. This report follows up on the literature review carried out earlier in the Cornwall Flow Accelerator project, by taking the knowledge gained there and applying it in a life cycle analysis to pinpoint specific areas that are relevant for tower designs. This analysis should highlight the key opportunities for emissions reduction.

Three core tower designs were suggested, one steel and the second concrete. These use data taken from two reference wind turbine structures, the steel UMaine VolturnUS-S IEA 15MW turbine tower and the 15MW WindCrete concrete tower. A third hybrid design was suggested that uses a mixture of steel and concrete. The materials (steel and concrete) have been examined and understood for LCA definition. Transportation emissions were also included as part of steel and geopolymer concrete was also researched as a Portland Cement alternative. Research was also conducted on what a portside facility would resemble in terms of scale. The Celtic Sea area was reviewed based on the Crown Estate data and a site was chosen for selection.

Next, the LCA was defined using the data collected from the reference turbine, transportation requirements, site requirements, and material selection. This allowed the input data to be applied to the LCA tool, SimaPro for analysis.

The LCA noted that the concrete structure produced around 50% of the emissions produced by the steel structure, the emissions saved from a hybrid structure was around 27% over a steel design. Using entirely local content as opposed to long-distance imported steel reduced emissions by 25%. Low carbon solutions were also considered such as geopolymers noted up to an 80% reduction for concrete towers. A new concept of steel tower design was also introduced that used a greater diameter but reduced thicknesses as a way to greatly reduce the mass and as a result, emissions were cut by almost 60% although further technical studies will be needed to assess the feasibility of such a design.

Carbon Capture Storage was also highly effective for cutting emissions down. These results aligned with several LCAs that were examined in the literature. Realistically, concrete towers may not always be feasible for offshore structures but optimising designs, exploring other materials and potentially continuing further studies by exploring other more advanced materials such as composites may also highlight further opportunities.

The key opportunities identified for reducing carbon emissions in a tower are:

1. Exploring other materials beyond steel for tower structures
2. Driving the use of low carbon solutions (such as composites or geopolymers concretes)
3. Increasing the ability to manufacture locally
4. Reducing emissions from manufacturing processes, either through carbon capture storage, renewable energy, hydrogen or alternative refining processes
5. Continue developing more optimised tower designs that use less steel
6. Recycle and reuse materials when possible
7. Use greener transportation methods when necessary

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NOMENCLATURE

LCA	Life Cycle Analysis
O&M	Operations and Maintenance
GHG	Green House Gases
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
LCI	Life Cycle Inventory
TLP	Tension Leg Platform
FA	Fly Ash
GGBS	Ground Granulated Blast-furnace Slag
HMNS	High Nickel Magnesium Nickel Slag
CTV	Crew Transfer Vessel
OPC	Ordinary Portland Cement
IPCC	Intergovernmental Panel on Climate Change

1 INTRODUCTION

1.1 Background

With climate goals becoming increasingly important there is a practical and immediate need to accelerate the rate of offshore wind projects. In particular, the need to bring in floating wind projects will see significant growth over the next couple of decades. The UK has a significant amount of work planned in this area. The ScotWind leasing round will bring in just under 15GW of floating wind to Scotland. The UK overall has a target of 5GW for installed capacity by 2030.

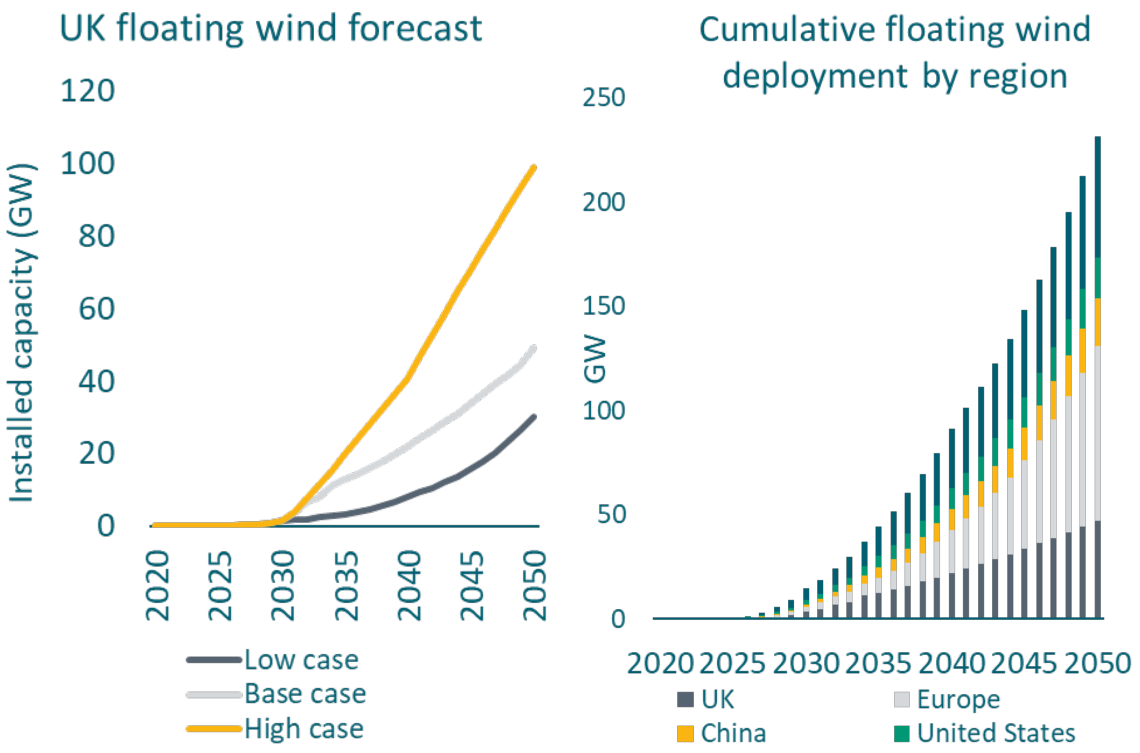

Figure 1: Left: UK floating wind installed capacity forecast. Right: Cumulative worldwide floating wind forecast

Recently, the Crown Estate has announced that there is an ambition to host 4GW for floating wind capacity in the Celtic Sea alone by 2035, the leasing round of which is expected to be in 2023 [1]. Internationally, parts of the USA, France, Japan, South Korea and Taiwan are also aiming to be key members of this rapidly growing market.

However, deployment at this scale and speed comes at a cost. Offshore wind turbines are huge structures that require huge volumes of materials, intensive manufacturing processes, require transporting and require consistent maintenance. These aspects leave a significant carbon footprint which needs to be checked and understood. If decarbonisation is a serious goal going forwards, understanding where these emissions come from and how we can tackle them will be a huge task.

The tower component of the turbine structure makes up a significant portion of the mass of the overall turbine and as a result, is responsible for a noticeable chunk of the CO_2 emissions. This particular component very much has an “industry standard” solution in place but that does not mean that there are no opportunities for innovation in place. This can involve what types of towers will be used, what materials are used and how the structure is made.

This report will aim to identify the key opportunities for reducing carbon emissions in the tower structure and will look to build on the initial knowledge that was built in the first part of this project [2] and apply that to an LCA of a prospective “reduced carbon design” in order to practically demonstrate the opportunities available for carbon reductions. The opportunities in this report will also prioritise the Cornish and by extension the overall Celtic Sea cluster’s ability to meet the demand that such opportunities require.

1.2 Objectives

This project has several main objectives and aims:

1. Develop a specification for a “baseline” tower substructure
2. Develop a specification for a prospective “greener” tower substructure
3. Define key materials to be used for the above structures
4. Develop a key understanding of manufacturing and facility requirements
5. Carry out an extensive life cycle analysis to assess the difference in greenhouse gas emissions between the chosen structures

1.3 Scope

The primary goals of this study are to produce a comprehensive specification for what a greener tower would look like. This study should define a typical design and compare it with the proposed new design. The priority here is to identify the opportunities for carbon reduction and emphasise them through the final LCA. For the analysis, a 15MW structure will be used.

1.3.1 Limitations

Whilst this study should provide a clear idea for identifying carbon reduction opportunities, there are key limits with what is currently publicly available in terms of data. Floating wind is a new industry with a lot of knowledge often being kept as confidential which can restrict the spread of knowledge.

With the above in mind, this report will be limited in the following ways:

- This report is focused purely on the physical structure itself so areas like transport of the substructure will only be loosely examined
- Similarly, areas such as O&M emissions will rely on assumptions being made for the sake of the LCA.
- Because of said issues with publicly available data, specific areas of the LCA (such as manufacturing or end-of-life), will rely heavily on assumptions, these will be explained in the relevant chapters of the report
- Finally, this project does not have the relevant resources to include a complete design of a tower, this would take a substantial amount of time and design work. Instead, this paper prioritises exposing the opportunities and will rely on reference wind turbine structures to use as an example.

2 METHODOLOGY

As mentioned in the introduction chapter this study will conclude with an LCA comparison for the chosen structure producing this LCA will require a series of data inputs all of which will need to be gathered within the scope that was explained earlier in the introduction.

An LCA is a form of analysis that quantifies the environmental impacts of a project, product or process from cradle to grave. LCAs are often carried out for multiple “solutions” allowing for an effective GHG emissions comparison. Traditionally, they are used to measure the carbon impact of works providing clear guidance for what actions to take for future works. LCA guidelines have been adopted from the ISO 14040 standards.

2.1 Study Requirements

In order to carry out the LCA the following aspects of data will need to be gathered:

1. Type of tower substructure
2. Environmental requirements
3. Type of materials
4. Mass or volume of said materials
5. Manufacturing processes
6. Material/ substructure transportation requirements
7. Operations and Maintenance requirements
8. Facility/ Portside requirements
9. End of Life (decommissioning) requirements

There may be other areas that may be required during the study but the above points are the key areas that will need to be addressed in order to carry out a comprehensive GHG assessment. Realistically, these LCA models tend to be simplified versions of a highly complex model and the key challenges will revolve around ensuring that the assumptions that are made do not distort the reality of the calculation. Additionally, there will be elements of this study that will have to be left out either due to a lack of data or due to a lack of GHG impact. Ensuring that these gaps are reported and examined will also be critically important.

2.2 Software Tools

This project from a technical perspective only requires one relevant software tool, SimaPro [3]. SimaPro is a powerful LCA tool used to analyse emissions through a fact-based approach. SimaPro supports a variety of LCI databases such as Ecoinvent [4] which has been utilised by ORE Catapult in past projects. SimaPro allows the end user to measure the CO_2 impact at all life cycle stages, for this project being able to directly compare the impact of materials, manufacturing and transport will be very important for identifying the key opportunities for emissions reduction.

Ecoinvent is an online subscription database that supplies embodied carbon values for a large range of materials and manufacturing processes. These figures come from the IPCC directly and give a clear idea for the GWP100 value for each defined material. The values for both materials and manufacturing processes will be applied during the LCA. There may be situations where new materials or manufacturing processes may be used for this analysis that might not be included in the Ecoinvent database, in these instances relevant assumptions will need to be made.

2.3 Outputs

LCAs are typically quite straightforward in terms of direct outputs, producing tables and graphs that illustrate the carbon emissions at specific points in a project or product's life cycle.

For this project, the assessment should highlight emissions at the following stages:

- Materials comparison
- Manufacturing comparison
- If relevant transport, O&M and end of life.

These outputs should provide a very clear idea of what aspect of the tower has the most significant impact and therefore what can be used to improve it the most.

3 TOWER STRUCTURE

The first key step in this study will be to identify the key aspects and designs of the chosen substructure. This chapter should provide a clear description of some of the dimensions and mechanical properties of the chosen substructures. There should be a chosen baseline structure and a chosen “lower carbon” alternative, having at least two structures will ensure that there is a clear comparison for further analysis.

3.1 Structure Selection

As identified back in the first part of this project [2], there is a wide range of wind turbine towers ranging from typical tubular structures to lattice and hybrid structures. Although studies studied in the literature review have demonstrated that the lattice structure outperforms the tubular structure due to a low mass and fewer overall materials. The tubular structure will be used due to issues regarding performance and practicalities with a lattice design.

Figure 2: Types of wind turbine towers [5]

Reasons for choosing the tubular structure vs the lattice structure include:

- Simpler manufacturing processes will likely lend themselves to reduced emissions opportunities.
- Better at handling heavy loading conditions, a lattice structure would likely fail in an offshore environment
- Safer design (lattice structure would be heavily exposed in an offshore environment)
- Proven design in offshore wind sector
- Wide range of potential reference designs available for use in LCA

3.1.1 Steel Tower (Baseline)

One of the key advantages of using the tower is that there is a wide range of designs that can be used. At 15MW scale there is a clear choice of structure that could be used as an effective baseline. The UMaine VolturnUS-S RWT [6] was designed to specifically support a 15MW wind turbine. The key dimensions and properties for the turbine and tower can be seen in Table 1 and Figure 3. The tower possesses a variable thickness throughout (82.954mm thickness at the base and 21.211mm thickness at the top).

Table 1: Dimensions for the UMaine VolturnUS-S RWT [6]

Parameter	Units	Value
Turbine rating	MW	15
Hub height	m	150
Tower height/ length	m	129.495
Tower mass	t	1263
Rna mass	t	991
Total system mass	t	20,093
Tower material	-	Steel
Base outer diameter	m	10
Top outer diameter	m	6.6

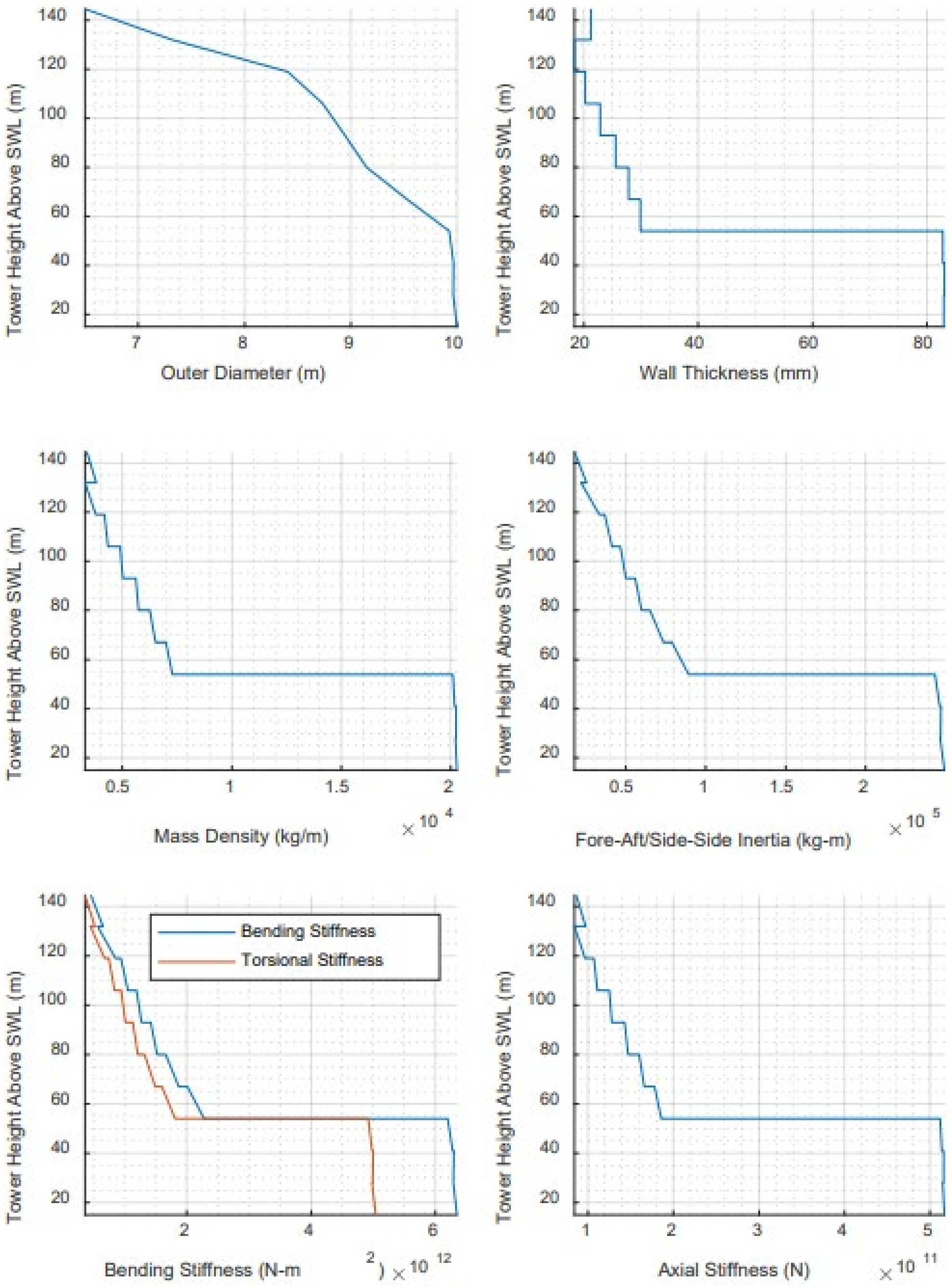

Figure 3: Tower structural properties vs tower height above sea level [6]

3.1.2 Concrete Tower

For the concrete tower there is only realistically one publicly available offshore concrete design with sufficient enough data for analysis. WindCrete [7] is a concrete tower developed by COBRA and ESTEYCO. This is designed differently to the steel design as it is intended for a Spar design as opposed to a semi-sub. Regardless of that since the tower possesses similar heights and are both designed with 15MW turbines in mind. The dimensions for this structure can be seen in Table 2 and Figure 4. One of the main differences here is that there is a near constant thickness of 0.4m as opposed to the variable thickness in the steel design.

Table 2: Dimensions for the ActiveFloat Concrete Tower [7]

Parameter	Units	Value
Turbine Rating	MW	15
Hub Height	m	150
Tower Height/ Length	m	129.495
Tower Mass	t	3258.852
RNA Mass	t	1017
Total System Mass	t	39805
Tower Material	-	Concrete
Base Outer Diameter	m	13.2
Top Outer Diameter	m	6.5

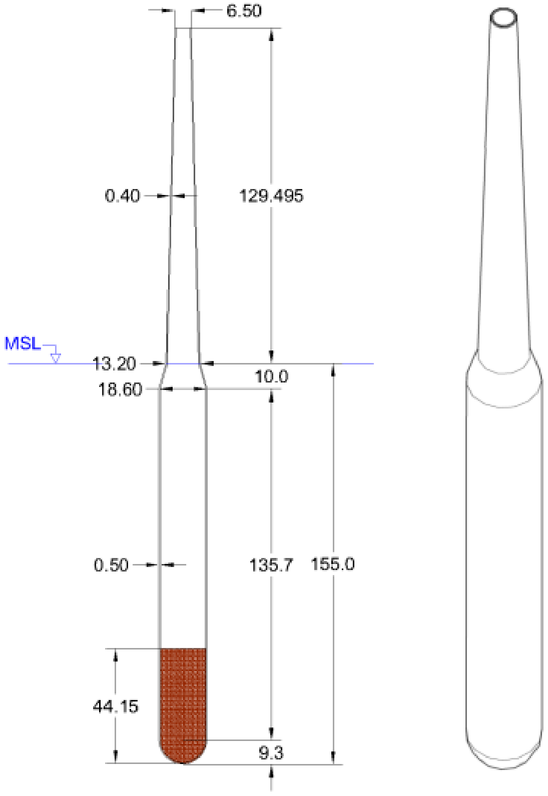

Figure 4: Arrangement and dimensions for the WindCrete Tower and Spar floater [7]

3.1.3 Steel/ Concrete Hybrid

Typically, there are problems when using a concrete tower design in an offshore environment:

- A far greater weight which means a larger substructure is required to support
- Less flexible to work in rougher offshore conditions

However, there are a number of companies that specialise in hybrid towers, these structures often use a concrete base and a steel part up top. The concrete portion should lend itself well to reduced emissions whilst the steel portion will help control the weight and ensure that there is a bit of flexibility in the tower.

Max Bögl [8] and Inwind [9] are two companies that construct these hybrid designs. In fact, Max Bögl at one point held the record for the tallest tower design using a hybrid design (190m) which demonstrates the potential for use offshore. At the time of writing there are no reference designs but using what little publicly available data there is, a basic suggestion for a design can be proposed for the purposes of the LCA.

Inwind have developed a 170m hybrid structure using either 50m or 90m tall concrete segments (Figure 5). This core design could be used here albeit with a shorter 150m design and a 50m concrete segment, masses for each individual segment were calculated using mass densities and thicknesses provided in the two prior baseline designs.

Table 3: Dimensions for the proposed hybrid tower design. [9]

Parameter	Units	Value
Turbine Rating	MW	15
Hub Height	m	150
Total Tower Height/ Length	m	129.495
Tower Mass	t	2159.44
Concrete Component Height	m	50
Steel Component Height	m	70.495
Concrete Structure Mass	t	1384.12
Steel Structure Mass	t	775.32

Figure 5: 170m Inwind Hybrid Design [9]

4 MATERIALS

The main priority when it comes to emissions reductions is tackling what materials are used from the structure. The materials themselves drive the emissions through initial refining processes, manufacturing processes and if necessary material transport which can add up if importing from other continents is required.

4.1 Steel

Steel is the most widely used material in a complete wind turbine structure (Figure 6) and as a result, adds to being the biggest emitter across the global system.

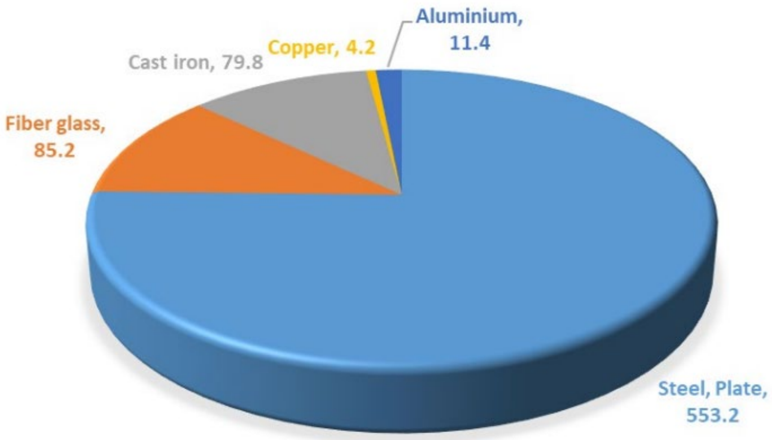

Figure 6: 6MW offshore wind turbine material mass breakdown (tonnes) [10]

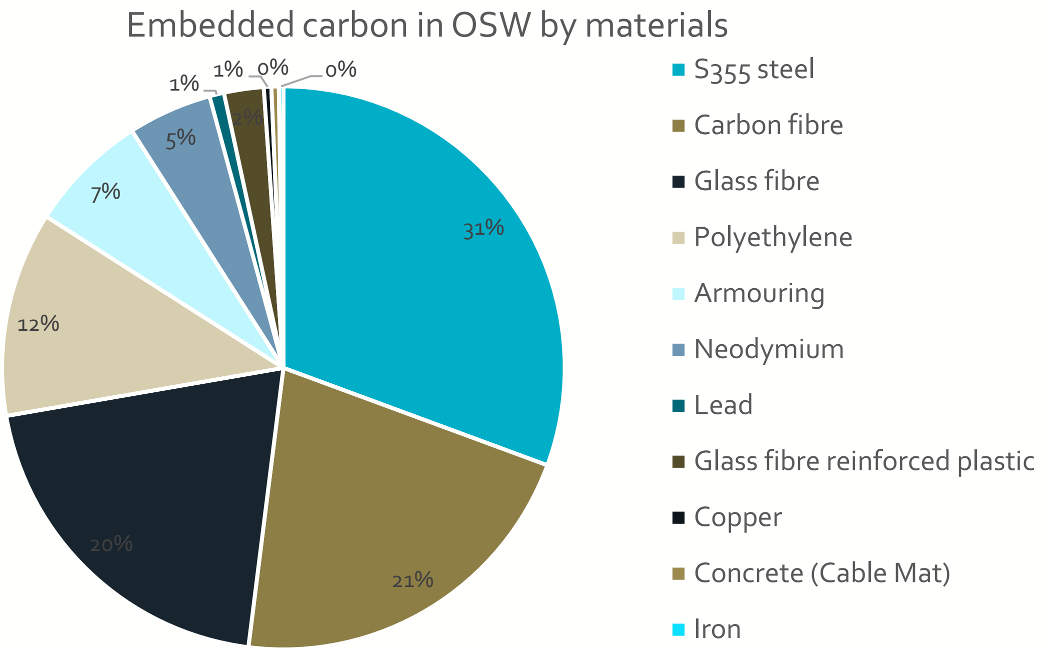

Figure 7: Embedded carbon in offshore wind turbines by materials

The primary source of these materials comes from the refining and smelting process which are highly energy intensive, additionally, the UK has very limited steel manufacturing capacity and for large wind turbine structures steel will likely have to be imported from Asia which will add up further emissions.

4.1.1 Material Properties

Typically for a wind turbine, S355 steel is used for wind turbines. This is a common choice of steel across the wind industry and in other "large scale" sectors such as construction and oil and gas. Typically for the large structural components of a turbine such as the floater or tower, a low-carbon steel is used.

The core mechanical properties are not directly relevant to this study but the Ecoinvent and SimaPro databases provide emissions data for steel, this is highly dependent on which manufacturing processes are used. Table 4 highlights the primary types of steel that will be used and the emissions associated with the steel.

Table 4: Material Carbon Dioxide Emissions

Material	Ecoinvent Name	Geography	Unit	kg CO2 - Eq
S355 steel	Low-alloyed steel	Global	per kg	1.4521
S355 steel	Hot Rolled steel	Global	per kg	1.7159

4.1.2 Manufacturing

Ultimately, the raw materials aren't the only cause of emissions, the manufacturing processes that are applied also play a substantial role here.

A tower is typically constructed through two processes and for the sake of the LCA, the assumptions for the construction for steel is as follows.

- The steel is produced through hot rolling (no seamless tubes) plates
- Welding (Gas or Arc) is used to attach all tubes together into one cohesive tower unit
- Whilst bolted connections are often used to fix parts of the tower together this has been judged to be unnecessary as such joints make up a low % of the mass of the overall tower

Realistically the UK at present does not possess the requisite plate steel manufacturing capability to produce these structures and a significant amount of investment will be required to meet the demand but would not guarantee cost competitiveness against overseas suppliers. The majority of emissions in the steelmaking process (Figure 8) are produced during the initial refining of the materials. The integrated route of sintering, coke ovens and blast furnaces is used by 72% of global steel production. Reducing or reworking these core processes will also play a key role in reducing emissions.

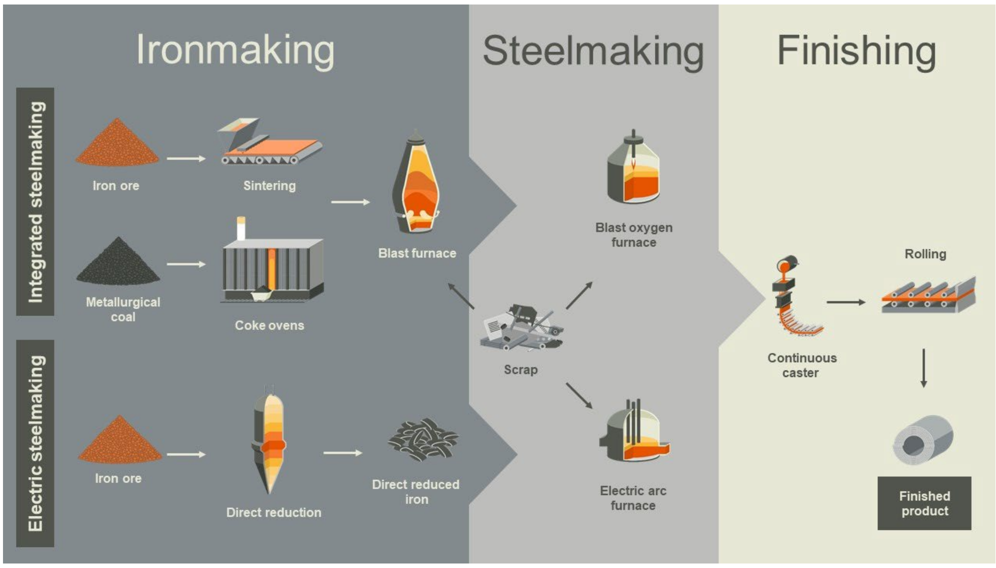

Figure 8: Primary steelmaking process routes [11]

4.1.3 Transport/ Integration

Due to the lack of domestic steel, the transport and production of steel will need to be taken into consideration. One potential route that this steel can take is mining in Australia, transport to India for the steel plate manufacture, then to the Netherlands for welding and fabrication, and finally arriving in the UK [12]

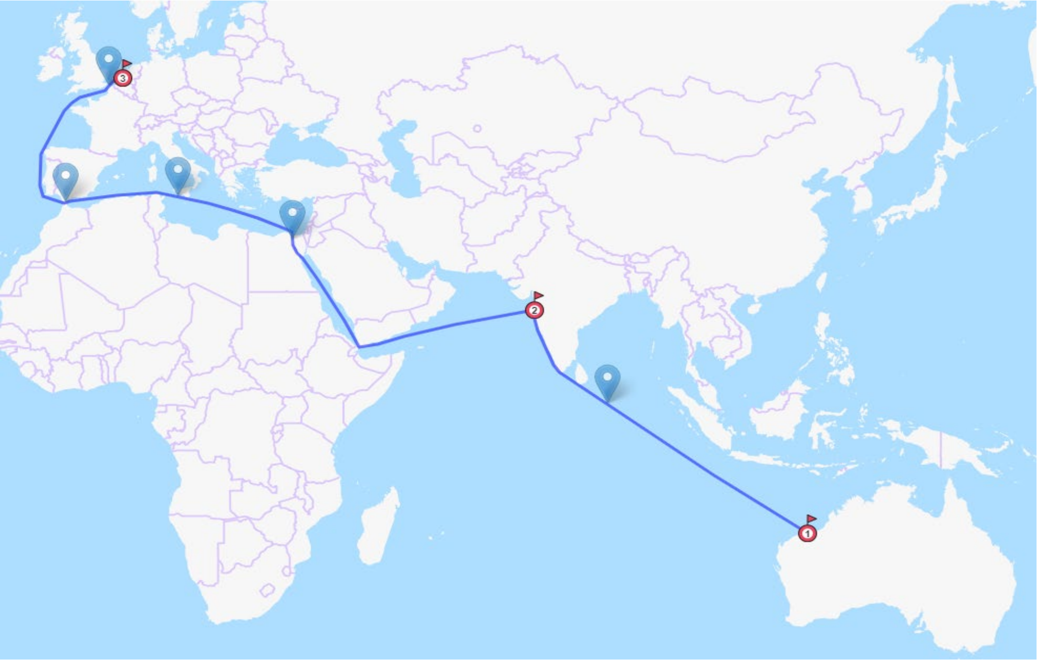

Figure 9: Shipping route from Australia to India, from India to the Netherlands and then the Netherlands to the UK

Table 5: Estimated shipping emissions from Australia to the UK

Process Steps	Materials	Tonnes/ Tonne of Steel	Grams/ Tonne km	km	The CO2/Te
Mining in NW Australia	Coal & Iron Ore	-	-	-	-
Rail transport to NW Australia Port	Coal & Iron Ore	2.2	25	400	0.022
Bulk carrier transport to Mumbai Port	Coal & Iron Ore	2.2	7.9	6860	0.118
Rail transport to inland steel plant	Coal & Iron Ore	2.2	25	160	0.009
Rail transport to Mumbai port	Steel plate	1	25	160	0.004
Bulk carrier transport to Netherlands	Steel plate	1	7.9	11770	0.093
Heavy lift vessel transport to NE of UK	Welded Tubular structure	1	18	500	0.009
TOTAL TRANSPORT	*Welded Tubular structure*	-	-	-	*0.224*

As can be seen from Table 5 (calculated from data provided in [13], [14], [15], [16]), these transport emissions are not insignificant especially when you consider that this is only relevant for 1 tonne of steel while over 17,000 tonnes will be required for 1 turbine. Following the LCA there may be a clear indicator that it may be worthwhile trying to improve steel manufacturing in the UK in order to meet this demand and reduce emissions.

4.1.4 Portside Facility

Typically steel substructures are built-in modules with the overall assembly being completed quayside and specific components are often built away from the port. Naturally, portside facilities require coastal access (and wet storage) with enough land to allow the assembly, dry storage and equipment. A previous ORE Catapult study [17] showcased the core construction and installation process in Figure 10.

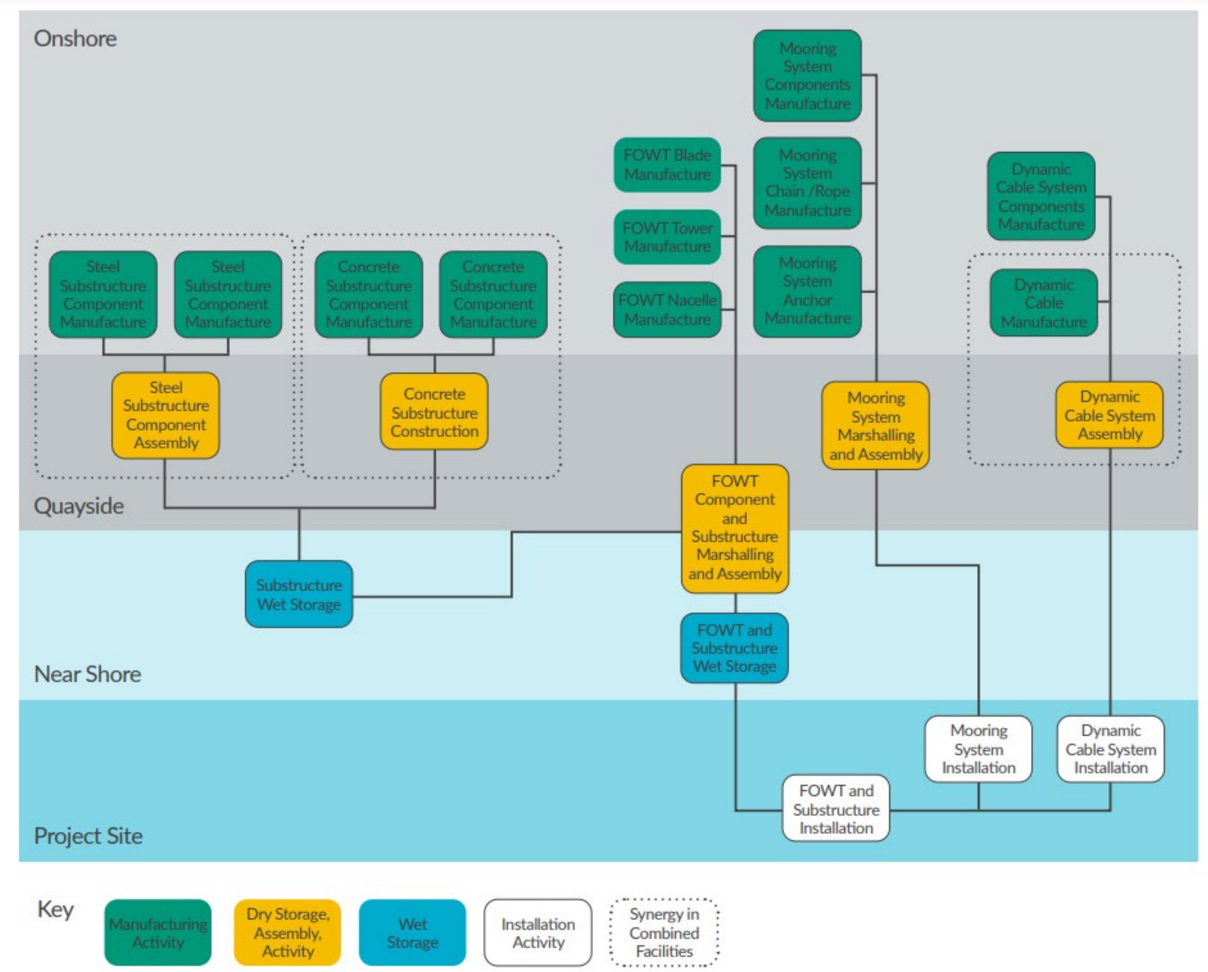

Figure 10: FOWT project construction process. (separate boxes represent separate facilities) [17]

For this specific tower design, an area of 130m x 15m will be considered for one turbine although given the wide range of turbine designs, these dimensions can vary considerably (although this will be at the larger end of the spectrum). Particular care will be needed if the investment is required to build these manufacturing/ assembly/installation facilities then adequate planning should be put in place to accommodate a potential range of sizes.

The schematic in Figure 11 shows a high-level idea of how this structure would be constructed and what size of facility would be required. The dimensions there have been adapted from the tower manufacturing facility that has been announced at the Port of Nigg [18] where towers above 1,000 tonnes will be manufactured. For a steel facility, the towers will be rolled, painted and welded in one location. Afterwards, said tower sections can be assembled (if necessary) and moved to the port for complete assembly or integration.

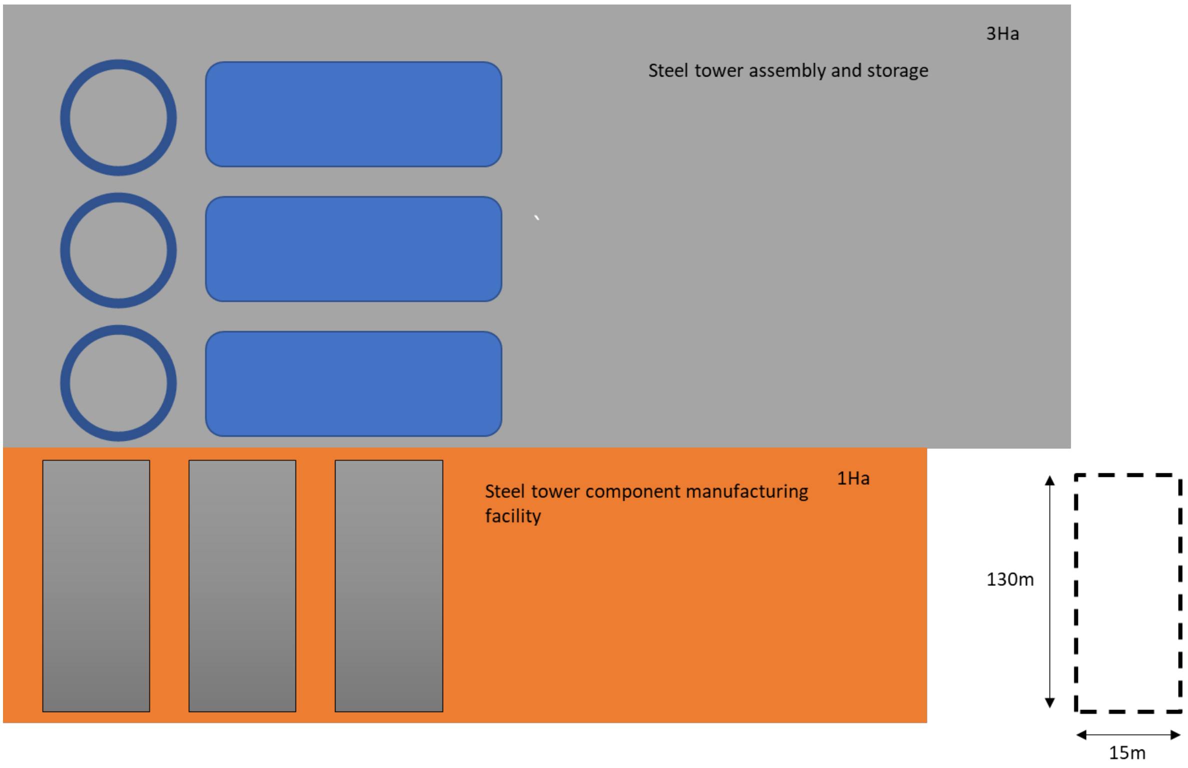

Figure 11: Steel tower manufacturing and assembly facility.

4.2 Concrete

At the time of writing, there have only been either steel or concrete towers at this scale although there may be opportunities for growth in the near future.

Given the improved local supply chain aspect of concrete, there are far less concerns surrounding the transportation of the material, additionally, manufacturing processes surrounding concrete structures are typically less demanding in terms of CO_2 emissions. However, the bulk of emissions generated by concrete production comes from its constituent components, in particular clinker in the cement sub-component. The most common cement that is used in these structures is Portland Cement which emits a significant amount of CO_2. An estimated 8% of the world's emissions in 2015 came from the concrete industry alone highlighting the immediate significance of decarbonising this sector [20].

4.2.1 Material Properties

Key properties of concrete are hard to measure as each mixture performs differently and will emit varying amounts of emissions. A report by IPCC [19] indicated that the focus should be on measuring the carbon content of clinker in particular as it is the key offender with regards to emissions. Magnadense

For carbon intensity factors, values were based on an environmental product declaration (EPD) for CEM I 52.5 Cement with cradle-to-gate. This was considered as a reliable source for carbon values. For concrete structures rebar would also need to be considered using values for steel reinforcement-based products.

For a lower carbon concrete secondary cementitious materials can be added to CEM l. Typically Fly Ash or Ground Granulated Blast-Furnace Slag is often used. Other types of concrete could be considered in the analysis that makes use of these materials but typical cement replacement materials are imported and may not be available within the UK. For the LCA in this analysis, the 50MW strength concrete will be used from the Ecoinvent database which closely resembles the CEM l mixture that has been used in other analysis.

Table 6: Key properties from Concrete 50MW (Ecoinvent)

Concrete Properties	Value
Strength	C50/60 (50MPa/60MPa)
Concrete composition	Cement (Portland), gravel, sand, fly ash, silica fume
Density	2.232 kg/m^3
Water to cement ratio	35%

4.2.2 Manufacturing

There are several types of manufacturing processes that may be used for a tower although it is largely based on size (and how many segments are required). Here, there are a few methods that may be usable. Precast methods may be useful to adopt, precast fabrication would allow the separate modules of the tower structure to be constructed separately and then these pre-cast components are then assembled at a station. The basic geometry of a tower and its separate segments lends itself well to these methods. Although, said geometry means that slip forming and newer manufacturing methods such as 3D Printing concrete adhesive may become more commonplace in the future.

4.2.3 Transport/ Integration

When compared to the steel industry, the UK industry is far better placed with regards to concrete production with a wide range of local businesses including in Cornwall that with the right consulting and proof of manufacturability would meet the required demand for concrete. With this in mind, there will be no need to include transportation emissions for the concrete construction as the travel distance would be negligible when compared to the steel travel distance. Although, transport for rebar will be included.

4.2.4 Different Types of Concrete (Lower Carbon Opportunities)

Given that the concrete industry has had a significant impact on the world's global carbon emissions there has been a great deal of research on the area of lower carbon concrete. One great, local example of potential innovation is raised by the company Real Green Concrete [21] based in Plymouth. Their solution is a geopolymer concrete that replaces the Portland Cement component with a greener alternative. Geopolymer concretes usually use an aluminosilicate precursor material (like Fly Ash or metakaolin), an alkaline reagent and water. Afterwards, hardening is achieved by adding calcium cations. Typically these solutions cure faster than Portland Cement but may take longer to set.

Bouaissi et al describe such a geopolymer in [22]. There they used a mixture of FA, GGBS and high-magnesium nickel slag to develop a geopolymer mixture, the properties of which can be seen in Table 7.

Table 7: Mixture properties of the geopolymer paste and concrete [22]

Materials	GP Paste Cubic Specimens	GP Concrete Cubic Specimens
Coarse aggregates, kg/m^3	-	1176
Fine aggregates, kg/m^3	-	504
Class F FA, kg/m^3	420	336
GGBS, kg/m^3	120	96
HMNS, kg/m^3	60	48
Na_2SiO_3 solution, kg/m^3	214.28	171.43
NaOH solution, kg/m^3	85.71	68.6
Na_2SiO_3/NaOH ratio	2.5	
Solid/alkaline activator ratio	2.0	

They used the above mixture but also ran experiments by changing the % of GGBS and FA. The results of this can be seen in Figure 12. That chart highlights how high the compressive strength of these geopolymer mixtures can get over time.

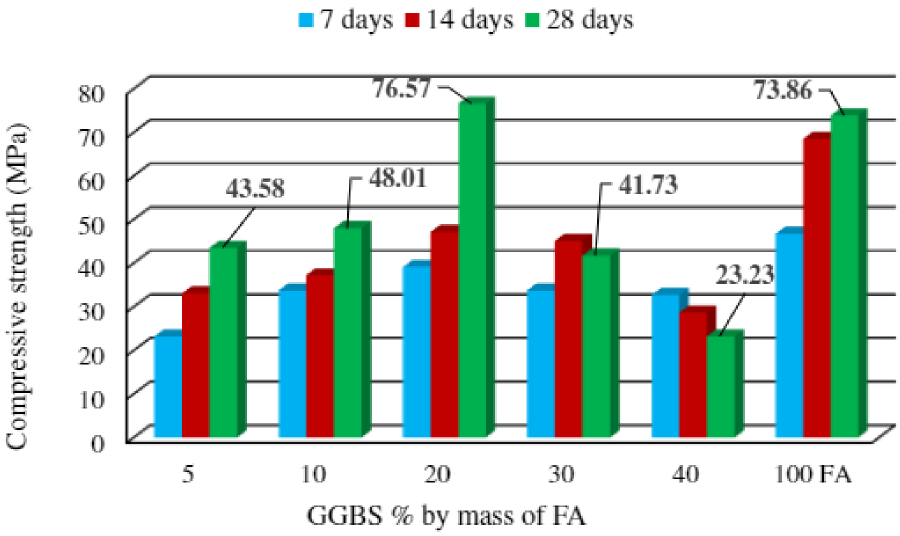

Figure 12: Compressive strength of the paste with different GGBS % [22]

Kumar et al [23] carried out a comparison of geopolymer concretes vs Portland cement specifically with a high-level comparison of both concretes see Table 8. Their comparison highlighted a roughly 80% CO_2 emissions reduction.

Table 8: Comparison of concrete solutions [23]

Properties	Portland Cement	Geopolymer
CO_2 emission	800-900 kg/ton	150-200 kg/ton
Embodied energy	4000-4400 MJ/ton	2200-2400 MJ/ton
Water requirement	≈600 litres/ton	≈450 litres/ ton

There are a few roadblocks regarding pushing this technology further. From a technical perspective, applying the higher temperatures required for large-scale applications needs to be further studied and that efflorescence has been observed at low temperatures. However, the main roadblock is nontechnical, there are no recognised standards for this technology and more investment will be required going forward to ensure that geopolymers can be used more heavily in the future. There is a strong drive within the sector to decarbonise Tarmac [24], a UK-based company that supplies sustainable construction materials are working on supplying a low carbon concrete that can supposedly reduce 70% of carbon emissions when compared to CEM l. Although it is not known what type of concrete they are using for this.

Elsewhere, Hanson [25] a UK based cement company also possesses a low-carbon concrete solution that is known as the EcoPlus Range. Here they use a percentage of GGBS to replace some of the Portland cement in the mixture. GGBS is a by-product of ironmaking so it feeds well into the circular economy and should help reduce CO_2 emissions by roughly 35%. Whilst this decrease is not as high as the geopolymer solutions that were explored above, this solution does comply with BS 8500 and BS EN206-1 standards. Additionally, unlike the other solutions this concrete has been used in large-scale construction projects granting the mixture validity that other solutions lack.

4.2.5 Manufacturing Facility

Similarly, to the steel portside facility, there would need to be an opportunity for carrying out the manufacture, assembly and storage of these structures on-site. Expecting to be a similar size when compared to their steel counterparts, a complete construction facility would be expected to have a similar size requirement. The below diagram is intended to show an extremely high-level overview of what such a facility would look like. There isn't a need for it to be based portside but would benefit by being as close as possible. Here assuming a pre-cast process each tower segment is made individually and then is stored and assembled, alternatively, each precast segment may be transported individually to the port.

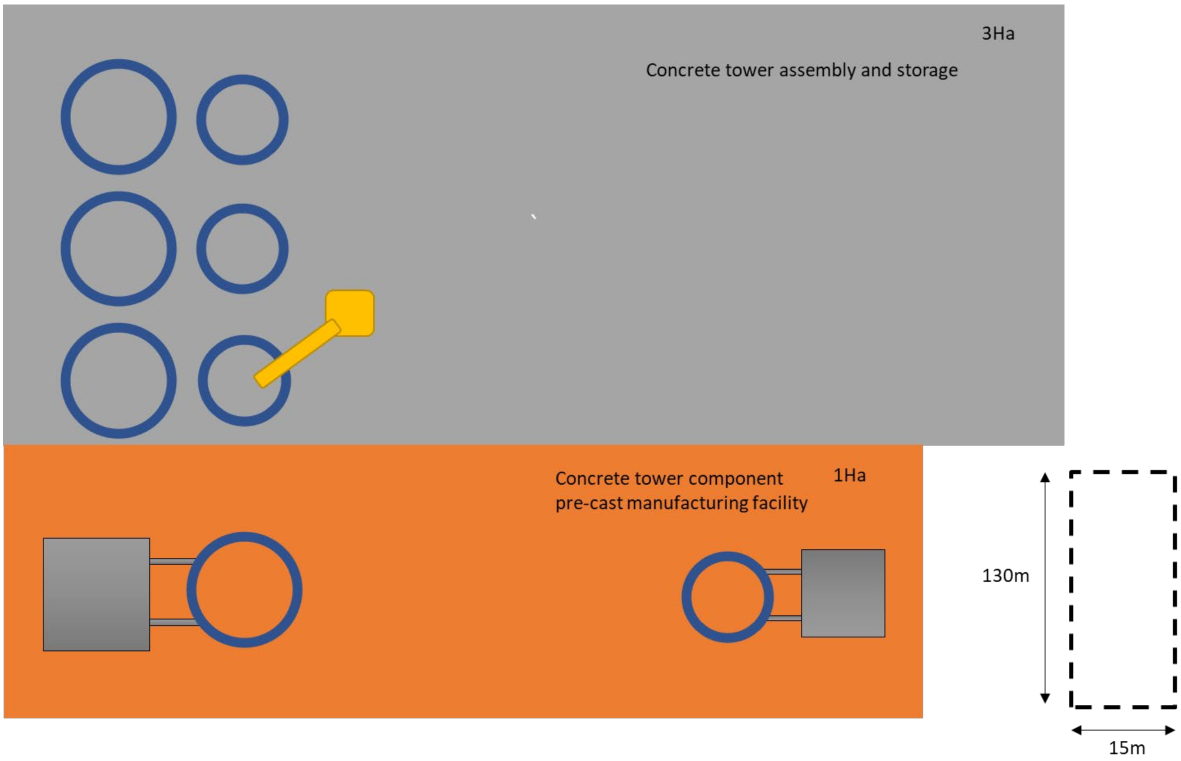

Figure 13: Concrete Tower Construction Facility

5 CELTIC SEA REQUIREMENTS

5.1 Site Leasing

Part of the reason why this topic of emissions reduction is of so much interest at the moment is that there is a real drive to increase floating wind production in the Celtic Sea. As previously mentioned there is a leasing process that the Crown Estate have scheduled to begin in 2023.

This leasing round has ambitions to raise to 4GW of floating offshore wind in the Celtic Sea area by 2034. Currently, they have carried out an extensive study to identify key areas for floating turbines and to pinpoint key risks in the area. From this project's perspective. The points of interest here are the site conditions. The chosen site will also provide information for aspects such as transport and O&M costs which may be used in the LCA calculation.

5.1.1 Celtic Sea Areas of Search

The identified areas of search can be seen in Figure 14. These areas were selected following an extensive study on the economic, environmental, social and accessibility of the available sites. These areas are still under refinement and change further as studies continue before the leasing round. From the perspective of a tower, the sites have already been identified to be suitable from the point of sedimentation and shipping lanes, the only physical impact the sites would have on tower selection is transport distance and potentially typical environmental conditions.

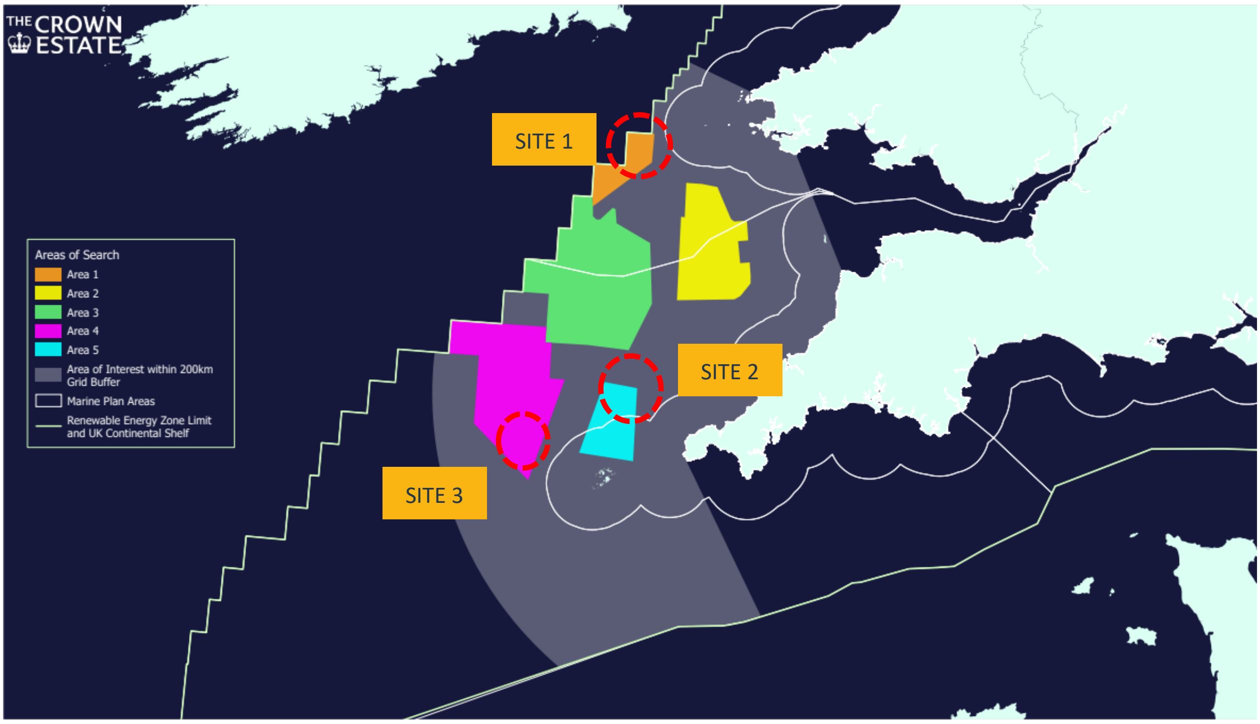

Figure 14: The five identified areas of search produced by the Crown Estate [1]

Currently, these areas of interest are too broad to contain specific site conditions, but following past work on modelling array sites in the Celtic Sea, 3 specific sites within these areas of search have been identified and selected. The site conditions of which can be seen in Table 9.

Table 9: Summary of the core site conditions

Site Parameter	Site 1	Site 2	Site 3
Water depth average (m)	107.7	72.3	113.5
Water depth range (m)	81.8 – 117.8	62.2 – 82.2	107.4 – 116.5
Mean wind speed at 150m height (m/s)	10 - 12	10-12	10-12
Bedrock	Chalk, gneiss	Mudstone	Chalk, mudstone
Sediment	Sand, muddy sand	Gravelly sand, gravel	Muddy sand, gravelly sand, sand
Annual mean significant wave height (hs, m)	2 – 2.5	2-2.5 (~5% 1.5-2)	2-2.5
Annual mean neap tide (m/s)	0.2-0.3 (minority 0.3-0.4)	0.2-0.3 (~25% 0.3-0.4)	0.2-0.3
Annual mean spring tide (m/s)	0.5-0.75, (~30% 0.25-0.5)	0.5-0.75	0.5-0.75
Location turbine 1 (lat, long)	51.59897, -6.26158	50.6076, -5.7779	49.81369, -7.1867

Whilst no specific site needs to be selected for this project, site 1 will be chosen in part due to deeper waters and proximity to Milford Haven which is one of the largest ports in the Celtic Sea Cluster.

5.1.2 Design Requirements

To summarise the above work the following assumptions will be made using the above site conditions:

Table 10: Design requirements summary

Wind Turbine Parameter	Dimension
Wind turbine capacity	15MW
Design life	25 years
Structure type	Tubular tower
Required tower height	129.495m
Required Space for Turbine Structure (H, L, W)	270m, 240m, 90m
Water depth	107m
Estimated Distance from Site to Nearest Port	90km

6 LIFE CYCLE ANALYSIS

This chapter will aim to define the LCA and produce the results of the analysis. First, the stages of the LCA will be defined with each specific section detailed. Afterwards, those inputs will be applied to the final assessment and the results will be generated.

6.1 Lifecycle Stages

An LCA essentially revolves around 4 separate steps:

1. Identify the scope or goal of the analysis
2. Take the life cycle inventory (defining inputs for the analysis)
3. Carrying out the calculation and producing the assessment
4. Interpreting the results

The first step has been carried out across the first couple of chapters in this report and defining the life cycle inventory (LCI) is what takes up the majority of this study.

Figure 15: Life cycle analysis workflow [26]

The above workflow show cases the various steps that need to be determined for the completion of an LCA. The raw materials, the manufacturing processes, assembly (including transportation, maintenance, etc) and finally the end of life will need to be considered.

Defining system boundaries will also be critical to ensure that results are kept concise, accurate and relevant. Figure 16 shows the core workflow to what stages of a wind turbine need to be defined.

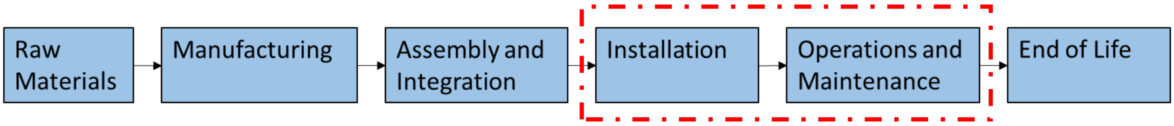

Figure 16: Wind Turbine Construction Process. Boxes within the red dashed line will be omitted from the LCA.

Naturally, the materials and manufacturing are the main areas of difference between each of the chosen designs (concrete vs steel, cast forming vs rolling and welding, etc). The core turbine installation and O&M will be the same for both turbines as the same site is used for both, therefore they will be emitted from the analysis due to having the same GHG emissions for both structures.

6.2 Lifecycle Assessment Assumptions

This subchapter will aim to list the core inputs and requirements for each of the steps that were previously mentioned.

6.2.1 Considered Materials

The materials were already listed and described in chapter 4, as a summary Table 11 has been created to show the main materials that are under consideration. LCA’s typically use volume as a metric over mass for concrete applications, this can be tricky to calculate due to differing concrete types possessing varying densities and water % content. Here, using the mass densities taken from the reference turbines and data from the LCA databases were used to calculate rough values for concrete volume. In reality, these figures may be higher or lower but the calculated figures should at least provide a ballpark figure that can sufficiently showcase emissions impact.

Table 11: Summary of the core materials that are being setup for the analysis

Tower Type	Primary Steel	Steel Mass (t)	Concrete	Concrete Volume (m^3)	Rebar Material	Rebar Mass (t)
Steel	Yes, Low alloyed Steel	1263	No	N/A	No	N/A
Concrete	No	N/A	Concrete, 50MPa	1385.0121	Reinforcing steel	300
Hybrid	Yes, Low alloyed Steel	775.32	Concrete, 50MPa	588.251	Reinforcing steel	127.42

6.2.2 Manufacturing (LCA)

As previously stated manufacturing is a hard area to accurately define in an LCA, especially in a new sector like the wind industry where many manufacturing processes are either unique and difficult to define or cannot be replicated due to data availability. Based on prior LCA work in literature, the chosen methods for a steel structure use rolling and welding processes. For aspects such as refining, casting, mixing, etc most of those core processes are included as part of the materials emissions. It was considered at the start of the study to compare different specific manufacturing processes such as arc vs gas welding but due to Ecoinvent definitions the results there are largely identical.

Table 12: Summary of relevant manufacturing processes

Manufacturing Processes	Material
Arc welding	Steel
Hot/ sheet rolling	Steel
Concrete- precast tower construction	Concrete

6.2.3 Transportation

As discussed in chapter 4.1.3, following some estimations of travel distance for the steel shipments the below estimations will be used in the transport calculations. Concrete has been assumed to be locally sourced but steel will need to be imported.

Table 13: Summary of LCA input for material transport

Travel Distance (km)	11,770
Ton-kilometre (tkm)	14,865,510 (Transport, bulk, sea freight)

6.2.4 Installation, Operations and Maintenance

As stated previously, the processes for installation, operations and maintenance would be identical for both the concrete and steel structures would have identical O&M requirements. That said these aspects elements do have an impact on emissions so may be worth investigating for further overall suggestions.

Table 14: Installation and O&M assumptions

Aspect of O&M	**Parameter**
Turbine Life	25 years
Inspection Rate	Annual
O&M vessel strategy	CTV
Distance from Site to Port	90km

6.2.5 End of Life

End of life is another important area of an LCA that needs to be defined. The literature review [2] briefly reviewed the end of life for a group of materials and those same assumptions may also be made here.

Table 15: End-of-life scenarios

Material	**End-of-life treatment**
Concrete	Landfill 100%
Cast Iron	Recycling with 10% loss
Copper	Recycling with 5% loss
Epoxy	Incinerated 100%
Fibreglass	Incinerated 100% (although heat and treatment services exist that allow fibres to be retrieved for building materials)
Plastic	Incinerated 100%
Stainless Steel	Recycling with 10% loss

6.3 Carbon Emissions Assessment

6.3.1 Assessment Limitations

The prior chapter covered what was to be included in the study but there are still a number of areas that were not included as part of the study.

- As previously mentioned, the operations and maintenance processes were considered to be effectively the same for both turbines so won't be considered in the analysis
- Again, manufacturing processes are hard to define accurately but here they are judged to be the best representative of real-life processes based on the literature
- Ideally, low carbon concrete would be modelled using the precise mixture for the chosen concrete solution however due to the relatively new nature of these materials acquiring specific data mixture %s is very challenging. Instead from literature, a CO_2 saving % can be applied as a specific input to provide a representative number
- As listed in the prior literature review, Carbon capture storage can have a substantial impact on carbon emissions although this can be a hard area to model accurately in an LCA. Similar to the DNV comparison report, a saving % can be applied to specific processes to highlight the benefit of using such a technology
- In terms of transport, long-distance transport was considered but not short-distance domestic transport, again like O&M processes, this is assumed to be equal for both structures.

6.3.2 Baseline Assessment

There are a wide variety of areas that can be assessed against for this analysis. To begin with, the core baseline models for the three main tower structures will be compared.

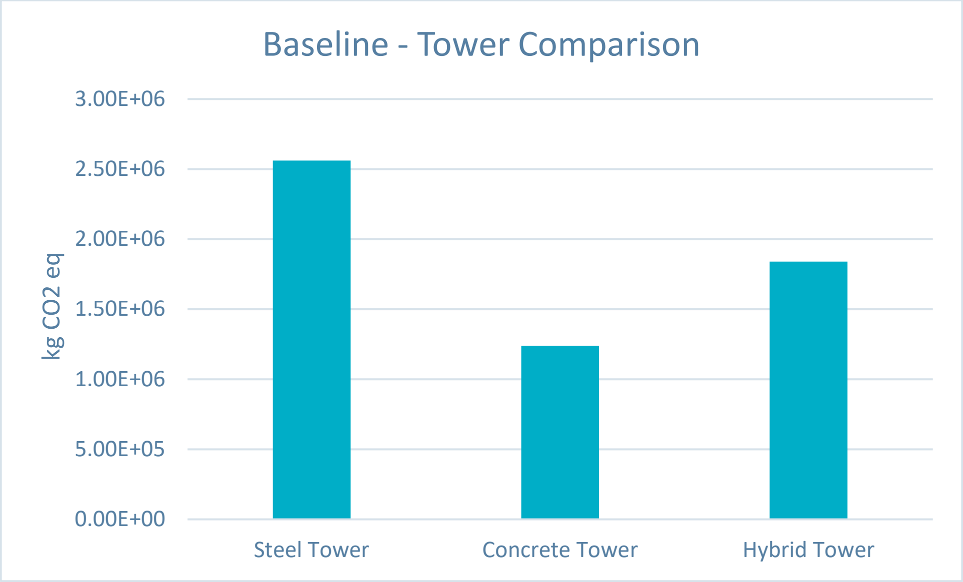

Figure 17: LCA results: Baseline tower comparison

Due to the UK having little manufacturing capacity with regards to steel, a steel tower will need to be transported. This has been used in the above analysis however the following figure will showcase the difference between transported content and "local" content that has no transport mileage.

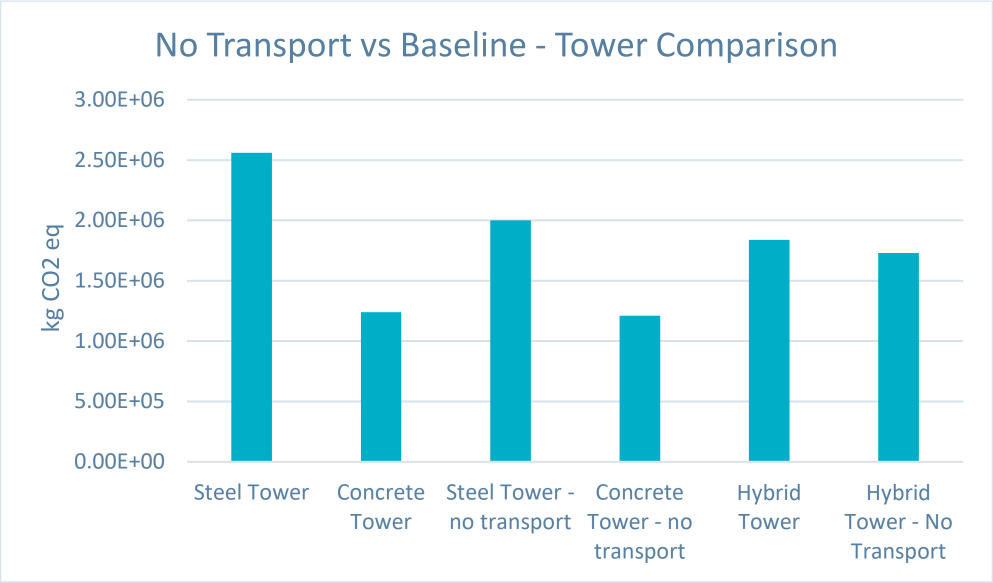

Figure 18: LCA result: Base structures vs locally sourced materials

Following the descriptions in section 0, there is huge potential for low carbon concrete as a material source, whilst it is hard to accurately define these materials fully in an LCA software due to a lack of publicly available data assumptions on % of carbon emissions has been made based on the claims made by the manufacturers.

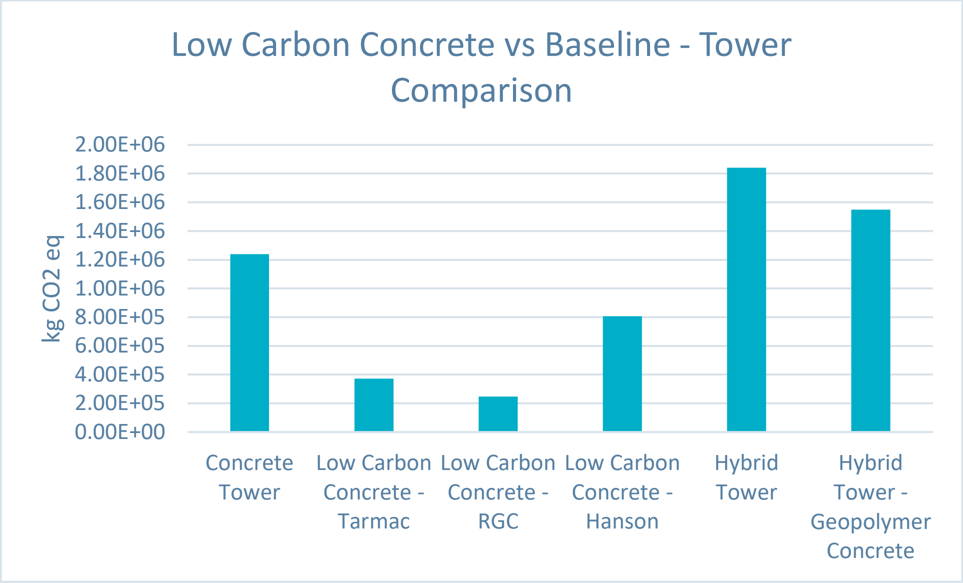

Figure 19: LCA result: Comparison of different concrete structures

Additionally, as hinted at in the prior literature review carbon capture storage (CCS) will have a significant role to play in reducing emissions across most sectors worldwide. Here several assumptions have been made for CO_2 savings based on literature ([30], [31], [32])and have been applied in the LCA calculation.

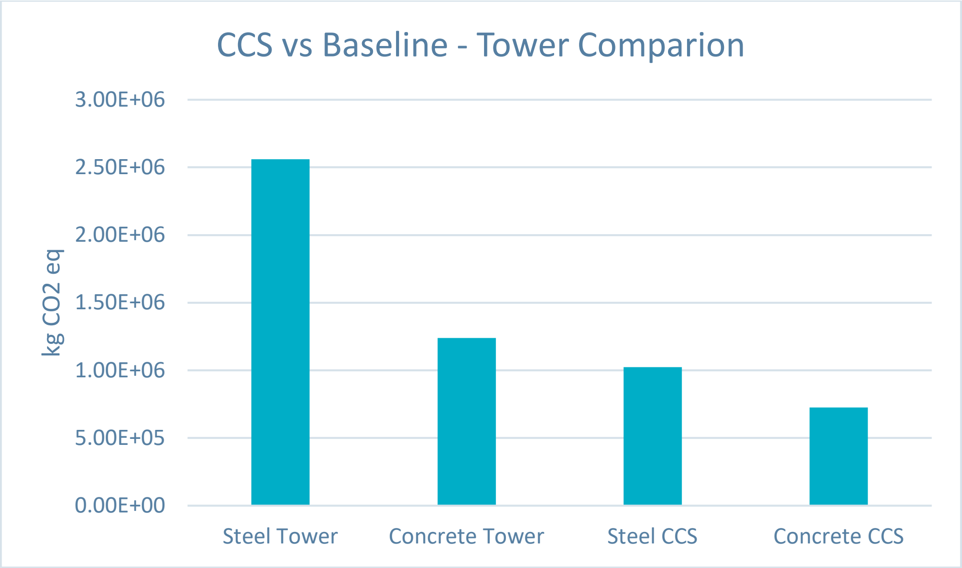

Figure 20: LCA result: carbon capture comparison

6.3.3 Discussion

As can be seen from the above charts there is a noticeable difference between both structures when directly comparing both structures, the concrete tower leads to a roughly 50% decrease in CO_2 emissions. These results line up well with the results produced by Gkantou et al [27] which show a similar % despite differing assumptions between the studies (Figure 21).

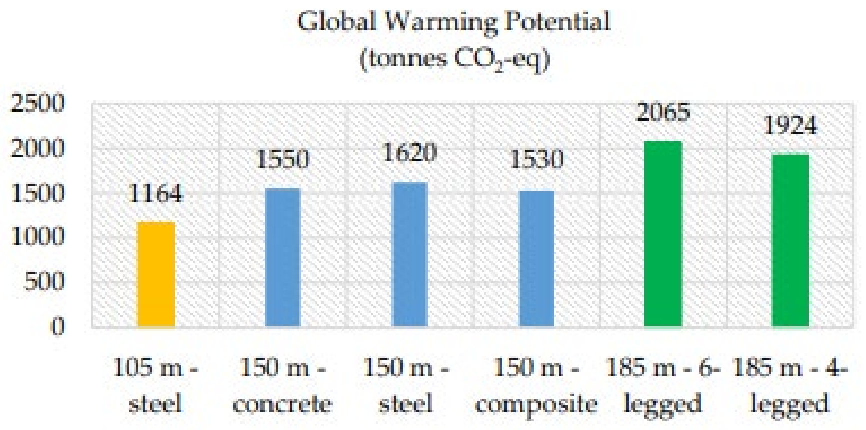

Figure 21: Gkantou LCA Results. Comparison between various tower designs. [27]

The key differences in this analysis are that concrete outperforms steel in terms of emission output but the difference between the two is greater in this study than in the one shown in the above figure. The steel tower in this analysis produced just over 2500 tonnes CO_2 eq per tower as opposed to 1620 above, this is largely down to the fact that more significant transport emissions were applied and that the steel tower used is heavier due to being designed for offshore deployment. The concrete structure on the other hand shows a reduced performance from 1240 in this analysis in comparison with Gkantou et al's study value of 1550. This is largely due to how that study included foundations (as it is an onshore turbine instead). The hybrid tower falls into a middle ground as expected with around 1840 tonnes of CO_2 eq per tower. Given the additional technical challenges that offshore concrete towers would need to overcome, a hybrid tower could be a useful middle ground.

Figure 18 highlights the potential improvements that may be made by using locally sourced content, the “no transport” scenario for a steel tower reduced emissions by around 21%. This difference had far less impact with concrete with only around a 2.4% as the concrete content is local and only the rebar requires it to be imported. The hybrid tower saw a roughly 6% emissions decrease for local content.

Low-carbon concrete is an area that is becoming more widely explored and will likely play a big role going forward, not only in the offshore industries but also the construction sector. Cement is the largest cause of concrete related emissions and almost all of these low-carbon alternatives seek to reduce or remove it entirely. DNV [28] carried out a breakdown of their exact concrete related emissions in Figure 22, again highlighting the key area of improvement for a concrete design. In a DNV study cement was worth around 52% of concrete specific emissions. However, depending on the choice of concrete (such as the more popular variants that rely more heavily on OPC) this percentage may increase further.

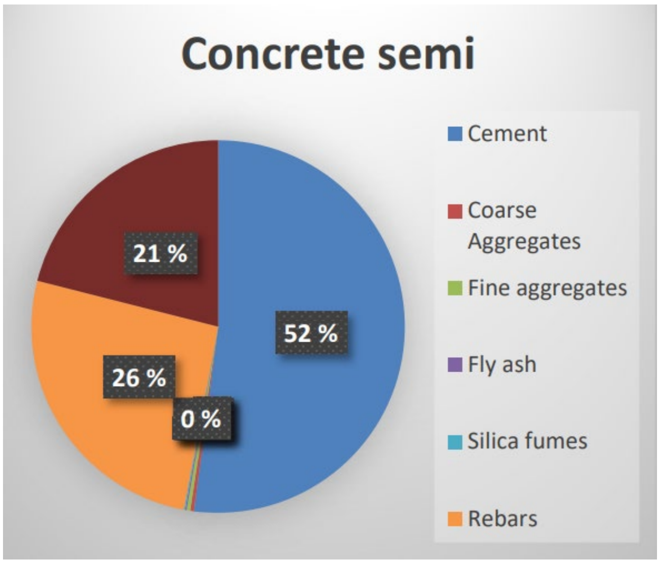

Figure 22:DNV LCA results: % of emissions breakdown for a concrete semi-sub [28]

Whilst the assumptions used for the low carbon content studies rely heavily on claims and estimated content percentages, there is clear potential for emissions reductions there with a potential 80% reduction when using specific mixtures. Given that specific geopolymer solutions use industrial waste materials as a direct input, there may be strong opportunities there to connect with other offshore sectors. That said, there is also a clear drive by the industry to push for low carbon concretes as companies like the National Composites Centre and Skanska have successfully demonstrated other low-carbon concrete solutions with large projects such as the M42 Highway project (ongoing) [33] and the construction of a concrete composite bridge [34].

Finally, assumptions for CCS were applied to analyse the impact of that type of technology, the analysis here showed around a 40% reduction of carbon emissions for a concrete structure and a far greater saving of 60% for steel structures.

6.3.4 New Concept Steel Structure

It is clear that whilst the core opportunities lie with manufacturing and material selection, there are further opportunities to better optimise the design of a steel tower. One such method could be by increasing the diameter of the tower and decreasing the overall thickness.

Table 16: Optimised Steel Tower Dimensions

Optimised Tower Design	
Tower Length (m)	129.5
Tower Mass (Tonnes)	640.32
Base Diameter (m)	14

As can be seen, the mass of such an optimised structure is around half of the reference tower and as a result, the LCA comparison between these structures shows a similar GHG saving (Figure 23). Whilst, more detailed design and technical feasibility work will need to be carried out to validate this new optimised design it is clear that there is significant potential here for reducing emissions.

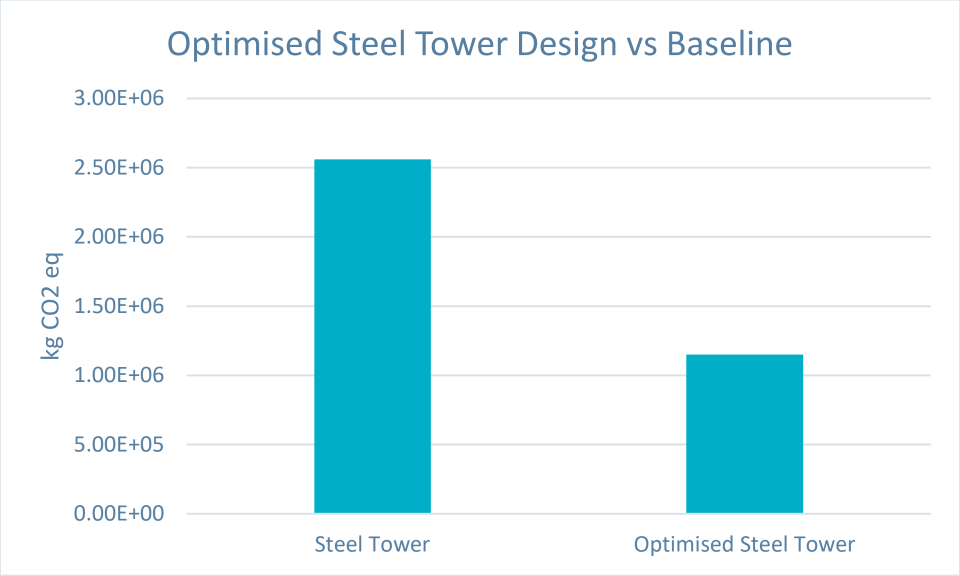

Figure 23: LCA result: Comparison between the baseline steel tower and the optimised tower

7 CARBON EMISSIONS REDUCTION OPPORTUNITIES SUMMARY

To summarise the above work, there are a wide number of improvements that could be made to reduce carbon emissions, these have been split into process, design and transport/O&M/ logistic improvements.

7.1 Process Improvements

7.1.1 Materials, reduce steel content and increase concrete content

From the above analysis it is clear that the materials play the biggest role in emissions. Currently, only two different materials have been used in structures across the industry. In terms of reducing emissions concrete has been shown to outperform steel so it should be more widely considered for these structures.

That is to say that these are the only two materials, there may be work in the near future that will make use of other materials. Composites, for example, may demonstrate high emissions reduction potential by reducing mass, reducing O&M requirements, providing local opportunities and increasing lifespan. Other metals and other materials may also make for viable candidates. Without a precise design and knowledge of specific manufacturing processes it would be very difficult to represent a new material accurately.

7.1.2 Reduce emissions during manufacturing

The specific refining and manufacturing processes for both steel and concrete components can be reduced. Both can make use of CCS to reduce emissions as demonstrated in this work.

For more specific changes, cutting down specific intensive processes or using alternative approaches would help cut down emissions further. A key highlighted example for steel is using an electric arc furnace or oxygen blast furnace as opposed to more traditional blast furnaces. Additionally, using recycled/scrap steel can greatly reduce emissions as it will help cut down transport emissions and cut down on those more intensive refining processes. Also using renewable energy, hydrogen and biofuels during these processes can also help reduce harmful emissions further.

BHP, an Australia mining and metals company provided a blueprint for manufacturing greener steel [33], effectively breaking down its processes into three stages:

- Optimisation (using renewables, recycling gases and using more scrap materials)
- Transition (using CCS, smelting reduction, using low carbon fuels, biomass and hydrogen during production)
- Green end state is the end state where steel is being manufactured at near or zero emissions due to the above transition periods. This can be achieved either through access to renewable technologies that are cost-competitive for deployment or through hydrogen-based steelmaking.

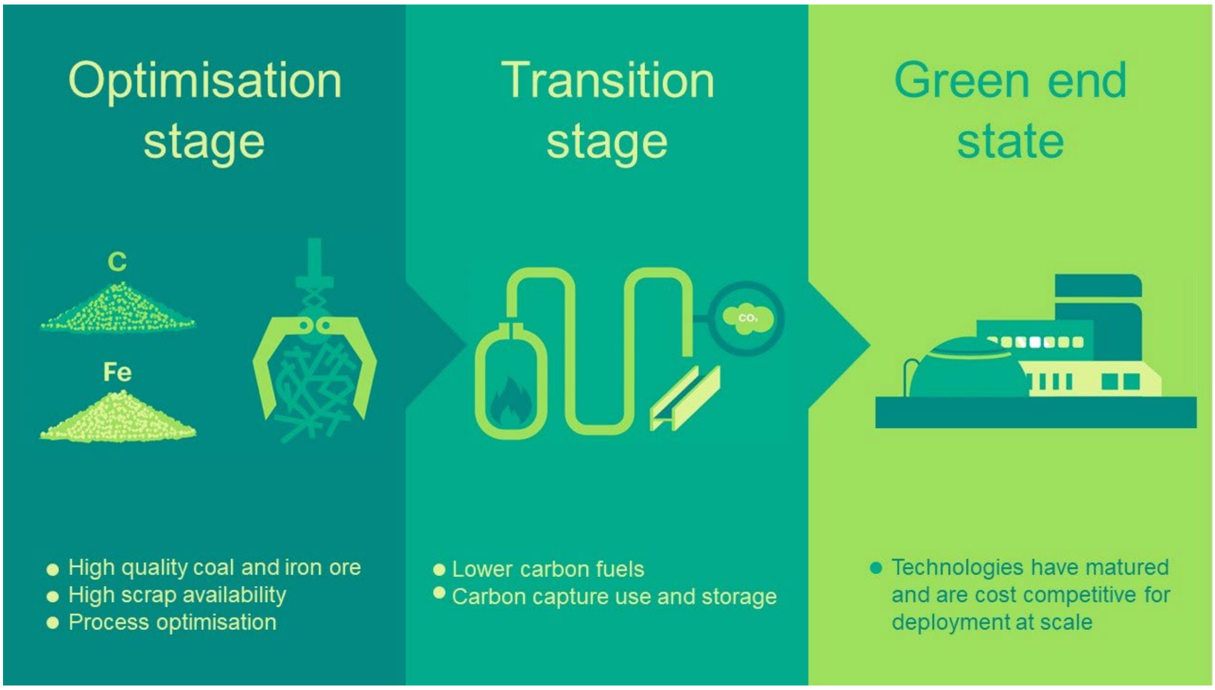

Figure 24: BHP's Steel Decarbonisation Framework [11]

This particular area isn't technically directly linked to the tower specific area but as this is the greatest source of emissions, sourcing materials from companies that are decarbonising their steel supply will play a big role in reducing their emissions.

For tower manufacturing specifically, following a similar framework as BHP could be applied here. Use a clean source of steel, apply CCS when necessary, use renewable electricity and hydrogen/biomass for fuels then the overall emissions there will be reduced as well.

From a concrete perspective, mapping specific points for improvement is a little bit more challenging as each concrete mix will utilise different processes. Creating clinker is seen as the most intensive process so using renewable sources throughout these processes will have a noticeable impact. Ultimately, though using a different concrete solution to replace the clinker entirely is the best solution here.

7.1.3 Low Carbon solutions

This was already heavily discussed in section 0 but as can be seen from Figure 19, these low-carbon solutions will be the main player when it comes to reducing emissions for any concrete structure. Couple these low-carbon solutions with "green" steel and that structure would then produce very low emissions overall. However, the investment will be required to push these low-carbon alternatives further and further testing will be required to assess feasibility.

7.2 Design Improvements

7.2.1 End-of-Life

Designing a structure to allow for easy decommissioning and recycling will aid the circular economy and reduce emissions from decommissioning. In this case, a steel structure will benefit more here due to improved recycling processes.

7.2.2 Optimised design

Improving and optimising structure designs will also be a key role. Reducing mass will reduce the materials with it along with accompanying emissions. Whilst, the design used in Table 16 is only a high-level design there are opportunities in that area that could play a role.

7.2.3 Increase structure lifespan

It stands to reason, that if structure life can be increased then the overall wind farm emissions will be reduced. Typically, turbines are designed for 20-25 lifespans. If this can be increased even further either by improving the design, efficient O&M practices and using higher quality materials. Longer-lasting turbines will require fewer replacement components and wind farms will be able to run longer keeping emissions lower.

7.3 Transport, O&M and Logistics Improvements

7.3.1 Local content

Keeping content as close to the local supply chain as possible is key as previously explored. Avoiding long-distance travel will aid local businesses, save money (see **Error! Reference source not found.**) and reduce emissions.

7.3.2 Green transport

The UK doesn't have much capacity in terms of manufacturing so long-distance travel is largely unavoidable. However, with up to 8% of global GHG emissions being caused by freight transportation [35] there is naturally a drive to reduce these. The key to reducing these emissions is by using battery/hydrogen-powered vehicles for land-based transport. Typically, larger modes of transport like freighters and planes are considered too large for current battery/ hydrogen technology. However, new concepts such as the Energy Observer 2 demonstration vessel [36] showcase a potential hydrogen-based future for large-scale marine transport. Ensuring that any and all imported goods take a greener route will reduce transport emissions. Additionally, a potential hydrogen-based vessel would also be useful from an O&M perspective.

Figure 25: The Energy Observer 2 [36]

7.3.3 Digital O&M

Improving and introducing more digital O&M technology will also reduce emissions. At the moment the exact impact is hard to quantify but through new areas such as digital twins and robotics, the need to send vessels and crew members offshore to inspect the towers in person will be reduced. Compared to material selection and manufacturing this would have a minor impact on emissions but is worth mentioning here.

8 CONCLUSIONS

8.1 Summary

As can be seen from the prior chapters, there is a tremendous amount of work required to generate a significant amount of CO_2 emissions reduction across the life cycle of a tower. However, this also means that there are many opportunities to do so.

The main opportunity lies within the main material choice, the LCA carried out here comes to the conclusion that using concrete leads to lower emissions both in terms of manufacturing processes and in terms of transportation. These emissions could see a further significant reduction through newer low-carbon concretes that are beginning to emerge both in industry and academia.

That is not to say that concrete is a perfect all-around choice either with performance and mass a key concern. However, a hybrid design could be used to mitigate those points. Whilst more experimental material choices may yet have a role to play (composites, low carbon concrete as an example).

Specific aspects of the manufacturing processes could be improved directly to reduce emissions and waste products. For example, using an electric arc furnace as opposed to a blast furnace during steel production will lead to less CO_2 and other waste products. As demonstrated in this work, CCS could play a significant role in decarbonising manufacturing processes going forward although establishing the exact impact is challenging.

Local content will also play a large role for the future of emissions reduction, earlier it was noted that a significant amount of emissions could be saved by cutting the shipping process. Whilst this impact may not be completely accurate, it cannot be denied that a large number of GHGs may be reduced across the offshore wind sector if there was more scope for local manufacturing. This would require a massive amount of investment but may lead to being beneficial from an economic perspective although further cost analysis-related work would be required to fully demonstrate that. To add to this further, O&M work can add emissions through regular turbine inspections, introducing “greener” vessels when necessary and incorporating more digital O&M technologies to reduce the need for physical visits would all contribute towards lowering emissions.

Improved optimisation or design work could be used to further curb emissions, it goes without saying but a structure that uses fewer materials will produce fewer emissions. Whilst this might seem like an unrealistic ambition but there are many examples across the industry of various core components being redesigned and improved on (lighter blades, lighter drivetrain, alternative materials). Such redesigns would lead to a lighter turbine that would lead to reduced emissions.

Typically, a wind turbine is designed to last between 20 – 25 years. Naturally, finding ways to extend the life of a turbine would help reduce manufacturing demand significantly. Previously mentioned areas such as improved digital O&M technologies, more advanced materials and improved structural designs would all contribute towards extending the lives of these structures.

The Celtic Sea and Cornwall area possesses a lot of potential for offshore floating wind turbines. The region has strong connections to concrete production and by UK standards the steel industry also. One final non-technical area to flag with regards to future developments is ensuring that the future workforce is a diverse and inclusive one. Having a strong diverse workforce will allow encourage new ideas, ensure low staff turnover, improve industrial and international connections going forward.

8.2 Future Work

This study has covered a wide array of points regarding wind turbine towers but there have been assumptions and limitations that may allow for further projects going forward. Additionally, there were other areas that lay out with the scope of this work that may be worth studying in the near future.

- A deeper dive into the precise aspects of the manufacturing processes (would require collaboration with manufacturers or developers)
- A more advanced design of the structures examined here (can look at exact materials, minor components, construction requirements, etc. This would provide a far more detailed view of both emissions, costings and technical performance
- Testing and validation of low-carbon concrete solutions
- Testing and validation of composite solutions

- Testing and validation of optimised steel solutions
- A more developed plan for a portside facility (would require collaboration with ports)
- Cost or economic analysis for a structure, facility, or a wind farm
- Explore other more experimental materials (such as composites) at a high level to assess technical feasibility
- Further develop LCA with further data on steel processes, concrete compositions, O&M, integration and exact manufacturing processes for a more detailed breakdown

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