Cornwall FLOW Accelerator

WP4 – D3.1. REDUCING CARBON FOOTPRINT OF FLOATING FOUNDATION MANUFACTURING – LITERATURE REVIEW

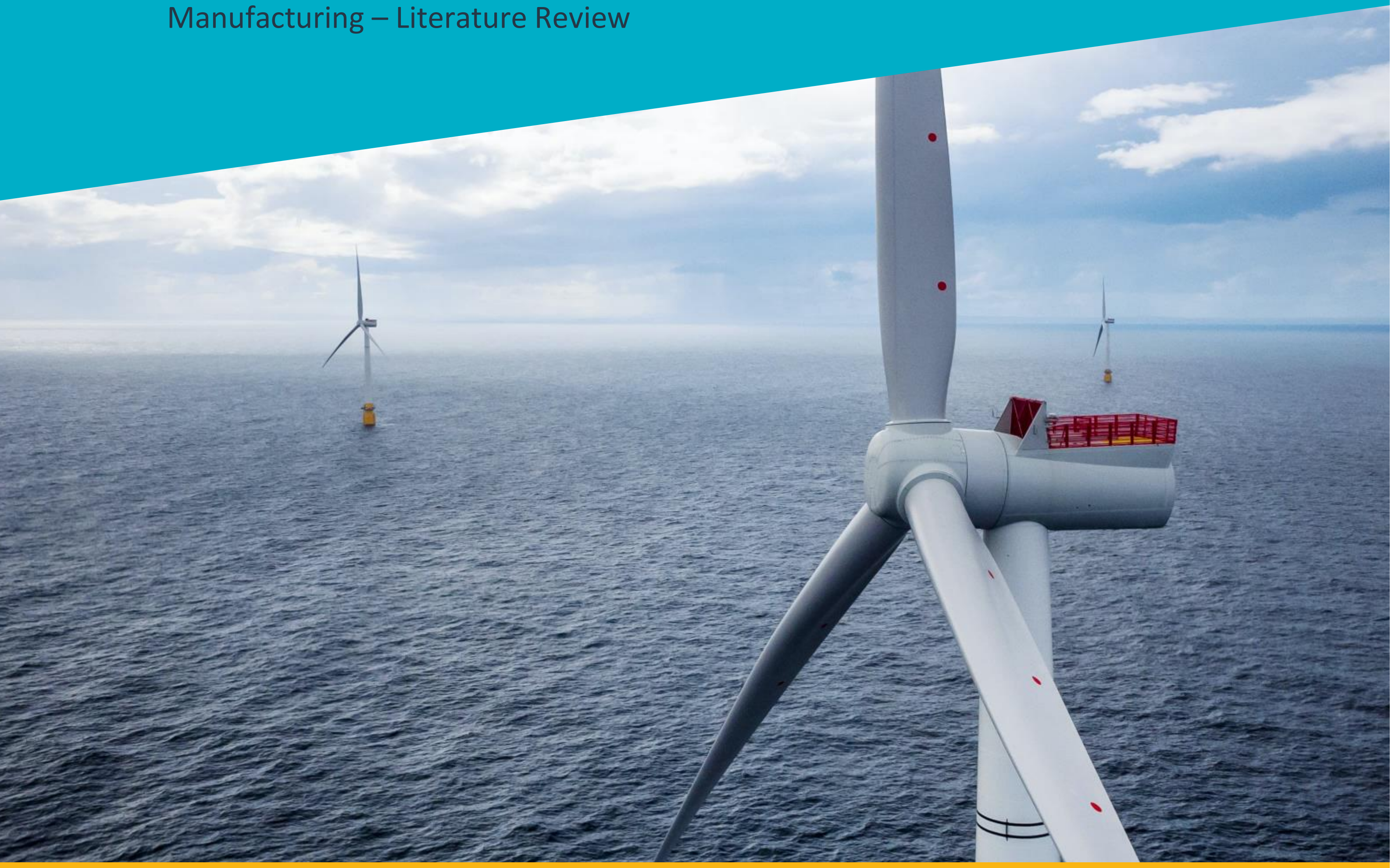
Document Title		WP4 – D3.1. REDUCING CARBON FOOTPRINT OF FLOATING FOUNDATION MANUFACTURING – LITERATURE REVIEW	
Document Reference		CFAR-OC-019-31032022	
Date of Issue		31/03/2022	
Author		Dylan Duncan	
Revision History	**Date**	**Amended by**	**Reviewed By**
First Draft	-		
Second Draft	-		
First Issue	31/03/2022		Hyunjoo Lee
Rev 1			
Rev 2			
Rev 3			
Rev 4			

HM Government

European Union
European Regional Development Fund

CORNWALL ERDF PRIORITY AXIS 4 LOW CARBON FLOW

TASK 3: Reducing Carbon Footprint of Floating Foundation Manufacturing – Literature Review



GENERIC REPORT

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Date: 31/03/2022

In partnership with:

DOCUMENT HISTORY

Revision	Date	Prepared by	Checked by	Approved by	Revision history
1	31/03/2022	Dylan Duncan	Wooyong Song	Hyunjoo Lee	1

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Introduction

As the demand in offshore wind turbines increases so to does the demand for materials and manufacturing. One of the largest and perhaps least researched components within a wind turbine is the floating foundation. Various studies have shown that the majority of CO_2 emissions produced by offshore wind occur during manufacturing so it stands to reason that establishing how to reduce emissions during the floater manufacturing process will be critical going forward.

Additionally, there is now a key industrial drive to develop more manufacturing/ assembly factories within the UK. Particularly in Cornwall where the number of offshore renewable energy projects is greatly increasing.

This literature review will examine the current state-of-the-art materials that are used in the FOWT floaters, alternative materials, alternative structures and improved manufacturing processes. This is to identify areas of potential interest for future development.

Finally, a summary will be produced to assess the GHG emissions of the current and new materials/ processes based on prior findings.

Literature Review Structure and Scope

The literature review will consist of four chapters:

1) Materials
2) Wind Turbine Floater Structures
3) Manufacturing Processes
4) Overall Summary

The first section will cover the materials, initially covering what is typically used and the primary characteristics of these materials. Afterwards alternative materials that have been raised either in industry or academia will be examined and compared. The comparison should provide an effective indicator as to whether or not new materials should be prioritised with the transition.

Next, the type of structures that are used for wind turbine floaters will be identified, this is to see what difference in material usage and general characteristics exist between each structure type. Alternative structures may serve as a better change to make over changing materials so this section will aim to see which foundation type produces the least CO_2 emissions.

Manufacturing is where the majority of emissions occur during an offshore wind turbine's lifecycle. So, a significant part of this literature review will review various methods or alternative processes that can be used to greatly reduce emissions.

Finally, once the materials, structures and manufacturing processes have been identified a summary will be produced for the purposes of emission comparison.

Materials

Floater Industry Standard Materials

Floating wind is still very new in the wider scheme of wind energy. As a result of this, there is a noticeable lack of direct research into aspects into material research components within a wind turbine assembly. Additionally, there has been no research into areas such as how much emissions have been generated by each type of floater.

There hasn't been a type of floater that has been identified as "industry standard" however, almost every type of floater that is under development is constructed using either steel, concrete or a hybrid of the two. Low carbon, structural steel is the main choice of steel, in prior work, S355 structural steel was identified as being a popular choice for steel across all wind turbine components. Several properties of which can be seen in Table 1 and Table 2.

Table 1: Properties of S355 structural steel

S355 Steel	Unit
Density	7850 kg/m3
Yield Strength (depending on diameter)	275 - 355 MPa
Tensile Strength (depending on diameter)	450 - 680 MPa
Young's Modulus	190 – 210 GPa

Table 2: Properties of concrete.[1]

Concrete	
Young's Modulus (concrete aga of 28 days)	44.4 GPa
Compressive Strength	80 MPa
Poisson's Ratio	0.2
Fracture Energy	163.4 N/m

Ultimately, the direct material properties are not the primary focus of this report, but it is useful for assessing aspects such as the floater's ability to withstand loads and general environmental conditions. Even if there are materials that produce reduced emissions, if their properties are substantially lower then it stands to reason that they may not last as long and as a result, the overall lifetime emissions may increase.

The CO_2 emissions per kg that are produced by S355 steel and concrete have been taken from the life cycle inventory database, ecoinvent [2].

Table 3:Material CO2 emissions.[2]

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
Concrete (Cable Mat)	market for concrete block	Rest of World	per kg	0.15729

The majority of a wind turbine (tower, drivetrain, rotor, etc) is usually manufactured from this steel and as suspected, steel is what makes up the majority of emissions, see Figure 1.

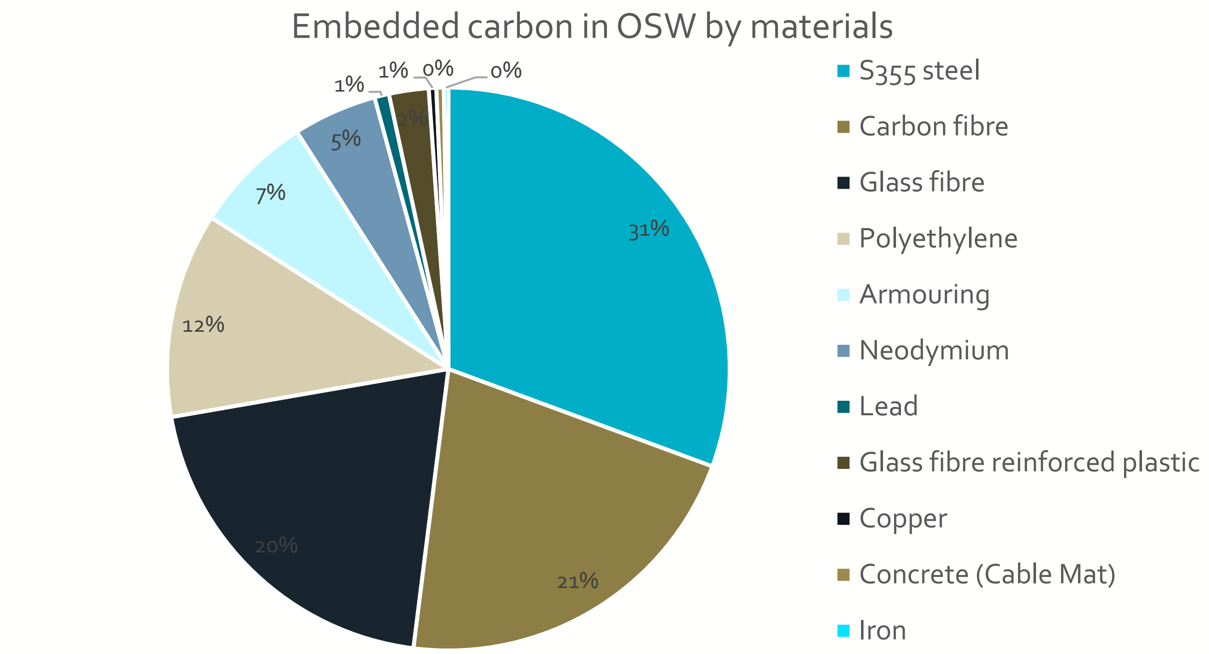

Figure 1: Embedded carbon in offshore wind turbines by materials

Just over 30% of the embedded carbon within a wind turbine comes from steel, which indicates the need for looking at alternative “Greener” materials. It is, however, worth mentioning that steel can be widely recycled and whilst the initial emission cost of manufacturing is quite high, the ability to reuse and rebuild using the same materials is a considerable advantage. In fact, analysis has shown that recycling can save up to 35% of carbon emissions [3]. This ability to reuse the material will reduce the need to extract more materials and it may also provide the advantage of being able to set up more local facilities that can offer recycling services.

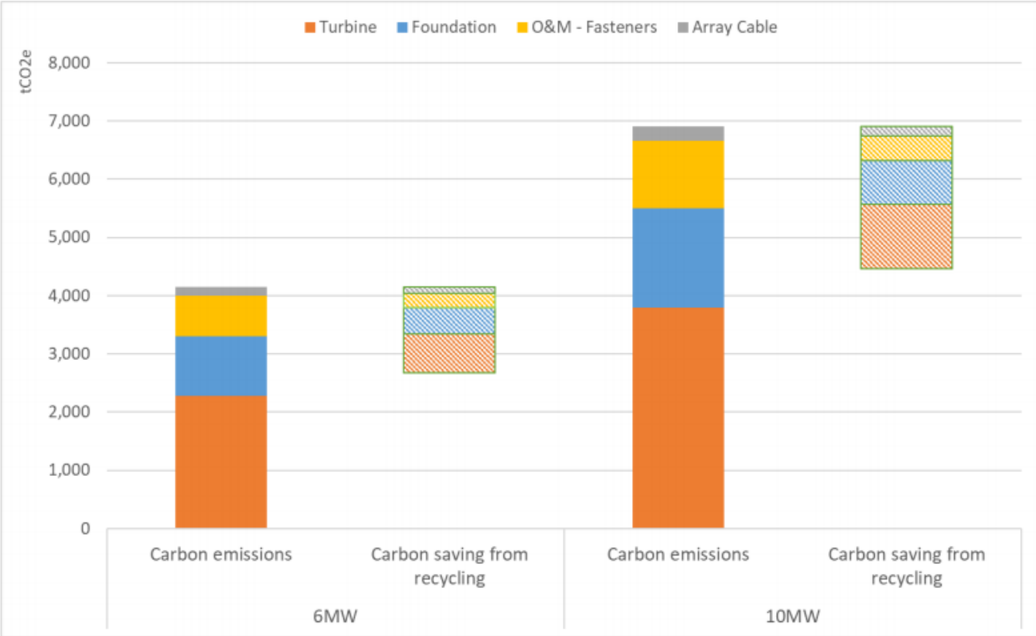

Figure 2: Emissions and savings when recycling windfarm components. [3]

Figure 2 shows roughly how much the foundations of a wind turbine can contribute towards the overall CO_2 emissions caused by the development of a complete wind turbine (around 20%). Whilst this figure isn't necessarily applicable to floating wind, it does highlight the need to identify ways of reducing these emissions.

Alternative Materials

Selecting the materials for a wind turbine floater is incredibly important for a number of reasons. It needs to be able to support the mass of the turbine whilst withstanding heavy loads caused by the waves and wind. They need to be able to function within a range of depths and be stable throughout. Currently, only steel and concrete have been used for floating wind but there may be appetite in the future for expanding this further.

One core advantage of a number of floating structures is that they can be manufactured using processes that are already used in the creation of other components such as the tower. Whilst there is little research on floating structure materials, there have has been research on the tower, which for the time being could be used to provide a rough idea as to what materials could be used in future floater applications. Rashedi et al [4] carried out a multiobjective material selection for a wind turbine tower. This study aimed to look at material selection for small- and large-scale horizontal wind turbines for both onshore and offshore applications. The selection was carried out via a "compound objective-based design optimisation procedure". In this case, the authors prioritised aspects such as mass, fatigue limit, fracture toughness and CO_2 footprint.

The results of this analysis produced several logarithmic plots that looked at several aspects. Figures 5, 6 and 7 examine materials based on their carbon footprints, embedded energy and price per density respectively.

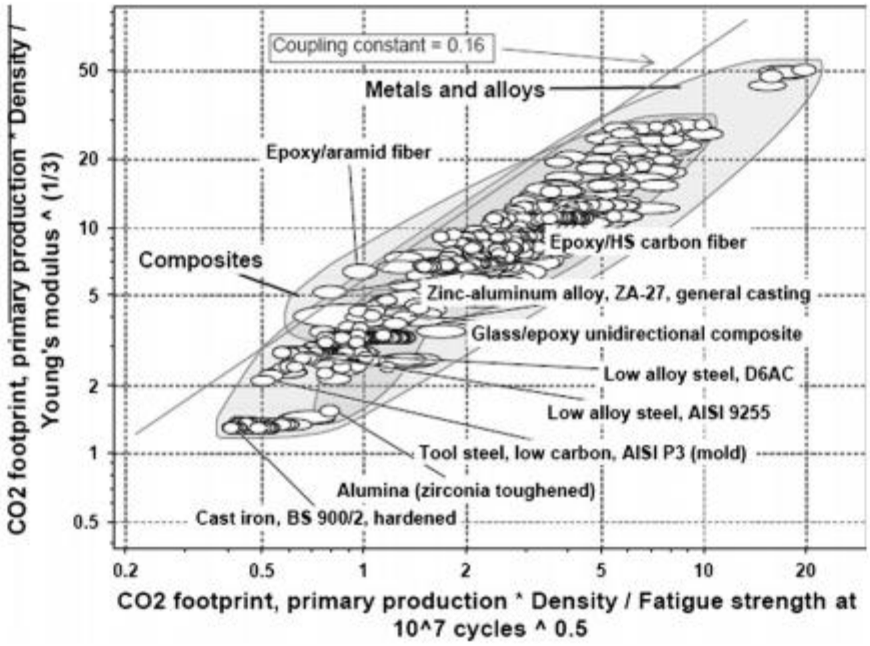

Figure 3: Material index on buckling against material index on bending (for carbon footprint). [4]

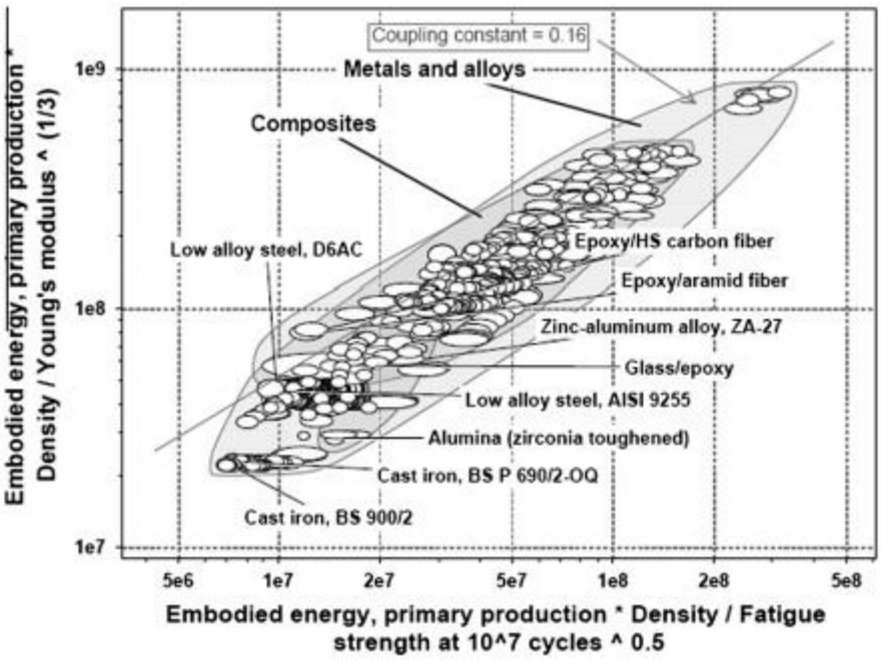

Figure 4: Material index on buckling against material index on bending (for embodied energy). [4]

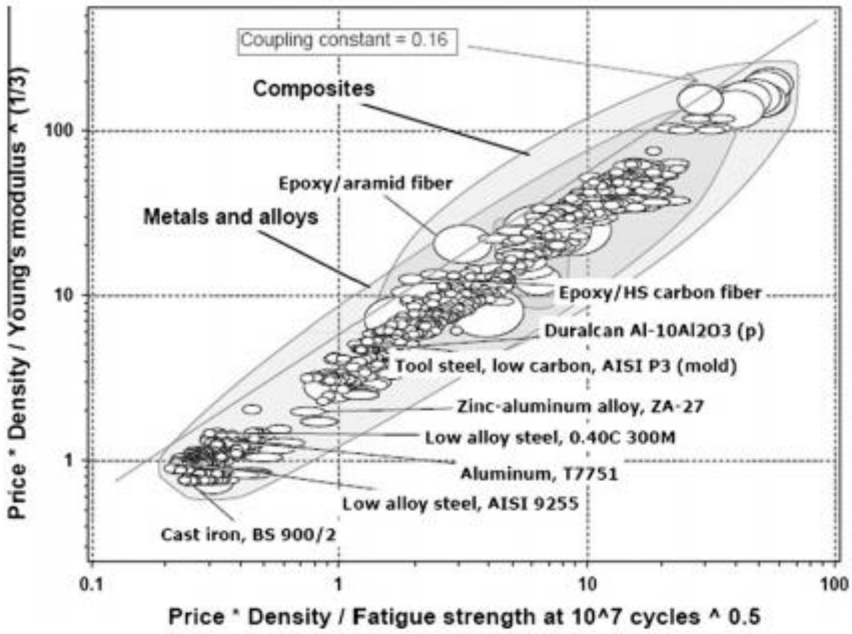

Figure 5: Material index on buckling against material index on bending (for cost). [4]

A review of these graphs provides some very useful findings in terms of identifying potential materials. With regards to general material properties per density, composites outperform other material types, indicating a reduction in mass. In Figure 3, cast iron and various types of steel outperform others with regards to reducing carbon footprint, Epoxy/HS carbon fibre which is the best performing composite in terms of carbon footprint is still significantly higher than that of these metals. In terms of embedded energy, Figure 4 (the energy consumption per kg of production), Cast iron and steel once again outperform other material types. In terms of costings, metals naturally outperform composites with cast iron, once again performing the best.

The authors also compared different material indices with bending and buckling constraints. Here epoxy/ HS carbon fibre composites performed the best of the set materials, a cast iron based nodular graphite alloy BS 900/2 also performed very well but would produce a significantly heavier design. BS 900/2 experiences significant improvements over mass, carbon footprint, embodied energy and cost reduction. Th epoxy/ HS carbon fibre composite provides greater weight savings with an appropriate level of carbon footprint and embedded emissions reductions but comes at a far higher cost.

Jaksic et al [5] continued this research trend by examining the feasibility of using composite materials for a new offshore wind turbine tower design. Unlike the prior study, the emphasis here was on costs and weight. Two composite towers were chosen, both which used an E-glass/ epoxy composite, the main difference between the two is that one used carbon fibre plies in a different direction.

They observed several significant differences with regards to weight for both towers which saved more than 60% of mass. To assess the commercial feasibility of using these materials, the weight and the strength of materials were established. The weight reductions that were calculated, highlights the potential for significant cost savings due to transportation, maintenance and installation. However, this study did not provide more detailed analysis on costings, nor did it look at the environmental impact of using these materials. These aspects could make for useful future studies. That said, it still provides a good example of how a material change could positively impact the wind turbine tower and may highlight potential avenues that may be exploited with regards to floating foundation development.

A separate study by Stavridou et al [6], looked at a comparative life-cycle analysis of onshore steel wind turbine towers. This particular report focused mainly on quantifying the emissions produced during the wind turbine's lifetime and how they can best be reduced. A significant part of the report looked at aspects such as alternative tower structures, but alternative materials were also explored. Again, recycling was raised as a crucial part of analysing the environmental impact of a wind turbine tower, Table 4 showcases the scenarios for how different materials are handled at the end of their respective design life.

Table 4: Recycling scenarios.[6]

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%
Plastic	Incinerated 100%
Stainless Steel	Recycling with 10% loss

These end-of-life scenarios were used in the author's life-cycle-assessment but didn't make a huge impact on calculating the impact of a tower. The key finding from the report, was that the manufacturing makes the most significant impact and the keyway to reducing the impact is by using less material overall. It stands to reason then, that new materials could make an impact if the overall mass of the turbine is reduced but perhaps more importantly, changing the physical structure and the manufacturing processes will likely make a larger overall impact.

That said, it is hard to gauge the overall impact of changing the materials. It has been identified that composites would lead to a lighter tower, indicating that less material will be required but they require more energy during manufacturing, cost more and cannot be recycled. Carrying out a LCA would be very useful for determining the actual difference that changing the materials would have on reducing the emissions whilst keeping costs low and structural strength high.

These studies aren't related to floating foundations specifically but given that both are made using similar processes, using similar materials and undergo similar experiences with aspects like transportation there are key lessons that may be applied here. For example, minimising weight would lead to less materials and therefore reduced emissions. Extra elements such as examining different types of floaters will also be critical as different structures will each require different amount of materials. Finally, taking recycling into account will also be incredibly important as reusing materials will play a key role in reducing manufacturing requirements and general material demand.

Wind Turbine Floater Structures

Installing Offshore wind turbines is an immense task that requires a significant work to assess which one is the best for the given environment. There are a lot of parameters to consider, water depth, seabed, sea conditions, wind conditions, size of turbine, etc.

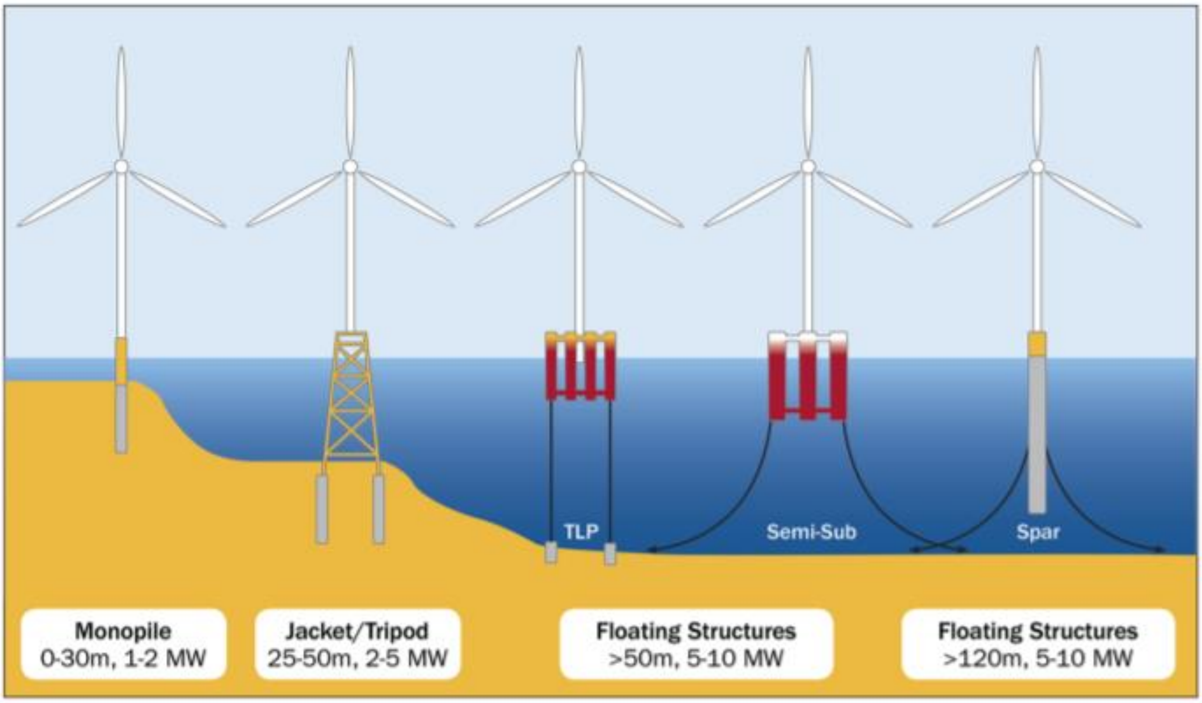

Figure 6: Types of Offshore Wind Foundations. [1] Van Zyl, W. S. (2014). *Concrete Wind Turbine Towers in Southern Africa* [Master's thesis]. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.949.5366&rep=rep1&type=pdf

[2] ecoinvent. (2021). *ecoinvent database*. https://www.ecoinvent.org/

[3] Spyroudi, A. (2021, April). *Carbon Footprint of Offshore Wind Components*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2021/04/Carbon-footprint-of-offshore-wind-farm-components_FINAL_AS-3.pdf

[4] Rashedi, A., Sridhar, I., & Tseng, K. (2012). Multi-objective material selection for wind turbine blade and tower: Ashby's approach. *Materials & Design*, *37*, 521-532.

[5] Jaksic, V., & O'Bradaigh, C. (2018, April). Design of Offshore Wind Turbine Tower Using Composite Materials [Paper presentation]. Civil Engineering Research in Ireland (CERI2018), Dublin, Ireland.

[6] Stavridou, N., Koltsakis, E., & Baniotopoulos, C. C. (2019). A comparative life-cycle analysis of tall onshore steel wind-turbine towers. Clean Energy, 4(1), 48-57.

[7]

Figure 6 shows the primary types of wind turbine structures. They are split into two main categories fixed and floating. Fixed wind turbines will use either monopile or jacket foundations that are fixed directly to the seabed, these are typically used in shallower waters. Floating wind structures on the other hand use foundations that float and are fixed in placed via anchoring/ mooring technology, this is ideal for deeper waters where a fixed foundation would otherwise be impractical. For this report, fixed structures will not be considered. It is worth noting that the foundations shown in the above figure do not show all the types of floating wind structures and other types such as barges and semi-spars will also be considered.

Ultimately, offshore wind as an industry is beginning to rapidly grow and with that, the demand for deploying floating foundations will also increase. Identifying the structure that will produce the least amount of green house gas (GHG) emissions will go a long way to ensuring that the global amount of emissions produced by this new wave of offshore technology is minimised.

It is also worth noting that it is not just the structures that may be responsible for the bulk of emissions, floating technology has been evolving rapidly with new designs being deployed by new renewable firms across the world. Each new design will use different materials, employ different manufacturing processes and will take into account different design considerations (such as loads and being built to last varying amounts of time). Each of these aspects will need to be considered in this chapter but specific information such as materials or manufacturing processes will be explored in later chapters.

Spar Structure

One interesting concept for floating offshore wind turbines is the spar system. This is one of the better understood concepts with several technical research studies and real-life examples of the technology in use across the world. Each spar system will vary between designs, but one example can be seen below.

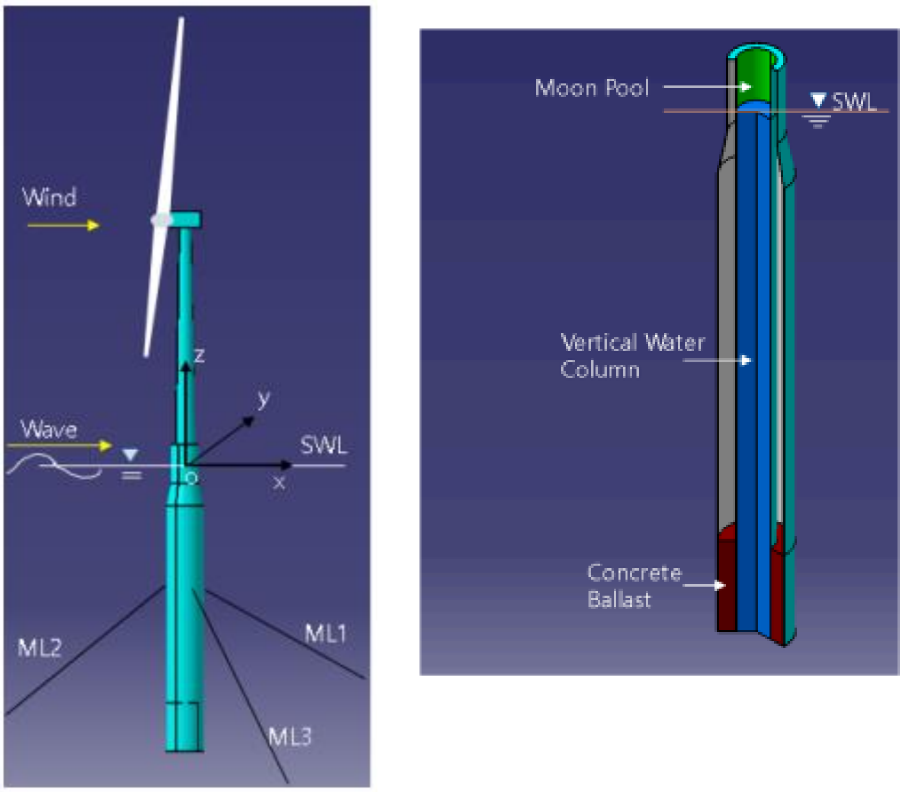

Figure 7: Spar concept diagrams. Left: Overview of complete spar floating system. Right: Spar system with moonpool. [8]

This example is of a catenary moored spar system with three mooring lines that can attach around the spars circumference and a moonpool. These mooring lines allows the wind turbine to remain stationary against the surge and sway of the environment. The moonpool allows seawater to be freely displaced. The ballast was chosen to be concrete to improve stability.

One key advantage of using this technology is that they are designed to be similar to the steel towers ensuring that manufacturing processes can be kept similar throughout. One live example of a spar floating offshore wind turbine (FOWT) is the TetraSpar project [9] which uses a unique tetrahedral structure instead and is currently deployed at the Marine Energy Test Centre in Norway. It boasts an efficient manufacturing process, low material costs and easy installation.

Table 5: Summary of Spar parameters.

Turbine Capacity	Material	Ideal Water Depth (m)
5–10MW (TetraSpar is installed with 3.6MW) [1**] Van Zyl, W. S. (2014). *Concrete Wind Turbine Towers in Southern Africa*** [Master's **thesis]. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.949.5366&rep=rep1&type=pdf** **[2] ecoinvent. (2021). *ecoinvent database*. https://www.ecoinvent.org/** **[3] Spyroudi, A. (2021, April). *Carbon Footprint of Offshore Wind Components*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2021/04/Carbon-footprint-of-offshore-wind-farm-components_FINAL_AS-3.pdf** **[4] Rashedi, A., Sridhar, I., & Tseng, K. (2012). Multi-objective material selection for wind turbine blade and tower: Ashby's approach. *Materials & Design*, *37*, 521-532.** **[5] Jaksic, V., & O'Bradaigh, C. (2018, April). Design of Offshore Wind Turbine Tower Using Composite Materials [Paper presentation]. Civil Engineering Research in Ireland (CERI2018), Dublin, Ireland.** **[6] Stavridou, N., Koltsakis, E., & Baniotopoulos, C. C. (2019). A comparative life-cycle analysis of tall onshore steel wind-turbine towers. Clean Energy, 4(1), 48-57.** **[7**], [9]	Steel. May also use concrete [8], [9]	100-1000 [9]

Figure 8: TetraSpar being towed to its new location. [9]

Semi-Submersible

Another more common example of FOWT technology is the semi-submersible floating platform. These configurations can be of differing shapes and sizes but traditionally is made up of a central column or section that the tower is fixed to, this then connects to several pontoons that help support the wind turbine below the water surface. Again, similarly to the Spar concept, this semi-submersible configuration is fixed in place via a mooring system (usually a catenary system).

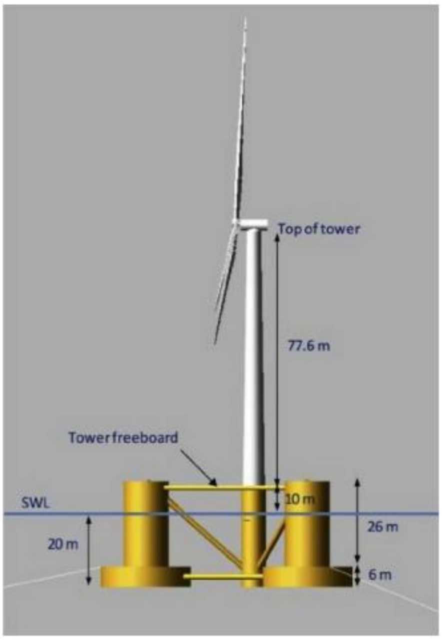

Figure 9: Diagram of a semi-submersible FOWT concept. [10]

One recent example of a semi-submersible wind turbine is the WindFloat project [11]. It makes clever use of “water trap plates” which are at the bottom of three pillars which helps the system’s stability. The system can be built entirely onshore helping to streamline the installation process. The system has been deployed in various locations and in offshore wind farms such as the Kincardine Offshore Wind farm.

Table 6: Summary of semi-submersible parameters.

Turbine Capacity	**Material**	**Ideal Water Depth (m)**
5–10MW (TetraSpar is installed with 8.4MW) [1**] Van Zyl, W. S. (2014).** ***Concrete Wind Turbine Towers in Southern Africa*** **[**Master's **thesis]. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.949.5366&rep=rep1&type=pdf** **[2] ecoinvent. (2021).** ***ecoinvent database*****. https://www.ecoinvent.org/** **[3] Spyroudi, A. (2021, April).** ***Carbon Footprint of Offshore Wind Components*****. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2021/04/Carbon-footprint-of-offshore-wind-farm-components_FINAL_AS-3.pdf** **[4] Rashedi, A., Sridhar, I., & Tseng, K. (2012). Multi-objective material selection for wind turbine blade and tower: Ashby’s approach.** ***Materials & Design*****,** ***37*****, 521-532.** **[5] Jaksic, V., & O'Bradaigh, C. (2018, April). Design of Offshore Wind Turbine Tower Using Composite Materials [Paper presentation]. Civil Engineering Research in Ireland (CERI2018), Dublin, Ireland.** **[6] Stavridou, N., Koltsakis, E., & Baniotopoulos, C. C. (2019). A comparative life-cycle analysis of tall onshore steel wind-turbine towers. Clean Energy, 4(1), 48-57.** **[7**],[11]	Steel, concrete or hybrid [11],[12]	>50 [7]

Figure 10: Windfloat installation. [11]

Tension Leg Platform (TLP)

TLPs are often used in various offshore applications such as oil rigs naturally, this makes the TLP concept a fairly popular choice for FOWTs. The TLP concept consists of a buoyant platform that offsets the mass of the wind turbine, the tension leg mooring system keeps the turbine in place by allowing for horizontal movement but halting vertical movement.

Bachynski and Moan [] analysed the design considerations for developing TLP FOWT. They state that costs will line up with increasing displacement and pretension, therefore when developing TLPs the primary target should be achieving optimal performance with as low of a displacement and pretension as possible. They noted that the TLP system was more dependent on natural period and stiffness changes as opposed to diameter and water depth.

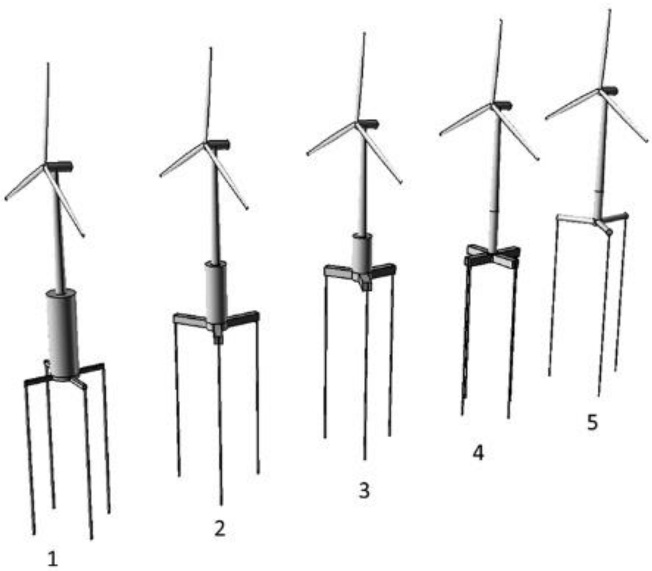

Figure 11: Selection of TLP designs. [13]

One such example of a TLP wind turbine is TLPWIND which is run by Iberdrola. Their design consists of a steel platform with four arms, each of which has two tensioned mooring lines attached. This design is focused on 5MW platforms that are designed with Northeast Scotland's coast in mind. A collaboration project with ORE Catapult, University of Strathclyde and Iberdrola [14] has demonstrated that this technology would be very effective in this environment. It can adapt to variable site conditions whilst being lightweight, possesses simple geometry which lends to more straight forward manufacturing and is cost competitive.

Table 7: Summary of TLP parameters.

Turbine Capacity	Material	Ideal Water Depth (m)
5–10MW (TLPWIND was designed with 5MW in mind) [1**] Van Zyl, W. S. (2014). *Concrete Wind Turbine Towers in Southern Africa* [Master's thesis]. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.949.5366&rep=rep1&type=pdf** **[2] ecoinvent. (2021). *ecoinvent database*. https://www.ecoinvent.org/** **[3] Spyroudi, A. (2021, April). *Carbon Footprint of Offshore Wind Components*. ORE Catapult. https://ore.catapult.org.uk/wp-content/uploads/2021/04/Carbon-footprint-of-offshore-wind-farm-components_FINAL_AS-3.pdf** **[4] Rashedi, A., Sridhar, I., & Tseng, K. (2012). Multi-objective material selection for wind turbine blade and tower: Ashby's approach. *Materials & Design*, *37*, 521-532.** **[5] Jaksic, V., & O'Bradaigh, C. (2018, April). Design of Offshore Wind Turbine Tower Using Composite Materials [Paper presentation]. Civil Engineering Research in Ireland (CERI2018), Dublin, Ireland.** **[6] Stavridou, N., Koltsakis, E., & Baniotopoulos, C. C. (2019). A comparative life-cycle analysis of tall onshore steel wind-turbine towers. Clean Energy, 4(1), 48-57.** **[7**],[14]	Steel or hybrid	>50 [7], [14]

Barge

A barge floater bears a strong resemblance to that of a semi-submersible, but it differs in the sense that semi-submersible uses distributed buoyancy and is made up of columns whilst a barge uses a flat surface. At the time of writing there are not many active barge concepts however, there are a few in active operation.

BW Ideol uses a barge design with a central moonpool which helps the system maintain stability with a system of 6 nylon mooring lines that help keep it fixed in place. Their first platform the Floatgen [15], has produced 12.8GWh over a two-year period (record in February 2020) and was demonstrated to be able to handle rough conditions. In more recent years they have begun larger scale projects with an aim of installing a 10MW turbine. It is primarily constructed of concrete. Figure 12 shows an image of the barge concept and Table 8 highlights some of the key parameters.

Figure 12: BW Ideol Floatgen Barge Floater. [15]

Table 8: Summary of Barge parameters (Using BW Ideol system).

Turbine Capacity	Material	Ideal Water Depth (m)
2–10MW (BW Ideol currently developing 10MW system) [15]	Concrete, hybrid, may use some steel. [15]	30 – 100m [15]

Semi-Spar

The semi-spar is a highly conceptional design that is still in its early days but may well have high potential in future floating wind farms. Essentially, the idea combines the advantages from both semi-submersible and spar concepts to produce an efficient system. There are not many developers of this kind of technology, one example has been developed by ACS Cobra [16]. Their platform uses a central cylinder that helps provide “structural continuity to the tower” and three cylinders around it which help provide stability during operation, these cylinders are connected to the central column via pontoons. Their systems possess as ballasting system which should minimise the tilting angle caused by the wind thereby increasing energy production. Their system is made with entirely out of concrete. It’s core advantages regarding ease of manufacture and installation has helped it gain recognition for potential use in projects such as the Kincardine offshore wind farm project [17].

Table 9: Summary of Semi-Spar parameters (using ACS Cobra system).

Turbine Capacity	Material	Ideal Water Depth (m)
At least 6MW [16]	Concrete [16]	>50-60m [16]

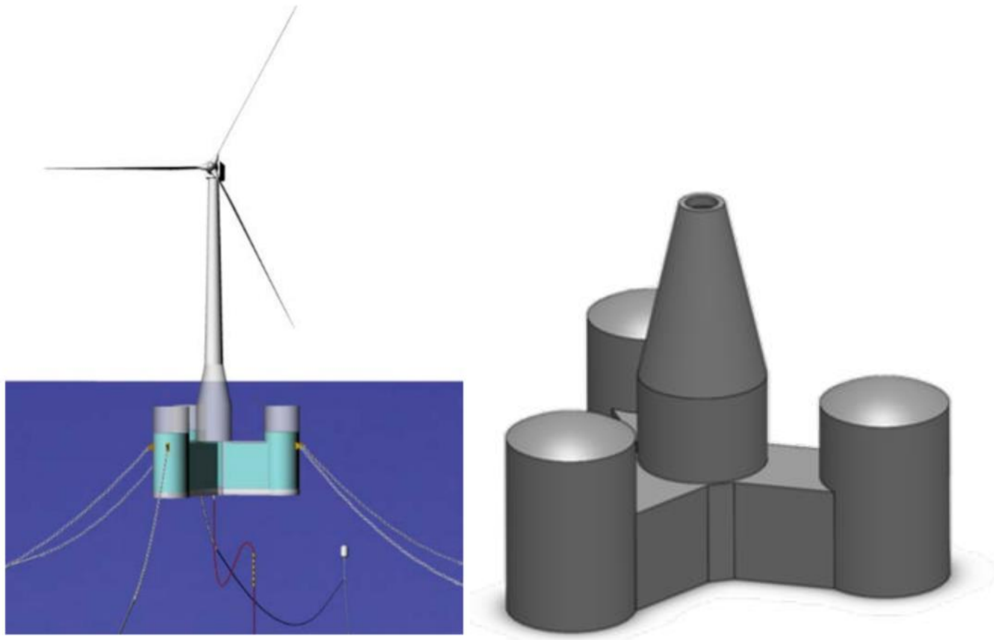

Figure 13: Left: Model of complete turbine with mooring lines. Right: Model of the semi-spar system. [16]

Other Designs

The lack of an industry standard solution for floating wind lends itself well to very experimental designs that haven't quite reached the same level of usage or support as the prior designs. One highly conceptual yet interesting design is the trivane [18]. This operates as a trimaran that "weathervanes around the turret mooring and can carry a singular turbine" This design possesses a number of potential features that may prove highly advantageous in the future such as high stability, straight forward construction and large deck space which may be used for other technologies such as batteries.

Figure 14: A model of the trivane turbine support structure. [18]

One other interesting concept is the wind turbine support structure (WTSS) produced by Offshore Kinematics [19]. Their design bares a similarity with a typical fixed monopile and functions similarly to a spar with a fixed point on the seabed, their design removes the need for moorings, reducing environmental impact and simplifying commissioning/ decommissioning processes. This design has been used at small scale in Norway but has yet to see a full-scale deployment yet.

Figure 15: Left: the scale model currently in deployment. Right: A 3D model of the full-scale concept design. [19]

These two designs are just a few examples of some of the highly conceptual work that is ongoing within the floating wind sector. Given the lack of an industry standard solution, there is a real market drive to produce a design that can cater to the various challenges that an offshore wind turbine/farm will undertake. Given the diverse environmental conditions that can vary throughout the world, it is unlikely that there will a be all/end all design that fulfils every criteria and it highly experimental solution such as these may see high levels of deployment in the future.

However, as information on these high-level concept designs is even more limited than the primary floating concepts, these will not be considered for further analysis. It is worth noting that in the future. It is not improbable and worth noting that one of these unique concept designs may perform far better in terms of emissions produced when compared to more traditional designs.

Estimated Emissions due to Structure Type

Naturally, given the inherent lack of research on the topic of floating foundation emissions and a lack of industry standard solutions it can be very hard to quantify how much emissions each structure is responsible for especially when different companies employ different designs and different materials even if they are using the same core floater type.

However, one potential method that we can use for estimating structure mass is by assessing roughly how much different substructures weigh and scale/ average them out for a 15MW turbine with projected “Higher and lower” values. This work was carried out as part of a different ORE Catapult project, but these predicted masses can be used here, see Table 10.

Table 10: Mass comparison for different substructure types

Substructure Type		Platform mass (t)
Semi-sub Steel	High	4,500
	Low	3,500
Semi-sub Concrete	High	20,000
	Low	16,000
Barge Concrete	High	20,000
	Low	15,000
Suspended Spar Steel	High	5,000
	Low	3,750

Additionally, a summary regarding some of the key characteristics from some ongoing projects can also be produced including masses, turbine size, materials, water depth, etc. Table 11 showcases this summary which covers several examples of each type of turbine.

Table 11: Summary of key parameters for notable floater projects.

Project/ Owner	Structure Type	Material	Weight (t)	Dimensions. Length x Width x Height (m)	Min Water Depth (m)	Tested Turbine Output (MW)	Tons/ MW Est	TRL
Hywind Tampen/ Equinor	Spar	Concrete	5000	14.5 x 14.5 x 110	N/A	8	571	7
Hywind Scotland/ Equinor	Spar	Steel	2300	14.5 x 14.5 x 91	75	6	310	8
Floatgen/ Ideol	Barge	Concrete	4360	36 x 36 x 9.5	26	2	2230	8
Hibiki/ Ideol	Barge	Steel	10560	45 x 45 x 10	28	3	3586	8
Windfloat/ Principle Power	Semi-sub	Steel	2750	75 x 75 x 30	40	9.6	298	8
EOLINK / EOLINK	Semi-sub	Hybrid	1900 (steel) mass of concrete not known	66 x 59 x 50	50	15	N/A	6
TLPWind/ Iberdrola	TLP	Steel	940	50 (length)	60	5	188	5
GICON SOF GICON	TLP	Hybrid	75 (steel), 600 (concrete)	32 x 32 x 26	45 - 350	6 - 8	214	5
Hybrid Semi spar/ ACS Cobra	Semi-spar	Concrete	N/A	N/A	60	N/A	N/A	5
WTSS/ Offshore Kinetics	Other	Steel	N/A	N/A	N/A	N/A	N/A	6
Trivane/ Trivane	Other	N/A (Steel for practice turbine)	N/A (425 for practice turbine)	150 x 55 x 6	Up to 50	Designed for 10	N/A	4

Painting

Floaters have to be able to function within a challenging environment where tackling issues potential faults such as corrosion are critical. Choi et al [20] examined corrosion protection design for floating offshore wind turbines. They defined several zones (atmospheric, splash zone and immersed zone) based on their environmental conditions see Figure 16. Naturally for the floating foundations, they would be classed within both the splash zone and immersed zones.

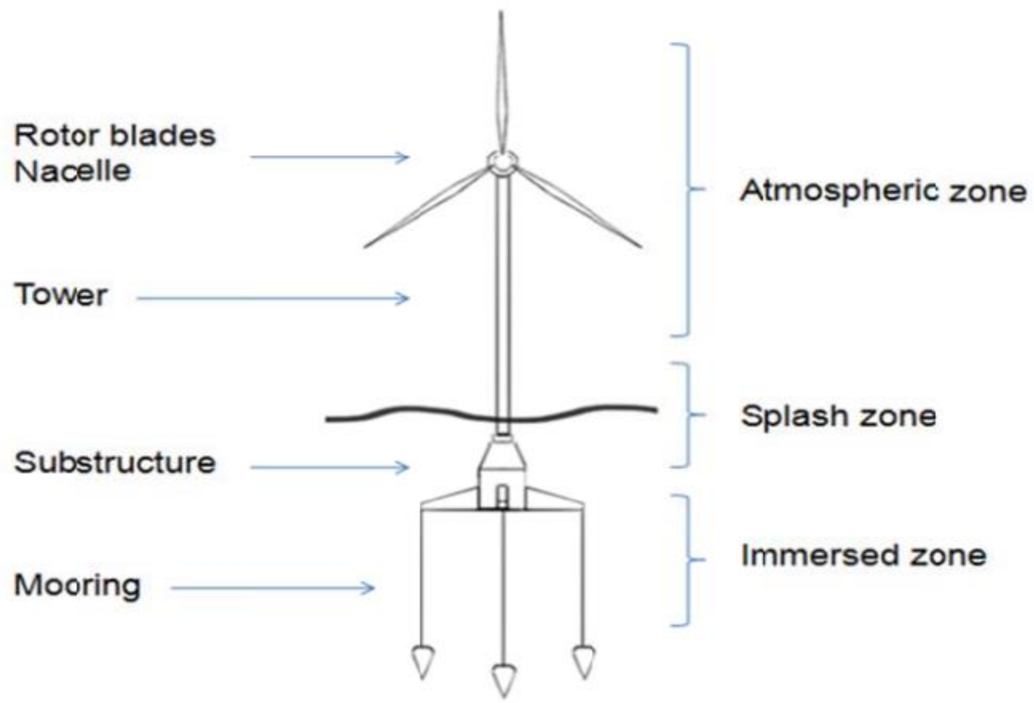

Figure 16: Diagram showcasing a floating wind turbine and the location of the three different zones. [20]

Each kind of zone would be susceptible to corrosion at varying rates see Table 12. It is clear that whilst immersed the floater is highly prone to corrosion. With that in mind it is critical that the foundations are painted and protected appropriately as without that protection it will be become more likely to fail. However, the paint that is often used in these applications can produce harmful emissions. In these environmental conditions it has been identified within the relevant standards that epoxy primers, cathodic protection or coal tar epoxy are the best coating systems to apply.

Table 12: Corrosion rates due to the corrosion environment. Where ZP: Zinc Rich Primer, EP: Epoxy Primer, PUR: Polyurethane, CP: Cathodic Protection and CE: Coal Tar Epoxy. [20], [21], [22]

Corrosion environment	Corrosion rate	Standard ISO 12944-5	Standard NORSOK M-501
Atmospheric zone	0.08 ~ 0.2 mm	EP, PUR	ZP, EP
Splash zone	0.4 mm	CE	EP, CP

Immersed zone	0.2 mm	CE	EP,CO

There is little research that specifically looks at this field from an emissions stand point but one notable paint supplier that caters specifically to the wind industry is Hempel **Error! Reference source not found.**], who possess a noticeable library of wind turbine solutions (although these are predominately focused more on the tower).Hempel also claim that they are looking at developing more robust low-VOC (Volatile Organic Compounds) and higher volume solid coatings specifically intended to reduce emissions. However, currently there is no data on the amount of emissions that these paints generate making the overall, impact difficult to quantify.

However, there have been studies on the impact of paint in other industries that may at least provide an insight into how much emissions may be generated. One such study **Error! Reference source not found.**] looked at VOC emissions in the automotive industry identifies that the majority of harmful emissions from paint come from spraying. The author points out that some manufacturers such as Ford have developed a process which captures VOCs and converts them into energy. A few other suggestions that were suggested included absorption and biological removal techniques that could help directly remove harmful chemicals.

It is still hard to determine whether or not painting would have a significant impact on the global emissions of a steel turbine but given the scale of emissions that comes from the core carbon emissions produced during the manufacturing stages, it could be safely assumed that painting would likely have a more minimal effect. In the context of this project, specific paint applications that meet the specific quality requirements and make use of the appropriate technologies to minimise emissions would be sufficient.

Internal Structure

Floater is a complex structure with additional structural/ safety features such as ladders and electrical equipment (cables, alarms, etc) and various pieces of safety equipment. Whilst manufacturing and installing this equipment would have an impact on emissions, it could be safely assumed that due to the relatively low mass of this equipment when compared to the core foundation structure that the impact on emissions would be negligible. In practice, it would be preferable that any focus on these features is put into using the safest and most robust equipment possible.

Manufacturing Processes

Regardless of the materials used or the design of the wind turbine floater, it is clear that manufacturing plays the largest role in producing carbon emissions. Therefore, newer manufacturing processes should be examined and identified to show a "greener" way to create these structures.

Current Manufacturing and Fabrication Processes

The relative rarity of floating wind turbine technology means that there is little to no public information on how these various structures are constructed. This is likely due to the fact that the technology hasn't been used at a large scale and there has been no established industry standard solution. One core advantage of the more common floater structures is that they share manufacturing DNA with the tower component. In the case of tubular towers, manufacture is usually carried out by rolling steel plates into the conical subsection. Additionally, floaters come in a variety of materials which would be manufactured in completely different ways.

Whilst specific manufacturing processes are not documented there have been studies that have covered the core differences in fabrication and installation between different floater materials such as Matha et al [25]. A summary of which can be seen in Table 13 and Table 14.

With regards to material selection, there are other key factors that come into play during construction. Site selection can impact the ability to use specific materials quite considerably. Depending on aspects such as site size, individual equipment requirements, storage facilities and how it interfaces with the port.

Table 13: Advantages and disadvantages of steel floaters. [25]

Advantages	Disadvantages
Well established in offshore wind and energy sectors	Will produce components with larger dimensions.
Fast assembly provided components have been prefabricated	Expensive and is subject to fluctuating prices
Light than concrete	Requires specialised equipment (such as large-scale welding machines and heavy-duty cranes)

Table 14: Advantages and disadvantages of concrete floaters. [25]

Advantages	Disadvantages
Concrete supply is adaptable to local conditions and project requirements	Limited overall usage within wind industry
Local content is ensured (workforce, supply chain)	Large dimensions require large construction areas

No specialised equipment required	High weight
Low costs	Manufacturing will require other procedures such as pre-tensioning
Easy to make adjustments due to casting process	Can be restricted by weather conditions during construction
Less storage required (no raw material needs to be stored)	Will require higher levels of quality assurance due to a potentially inaccurate mixing process

Manufacturing Process Improvements

It has been established in the prior chapter that steel and concrete are the two materials that have been used for floaters, at the time of writing there have been no floaters that use any other materials. Therefore, the primary step will be to identify how to improve the processes involved with regards to reducing emissions across the steel sector.

Holappa [27] carried out a case study on the impact that the steel industry has as whole on overall emissions and what is the vision for the future. Whilst the study looks at the state of the steel industry rather than focusing in on specific sectors or regions, it provides some a clear idea of what will need to be done in the future up to the year, 2050. Currently, the steel industry is predicted to grow by around 25-30% by 2050 but the steel industry is responsible for around 7% of all anthropogenic CO_2 emissions. In order to achieve future climate targets, it is absolutely essential that this industry makes changes.

The author listed multiple ways for making this change starting off with improving energy efficiency typically achieved by "modernizing" plants and adopting new technologies. Another suggestion revolved around mitigating emissions during ore production by modifying existing technology. Examples of these methods include:

- Better usage of unused waste heat
- Heat recovery
- Transfer to coke dry quenching in coke making (CDQ)
- Using biomass as an alternative fuel source as opposed to fossil fuels

These examples are naturally relevant to the production of steel itself which is not what the proposed floater manufacturer would implement themselves, but it is important to note that if reducing emissions is the main goal then working alongside steel plants that use these technologies would be essential.

One of the most important technologies that has been heavily invested in recent years is carbon capture storage (CCS). This technology has become more commonly used in the oil & gas industry but is now seeing further usage in other sectors. An alternative to CCS is carbon capture combine with carbon utilisation (CCU) or using a combination of the two to create CCUS. Theoretically, these technologies could reduce overall ironmaking CO2 emissions by up to 50%. However, that would still not be enough to achieve climate goals. The use of hydrogen in place of coal or coke has been considered, primarily for transportation or hearing [27]. Hydrogen would typically be produced via steam reforming of gas or oil; this is not a carbon zero alternative but when couple with a process such as CCS there is considerable potential. Particularly with "greener" sources of hydrogen are used such as water electrolysis or biochemical solutions (fermentation or algae).

Finally, the two final points that are raised by Holappa are the use of renewable energy sources for the purpose of electricity generation and increasing recycling. When looking at the use of renewable energy it can be seen in Table 15 that renewable sources produce far fewer emissions than industrial standard fossil fuels. In particular wind and nuclear produce very low figures. It is worth noting that whilst biomass appears to produce rather high figures, this is due to direct emissions whereas more modern biomass processes such as combined heat and power systems produce substantially less.

Table 15: CO_2 emissions (g/kWh) from electricity generation through using different sources of energy.Matha, D., Brons-Illig, C., Mitzlaff, A., & Scheffler, R. (2017). Fabrication and installation constraints for floating wind and implications on current infrastructure and design. *Energy Procedia*, *137*, 299-306.

[26]

Primary Energy - Fossil		**Bio**	**Fossil with CCS**	
Coal	Natural gas	Biomass	Coal with CCS	Natural gas with CCS
820	490	740:230[1]	160-220	170
Renewable or Non fossil Energy				
Geothermal	Hydro	Nuclear	Solar	Wind
38	24	12	48	12

1 Biomass covers cofiring vs dedicated processes

All of these methods could make a huge difference overtime and should lead to far lower emissions, see Figure 17. Through this figure, the author has provided a clear pathway to a greener iron/steel industry.

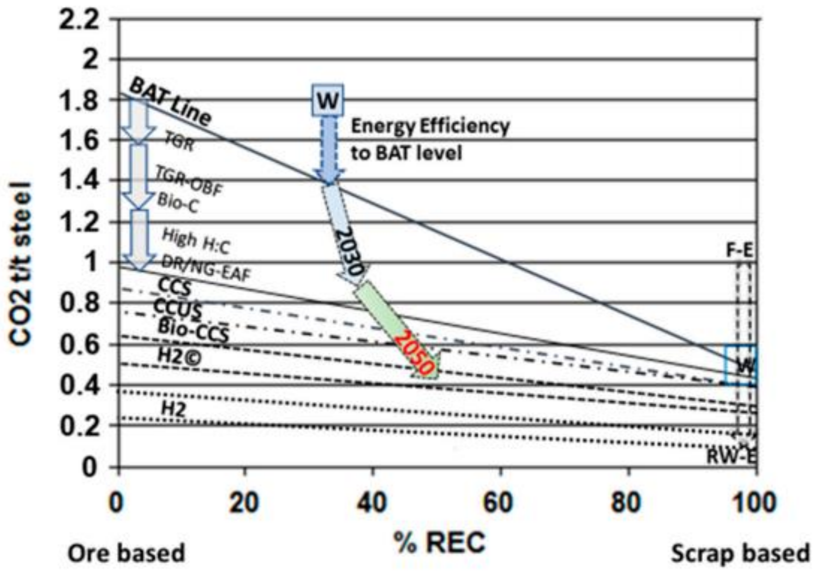

Figure 17: Summary of a potential pathway to reducing CO2 emissions in the steel/iron industry. Each different line shows the assessed reductions levels that are achievable via each labelled method. The arrows show a plan for the future for the industry up to 2050. Where BAT means best available techniques, TGR is top gas recycling in oxygen blast furnace, DR/NG.EAF reference direct reductions: natural gas, electric arc furnace. [27]

Again, this study was very much aimed at the global iron/steel making industry but many of the techniques and lessons that were applied here would be applicable to a potential manufacturing plant. Additionally, if a wind turbine floater manufacturing facility were to be set up, it would be absolutely critical that these same methods are employed by any potential partner involved.

Keeping the idea of looking at the wider steel industry in mind, Toktarova et al Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. Metals, 10(9), 1117.

[28] produced a similar pathway for a low carbon transition in the Swedish steel industry. Similarly, to [27], they set out a plan for reducing emissions from steel production with suggestions such as CCS, biomass, hydrogen direct reduction of iron ore (H-DR) and electric arc furnaces (EAF). See Table 16 for more information.

Table 16: Currently available and new low CO_2 production process for steel making in Greenfield production facilities. Adapted from Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. Metals, 10(9), 1117.

[28]

Process	TRL Status	Tonne CO_2 / Tonne Steel	Capital Expenses, €/Tonne
Primary steel production			
Blast furnace with basic oxygen furnace (BF/BOF)	Commercial, TRL 9	1.6 – 2.2	386-442
Top gas recycling blast furnace (TGRBF/BOF)	TRL 7	1.44 – 1.98	632
CO2 capture technology	TRL 6-9	CO_2 Capture Efficiency: 90%	25-85
Smelting reduction (SR/BOF)	Commercial, TRL 9	1.2-2.25	393
Direct reduction using electric arc furnace (DR/EAF)	Commercial, TRL 9	0.63-1.15	414
Hydrogen direct reduction using electric arc furnace (H-DR/EAF)	TRL 1-4	0.025	550-900
Electrowinning (EW)	TRL 4-5	0.2-0.29	639
Secondary steel production			

Electric arc furnace (EAF)	Commercial, TRL 9	0.6	169-184
Electric arc furnace/biomass (EAF/biomass)	TRL 6-8	0.005	169-184

Through identifying these different methods, the author put forward three potential "pathways", these pathways are essentially different processes that could be implemented in the future. These are described in Table 17.

Table 17: Description of pathways and production rate estimate. Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. Metals, 10(9), 1117. [28]

Pathway	Primary Steelmaking	Commercially Available	Secondary Steelmaking	Production Rate
1	TGRBF/BOF + CCS + biomass	2030	EAF/biomass	Constant
2	H-DR/EAF	2040	EAF/biomass	Constant
3	H-DR/EAF	2040	EAF/biomass	Increased

These pathways were analysed and compared with each other. They found that by 2030, cutting emissions down by up to 80% could be achievable by utilising TGRBF/CCS with biomass (primary process) alongside with electric arc furnace with biomass (secondary process) as CO2 mitigation options (Figure 18). In comparison pathway 2 shows a 10% reduction with the main challenge being that the electricity demand there would be close to 14TWh by 2045.

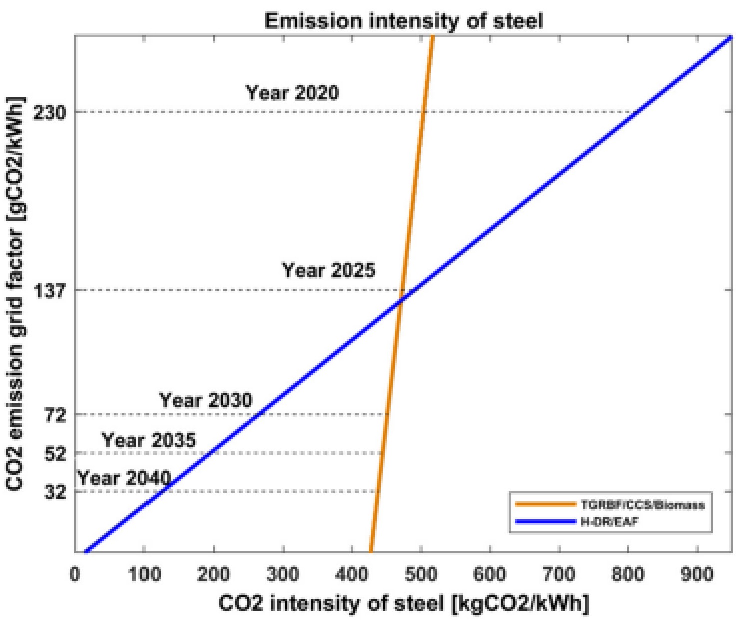

Figure 18: CO_2 emissions intensity for primary steelmaking in pathways 1 (orange) and 2,3 (blue) as a function of European CO_2 emission grid factor. Dotted lines indicate development of European CO_2 emission grid factors that have been estimated by IEA. Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. Metals, 10(9), 1117.

[28]

The international energy agency carried out an extensive technology roadmap on how to work towards more sustainable steelmaking Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for low-carbon transition of the steel industry—A Swedish case study. Energies, 13(15), 3840.

[29]. Stating that the steel/ iron industry is responsible for 7% of energy sector CO_2 emissions and 8% of global energy demand. The paper developed here laid down a comprehensive roadmap (similar to the prior papers) that should highlight the innovations that would reduce these statistics substantially. Firstly, they state that steel has am incredibly high recycling rate (80 – 90% globally) but unfortunately due to steel production being higher than recycled production, this alone will not be suitable enough on its own. The study also mentions the use of efficient steel usage which could tie into Table 11 where the weight of several floater structures was looked at. Again, like the previous report they also look at alternative steelmaking processes. Citing that there is "no right answer" with a lot of the new technology still being relatively new whilst requiring relatively rapid deployment but it was also noted that large emission reduction will not be achievable outright without using this technology. Pushing for technical innovations, especially in the fields of using CCUS and low-carbon hydrogen will be crucial in order to achieve net-zero.

Table 18: Main emission reduction technologies for achieving near/net-zero in steel and iron sector (where DRI is direct reduced iron). Adapted from Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for low-carbon transition of the steel industry—A Swedish case study. Energies, 13(15), 3840.

[29]

Technology	TRL	Year available (Importance for net-zero)
CCUS		
Blast furnace: off-gas hydrogen enrichment and/or CO2 removal for use or storage	5	2030 (Very high)
Blast furnace: Converting off-gases to fuels	8	Present (Medium)
Blast furnace: Converting off-gases to chemicals	7	2025 (Medium)
DRI: Natural gas-based with CO2 capture	9	Present (Very high)
Smelting reduction: with CCUS	7	2028 (Very high)
Hydrogen		

Blast furnace: Electrolytic H2 blending	7	2025 (Medium)
DRI: Natural gas-based with high levels of electrolytic H2 blending	7	2030 (High)
DRI: Based solely on electrolytic H2	5	2030 (Very high)
Smelting reduction: H2 plasma reduction	4	--- (Medium)
Ancillary processes: H2 for high-temperature heat	5	2025 (High)
Direct electrification		
Electrolysis: Low-temperature	4	--- (Medium)
Electrolysis: High-temperature molten oxide	4	--- (Medium)
Bioenergy		
Blast furnace: Torrefied biomass	7	2025 (Medium)
Blast furnace: Charcoal	10	Present (Medium)

Table 18 shows the primary technologies that could be used for in sectors in the future. Again, whilst this focuses on reducing emissions across the global steel production sector it is clear that for a local manufacturing facility to minimise emissions using the above technologies will be absolutely essential. Especially as each of the prior papers have identified the "very high" level of importance that CCUS and hydrogen will have gone forward. Therefore, it is clear from the perspective of a wind turbine floater manufacturing facility that in order to minimise emissions, these technologies need to be incorporated, potentially using a renewable energy source.

To further emphasise how carbon intensive these manufacturing processes can be, Salonitis et al [30] looked at the difficulties associated with energy efficient casting process. Given that cast iron was one of the potential materials that was explored earlier, it is worth understanding the challenges and potential solutions for the manufacture of such a component.

Table 19 provides an effective summary of some of the key challenges that can occur within the casting cycle. The key take away from the study is that the melting and holding processes are responsible for 30% of total energy usage each, meaning that this is a key area for improvement with regards to emissions reduction. Aspects such as air compression and plant actuation possess the highest energy cost in a casting foundry.

Whilst this study was not directly aimed at wind turbine manufacturing, there are key lessons that can be taken, one of which is how much numerical simulation and effective plane management could help with reducing energy consumption. Numerical simulations can be used to predict process performance, helping to reduce physical experimentation and inspections which helps keep production smooth and efficient. Plant management is critical, the authors highlight the importance of using technology such as air compression for providing air efficiently during combustion and efficient heating would help significantly reduce energy consumption. However, air consumption does require a lot of electricity to operate therefore effective management processes are required to ensure optimal performance.

Table 19: Energy loss and energy saving opportunities summary. [30]

	Energy loss reason	**Saving method**	**Saving type**
Melting	1. Inefficient melting 2. Permanent metal loss	1. Correct size of furnace 2. Rapid melting 3. Keep melt away from air	Direct/Indirect
Refining	Permanent metal loss	1. Using high-quality charging metal 2. Cleaning melting	Indirect
Holding	1. Long-term holding 2. Permanent metal loss	Reducing holding time	Direct/ Indirect
Fettling	Low casting yield	Increasing casting yield	Indirect
Machining	Rough shape of casting	Making net shape casting	Indirect
Inspection	Defects (poor surface finish, porosity)	1. High-quality melting 2. Good running system	Indirect

An additional study [31], which evaluated the environmental impact of cast iron also noted that the primary source of negative environmental impact was caused by the melting process (up to 74.1%) which lines up well with the prior study. There were several key suggestions that were made during this study on how to reduce this impact. The key aspect was reducing the demand for materials via aspects such as recycling. Through the use of a LCA, the environmental impact of smelting was reduced by around 9% by simply recycling metal waste. Additionally, reducing energy consumption as similar to what was suggested in Table 19, preventing the release of emissions to the atmosphere and reducing water usage were also cited as important actions that should be employed. Additionally, the act of changing industrial waste into raw materials was seen as a vital step in this work.

Carbon Capture Storage

As identified in the prior subchapter, CCS looks like it will be one of the most important technologies going forward. So, the current question is, how could it be implemented and what direct impact could it have? Arasto et al [32] looked at the costs and potential of CCS at a steel mill. They considered a range of different CCS technologies such as post combustion carbon capture and oxygen blast furnaces. Ultimately, they found that not only could carbon capture technology greatly reduce greenhouse gases, but it also has a strong economic effect. In this paper, it is assumed that the plant owner will operate in the range of 46 – 90 €/t CO_2*, if electricity prices hover between 80 – 100* €/MWh then the cost of "avoided" emissions will run in the range of 60 – 100 €/t CO_2. Figure 19 showcases these statistics and highlights when CCS would be most economically feasible.

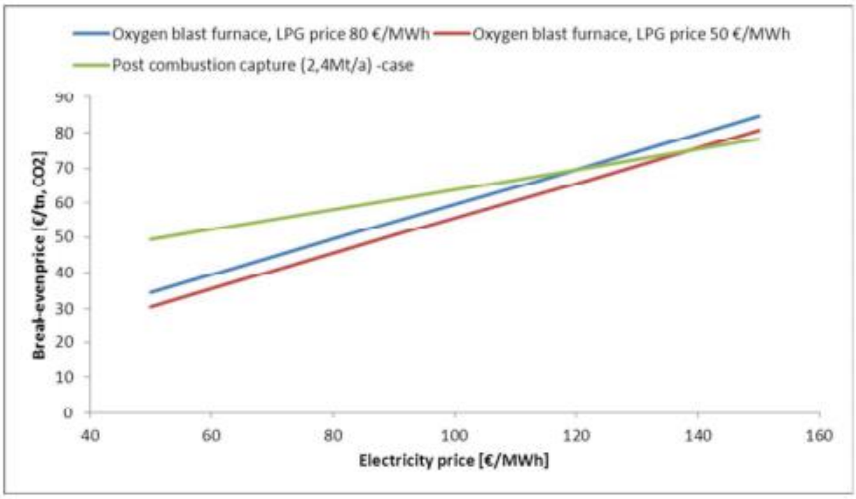

Figure 19: The effect that electricity price has on the "break-even" price when CO_2 capture becomes more feasible than buying CO_2 emission allowances. [32]

Tian et al Arasto, A., Tsupari, E., Kärki, J., Sihvonen, M., & Lilja, J. (2013). Costs and potential of carbon capture and storage at an integrated steel mill. Energy Procedia, 37, 7117-7124.

[33] ran a study that covered the wide potential of deploying a decarbonisation plan that uses CCS technology in the steel/iron making industry. The specific technology that was explored in this case was the use of a calcium-looping lime production (CaL-LP) scheme, see below figure. This process works via a feedstock processing unit that includes a coke oven, sinter plant and a lime kiln, this technology pyrolyses coal into coke, iron ore into pellets and limestone into lime. The coke reduces the pellets to pig iron in the blast furnace where the lime is used as a flux to remove any impurities from the pig iron Arasto, A., Tsupari, E., Kärki, J., Sihvonen, M., & Lilja, J. (2013). Costs and potential of carbon capture and storage at an integrated steel mill. Energy Procedia, 37, 7117-7124.

[33].

The new scheme adds an extra kiln that can be interconnected with the lime kiln, where the limestone or lime solids are circulated between both kilns. In doing so, the CO_2 emissions in the flue gas produced by the plant is captured by the lime that is brought over from the lime kiln via an exothermic reaction. With the additional kiln, the lime will be produced via an oxy-fuel calcination which leads to a produced "high-purity" CO_2 stream which can either be stored or utilised in other applications.

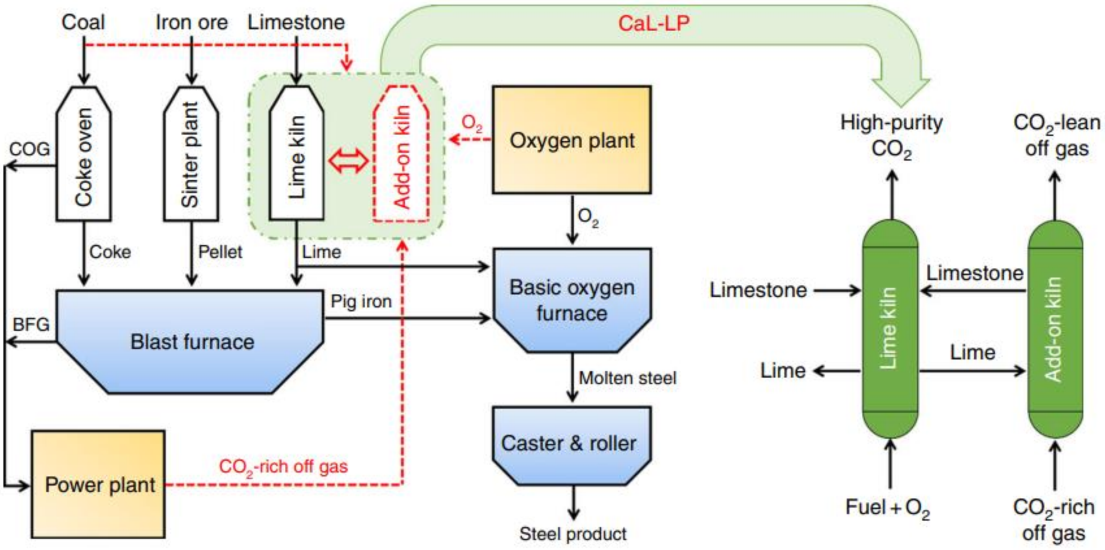

Figure 20: Proposed concept for integrating CCS into iron and steel production. This depicts a steel mill using calcium-looping lime prodiuction (CaL-LP) for CO_2 emission reduction. The red lines indicates mass flow due to the scheme and the solid black lines show the mass flow due to present manufacturing technology. Arasto, A., Tsupari, E., Kärki, J., Sihvonen, M., & Lilja, J. (2013). Costs and potential of carbon capture and storage at an integrated steel mill. Energy Procedia, 37, 7117-7124.

[33]

This amended process possesses a number of advantages, including the fact that it does not require much modification with regards to amending existing manufacturing processes. The authors ran further studies to better assess the potential of this technology. Figure 21 shows the potential that implementing this technology has up to 2050. Depending on operating conditions, between 49-83% of total CO_2 emissions may be reduced due to these processes. This technology also manages to surpass EU and Japan CO_2 emissions targets.

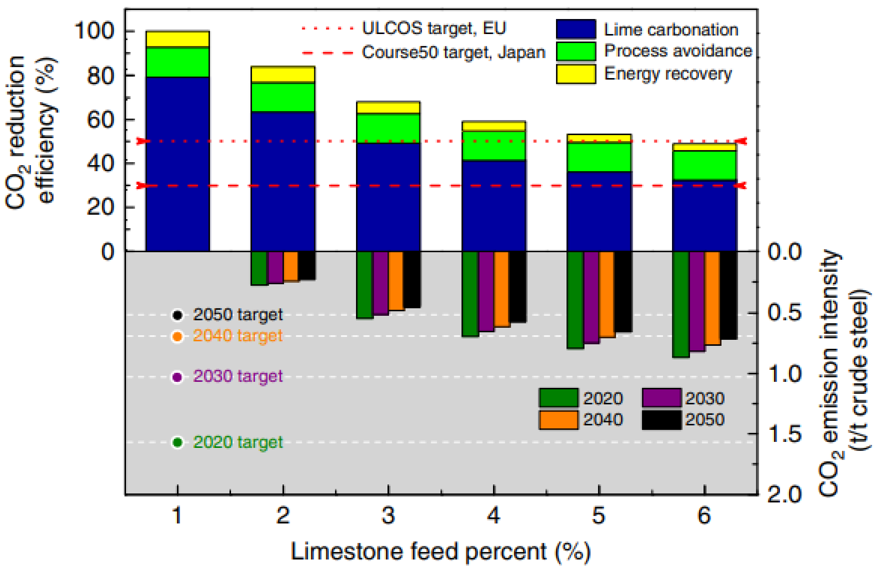

Figure 21: Potential for decarbonisation in a typical steel mill whilst using the CaL-LP process. [33]

However, they also concluded that this concept would produce a CO_2 avoidance cost of around 12.5-15.8 $€_{2010}$/t which is lower than the anticipated CO_2 trading cost in 2020 and isn't anticipated to become financially feasible until 2030. Thus, the authors proposed adopting this technology as an emission reduction solution in the mid to long term.

Hydrogen

The European parliament ran a study that explored the potential for decarbonising steel manufacturing through hydrogen [34]. Hydrogen can be used in place of coal and can be generated via renewable energy. There are a number of pros and cons to using this relatively new technology such as using hydrogen would drive up the cost of steel by around a third, but this cost could disappear by 2030 due to decreasing renewable energy costs and emission pricing. One additional advantage is that hydrogen could be used as a form of electricity storage in the event that renewable energy generation is not possible. This study indicated that there are several "pilot projects" in progress so lessons learned from those projects will be essential with regards to figuring out optimal hydrogen implementation.

Material Manufacturing – Concrete

Concrete is a common choice as the primary material for floaters and may also be used as the secondary material in several hybrid applications. Essentially, this means that whilst reducing emissions due to steel manufacturing will likely be the most important factor, examining different ways of reducing concrete CO_2 emissions will also play a noticeable as well.

Miller et al [35] examined various techniques that could reduce CO_2 emissions that are generated during concrete production. Such methods could include simply using more efficient equipment to employing new technologies. They point out that one of the biggest cause of CO_2 emissions is caused by clinker ("a kilned and quenched cementitious product) that is used as an important constituent in the creation of cement (responsible for 90-98% of cement green house gas emissions). This is due to two processes that are used during the creation of clinker, the first is a calcination process where calcium carbonate undergoes a reaction that will generate CO_2 and the second is where the materials used to make clinker are heated to extremely high temperatures that requires high energy input and will also generate GHG emissions. Depending on what part of the world you are in, the characteristics of concrete will vary but typically 90 – 95% of GHG emissions caused by concrete are due to cement [35].

As a result of this, the author suggests a number of alternatives that could be used for reducing GHG emissions:

1) Changing raw materials used during cement production
2) Using different fuels during manufacturing (potential for hydrogen or biomass usage)
3) Improve efficiency and electricity usage
4) Using CCS

Naturally each of these solutions have barriers that would cause problems during implementation but ultimately, by employing similar techniques to what was used for steel manufacturing like CCS or hydrogen and renewable energy for electricity a significant amount of emissions can be reduced. As previously mentioned however, the key source of emissions with concrete is the creation of cement and clinker. It is pointed out in [35] that there are alternatives that can be used to reduce the amount of clinker in the cement thereby reducing overall CO_2 emissions. Using other supplementary cementitious materials (SCMs) like fly ash, slag and limestone. Using these other SCMs may lead to reduced emissions see Figure 22.

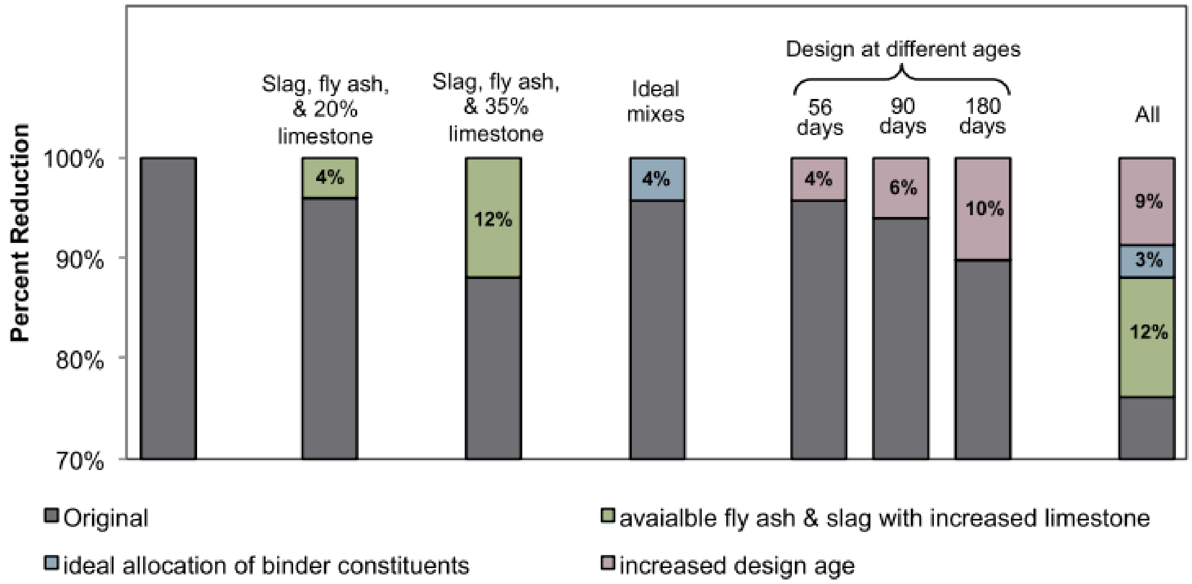

Figure 22: A graph showing the original emissions generated by concrete in 2012 along with three proposed methods for reducing emissions. The combination of each of these three designs assumes a design age of 180 days. [35]

Despite that however the authors conclude that the defining way of reducing emissions during concrete manufacturing is to use more limestone, increase design age so there is less long term need for more concrete and improve the selection of ideal concrete mixture proportion (improve the quality of concrete) . These three aspects alone could be responsible for up to 95% of emissions reductions.

Each study looked at so far points out the wide potential of CCS, but few explore what the captured CO_2 is used for. Lim et al [36] ran a study that focused more on CO_2 utilisation as opposed to avoidance. They carried out this work by looking at the net emissions reduction and cost impact by reducing binder (component that makes up cement, for example: cement) loading whilst adding CO_2 during the manufacturing process. They proposed adding CO_2 at three different stages during manufacturing, during mixing, curing and using it with recycled concrete aggregate (RCA). Figure 23 helps provide a rough idea as to the maximum reductions that could be made by implementing these processes.

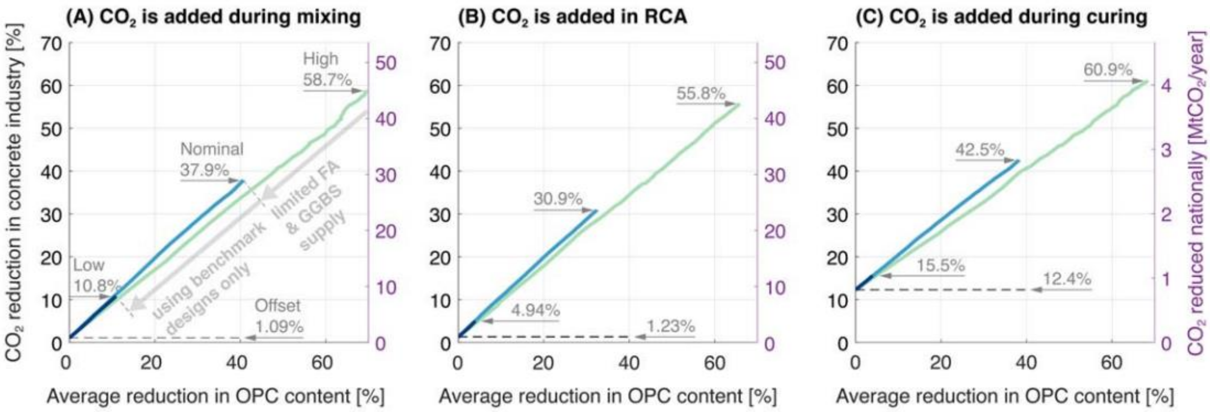

Figure 23: CO_2 mitigation via implementing a strategy that reduces binder and adds CO_2 during formulation. The results displayed here only show the largest CO_2 mitigations achievable and present median values. [36]

Additionally, the authors used these results to show the impact that this could have on costs and found that by saving these materials, the additional cost brought on by further CO utilisation could be fully met. However, their findings were aimed at a plant in USA which will use different processes and face different laws.

Ultimately, the potential floater manufacturing facility that will be examined as part of this project, will not include the manufacture of concrete but it is important to recognise the differences in GHG emissions that these changes can make. Therefore, as part of the future facility requirements, it should be established how local concrete manufacturers carry out their work.

Alternative Material Manufacturing - Composites

One final material that has been considered are composites. It has already been identified that the use of composites could reduce the mass of the tower in prior work but in the future there may be future demand to expand work for the development of composite floaters. It would reduce the amount of material required which may lead to a reduction in lifetime CO_2 emissions.

There are a wide variety of composite materials that could be used for tower/floater manufacturing, one of which is carbon fibre. Carbon fibres are composites that consist with around 92% carbon content Lim, T., Ellis, B. R., & Skerlos, S. J. (2019). Mitigating CO 2 emissions of concrete manufacturing through CO 2 -enabled binder reduction. Environmental Research Letters, 14(11), 114014.

[37] and can be made with a wide range of materials such as Acrylonitrile. The manufacturing process for creating each fibre is complex and consists of multiple steps. Carbon fibres can be up to 10 times stronger than steel, 5 times lighter and possess superior fatigue and corrosion resistance Lim, T., Ellis,

B. R., & Skerlos, S. J. (2019). Mitigating CO 2 emissions of concrete manufacturing through CO 2 -enabled binder reduction. Environmental Research Letters, 14(11), 114014.

[37]. However, whilst this is a significant advantage with regards to performance, the process of creating the material is an intensive process. Therefore, the manufacturing process must be explored in order to identify opportunities with regards to CO_2 emissions reduction.

Cook et al Cook, J. J., & Booth, S. (2017, June). Carbon Fiber Manufacturing Facility Siting and Policy Considerations: International Comparison. https://www.nrel.gov/docs/fy17osti/66875.pdf

[38] carried out a LCA for carbon fibre reinforced composites and identified the advantages of two precursor types (textile acrylic fibres and renewable based lignins) whilst using several manufacturing processes with fibre recycling technology. The scenario that was presented in this study was squarely aimed at the automotive sector although there are aspects here that could be directly applied at a potential floater facility. The authors listed five separate scenarios for their LCA including Cook, J. J., & Booth, S. (2017, June). Carbon Fiber Manufacturing Facility Siting and Policy Considerations: International Comparison. https://www.nrel.gov/docs/fy17osti/66875.pdf

[38]:

- Steel: Stamped steel.
- PAN sheet moulding compound (SMC): Textile-grade precursor to polyacrylonitrile (PAN) carbon fibre mixed with SMC manufacturing technology.
- PAN P4: Textile-grade precursor to PAN carbon fibre mixed with programmable powdered pre-forming process(P4) manufacturing technology.
- Lignin SMC.: Lignin-precursor carbon fibre mixed with SMC manufacturing technology.
- Lignin P4: Lignin-precursor carbon fibre mixed with P4 manufacturing technology.

The initial results of the analysis can be seen in Table 20 and it is clear that the primary energy used for production and the GHG emissions per kg are far higher than that of steel. However, the life cycle primary energy and emissions are actually very similar. This may provide a good indicator as to how viable composite floaters may be as the lifecycle performance matches up. With improved processes and by using alternative structures it may be possible to construct turbines that will not only require fewer emissions but may also last longer. Although it is worth noting that this study was aimed at the automotive industry and relied on a number of assumptions during the analysis.

Table 20: Primary energy and CO emissions estimates for carbon fibre reinforced polymers. Cook, J. J., & Booth, S. (2017, June). Carbon Fiber Manufacturing Facility Siting and Policy Considerations: International Comparison. https://www.nrel.gov/docs/fy17osti/66875.pdf

[38]

Material/ Technology Unit (Per kg of material or part)	Primary Energy (MJ)	CO_2 equivalent emissions (kg)
PAN carbon fibre	704	31
Lignin carbon fibre	670	24.2
PAN SMC part	345	16.9

PAN P4 part	323	14.6
Lignin SMC part	336	14.9
Lignin P4 part	312	12.5
Stamped steel part	56	4.4
Life cycle PAN SMC	18,804	1,407
Life cycle PAN P4	18,232	1,347
Life cycle lignin SMC	18,800	1,400
Life cycle lignin P4	18,185	1,338
Life cycle stamped steel	18,308	1,478

The primary manufacturing process for carbon fibre has been detailed by Bhatt and Goel [39]. They focused in on PAN carbon fibres as around 90% of carbon fibre is produced from polyacrylonitrile with the 10% being split between petroleum pitch and rayon. These initial materials are called the precursor, and each is an organic polymer with a composition that will vary between manufacturers. Figure 24 summarises the complete manufacturing process.

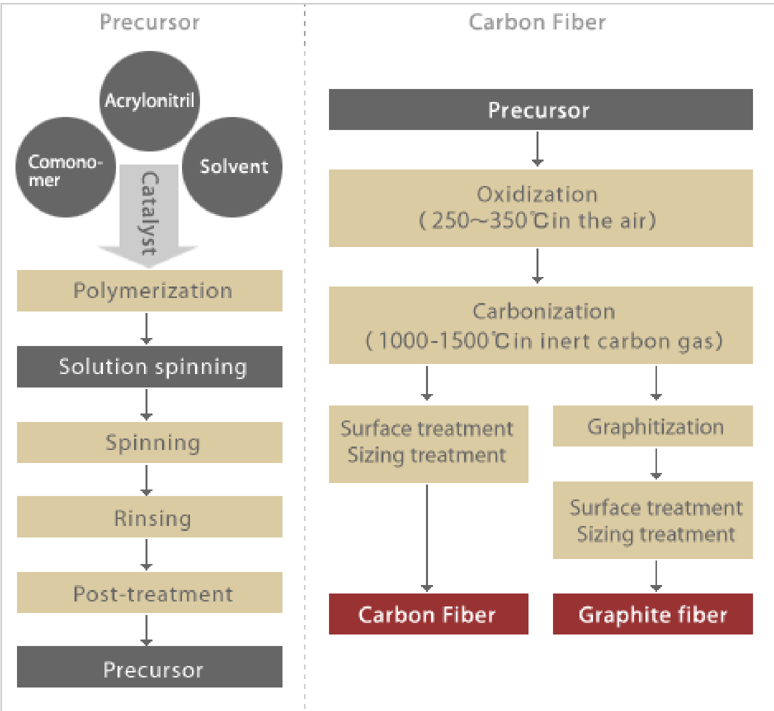

Figure 24: Carbon fibre manufacturing process. [40]

The first key step is spinning, this is often achieved by mixing Acrylonitrile with other plastics and with the use of a catalyst in a polymerisation process to form the polyacrylonitrile plastic. This plastic can then be spun into fibres via several methods. The spinning method is hugely important as this is what will determine the atomic structure of the composite. Afterwards they can be washed and stretched to achieve the fibre diameter.

Typically, after the spinning and washing treatments are complete, and before the carbonisation processes begin, the fibre needs to be further altered to change their bonding. This involves heating processes that will produce emissions. However, the carbonising process is applied after stabilisation, and this involves heating the fibre to around (1,000-3,000° C) which can also require a lot of energy so using heat efficiently is key. Despite the fact that the carbonising process does not involve oxygen, there will be harmful emissions that include CO_2, carbon monoxide and ammonia. Afterwards there are more processes such as oxidation which will also produce emissions. Finally, the fibre is finished after a surface treatment and a sizing process where the fibres are coated and then weaved,

Emissions Reduction Summary and Suggestion

To summarise the overall report, there are a range of potential structures, materials and structures that may be used to reduce the emissions produced during the production of offshore wind turbine floaters.

Steel is more widely used throughout the industry and produces less CO_2 emissions per eq than its alternatives. However, an increase in maintenance requirements, a potentially lower lifespan and added challenges during transportation/ installation may lead to increased emissions overtime.

Each separate structure possesses their own unique characteristics which lend to different advantages and disadvantages. From an emissions reduction point of view, reducing mass, easing transportation requirements, simplifying maintenance and installation requirements are the clear priorities. Concrete structures will naturally weigh more but depending on their lifetime emissions may even out over the course thanks to those other aspects. Additionally, the proposed manufacturing facility will tend to the Celtic Sea specifically so understanding the environmental conditions will also play an important role as the structure needs to be able to withstand said conditions and operate efficiently.

This manufacturing facility will need to develop these components and will not need to be concerned with the direct source of the raw materials. However, it is in these environments where steel and concrete are produced where the largest cases of emissions are produced. Therefore, to minimise impact, further identifying opportunities within the local supply chain to acquire materials that have been produced in a way as to minimise impact. Finally, utilising technology similar to what is described in Table 23 will help ensure that emissions are kept to a minimum.

There are a lot of factors that could influence the results of this proposed facility, so a detailed LCA will be essential in determining the best choice going forward.

Table 21: Summary of the CO_2 emissions produced by different materials.

Material	CO_2 emissions (kg per eq)
Steel (industry standard)	1.4521
Concrete	0.15729
Carbon fibre	83.874

Table 22: Summary of the mass produced by different floater 15MW structures.

Substructure Type	Est Platform mass (t)
Semi-sub Steel	4,000
Semi-sub Concrete	18,000
Barge Concrete	17,500
Suspended Spar Steel	4,375

Table 23: Summary showing the primary source of emissions and solutions for different material manufacturing processes.

Material for component	Manufacturing process – sources of emissions	Emission reduction solutions
Steel	Produced across entire process, melting/foundry is the primary source	Recycling, CCS, hydrogen, reusing waste materials, renewable electricity generation, efficient/accurate plant management
Concrete	Main source is during the manufacture of cement	New binder constituents (limestone), CCS, renewable electricity generation
Composite	Highly energy intensive process with various stages that require frequency heating	Recycling, CCS, efficient/accurate plant management, renewable energy generation

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