Cornwall FLOW Accelerator

WP4 – D2.1. REDUCING CARBON FOOTPRINT OF TOWER MANUFACTURING – LITERATURE REVIEW

Document Title		WP4 – D2.1. REDUCING CARBON FOOTPRINT OF TOWER MANUFACTURING – LITERATURE REVIEW	
Document Reference		CFAR-OC-018-31032022	
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 FOW

TASK 2: REDUCING CARBON FOOTPRINT OF TOWER MANUFACTURING – LITERATURE REVIEW

GENERIC REPORT

Author: Dylan Duncan

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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1 Literature Review

1.1 Introduction

As the demand in offshore wind turbines increases so too does the demand for materials and manufacturing. One of the largest and most demanding (at least in terms of the volume of required material) components to manufacture is the tower. However, prior studies have shown that the majority of CO_2 emissions produced by offshore wind occur during manufacturing and a general breakdown of the embedded carbons per asset has been produced (Figure 1).

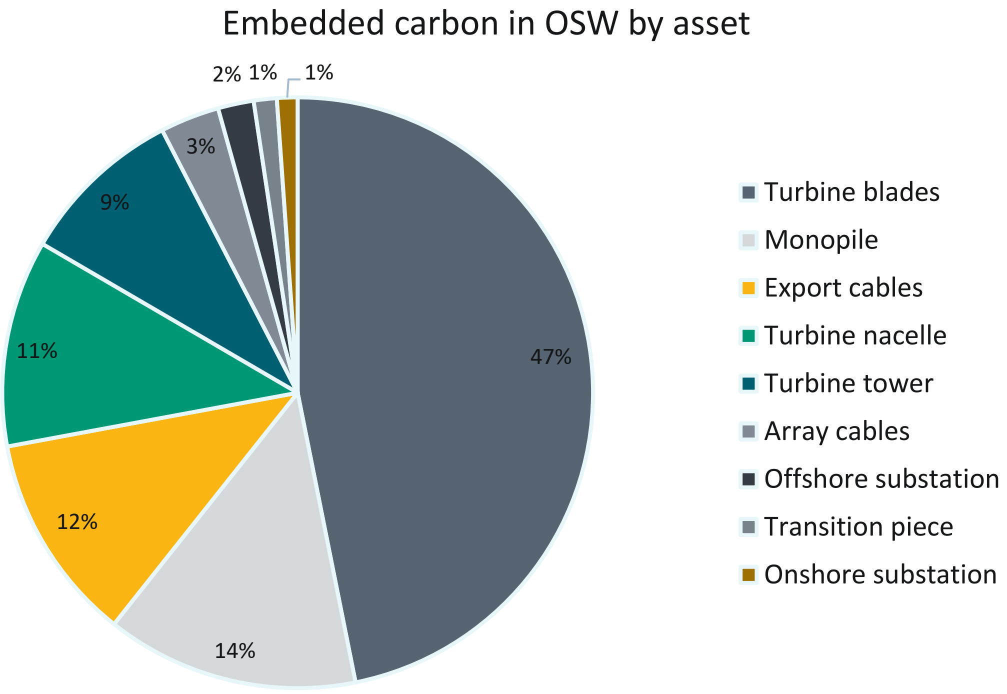


Figure 1: Embedded carbon in offshore wind turbines by component

We can see that around 9% of embedded carbon in a typical offshore wind turbine comes from the turbine tower. This showcases a need to examine more eco-friendly materials and how to reduce emissions during manufacturing.

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 towers, alternative materials, alternative structures and improved manufacturing processes. This is to identify areas of potential interest for future development.

1.1.1 Literature Review Structure and Scope

The literature review will consist of four chapters:

1) Wind turbine tower material selection
2) 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 in wind turbine towers will also 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 is changing structure type if worthwhile.

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.

1.2 Wind Turbine Tower Material Selection

1.2.1 Tower Industry Standard Materials

The tower is one of the simpler components within a wind turbine assembly. The majority of wind turbines are constructed as tubular steel towers. There are some hybrid designs that also utilise concrete. These combined concrete and steel designs are known as hybrid towers and are well suited to larger turbines. Essentially concrete forms the bottom section for increased stability and steel forms the upper sections.

Table 1: Estimated mass of a 15MW wind turbine tower

Component	Mass	Material
Tower	860,000 kg	S355 steel
Transition Piece	100,000 kg	S355 steel

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 2 and

Table 3.

Table 2: 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 3: Properties of concrete. [1]

Concrete	Values
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 tower's ability to withstand loads, vibrations 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 even out.

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 4: Material CO2 emissions. [2]

The majority of a wind turbine (tower, drivetrain, rotor, etc) are typically manufactured from steel and as suspected, steel is what makes up the majority of emissions, see

Figure 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 (Tower)	market for concrete, 50MPa	Rest of World	per kg	406.31

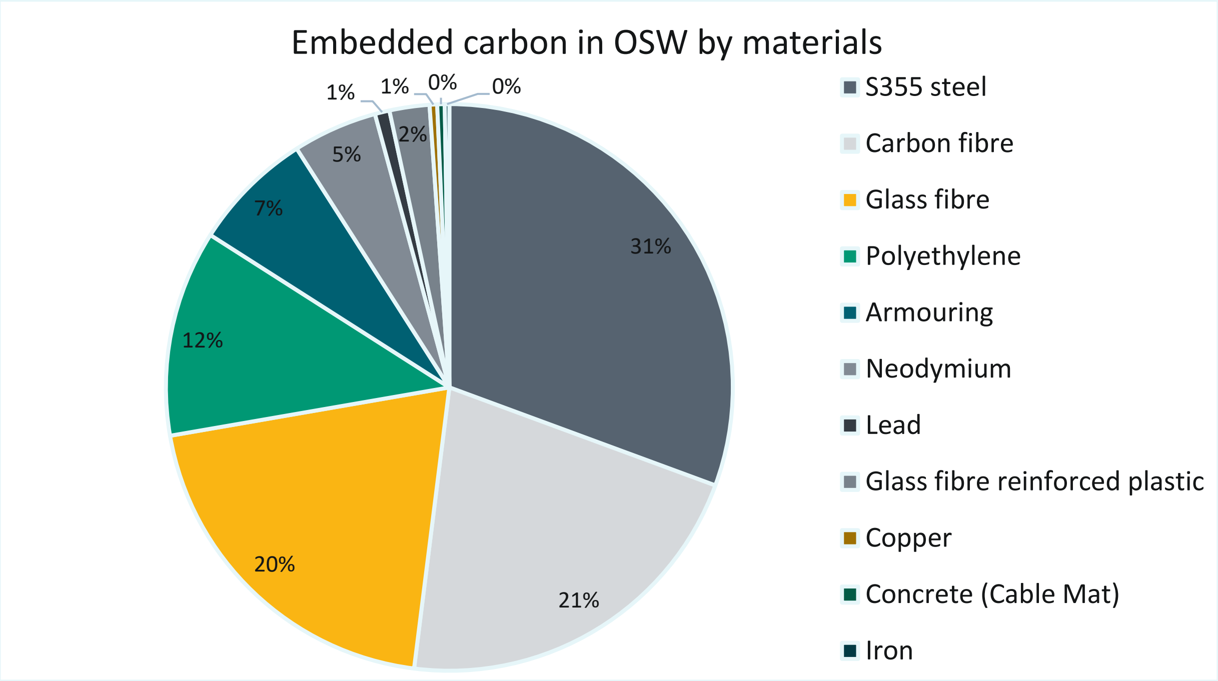


Figure 2: Embedded carbon in offshore wind turbines by materials

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 ecoinvent. (2021). *ecoinvent database*. https://www.ecoinvent.org/
[3],

Figure 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.

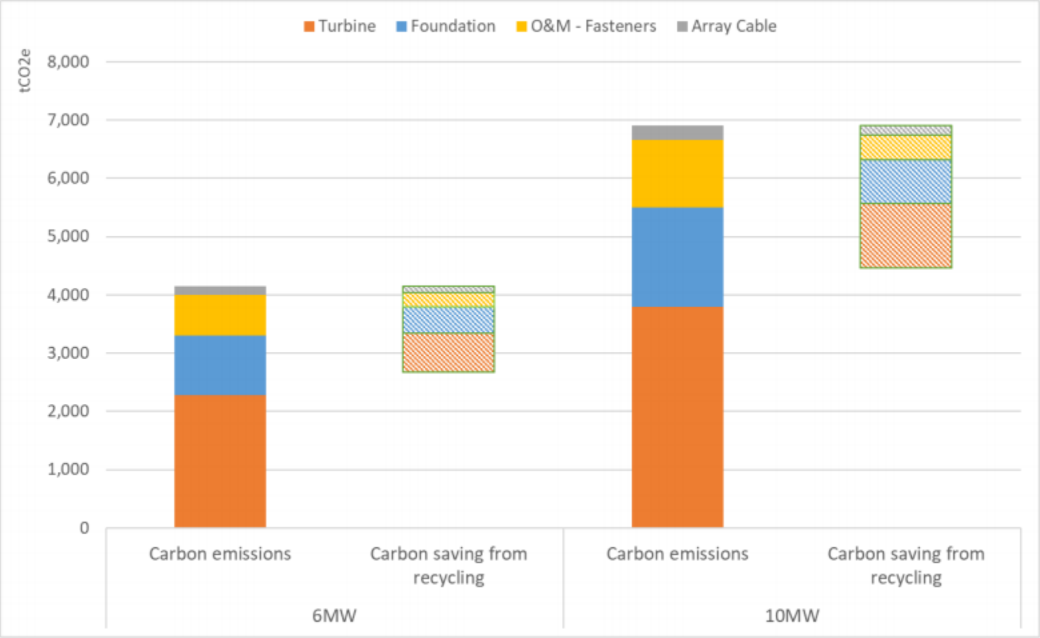


Figure 3: Emissions and savings when recycling windfarm components. ecoinvent. (2021). *ecoinvent database*. https://www.ecoinvent.org/

[3]

1.2.2 Alternative Materials

Selecting the materials for a wind turbine tower is incredibly important for a number of reasons. It is the heaviest component and has to endue high turbulent loads, many fatigue cycles over the course of its design life. Unlike other components, it also needs to be able to withstand the loading caused by rotor and nacelle and the loading caused by the environment (waves and current forces). Finally, it needs to be able to resist bending and buckling.

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 tower in this case was assumed to be a tapered hollow tubular tower,

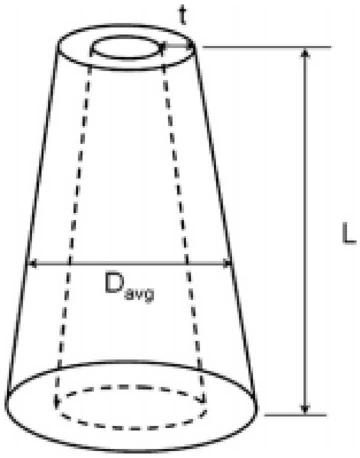


Figure 4: Diagram of a hollow tapered tower. [4]

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.

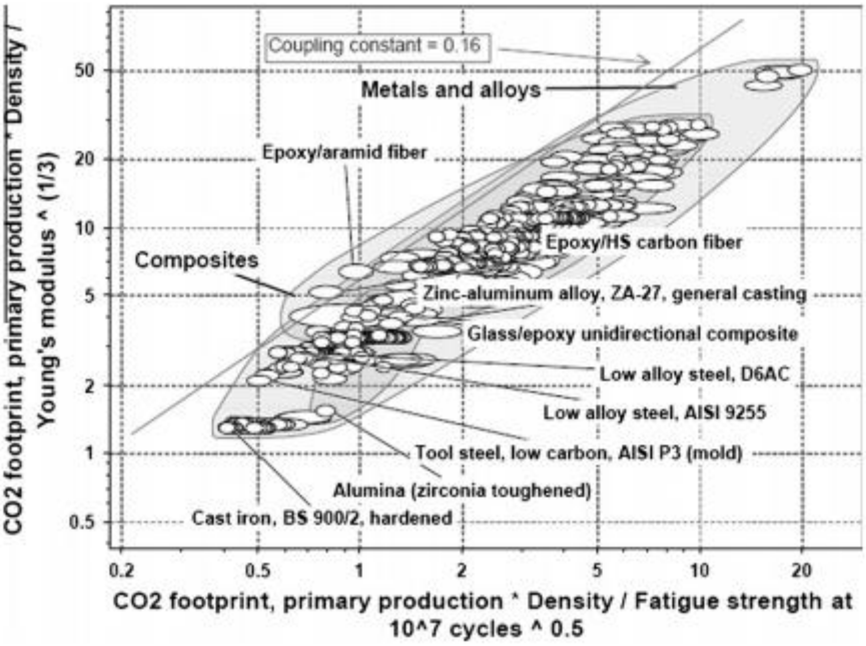


Figure 5: Material index on buckling against material index on bending (for carbon footprint). [4]

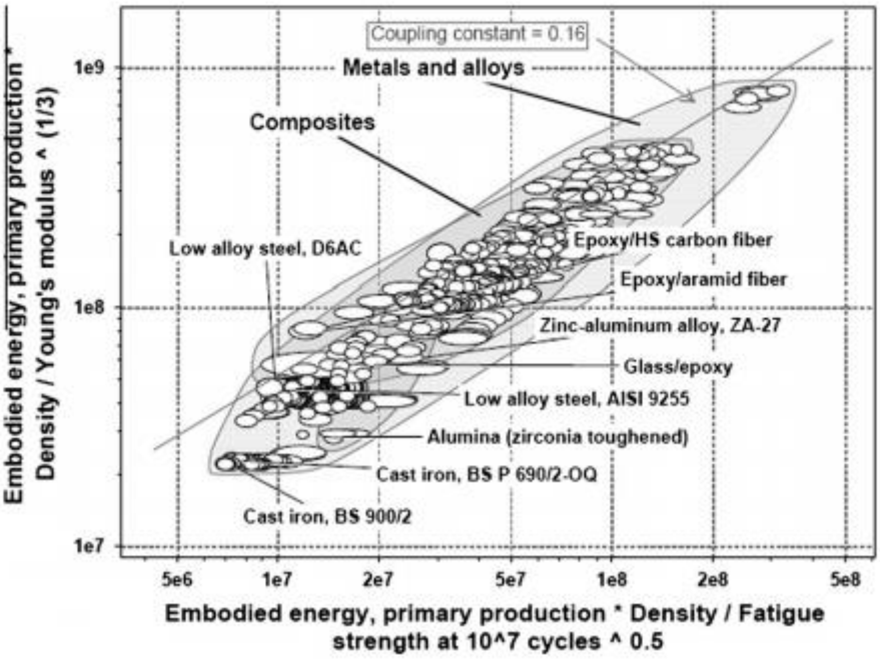


Figure 6: Material index on buckling against material index on bending (for embodied energy). [4]

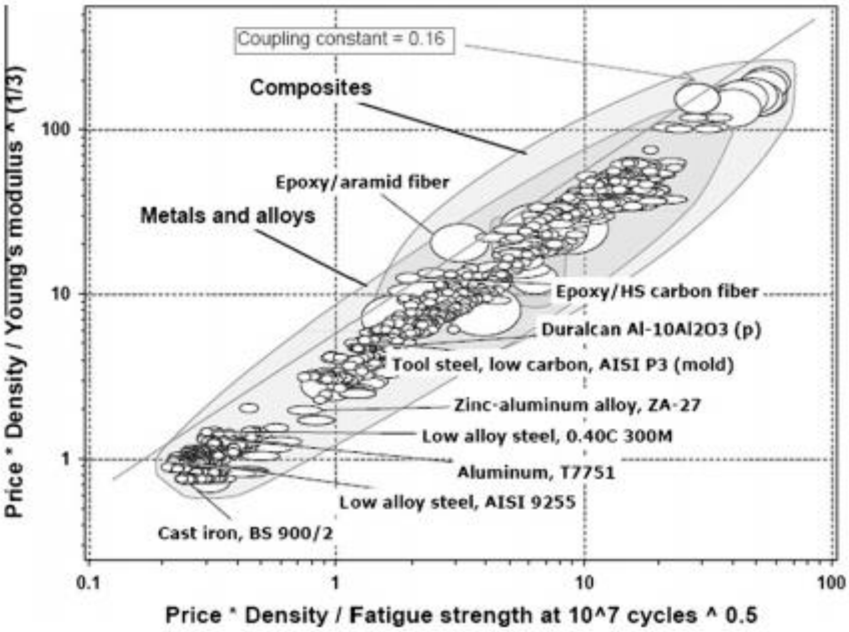


Figure 7: Material index on buckling against material index on bending (for cost).[4]

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 5, 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 6 (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. These two designs were compared with NREL's 5MW steel tower. An overall set of results can be seen in Table 5.

Table 5: Results comparison of different tower materials.[5]

Parameter	**270 – 280-280 mm T1**	**270 mm T2**	**Steel Tower**	**NREL 5MW Tower**
% of Strain Limit	38.74	9.27	8.56	Unavailable
Deflection Limit	99.5	33.2	10.3	Unavailable
Weight (tonnes)	75.82	58.52	550.7	224.8

It can be seen that differences across weight for the two composite towers is significant, with both T1 and T2 saving 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.

A separate study by Stavridou et al 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], 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 structures (see section 1.3) 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 6 showcases the scenarios for how different materials are handled at the end of their respective design life.

Table 6: Recycling scenarios. 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]

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 will 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.

One final material that is also worth considering is wood. Whilst it may be an unconventional choice there have been a number of onshore projects that use wood across Scandinavia and central Europe. By using wood, it can act as a carbon sink which can potentially make the wind turbines carbon neutral. Companies such as Modvion have agreed deals for producing wooden turbines that have a hub height of around 150m [7].Given the more extreme conditions that offshore wind turbines have to deal with, it is unlikely that wooden towers will be of serious consideration. However, if more companies such as Vestas start investing more into the research and development of these turbines then the technology involved may reach a point where offshore deployment may become a realistic prospect. It is also worth mentioning that if wooden turbines did become more commercially viable then the impact of acquiring the wood (via deforestation) in the first place would also need to be taken into consideration.

Figure 8: The inside of a Modvion wooden wind turbine under construction. Farmer, M. (2021, May 10). Reach for the sky: A tale of wood and wind. Power Technology. https://www.power-technology.com/features/reach-for-the-sky-a-tale-of-wood-and-wind/

[8]

1.3 Wind Turbine Tower Structure

It has been established then that one of the key aspects then with regards to emissions reductions is minimising material usage. The primary way of doing this is by changing how we design the structure of the turbine tower.

The two classic forms of turbine structure, the modern industry standard design is a tubular tower and a lattice structure. Although there are more experimental types of tower such as three-legged towers and hybrid towers which use a tubular and lattice combination (Figure 9).

Figure 9: Wind turbine tower structures. From left: tubular, lattice, concrete tubular, three-legged and hybrid. Mavrokefalidis, D. (2020, May 1). Sweden launches its 'first' wooden wind power tower. Energy Live News. https://www.energylivenews.com/2020/05/01/sweden-launches-its-first-wooden-wind-power-tower/

[9]

Despite the variety in types of tower structures, the tubular standard is used most commonly and is practically the only choice for large offshore wind turbines. This is for a number of reasons; the tubular tower is designed like a cantilever structure and is resistant against elements such as buckling loads caused by the wind pressure across the tower and the vertical load created by the rotor. By reducing the amount of material used via different structures, the structural integrity of the tower may be reduced, and the tower will become more susceptible to various failure modes.

Previously, a comparative analysis 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] was examined, this comparison study compared the difference in emissions between both lattice and tubular wind turbine structures through the use of a LCA. The below table showcases the significant difference of material requirements between tubular and lattice towers.

Table 7: Difference in material requirements between tubular and lattice wind turbine components.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]

	Tubular Tower		**Lattice Tower**	
Component	**Mass (t)**	**Weight fraction**	**Mass (t)**	**Weight fraction**
Rotor	34	0.04	34	0.07
Nacelle	55	0.06	55	0.11
Tower	127	0.13	77.47	0.15
Foundation	750	0.78	350	0.68
Total	966		516.47	

As it can be seen, the lattice tower requires significantly less materials than its tubular counterpart (the difference being 49.53 t for the tower component alone) this reduction will lead to a reduced emissions produced during the manufacturing stage. Figure 10 shows the the difference that this change in structure can have on overall emissions. Through the reduction of materials used, the % of emissions caused by manufacturing is reduced from 82% down to 75%.

Figure 10: The distribution of life stage CO_2 emissions. Left: Tubular Tower. Right: Lattice Tower. 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]

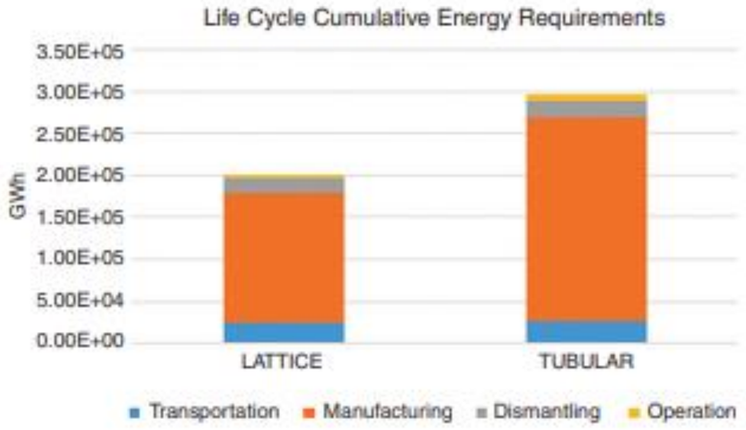


Figure 11: Life cycle cumulative energy requirements. Jaksic, V., & O'Bradaigh, C. (2018, April). Design of Offshore Wind Turbine Tower Using Composite Materials [Paper presentation]. Civil Engineering Research in Ireland (CERI2018), Dublin, Ireland.

[6]

Naturally, the reduction in manufacturing emissions will lead to a noticeable improvement in terms of life cycle energy requirements, see Figure 11. Additionally, the authors of this particular study noted that due to the significant impact on the energy requirements, the energy payback time is reduced for the lattice tower (5-6 months for the tubular tower and 4 months for the lattice tower). This may not sound like a major difference but in the case of worldwide wind farm developments especially for large scale offshore turbines, the overall cumulative payback time difference may prove to be quite substantial. Whilst this study is very useful for providing a good case for the positive impact of investigating new turbine structures, it is still an early study and more comprehensive studies on different types of wind turbine (offshore wind turbines) will be required going forward. However, the core LCA methodology used here could be adapted for use for a separate emissions study.

Stavridou et al [10] ran a comparative structural investigation between lattice and tubular towers with an emphasis on construction costs and energy consumption. Again, like in the prior paper they noted a noticeable difference in terms of weight with a roughly 40% steel reduction seen in the lattice tower. They also noted that lattice towers offer greater advantages in terms of transportation and on-site construction. Through this reduction, they were also able to estimate that the initial construction cost will decrease by around 15% if the lattice tower were to be adopted instead. It is clear from these papers that there are clear positives from looking at alternative tower designs.

That said, the amount of research that has been undertaken on comparing tower structures is limited at the time of writing and there are multiple areas where further expansion could be applied. Areas include; factoring in other types of tower structure (hybrid, concrete, etc), looking at offshore wind turbines (both floating and fixed) and taking into account general structural performance. It is known that tubular towers are typically more robust in terms of performance so it would also be worthwhile to run a comparison that takes into account potential failure rates in rough conditions as the positive emissions impact that lattice towers have may be offset if there is a greater chance of failure.

Whilst there isn’t much in terms of direct research for tower comparisons, there is some clear interest from the industry for looking at alternative structures. A number of patents have been put out that detail newer alternative designs. One such patent, ES2319709A1 [11], looks at a turbine structure that consists of a tower that is composed of three legs resembling that of a lattice/tubular hybrid design. However, as noted in the patent, this design has a lower concrete requirement and will use less materials overall.

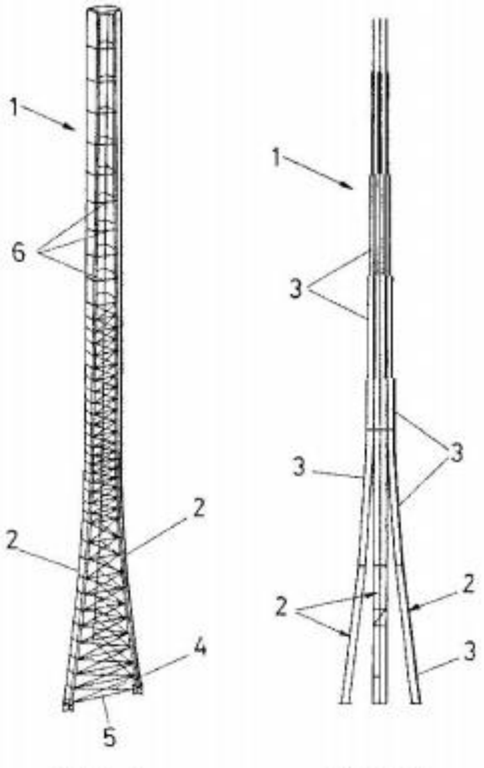


FIG.1 FIG.2

Figure 12: Two views of a proposed tower design. [11]

Another interesting patent includes a segmented tower, assigned to GE [12] where the tower is split into different “socket” and “plug” segments. This design and installation method should improve speed and efficiency with regards to offshore tower construction but may also have a positive impact with regards to reduced emissions due to transportation and manufacturing due to the tower consisting of separate smaller segments.

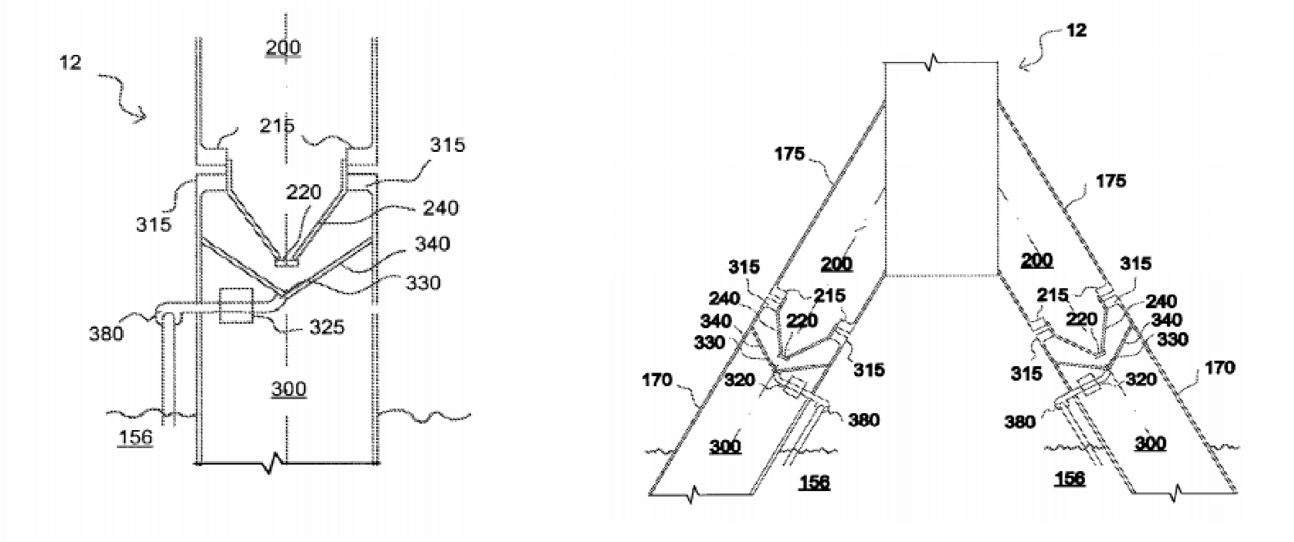
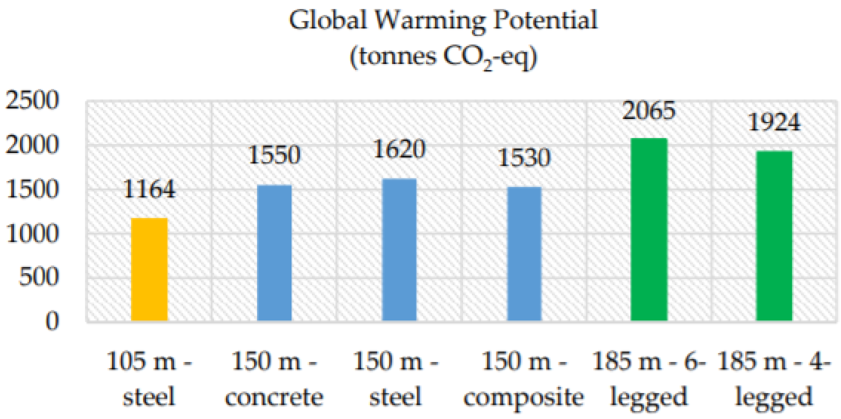


Figure 13: Views of the wind turbine socket and plug segment. [12]

There have not been many studies that have covered the potential emissions of these alternative structures, however Gkantou et al [13] managed to conduct a LCA on hybrid steel wind turbine towers (4 legged and 6 legged structures) and compared them to other tower sizes. Each type showed similar overall performance levels, although the hybrid towers (6 and 4 legged) performed only marginally worse despite being noticeably larger.



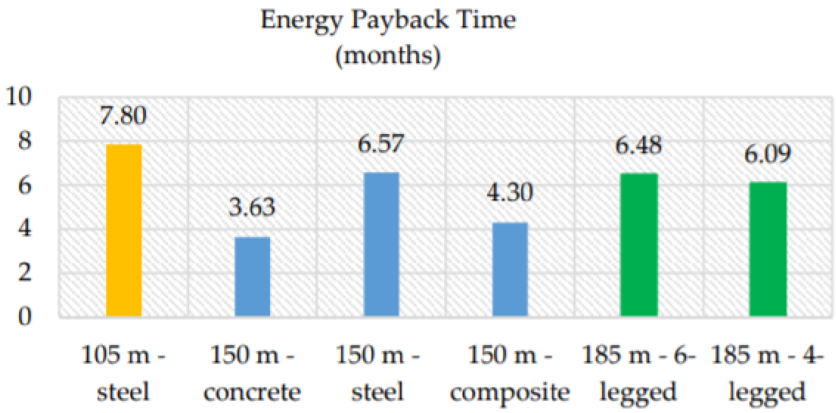


Figure 14: Top: The CO_2 emissions produced by different sizes and types of turbines. Bottom: The energy payback time for each separate type. [13]

1.3.1 Concrete, Steel and Hybrid Tower Comparison

Previously, the differences between the emissions between different materials were identified. However, there has been a substantial amount of work comparing the performance of both. Given that the industrial standard involves the use of one of these materials, it is highly likely that the prospective manufacturing facility would also build towers through these materials. Additionally, assessing emissions is more complex than simply looking at how many GHGs are generated during manufacturing. For example, a steel tower and a concrete tower will perform differently and as a result may be prone to different failure modes which may lead to varying lifespans. Therefore, understanding the mechanical differences between each will be very important with regards to deciding which will be the superior choice.

Quilligan et al Gkantou, M., Rebelo, C., & Baniotopoulos, C. (2020). Life cycle assessment of tall onshore hybrid steel wind turbine towers. Energies, 13(15), 3950.

[14] carried out a fragility analysis across both concrete and steel towers for a variety of tower heights (88m-120m). They were able to carry out this analysis by taking elements from a 5MW reference turbine. A lagrangian approach was used to create the equations of motion for a dynamic system which would allow the authors to include tower couplings and blades. Their study started off by examining the maximum tower tip displacements (

Figure 15), it was noted that the effect of increasing the level of turbulence had a high effect on the displacement but there was no noticeable change for either material. However, it should be noted that concrete towers experienced less displacement than that of steel towers.

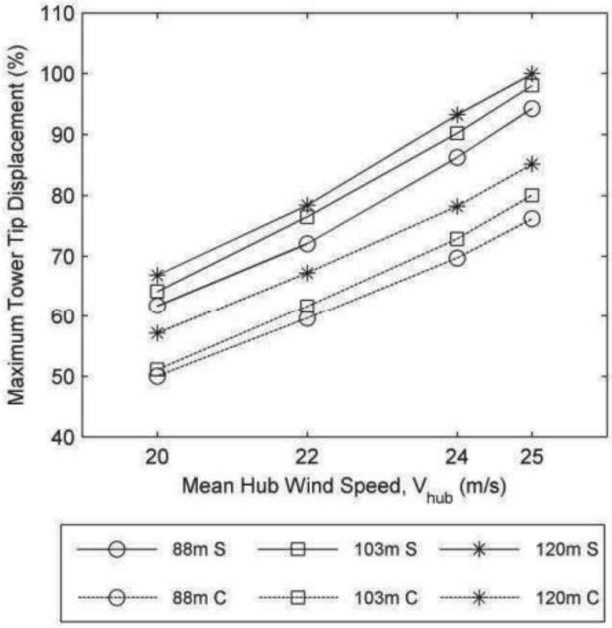
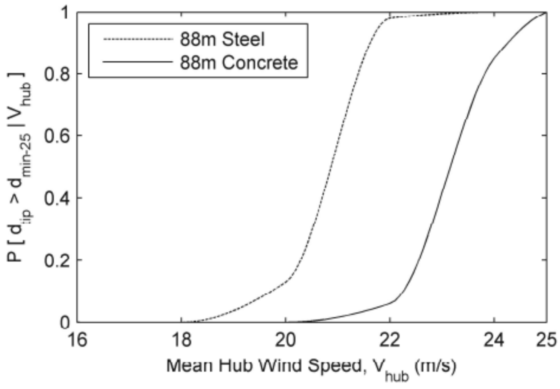
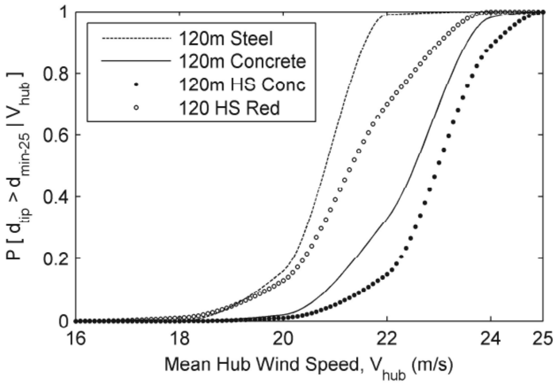


Figure 15: Maximum tower tip displacement for steel and concrete towers across a range of sizes. Gkantou, M., Rebelo, C., & Baniotopoulos, C. (2020). Life cycle assessment of tall onshore hybrid steel wind turbine towers. Energies, 13(15), 3950.

[14]

Fragility curves were also generated(figure x shows one example of the 88m tower). The limit state was made to be equal to the lowest maximum tip displacement. As can be seen steel shows a higher probability of experiencing limit state exceedance, indicating that concrete could perhaps perform better. However, a model of the long-term effects of prestressed concrete (creep or shrinkage) was applied and





that showed that steel would outperform concrete at lower wind speeds. For this reason, high strength concrete was suggested for "high performance" structures, the impact of which can also be seen in Figure 16. High strength concrete performed better than both regular concrete and steel.

Figure 16: Fragility analysis of concrete and steel. Left: 120m steel and concrete towers without considering long term effects. Right: A more detailed graph that considers long term effects and includes high strength concrete. Gkantou, M., Rebelo, C., & Baniotopoulos, C. (2020). Life cycle assessment of tall onshore hybrid steel wind turbine towers. Energies, 13(15), 3950.

[14]

Technical advantages aside, assessing the difference in costings between both materials is also important. Way and Van Zijl carried out a study on the material costs for wind turbines in South Africa [15]. Similar to this report they identified the three primary types of turbine tower as tubular steel tower, segmented concrete tower and the hybrid tower. They also ran a FEM analysis for these three different types of tower, the results of which can be seen below.

Table 8: The results of the FEM analysis comparing key results against different tower types at different sizes. [15]

Tower Height (m)	**Tower Type**	**Natural frequency (Hz)**	**Buckle value**	**Tower deflection (m)**
80	Steel	0.285	1.65	0.92
	Concrete	0.432	10.1	0.37
	Hybrid	0.407	2.25	0.52
100	Steel	0.251	2.84	1.35
	Concrete	0.333	4.65	0.60
	Hybrid	0.338	2.25	0.80
120	Steel	0.238	3.48	1.48
	Concrete	0.261	2.38	0.99
	Hybrid	0.297	2.27	1.06

As can be seen the table, concrete and hybrid towers possess a higher natural frequency than that of steel, showcasing that they possess sufficient stiffness, although care should be taken as in some cases the frequencies may be too high. The buckling values vary between each material at different turbine sizes. Finally, Steel towers experience more issues with tower deflection.

Table 9: A comparison of material usage and cost across different types and sizes. Cost from original source were in South African Rand and were converted through exchange rate in December 2015. [15]

Tower Height (m)	**Tower Height (m)**	**Mass of Steel (ton)**	**Volume of Concrete (m^3)**	**Tower cost (£)**
Steel	80	183.6	-	150314.04
	100	330.6	-	270714.87
	120	685.7	-	561512.62
Concrete	80	-	306	57277.42
	100	-	457	101621.25
	120	-	608	168206.03
Hybrid	80	72.2	147	91437.28
	100	72.2	221	114489.23
	120	72.2	434	154522.75

The material costs can also be seen in **Error! Reference source not found.**. The costs in this case cover the materials (including concrete reinforcing and prestressing processes), production, installation and transportation costs. As can be seen both concrete and hybrid towers are noticeably cheaper.

There are other key advantages that concrete towers ~~ayh~~hold over their steel counterparts. One key one is that concrete towers are constructed in segments which allows for easier transportation. Given the fact that turbines are increasing in size, the need to modularise them will become essential for transportation. An example of such a tower can be seen in **Error! Reference source not found.**.

Figure 17: An onshore segmented concrete tower under construction. [16]

1.3.2 Bolts and Tower Connections

A tower is typically assembled through the use of bolts and flanges which can have an impact on the overall mass of the tower. Additionally, these same connections can have an impact on other key structural aspects such as structural strength and fatigue resistance. Issues with bolt loosening during operation can also arise. If tower joints are poorly designed then the tower could potentially experience a major failure which would have a catastrophic impact on lifetime emissions and the local environment.

Whilst there is no core connector configuration that is specifically built for the purposes of emissions reduction but using new, improved structural joint technologies whilst employed the latest in O&M techniques will be of vital importance with regards to ensuring structural integrity remains consistent.

With regards to what type of bolted connection is most typically used, for a standard cylindrical tower, bolted flanges with pre-stressed bolts are most common. Lattice towers naturally have widely different connections differences and will rely on more traditional steel bolts are a way of fixing structural members to each other. However, there is an industry desire to look into new alternative joining methods, for example GE have a patent [17] for an alternative joint that uses a joint through a tapered edge. The claim with such a joint is that it could potentially minimise or remove the need for flanges entirely. This would reduce materials, costs, weights, removes the need for welding and may help simplify the construction process.

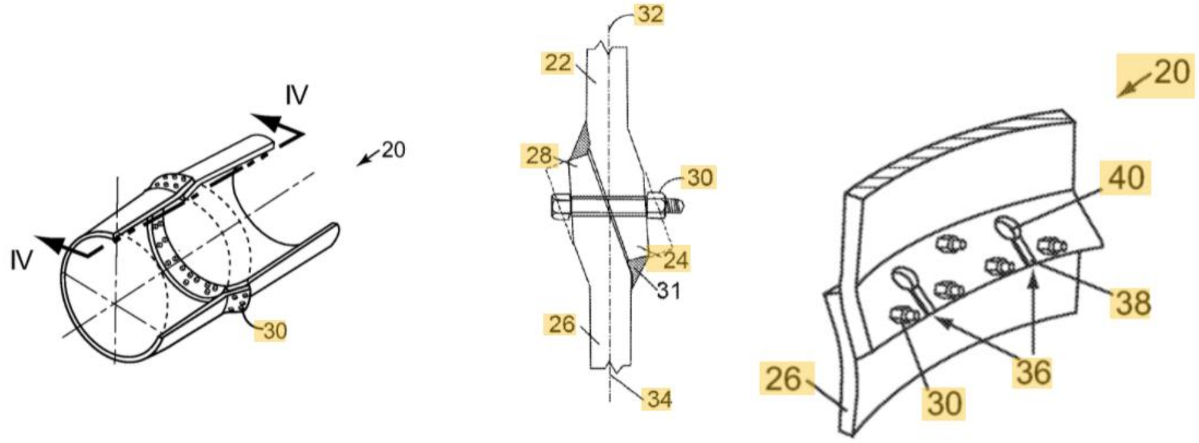


Figure 18: Diagram of the patented GE tapered edge design. [17]

Ultimately, such joining tehcniques are largely untested in the field so a more traditional connection system will be considered for the purposes of this study. In this case, ensuring continued operation of the tower will be of vital importance. Bolt looseness occurs due to long-term vibration and can be difficult to detect and reoslve in an offshore environment but it can also lead to potentially catastrophic failures if left untreated. One detection method was proposed by Xianlong and Tianli [18]. This method looks at a change in measured phase difference and can provide quick looseness detection in real-time. Alternatively, companies such as R&D A/S have developed a monitoring system Xianlong, H., & Tianli, S. (2019). A new identification method for bolt looseness in wind turbine towers. *Shock and Vibration*, *2019*, 1-10.

[19] that utilises ultrasonic sensor to look at bolt tension. Ensuring continued operation of the wind turbine tower will have a more profound on lifetime emissions by ensuring the turbine can reach it's operational lifespan and possibly beyond.

1.3.3 Internal Structure

The tower does not just consist of a solid vertical structure, the inside has an internal structure that can consist of ladders, stairs, 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 tower structure that the impact on emissions would be negligible. In practice, it would be preferable that any focus on the internal structure is put into using the safest and most robust equipment possible.

Figure 19: Inside of a wind turbine. [20]

1.3.4 Painting and Cleaning

As with any large engineering structure, painting and cleaning can be a significant undertaking especially in the case of offshore wind turbines where accessibility remains a key challenge with regards to any O&M work. There are a number of potential paint solutions in the industry which can help mitigate against corrosion and abrasion.

One notable paint supplier that caters specifically to the wind industry is Hempel Power and Cables. (2022). *Wind Turbine Tower*. https://www.powerandcables.com/cable-cleats-wind-energy/wind-turbine-tower/

[21], who possess a noticeable library of wind turbine solutions with a keen interest in solutions that can deliver a complete painted tower with 2 or 3 coats reducing costs and increasing speed of application. 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 [22] 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.

From a sustainability perspective, painting the turbines a different colour could potentially reduce bird fatalities. A study conducted by May et al [23] highlighted that painting blades black could potentially reduce the fatality rate by 70%. Whilst this is more relevant to the blades more than the tower, it is worth noting here as well.

Figure 20: Hempel spray painting process. Power and Cables. (2022). *Wind Turbine Tower*. https://www.powerandcables.com/cable-cleats-wind-energy/wind-turbine-tower/

[21]

Similar to painting processes, the chemicals used in cleaning procedures can also produce high amounts of VOCs. However, also similarly to painting, there is a noticeable lack of data on the specifics of cleaning emissions, but it could be assumed that the values would be negligible when compared to manufacturing emissions.

Painting and cleaning processes would also generate emissions during the turbine's operation due to transportation. It's already been shown that the operation of the turbine only makes a small percentage of emissions. This can be mitigated further by using longer lasting paints to increase time between applications and potentially using new technologies such as robotics [24], this would help lead to more environmentally friendly and ultimately, safer O&M practices.

1.4 Reducing Emissions During Manufacturing

Regardless of the materials used or the design of the wind turbine tower, 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 wind turbine towers.

1.4.1 Current Manufacturing Processes

With the sheer variety in different types of wind turbine towers (in terms of materials, design and size), it will be difficult to identify a clear universal manufacturing process and what the emissions produced for each type is. However, it will be worthwhile to examine several current manufacturing processes as further improvements can be suggested later on and assumptions can be made with regards to emissions impact.

It has already been established that the most common type of wind turbine tower are conical tubular towers. The manufacturing process for this uses a complex method by taking a steel plate and rolling it into a conical subsection. Producing these parts is a challenge as achieving a conical shape requires the applied tension on the steel rollers to be different on two sides to make the proper shape [25]. These subsections are then welded together.

Figure 21: The rolling process for manufacturing a steel conical tubular tower.[25]

There are several manufacturers that create these large towers but at the time of writing there are not any currently based in the UK. Valmont SM are an example of a world leading manufacturer that specialise in manufacturing wind turbine towers. They use automated production lines that can create towers up to 7m in diameter. Additional forms of surface treatment are used such as sand blasting, metallization and coating. Many of these processes are fully automated.

Figure 22: Top: Valmont SM automated coating line. Bottom: Tower manufacturing line.Krohn, S. (2000, August 6). Manufacturing Wind Turbine Towers. WindPower. http://ele.aut.ac.ir/~wind/en/tour/manu/towerm.htm

[26]

There are alternative forms of manufacturing that have been suggested or applied at smaller scales. The sheer size of turbine towers can cause severe issues during transportation limiting size potential. A new manufacturing technology (spiral welding) has been used to create on-site, automated tower fabrication. Jay and Myers [27] examined design standards for using slender shells and applicability to shells manufactured by spiral welding. They focussed on buckling and fatigue whilst examining performance differences between traditional towers and spiral towers. The below figure shows the geometry of the rolled and unrolled tower.

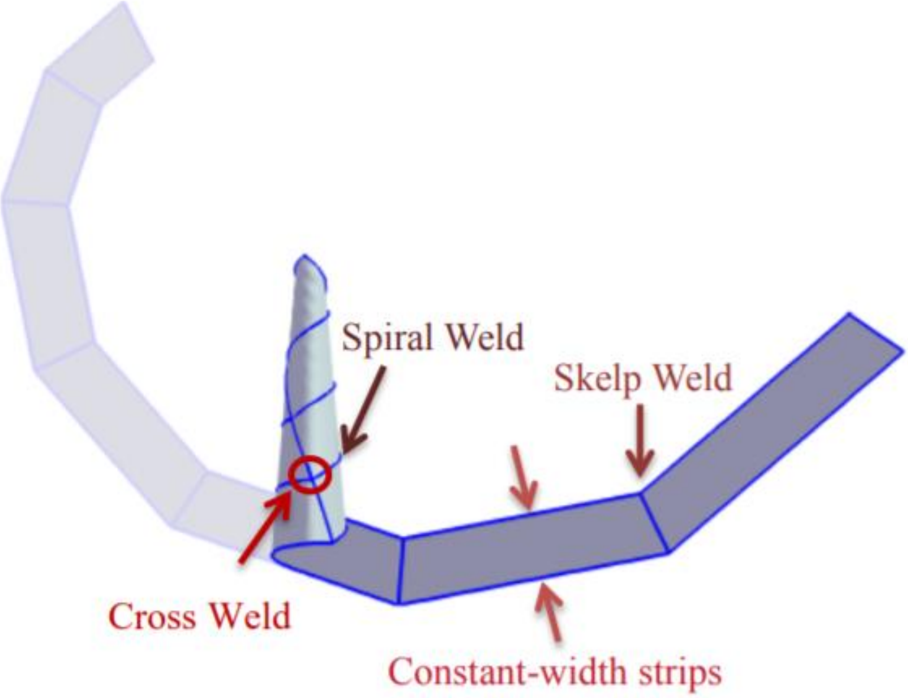


Figure 23: Geometry of a rolled and un-rolled conical tubular tower that has been manufactured via spiral welding. [27]

This spiral welded tower contains unique features that may result in imperfections that could impact the buckling or fatigue strength. Although whilst performance may be a hard aspect to assess due to these imperfections, alternative processes such as this may prove to be more economically viable and by reducing transportation may also produce fewer emissions. Although there is no work currently that proves that.

Sainz [28] has listed the primary manufacturing techniques that are using each core turbine component. He states that the construction of a tower involves Cutting “fan-shaped” plate sections from steel plates, rolling and welding them into cone sections. The author states that in order to achieve the required levels of accuracy and repeatability, there needs to be solutions that can increase productivity whilst improving structural strength, through this requirement the development of several technologies is suggested but it has not been identified whether or not these technologies would help reduce emissions.

However, the prospect of using precast concrete towers was also suggested. Offering high levels of stability, structural dampening, requiring less maintenance due to fewer smaller “joining” components and are also easier to transport. A concrete turbine would naturally require different but relatively simple processes (using moulds and templates), similar to those that could be found in normal concrete manufacturing plants in other industries. As stated earlier on, there is potential in using hybrid towers which can be formed by creating the lower section with concrete and adding a separate metal part on top. The combinations show promise in terms of being more rigid closer to the bottom whilst still offering the required levels of flexibility at the top. Again, it is not clear how the different manufacturing processes would impact the emissions levels here but the potential for increasing performance levels, reducing maintenance costs and easing transportation will likely make a positive impact.

That said, these current studies do not take into account factors like the production of the materials themselves or consider alternative sources of fuel. These factors are responsible for the highest levels of emissions and will likely be vital going forward in the future.

1.4.2 Manufacturing Process Improvements

Having established a general understanding as to how wind turbine towers are manufactured, the next step will be to figure out how to improve the processes involved with regards to reducing emissions across the steel sector.

Holappa [29] 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 tower 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 combined 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 [29]. 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 10 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 10: CO_2 emissions (g/kWh) from electricity generation through using different sources of energy.[28]

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 24. Through this figure, the author has provided a clear pathway to a greener iron/steel industry.

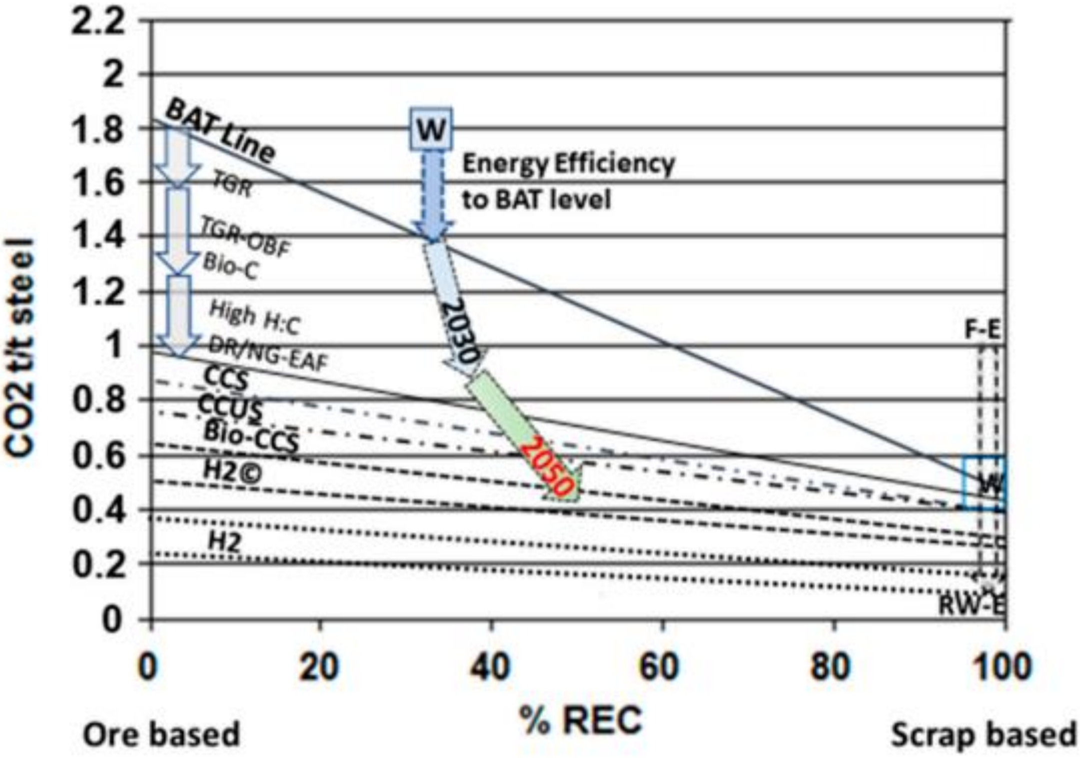


Figure 24: Summary of a potential pathway to reducing CO2 emissions in the steel/iron industry. Each different line shows the assessed reductions levels that are achievable via each labelled method. The arrows show a plan for the future for the industry up to 2050. Where BAT means best available techniques, TGR is top gas recycling in oxygen blast furnace, DR/NG.EAF reference direct reductions: natural gas, electric arc furnace. [29]

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 tower 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.

[30] produced a similar pathway for a low carbon transition in the Swedish steel industry. Similarly, to Holappa [29], 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 11 for more information.

Table 11: 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.

[30]

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 12.

Table 12: 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.

[30]

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 25). 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.

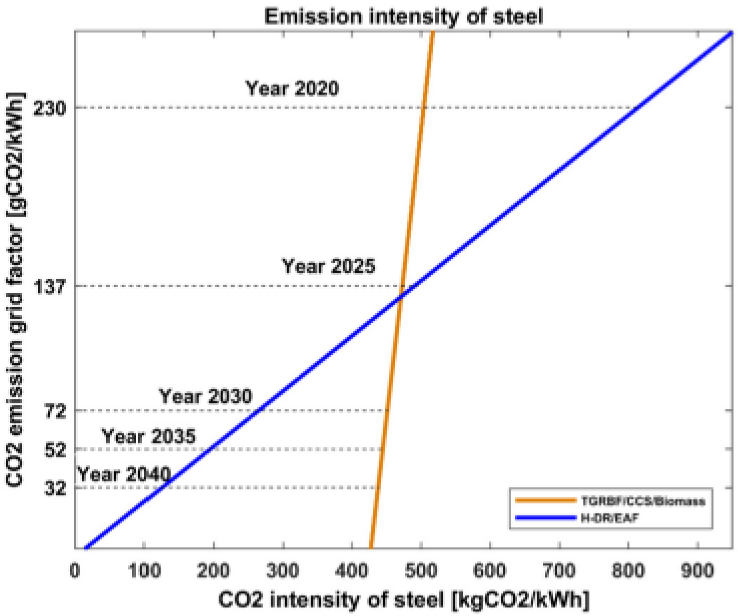


Figure 25: CO_2 emissions intensity for primary steelmaking in pathways 1 (orange) and 2,3 (blue) as a function of European CO_2 emission grid factor. Dotted lines indicate development of European CO_2 emission grid factors that have been estimated by IEA. Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. Metals, 10(9), 1117.

[30]

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.

[31]. 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 an 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 section 1.3 where the potential use of alternative tower structures was looked at with regards to reducing materials/ weight. 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 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 13: 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.

[31]

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 13 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 tower 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 [32] looked at the difficulties associated with energy efficient casting process. Given that cast iron was one of the potential materials that was mentioned earlier, it is worth understanding the challenges and potential solutions for the manufacture of such a component.

Table 14 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 plant 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 14: Energy loss and energy saving opportunities summary. [32]

	Energy loss reason	**Saving method**	**Saving type**
Melting	1. Inefficient melting	1. Correct size of furnace 2. Rapid melting	Direct/Indirect

	2. Permanent metal loss	3. Keep melt away from air	
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 [33], 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 14, 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.

1.4.3 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 [34] 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 26 showcases these statistics and highlights when CCS would be most economically feasible.

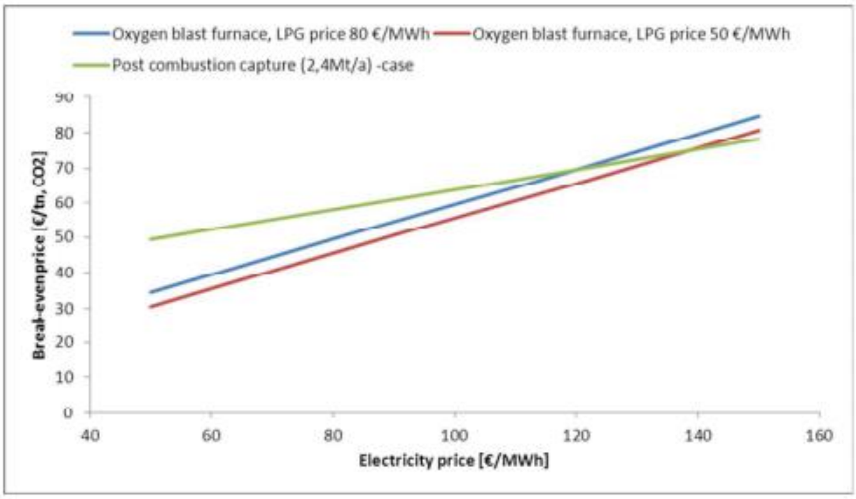


Figure 26: The effect that electricity price has on the "break-even" price when CO_2 capture becomes more feasible than buying CO_2 emission allowances. [34]

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.

[35] 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.

[35].

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.

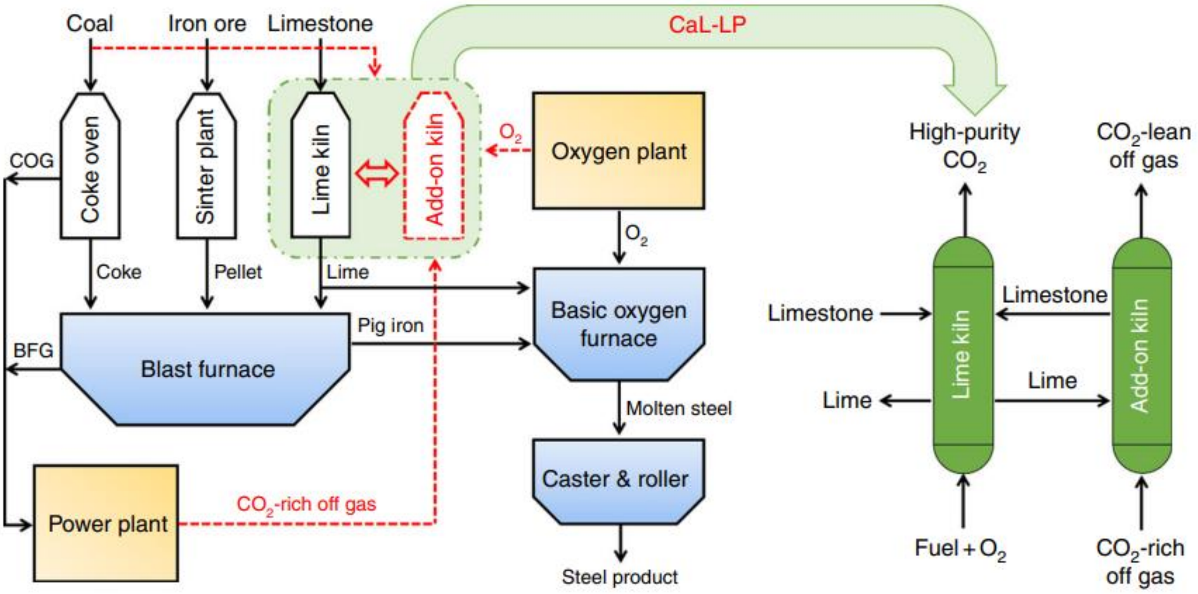


Figure 27: Proposed concept for integrating CCS into iron and steel production. This depicts a steel mill using calcium-looping lime prodiction (CaL-LP) for CO_2 emission reduction. The red lines indicates mass flow due to the scheme and the solid black lines show the mass flow due to present manufacturing 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.

[35]

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 28 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.

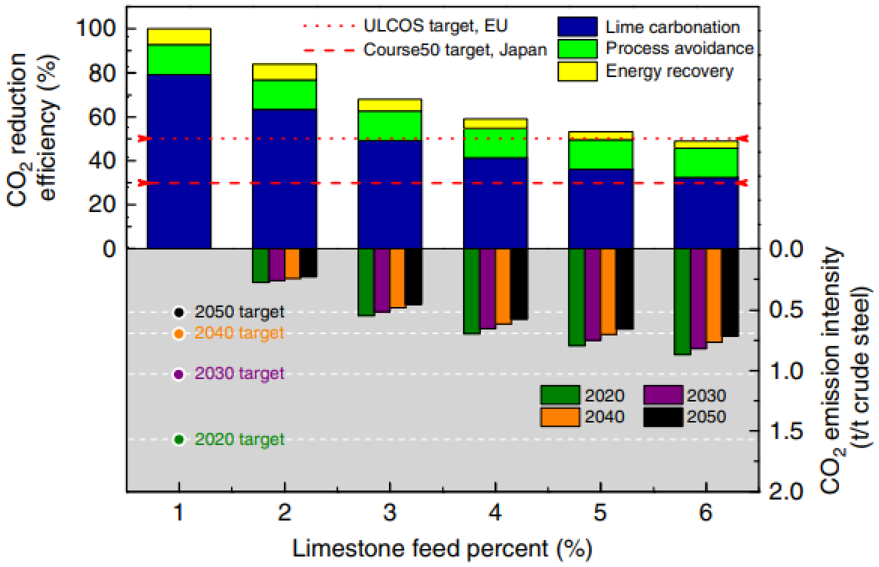


Figure 28: Potential for decarbonisation in a typical steel mill whilst using the CaL-LP process. [35]

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.

1.4.4 Hydrogen

The European parliament ran a study that explored the potential for decarbonising steel manufacturing through hydrogen [36]. 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.

1.4.5 Alternative Material Manufacturing – Concrete

Ultimately steel and iron are not the only two materials that could be used, the use of concrete has been shown to be effective at manufacturing towers. There is also the potential development of hybrid wind turbines which use both steel and concrete. 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 [37] 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 causes 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 greenhouse 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 [37].

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 [37] 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 29.

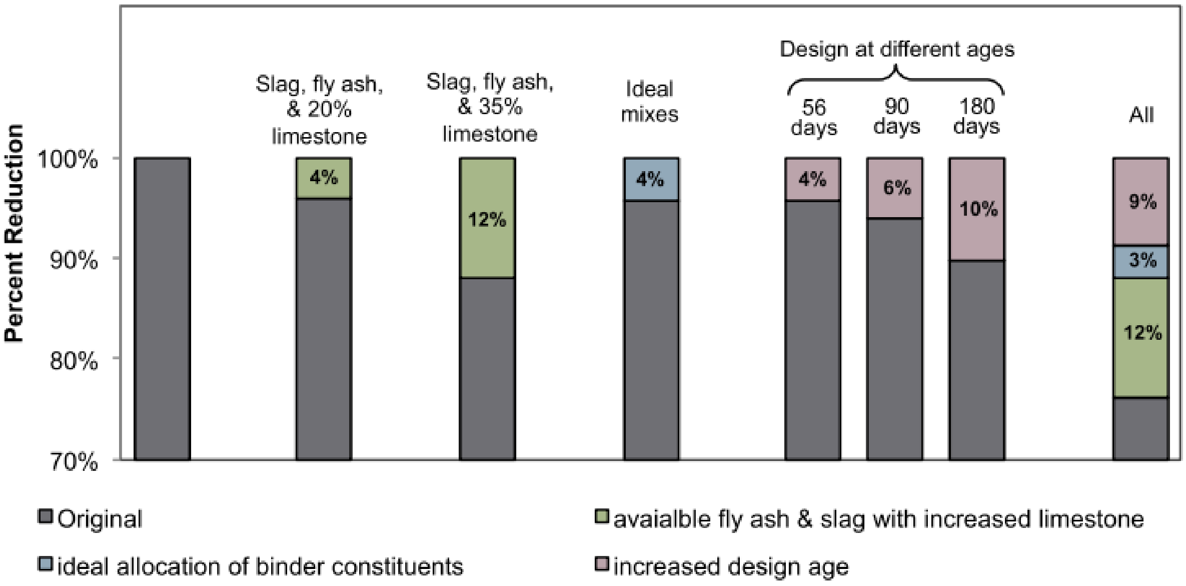


Figure 29: A graph showing the original emissions generated by concrete in 2012 along with three proposed methods for reducing emissions. The combination of each of these three designs assumes a design age of 180 days. [37]

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 [38] 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 concrete~~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 30 helps provide a rough idea as to the maximum reductions that could be made by implementing these processes.

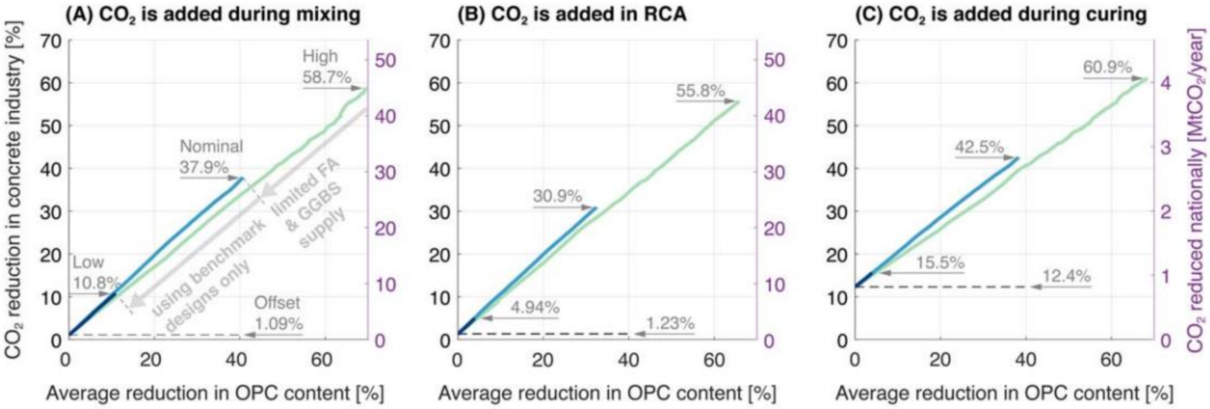


Figure 30: CO₂ mitigation via implementing a strategy that reduces binder and adds CO₂ during formulation. The results displayed here only show the largest CO₂ mitigations achievable and present median values. [38]

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 tower 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.

1.4.6 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 and reduce the amount of material required which may lead to a reduction in CO₂ emissions.

There are a wide variety of composite materials that could be used for tower 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.

[39] 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.

[39]. 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 CO₂ emissions reduction.

Das 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

[40] 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 tower 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

[40]:

- Steel: Stamped steel.
- PAN sheet moulding compound (SMC): Textile-grade precursor to 44polyacrylonitriles (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 15 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 towers 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 15: 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

[40]

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 [41]. 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 31 summarises the complete manufacturing process.

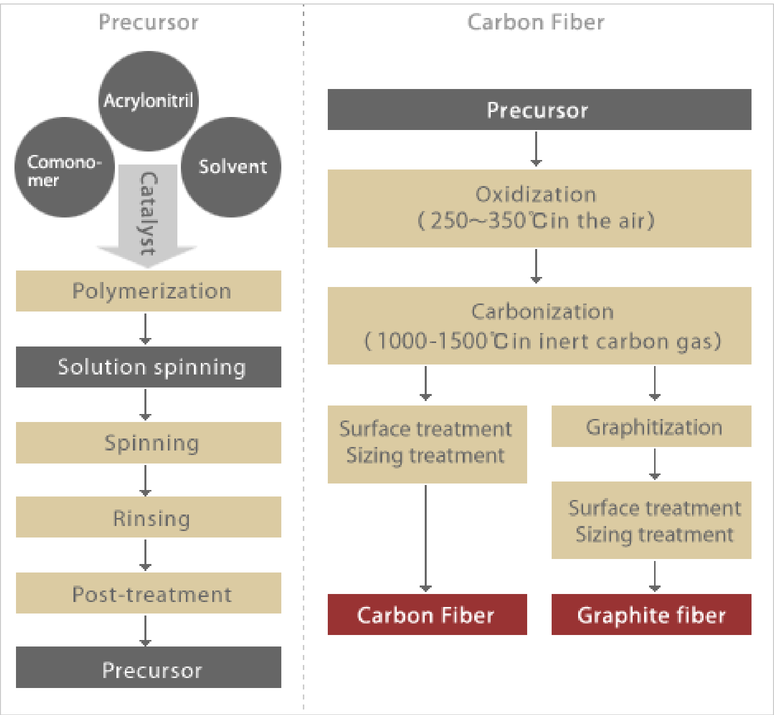


Figure 31: Carbon fibre manufacturing process. [42]

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.

1.5 Emissions Reduction Summary

Overall, the potential for tower innovation in terms of emissions reduction has been explored. In order to reduce emissions, the two critical areas are material selection and structural design. With regards to material selection, each material produces varying levels of emissions, and it would be worthwhile to look into mechanical performance as whilst a wooden tower would likely outperform other materials in terms of emissions it would likely fail in offshore conditions. At the time of this report writing, steel towers are the norm due to high stiffness and ease of manufacture. Possibly by taking advantage of the methods described in section 1.4, the steelmaking process can be made less carbon intensive. Additionally, concrete towers show potential with a slight reduction in overall emissions over their steel counterparts.

There are also opportunities within structure design, on paper the lattice tower has a clear advantage over the industry standard tubular design in terms of direct emissions reductions due to it using far fewer materials, but it's reduced structural performance may lead to higher failures which would then lead to greater emissions and higher LCoE. With this in mind there is an active interest in producing a more efficient design through hybrid, concrete or more highly conceptual designs (Figure 18). Potentially going forward in the future, we may see more conceptual designs that make use of modular designs for easier manufacturing, transportation and installation with more advanced materials (for example, composites) that may last longer thus providing a more eco-friendly solution.

Table 16: Summary of the CO_2 emissions produced by different materials.

Material	**CO_2 emissions (kg per eq)**
Steel (industry standard)	1.4521 [2]
Concrete	1.7159 [2]
Iron	406.31 [2]
Carbon fibre	83.874 [2]

Table 17: Summary of the CO2 emissions produced by different structures.

Structure/material Type	Estimated CO_2 emissions (tonnes CO_2 per eq)	Emissions Savings (%)
Tubular steel (Industry Standard)	1620 (150m) [13]	-
Concrete	1550 (150m) [13]	4.32% reduction
Steel lattice	1530 (150m) [13]	5.55% reduction
Hybrid (steel lattice and tubular)	2065 (185m) [13]	27.47% increase
Hybrid (concrete and steel)	No study in literature	N/A

Table 18: 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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