Title	Optimization of composite material tower for offshore wind turbine structures
Authors(s)	O'Leary, Kieran, Pakrashi, Vikram, Kelliher, Denis
Publication date	2019-09
Publication information	O'Leary, Kieran, Vikram Pakrashi, and Denis Kelliher. "Optimization of Composite Material Tower for Offshore Wind Turbine Structures." Elsevier, September 2019. https://doi.org/10.1016/j.renene.2019.03.101.
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/10499
Publisher's statement	This is the author's version of a work that was accepted for publication in Renewable Energy. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Renewable Energy (140, (2019)) https://doi.org/10.1016/j.renene.2019.03.101
Publisher's version (DOI)	10.1016/j.renene.2019.03.101

Optimization of composite material tower for offshore wind turbine structures

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Abstract

The focus of this study was to investigate the application of lightweight fiber reinforced composite materials in the construction of offshore wind turbine support structures. A composite tower design suitable for the NREL 5MW reference wind turbine is presented. The design is based on the most automated and low cost composite manufacturing methods (pultrusion and filament winding) and the conclusions of this study may not be applicable for offshore structures using different composite material construction techniques. The mass of the tower was minimized using gradient based optimization approach. The cost of a composite tower was calculated and levelized cost of energy (LCOE) projections are discussed in comparison with the existing steel tower cost. The study determined that while the composite tower is technically feasible and has a lower mass than a comparable steel tower, uncertainty remains in how it compares economically in terms of LCOE.

Keywords: Composite materials, offshore wind support structure, optimization
2010 MSC: 00-01, 99-00

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1. Introduction

The offshore wind energy industry has grown successfully for the past two decades. A factor in this growth comes from the partial standardization of support structures through the industry's acceptance of standardized construction methods [1], primarily monopile foundations supporting cylindrical shell towers manufactured from steel. The industry is approaching the limits of practicality for the established construction methods and a growth of wind farms in both shallow to intermediate water and deep water locations have become possible with improved competitiveness and novel support structure concepts respectively [2, 3, 4].

While alternative foundation structures and higher capacity turbines have been trialled with success, the tower between foundation and turbine has not been a focus of innovation [3, 5]. Until recently it was commonly accepted that a diameter of 6.0 m - 8.0 m for monopiles and steel towers was the upper limit in terms of practicality for manufacturing,transport and offshore operations. Larger diameter cylinders were expected to be manufactured and transported in sections before dockside assembly.

The manufacturers of monopiles and towers gained enough knowledge during the first generation of offshore wind turbines (OWTs) to develop extra large monopiles and towers up to a 10.0 m outer diameter (which may be suitable for waters depths of up to 40 m while supporting larger capacity turbines) [6]. This development has slowed the advance of alternative types of support structures. As the market continues to grow, the water depths, turbine mass and size, and the tower height are also increasing which requires a re-evaluation of what type of support structure is most suitable [7]. The increasing size of structures reduces the benefits of steel. The self-weight of steel towers may become a design driver for larger offshore wind turbine structures.

Composite materials such as carbon or glass fibers in an epoxy resin matrix are being considered as an alternative construction material to steel due to potential benefits that are useful in offshore environments. The potential benefits include improved fatigue performance and corrosion resistance which could offset the initial higher costs by extending a structures lifetime and lowering the mass which would ease installation and removal operations.The proof of concept studies produced for composite towers [8, 9, 10, 11] have demonstrated that a composite tower is viable structurally, however the commercial feasibility of the composite towers has not been discussed due to commercial sensitivity.

The best measure of the potential benefit of large scale composite structures would be a comparison between the levelized cost of energy (LCOE) [12] for traditional steel offshore structures and composite alternatives. LCOE quantifies the competitiveness of energy and it is crucial that the LCOE for offshore wind energy be comparable to traditional fosil fuel energy without government assistance if renewable energy usage is to increase. The offshore wind industry continues to reduce the LCOE through economies of scale, turbine technology innovation, supply chain maturation, simplifying offshore operations and more efficient structures that minimize mass while simplifying manufacturing [6] to bridge the knowledge gaps of a lack of available information on design drivers, efficient designs, costs and design life.

The knowledge gaps which remain for composite structures are significant and there is not currently sufficient information available on the long term behaviour and structural integrity of large offshore composite structures for a detailed LCOE to be determined with confidence.

The aims of this study are to investigate the application of lightweight fiber reinforced composite materials in the construction of offshore wind turbine support structures and to add to the discussion on economic viability of composite alternatives to traditional steel offshore structures. To achieve these aims the study presents a mass optimised composite tower design suitable for the NREL 5MW reference wind turbine, determines the limiting constraint for this design, establishes a preliminary LCOE for the tower and evaluates mass, design and LCOE in comparison with existing traditional steel designs.

2. Literature Review

The development of large composite structures for most applications remains in the scaled prototype or first generation demonstration stages due to the complex nature of the material and the proven history of traditional materials. Various applications have been trialled including civil infrastructure [13, 14, 15] such as pedestrian and road bridges, aerospace industry such as planes fuselages [16], naval vessels [17] and high voltage transmissions towers [18, 19, 20].

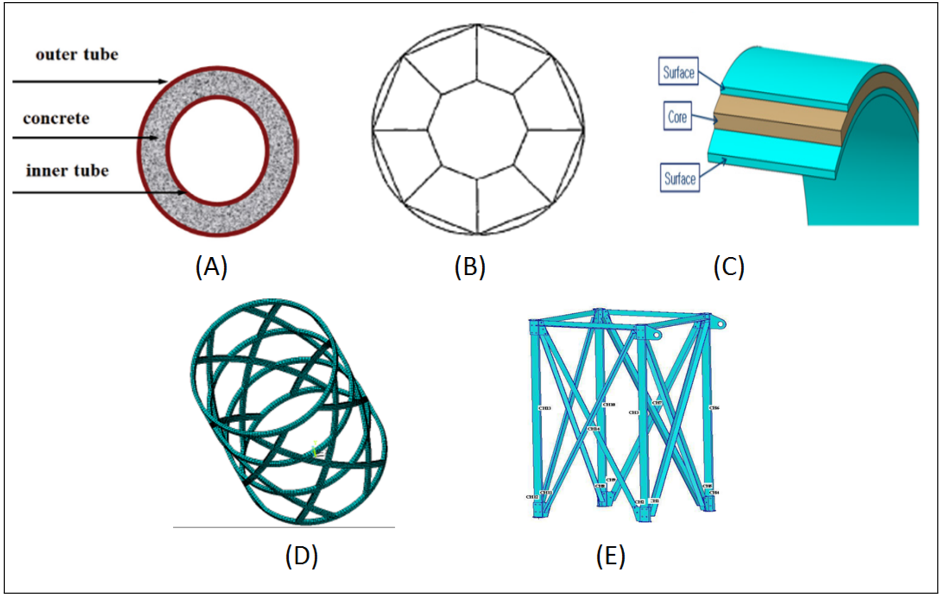
Wind turbine blades are more developed and a faster growing industry compared to other types of large composite structures, with several generations of composite blade design now established. The largest wind turbine blade currently developed will have a total length of 107.00 m and is due to be shipped in 2021 [21].

Designs for similar length blades [22, 23] form the basis to develop 200.00 m long blades for a 50 MW turbine as part of the Segmented Ultralight Morphing Rotor (S.U.M.A) project [24]. Fichaux et al. [25] and Ashuri et al. [26] have proposed initial concepts for blade lengths of 120.00 m and 135.00 m respectively.

These studies are indicative of the potential path other large scale composite structures may take during development. The trends indicate that the use of higher capacity materials such as carbon fiber are required to provide sufficient rigidity and load capacity to allow larger structures and higher loads. Beyond a certain point the relatively lower stiffness of composite materials (include carbon fiber composites) requires a move away from rigid structures towards compliant structure design and the acceptance of significant deflections as ordinary behaviour, either through pre-deformed geometry [25] or load reducing deformations [23].

Composite towers have been investigated in a range of studies over the last 20 years for both wind turbine support structures and electricity transmission towers. These studies generally falls into a few categories; subcomponent testing, scaled proof of concept work or analytical and numerical analyses investigating the effects of varying fiber angle on the structures behaviour. Examples of

Figure 1: Composite Tower Concepts



(A) Concrete filled composite tubes [27], (B) Multi-cell [11], (C) Sandwich composite [28], (D) Isogrid [29], (E) Lattice truss [19]

the different tower concepts are presented in Figure 1 and the following section details the studies to demonstrate the development of the concept.

Selvaraj et al. [30] designed and tested a full scale 66 kV 16.60 m transmission lattice tower built up with pultruded axial members. The composite tower was found to have advantages in reducing tower height and weight. Hernandez-Corona and Ramirez-Vzquez [18] determined that pultruded members can act as suitable alternative components for transmission towers to reduce the theft of steel structural components. Godat et al. [20] also investigated power transmission lattice towers with pultruded members. They compared analytic critical buckling loads with experimental results for a range of member profiles and concluded the design manuals [31, 32] published for pultruded members predict failure with acceptable accuracy.

Saboori and Khalili [33] investigated the effects of fiber angle and type, fiber volume fraction, number of plies and geometry on the structural behaviour of monolithic composite electrical transmission poles. Rashedi et al. [34] used

Ashby's material selection approach to identify potentially suitable materials for a monolithic tower for OWT considering structural rigidity, cost effectiveness, mass, embedded energy and carbon footprint. A laminate of high strength carbon fiber epoxy resin and cast iron were identified as the best performing materials for chosen criteria.

Omar and Aravinthan [35] investigated the failure mechanisms of a triangular tower with flat sandwich panel construction. Han et al. [27] proposed a double-skinned composite tubular tower for OWT applications. The tower consists of two concentric composite cylinders joined by a concrete grout. An initial design using this concept was sized for a 5 MW turbine tower.

Han et al. [36] investigated how alternative methods to model composite laminates affect the stiffness of a FE model of a filament-wound monolithic tower. They found negligible difference between the effective properties method (based on classical laminate theory) and stacking method (explicit modelling of individual plies) for the critical buckling load and the natural frequency.They also investigated how winding angle affects the structural response. Kayran and brahimolu [37] examined how precise manufacturing control can influence the winding angle, laminate thickness, stiffness, and natural frequency of a filament wound monolithic tower through the use of semi-geodesic winding and winding friction.

The application of aerospace concepts such as grid stiffened tubular and lattice structures to composite wind turbine towers was considered in two embargoed studies by TUDelft [38, 39] based on the work of Shroff et al. [40]. Feasible designs for a 5MW turbine were produced for both carbon fiber and glass fiber composites. An economic analysis concluded that both the tubular grid stiffened and the lattice tower are only commercially viable as an alternative to a steel tower for hub heights below 100 m. The studies noted that the steel tower self-weight becomes an issue for hub heights above 100 m, concluding that a composite tower was not a suitable solution for this issue.

A team in the University of Manitoba investigated lattice meteorological towers [41], electrical transmission poles [42], and wind turbine towers [11] constructed with composite materials. The wind turbine tower consisted of a multi-cell cross-section with both the individual cells manufactured and overall structure joined together using the filament winding process. The study compared finite element (FE) studies with experimental results for both static and dynamic behaviour and concluded that the FE model was acceptably accurate. The study also confirmed the manufacturing technique as a potentially viable process.

Gutierrez et al. [8] investigated the possibility of manufacturing composite towers on site for remote mountainous locations and tested 1/3 scale prototypes of a monolithic structure and a sandwich structure which incorporated a mortar grout fill. The monolithic filament wound tower met the design criteria while issues with manufacturing quality and the bonding of grout to the laminate led to unacceptable performance of the sandwich structure tower. A static test of a full scale 40.00 m tower of a 1.3 MW turbine that included both sandwich and monolithic sections concluded that a composite tower was feasible for static loading. The dynamic behaviour of the tower was not investigated.

Lim et al. [28] proposed a conical composite tower design with filament wound sandwich construction for a 2MW turbine. The optimal filament winding process was determined by altering the layup ratio of the sandwich panel while minimizing stress and deformations. A campbell diagram was used to check for potential resonance issues and a manufacturing cost analysis was presented courtesy of FiberTec Ltd. This study was continued by Park [43] who manufactured a scaled model of the composite tower and tested the structural viability of the concept through experimentation.

van der Zee et al. [10] describes the work of the "C-Tower" project, the first study to investigate the use of a composite tower to support the next generation of turbines by designing a tower for the DTU 10 MW reference turbine [44]. The study focused on two concepts: a rigid "soft-stiff" tower with a natural frequency range between 1P and 3P excitation zones and flexible "soft-soft" tower with a natural frequency range below the 1p, and between the wind and wave excitation zones. Both concepts were assumed to be filament wound sandwich composite structures. The soft-stiff tower design was found to be heavier that the reference steel tower and was deemed uncompetitive compared to steel towers. The soft-soft tower design was optimized for minimum mass considering a variable of wall thickness with constraints on natural frequency, buckling, material stress, nacelle displacement. Fatigue was omitted from the optimization due to computational limitations and was later confirmed to be acceptable once an optimized design was found.

The C-Tower project will continue in a second phase to manufacture and test a scale model of the soft-soft flexible tower. The study is notable in that it is the only study to consider the possibility of manufacturing of the 105 m long 8 m diameter tower as a single piece via a discontinuous filament winding process. All other studies have assumed the tower would be fabricated in multiple sections and assembled dockside before transferring to installation vessels. Such assumptions are based on concerns about the feasibility of using filament winding to manufacture a single structure that is significantly longer and wider than the largest existing commercial airliner fuselage.

The most advanced work on the topic of composite towers has been produced by the VolturnUS team project which pairs a composite tower with a concrete floating platform. The lower mass of the composite tower decreases the centre of gravity of the structure which reduces instability and the amount of buoyancy required to resist gravity loads allowing the use of a smaller floating platform. Young et al. [9] stated that for a steel spar platform, every kg of tower mass removed allowed approximately 9 kg of steel and ballast to be removed. The suggested manufacturing process involved vacuum infused laminate in the form of curved panels that are placed together on a rotating mandrel before being bound with filament wound outer layer. The resulting cylindrical sections are joined by steel connection joints would form a composite tower.

The VolturnUS tower was designed through a genetic algorithm optimization approach. The optimization goal was to minimize mass and considered natural frequency, strength and serviceability criteria with a fatigue load analysis completed after an optimized solution was found. The work considered both sandwich and solid laminate construction. The optimized solution for the sandwich panel resembled solid laminate panel.The project involved the design analysis and manufacture of 1:8 scale (0.905 m diameter and 10.15m long) [45], half scale (3.15 m diameter and 18.19m long) [46], and full scale (8.15 m diameter and 83.5 m long) prototypes [9]. The 1:8 scale prototype was used to validate the analysis, design and optimisation methodology and for offshore testing. The half scale model was used to demonstrate the fabrication methods. The full scale prototype will form part of a two 6 MW demonstration wind farm connected to the grid in 2019.

A comparison of these studies identifies several recurring concepts. The reoccurring concepts suggests there is a consensus between researchers on the most suitable form for composite material offshore wind turbine support structures. The majority of the studies focus on monolithic towers [28, 43, 37, 47, 33, 11, 9, 46, 10, 8] rather than lattice towers[30, 20]. The most commonly suggested construction techniques are filament winding, vacuum assisted resin transfer mould (VARTM), and pultrusion. The monolithic towers are all assumed to be manufactured either solely by filament winding, or a combination of filament winding and another manufacturing process such as hand laid VARTM laminates. The few lattice tower concepts are typically designed with pultruded axial members.

Filament winding is ideally suited to fabricating cylindrical sections and is highly automated reducing labour cost. Many of these studies have also noted that filament winding is not well suited to laying fiber along the longitudinal axis of a cylinder as existing filament winding machines are designed for fabricating piping, pressure vessels and other applications.

Such applications require hoop and radial reinforcement (typically 45°- 90°fiber winding angle to the longitudinal axis) more than axial reinforcement (approaching 0°to the longitudinal axis) and thus the lowest possible fiber winding angle on a general purpose filament winding machine tends to be 35°to the longitudinal axis.

Several of the studies identify the most structurally efficient fiber orientation as longitudinal. Fabricating a structure to resist bending and axial loads using a 35°fiber placement angle is an inefficient use of material and negates one of the benefits of composites; precise reinforcement placement and orientation. Thicker laminates or higher capacity fibers would be needed to provide the level of reinforced required, both of which raise manufacturing costs.

The three most advanced studies suggest different approaches to overcome this limitation. Gutierrez et al. [8] of the MEGAWIND project identified pultrusion and filament winding as the most suitable manufacturing methods. The project initially focused solely on manufacturing via filament winding. Due to concerns about the limitations in winding angle, the final manufacturing process combined longitudinally orientated uni-directional fiber layers with filament winding layers. Young et al. [9] suggested a manufacturing process that combined VARTM curved laminate panels with longitudinally orientated fibers that are filament wound together to create a monolithic tower shell. The VARTM process is labour intensive and is not seen as cost effective for large scale manufacturing as other more automated methods. van der Zee et al. [10] suggests this limitation could removed through non traditional discontinuous filament winding techniques, specialised equipment and alterations to the winding machine.

Additionally, multiple studies [8, 28, 9, 46] noted that the monolithic construction of an offshore wind turbine tower could result in difficulties for logistics and transportation to site or dockside. These studies suggested that interconnecting panels (solid laminate or sandwich laminate with core material) could be manufactured individually before being shipped to an assembly stage. The panels would then be joined together and locked in place either via internal grid frame or an external filament wound wrapping layer. It was noted by both Young et al. [9] and van der Zee et al. [10] that alteration of the turbine controller settings and strategy is beneficial in achieving an acceptable structural response by frequency hopping and increasing blade drag to reduce displacements.

This study attempts to address two of the existing knowledge gaps; efficient structural arrangement considering manufacturing constraints, and economic viability. The mass and structural response of the structure are chosen to quantify efficiency as low mass is desirable for offshore structures. Composite towers have the potential for relatively lower masses which facilitate the shift to deep water locations as minimizing mass reduces the complexity of offshore operations, increases weather window durations, reduces the need for specialised heavy lift vessels, and increases safety. The economic viability of a composite offshore structure in comparison with a traditional steel structure depends on the initial manufacturing cost, installation, maintenance, decommissioning and expected lifespan. Many studies have suggested that the initial higher costs of a composite structure could be offset by lower installation, maintenance, and decommissioning costs combined with a longer lifespan. These "Proof of Concept" studies have demonstrated that a composite tower is viable structurally but have not yet demonstrated that it is viable economically. These studies are generally optimistic and confident in the feasibility and success of the concept, possibly in the hope of commercialization of designs or patents. The current study seeks to share a LCOE estimate for a composite wind turbine tower for the first time.

3. Methodology

3.1. Model

This study investigates a novel combination of both filament winding and pultrusion for the fabrication of a composite tower. Pultrusion is a highly automated process that can continuously produce significant quantities of low cost structural members with complex cross-sections, high-fiber fractions, and consistent quality. Pultruded structural members primarily consist of longitudinal fiber reinforcement making it a potentially suitable manufacturing process for the composite tower which is dominated by axial and bending loads.

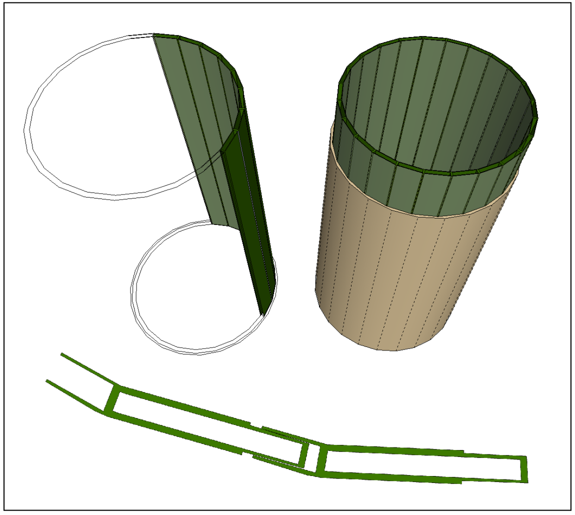
The construction form was chosen based on the experiences and lessons learnt of the existing studies discussed in the previous section. These studies identified filament winding combined with an additional process that allows longitudinal fiber placement as the most suitable choice for composite offshore wind turbine support structures. Such a combination mitigates the limitation of filament winding. The most advanced existing studies suggested labour intensive methods such as VARTM [9] and hand laying uni-directional plies on to winding mandrel [8] or creating specialised equipment [10].

The current concept of combining filament winding and pultrusion was chosen as both processes are widely recognised as less labour intensive due to high automation and thus more economical than most other types of composite manufacturing. Additionally the strengths of each process compliment the weaknesses of the other. A schematic is presented in Figure 2. A series of interlocking pultruded panels would provide the longitudinal reinforcement required for axial and bending loads while a filament wound laminate would bind the structure together and provide torsional and shear reinforcement.

Both single and double wall panels are considered. The double wall box panel was investigated as a method to increase the local buckling capacity of the wall. This design feature is similar to the VARTM foam core sandwich composites [9, 28] or internal cell walls [11] proposed in existing studies. The hollow box form was chosen rather than the foam core sandwich panel as the profile is simple to create using the more economical pultrsion process. This profile increases the local rigidity of the tower shell with the larger local second moment of area for the same cross sectional area. The interlocking profile design allows dockside assembly to overcome the issues in logistics and transportation of large offshore wind structures experienced by the industry and discussed in previous studies.

A composite of glass fiber in an epoxy resin was chosen as it is the most economical option available. The elastic modulus was set as 40 GPa based on the rule of mixtures assuming a 53% longitudinal fiber volume fraction for E-glass fibers in an epoxy resin with elastic modulii of 73.1 GPa and 3.1GPa [48] respectively. This value is at the upper limit of stiffness possible for composites reinforced solely with glass fibers [49]. The other material properties (Table 1) are based on the longitudinal elastic modulus and are in-line with the properties of mass produced commercial structural composites [32, 31]. Pultruded cross-

Figure 2: Composite Tower Concept



Pultruded double wall panel sections (green) bound together by filament wound laminate (light brown)

sections are typically limited to a maximum wall thickness of 70-80 mm and a maximum over overall dimension of 1350 mm [50].

The filament wound layer was assumed to consist of Silenka E-glass 1200 tex and MY750/HY917/DY063 epoxy [51, 52]. Filament winding consists of a single filament that, when aligned, can be modelled as a unified ply with properties defined in Table 2. The winding angle chosen was ±45 to create a biaxial laminate which provides torsional stiffness. Classical Laminate Theory (CLT) was used to determine the laminate properties for the filament wound layer resulting in orthogonal (longitudinal 0°and hoop 90°) modulii of 17.6 GPa and a shear modulus of 13.6 GPa. The material density was assumed to be 2100 kg/m^3 for both filament wound and pultruded material to incorporate secondary structural weight.

The 5MW wind turbine reference design developed by the National Renewable Energy Labs (NREL) [53] was chosen as a basis for the study as there is a significant amount of literature, experience and knowledge about offshore support structures for the NREL 5MW wind turbine. This knowledge provides

Table 1: Pultruded Member Parameters

Parameter	Value
Longitudinal modulus $\mathrm{E_L}$ [GPa]	40.0
Transverse modulus $\mathrm{E_T}$ [GPa]	5.0
Shear modulus $\mathrm{G_{LT}}$ [GPa]	3.0
Poisson Ratio	0.3
Maximum Stress [MPa]	414

Table 2: Filament Wound Laminae Parameters

Parameter	Value
Longitudinal modulus $\mathrm{E_1}$ [GPa]	45.6
Transverse modulus $\mathrm{E_2}$ [GPa]	16.2
Shear modulus $\mathrm{G_{12}}$ [GPa]	5.8
Poisson Ratio	0.278
Longitudinal tensile strength $\mathrm{X_T}$ [MPa]	1280
Longitudinal compression strength $\mathrm{X_C}$ [MPa]	800
Transverse tensile strength $\mathrm{Y_T}$ [MPa]	40
Transverse compression strength $\mathrm{Y_C}$ [MPa]	145
In-plane shear strength $\mathrm{S_{12}}$ [MPa]	73

Table 3: Metocean Overview

Parameter	1 yr	50 yr
H_s [m]	5.4	7.0
T_p [s]	9.9	12.1
H_{max} [m]	10.1	13.5
T_{ass} [s]	9.3	10.2
U_{100}- 1hr [m/s]	31.2	40.4
Gamma γ	2.1	1.2
V_{surf} [m/s]	1.2	1.5

a good benchmark and perspective on the relative suitability and competitiveness of a composite tower. The transition piece (TP) and the yaw bearing are located at 10.0 m and 97.6 m above mean sea level (MSL) respectively, thus the tower length is 87.6 m.

3.2. Environmental Conditions

Site specific environmental conditions are required by the IEC 61400-3 standard, the site chosen for the analysis is the Hollandse Kust Zuid Wind Farm [54], which lies to the west of the Netherlands, offshore from the province of Zuid-Holland (South Holland). The Netherlands Enterprise Agency has made significant amounts of data about the wind farm location freely available for commercial and academic use to encourage tariff free developments. The site specific metocean data is presented in Table 3 and the water depth was assumed to be 20 m.

In addition to the environmental conditions corresponding to 1 year and 50 year return period extreme events in Table 3, the study also considered normal sea-state parameters associated with hub height wind speeds between 4.0 m/s and 26 m/s for normal operating and power producing conditions. A 1/7th power law current profile and JONSWAP spectrum was assumed for current and wave conditions respectively.

3.3. Loadcases

The IEC 61400-3 standard [55] provides guidance on the structural analysis and the design requirements for offshore wind turbines. It is used to identify critical loads during extreme events and over the lifetime of the structure for ultimate and fatigue analyses respectively.

The standard provides design load-cases (DLCs), which describe a range of parameters and scenarios that are likely to occur during the OWT's design life.The chosen DLCs, shown in Table 4, are often the critical loadcases for the substructure and tower of an OWT [56, 57, 58, 59]. The analysis omitted DLCs related to faults, operations, start-up, and shut-down events as they do not involve extreme environmental conditions and are generally critical for the turbine rather than the support structure.

Normal production DLCs require a range of wind speeds (and associated seastates) from the cut-in wind speed $\mathrm{V_{in}}$ [4m/s] to the cut-out wind speed $\mathrm{V_{out}}$ [26 m/s] with the initial rotor speed and blade pitch increasing as the wind speeds increase.

For DLCs corresponding to an extreme event such as a 50 year return period storm, the turbine was modelled as parked and idling in a storm survival mode which included disabling the active pitch control of the blades, the yaw motion of the nacelle, and the generator function. The blades were feathered to a pitch of 90°to minimize the wind loading. A yaw error of ±8°was assumed to account for shifts in wind direction that the turbine has not yet reacted to.

3.4. Recommended Practice

There are multiple standards available that offer guidance on the structural use of composite materials. Established standards typically consider composite subcomponents [60, 61, 52] or offshore wind turbine blades [62] while more generalised standards are being developed in anticipation of the increasingly larger structures made entirely from composites [48, 63].

An important aspect of the design of composite structures is the consideration of knockdown or material factors. The material factors are required to

Table 4: IEC 64100:3 Critical Design Load Cases

Load Case	DLC 1.3	DLC 1.6	DLC 6.1	DLC 6.3	DLC 1.2	DLC 6.4
Load Type	Ultimate	Ultimate	Ultimate	Ultimate	Fatigue	Fatigue
Safety Factor	1.35	1.35	1.35	1.35	1.00	1.00
Status (Event)	Producing	Producing (Extreme Seas)	Parked (Storm)	Parked (yaw error)	Producing	Parked
Wind	V_{in}-V_{out}	V_{in}-V_{out}	V_{50yr}	V_{1yr}	V_{in}-V_{out}	V_{in}-0.7*V_{ref}
Yaw Error [°]	0°, ±10°	0°	±8°	±20°	0°, ±10°	±8°
Turbulence	ETM	NTM	11%	11%	NTM	NTM
Wind Shear	0.14	0.14	0.11	0.11	0.14	0.14
Seastate	H_s,T_p=$f(V_{hub})$	50 yr	50 yr	1 yr	H_s,T_p=$f(V_{hub})$	H_s,T_p=$f(V_{hub})$
Directionality	Uni	Uni	0°, ±30°	0°, ±30°	0°, ±10°	0°, ±10°
Wind Seeds	6	6	6	6	6	6
Wave Seeds	3	3	3	3	3	3
Duration [s]	1500	600	3600	3600	600	600
Simulations	648	648	72	72	1944	216

account for the changing behaviour of composite materials over time. Composites are susceptible to degradation due to a range of effects; fabrication processes, moisture, ultraviolet light exposure, temperature, creep, weathering.

The degradation is not consistent for all properties of the material, the individual processes degrade material properties, such as strength or stiffness, in different ways through different mechanisms. The partial material factors for each degradation process are typically combined to provide an overall material factor for each failure mode.

As there is no recommended practice for large composite offshore structures, the material factors from multiple standards [60, 61, 52, 62, 48, 63] were compared and are presented in Table 5. The material factors of the proposed Eurocode standard [48] were chosen as it provides guidance on both filament winding and pultruded structures, and the factors are comparable with Clarke [52] and DNV-GL [61].

3.5. Pultruded Panels

The design of composite structures typically requires detailed FE modelling. For preliminary analysis and sizing, both analytical and numerical solutions are

Table 5: Material Factors

	DNVGL-ST-376	DNVGL-OS-501	EuroComp	Eurocode	A.S.C.E. LRFD	GL Renewables
Material Failure	2.67			2.25	2.41	2.43
Local Buckling	2.83	2.50	2.55	2.50	1.96	2.04
Global Buckling	2.83			2.25	2.24	2.04

acceptable. Analytical solutions were chosen as they simplify the optimization process, reduce optimization duration, and if suitable can be combined with continuous functions and gradient based optimization algorithms more readily than FE methods.

The tower concept consists of interlocking pultruded panels wrapped in a filament wound layer. It is expected that the failure of the structure due to buckling would be on an individual panel basis, similar to the panel buckling behaviour of composite wind turbine blades. Analytical solutions have been used successfully to predict panel buckling of wind turbine blades [64, 65, 66] suggesting that a similar approach would be suitable for the prediction of panel buckling of a composite tower. Detailed connections were not considered as the focus was on initial sizing of the structure.

The critical buckling stress of curved pultruded panels due to axial compression $\sigma_{\text{cr-Buckle}}$ and shear $\tau_{\text{cr-Buckle}}$ were calculated in accordance with Young et al. [67] assuming all edges of the panel are simply supported. The interaction between axial and shear buckling modes is given in 1. Material failure is taken as the maximum utilization for either crushing or rupturing and is given in 4.

$$U_{Buckle} = \left(\frac{\sigma_{xxBuckle}}{\sigma_{crBuckle}}\right) + \left(\frac{\tau_{xyBuckle}}{\tau_{crBuckle}}\right)^2 \tag{1}$$

and

$$\sigma_{cr-Buckle} = \frac{1}{6}\frac{E}{1-\nu^2}\left[\sqrt{12(1-\nu^2)\left(\frac{t}{r}\right)^2 + \left(\frac{\pi t}{b}\right)^4} + \left(\frac{\pi t}{b}\right)^2\right] \tag{2}$$

$$\tau_{cr-Buckle} = 0.1E\frac{t}{r} + 5E\left(\frac{t}{b}\right)^2 \tag{3}$$

where

E = Modulus of Elasticity

ν= Poisson's ratio

b = width of panel measured on arc;

r = radius of curvature

$$U_{MaterialFailure} = \frac{\sigma}{X} \tag{4}$$

where

σ= applied stress in ply

X = maximum allowable stress in ply

3.6. Filament Wound Layer

The balanced and symmetrical ±45°plies of the filament wound layer were analysed according to classical laminate theory (CLT)[68]. The CLT approach provides a reasonable approximation of the behaviour of a laminate while reducing the complexity of a three dimensional response to a two dimensional problem, incorporating the stress-strain relationship with orientation transformations to account for varying ply angle.

Hinton et al. [51] demonstrates that there is no universally agreed method in determining the failure of laminated composites. Adopting the limit of first ply failure is often used as a conservative alternative. First ply failure assumes the laminate has failed when a ply level criterion is exceeded, which ignores the true damage accumulating nature of the laminate. The first ply failure can be more accurately predicted than ultimate strength failure of the laminate as the load path becomes extremely complex and changeable between first-ply failure and laminate failure.

Several different failure criteria were included in the study to due to the numerous failure modes possible. The Tsai and Wu [69] failure criteria were chosen to account for the interaction of multiaxial stresses while the maximum stress criteria was considered to account for ply failure due to a single axis stress.

$$U_{FW} = F_1\sigma_x + F_2\sigma_y + F_6\sigma_{xy} + F_{11}\sigma_x^2 + F_{22}\sigma_y^2 + F_{66}\sigma_{xy}^2 + 2F_{12}\sigma_x\sigma_y \tag{5}$$

where

$$\begin{array}{ccc} F_1 = \frac{1}{X_t - X_c} & F_2 = \frac{1}{Y_t - Y_c} & F_6 = 0 \\ F_{11} = \frac{1}{X_t X_c} & F_{22} = \frac{1}{Y_t Y_c} & F_{66} = \frac{1}{S_{xy}^2} \end{array}$$

$$F_{12} = \frac{-1}{2\sqrt{X_t X_c Y_t Y_c}}$$

σ_x : stress in ply x axis

σ_y : stress in ply y axis

σ_{xy} : shear stress

X_t : maximum allowable tensile stress in ply x axis

X_c : maximum allowable compressive stress in ply x axis

Y_t : maximum allowable tensile stress in ply y axis

Y_c : maximum allowable compressive stress in ply y axis

S_{xy} : maximum allowable shear stress

3.7. Optimization Process

Large scale composite structures are a developing area, which lacks established efficient designs or information on critical design parameters. This study focused on optimizing a composite tower in an attempt to establish an efficient design and to identify the limiting constraint. The optimization process combines continuous functions with gradient based optimization algorithms (using MATLAB's [70] optimization toolbox) with the NREL FAST software suite [71],and buckling, fatigue and natural frequency checks.

A Gradient based optimization and analytical constraints were chosen over genetic algorithms and detailed FE models as the gradient based optimization process can provide insight on the design space and is typically less computationally expensive. The level of accuracy available with the analytical approach was deemed sufficient for a preliminary and generalized design study. For a particular design project, this would be an initial step before detailed FE solid modelling is used to verify the composite structure's final design.

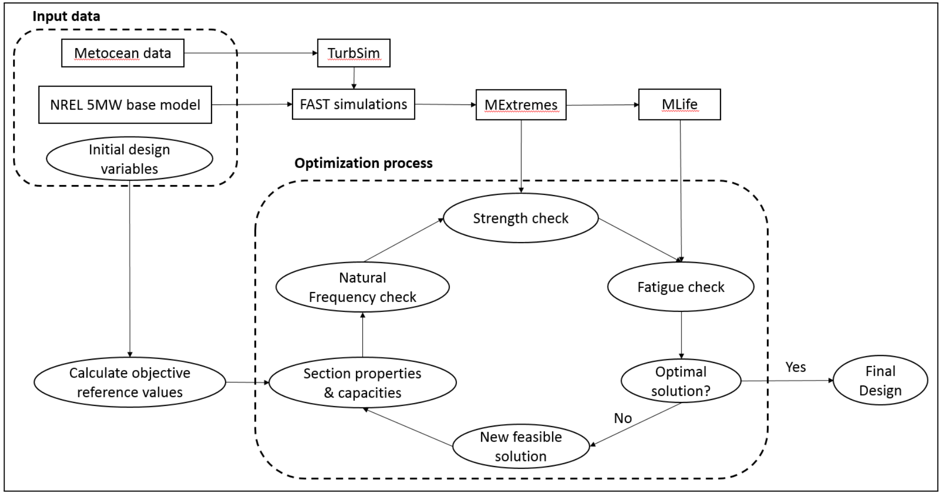
The optimization function FMINCON in MATLAB [70] uses the interior point approach to convert an inequality constrained problem into a series of equality unconstrained approximate sub-problems[72]. This series of sub-problems can be solved with either the direct step or conjugate gradient approaches at each iteration in the optimization process[70]. The direct step is the default method and the conjugate gradient method is used when the direct step method is not suitable. (i.e. the approximate sub-problem is not convex in the design space surrounding the current iteration point).

A schematic for the optimization process is presented in Figure 3. The principle input data required is the metocean data, structural model and initial design variables.The metocean data and structural model is input into the FAST software suite to pre-process, simulate and post-process the loads and reactions of the structure for each loadcase. The optimization process first takes in the various inputs for bounds, constraints, variables for initial point, and checks to ensure the upper and lower bounds are respected (shifting the initial point if necessary). The initial point must be located in the feasible zone of the design space or the interior point algorithm will struggle to resolve the problem.

If the initial design variables are valid, the objective reference value is determined. This reference value is used throughout the optimization process to determine the current iteration's optimality relative to the starting value. The reference value is an initial value calculated for the specified objective parameter. As this is a study to minimize mass, mass is the objective parameter and the reference value is the mass corresponding to the initial design variables. The current iteration's mass optimality is determined by comparison with the initial iteration's mass.

The optimization loop begins with the calculation of the section properties and capacities of the tower at each section. The constraints are evaluated using the post-processed results from the FAST simulations. The optimization loop's

Figure 3: Optimization Process Flowchart



next step is to check the current iteration point's optimality before searching for good directions in the design space that result in feasible solutions with lower minima corresponding with lower tower mass. The next iteration moves in the direction of the feasible solution which produces the lowest objective value. If no good directions are found or the maximum number of iterations is reached, a local minimum has been found. The design variables and objective value that corresponds to the local minimum is chosen as the final design.

The analysis considered a total of 1440 and 2160 simulations for the strength and fatigue DLCs respectively. Due to the level of discretization required for stable wind turbine simulation the ratio of simulation time to real time approached 1:1. On a single CPU the duration required for all simulations was over 800 hrs (more than 30 days) and it was not realistic to re-analyse the DLCs for each iteration of the optimization process, even with the use of parallel cores. Additionally, the rerunning of DLCs for every iteration could introduce variability into the optimization process that the algorithm could not account for, possibly leading to self propagating divergence from an optimal solution. It was decided to run the simulations once with a preliminary design and then maintain a consistent loadset for the following optimization. The formation of the optimization problem requires the definition of variables, constraints and properties to be optimized.These are defined in the following sections.

Each DLC was analysed via a time domain simulation of the structure's response to loads generated by wind, waves and the turbine. The simulations considered a range of seeds for both wind and waves (Table4). TurbSim [73] was used to generate times series data of stochastic turbulent wind speed vectors which are used as input in the calculation of aerodynamic loadings on the wind turbine and its blades above the yaw bearing (for both parked and producing modes). NREL's FAST combines the aerodynamic loads with stochastic wave loads, semi-static current loads and turbine control algorithms with structural modelling to simulate the full aero-hydro-servo-elastic behaviour of the structure. The loads are applied to the structure in 0.005 second time steps for the simulation duration required for each DLC.

The internal reactions (three forces and three moments) at nodes along the length of the tower are calculated for each time step. For each DLC, the minimum extreme and maximum extreme values of individual reactions at each node are identified. The corresponding 5 other reactions for the critical simulation at the same time step are summarized and are included in the DLC's extreme event table [74]. These tables are used to identify the most extreme events and check the structural capacity of the tower for each extreme event after applying the appropriate load and resistance factors.

For structural checks, the tower was divided into 8 sections connected by 9 nodes along its length. The filament wound layer checks assessed each individual ply at 8 locations around the circumference of each node. The pultruded panel checks assumed that the circumference of the tower is created from 20 interconnecting panels. For a 8.00 m outer diameter, each panel would be 1.26 m wide, which is at the upper limit of the manufacturing capabilities of existing pultrusion machinery. The maximum stress across the cross-section was calculated and checked against the critical buckling stress.

The natural frequency of the composite tower was determined using BModes [75], a FE code developed by NREL for the modal analysis of both turbine blades and offshore wind towers. When analysing a tower, the code takes the effect of the foundation and the nacelle into account for the natural frequency of the tower. As Bmodes is limited to calculating only the natural frequency, it did not significantly effect the duration of the optimization process making it suitable to be used rather than an analytical natural frequency calculation.

There is much debate on the suitability of existing models for varying amplitude fatigue of composite materials. This preliminary study did not have the information required to calculate material constants for the fatigue modulus used in more advanced fatigue models such as the residual stiffness model [76]. The residual stiffness model incorporates a reduction to the material stiffness for more accurate fatigue predictions. For this study, the material degradation was accounted for by applying the material safety factor to both the stiffness and the strength of the composite.

The fatigue analysis was completed using the FAST post-processor MLife [77], which follows the approach recommended by IEC-61400-3 [78]. The fatigue damage is assumed to accumulate linearly according to Palmgren-Miner rule with rainflow counting. The total accumulated lifetime damage is extrapolated from the numerous DLC simulations, which have a significantly shorter duration that the tower lifespan. The fatigue DLC's for power production and parked modes are binned according to wind speed distribution and a Weibull distribution is used when extrapolating damage cycle counts. The analysis did not consider discrete events such as maintenance operations, failure, grid connection loss etc.

The total damage, $\mathrm{D}^{\mathrm{Life}}$, will be given by

$$D^{Life} = \sum_{j} D_j^{Life} \tag{6}$$

$$D_j^{Life} = \sum_{i} \frac{n_{ji}^{Life}}{N_{ji}} \tag{7}$$

$$N_{ji} = \left(\frac{L^{ult}}{\frac{1}{2} L_{ji}^{R}} \right)^{m} \tag{8}$$

where

$D^{Life}{}_{j}$: j^{th} timeseries damage extrapolated to design life,

$n^{Life}{}_{ji}$: is the extrapolated cycle counts,

N_{ji} is the cycles to failure, $L^{R}{}_{ji}$ is the range about a load mean $L^{M}{}_{ji}$ of for the i^{th} cycle in the j^{th} time-series.

3.8. Variables

The design variables initially included the elastic modulus of the pultruded panels and the thickness of filament wound layer. An initial optimization of these variables resulted in consistent values along the length of the tower. The elastic modulus tended to the upper bound for every iteration and the filament wound thickness required to resist the torsion remained consistent in magnitude through the length of the tower. Thus both former variables were set to values determined in the initial round of optimization, a thickness of 20mm for the filament wound layer and 40 GPa for the elastic modulus of the longitudinal reinforcement.

The variables chosen were outer diameter (OD), wall thickness of pultruded panel (t_p), and depth of pultruded panel (D_p). The structures dimensions were chosen as they control the structural response and allow the use of continuous functions in the optimization process. Both double and single wall pultruded panels were considered. For the single wall panels the D_p variable was omitted as it was not applicable. The upper bounds (6) were based on the maximum dimensions that are currently manufactured commercially. The outer diameter was assigned two upper bound limits, a 10.00 m limit for manufacturability and a 7.00 m limit to be in-line existing offshore wind transportation infrastructure and construction techniques. The lower bounds were set to prevent the optimization solver from entering unfeasible regions of the design space.

3.9. Constraints

The natural frequency f_n of the structure must be limited to avoid resonance with the forcing frequencies of the wind, waves, turbine and blade passing loads.

Table 6: Upper and Lower Bounds on Variables

Variable	Lower Bound	Upper Bound
Outer Diameter (OD) [m]	4.0	10.0 / 7.00
Pultruded Wall Thickness (t_p) [m]	0.01	0.08
Pultruded Depth (D_p) [m]	0.10	0.8

The NREL 5MW reference design natural frequency is in the 'soft-stiff' viable frequency range between 0.20 Hz and 0.35 Hz, the upper limit of the turbine variable frequency (1p) and the lower limit of the blade passing frequency (3p) respectively. The composite tower natural frequency must be in the 'soft-stiff' frequency range as it is being considered as a direct replacement for the original steel tower.

$$0.20Hz \leq f_n \leq 0.35Hz \tag{9}$$

The failure modes of pultruded panels and filament wound layers are described in the "Filament Wound Layer" and "Pultruded Panels" subsections. The structural integrity of the tower requires that the utilization for each failure mode not exceed 1.00. The utilization for the pultruded panels U_P is the maximum utilization for material crushin/rupturing ($U_{MaterialFailure}$) and buckling U_{Buckle} of individual subcomponents and is defined in equation 10. The utilization for the filament wound layer U_{FW} is the maximum utilization for first ply failure for along the tower.

$$U_P \leq 1.00 \tag{10}$$

where

$U_P = \max\,(U_{Buckle}, U_{MaterialFailure})$

$$U_{FW} \leq 1.00 \tag{11}$$

The fatigue utilization U_F is a measure of accumulated damage compared to the allowable damage over the lifetime of the tower. The allowable fatigue damage is based on the maximum allowable loads for the composite materials. Offshore wind turbines typically have 20 year operating period, which was specified as the tower design life span. It was also conservatively assumed that the load and corresponding damage originates from one direction. A Wöhler material exponent of m = 10 was chosen for the composite materials under investigation. This value is typically used for generalised design studies of composite turbine blades, which undergo levels of fatigue cycles and are to environmental conditions comparable to the tower.

3.10. Optimization Function

The objective of the optimization is to minimize the mass of tower. Mass was chosen as the attribute to minimise as the material cost makes up a significant portion of total capital cost of a tower. Mass is an excellent surrogate for capital costs and therefore it was selected as the objective function in this research.

$$
\begin{aligned}
& findx = (OD, t_p, D_p) \\
& minimize \\
& \qquad Mass(x) = f(OD, t_p, D_p) \\
& subject\ to \\
& \qquad g_1(x) : 0.22Hz \leq f_n \leq 0.34Hz \\
& \qquad g_2(x) : U_P \leq 1.00 \\
& \qquad g_3(x) : U_{FW} \leq 1.00 \\
& \qquad g_4(x) : U_F \leq 1.00 \\
& for\ variables \\
& \qquad 5.0 \leq OD \leq 10.00 - (Unrestricteddiameter) \\
& \qquad 5.0 \leq OD \leq 7.00 - (Restricteddiameter) \\
& \qquad 20 \leq t_p \leq 80 \\
& \qquad 200 \leq D_p \leq 800
\end{aligned}
\tag{12}
$$

The optimization duration was approximately 15 hours when the fatigue constraints was included in the optimization and approximately 30 minutes when the fatigue constraint was omitted from the optimization and checked at the end of the process to verify the solution's suitability. The long duration of the optimization with the fatigue constraint included could be reduced if desired as the majority of the time was spent accessing the data. If the data was held in the memory rather than re-accessed for every iteration, the duration would be reduced. This approach was not taken as the optimization is not a regular activity.

3.11. LCOE Estimation Methodology

The LCOE incorporates the total capital cost, operational cost, fixed charge rate, and annual energy production. The LCOE calculation is presented in eqn. 13 with the relevant input data used to determine the 2016 LCOE included[79].

$$LCOE = \frac{CapEx}{8760 \times CapacityFactor} \frac{WACC(1+WACC)^n}{(1+WACC)^n - 1} \frac{1 - TD_{pv}}{1(1-T)} + \frac{OpEx}{8760 \times CapacityFactor}$$

$$LCOE = \frac{(CapEx \times FCR) + OpEx}{AEP_{net}} \tag{13}$$

where

CapEx : Capital cost (\$4579/kW)

OpEx : Operational cost (\$158/kW/yr)

Capacity factor : % of year generating power (41.7%)

AEP: Annual energy production (3,650 MWh/MW/yr)

WACC : Weighted-Average Cost of Capital (6.5%)

n : Lifetime in years (20 yrs)

FCR : Fixed charge rate (10.3%)

T : Effective Tax rate (42.5%)

D_{pv} : present value of depreciation (82%)

The total capital cost includes the turbine cost (nacelle, generator, blades, tower), balance of system cost (foundation, infrastructure, installation etc) and financial cost (insurance, financing, contingency etc). The average turbine cost was estimated to be \$1,505/kW, of which 15.1% or \$227/kW can be attributed to the tower assuming the same turbine cost distribution as a land based turbine [79].

Fullenkamp and Holody [80] estimated the capital cost associated with a 5MW steel tower in 2014 to be between \$683,251 (\$137/kW) and \$1,234,628 (\$247/kW), which is line with the average tower cost of \$227/kW determined by Stehly et al. [79]. The sub cost of steel tower manufacturing (materials, labour and burden) ranged between \$486,957 and \$902,127 with the cost of profit, logistics, engineering and general sales/administration making up the difference[80]. Composite blades had a similar cost distribution of approximately 70% - 30% between manufacturing and administration costs. It is assumed that there would be a similar cost distribution for composite towers.

The most cost effective manufacturing processes for composites pultrusion and filament winding are estimated to cost €4/kg and €6.17/kg (covering materials, labour and equipment) in 2013 [81]. These values correspond to \$5.28/kg and \$8.14/kg using the average 2013 euro - US dollar exchange rate of 1.32.

While more recent cost data would be ideal, the values stated are the most recent data found after an extensive search. Due to the nature of the industry, there is a lack of information available as manufacturers are unwilling to share commercially sensitive data such as manufacturing costs. It is hoped that by using contemporary cost values, from a similar time (2013-2014), for materials and labour for all manufacturing processes discussed (steel, pultrusion, filament winding, VARTM) that this limitation would be minimized. Thus the LCOE assessment is limited by such constraints and is presented as a first attempt at quantifying the economic viability of composite structures rather than a definitive statement.

4. Results

4.1. Optimization Analysis

The study investigated both single wall and double wall pultruded panel solutions. The double wall was considered as there is a limit of the practical thickness that can be manufactured using the pultrusion process. Excessively thick pultruded components may not fully cure evenly across the section. The double wall construction should allow a thinner wall thickness while maintaining an equivalent cross-sectional area for a consistent global stiffness.

The results presented in Table 7 show that the single wall concept results in a lower mass for both outer diameter sensitivities. Both double and single wall results are similar in outer diameter and total wall thickness (i.e. the single wall results have approximately double the thickness of the double wall results). The presence of the webs between the double wall is likely to contribute to the higher mass for the double wall concept than the single wall concept. The mass of the NREL 5MW reference turbine tower is 347,460 kg. This is higher than the mass of the composite tower for both the single and double wall concepts in the unrestricted outer diameter case, 235,334 kg and 284,017 kg respectively.

4.2. Optimization Sensitivity

Gradient based optimization algorithms are sensitive to the initial design variables chosen and are likely to converge on a local minimum rather than the global minimum. The sensitivity of the study's optimization was investigated using multiple combinations of the initial variables. Table 8 presents the results of the sensitivity analysis for the single wall design with no upper bound on the diameter. It is noted that while converging on a valid result is sensitive to the initial variables, when the optimization does converge the values are not significantly effected by initial variables. The average result of the values presented in Table 8) is 242,403 kg, the lowest result is 235,334 kg (97% of the average result) and the highest result is 249,267 kg (103% of the average result).

Table 7: Optimzation Results

	Double Wall	Single Wall	Double Wall	Single Wall
Upper Bound Diameter [m]	7.00	7.00	10.00	10.00
$\mathrm{OD}_{\mathrm{base}}$ [m]	6.68	6.88	8.09	8.45
$\mathrm{OD}_{\mathrm{hub}}$ [m]	6.31	5.59	5.48	6.48
$\mathrm{T}_{\mathrm{p\text{-}base}}$ [mm]	38	73	23	42
$\mathrm{T}_{\mathrm{p\text{-}hub}}$ [mm]	30	61	21	27
$\mathrm{D}_{\mathrm{p\text{-}base}}$ [mm]	429	-	444	-
$\mathrm{D}_{\mathrm{p\text{-}hub}}$ [mm]	350	-	207	-
Natural Frequency [Hz]	0.219	0.224	0.220	0.221
Strength Utilization	0.835	0.950	0.989	0.951
Fatigue Damage	<0.0001	<0.0001	<0.0001	<0.0001
Mass [kg]	389,065	309,301	284,017	235,334

Table 8: Optimization Sensitivity Analysis - Mass [kg]

	$\mathrm{T}_{\mathrm{p\text{-}base}}$ [mm]	50	55	60	65	70	75
	$\mathrm{T}_{\mathrm{p\text{-}hub}}$ [mm]	30	35	40	45	50	55
$\mathrm{OD}_{\mathrm{base}}$ [m]	$\mathrm{OD}_{\mathrm{hub}}$ [m]						
8.00	7.00	-	-	-	-	-	-
8.25	7.25	243,798	248,046	-	-	239,270	-
8.50	7.50	235,334	244,107	-	241,760	245,140	249,267
8.75	7.75	238,313	238,299	239,128	241,783	242,071	
9.00	8.00	241,331	242,846	-	238,939	246,224	247,606

4.3. LCOE Estimation

Considering the uncertainties and 2016 input data discussed in the methodology section, a simplified LCOE calculation based primarily on the material, labour and equipment costs with a rough estimate for maintenance is now presented for informative comparison rather than detailed analysis.

The lowest mass for the double wall concept was 284,017kg. This filament wound layer had a mass of 78,152kg and the pultruded double wall panels had a total mass of 205,865kg. The cost of materials, labour and equipment is estimated to be \$1,723,124, assuming this is 70% of total costs, the total cost of a composite tower using filament winding and pultrusion would be \$2,461,606. This can be stated as \$492/kW for a 5MW wind turbine.

The single wall concept has a lower mass and is at the upper limit of pultrusion manufacturing capabilities due to its wall thickness. With a filament wound mass of 86,059 kg and a pultruded mass of 149,275 kg, the single wall concept would cost \$1,488,692 to be manufactured with a total cost of \$2,126,703 (\$425/kW).

If the single wall concept cannot be pultruded it is assumed that the vacuum assisted resin transfer mould (VARTM) process would be used instead. This is a process that is commonly used for large wind turbine blades of similar dimensions. Griffith and Johanns [22] created a cost model for large turbine blades (100 m in length and maximum chord length of 7.5m) based on the VARTM process. This cost model was adapted for a composite tower manufactured via the VARTM process. The estimated cost of materials, labour and equipment is \$1,512,469 and a total of \$2,160,670 (\$432/kW) following the previously stated cost distribution assumption.

It should be noted that the VARTM process was expected to produce a higher cost than the pultruded and filament wound process due to a significantly higher amount of labour required. It is possible that input from a composite manufacturer could help validate these estimates further.

A single wall concept tower cost of \$425/kW increases the turbine cost by \$198/kW from \$1,505/kW for a steel tower to \$1,703kW. The other factors that

Table 9: LCOE Projection for Single Wall Concept

		Lifetime [yr]										
		20	22	24	26	28	30	32	34	36	38	40
WACC [%]	6.5	178	172	167	163	160	157	155	153	151	149	148
	7	183	177	173	169	165	163	161	159	157	156	155
	7.5	189	183	178	175	171	169	167	165	163	162	161
	8	194	189	184	180	177	175	173	171	170	169	168
	8.5	200	194	190	187	184	181	179	178	176	175	174
	9	206	200	196	193	190	188	186	184	183	182	181

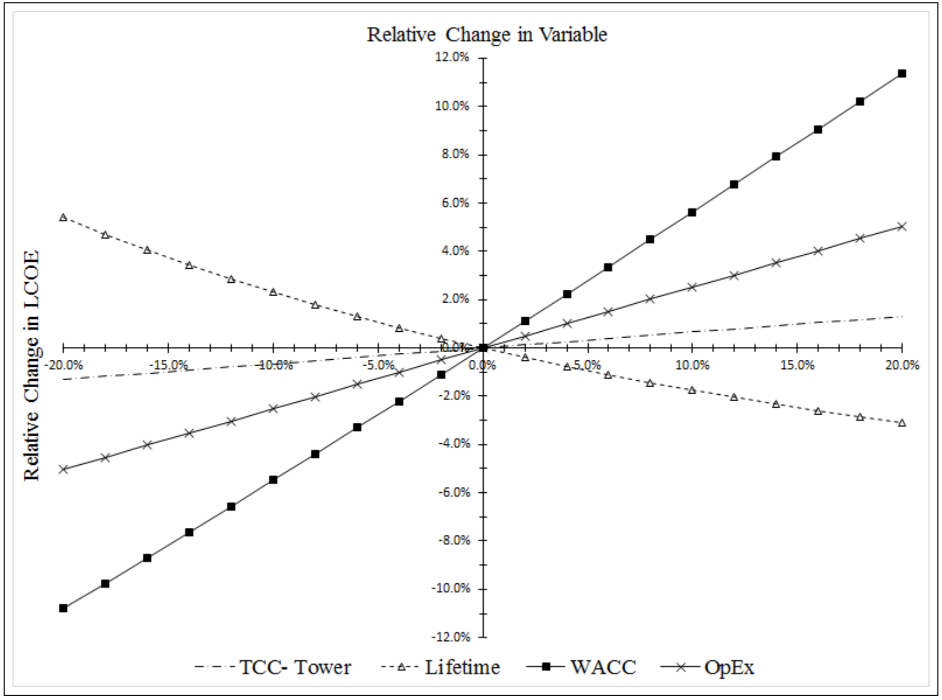
make up the capital costs (balance of system and financial costs, insurance) are likely to also increase due to uncertainties in the development, assembly, logistics, and installation of a tower without a proven history. These higher costs and uncertainties would raise the LCOE and make the the composite tower economically unrealistic for the standard offshore wind turbine design life of 20 years.

The fatigue performance of composites may allow for a longer design life which would reduce the LCOE. A projection of LCOE based on varying the weighted average cost of capital (WACC : incorporates uncertainty and capital cost for extended lifetime) and the design lifetime (n) is presented in Table 9. For the projection it is assumed that the operating cost remains unchanged and that additional costs due to the novel structure and the life extension are be included in the WACC for simplicity.

4.4. LCOE Sensitivity

The relative sensitivity of the LCOE to factors that may change depending on tower material is presented in Figure 4 in a format similar to Ragnarsson et al. [82]. The factors that change depending on tower material include lifetime (assuming the foundation has similar lifetime), OpEx (assuming different material would change maintenance costs), TCC-tower (total capital cost for the tower as part of CapEx). WACC (weighted average cost of captial) is included as an indicator of the sensitivity of the LCOE to financial factors which are affected by the entire project, not just the tower.

Figure 4: LCOE Sensitivity to Various Factors



If TCC-tower is assumed to represent a variation in tower mass at fixed material costs then Figure 4 can be used to assess the sensitivity of LCOE to a differnt construction form or structure type with a mass of ±20% the current structure's mass. Alternatively TCC-tower can be assumed to represent a variation in material costs to illustrate the effect of decreasing material costs on the LCOE as the costs of composite materials may change over time. Figure 4 shows that a 20% decrease in either material costs or structural mass would result in a 5% reduction in the total TCC and a 1.3% reduction in LCOE. Thus it can be seen in Figure 4 that lower material costs has limited influence on LCOE and that other aspects (OpEx, remaining CapEx costs, financing structure) of the LCOE have a much more significant effect.

5. Discussion

5.1. Renewable Energy Policy

The global push towards renewable energy is based on the United Nations Framework Convention1 on Climate Change (UNFCCC) and the Kyoto Protocol which seek to stabilise and reduce the worldwide greenhouse gas (GHG) levels in the atmosphere to concentrations that do not significantly impact global and local climate systems[83]. This approach seeks to ensure that climate change is gradual and allows ecosystems to adapt naturally. Rapid climate change could severely affect the balance in existing ecosystems. The gradual adaption of ecosystems is necessary to ensure that food production is not threatened and that economic development is sustainable.

Through both the 2020 Climate and Energy Package and the Paris agreement the European Union (EU) has pledged to reduce domestic GHG levels by 40% compared to 1990 levels between now and 2030[83]. Both EU and Irish renewable energy policies have identified offshore energy, primarily offshore wind energy, as an important potential resource in achieving the renewable energy targets. The EU Energy roadmap 2050 [84] has highlighted the northern seas and the Atlantic sea basin as areas that can supply significant amounts of energy as costs decline. The Irish government's offshore energy assessment[85] and the relevant authority, the Sustainable Energy Authority Of Ireland[86], have determined that there is potential for up to 16GW of onshore wind and 30GW of offshore wind by 2050 and should be a central element in the country's energy plan.

The Irish government's renewable energy policy papers[83, 85, 86] and relevant legislation, the Climate Action and Low Carbon Development Bill 2015, have identified the need to encourage new technologies and accelerate the deployment of wind energy with the aims of moving to a low carbon energy system, reducing energy dependence foreign fossil fuel imports and the creation of jobs in installing and maintaining onshore and offshore wind turbines. The work in this paper may contribute to the development of the new technologies and increased competitiveness highlighted as critical in achieving renewable energy targets in global, Europe and Irish policy.

5.2. Optimization

The optimization process has identified composite tower designs that result in a lower mass than that of the reference steel tower, which satisfies the aim of this study. Mass was chosen to be optimized as accurate LCOE studies require more information on the long term behaviour of large scale composite structures in extreme environments.

The fatigue constraint not found to be a design driver and the accumulated damage was not significant suggesting that the tower should maintain structural integrity for the design lifetime of 20 years. A more detailed fatigue study would be required to determine a likely fatigue lifetime with confidence. The natural frequency appears to be the primary constraint on viable solutions. The optimal solutions balance this primary constraint with the constraint of ultimate strength (of panel buckling and first ply failure) nearing it's limit. This observation is in line with expectations.

Composite materials with glass fibers typically have high strength and good fatigue properties with a relatively low modulus of elasticity. The natural frequency constraint is governed by the stiffness of the structure, thus the low modulus of elasticity must be balanced by a larger cross-sectional area, second moment of area, and mass. This results in designs with larger tower diameters or thicker walls than the existing NREL 5MW reference design. Similar issues have been found for other large scale composite structures. Where significant stiffness is needed (to prevent large deflections or to meet required natural frequencies) composites do not always lead to lighter or cheaper structures than steel. Bridges constructed entirely from composites are rare as the low modulus of elasticity of the e-glass typically results in designs with very large girder cross-sections that while structurally acceptable are not justified economically[87]. Composites are also noted to perform better in tension than compression.

5.3. LCOE Estimation

The average LCOE for a traditional steel tower supported 5MW offshore turbine in 2016 was \$173/MWh [79]. The LCOE projection in Table 9 shows that with an increased lifetime and suitable financing, the LCOE for a composite tower may be economically competitive with that of a steel tower. This comparison is based on the current construction form, which uses the most economical methods of composite material manufacturing, and may not be applicable to other composite structures constructed with different manufacturing techniques.

As material cost makes up a significant portion of the tower cost, reducing the mass and hence material costs further would be beneficial. Carbon fiber is often used to increase the stiffness and reduce the cross-sectional area and mass of components. With a cost an order of magnitude more expensive than glass fiber, carbon fiber is unlikely to be suitable for this application. E-glass with it's relatively low modulus of elasticity remains the only fiber that is potentially economically viable.

An area of uncertainty is the maintenance and repair of a composite tower with associated cost. Traditional steel offshore structures can be repaired in-situ if damaged with a minimum of disruption to normal operations. In-situ patching and laminate repair is not advised for composite materials. Composite repair typically takes place in protected environments that can control ambient temperature and the moisture content of the surrounding air. Repairs to a composite turbine blade involves removing the blade and transporting it to a dedicated facility onshore. Replacement blades allow the turbine to maintain operations with a minimum of disruption. The removal, replacement and transportation of a blade is much less complicated than the removal, replacement and transportation of a tower would be as the turbine does not need to disconnected or removed for a switch.

Blades need to refurbished at regular intervals due to wear and pitting on the leading edge. The intervals are typically 8-12 years for onshore blades and 3-5 years for offshore blades due to the more extreme environment present offshore.

It is unknown what the refurbishment interval of a composite tower would be as it does not have the same failure mechanisms as blades and may not require as much maintenance as a steel tower that is susceptible to corrosion and rust. It is uncertain whether the maintenance of a composite tower would increase or decrease the operating cost of a wind farm project.

A potential benefit of the composite tower is it's lower mass and construction. The lower mass would require smaller, cheaper installation vessels that could operate in wider weather windows. Any reduction in duration of offshore operations is beneficial from both a financial and safety viewpoint. Composite manufacturing facilities can be relocated more easily than steel manufacturing facilities. Dockside composite manufacturing would lower logistical and assembly costs.

The other components of the structure and turbine would need to retain structural integrity and power generation efficiency for the extended lifetime or be replaced, which is likely to also increase the associated capital and maintenance costs.The information that could be gained through the testing and measurement of both in-situ scale models and full scale demonstration units is required before a more detailed LCOE projection can be determined.

5.4. Further Research

While it has been determined that the composite tower is technically feasible, uncertainty remains in how it compares economically with the steel tower. The LCOE projections indicate that simply replacing a steel tower with a composite tower may not be suitable for fixed bottom offshore wind turbines in the "soft-stiff" natural frequency range depending on financing options. A more holistic redesign and optimization of the entire structure include the foundation and turbine may produce beneficial results. Significant redesign of the entire structure, incorporating foundation, tower and turbine, may produce economically attractive LCOEs. Potential concepts include:

- vertical axis wind turbines (VAWTs); the relocation of turbine mass to the base of the tower from the top produces a higher natural frequency range and composite materials may be mitigate the fatigue issues associated with steel and aluminium VAWT.

- compliant structures that are not limited by the low modulus of elasticity such as "soft-soft" designs [10],
- reviewing the development and advances in composite blade design to identify potentially suitable ideas,
- concepts that make use of the secondary effects of a lower tower mass [9],
- or alterations to the control system of the turbine to reduce loads and deflections via frequency hopping to avoid resonance or active pitch control to alter blade angles which would increase blade drag and aerodynamic damping.

6. Conclusion

The study presents a mass optimised composite tower design suitable for the NREL 5MW reference wind turbine, determines the limiting constraint for this design, and establishes a preliminary LCOE for the tower and evaluates mass, design and LCOE in comparison with existing traditional steel designs.These contributions to the area will add to the understanding of the application of lightweight fiber reinforced composite materials in the construction of offshore wind turbine support structures and to the understanding of the economic viability of composite alternatives to traditional steel offshore structures.

The optimization process has found a combination of variables that results in composite tower with a lower mass than the reference steel tower which is desirable for offshore operations.The double wall concept and combination of filament winding and pultrusion have been investigated and do not have significant advantages over other construction techniques in terms of final cost. A single wall composite tower resulted in the lowest estimated costs.

7. Acknowledgements

The authors gratefully acknowledge the financial support of the Ove Arup Foundation and of Science Foundation Ireland (SFI) Research Centre: MaREI Centre for Marine and Renewable Energy (12-RC-2302). Thanks are also extended to NREL for providing FAST and associated suite of tools and the Netherlands Enterprise Agency for releasing the metocean data for Hollandse Kust Zuid wind farm site.

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