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IEA Wind TCP Task 37

Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine

Technical Report

iea wind

Definition of the IEA 15-Megawatt Offshore Reference Wind

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NOTICE

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Staff from the National Renewable Energy Laboratory (NREL) and the Technical University of Denmark (DTU) collaborated closely, via the International Energy Agency (IEA) Wind Task 37 on Systems Engineering in Wind Energy, to design the reference turbine described in this report. The authors from the University of Maine (UMaine) leveraged their expertise and resources to contribute the floating platform semisubmersible design. To better capture the individual contributions, and as a resource for future inquiries, the following table lists the roles and responsibilities for all of the authors involved.

Name	Institution	Contribution
Evan Gaertner	NREL	Primary design engineer who led the blade, tower, and monopile design
Jennifer Rinker	DTU	HAWC2 lead, design load basis, controller tuning
Latha Sethuraman	NREL	Designer of permanent-magnet direct-drive generator, drivetrain, bedplate, nacelle, and other subsystems
Frederik Zahle	DTU	Bend-twist coupling contribution, rotor and blade design review
Benjamin Anderson	NREL	Created nacelle CAD model and performed drivetrain and bedplate analysis
Garrett Barter	NREL	Project principal investigator
Nikhar Abbas	NREL	Reference OpenSource Controller lead and tuning
Fanzhong Meng	DTU	Controller lead and tuning
Pietro Bortolotti	NREL	Blade design support
Witold Skrzypiński	DTU	Tool development for blade design
George Scott	NREL	Drivetrain design support
Roland Feil	NREL	Detailed blade structural analysis
Henrik Bredmose	DTU	COREWIND principal investigator
Katherine Dykes	DTU	General support
Matt Shields	NREL	Monopile and transition piece design support, report editing
Christopher Allen	UMaine	Lead semisubmersible design engineer
Anthony Viselli	UMaine	Semisubmersible principal investigator

Beyond IEA Wind facilitated collaboration between NREL, DTU, and UMaine, the larger networks of individual staff members and the IEA Wind Task 37 effort were leveraged to ensure that the design represented a conservative estimate of industry capabilities. These industry contacts gave invaluable information to calibrate our design assumptions and input values. Without their input, the 15-MW reference turbine would not be nearly as professional of a design or as useful to the broader community. In no particular order, we extend our thanks to the following companies and individuals:

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Nomenclature

Acronyms	
3D	three-dimensional
BECAS	BEam Cross section Analysis Software
DLC	design load case
DTU	Technical University of Denmark
HAWTOpt2	Horizontal Axis Wind Turbine Optimization 2nd generation
HAWC2	Horizontal Axis Wind turbine simulation Code 2nd generation
IEC	International Electrotechnical Commission
IEA	International Energy Agency
metocean	meteorological ocean
NREL	National Renewable Energy Laboratory
NdFeB	neodymium
PSD	power spectral density
PI	proportional integral
ROSCO	Reference OpenSource Controller
RMS	root mean squared
SRB	spherical roller bearing
SST	shear stress transport
TDO	tapered double outer
TSR	tip-speed ratio
UMaine	University of Maine
WindPACT	Wind Partnership for Advanced Component Technology
WISDEM®	Wind-Plant Integrated System Design Engineering Model
WP	work package
Units	
A	ampere
h	hour
Hz	hertz
kg	kilogram
m	meter
min	minute
N (kgm/s^2)	Newton
rad	radian
rpm	revolutions per minute
P	period
Pa (N/m^2)	pascal
s	second
t	metric tonne
T	tesla
V	volt
W	watt
Prefixes	
m	milli
k	kilo
M	mega
G	giga

Executive Summary

Overview and Motivation

Reference wind turbines serve multiple roles within the wind community and have therefore grown in importance in recent years. First, they serve as open benchmarks that are defined with publicly available design parameters to be used as baselines for studies that explore new technologies or design methodologies. Second, as an open design, reference wind turbines enable collaboration between industry and external researchers. Finally, reference wind turbines offer an entry point and educational platform for newcomers to wind energy to understand fundamental design elements and system trade-offs.

For fixed-bottom offshore wind energy, the average turbine size for European deployment in 2018 was 6.8 MW [1], and GE will launch its 12-MW Haliade-X offshore turbine to the market in 2021 with a rotor diameter of 218 m and direct-drive configuration. To be relevant now and in the coming years, a new reference wind turbine should leap ahead of the current generation of industry wind turbines, but cannot leap so far that aggressive technology innovations are required. Therefore, a reference wind turbine above 10 MW [2], yet below 20 MW [3], is needed, that continues on the same growth trend as the GE Haliade-X using a similar drivetrain configuration and specific power.

This report describes a 15-megawatt (MW) offshore wind turbine with a fixed-bottom monopile support structure. This reference wind turbine is a Class IB direct-drive machine, with a rotor diameter of 240 meters (m) and a hub height of 150 m. An overview of the design is presented in Figure ES-1 and Table ES-1. The design reflects a joint effort between the National Renewable Energy Laboratory (NREL), sponsored by the U.S. Department of Energy, and the Technical University of Denmark (DTU), sponsored by the European Union's H2020 Program, through the second work package of International Energy Agency (IEA) Wind Task 37 on Wind Energy Systems Engineering: Integrated RD&D. A forthcoming report will detail a semisubmersible floating support structure developed by the University of Maine (UMaine).

Blade and Rotor Properties

Top level rotor configuration decisions were informed by discussions with industry partners, on what would be technically feasible for the next generation of wind turbines. The blade design was driven by the selection of 240 m as the rotor diameter and a maximum tip speed of 95 meters per second (m/s). A fairly traditional structural configuration was selected, comprising of two main load-carrying, carbon-reinforced spars, connected by two shear webs, with reinforcement along the trailing and leading edge and foam fillers. The DTU FFA-W3 series of airfoils were used due to their publicly available polars and geometries. The blade chord, twist, airfoil positions, tip speed ratio, and spar cap thickness were selected through a design optimization study. Table ES-2 summarized key features of the blades, including a design power coefficient, C_P, of 0.489 and 65 metric tons (t) of blade mass.

Tower and Monopile Properties

The tower and monopile were designed as an isotropic steel tube. Frequency considerations constrained much of the design in that the first tower-monopile mode, 0.17 hertz (Hz), lies between the 1P and 3P blade passing frequencies for all wind speeds. This is also sufficient to avoid the range of highest energy ocean wave frequencies for a generic East Coast site (0.10 Hz to 0.13 Hz). The tower height was chosen such that the hub height reaches 150 m, allowing for 30 m of ground (water surface) clearance with up to 120-m blades. The monopile foundation has a 10-m outer diameter, which pushes the limits of current manufacturing and installation technology, and a thickness profile that varies from 55 millimeters (mm) in the pile to 44 mm at the transition piece.

Nacelle and Drivetrain Properties

The 15-MW reference wind turbine uses a direct-drive layout with a permanent-magnet, synchronous, radial flux outer-rotor generator in a simple and compact nacelle layout. Figure ES-2a shows a simple direct-drive nacelle layout with an outer-rotor permanent-magnet generator. The assembly consists of a hub shaft supporting the turbine

Table ES-1. Key Parameters for the IEA Wind 15-MW Turbine

Parameter	Units	Value
Power rating	MW	15
Turbine class	-	IEC Class 1B
Specific rating	W/m^2	332
Rotor orientation	-	Upwind
Number of blades	-	3
Control	-	Variable speed
		Collective pitch
Cut-in wind speed	m/s	3
Rated wind speed	m/s	10.59
Cut-out wind speed	m/s	25
Design tip-speed ratio	-	9 0
Minimum rotor speed	rpm	5.0
Maximum rotor speed	rpm	7.56
Maximum tip speed	m/s	95
Rotor diameter	m	240
Airfoil series	-	FFA-W3
Hub height	m	150
Hub diameter	m	7.94
Hub overhang	m	11.35
Rotor precone angle	deg	-4.0
Blade prebend	m	4
Blade mass	t	65
Drivetrain	-	Direct drive
Shaft tilt angle	deg	6
Rotor nacelle assembly mass	t	1,017
Transition piece height	m	15
Monopile embedment depth	m	45
Monopile base diameter	m	10
Tower mass	t	860
Monopile mass	t	1,318

deg	degrees	rpm	revolutions per minute
m	meters	t	metric tons
m/s	meters per second	W/m^2	watts per square meter

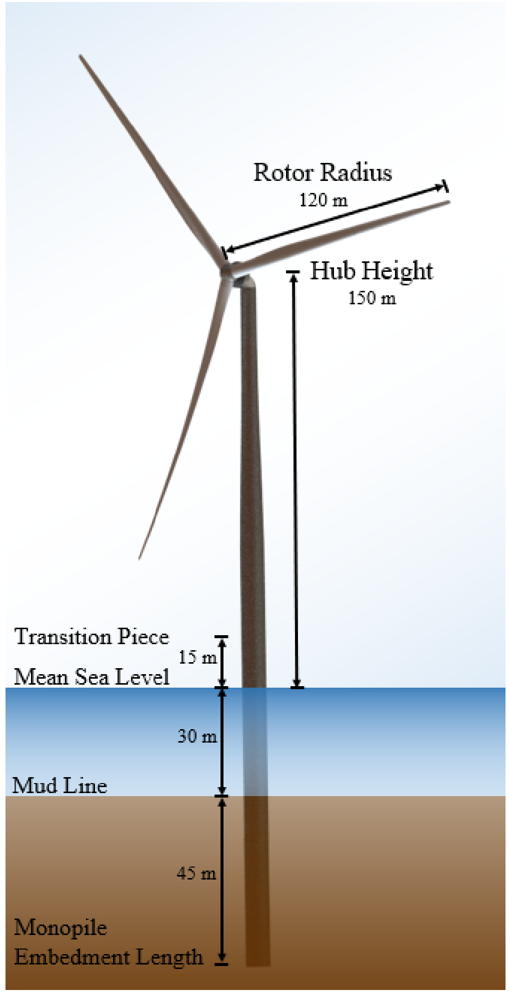


Figure ES-1. The IEA Wind 15-MW reference wind turbine

and generator rotors on two main bearings housed on a stationary turret that is cantilevered from the bedplate. The hub is a simple spherical shell, with cutouts for the blades and the flange. The main shaft has a hollow cylindrical cross section, with a constant wall thickness and a tilt angle of 6°. The main shaft, along with the rotor, is supported by two main bearings. Both these main bearings have rotating outer raceways and fixed inner raceways. The outer raceways and bearing housing are accommodated by a turret held by the bedplate. The entire weight of the turbine rotor, generator rotor, and hub loads are transmitted by the main shaft to the turret via the bearings. The bedplate is a hollow, elliptically curved, cantilever beam with circular cross sections. The yaw system bearings are double-row, angular, contact ball bearings.

The generator construction features an external rotor radial flux topology machine with a surface-mounted permanent magnet (shown in Figure ES-2b). The outer rotor layout facilitates a simple and rugged structure, easy manufacturing, short end windings, and better heat transfer between windings and teeth than the inner rotor configuration. The stator design features fractional, slot-layout, double-layer concentrated coils, which maximize the fundamental winding factor.

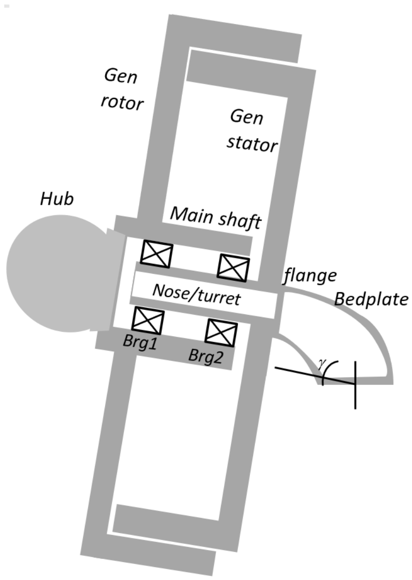
Load Analysis

This work assumes a generic U.S. East Coast site with a wind speed described by a Weibull distribution with a mean velocity of approximately 8.65 m/s and a shape parameter of 2.12. At this mean wind speed, the corresponding significant wave height is approximately 1.4 m, with a peak spectral period of 7.9 seconds (s). The fixed-bottom

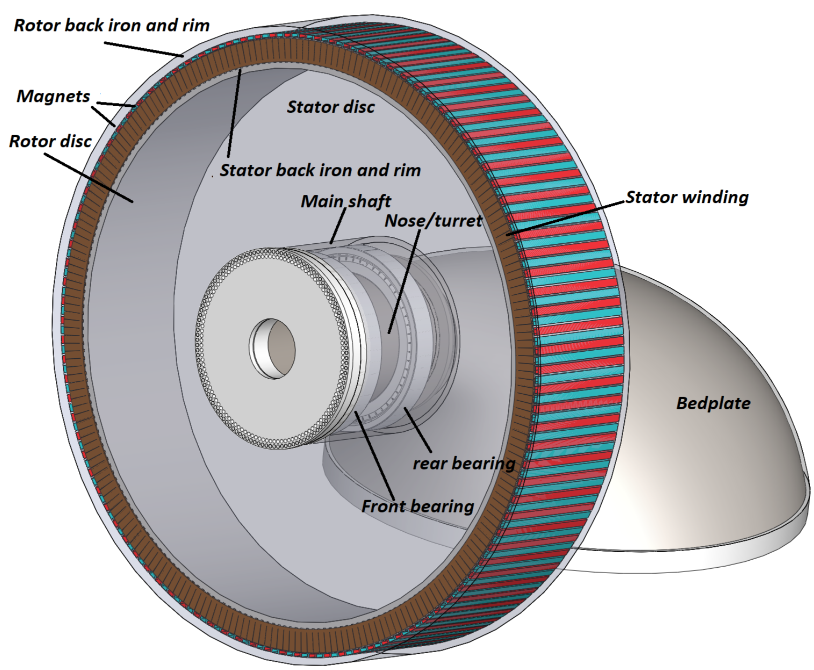
Table ES-2. Blade Properties

Description	Value	Units
Blade length	117	m
Root diameter	5.20	m
Root cylinder length	2.34	m
Max chord	5.77	m
Max chord spanwise position	27.2	m
Tip prebend	4.00	m
Precone	4.00	deg
Blade mass	65,250	kg
Blade center of mass	26.8	m
Design tip-speed ratio	9.00	-
First flapwise natural frequency	0.555	Hz
First edgewise natural frequency	0.642	Hz
Design C_P	0.489	-
Design C_T	0.799	-
Annual energy production	77.4	GWh

deg	degrees	kg	kilograms
GWh	gigawatt-hours	m	meters
Hz	Hertz		



(a)



(b)

Figure ES-2. A sketch and CAD model of the nacelle layout of the 15-MW direct-drive wind turbine. Not to scale and some structural details omitted. Blades (not shown), hub, shaft, and generator rotor rotate.

monopile support presented in this report is designed around a water depth of 30 m.

An International Electrotechnical Commission design load case [4] analysis study was conducted to determine the worst-case ultimate loading on key design constraining components. Yaw-misaligned parked conditions with extreme wind speeds and extreme coherent gust with a direction change result in the worst-case loading for this design. The worst-case out-of-plane tip deflection is 22.8 m, leaving more than sufficient tower clearance, with an unbent blade tip-to-tower clearance of 30.0 m. This margin suggests that the blade design is conservative and further aeroelastic optimization could potentially improve the aerodynamic performance or cost of energy while still remaining within recommended safety margins. A full fatigue analysis of this blade was not conducted, which could potentially be an issue for the edgewise blade bending moments for very large blades.

Availability

To foster further collaboration, the reference turbine design is available for use by the broader wind energy community in input files that support a variety of analysis tools, including OpenFAST, HAWC2, the Wind-Plant Integrated System Design & Engineering Model (WISDEM), and HawtOpt2. These files are hosted on GitHub at github.com/IEAWindTask37/IEA-15-240-RWT, with the intent that the community will contribute back to the effort by submitting their design variants for inclusion in the repository.

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1 Introduction

1.1 The Role of Reference Wind Turbines

Reference wind turbines serve multiple roles within the wind community and have therefore grown in importance in recent years. First, they serve as open benchmarks that are defined with publicly available design parameters to be used as baselines for studies that explore new technologies or design methodologies. Traditionally, reference wind turbines have been realistic, but not fully optimized, designs so that they can be updated and improved upon by the active wind energy community. Second, as an open design, reference wind turbines enable collaboration between industry and external researchers. By using a reference turbine, industry can protect its intellectual property yet still explore advanced technology development with outsiders. Finally, reference wind turbines offer an entry point and educational platform for newcomers to wind energy to understand fundamental design elements and system trade-offs.

The history of reference wind turbines begins in the early 2000s with the National Renewable Energy Laboratory (NREL) Wind Partnership for Advanced Component Technology (WindPACT) turbine series, which includes 0.75-, 1.5-, and 3-megawatt (MW) turbines [5]. Their use, however, was restricted to national laboratories in the United States. The first widely adopted reference turbine by the larger international community was the NREL 5-MW turbine [6], which is still used by many researchers today. More recently, the Technical University of Denmark (DTU) developed a 10-MW turbine for offshore wind applications [7]. These two turbines have been supplemented by other turbines, such as an 8-MW turbine in the European Union FP7 project LEANWIND [8], the Sandia National Laboratories' 100-meter (m)-blade studies [9], and a conceptual study of a 20-MW turbine in the INNWIND project [3]. Most recently, the IEA Wind Task 37, which coordinated this effort, also released modernized 3.35-MW land-based and 10-MW offshore reference turbines [2]. These designs have been released quickly on the heels of one another as the industry has rapidly increased the power rating and size of its product lines. For fixed-bottom offshore wind energy, the average turbine size for European deployment in 2018 was 6.8 MW [1], and GE will launch its 12-MW Haliade-X offshore turbine to the market in 2021 with a rotor diameter of 218 m and direct-drive configuration.

To be relevant now and in the coming years, a new reference wind turbine must leap ahead of the current generation of industry wind turbines, but cannot leap so far that aggressive technology innovations are required. The current slate of reference wind turbine designs cannot fully meet the needs of the research community and industry to advance the state of the art in blade scaling, floating foundation design, wind farm control, logistic studies, and many other topics. Therefore, a reference wind turbine above 10 MW, yet below 20 MW, is needed that continues on the same growth trend as the GE Haliade-X using a similar drivetrain configuration and specific power.

This is the motivation for the design effort of this IEA Wind 15-MW reference wind turbine described in this report. This reference wind turbine, Figure 1-1, is a Class IB direct-drive machine, with a rotor diameter of 240 m and a hub height of 150 m. The design reflects a joint effort between NREL, sponsored by the U.S. Department of Energy, and DTU, sponsored by the European Union's H2020 Program, through the second work package of IEA Wind Task 37 on Wind Energy Systems Engineering: Integrated RD&D. This report describes an offshore fixed-bottom monopile support structure, with a forthcoming report to detail a semisubmersible floating support structure developed in collaboration with the University of Maine (UMaine).

1.2 Overall Turbine Parameters

The overall parameters for the turbine are stated in Table 1-1. The table also shows the data for the DTU 10-MW reference wind turbine [7] for comparison.

1.3 Design Tools and Methodologies

The IEA Wind 15-MW reference turbine was jointly designed by NREL, DTU, and UMaine. The analysis and design tools that were leveraged as part of this effort are listed in Table 1-2. These model names will appear frequently in the discussion of the design in the sections to come.

Table 1-1. Key Parameters for the IEA Wind 15-MW Turbine, As Compared to the DTU 10-MW Turbine

Parameter	Units	DTU 10-MW Turbine	IEA Wind 15-MW Turbine
Power rating	MW	10	15
Turbine class	-	IEC Class 1B	IEC Class 1B
Specific rating	W/m^2	401	332
Rotor orientation	-	Upwind	Upwind
Number of blades	-	3	3
Control	-	Variable speed	Variable speed
	-	Collective pitch	Collective pitch
Cut-in wind speed	m/s	4	3
Rated wind speed	m/s	11.4	10.59
Cut-out wind speed	m/s	25	25
Rotor diameter	m	178.3	240
Airfoil series	-	FFA-W3	FFA-W3
Hub height	m	119	150
Hub diameter	m	5.6	7.94
Hub overhang	m	7.1	11.35
Drivetrain	-	Medium speed	Low speed
	-	Multiple-stage gearbox	Direct drive
Design tip-speed ratio	-	7.5	9.0
Minimum rotor speed	rpm	6.0	5.0
Maximum rotor speed	rpm	9.6	7.56
Maximum tip speed	m/s	90	95
Gearbox ratio	-	50	—
Shaft tilt angle	deg	5	6
Rotor precone angle	deg	-2.5	-4.0
Blade prebend	m	3.332	4
Blade mass	t	41	65
Rotor nacelle assembly mass	t	674	1,017
Tower mass	t	987	860
Tower base diameter	m	8	10
Transition piece height	m	10	15
Monopile embedment depth	m	42.6	45
Monopile base diameter	m	9	10
Monopile mass	t	2,044	1,318

deg	degrees	rpm	revolutions per minute
m	meters	t	metric tons
m/s	meters per second	W/m^2	watts per square meter
MW	megawatts		

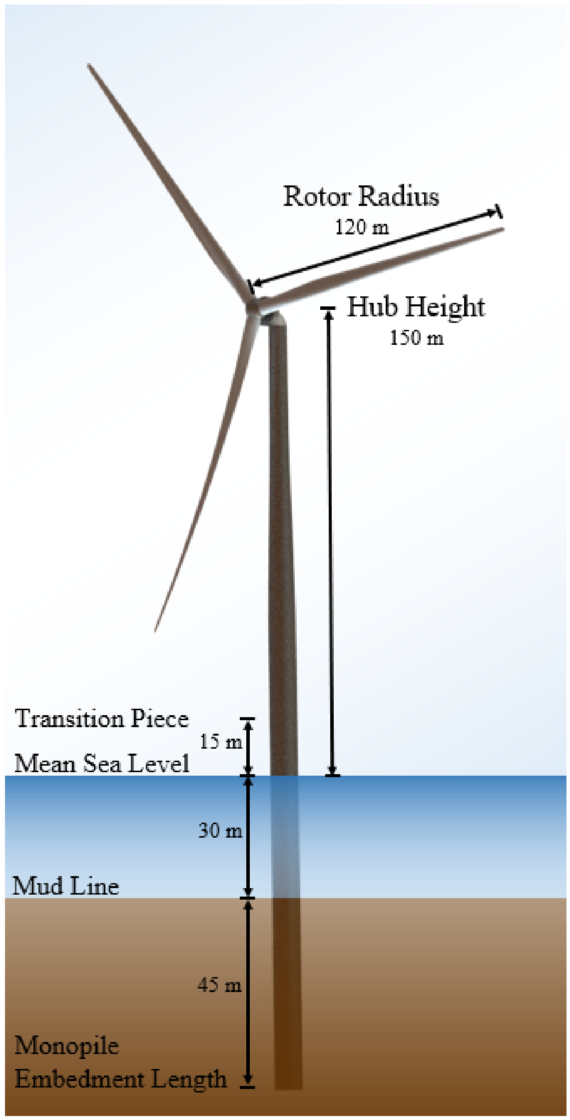


Figure 1-1. The IEA Wind 15-MW reference wind turbine

Table 1-2. Models Used for Design and Analysis of the IEA Wind 15-MW Reference Wind Turbine

Role	NREL Tool Chain	DTU Tool Chain
System Design	WISDEM [10], [11] CCBlade [14] RotorSE [15] DrivetrainSE TowerSE	HAWTOpt2 [12], [13]
Preprocessors	PreComp [16] BModes [18]	BECAS [17]
Aeroelastic Analysis	OpenFAST [19], [20]	HAWC2 [21] HAWCStab2 [22]

Most of the design was conducted within the Wind-Plant Integrated System Design & Engineering Model (WISDEM®), which is a family of models that are generally simplified and quasi-static to enable rapid design optimization at a limited number of design points. WISDEM is built on top of National Atmospheric and Space Administrations's OpenMDAO library, which drives the optimization and serves as the glue code between different models [23]. Conceptual designs were verified and enriched with more complete load and performance analysis using the nonlinear transient models of OpenFAST, HAWC2, and HAWCStab2. The results of these higher-fidelity simulations were used to update the design variable bounds and constraint values within WISDEM, and the process was iterated.

1.4 Model Availability

The reference turbine design is available for use by the broader wind energy community in input files that support a variety of analysis tools, including OpenFAST, HAWC2, WISDEM, and HawtOpt2. Additionally, the data depicted in graphs and tables in this report are also available electronically, in Microsoft Excel format, instead of writing them out as appendices. These files are hosted on GitHub at:

- github.com/IEAWindTask37/IEA-15-240-RWT
- github.com/IEAWindTask37/IEA-15-240-RWT/blob/master/Documentation.

The open-source availability of the IEA Wind 15-MW reference wind turbine is intended to encourage the community to contribute back to the effort by submitting their design variants for inclusion into the repository and further use by others.

1.5 Meteorological Ocean Environment

As a generic reference turbine, the design is intended to apply to many different offshore locations. However, the analysis of ultimate loads and the design of the substructure depend on the particular wind, wave, and soil profiles. The work of Stewart et al. [24] provides a general yet specific enough meteorological ocean (metocean) environment to execute the analysis and design. This work assumes a generic U.S. East Coast site, with detailed wind and wave probability distributions found in the repository documentation listing described in the previous subsection. As a quick summary, the wind speed is described as a Weibull distribution with parameters [9.767, 2.12], which gives a mean velocity of approximately 8.65 meters per second (m/s). At this mean wind speed, the corresponding significant wave height is approximately 1.4 m, with a peak spectral period of 7.9 seconds (s). The fixed-bottom monopile support presented in this report is designed around a water depth of 30 m.

2 Blade Properties

The blade length of this IEA Wind 15-MW reference turbine is 117 m with a root diameter of 5.2 m and a maximum chord of 5.77 m at approximately 20% span. The overall blade mass is around 65 metric tons (t) and is designed to achieve a power coefficient, C_P, of 0.489. A top-down and edge view of the blade are shown in Figure 2-1 and a more complete statistical breakdown is listed in Table 2-1.

Figure 2-1. View from the suction side (top) and trailing edge (bottom) of the offshore wind turbine blade

Table 2-1. Blade Properties

Description	Value	Units
Blade length	117	m
Root diameter	5.20	m
Root cylinder length	2.34	m
Max chord	5.77	m
Max chord spanwise position	27.2	m
Tip prebend	4.00	m
Precone	4.00	deg
Blade mass	65,250	kg
Blade center of mass	26.8	m
Design tip-speed ratio	9.00	-
First flapwise natural frequency	0.555	Hz
First edgewise natural frequency	0.642	Hz
Design C_P	0.489	-
Design C_T	0.799	-
Annual energy production	77.4	GWh

deg	degrees	kg	kilograms
GWh	gigawatt-hours	m	meters
Hz	Hertz		

2.1 Blade Aerodynamic Properties

The DTU FFA-W3 series of airfoils for use in the blade design. These are publicly available and well-documented airfoils that were also used in the IEA Wind/DTU 10-MW offshore reference wind turbine and are shown in Figure 2-2.

The airfoil data for each of the FFA-W3 airfoils was generated at a Reynolds number of $Re = 10^7$. To compute the aerodynamic coefficients in the range of $-32°$ to $32°$, we used the two-dimensional incompressible Navier-Stokes solver, EllipSys2D [25–27]. The meshes were generated using HypGrid2D [28], with a 512-by-256-cell radial grid. Simulations assumed fully turbulent and freely transitioning boundary layers, based on the $k-\omega$ shear stress transport (SST) turbulence model [29] and the Drela-Giles transition model [30], assuming a freestream turbulence intensity of 0.1%. We performed a 360° extrapolation using AirfoilPreppy, but three-dimensional (3D) corrections were not applied to the polars because the spanwise distribution of relative thickness was a free design variable. A Du-Selig [31] stall delay 3D correction was applied to the polar data for the OpenFAST model of the final design. Figure 2-3 shows the aerodynamic characteristics of the airfoils used on the blade. Tabular data of airfoil shapes and performance polars are provided in the parallel spreadsheet documentation.

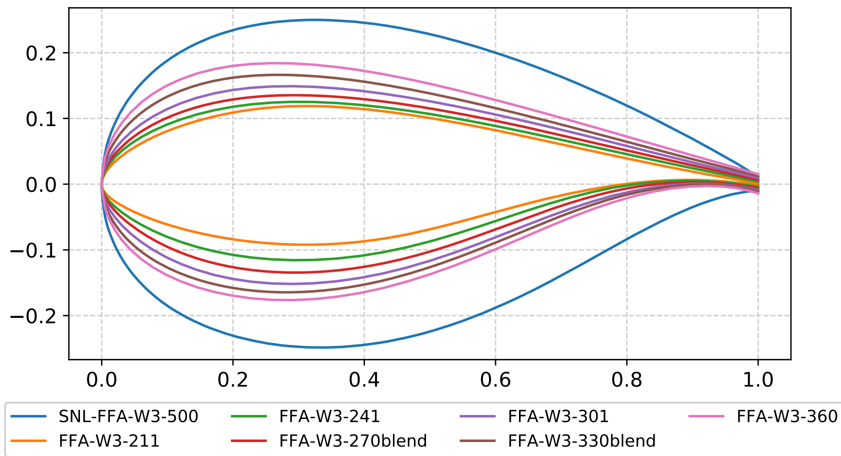
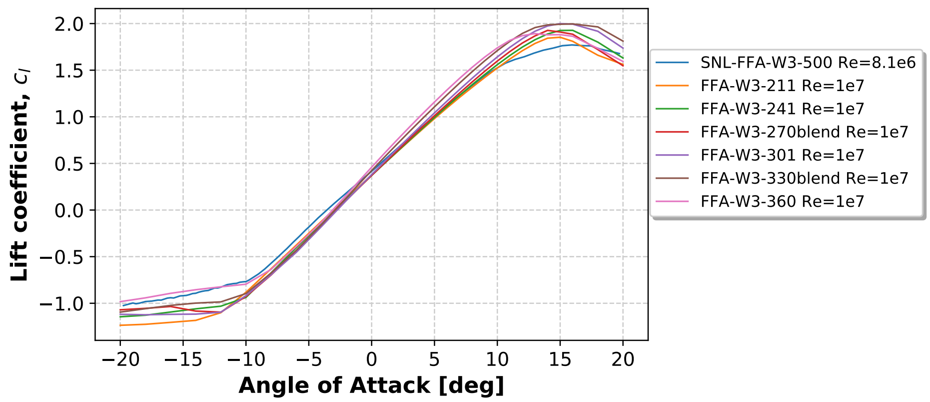


Figure 2-2. DTU FFA-W3 airfoil family used in the IEA Wind 15-MW blade design

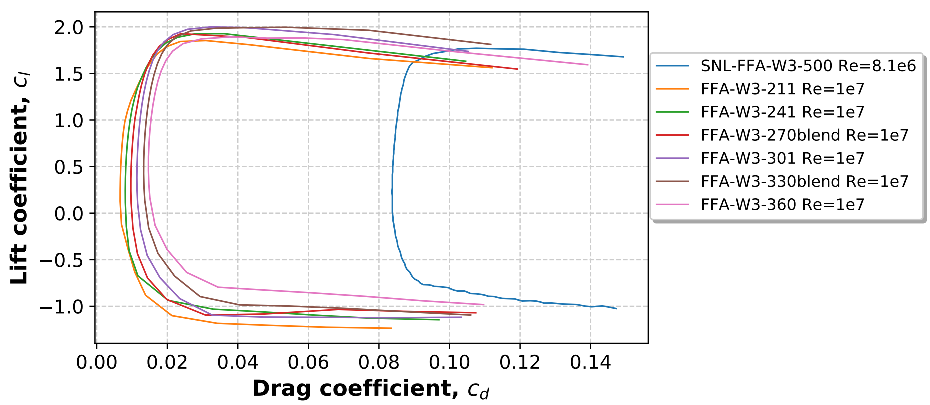
The blade planform design variables are plotted in Figure 2-4. The aerodynamic center of the airfoils is used for the blade pitch axis. There are a number of aerodynamic design characteristics that are worth noting. The transition from a cylinder cross section to the thickest 50% airfoil occurs between 2.34 m to 17.55 m or 2%–15% of the span, with the maximum chord of 5.77 m at 27.2 m of span (23.3%). This is shown in the chord and relative thickness profiles in Figure 2-4a–b. With such a large blade radius, the design was heavily driven by the tip deflection loading and tower clearance constraint. The twist profile in Figure 2-4c shows some unloading at the blade tip, which sheds some energy production to mitigate the strongest thrust loads at the most flexible part of the blade. This behavior will be evident again in the rotor performance plots in Section 3. The blade was designed with a significant prebend away from the tower to provide additional tip clearance, with 4 m separating the tip chordline from the root (Figure 2-4d). When axially stacking the airfoils to generate the lofted blade shape, the cant angle from prebend curvature is not considered. More prebend would have given further margin, reducing stiffness requirements, but the value was limited to 4 m based on blade molding and other manufacturing challenges, as communicated by industry. Advanced manufacturing techniques may enable greater blade prebend in the future, but this is a reasonable constraint at this time.

2.2 Blade Structural Properties

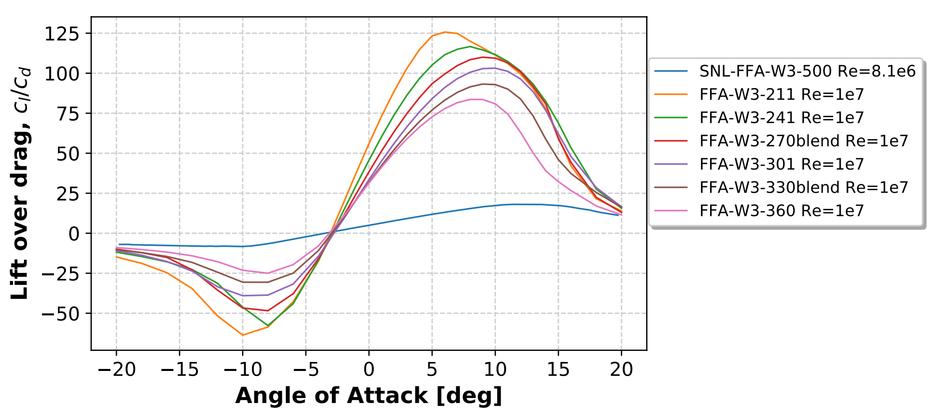
The lofted blade shape is shown in Figure 2-5 and an internal structural layout at 70% span is shown in Figure 2-6, with additional spanwise locations in Appendix A. The structural layout of the blade is fairly traditional, comprising two main load-carrying spars placed on a straight line connecting the root and the tip, along with reinforcement along the trailing and leading edges. One of these spar caps is placed on the airfoil pressure side and the other on the suction side. These spar caps are made out of carbon fiber to provide as much stiffness with as little weight as possible. The blade has two shear webs that connect the pressure side and suction side, attached to the main spars, extending from a 10% to 95% span; shown in Figure 2-6 as the vertical members. Leading and trailing edge reinforcements are also added using uniaxial glass fiber to provide additional edgewise stiffness. Foam filler panels were added between the leading-edge and trailing-edge reinforcement and the spar caps, on both the pressure side and suction side.



(a) Airfoil lift coefficients

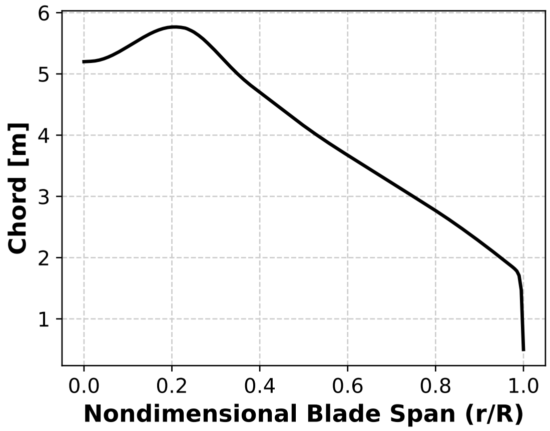


(b) Airfoil lift-drag polars

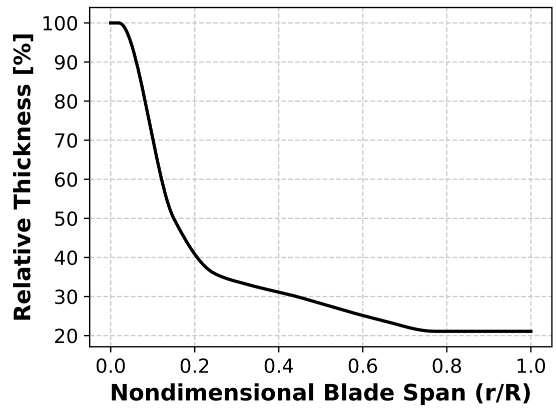


(c) Airfoil lift-to-drag coefficients

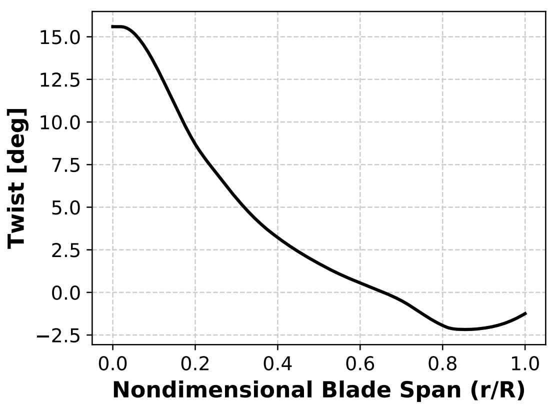
Figure 2-3. Aerodynamic polars for the airfoils used on the blade



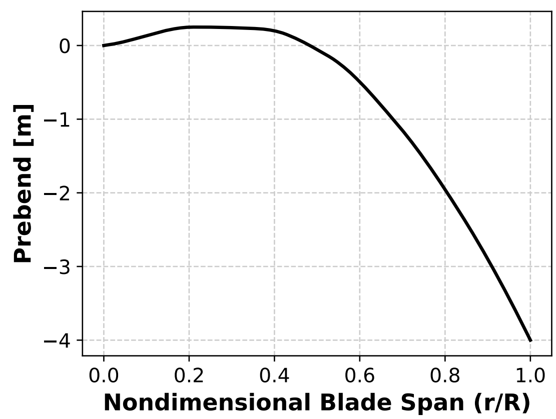
(a) Chord length



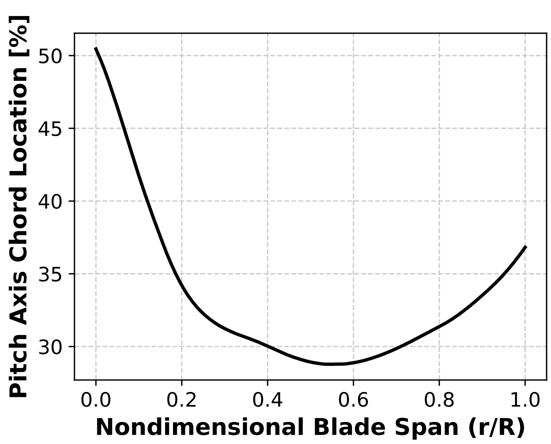
(b) Relative thickness



(c) Twist



(d) Prebend



(e) Chordwise offset

Figure 2-4. Blade planform spanwise quantities

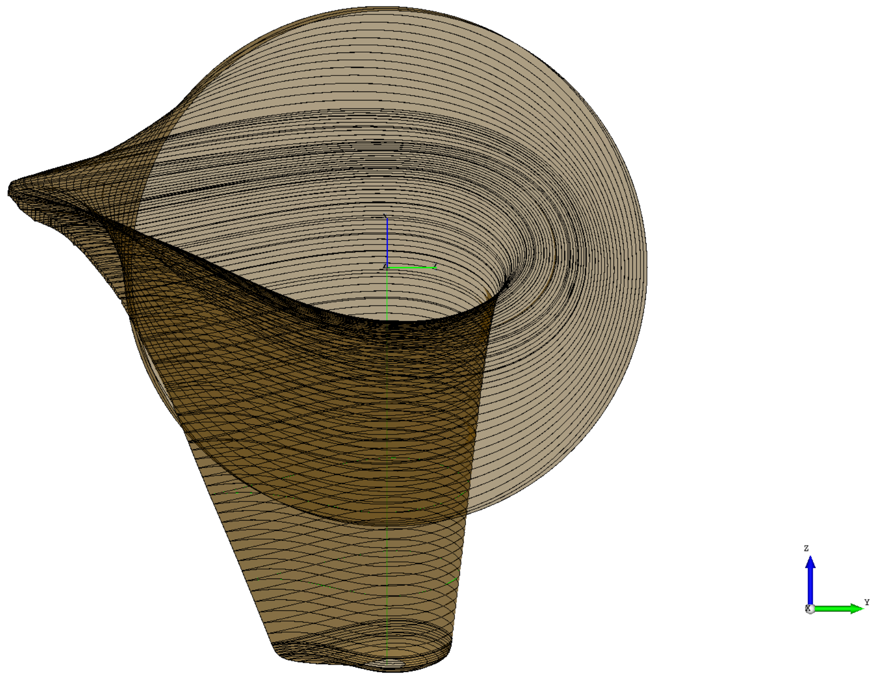


Figure 2-5. Lofted blade shape

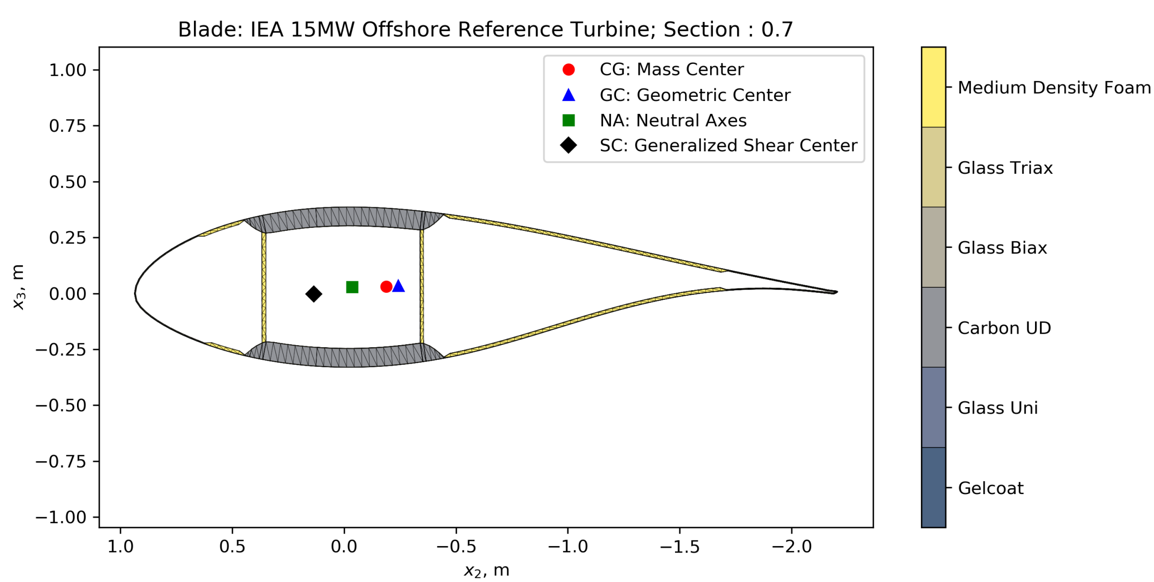


Figure 2-6. Blade cross section at 70% span

The internal structure and composite layup of the blade is defined according to the IEA Wind Turbine Ontology [32]. Composite layers are defined as spanwise elements superimposed on the blade shell or shear webs, following the curved blade reference axis. The wind turbine ontology allows for multiple methods of defining elements, dimensionally, using the layer width (arc length), offset, and rotation relative to a reference position, or nondimensionally, using the normalized arc length positions, as shown in Figure 2-7. The normalized arc length position coordinate (*s*) is defined as zero at the suction-side trailing edge and as one at the pressure-side trailing edge. For flatback airfoils, the trailing edge is defined as the midpoint of the flatback surface.

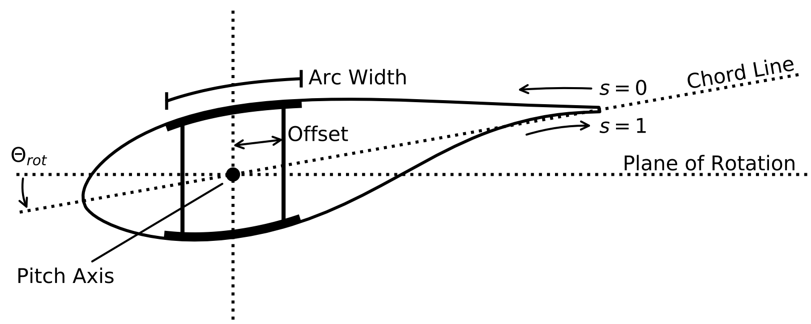


Figure 2-7. Schematic of IEA Wind Turbine Ontology composite definition, from root to tip

The material layup of the blade is plotted in Figures 2-8 and 2-9, shown along the airfoil shell as a function of the arc length *s*-coordinate and for the shear webs. The complete layup definition of the structural components is provided in the accompanying blade ontology and Microsoft Excel files. With the composite layup defined, the blade beam structural properties were computed with PreComp [16] and VABS [33, 34] (in the NREL tool chain) or BECAS [17, 35] (in the DTU tool chain). Specifically, these tools calculated the stiffness matrices for each cross section along the blade, which were then used in OpenFAST or HAWC2. A comparison of the turbine performance between the NREL and DTU modeling tools is discussed in Rinker et al. [36]. Figures 2-10 and 2-11 show the resulting blade beam structural properties. The structural damping of the first flapwise, edgewise, and torsional modes were assumed to be 3%, 3%, and 6%, respectively.

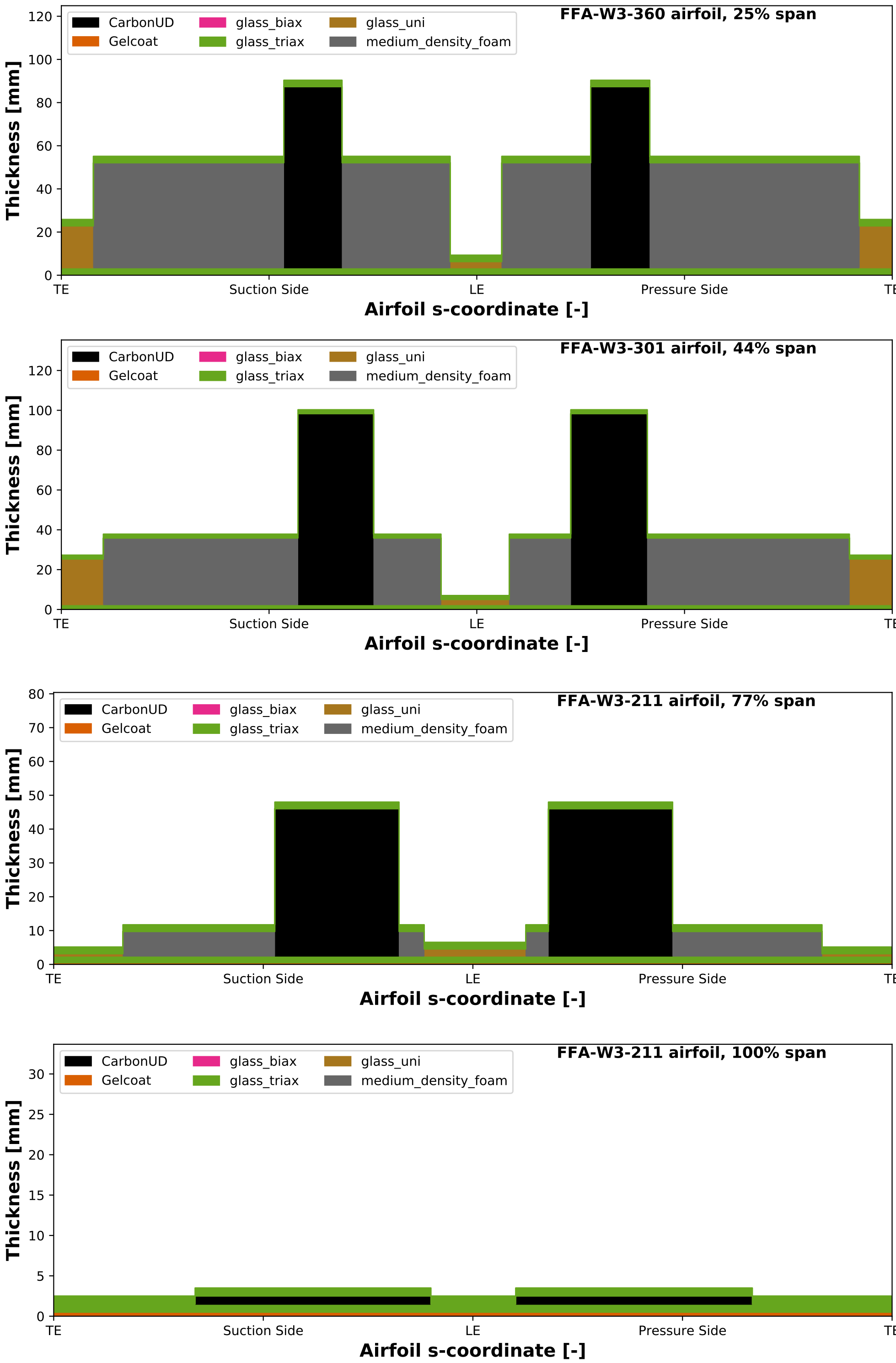


Figure 2-8. Blade layup layer thickness as a function of the normalized s-coordinate around the airfoil at various span positions