Description of an 8 MW reference wind turbine

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Description of an 8 MW reference wind turbine

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Abstract.
An 8 MW wind turbine is described in terms of mass distribution, dimensions, power curve, thrust curve, maximum design load and tower configuration. This turbine has been described as part of the EU FP7 project LEANWIND in order to facilitate research into logistics and naval architecture efficiencies for future offshore wind installations. The design of this 8 MW reference wind turbine has been checked and validated by the design consultancy DNV-GL.

This turbine description is intended to bridge the gap between the NREL 5 MW and DTU 10 MW reference turbines and thus contribute to the standardisation of research and development activities in the offshore wind energy industry.

1. Introduction

The LEANWIND project is focused on the application of lean principles to the offshore wind energy industry. It is anticipated that up to 14% cost reduction can be achieved by minimising waste and introducing innovative technical solutions to this rapidly developing industry [1].

An integral component of LEANWIND is the design of wind turbine support structures and service vessels for the installation, maintenance and decommissioning of offshore wind farms. In order to progress the project, it was necessary to select a reference wind turbine; data for which would be made available to all members of the consortium. Two viable options were identified, the 5 MW reference wind turbine devised by the National Renewable Energy Laboratory (NREL) [2] and the 10 MW turbine described by the Technical University of Denmark (DTU) [3].

Feedback from the LEANWIND project's Industry Advisory Group (IAG) and consortium members indicated the need for a wind turbine sized between the NREL and the DTU in order to ensure the commercial relevance of the project at its conclusion in November 2017. To this end, a description of the LEANWIND 8 MW reference turbine (LW) was developed based primarily on published data relating to the Vestas V164 – 8 MW turbine [4]. Where data were not available, they were derived by scaling between the NREL and DTU turbines and by using engineering judgement.

The LW turbine design has been validated by DNV-GL, a leading provider of independent wind turbine engineering services, using their internal conceptual turbine design tool Turbine.Architect (TA). TA is the product of over a decade of legacy Garrad Hassan experience in turbine design and comprises a suite of tools that enable accelerated design of turbine components and cost estimation. The tool operates by numerically optimizing a baseline turbine in accordance with engineering design principals and DNV-GL experience to produce a viable turbine design. The results from TA are continuously verified against available industry data to ensure the sub-models and assumptions remain relevant. An overview of the calculation process employed by TA is provided in Figure 1.

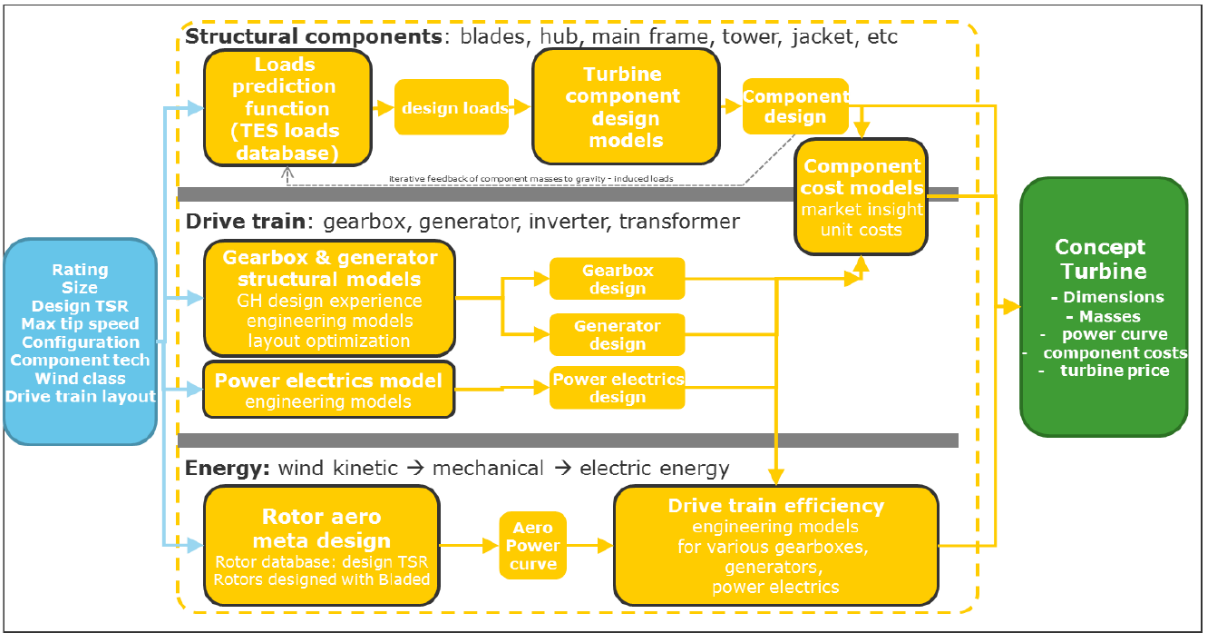

Figure 1. Turbine.Architect calculation overview.

The description of the LW turbine does not offer the same high level of design detail as published elsewhere for the NREL and DTU turbines. However, the LW description will contribute to the standardisation of research and development activities focused on the short to medium term requirements of the offshore wind energy industry.

Details of the LW 8 MW reference turbine are provided in Section 2 and details of the methodologies used to derive these data are given in Section 3.

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2. Turbine Description

2.1 General overview

A summary of the main characteristics of the LW reference wind turbine is given in Table 1. For reference, details are also provided for the NREL and DTU turbines.

Table 1. Summary of NREL, LW and DTU wind turbine characteristics.

Turbine	NREL	LW	DTU
Rating	5 MW	8 MW	10 MW
Rotor Orientation, Configuration	Upwind, 3 blades	Upwind, 3 blades	Upwind, 3 blades
Rotor Diameter	126 m	164 m	178.3 m
Hub height	90 m	110 m	119 m
Cut-in, Rated, Cut-out wind speed	3 m/s , 11.4 m/s, 25 m/s	4 m/s , 12.5 m/s, 25 m/s	4 m/s , 11.4 m/s, 25 m/s
Rotor speed range	6.9 – 12.1 rpm	6.3 - 10.5 rpm	6 – 9.6 rpm
Hub mass	56,780kg	90,000 kg	105,520 kg
Nacelle mass	240,000 kg	285,000 kg	446,036 kg
Blade mass	17,740 kg	35,000 kg	41,716 kg
Nacelle dimensions (L x W x H)	NA[1]	20 m x 7.5 m x 7.5 m	NA[1]
Tower Mass	347,460 kg	558,000 kg	605, 000 kg
Tower Height	87.6 m	106.3 m	115.6 m
Tower top thickness, diameter	20 mm, 3.87 m	22 mm, 5 m	20 mm, 5.5 m
Tower bottom thickness, diameter	27 mm, 6 m	36 mm, 7.7 m	38 mm, 8.3 m
Overall Centre of Mass	-0.2 m , 0.0 m 64.0 m	0 m, 0 m, 77 m	NA[1]

Notes: [1] Data not available.

2.2 Power & thrust curves

The power and thrust curves for the LW reference wind turbine are detailed in Figure 2 and Figure 3 respectively. Data are also provided for the NREL and the DTU turbines for reference.

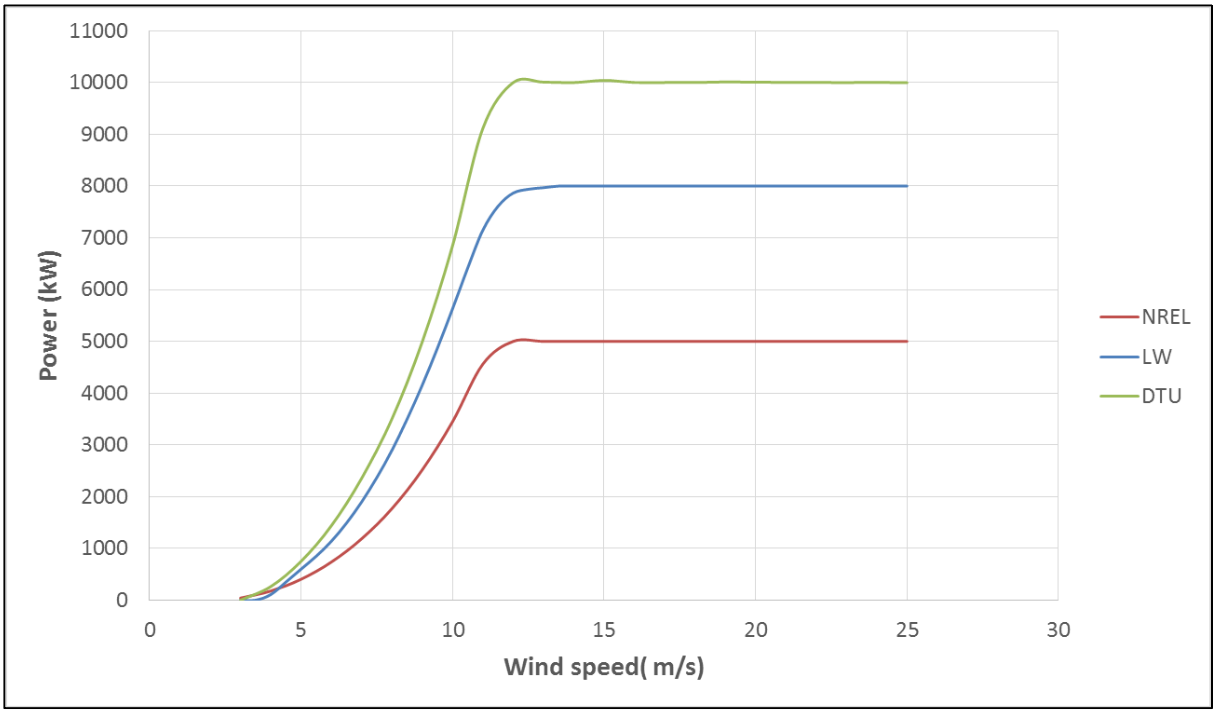

Figure 2. Power curves for the NREL, LW and DTU wind turbines.

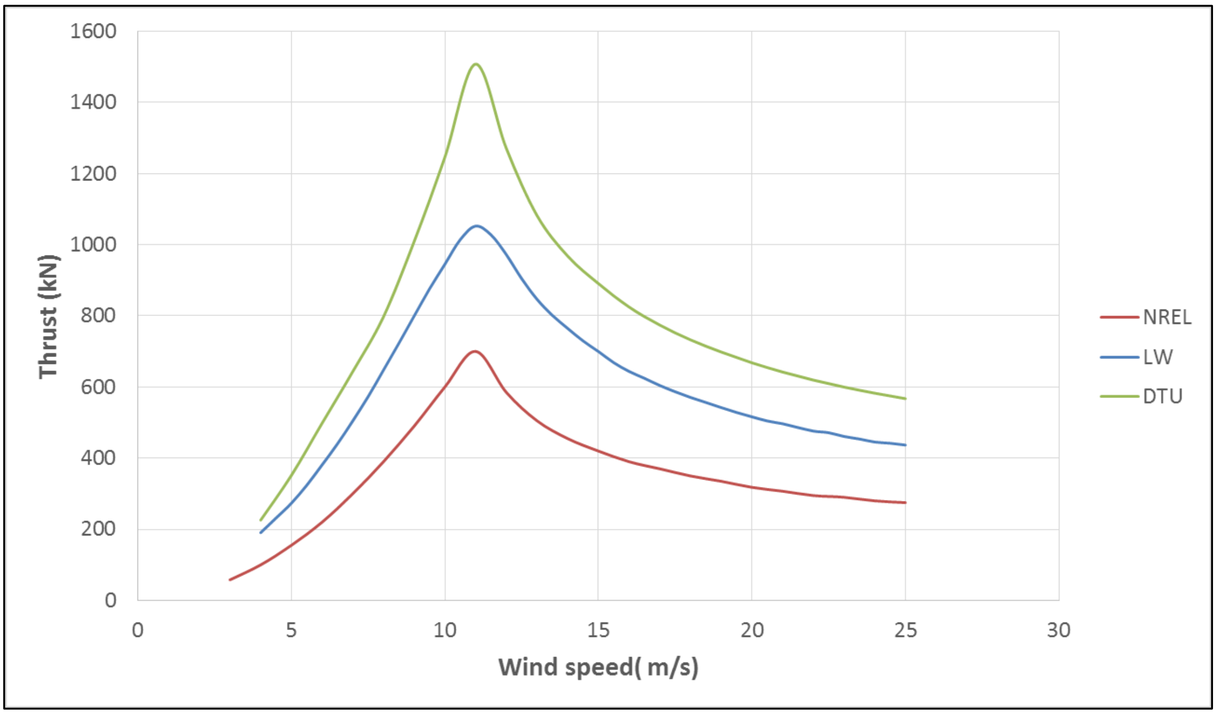

Figure 3. Thrust curves for the NREL, LW and DTU wind turbines.

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Power production and thrust data for the LW 8 MW turbine are also presented in Table 2.

Table 2. Summary of the LW 8 MW Power and Thrust Curves.

Wind speed [m/s]	Power [kW]	Cp [-]	Thrust [kN]	Ct [-]
4	110	0.13	190	0.92
4.5	350	0.3	232	0.88
5	600	0.37	273	0.85
5.5	850	0.39	324	0.83
6	1140	0.41	381	0.82
6.5	1490	0.42	440	0.81
7	1900	0.43	505	0.8
7.5	2370	0.43	573	0.79
8	2900	0.44	648	0.78
8.5	3500	0.44	723	0.77
9	4155	0.44	800	0.76
9.5	4870	0.44	876	0.75
10	5630	0.44	945	0.73
10.5	6420	0.43	1014	0.71
11	7150	0.42	1052	0.67
11.5	7610	0.39	1028	0.6
12	7865	0.35	972	0.52
12.5	7940	0.31	905	0.45
13	7970	0.28	847	0.39
13.5	8000	0.25	801	0.34
14	8000	0.23	765	0.3
14.5	8000	0.2	730	0.27
15	8000	0.18	700	0.24
15.5	8000	0.17	668	0.22
16	8000	0.15	644	0.19
16.5	8000	0.14	624	0.18
17	8000	0.13	604	0.16
17.5	8000	0.12	587	0.15
18	8000	0.11	571	0.14
18.5	8000	0.1	557	0.13
19	8000	0.09	542	0.12
19.5	8000	0.08	528	0.11
20	8000	0.08	516	0.1
20.5	8000	0.07	505	0.09
21	8000	0.07	497	0.09
21.5	8000	0.06	486	0.08
22	8000	0.06	476	0.08
22.5	8000	0.05	472	0.07
23	8000	0.05	461	0.07
23.5	8000	0.05	454	0.06
24	8000	0.04	445	0.06
24.5	8000	0.04	442	0.06
25	8000	0.04	437	0.05

Note: Cp – Power coefficient.
Ct – Thrust coefficeint.

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2.3 Design frequencies

The natural frequency of the support structure is an important design consideration as resonances with excitation forces will introduce significant fatigue loading. For offshore wind turbine structures excitation is mainly provided by waves and wind.

For wave excitation, high frequency sea states will have the most significant impact. In Figure 4, the excitation to be expected for a sea state with significant wave height, H_s = 1 - 1.5 m and zero crossing period, T_z = 4 - 5 sec is shown for demonstrative purposes [5]. The actual range of wave excitation frequencies will be dependent on the metocean conditions at the specific site under consideration.

For wind excitation, the frequencies to be avoided are the range of rotational speed of the turbine rotor (1P) and the blade passing period (3P). Using the rotor speeds detailed in Table 1, the natural frequencies to be avoided for the LW turbine support structure are detailed in Figure 4.

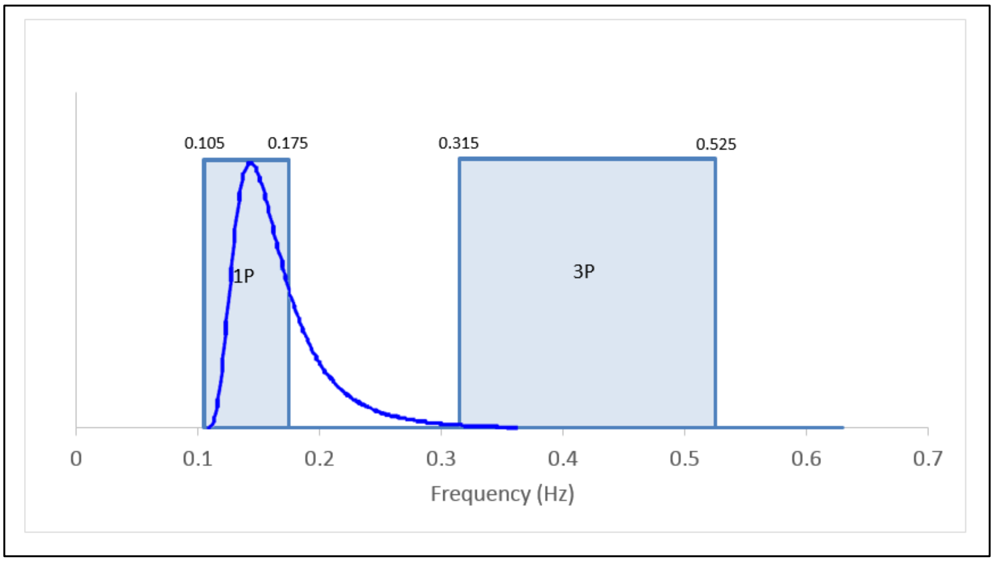


Figure 4. Allowable frequency range and excitation frequencies for the LW 8 MW turbine. The dark blue line shows the expected occurance of wave periods for a sea state with H_s = 1 - 1.5 m and T_z = 4 - 5 sec [5].

It is typical that the first natural frequency of the support structure will lie in the range between the maximum of 1P (0.175 Hz) and the minimum of 3P (0.315 Hz), while the second natural frequency will lie above the maximum of 3P (0.525 Hz). However, the actual design methodology used will be heavily dependent on the specific constraints at the site under consideration.

It is recommended that the 1P and 3P ranges are avoided by at least 10% [5].

2.4 Design loads

The design loads incident on the structure will be dependent on the support structure design and the metocean conditions present at the site under consideration. Given time and resource limitations, it was not possible to devise a full description of the LW 8 MW turbine control strategy which would allow the use of dynamic aero-elastic analysis software packages such FAST [6]. Therefore, in this report we will employ the extreme tower top thrust load calculated by the DNV-GL TA software.

TA loads prediction is based on the DNV-GL Turbine Engineering Services Bladed loads database. The trend fit on which the loads estimation for tower top thrust is based, contains more than 50 data points. Each data point is the maximum of all load cases for that particular IEC load set [7]. The scatter in which load case is driving the extreme tower top thrust load is large and there is no clear recurring typical driving load case for extreme tower top thrust.

The TA load predictions for the NREL, LW and DTU turbines are given in Table 3.

Table 3. *Summary of the maximum tower top thrusts estimated for the NREL [2], LW and DTU [3] turbines.*

Turbine	Approximated maximum tower top thrust (kN)
NREL 5 MW	1619
LW 8 MW	2743
DTU 10 MW	3242

Note: The values given in this table include safety factors.

The values presented in Table 3 for the maximum thrust on the LW turbine are insufficient to conduct a full design for a wind turbine support structure. However, these values will facilitate scaling of substructures designed for the NREL or DTU reference turbines.

2.5 Dimensions and weights

The dimensions and weights of the key components of the LW turbine are detailed in the following sub sections.

2.5.1 Blade

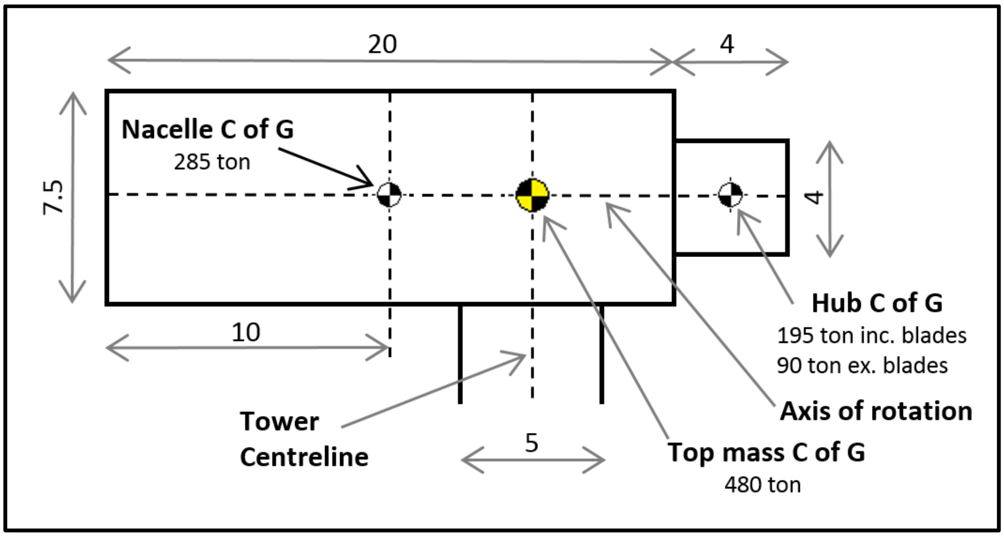
The key dimensions for the LW turbine's blades are presented in Table 4. These values have been scaled from the values presented for the NREL turbine in [1].

Table 4. LW turbine blade properties.

Property	Value
Length (w.r.t Root along pre cone axis)	80 m
Mass	35,000 kg
Centre of Gravity (w.r.t Root along pre cone axis)	25.8 m
Second Mass Moment of Inertia	37,398,334 kg.m^2
First Mass Moment of Inertia	915,514 kg.m

2.5.2 Nacelle & Hub

The mass distribution of the LW turbine nacelle and hub are given in Figure 5.



Note: All dimensions are in metres unless otherwise stated.

Figure 5. Top mass distribution for the LW turbine.

The dimensions of the nacelle are 20 m x 7.5 m x 7.5 m. The hub is taken to be a cylinder of height 4 m and diameter 4 m.

2.5.3 Tower

DNV-GL have provided a tower description for the LW turbine based on the TA analysis. The properties of this tower are summarised in Table 5.

Table 5. LW turbine tower properties.

Property	Value
Height	106.3 m
Mass	558,000 kg
Centre of Gravity (above base)	46 m

Additional details relating to the LW tower are given in Figure 6 and Table 6.

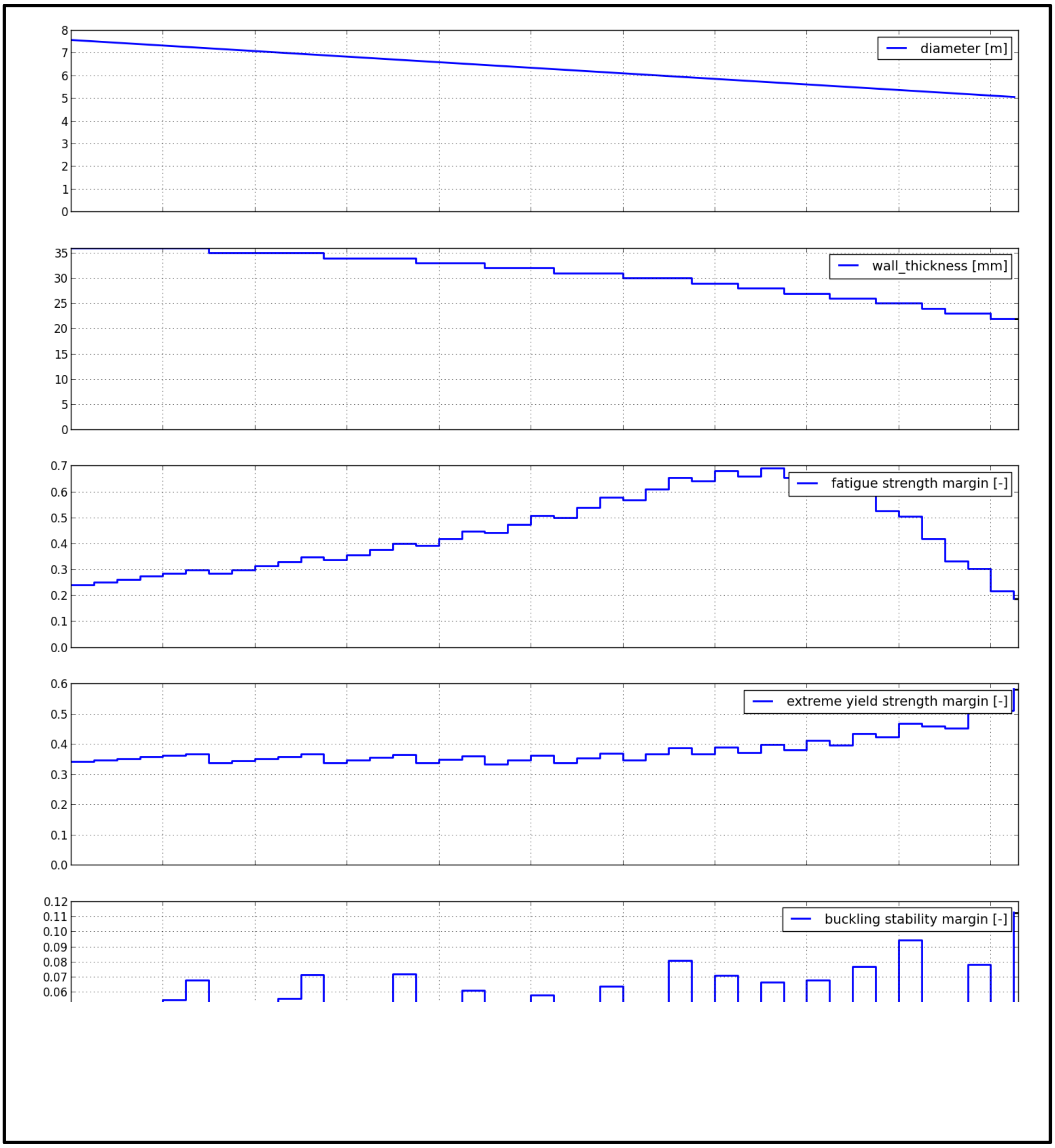


Figure 6. LW turbine design parameters.

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Table 6. Tower can data. Mass of flanges are not included in this table.

z_can_bottom	z_can_top	D_can_outer_bottom	D_can_outer_top	can_length	wall thickness	can mass
[m]	[m]	[m]	[m]	[m]	[mm]	[kg]
0	2.5	7.69	7.628	2.5	36	16919
2.5	5	7.628	7.566	2.5	36	16782
5	7.5	7.566	7.504	2.5	36	16645
7.5	10	7.504	7.442	2.5	36	16507
10	12.5	7.442	7.38	2.5	36	16370
12.5	15	7.38	7.319	2.5	36	16233
15	17.5	7.319	7.257	2.5	35	15650
17.5	20	7.257	7.195	2.5	35	15517
20	22.5	7.195	7.133	2.5	35	15383
22.5	25	7.133	7.071	2.5	35	15250
25	27.5	7.071	7.009	2.5	35	15116
27.5	30	7.009	6.947	2.5	34	14557
30	32.5	6.947	6.885	2.5	34	14427
32.5	35	6.885	6.824	2.5	34	14297
35	37.5	6.824	6.762	2.5	34	14168
37.5	40	6.762	6.7	2.5	33	13627
40	42.5	6.7	6.638	2.5	33	13501
42.5	45	6.638	6.576	2.5	33	13375
45	47.5	6.576	6.514	2.5	33	13249
47.5	50	6.514	6.452	2.5	32	12728
50	52.5	6.452	6.39	2.5	32	12606
52.5	55	6.39	6.329	2.5	32	12484
55	57.5	6.329	6.267	2.5	31	11977
57.5	60	6.267	6.205	2.5	31	11859
60	62.5	6.205	6.143	2.5	31	11741
62.5	65	6.143	6.081	2.5	30	11249
65	67.5	6.081	6.019	2.5	30	11135
67.5	70	6.019	5.957	2.5	30	11020
70	72.5	5.957	5.895	2.5	29	10544
72.5	75	5.895	5.834	2.5	29	10434
75	77.5	5.834	5.772	2.5	28	9969
77.5	80	5.772	5.71	2.5	28	9862
80	82.5	5.71	5.648	2.5	27	9408
82.5	85	5.648	5.586	2.5	27	9305
85	87.5	5.586	5.524	2.5	26	8863
87.5	90	5.524	5.462	2.5	26	8764
90	92.5	5.462	5.4	2.5	25	8333
92.5	95	5.4	5.339	2.5	25	8238
95	97.5	5.339	5.277	2.5	24	7818
97.5	100	5.277	5.215	2.5	24	7727
100	102.5	5.215	5.153	2.5	23	7318
102.5	105	5.153	5.091	2.5	22	6918
105	106	5.091	5.066	1	22	2744

3. Scaling Methodology

As mentioned in the introduction, the design of the LW turbine is primarily based on publically available data for the Vestas V164 8 MW turbine [4]. Where data were not available, scaling using available data, the output of DNV-GL's TA software and engineering judgement were used. Details of the methodologies used are summarised below.

3.1 Hub height

In order to estimate the appropriate hub height for the LW reference turbine, a trend line was fitted to available data for the 8 notional turbines described in [5], the NREL and DTU.

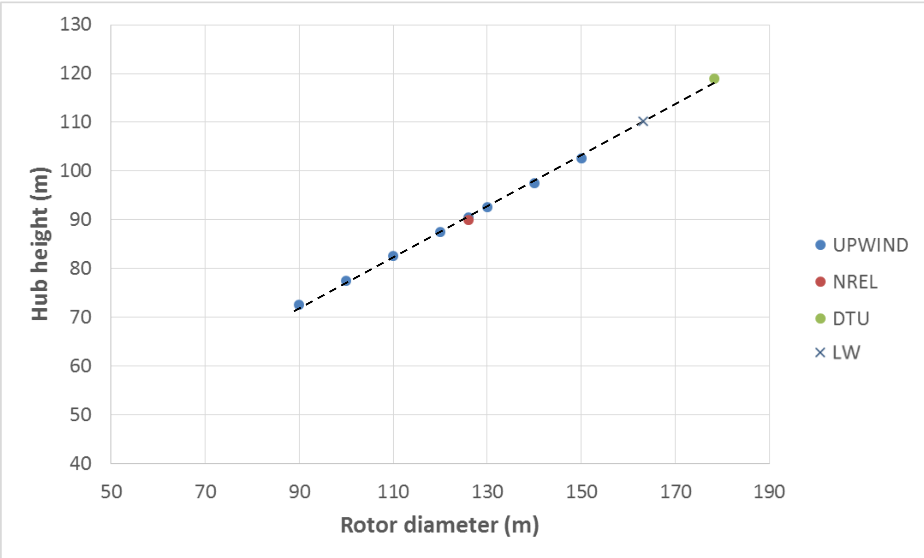


Figure 7. Scaling hub height by rotor diameter.

By this method a hub height of 110 m was estimated for the LW reference turbine which has a rotor diameter of 164 m. It should be noted that it may be necessary to vary the actual hub height used for the substructures in WP2 in order to satisfy the particular design constraints of the support structure and metocean conditions under consideration.

3.2 Rotor speed

The rotor speed range of 4.8 – 12.1 RPM stated in the Vestas V164 documentation [4] results in frequency range as shown in Figure 8 where values are also presented for the NREL and DTU turbines.

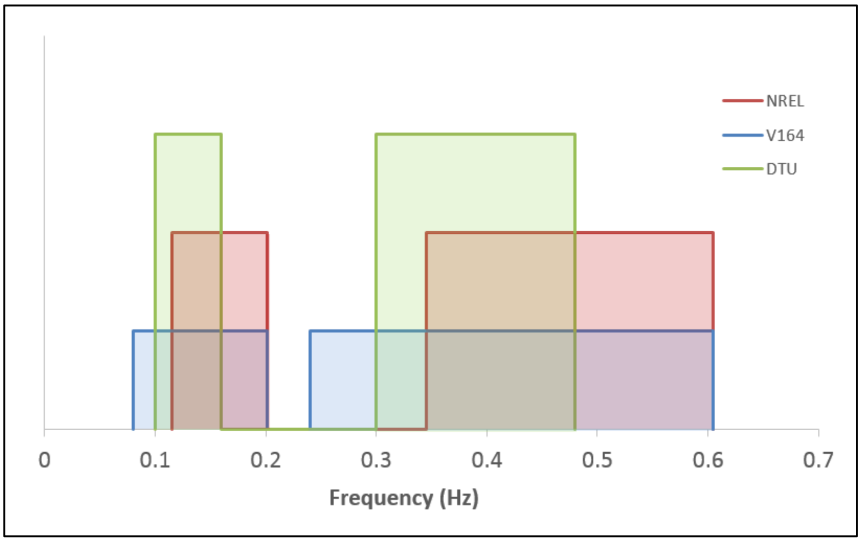


Figure 8. Wind excitation frequencies for the NREL and DTU turbines compared to those derived for the Vestas V164 based on published rotor speed range.

It would be difficult to design a structure for which the first natural frequency fits within the small frequency band between the maximum 1P and minimum 3P for the Vestas V164 as outlined in Figure 8. For a detailed offshore turbine design, the operational range is an outcome of an integrated iterative design process. Over the course of this process, a trade-off is made between max tip speed, energy yield, support structure loads, cost and other design elements, such that the lowest levelised cost of energy is achieved. It is likely that the range quoted for the V164 represents the upper and lower limits that can be considered during this process.

As the narrow frequency band between the maximum 1P and minimum 3P for the Vestas V164 would be a major driver for cost, the rotor speed ranges quoted for the Vestas V164 in [4] were disregarded. The following methodology was used to derive an appropriate rotor speed range for the LW reference wind turbine.

1. The tip speed ratio at rated wind speed was calculated for the NREL and DTU turbines.
2. The rotational speed required to achieve a similar tip speed ratio at rated wind speed was calculated for the LW 8 MW turbine.
3. This rotational speed was taken to be the upper rotational speed limit for the LW reference turbine as per the NREL and DTU turbines.
4. The lower rotational range for the LW reference turbine was selected in order provide a frequency band of 0.140 Hz between the 1P and 3P wind excitation frequencies as per the NREL and DTU turbines.

The higher limit on the rotor range for the LW turbine is equal to the nominal value quoted for the V164 whilst the derived lower rotor speed limit lies between the corresponding values for the NREL and DTU turbines. Rotor speed ranges for the LW reference turbine are given in Table 1 and are illustrated in Figure 9.

DNV-GL have reviewed the rotational speed range for the LW turbine and note that the upper rotational speed range results in a maximum tip speed of approximately 90 m/s which is reasonable for a modern wind turbine. Several wind turbine designers are designing turbines with higher speeds, however this development is challenged by leading edge erosion issues.

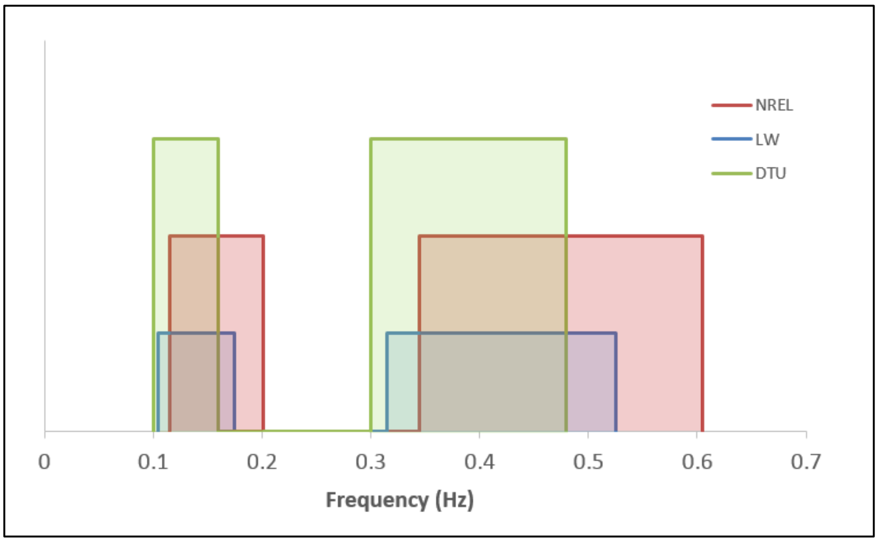


Figure 9. Wind excitation frequencies for the NREL and DTU turbines compared to those derived for the LW reference turbine.

3.3 Power and thrust curves

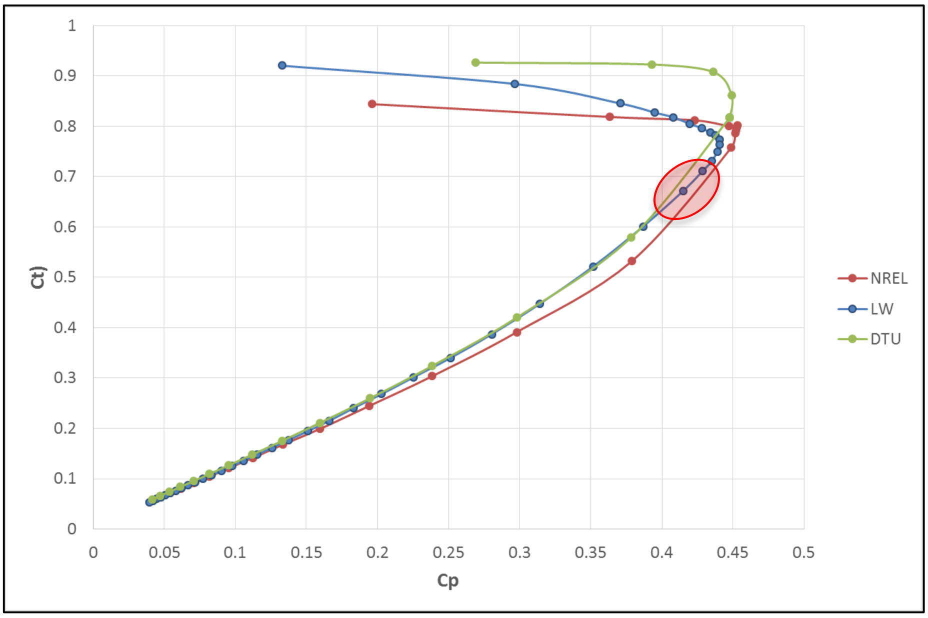
The power curve for the LW 8 MW reference turbine, shown in Figure 2, was derived by fitting to the curve presented in [4] for the Vestas V164. From this, the Power Coefficient, C_p, was calculated using Equation 1 [8] for each wind speed.

$$C_p = \frac{\text{Electrical power}}{0.5 \times \rho \times A \times \bar{U}^3} \qquad [1]$$

An initial Thrust Coefficient (C_t) curve for the LW reference turbine was then derived using the C_p-C_t curve of the NREL turbine. The position of the apex of the derived LW C_p-C_t curve was then adjusted, by varu=ying the values of C_t, in order to allow a smooth transition for C_t at all stages of turbine operation. The definition of C_t can be found in in [8] and is given below in Equation 2.

$$C_t = \frac{\text{Aerodynamic thrust}}{0.5 \times \rho \times A \times \bar{U}^2} \qquad [2]$$

The resulting C_p-C_t curve for the LW turbine is shown in Figure 10 along with curves for the NREL and DTU turbines for reference. Also shown on this curve, highlighted in red, is the locus of the point which typically corresponds to the maximum trust experienced by a modern three bladed turbine.



Note: The area highlighted in red is the locus of the point at which maximum rotor thrust is expected to occur.

Figure 10. Publised Cp –Ct curves for the NREL and DTU turbines compared to that dervied for the LW referecne turbine

The Cp and Ct curves for the LW reference wind turbine are detailed in Figure 11 and Figure 12 and respectively. Data are also provided for the NREL and the DTU turbines for reference.

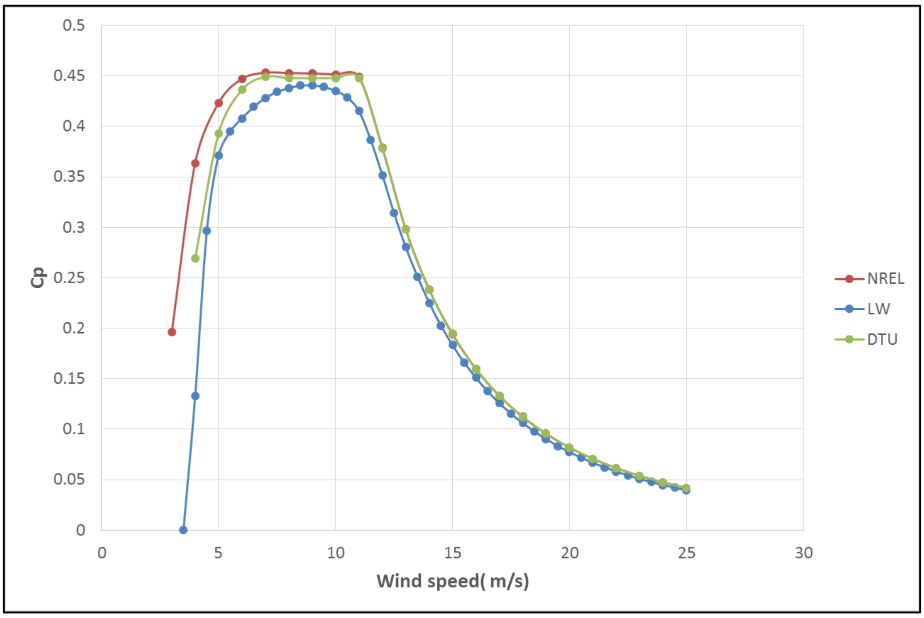


Figure 11. Publised C_p curves for the NREL and DTU turbines compared to that dervied for the LW referecne turbine.

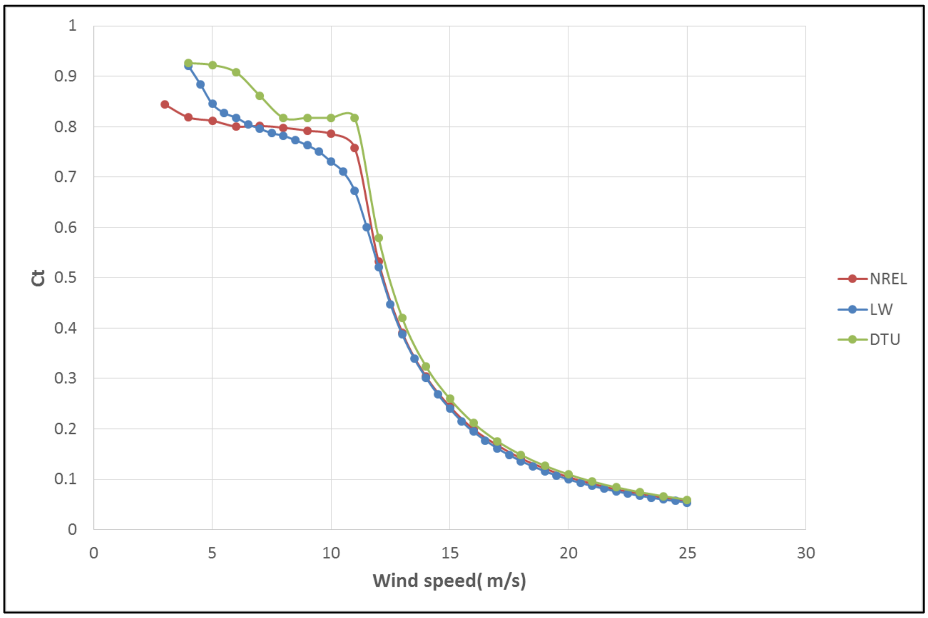


Figure 12. Publised C_t curves for the NREL and DTU turbines compared to that dervied for the LW reference turbine.

As can be seen in Figure 12, the selection of an appropriate apex for the LW 8 MW C_p-C_t curve, as shown in Figure 10, allows a smooth transition between subsequent C_t values as the wind turbine moves through its power curve. This is vital for the safe operation of the wind turbine as step changes would result in considerable fatigue loading. DNV-GL have reviewed the values presented in Figure 10, Figure 11 and Figure12 and the data agree with their expectations.

4. Conclusion

A description has been provided for the LW 8 MW reference wind turbine in terms of power curve, thrust curve, C_p - C_t curve, design criterion, dimensions and weights. In general terms, the turbine described is a 3 bladed upwind design with a rotor diameter of 164 m and hub height of 110 m. The rated, cut-in and cut-out wind speeds for the LW 8 MW turbine are 4 m/s, 12.5 m/s and 25 m/s respectively.

The description of the LW 8 MW turbine has been reviewed and validated by DNV-GL and is intended to provide a stepping stone between the NREL 5 MW and DTU 10 MW turbines which have been described in detail elsewhere. The LW 8 MW turbine will provide a reference for research and development actives which are focused on short to medium developments in the offshore wind energy industry.

5. Acknowledgments

The research leading to these results has been conducted under the LEANWIND project which has received funding from the European Union Seventh Framework Programme under the agreement SCP2-GA-2013-614020.

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