C2Wind

Benchmark and Validation of the Vestas V236 15 MW turbine model in C2FLEX

REPORT

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Table 2-1	Removed RNA properties from table.
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List of abbreviations

Abbreviations and variables	
Abbreviation	**Meaning**
AEP	Annual energy production
CoG	Centre of gravity
DEL	Damage equivalent load
DEM	Damage equivalent bending moment
DLC	Design load case
FEED	Front-end engineering design
FLS	Fatigue limit state
IEC	International Electrotechnical Commission
ILA	Integrated load analysis
NDA	Non-disclosure agreement
PLF	Partial load factor
RNA	Rotor–nacelle assembly
ULS	Ultimate limit state
VTS	Vestas Turbine Simulator
WTG	Wind turbine generator
A	Weibull scale parameter
C_{p}	Power coefficient
C_{t}	Thrust coefficient
k	Weibull shape parameter
m	Wöhler-curve exponent used in damage-equivalent load calculations
M_{gen}	Generator torque
M_{res}	Resulting tower-bottom bending moment
Mx	Fore-aft tower-bottom bending moment
My	Side-to-side tower-bottom bending moment
Nref	Reference number of load cycles for damage-equivalent load calculation

1. Introduction

This document benchmarks the C2Wind C2FLEX model against information provided by Vestas Wind Systems A/S (Vestas) to C2Wind in [LOADCON]. In addition to the information shared in [LOADCON], key turbine parameters are benchmarked as well. The data used for this benchmark were shared by Vestas with C2Wind under a non-disclosure agreement (NDA) between Vestas and C2Wind. For ease of reading, a reference to the data is [DATANDA]. Whenever turbine data from [DATANDA] are used in the benchmark analysis, the data are normalised. In [DATANDA], more detailed simulation data, compared with [LOADCON], is available. This data is used throughout this report for comparison with the C2FLEX input/results.

The benchmark is performed in a wind-only scenario similar to the rather simple analysis setup in [LOADCON]. The support structure includes a tower and monopile, with hydrodynamic loading excluded.

To distinguish between the Vestas and the C2FLEX models, the following nomenclature is used:

- **Vestas V236 15 MW** – The WTG model from Vestas simulated in Vestas Turbine Simulator (VTS).
- **C2FLEX V236 15 MW** – The independent WTG model developed by C2Wind to represent the global aeroelastic behaviour of the Vestas V236 15 MW turbine.

The resulting C2FLEX V236 15 MW model is considered a high-fidelity independent engineering representation of the Vestas V236 15 MW turbine. It is suitable for global aeroelastic simulations, controller-response assessments and evaluation of turbine loads transferred to the support structure. The model should not, however, be interpreted as the Vestas certified aeroelastic model. Applications requiring detailed local blade stresses, proprietary component loads, exact higher-mode blade behaviour or component-level certification remain outside the intended use of the C2FLEX model.

2. The C2FLEX model

This section presents the C2FLEX aero-servo-hydro-elastic model of the C2FLEX V236-15 MW WTG. It provides an overall description of the turbine and support-structure model, including the aerodynamic representation, pitch and torque control systems, structural flexibility and overall load effect response.

The section also presents the principal modal properties of the fully coupled wind turbine and support structure. While the complete turbine dynamics are considered, the assessment focuses primarily on the support structure, including its natural frequencies, mode shapes, modal mass and interaction with the rotor harmonics and controller dynamics. Selected time-domain results are included to demonstrate the overall dynamic response and confirm the suitability of the model for the subsequent Integrated Load Analysis. Further, the model assessment includes verification of the steady-state power and thrust performance, rotor-speed and blade-pitch behaviour, and the performance of the turbine controller across the operating wind-speed range. Particular attention is given to the transition between the different operational control regions, rated-power regulation and the controller response under turbulent wind conditions.

2.1 C2FLEX general description

C2FLEX is a hydro-aero-servo-elastic computer software designed to model the dynamic behaviour of horizontal axis wind turbines. The program is based on modal superposition which operates in the time domain. The model calculates the coupled dynamic response of the complete wind turbine and support structure and produces time series of loads, accelerations, displacements and operational parameters at the relevant interfaces and structural locations. The program is based on the original Flex5 code commercially provided by Stig Øye (DTU-Risø). C2Wind has subsequently extended and adapted the original code to support modern, large-scale offshore wind turbines and contemporary ILA requirements. These developments include updated aerodynamic modelling, controller implementation, hydrodynamic loading, foundation representation, automated simulation handling and post-processing of design-load quantities. The Vestas Turbine Simulator (VTS) used by Vestas is in a similar way based on original Flex5 code.

The structural response of the wind turbine and support structure is represented using a reduced-order modal formulation with a total of 28 degrees of freedom. Shape functions are used to represent the principal elastic deformation modes of the blades and tower, while the nacelle, hub and rotor shaft are represented by rigid bodies connected through the relevant flexible and rotational degrees of freedom. The formulation includes the flap-wise and edge-wise blade deflections, tower fore-aft and side-to-side response, drivetrain rotation, rotor azimuth and the relevant nacelle and support-structure motions. This provides an efficient representation of the global turbine dynamics while retaining the structural modes that govern the transfer of loads from the rotor through the drivetrain and tower to the support structure.

The blade model includes representative spanwise distributions of blade chord, aerodynamic twist, relative airfoil properties, structural properties and reference-axis offsets. Blade prebend is represented explicitly, allowing its influence on the undeformed rotor geometry, elastic blade response, rotor–tower clearance and global turbine load effects to be included. The applied aerodynamic data are representative of the Reynolds-number range expected for a 118 m blade. The resulting aerodynamic representation has been evaluated and tuned against the available Vestas V236 power-performance, operational and load information. The primary aim of the C2FLEX tuning is intended to reproduce the support-structure load response predicted by the Vestas model; validation of power-performance accuracy for annual energy production (AEP) assessment is outside the model validation.

A visualising of the C2FLEX V236 15 MW turbine under normal operation at a mean wind speed at 12 m/s can be found in Appendix B. Please note that the deformations are scaled.

2.2 C2FLEX benchmark model

The C2FLEX V236-15 MW WTG model represents the principal mechanical and operational characteristics of the Vestas V236 15 MW turbine, including:

- 236 m rotor and three 118 m blades.
- Blade geometry, prebend, mass and stiffness representation.
- Rotor, hub, drivetrain and nacelle properties.
- Generator torque and power regulation.
- Blade-pitch control.
- Rotor-speed limits and operational transitions.
- Interaction between the turbine controller and the flexible turbine structure.

The C2FLEX V236 15 MW model is an independent engineering representation of the Vestas V236 15 MW model and is not a copy of the original Vestas aeroelastic model. However, the relatively extensive turbine-specific information available to C2Wind through [DATANDA] allows the model to be calibrated and validated to a significantly higher level than would be possible using publicly available turbine information alone.

Following the creation of the representative model in C2FLEX, C2Wind tuned the integrated aeroelastic WTG model to match the properties of the Vestas V236 15 MW WTG model. This work included the interaction between the flexible blades, rotor aerodynamics and turbine controller, including variable-speed torque control below rated wind speed, the transition into rated operation and pitch control above rated wind speed.

The high-level parameters of the C2FLEX model are outlined in Table 2-1 for which the primary source is Table 2 or Table 3 of [LOADCON]. A few parameters cannot be found in [LOADCON] and are estimated by C2Wind. Other parameters available to C2Wind found through [DATANDA] are not repeated.

The blade-pitch control implemented in the C2FLEX model for this benchmark study uses a collective blade-pitch control algorithm, although individual blade-pitch control can also be enabled. The Vestas data used for comparison also uses collective pitch control in the benchmark configuration, although it supports individual blade-pitch control.

Description of technical data	Units	C2FLEX V236-15 MW
Blades and rotor		
Rotor Diameter	[m]	236
Blade length incl. hub	[m]	118
RNA		
The vertical distance from the tower top to the hub height	[m]	*Confidential*
Cone angle	[°]	*Confidential*
RNA mass (nacelle, hub, and 3 blades)	[tonnes]	*Confidential*
RNA Moment of Inertia wrt. RNA CoG (Ix, Iy, Iz)	[kg·m^2]	*Confidential*
Controller		
Nominal rotor speed	[rpm]	8.4
1P frequency	[Hz]	0.14
Cut-in wind speed	[m/s]	3.0
Cut out wind speed	[m/s]	31.0
Rated Wind Speed	[m/s]	11.1
Rated electric power (grid side)	[MW]	15.0
Blade-pitch control	[-]	Collective pitch
Tower		
Tower bottom diameter	[m]	7.50
Tower top diameter	[m]	*Confidential*
Length	[m]	119.76
Others		
Hub height	[mTwrBot]	123.95
Damping - 1st and 2nd mode	[%] log. dec.	4.9
1st natural frequency (excl. stress stiffening)	[Hz]	0.155

Table 2-1: Main technical data for the C2FLEX V236 – 15 MW.

2.2.1 Blade geometry and aerodynamic representation

The confidential blade information available to C2Wind in [DATANDA] is limited to the spanwise mass and stiffness per unit length, selected blade eigenfrequencies and the overall blade centre of gravity. C2Wind does not have access to the detailed blade geometry, sectional layouts, proprietary airfoil profiles, aerodynamic polars or the complete aeroelastic blade model.

The remaining blade properties have therefore been developed by C2Wind through reverse engineering. The objective has been to establish a representative blade model that reproduces the principal aerodynamic, structural and operational characteristics of the reference WTG without attempting to recreate the design in detail. The reverse-engineered blade geometry includes the spanwise distributions of chord, aerodynamic twist and airfoil properties, together with the blade prebend and relevant sectional

reference-axis offsets. These parameters have been developed iteratively using the available rotor dimensions, known turbine characteristics, publicly available information for comparable large offshore blades and aerodynamic design principles applicable to a 236 m rotor.

The blade prebend is explicitly represented in the aeroelastic model. This allows its influence on the undeformed rotor geometry, elastic blade deformation, tower clearance and global turbine response to be included. The geometry has been discretised with sufficient spanwise resolution to capture the main variations in the root-transition region, the principal aerodynamically active part of the blade and the flexible outer-blade region.

The available spanwise mass and stiffness properties have been implemented directly from [DATANDA], as the primary structural basis for the blade model. These data include mass per unit length and the relevant bending and torsional stiffness distributions. The model has subsequently been checked and, where necessary, adjusted within the uncertainty of the available information to provide consistency with the specified overall blade centre of gravity and the available blade eigenfrequencies. This ensures that the model provides a representative description of the blade's global mass distribution, flexibility and dynamic behaviour.

As the airfoil properties are unavailable, this has been established by C2Wind and have hence been estimated by C2Wind. The applied profile distribution covers relative thicknesses from approximately 18% in the outer-blade region to the circular root section. The aerodynamic profiles are based on publicly documented modern FFA-W3-type airfoils developed for large offshore rotors and have been mapped to the reverse-engineered assumptions of the blade-thickness distribution - however not included in this brief report.

The aerodynamic properties include lift, drag and pitching-moment coefficients over the complete angle-of-attack range from -180° to +180°. It can therefore represent normal power production, start-up and shutdown, idling, parked operation and conditions involving large angles of attack. The attached-flow data are representative of the Reynolds numbers experienced by a 118 m offshore blade, with nominal values of approximately 8e6 to 10e6 applied over most of the aerodynamically active blade.

The three-dimensional blade representation is shown in Figure 2-1. The origin of the blade coordinate system is located at the geometric centre of the blade-root section. The straight root-centre reference axis is indicated by the orange line and defines the undeformed spanwise direction. The modelled blade geometry is positioned relative to this axis, thereby illustrating the prescribed flap-wise and edgewise prebend. The dashed centreline follows the geometric centre of the individual blade sections and consequently shows the accumulated displacement of the blade relative to the root-centre reference axis. The combined chord, twist, thickness and prebend distributions provide a representative geometric basis for the C2FLEX aeroelastic model. The resulting integrated model provides a close representation of the available V236 turbine power-performance and operational-response data and is considered suitable for the present integrated load analysis.

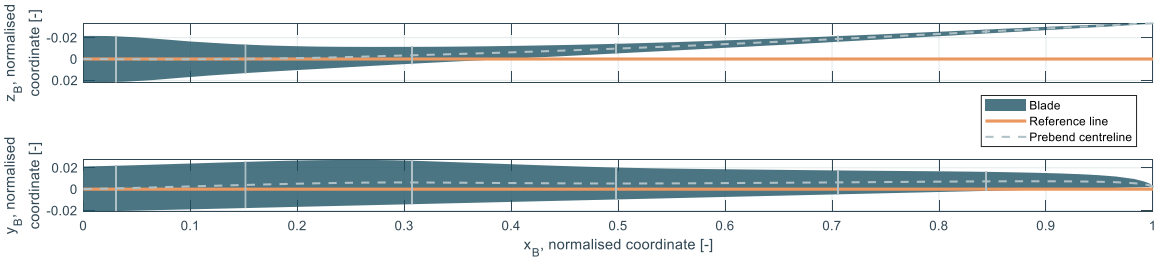


Figure 2-1: Three-dimensional representation of the C2FLEX V236 blade geometry. The orange line indicates the straight blade-root reference axis, while the dashed line follows the geometric centres of the modelled blade sections.

2.2.2 Variable speed, collective-pitch controller implementation

The Vestas V236 15 MW is represented using a variable-speed, collective-pitch controller. Below rated wind speed, generator torque is regulated to maintain efficient aerodynamic operation and a near-optimal tip-speed ratio. As rated rotor speed and rated power are approached, the controller transitions from below-rated torque control to above-rated pitch regulation. Above rated wind speed, collective blade pitch is used to regulate rotor speed and generator power while limiting turbine loading. The operating regions described below refer to Points O, C and D on the controller's steady-state power and rotor-speed characteristic as illustrated schematically in Figure 2-2 and are described as:

- **Below Point O – cut-in and minimum-speed operation:** At the lowest operational wind speeds, the rotor is accelerated from idling or cut-in conditions. The controller may maintain a prescribed minimum rotor speed to avoid operation in an unstable or inefficient low-speed region and to ensure a smooth transition into normal variable-speed operation. Generator torque is therefore controlled primarily to support rotor acceleration and stable operation rather than to maximise power capture.
- **Point O – C – optimum-power operation:** Between Points O and C, the turbine operates in the main below-rated, variable-speed region. Generator torque is controlled as a function of rotor speed to keep the turbine close to its optimum tip-speed ratio. The blade-pitch angle is maintained close to its minimum or aerodynamically optimal setting. This allows the rotor to operate near the maximum of the aerodynamic power-coefficient curve, C_P, thereby maximising energy capture for the available wind speed. This control region is therefore commonly referred to as maximum- C_P or optimum-power operation. Under ideal steady-state conditions, the resulting generator-torque demand is approximately proportional to the square of the rotor speed, while the extracted power is approximately proportional to the cube of the rotor speed.
- **Point C – D – transition to rated operation:** As the wind speed increases, the rotor approaches its upper operating-speed range. The torque controller progressively moves away from constant tip-speed-ratio operation, and generator torque is adjusted to provide a smooth transition towards rated power and rotor speed. The interaction between generator torque and blade pitch is particularly important in this region, as poor tuning can produce oscillations in rotor speed, power, drivetrain torque and thrust.

- **Above point D – rated-power and rotor-speed regulation**: Above rated wind speed, collective blade pitch becomes the primary means of regulating aerodynamic power and rotor speed. The pitch controller adjusts the blade-pitch angle in response to rotor-speed deviations, while the generator operates close to rated torque or rated power, depending on the applicable control strategy. Appropriate rotor-speed headroom and pitch-rate limitations are included to obtain realistic transient behaviour and load response.

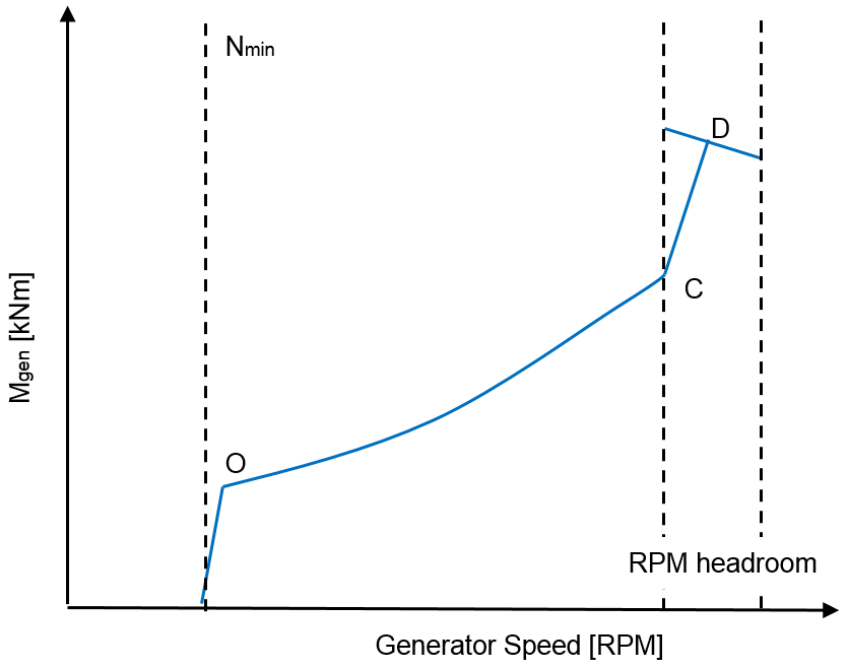


Figure 2-2: Schematic representation of the C2FLEX turbine-controller operating regions. The generator torque is represented by M_{gen}. The O, C and D are explained in the text.

2.2.2.1 Pitch controller tuning

The C2FLEX pitch controller has been tuned iteratively to match the data from [DATANDA] as accurately as possible. The tuning process has included:

- Adjustment of the below-rated torque-speed relationship to reproduce the Vestas V236 power curve and rotor-speed behaviour.
- Calibration of the minimum-speed and cut-in operating region.
- Adjustment of the transition between optimum- (C_P) operation and rated operation;
- Calibration of rated torque rated rotor speed and rated power.
- Tuning of the collective-pitch controller above rated wind speed.
- Adjustment of controller gains, filters, limits and actuator rates to provide stable dynamic behaviour.
- Assessment of the resulting effects on rotor thrust and the turbine load effects.
- No 1P controller features are modelled in the validation - as this is not included by Vestas in the available material.

Steady-state simulations have been performed over the operational wind-speed range (see the Ramp load case in Section 3) to compare power, generator speed, rotor speed, generator torque, blade pitch and rotor thrust with the available information from

[DATANDA]. Dynamic wind-speed staircase simulations have also been used to evaluate the response through the complete operating range. The staircase event subjects the controller to successive changes in wind speed and is particularly useful for identifying oscillations, controller under/overshoot, discontinuities or poorly damped behaviour in the transition and above-rated operating regions.

The result of the pitch controller tuning is outlined in Section 4, where the C2FLEX V236 15 MW results are compared with the Vestas V236 15 MW results.

2.2.3 Support structure

The main objective of the benchmark study performed in this report is to validate the deformations of the support structure, and thereby load effects, calculated using C2FLEX. To achieve this, the C2FLEX support structure shall represent the Vestas model as accurately as possible. The load effects provided in [LOADCON] are given for several different support structures with a 1st frequency range of 0.13 Hz to 0.23 Hz where the dataset in [DATANDA] is for a single support structure configuration. The support structure configuration used in [LOADCON] is not provided in detail other than the range of 1st natural frequencies. The support structure provided in [DATANDA] is for a 1st natural frequency of 0.155 Hz (without stress stiffening), which is close to one of the configurations in [LOADCON]. Based on this, the support structure information from [DATANDA] is used for all simulations in C2FLEX in this report.

The substructure is fully fixed at the seafloor which is equal to the approach in both [LOADCON] and [DATANDA]. This means that no soil-structure interaction is included in the ILA model.

A comparison of the 1st natural frequency and mode shape between the C2FLEX V236 15 MW and Vestas V236 15 MW models is shown in Figure 2-3, where a perfect match can be observed.

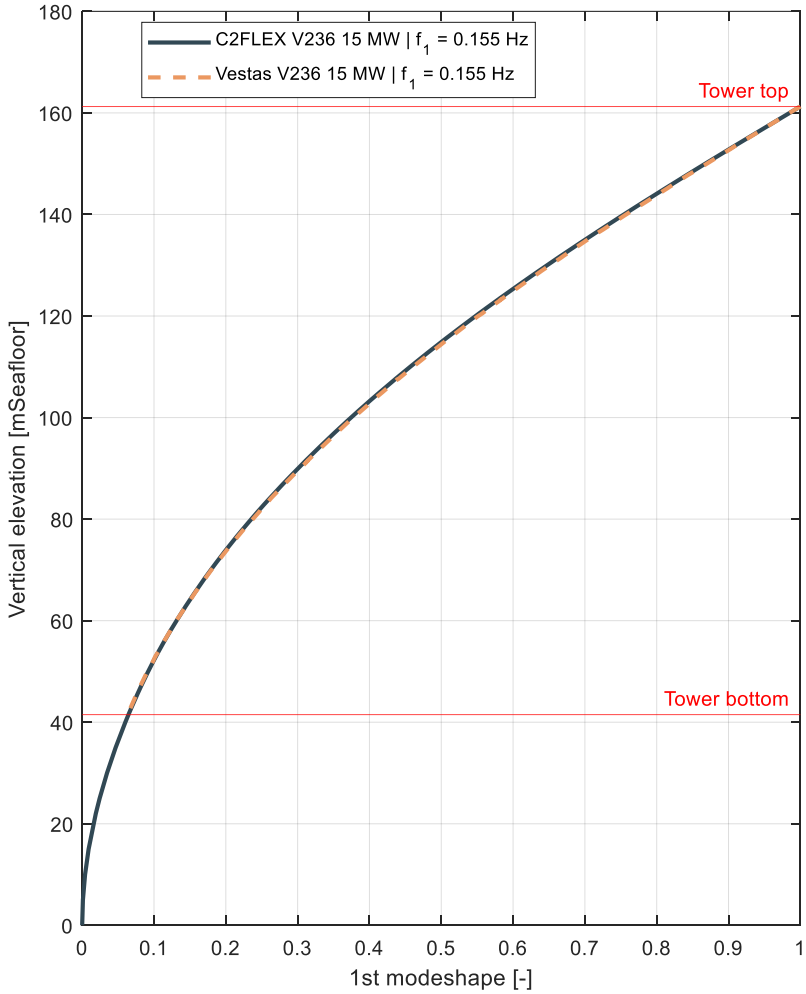


Figure 2-3:Modal parameter comparison between C2FLEX and Vestas. A perfect match between the two models is found.

3. Wind conditions and load cases

The simulations conducted are divided into the following three design load cases (DLCs):

- **Ramp**: A load case to test turbine control system using a steady state wind field across the rotor field.
- **DLC 1.2**: A fatigue limit state (FLS) load case during power production with turbulent wind.
- **DLC 6.1:** An ultimate limit state (ULS) load case in idling condition with turbulent wind.

As mentioned in Section 1, the simulations are wind-only. This means that DLC 1.2 and DLC 6.1 are not IEC-compliant DLCs according to Table 2 of [IEC6131] since the hydrodynamic loads are excluded - however the best approach isolate the validation the turbine model. A high-level overview of the input to the DLCs is outlined in Table 3-1 while a detailed list of all DLCs is summarised in Appendix A.

Parameter	Unit	DLC		
		Ramp	1.2	6.1
Limit state	[-]	-	FLS	ULS
Wind speed	[m/s]	3 to 25 (linear increase)	2 to 30	50
Wind shear exponent	[-]	0.14	0.14	0.11
Turbulence intensity	[-]	0.000	0.093 to 0.160	0.110
Turbulent wind seeds	[-]	-	6	6
Air density	[kg/m^3]	1.225	1.225	1.225
Yaw error	[°]	0	[-6, 6]	-8 to 8
Idling	[Yes/No]	No	No	Yes
Lifetime	[years]	-	30	-
No. of simulations	[-]	1	180	54
Simulation length	[s]	600	600	600

Table 3-1: High level DLC definition performed in the benchmark study conducted in this report. A detailed DLC list is outlined in Appendix A.

The turbulence intensity used in the simulations is based on Figure 2 of [LOADCON] and is shown in Figure 3-1. The occurrence frequency for each simulation is based on a Weibull distributed wind speed with the following Weibull parameters according to Table 2 of [LOADCON]:

- Mean wind speed at hub height: 10 m/s
- Weibull scale parameter, A: 11.29 m/s
- Weibull shape parameter, k: 2.2

The wind speed distribution is shown in Figure 3-1.The Ramp DLC are performed with a steady state wind field while DLC 1.2 and DLC 6.1 are conducted with a turbulent wind field. The turbulent wind field is generated using the Mann turbulence model, providing a three-dimensional representation of atmospheric turbulence with the spatial and temporal coherence required for aeroelastic load simulations.

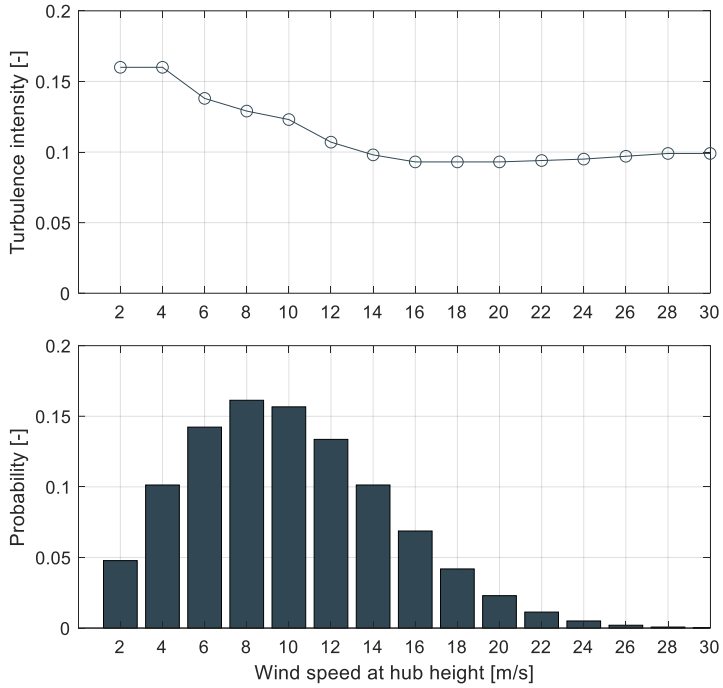


Figure 3-1: **Top**: Turbulence intensity as a function of wind speed used for DLC 1.2. **Bottom**: Distribution of wind speed at hub height using the Weibull parameters A = 11.29 m/s and k = 2.2.

4. WTG comparison

The WTG comparison is conducted for the following parameters in each of the load cases:

- Steady state wind speed ramp:
  - Active power
  - Rotor speed
  - Pitch angle
  - Bending moment at tower bottom
- Normal Power production - DLC 1.2:
  - Tower bottom load effect statistics
  - Damage equivalent bending moment at the tower bottom.
- Standstill and idle during storm conditions - DLC 6.1:
  - Extreme load effects at the tower bottom.

In addition to matching the turbine's operational performance as outlined in Section 2.2 as an important validation scheme, the C2FLEX V236 15 MW model is validated against the available wind only load effect information in [DATANDA]. This is essential because a good match of the power curve and controller performance alone does not demonstrate that the model reproduces rotor thrust, structural dynamics or the load transferred to the support structure. The load validation considers only the available quantities at the tower-bottom interface. Tower-bottom load effects usually provide a good indication of turbine behaviour, especially in a wind-only scenario. The comparison uses mean values, maxima, minima, standard deviations and, where relevant, damage-equivalent load effects.

Comparisons are primarily presented as a function of wind speed and through direct load validation. Differences between the C2FLEX and Vestas results are evaluated in view of the independent nature of the C2FLEX model, the level of turbine detail available and the model's intended application. The objective is not to reproduce every local or high-frequency response component of the WTG model, but to assess whether C2FLEX provides a representative prediction of the global load effects relevant to the ILA.

4.1 Performance during a Wind Speed Ramp

The wind speed ramp load case is a single simulation with a duration of 600 seconds where the wind speed increases linearly from 3 m/s at time 0 to 25 m/s at time 600, and the wind field is constant across the rotor field (including shear). It is included to compare the most important WTG parameters with tabular values from [DATANDA]. A comparison of the bending moment at the tower bottom is shown in Figure 4-1. The bending moment from the Vestas V236 15 MW model is calculated based on a thrust coefficient, C_t, which is available in [DATANDA] as a function of wind speed. Please note that C_t is calculated by Vestas using a slightly different input than the Ramp load case so an exact match cannot be expected. Generally good agreement between C2FLEX and Vestas is found.

As outlined in Section 2.2, the relationship between the rotor speed and the active power is of high importance. A direct comparison between these two parameters is shown in Figure 4-2. An almost perfect match between C2FLEX and Vestas can be observed.

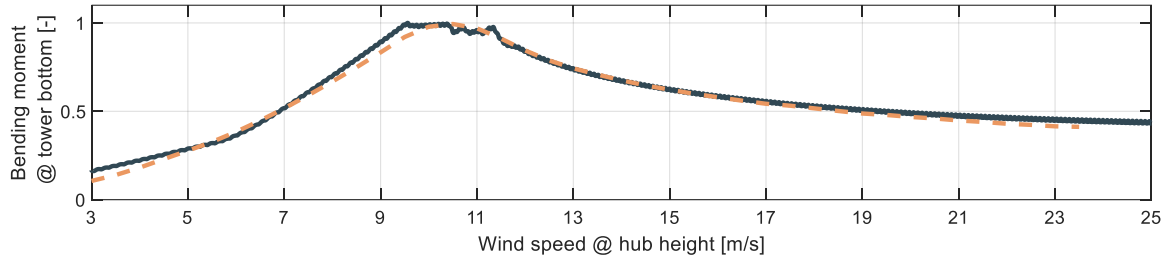


Figure 4-1: Comparison between the Vestas and the C2FLEX model of the V236 15 MW for the Ramp load case. The comparison is shown for the bending moment at the tower bottom. The plot is normalised by the maximum value from C2FLEX. The Vestas data are from [DATANDA].

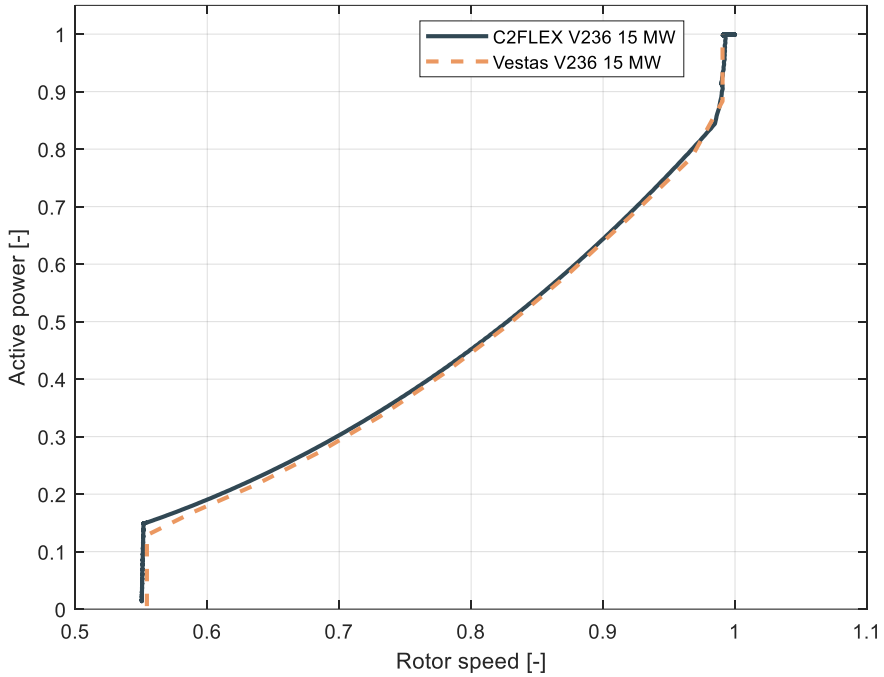


Figure 4-2: Comparison between the rotor speed and the active power for the Ramp load case. The plots are normalised by the maximum value from C2FLEX. The Vestas data are from [DATANDA].

4.2 Normal Power production - DLC 1.2

The DLC 1.2 load case is conducted to quantify the accuracy of the fatigue load effects. The measure for this is chosen as the damage equivalent load effect (DEL) at the tower bottom since this usually is a good variable for describing the overall fatigue load effect of the support structure. A comparison between the statistics of individual simulations is shown in Figure 4-3. Here, the statistics of the bending moment and shear force at the tower bottom is shown as a function of wind speed. In addition, the load effects using the C_t-curve is included as well. In general, a very good agreement is found between C2FLEX and Vestas.

A comparison between the damage equivalent bending moment (DEM) at the tower bottom between the Vestas model and the C2Wind model is shown in Table 4-1. The comparison is performed using the DEM from the Vestas model with a 1st natural

frequency of 0.150 Hz. This is slightly lower than the 1st natural frequency of the model used in this report which was 0.155 Hz according to Table 2-1. Based on the values presented in Table 11 of [LOADCON], this small difference seems not to have a significant influence on the DEM. The C2FLEX DEM is slightly higher than the Vestas result in both the fore-aft and side-to-side directions. This small difference is within an acceptable limit.

Model	Unit	M_x (fore-aft)	M_y (side-side)
		$N_{\text{ref}} = 1e7 \mid m = 5$	
Vestas	[MNm]	82.1	42.0
C2FLEX	[MNm]	84.2	46.2

Table 4-1: Damage equivalent bending moment at the tower bottom comparison between the Vestas and the C2FLEX model of the V236 15 MW. The Vestas data is for the model with a 1st natural frequency of 0.150 Hz from Table 11 of [LOADCON].

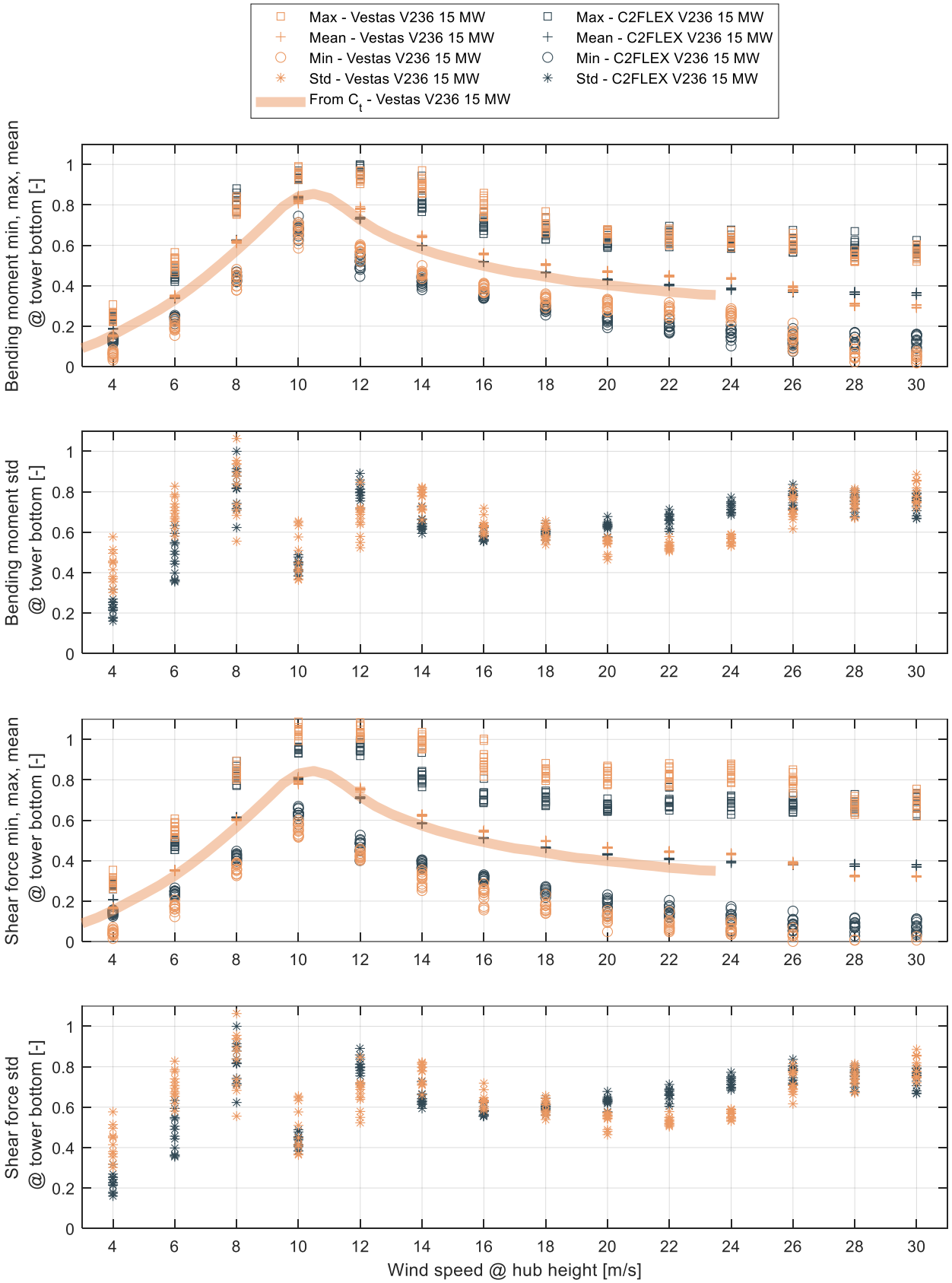


Figure 4-3: Comparison between the Vestas and the C2FLEX model of the V236 15 MW for the DLC 1.2 load case. Each marker shows the statistic from a single simulation, while the line shows the load effects at the tower bottom using the C_t-curve from [DATANDA] . The plots are normalised with the maximum value from C2FLEX. The Vestas data are from [DATANDA].

4.3 Standstill and idle during storm conditions - DLC 6.1

The DLC 6.1 load case is conducted to quantify the accuracy of the extreme load effects during a 50 year storm. The measure for this is chosen as the bending moment at the tower bottom. A comparison between the statistics of the individual simulations is shown in Figure 4-4 for the fore-aft and side-to-side directions individually. Here, the statistics of the bending moment at the tower bottom is shown as a function of yaw error. In addition, the mean of the maximum values from all simulations is also shown.

A comparison between the mean-of-max resulting bending moment, M_{res}, at the tower bottom between the Vestas model and the C2Wind model is shown in Table 4-2. The comparison is performed using M_{res} from the Vestas model with a 1st natural frequency of 0.150 Hz. This is slightly lower than the 1st natural frequency of the model used in this report which was 0.155 Hz according to Table 2-1. Based on the values presented in Table 8 of [LOADCON], this small difference seems not to have a significant influence on M_{res} from DLC 6.1. A slightly lower M_{res} is found from the C2FLEX model compared to the Vestas model. This small difference is within an acceptable limit.

Model	Unit	M_{res} [1]
Vestas	[MNm]	353
C2FLEX	[MNm]	343

1) The resulting bending moment includes a PLF of 1.35 and an additional 28 MNm due to out-of-verticality, according to Section 6.1 of [LOADCON].

Table 4-2: Resulting bending moment for DLC 6.1 at the tower bottom comparison between the Vestas and the C2FLEX model of the V236 15 MW. The Vestas data is for the model with a 1st natural frequency of 0.150 Hz from Table 8 of [LOADCON].

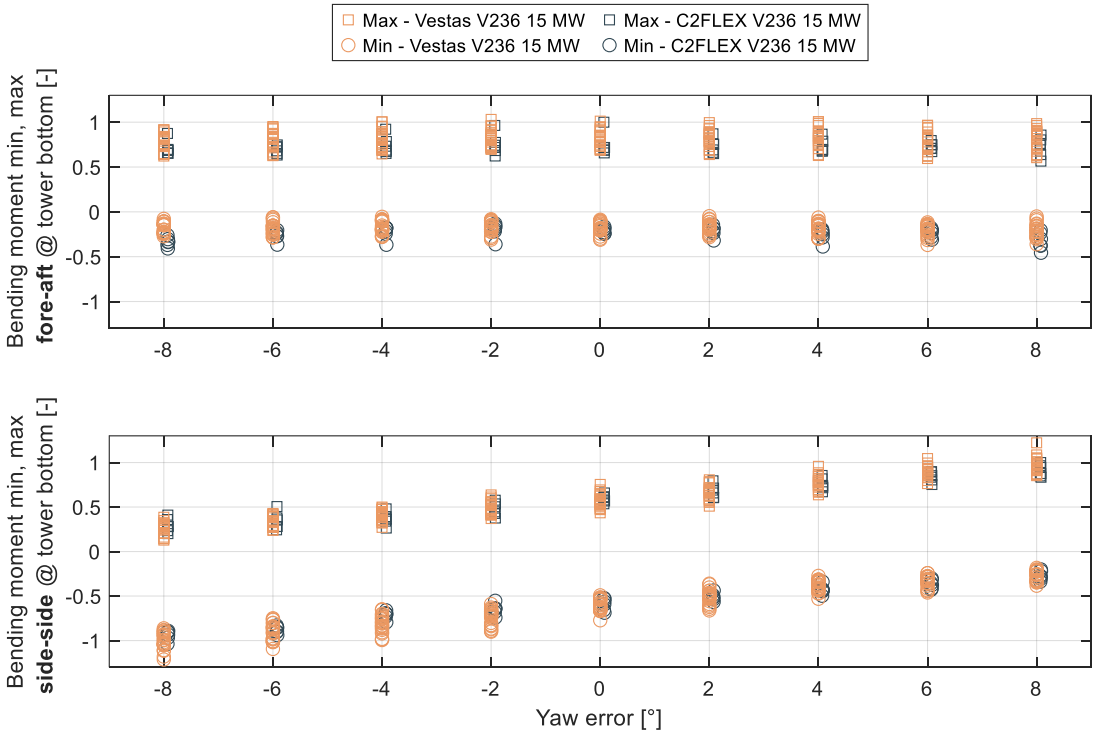


Figure 4-4: Comparison of bending moment statistics at the tower bottom between the Vestas and C2FLEX models of the V236 15 MW for DLC 6.1. Each marker shows the statistic from a single simulation. The plots are normalised by the maximum value from C2FLEX. The Vestas data are from [DATANDA].

5. Conclusion

The benchmark shows that the C2FLEX V236 15 MW model reproduces the available Vestas reference data closely for the assessed wind-only load cases. The wind speed Ramp simulation shows close and near to perfect agreement in active power, rotor speed and pitch angle, while the matched first natural frequency and mode shape support the consistency of the global structural representation.

For normal power production, DLC 1.2, the C2FLEX damage-equivalent bending moments impressive accurate agreement with the Vestas reference results. Likewise, for the 50-year storm simulations, DLC 6.1, the resulting mean-of-maximum bending moment is in good agreement with the Vestas reference. Overall, the comparison demonstrates a satisfactory agreement between the C2FLEX and Vestas results across the assessed load cases.

It should be noted that some differences are expected, as the model validation is based on independently generated stochastic turbulent wind fields. If the exact wind-field realisations originally used by Vestas had also been available for the C2Wind simulations, an even more direct and conclusive model-to-model validation could have been achieved.

The C2FLEX V236 15 MW model is considered suitable for assessing global aeroelastic response and tower-bottom load transfer for the wind-only cases evaluated in this report.

6. References

[DATANDA] **Vestas Wind Systems A/S**
V236 15 MW data shared to C2Wind by Vestas under an NDA between C2Wind and Vestas.

[IEC6131] **IEC**
IEC 61400-3-1: Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines. Edition 1.0. International Electrotechnical Commission (2019-04-05)

[LOADCON] **Vestas Wind Systems A/S**
Loads for Conceptual Foundation Design V236-15 MW
Doc. No. 0107-1336
Revision: 05
(2024-07-01)

C2WIND

Appendices

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Appendix A. Detailed DLC list

DLC	Wind speed	Wind shear exponent	Turbulence intensity	Turbulent wind seed	Yaw error	Idling	Hours
[-]	[m/s]	[-]	[-]	[-]	[°]	[Yes/No]	[-]
Ramp	3 to 25	0.14	0.000	-	0	No	-
1.2	2	0.14	0.16	A	6	Yes	1046.1
1.2	2	0.14	0.16	B	6	Yes	1046.1
1.2	2	0.14	0.16	C	6	Yes	1046.1
1.2	2	0.14	0.16	D	6	Yes	1046.1
1.2	2	0.14	0.16	E	6	Yes	1046.1
1.2	2	0.14	0.16	F	6	Yes	1046.1
1.2	4	0.14	0.16	A	6	No	2218.9
1.2	4	0.14	0.16	B	6	No	2218.9
1.2	4	0.14	0.16	C	6	No	2218.9
1.2	4	0.14	0.16	D	6	No	2218.9
1.2	4	0.14	0.16	E	6	No	2218.9
1.2	4	0.14	0.16	F	6	No	2218.9
1.2	6	0.14	0.138	A	6	No	3116.5
1.2	6	0.14	0.138	B	6	No	3116.5
1.2	6	0.14	0.138	C	6	No	3116.5
1.2	6	0.14	0.138	D	6	No	3116.5
1.2	6	0.14	0.138	E	6	No	3116.5
1.2	6	0.14	0.138	F	6	No	3116.5
1.2	8	0.14	0.129	A	6	No	3532.9
1.2	8	0.14	0.129	B	6	No	3532.9
1.2	8	0.14	0.129	C	6	No	3532.9
1.2	8	0.14	0.129	D	6	No	3532.9
1.2	8	0.14	0.129	E	6	No	3532.9
1.2	8	0.14	0.129	F	6	No	3532.9
1.2	10	0.14	0.123	A	6	No	3431.0
1.2	10	0.14	0.123	B	6	No	3431.0
1.2	10	0.14	0.123	C	6	No	3431.0
1.2	10	0.14	0.123	D	6	No	3431.0
1.2	10	0.14	0.123	E	6	No	3431.0
1.2	10	0.14	0.123	F	6	No	3431.0
1.2	12	0.14	0.107	A	6	No	2926.4
1.2	12	0.14	0.107	B	6	No	2926.4
1.2	12	0.14	0.107	C	6	No	2926.4
1.2	12	0.14	0.107	D	6	No	2926.4
1.2	12	0.14	0.107	E	6	No	2926.4
1.2	12	0.14	0.107	F	6	No	2926.4
1.2	14	0.14	0.098	A	6	No	2219.0
1.2	14	0.14	0.098	B	6	No	2219.0
1.2	14	0.14	0.098	C	6	No	2219.0
1.2	14	0.14	0.098	D	6	No	2219.0
1.2	14	0.14	0.098	E	6	No	2219.0
1.2	14	0.14	0.098	F	6	No	2219.0
1.2	16	0.14	0.093	A	6	No	1505.5
1.2	16	0.14	0.093	B	6	No	1505.5
1.2	16	0.14	0.093	C	6	No	1505.5
1.2	16	0.14	0.093	D	6	No	1505.5
1.2	16	0.14	0.093	E	6	No	1505.5
1.2	16	0.14	0.093	F	6	No	1505.5

1.2	18	0.14	0.093	A	6	No	917.1
1.2	18	0.14	0.093	B	6	No	917.1
1.2	18	0.14	0.093	C	6	No	917.1
1.2	18	0.14	0.093	D	6	No	917.1
1.2	18	0.14	0.093	E	6	No	917.1
1.2	18	0.14	0.093	F	6	No	917.1
1.2	20	0.14	0.093	A	6	No	502.6
1.2	20	0.14	0.093	B	6	No	502.6
1.2	20	0.14	0.093	C	6	No	502.6
1.2	20	0.14	0.093	D	6	No	502.6
1.2	20	0.14	0.093	E	6	No	502.6
1.2	20	0.14	0.093	F	6	No	502.6
1.2	22	0.14	0.094	A	6	No	248.0
1.2	22	0.14	0.094	B	6	No	248.0
1.2	22	0.14	0.094	C	6	No	248.0
1.2	22	0.14	0.094	D	6	No	248.0
1.2	22	0.14	0.094	E	6	No	248.0
1.2	22	0.14	0.094	F	6	No	248.0
1.2	24	0.14	0.095	A	6	No	110.2
1.2	24	0.14	0.095	B	6	No	110.2
1.2	24	0.14	0.095	C	6	No	110.2
1.2	24	0.14	0.095	D	6	No	110.2
1.2	24	0.14	0.095	E	6	No	110.2
1.2	24	0.14	0.095	F	6	No	110.2
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1.2	26	0.14	0.097	B	6	No	44.1
1.2	26	0.14	0.097	C	6	No	44.1
1.2	26	0.14	0.097	D	6	No	44.1
1.2	26	0.14	0.097	E	6	No	44.1
1.2	26	0.14	0.097	F	6	No	44.1
1.2	28	0.14	0.099	A	6	No	15.9
1.2	28	0.14	0.099	B	6	No	15.9
1.2	28	0.14	0.099	C	6	No	15.9
1.2	28	0.14	0.099	D	6	No	15.9
1.2	28	0.14	0.099	E	6	No	15.9
1.2	28	0.14	0.099	F	6	No	15.9
1.2	30	0.14	0.099	A	6	No	5.2
1.2	30	0.14	0.099	B	6	No	5.2
1.2	30	0.14	0.099	C	6	No	5.2
1.2	30	0.14	0.099	D	6	No	5.2
1.2	30	0.14	0.099	E	6	No	5.2
1.2	30	0.14	0.099	F	6	No	5.2
1.2	2	0.14	0.16	G	-6	Yes	1046.1
1.2	2	0.14	0.16	H	-6	Yes	1046.1
1.2	2	0.14	0.16	I	-6	Yes	1046.1
1.2	2	0.14	0.16	J	-6	Yes	1046.1
1.2	2	0.14	0.16	K	-6	Yes	1046.1
1.2	2	0.14	0.16	L	-6	Yes	1046.1
1.2	4	0.14	0.16	G	-6	No	2218.9
1.2	4	0.14	0.16	H	-6	No	2218.9
1.2	4	0.14	0.16	I	-6	No	2218.9
1.2	4	0.14	0.16	J	-6	No	2218.9
1.2	4	0.14	0.16	K	-6	No	2218.9
1.2	4	0.14	0.16	L	-6	No	2218.9
1.2	6	0.14	0.138	G	-6	No	3116.5

1.2	6	0.14	0.138	H	-6	No	3116.5
1.2	6	0.14	0.138	I	-6	No	3116.5
1.2	6	0.14	0.138	J	-6	No	3116.5
1.2	6	0.14	0.138	K	-6	No	3116.5
1.2	6	0.14	0.138	L	-6	No	3116.5
1.2	8	0.14	0.129	G	-6	No	3532.9
1.2	8	0.14	0.129	H	-6	No	3532.9
1.2	8	0.14	0.129	I	-6	No	3532.9
1.2	8	0.14	0.129	J	-6	No	3532.9
1.2	8	0.14	0.129	K	-6	No	3532.9
1.2	8	0.14	0.129	L	-6	No	3532.9
1.2	10	0.14	0.123	G	-6	No	3431.0
1.2	10	0.14	0.123	H	-6	No	3431.0
1.2	10	0.14	0.123	I	-6	No	3431.0
1.2	10	0.14	0.123	J	-6	No	3431.0
1.2	10	0.14	0.123	K	-6	No	3431.0
1.2	10	0.14	0.123	L	-6	No	3431.0
1.2	12	0.14	0.107	G	-6	No	2926.4
1.2	12	0.14	0.107	H	-6	No	2926.4
1.2	12	0.14	0.107	I	-6	No	2926.4
1.2	12	0.14	0.107	J	-6	No	2926.4
1.2	12	0.14	0.107	K	-6	No	2926.4
1.2	12	0.14	0.107	L	-6	No	2926.4
1.2	14	0.14	0.098	G	-6	No	2219.0
1.2	14	0.14	0.098	H	-6	No	2219.0
1.2	14	0.14	0.098	I	-6	No	2219.0
1.2	14	0.14	0.098	J	-6	No	2219.0
1.2	14	0.14	0.098	K	-6	No	2219.0
1.2	14	0.14	0.098	L	-6	No	2219.0
1.2	16	0.14	0.093	G	-6	No	1505.5
1.2	16	0.14	0.093	H	-6	No	1505.5
1.2	16	0.14	0.093	I	-6	No	1505.5
1.2	16	0.14	0.093	J	-6	No	1505.5
1.2	16	0.14	0.093	K	-6	No	1505.5
1.2	16	0.14	0.093	L	-6	No	1505.5
1.2	18	0.14	0.093	G	-6	No	917.1
1.2	18	0.14	0.093	H	-6	No	917.1
1.2	18	0.14	0.093	I	-6	No	917.1
1.2	18	0.14	0.093	J	-6	No	917.1
1.2	18	0.14	0.093	K	-6	No	917.1
1.2	18	0.14	0.093	L	-6	No	917.1
1.2	20	0.14	0.093	G	-6	No	502.6
1.2	20	0.14	0.093	H	-6	No	502.6
1.2	20	0.14	0.093	I	-6	No	502.6
1.2	20	0.14	0.093	J	-6	No	502.6
1.2	20	0.14	0.093	K	-6	No	502.6
1.2	20	0.14	0.093	L	-6	No	502.6
1.2	22	0.14	0.094	G	-6	No	248.0
1.2	22	0.14	0.094	H	-6	No	248.0
1.2	22	0.14	0.094	I	-6	No	248.0
1.2	22	0.14	0.094	J	-6	No	248.0
1.2	22	0.14	0.094	K	-6	No	248.0
1.2	22	0.14	0.094	L	-6	No	248.0
1.2	24	0.14	0.095	G	-6	No	110.2
1.2	24	0.14	0.095	H	-6	No	110.2

1.2	24	0.14	0.095	I	-6	No	110.2
1.2	24	0.14	0.095	J	-6	No	110.2
1.2	24	0.14	0.095	K	-6	No	110.2
1.2	24	0.14	0.095	L	-6	No	110.2
1.2	26	0.14	0.097	G	-6	No	44.1
1.2	26	0.14	0.097	H	-6	No	44.1
1.2	26	0.14	0.097	I	-6	No	44.1
1.2	26	0.14	0.097	J	-6	No	44.1
1.2	26	0.14	0.097	K	-6	No	44.1
1.2	26	0.14	0.097	L	-6	No	44.1
1.2	28	0.14	0.099	G	-6	No	15.9
1.2	28	0.14	0.099	H	-6	No	15.9
1.2	28	0.14	0.099	I	-6	No	15.9
1.2	28	0.14	0.099	J	-6	No	15.9
1.2	28	0.14	0.099	K	-6	No	15.9
1.2	28	0.14	0.099	L	-6	No	15.9
1.2	30	0.14	0.099	G	-6	No	5.2
1.2	30	0.14	0.099	H	-6	No	5.2
1.2	30	0.14	0.099	I	-6	No	5.2
1.2	30	0.14	0.099	J	-6	No	5.2
1.2	30	0.14	0.099	K	-6	No	5.2
1.2	30	0.14	0.099	L	-6	No	5.2
6.1	50	0.11	0.11	A	-8	Yes	-
6.1	50	0.11	0.11	B	-8	Yes	-
6.1	50	0.11	0.11	C	-8	Yes	-
6.1	50	0.11	0.11	D	-8	Yes	-
6.1	50	0.11	0.11	E	-8	Yes	-
6.1	50	0.11	0.11	F	-8	Yes	-
6.1	50	0.11	0.11	A	-6	Yes	-
6.1	50	0.11	0.11	B	-6	Yes	-
6.1	50	0.11	0.11	C	-6	Yes	-
6.1	50	0.11	0.11	D	-6	Yes	-
6.1	50	0.11	0.11	E	-6	Yes	-
6.1	50	0.11	0.11	F	-6	Yes	-
6.1	50	0.11	0.11	A	-4	Yes	-
6.1	50	0.11	0.11	B	-4	Yes	-
6.1	50	0.11	0.11	C	-4	Yes	-
6.1	50	0.11	0.11	D	-4	Yes	-
6.1	50	0.11	0.11	E	-4	Yes	-
6.1	50	0.11	0.11	F	-4	Yes	-
6.1	50	0.11	0.11	A	-2	Yes	-
6.1	50	0.11	0.11	B	-2	Yes	-
6.1	50	0.11	0.11	C	-2	Yes	-
6.1	50	0.11	0.11	D	-2	Yes	-
6.1	50	0.11	0.11	E	-2	Yes	-
6.1	50	0.11	0.11	F	-2	Yes	-
6.1	50	0.11	0.11	A	0	Yes	-
6.1	50	0.11	0.11	B	0	Yes	-
6.1	50	0.11	0.11	C	0	Yes	-
6.1	50	0.11	0.11	D	0	Yes	-
6.1	50	0.11	0.11	E	0	Yes	-
6.1	50	0.11	0.11	F	0	Yes	-
6.1	50	0.11	0.11	A	2	Yes	-
6.1	50	0.11	0.11	B	2	Yes	-
6.1	50	0.11	0.11	C	2	Yes	-

6.1	50	0.11	0.11	D	2	Yes	-
6.1	50	0.11	0.11	E	2	Yes	-
6.1	50	0.11	0.11	F	2	Yes	-
6.1	50	0.11	0.11	A	4	Yes	-
6.1	50	0.11	0.11	B	4	Yes	-
6.1	50	0.11	0.11	C	4	Yes	-
6.1	50	0.11	0.11	D	4	Yes	-
6.1	50	0.11	0.11	E	4	Yes	-
6.1	50	0.11	0.11	F	4	Yes	-
6.1	50	0.11	0.11	A	6	Yes	-
6.1	50	0.11	0.11	B	6	Yes	-
6.1	50	0.11	0.11	C	6	Yes	-
6.1	50	0.11	0.11	D	6	Yes	-
6.1	50	0.11	0.11	E	6	Yes	-
6.1	50	0.11	0.11	F	6	Yes	-
6.1	50	0.11	0.11	A	8	Yes	-
6.1	50	0.11	0.11	B	8	Yes	-
6.1	50	0.11	0.11	C	8	Yes	-
6.1	50	0.11	0.11	D	8	Yes	-
6.1	50	0.11	0.11	E	8	Yes	-
6.1	50	0.11	0.11	F	8	Yes	-

Table A-1: Detailed design load cases (DLC) performed in the benchmark study.

Appendix B. 3D visualisation of the C2FLEX V236 15 MW

The following file is embedded into the PDF can be opened with a mp4 player.

The file is a screen caption of a DLC 1.2 simulation with a turbulent wind speed field and a mean wind speed of 12 m/s.

- 02-000-025_1 Appendix B - 3D visualisation of the C2FLEX V236 15 MW.mp4