Final report

1. Project details

Project title	The Low-Wind turbine concept for optimal system integration
File no.	64019-0074
Name of the funding scheme	EUDP VIND
Project managing company / institution	DTU, DTU Wind Energy, DTU Management
CVR number (central business register)	30060946
Project partners	Vestas Wind System A/S, DTU
Submission date	15 March 2022

2. Summary

The overall objective of the project was to explore the potentials of a new wind turbine concept, the LowWind turbine, designed for optimal integration in a power system with considerable amount from renewable energy sources. We succeeded in meeting this objective as the simulations of the LowWind (LW) turbine power curve characteristics in the Northern Europe energy system did confirm a big advantage of boosting the energy production at low wind speeds, which is the characteristic of the LowWind turbine concept. The simulations showed further that even with an increase of the LowWind turbine CapEx up to 35-40% above a conventional turbine of the same rated power there would be investments in the LW turbine in 2045. Further, the simulations showed that the LW turbine is competing with grid investments such that lower LW CapEx means less grid investments and opposite for increasing LW CapEx.

We demonstrated with the conceptual design of the LowWind reference wind turbine (LW-RWT) of 3.4MW and a specific power of 100W/m^2 that it is possible on basis of conventional design approaches and technology to develop such turbines. Further, we investigated several other concepts with alternative designs in order to adapt the design to the unconventional design room of a huge rotor and a low stop wind speed of 12-14m/s. In particular, the downwind rotor concepts were investigated but overall they showed only potentially marginal advances compared with the upwind reference turbine LW-RWT. One drawback of the downwind rotor with some coning and flexible blades is that the projected rotor area decrease for wind speeds up to rated power in contrast to an upwind rotor with similar coning.

During the project we developed the optimization framework and simulation models further. As an example an improved low frequency noise simulation model for downwind rotors was developed.

Parts of the results of the design studies will be potentially utilized in the future by integration in the existing and future Vestas product line

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Det overordnede projektformål var at undersøge potentialet i et helt nyt vindmøllekoncept, LowWind (LW) møllen, som er designet og optimeret for optimal integration i et el-system med høj andel af vedvarende energi. Vi opfyldte projektmålet, idet simuleringer af Nordeuropas el system med input af LW møllens effektkurve bekræftede den store fordel, man opnår ved at booste effektproduktionen ved lav vind, hvilket er den grundlæggende egenskab ved LW rotoren. Endvidere viste simuleringerne, at selv med en 35-40% højere CapEx for LW møllen, sammenlignet med en konventionel mølle med samme mærkeeffekt, vil der stadig være investeringer i LW møllen. Endelig viste simuleringer også, at LW møllen konkurrerer med investeringer i net forstærkninger, således at lavere LW CapEx giver mindre investeringer i net og omvendt for højere LW CapEx.

Vi demonstrerede med et konceptuelt design af LW reference møllen (LW-RWT) på 3.4MW og med en 208m rotor i diameter og således en specifik effekt på 100W/m¨2, at det er muligt med konventionelle design metoder og teknologi at udvikle LW møller. Endvidere undersøgte vi andre koncepter med alternative designs ud fra mulighederne i det utraditionelle designrum for en meget stor rotor og en meget lav stopvindhastighed på 12-14m/s. Især er konceptet med rotoren nedstrøms undersøgt detaljeret, men overordnet viste disse koncepter kun marginale fordele hvis overhovedet nogen i forhold til det traditionelle design med en tre-bladet rotor opstrøms. Èn af ulemperne ved en nedstrømsrotor med nogen koning og fleksible vinger er, at det projekterede rotorareal reduceres mere og mere op til møllen når sin mærkeeffekt og begynder at pitche, hvilket er modsat en opstrømsrotor med tilsvarende koning.

Gennem projektet videreudviklede vi optimerings- og simuleringsværktøjer. Som et eksempel kan nævnes en forbedret model til simulering af lavfrekvent støj for en nedstrømsrotor.

Dele af resultaterne fra konceptstudierne vil blive søgt udnyttet og integreret i den aktuelle og kommende produktlinje hos Vestas.

3. Project objectives

The overall objective of the project is to explore the potentials of a completely new wind turbine concept – the Low-Wind turbine, designed for optimal integration in a power system with considerable amount of renewables. The Low-Wind turbine will produce more than the double amount of energy at low wind when the electricity prices typically are high but will be shut down already at 12-14m/s

As basis for exploration of the LowWind turbine concept, two reference turbines of the same rated power were developed as a first part of the project in work package 1 (WP1), see Figure 1. One of the turbines represents a state-of-the-art conventional onshore turbine technology and we have chosen the IEA 3.4 MW (exactly 3.37 MW electrical power) onshore reference turbine with a specific power (SP) of of 256 W/m2.

The other turbine is a LowWind reference wind turbine (LW-RWT). With a specified SP of 100 W/m2 and a rated power of 3.4 MW it leads to a 208m diameter rotor. The design of the LW-RWT rotor was carried out with the Multidisciplinary Horizontal Axis Wind Turbine Optimization Tool HAWTOpt2, which optimizes the blade outer shape and the internal structure using predefined airfoil data. The optimization was carried out maximizing AEP but respecting several constraints on e.g. blade root moment, tip deflection, and maximum chord. The final blade design has a weight of around 31 tons and its AEP is 46% higher than for the conventional turbine and fulfilling the target of more than double production at low wind compared with a conventional turbine. The nominal maximum flapwise blade root moment was constrained to 30% higher than for the IEA-

RWT and it resulted in a maximum thrust that is 10% lower than for the IEA-RWT. Both the relative maximum flapwise moment and thrust was achieved in the optimization by a combination of strong bend-twist coupling and so-called peak shaving, where the rotor pitches towards feather near rated wind speed to limit peak loads. The bend-twist coupling is enabled by reduced torsional stiffness and tailored placement of the shear centre.

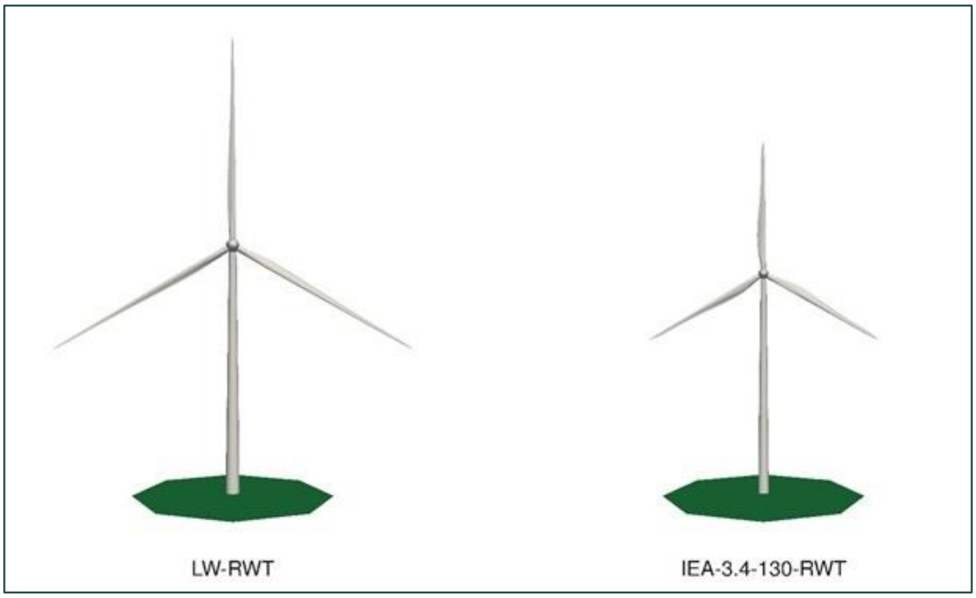
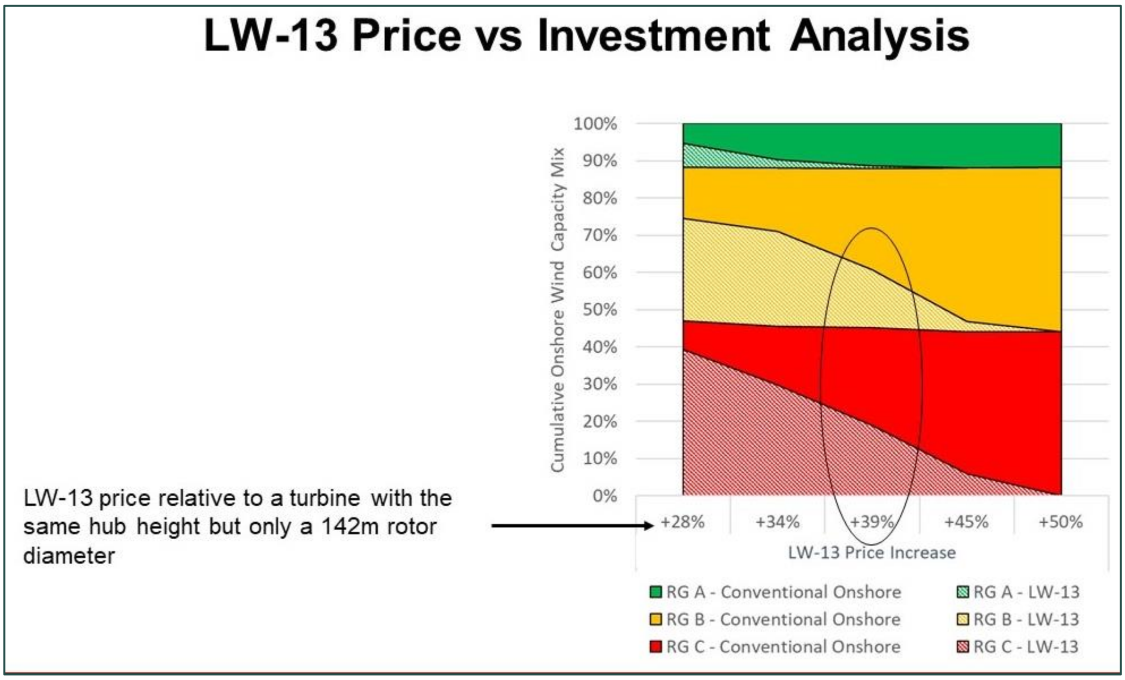


Figure 1 To the right the conventional turbine with a rotor diameter of 130 m which gives a specific power (SP) of 256 W/m2 based on the rated electrical power of 3.37MW. To the right the 208m diameter LowWind reference wind turbine (LW-RWT) designed and developed in the present project with specific power of 100W/m^2

A slightly reduced DLC analysis was carried out for both turbines to provide the basis for a load comparison. While the increase in fatigue loads typical was between 20-50% the increase in extreme loads was higher and in the range of 50-100% increase and even higher for some load components. The increased loading leads to higher CapEx for the LW-RWT but as mentioned above it has also an AEP that is 46% higher than a conventional turbine. The question is now how much higher the CapEx can be for the LW-RWT still to be competitive. This was one of the main questions to be answered in WP2 of the project.

The power curves of the two reference turbine were used in WP2 of the project for analyses of the impact of the LW technology in our energy system and at what price point the LW-RWT becomes competitive in Northern and Central Europe’s energy system. Similarly, the impact system flexibility has on LW investment was also analysed by limiting future transmission investment. Furthermore, we also analysed the amount of revenue this LW technology could generate compared to conventional turbines to further investigate the business case for this technology. The main finding here is that the LW technology see investment at prices below a 45% increase over a conventional onshore wind turbine with an equal hub height (127.5 m) and a smaller rotor diameter (142 m vs 208 m), Figure 2. The addition of LW technology also leads to a reduction in transmission investment, and similarly, reductions in transmission capacity lead to further investment in LW technology. Lastly, it is shown that in the future Northern and Central European energy system, in wind dominated areas such as Denmark, this LW technology could generate revenues that are more than double that of conventional turbines (per MW), making the case that this technology could be a worthy endeavour.



LW-13 price relative to a turbine with the same hub height but only a 142m rotor diameter

Figure 2 The graph shows the share (shaded areas) of the total market in the analyzed region (Northern and central Europe) that the LW technology will have in a future market in 2045, divided in three wind regions. Red has the lowest wind potential and green the highest.

After design of the LowWind reference turbine and comparing it with the conventional IEA-RWT the objective of the work in WP3 was to explore other designs of the LowWind concept than the traditional or conventional design (upwind 3-bladed rotor, pitch regulated and variable speed) that was the basis for the LW-RWT.

With the objective to determine the most promising innovations for further detailed design investigations in WP4 the concept exploration was initiated with design of a Concept description card where all LowWind project participants were encouraged to come up with concepts/ inventions of a component or a full turbine concept described on just one page. In total 15 concepts were proposed and four of these concepts were chosen for further exploration up to the evaluation at the end of phase 1 of the project. The four selected concepts are:

- LW-3b-dw-palm-tree
- LW-4b-dw-palm-tree
- LW-3b-dw-flapping-tip
- LW-3b-uw-smart-blade

Below in section 5 under ”Obtained technological results” we will describe the analysis of these concepts in more details.

The goal of the detailed design activities in WP4 is to mature the LowWind turbine concept which is identified as having the highest commercial potential. These efforts were identified and prioritized to achieve this objective with the aid of a concept failure mode and effects analysis (CFMEA) exercise. The budgeted project resources required to develop a detailed design included tasks in aeroelastic modeling, aerodynamic design, structural design, design for installation/service, and sub-scale component testing.

The CFMEA highlighted aerodynamic noise and AEP losses as top concept risks. These risks were then investigated in WP5 via a wind tunnel test campaign which is described later in this document. The objective of this testing is to improve the models used to develop the detailed design, thereby further maturing the selected LowWind turbine concept.

4. Project implementation

The original project period was 1-8-2019 to 30-9-2021. However, it took some time to finalize the project agreement plan, which was necessary to have in place before actual project work began. We asked therefore at an early stage of the project for an extension of the end date to 31-12-2021. This was approved as well for a recent extension to 31-1-2022.

Although most of the project period has been in the COVID lock down periods the project cooperation has worked well. About 12 project meetings, almost all of the virtually, have been held together with smaller planning meetings. And to coordinate the overall project work we have held 7 steering meetings.

One of the risks mentioned in the project application was: “The LowWind concept does not show sufficient system level impact to warrant the technological development investment for Vestas” However, the early energy system simulations in WP2 showed a big advantage of boosting the production at low wind speeds which is the basic characteristic of the LW concept.

Also the risk of not meeting the target capacity factors were mentioned in the application: “Target capacity factors needed for system level impact are not achievable with current manufacturing technology”.

Upon embarking on WP4, Vestas chose to target a less extreme capacity factor in the detailed design of their selected LWT concept. This choice was motivated by an intent to re-use the largest possible extent of existing turbine platform components in their design. This consideration allows for a higher TRL, reduced technical risk, and a more commercially feasible product (reduced manufacturing and R&D investment needed).

The LWT is based on a commercial product (which is inherently TRL level 9) with the adoption of a limited number of new LW-specific components and systems. All of these new components and systems have been designed using COTS (commercial off-the-shelf components) already proven in other applications. Within the scope of this project, we were able to begin system-level tests of the new systems (to make progress toward TRL6).

5. Project results

As mentioned above the overall objective of the project was to explore the potentials of a completely new wind turbine concept – the Low-Wind turbine, designed for optimal integration in a power system with considerable amount of renewables.

We succeeded in meeting this objective as the simulations of the LowWind turbine power curved characteristics in the Northern Europe energy system did confirm a big advantage of boosting the energy production at low wind speeds which is the characteristic of the LowWind turbine concept. Further we demonstrated with a design of the LowWind reference wind turbine of 3.4MW and a specific power of 100W/m^2 that it is possible on basis of conventional design approaches and technology to build such turbines. Further we investigated several other concepts with alternative designs.

Additionally, the project achieved its goal of identifying and developing a detailed design for a commercially promising, LowWind turbine concept. Specifically, the selected concept is innovative and expected to outperform the conventional wind turbine design based on the loads, aerodynamic, structural, and costing models developed in WP4. Finally, the experimental campaign in WP5 demonstrated a benefit in de-risking and improving the aforementioned models, providing new insight into key aspects of the newly-introduced technology which is specific to the new LowWind concept.

The obtained technological results

In this section we describe in more details the obtained technological results. We will do this in a chronological order through the five work packages from WP1 to WP5.

Work Package 1: Reference turbine, cost model, site selection and reference wind farm

The overall structure in the project work, touched above, is first to design two reference turbines in WP1:

1) a conventional turbine

2) a LowWind turbine, however still based on the conventional turbine concept; 3 bladed; upwind rotor; variable speed and pitch regulated.

This enables a first investigation of the power production and load levels of the LowWind turbine in comparison with a conventional turbine. Then in WP3 we investigate other design concepts of a LowWind turbine to investigate if they are competitive compared with the conventional designed LowWind reference wind turbine.

The conventional reference turbine

We decided to use the IEA Task 37 3.4 MW onshore turbine as the conventional reference turbine (IEA-RWT) because it is open access, already known by the research community and also well described [19]. It reflects the current onshore wind turbine technology designed for wind class IIIA with rated wind speed of 9.8 m/s. The rotor diameter is 130 m which gives a specific power (SP) of 256 W/m2 based on the rated electrical power of 3.37MW. The tower height is 110m, cone angle 3 deg, tilt angle 5 deg and the cut out wind speed is 25 m/s. It can be mentioned that the IEA-RWT specifications including the SP of 256 W/m2 to some extent were based on a survey that was conducted to identify the use cases and needs for RWTs in the research and development applications with a total feedback from 81 respondents.

The IEA 3.4 MW turbine was designed against a set of critical design loads cases (DLCs) including normal operation in turbulence (DLC 1.2), operation under extreme turbulence (DLC1.3), shut down events (DLC 2.1), operation in steady wind with a gust (DLC 2.3) and standstill cases in storm conditions (DLC 6.1, 6.2, 6.3). The optimization was performed for minimizing Cost of Energy (COE) using a cost model developed at NRE.

Design of the LowWind reference turbine LW-RWT[1,2]

The LW-RWT targets a specific power of 100 w/m2 based on a rated electrical power of 3.37 MW, resulting in a blade length of 102 m (208m diameter rotor). Assuming the same transmission losses as for the IEA-RWT turbine the rated aerodynamic power was set to 3.6 MW. The maximum tip speed of 80 m/s was kept the same as for IEA-RWT. In the initial design phase of the LW-RWT, cost models were not included, and we therefore seeked to maximize annual energy production, subject to various loads, mass and geometric constraints. An

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[1] Helge Aagaard Madsen; Filippo Trevisi; Athanasios Barlas; Fanzhong Meng; Frederik Zahle; Flemming Rasmussen; Riccardo Riva; Witold Robert Skrzypinski. " Optimization, design and analysis of the 3.4MW LowWind reference turbine in comparison with the 3.4MW IEA onshore reference turbine". DTU Wind Energy I-1048. July 2020.

[2] Madsen, H. A., Zahle, F., Meng, F., Barlas, T., Rasmussen, F., & Rudolf, R. T. (2020). Initial performance and load analysis of the LowWind turbine in comparison with a conventional turbine. Journal of Physics: Conference Series, 1618(3), 032011. https://doi.org/10.1088/1742-6596/1618/3/032011

initial blade model consisting of detailed internal structural layout and blade planform was made based on a combination of the IEA 10 MW RWT and the IEA 15 MW RWT.

Design variables and constraints

To obtain a blade design with as low mass as possible and large flexibility we opted for a single shear web design. The carbon based spar cap was set to a constant width of 0.6 m from root to tip, and the triax skin layout used on the IEA 15 MW RWT was mimicked. The root triax reinforcement thickness was set to 100 mm, however a detailed root design was not carried out. The FFA-W3 airfoil family was used on the blade, using the airfoil data computed for the IEA 10MW RWT by the CFD solver EllipSys2D assuming a mix of 70% free transition and 30% turbulent flow. Tower and drivetrain were based directly on the IEA 3.4 MW RWT.

The optimization problem consisted of a total of 31 aerostructural design variables, as well as rotor RPM and collective blade pitch at each of the operating wind speeds in the range [2:13].

The aerodynamic design variables are related to the blade geometry, characterised by chord, relative thickness, geometric twist angle and chord-wise offset of the cross-sections along the blade relative to the twist axis. The variation of these quantities with respect to the baseline are expressed as Bezier curves with control points at (0, 10, 20, 50, 80, 95, 100)% of the radial position. The control points of chord and relative thickness at (20, 50, 80, 95) % are design variables. The control points of blade twist and chord-wise offset at (20, 50, 80, 95, 100) % are design variables.

The structural design variables are related to the carbon spar cap thickness, and the trailing edge and leading edge uniax glass fiber thickness. The variation of these quantities with respect to the baseline are expressed as Bezier curves with control points at (0, 25, 65, 85, 100)% of the radial position. The control points at (25, 65, 85)% are design variables. The out of plane blade coordinate y (prebend) is modelled by control points at (0, 15, 25, 50, 90, 100) %, of which the one at (25, 50, 100)% are design variables.

Additionally, a design variable is related to the structural angle, which controls the main load carrying direction of the spar cap relative to the rotor plane, as well as the angle of the shear web relative to the rotor plane.

The operational design variables are the pitch angle and rotational speed at each wind speed (36 design variables), but in some of the design studies the rotational speed is controlled using the tip speed ratio value below rated (1 design variable).

The bounds and constraints are related to design variables and to design outputs. The chord cannot exceed 4.31 m. The chord and the relative thickness have higher and lower bounds. The out of plane blade coordinate y (prebend) has an upper bound (in the downwind direction); in the upwind direction the magnitude of the prebend is given by the value of the last control point of y. Other constraints are related to the slopes of the design variables with respect to the blade span and to the operational wind speed. These constraints are to avoid unrealistic designs.

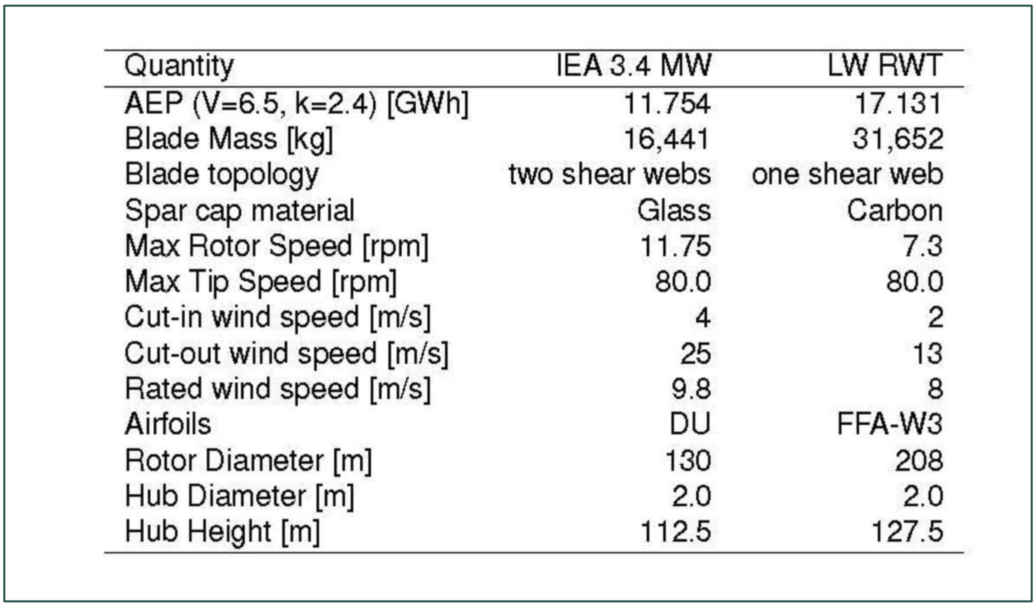
Constraints on the maximum power, maximum torque and maximum total thrust define the overall performance of the turbine. The root flap-wise bending moment and the tip deflection during operation and during the two off-design load cases are constrained to not exceed user defined values. The blade mass and the blade mass moment have an upper bound. A structural failure criteria based on maximum strain is evaluated over the blade and constrained to be below 1.The objective function used at this stage is the annual energy production. It is evaluated with 18 wind speeds between 2 and 13 m/s for steady state normal operation without turbulence and shear. The first off-design case specified has rated rotational speed and 0 degrees blade pitch, but evaluated at 12.8 m/s which is 4.8 m/s above the normal wind speed of 8 m/s for this operational point. The 4.8 m/s corresponds to 3 standard deviations as detailed in the normal turbulence model in the IEC-61400 standards. The second off-design case has a inflow wind speed of 42 m/s, but without rotational speed and with zero pitch.

The designed LowWind reference rotor

In Table 1 we compare the main design data and operational characteristics for the conventional reference turbine IEA-RWT (IEA 3.4 MW in the table) and the LowWind reference wind turbine (LW-RWT). As expected, the LW- RWT has a much higher AEP of 17.131 GWh than the IEA-RWT of 11.764 GWh although the rated power of the two turbines is the same and although the stop wind speed of 13m/s for the LW-RWT is much lower than the 25m/s for the IEA-RWT. This is due to the much bigger rotor of the LW-RWT, which also has the impact that the blade weight is almost the double compared with the IEA-RWT.

In Figure 3 the steady state performance of the two turbines is compared. The upper graph to the left shows the power curves of the two turbines and it is clearly seen that the LW-RWT produces much more at low wind speeds. At the bottom graph to the left the flapwise blade root moments (FBRM) are compared. In the optimization set-up the FBRM for the LW-RWT was limited to 30% above the FBRM for the IEA-RWT and only due to peak shaving by applying a positive pitch in that region the maximum FBRM can be limited to this value over a wind interval region of about 2m/s. The constraint on the FBRM has also an important effect of the maximum thrust which is seen to be lower than on the IEA-RWT.

The blades of the IEA-RWT and the LW-RWT are presented in Figure 4 together with a comparison of their planform and thickness distribution.



Quantity	IEA 3.4 MW	LW RWT
AEP (V=6.5, k=2.4) [GWh]	11.754	17.131
Blade Mass [kg]	16,441	31,652
Blade topology	two shear webs	one shear web
Spar cap material	Glass	Carbon
Max Rotor Speed [rpm]	11.75	7.3
Max Tip Speed [rpm]	80.0	80.0
Cut-in wind speed [m/s]	4	2
Cut-out wind speed [m/s]	25	13
Rated wind speed [m/s]	9.8	8
Airfoils	DU	FFA-W3
Rotor Diameter [m]	130	208
Hub Diameter [m]	2.0	2.0
Hub Height [m]	112.5	127.5

Table 1 A comparison of the main design data and operational characteristics for the conventional reference turbine IEA-3 3.4 MW (IEA-RWT) and the LowWind reference wind turbine (LW-RWT)

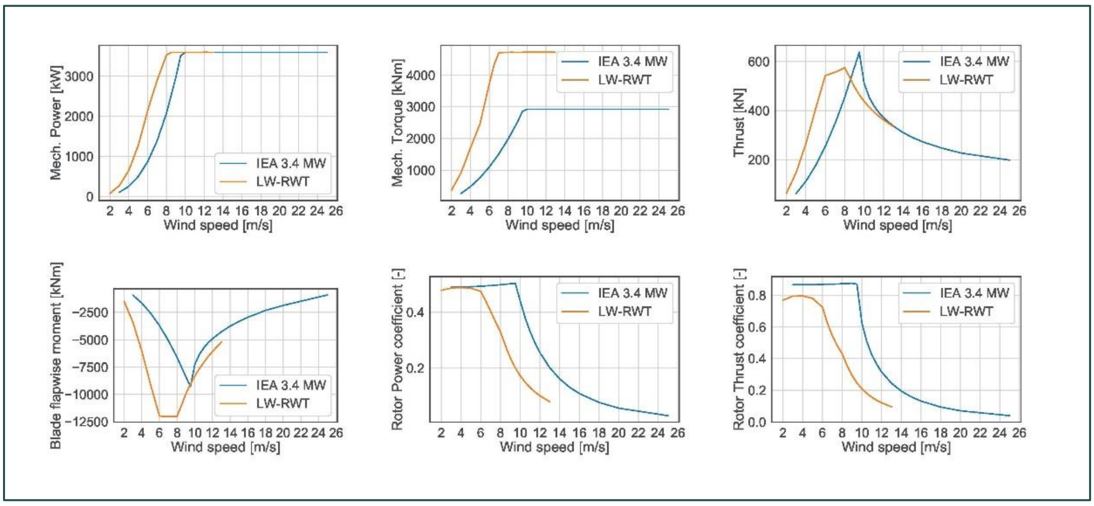


Figure 3 Steady state rotor performance of the LW -RWT compared to the IEA-RWT across their respective ranges of normal operation.

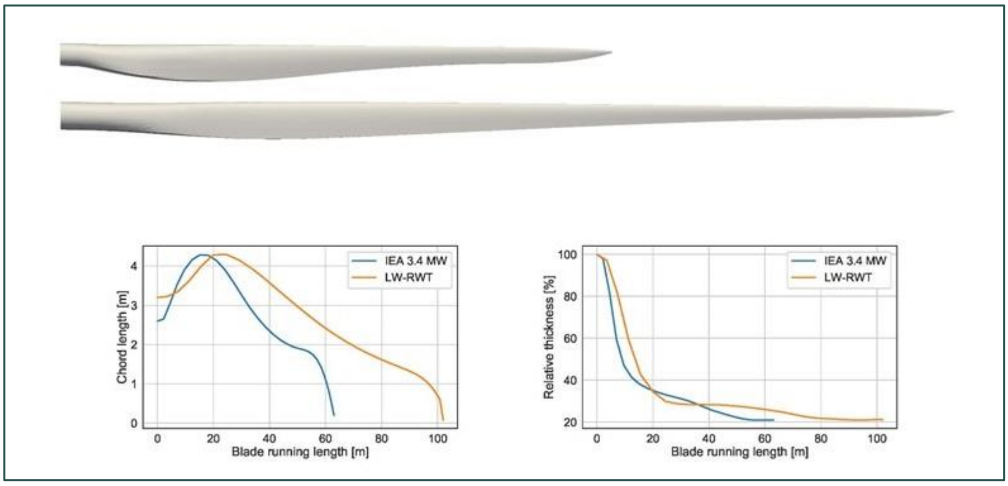


Figure 4 In the upper part of the figure the IEA-RWT (top) and LW-RWT (below) blades are shown. The lower part figures show a comparison of the planform and thickness distribution of the two blades.

The fatigue load comparison in the left graph of Figure 5 shows an increase for most of the components. Looking at the ratios for the most important components it can be seen that the load increase in the tower bottom is only in the range of 10-20% while the flapwise blade root moments increase with 60-70%.

The increase in extreme loads shown in the graph to the right in Figure 5 shows generally a bigger increase than the fatt. loads. The tower bottom bending in the wind direction increases about 50% while crosswise up to 350%. However, this is due to instabilities and a better-tuned controller could limit such instability.

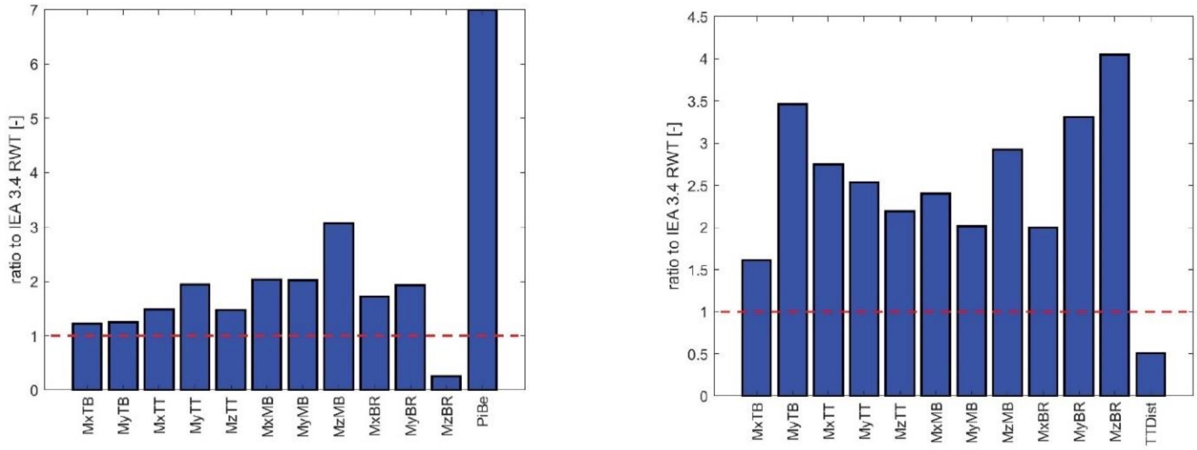


Figure 5 The columns in the fire to the left shows the fatigue loads for the different components of the LW-RWT relative to the IEA-RWT and to the right it is the ratio of the extreme loads.

Conclusions from WP1

The LowWind turbine concept is proposed with the objective to make a major contribution to the electrical system integration on the wind power production side. This is achieved by the LowWind turbine which is producing much more energy at low wind speeds compared with a traditional turbine, enabled by a low specific power (SP) of 100 W/m^2.

Two reference turbines of the same rated power have been presented and analyzed in the present report. One of the turbines represents state-of-the-art conventional onshore turbine technology and we have chosen the IEA 3.4 MW onshore reference turbine with an SP of of 256 W/m^2.

We designed the 208 m diameter LowWind reference wind turbine (LW-RWT) rotor with the Multidisciplinary Horizontal Axis Wind Turbine Optimization Tool HAWTOpt2 and enabled to design a 102 m long blade with a mass of just 31 tons. The AEP for rotor is 46% higher than for the conventional rotor while the maximum thrust is 10% less and the maximum flapwise blade root moment only 20% higher for operation in steady wind.

A slightly reduced DLC analysis was carried out for both turbines to provide the basis for a load comparison. While the increase in fatigue loads typical was between 20-50% for the LW-RWT the increase in extreme loads was higher and in the range of 50-100% increase and even higher for some load components. These results are still preliminary for the LW-RWT and might be negatively affected by e.g. non-optimal aeroelastic tuning of frequencies.

A further exploration of new design concepts for the LowWind turbine was carried out in WP3 and is reported below.

Work Package 2: Power and Energy System Modelling

WP 2 focuses on modeling the impact of the LowWind technology on European power and energy systems. In addition to analyzing the impacts on the system, the work package has investigated the revenues of LowWind technology in different regions around Europe in scenarios towards 2050. A significant part of the findings was reported in a journal paper[3]; the following gives an overview of the key findings and presents some additional results achieved after the writing of the paper.

European LowWind time series simulation

To facilitate the study of the LowWind technology on system level, the first step was to find power plant-level power curve for the LowWind turbine. This was done because system-level time series simulation software usually model plant-level, but not turbine level. This is also the case in the Correlations in Renewable Energy Sources (CorRES) software used in this project[4] As an important objective of WP2 is to make a fair comparison between the LowWind technology and traditional turbines, it was chosen that the land area-use per MW installed should be the same for LowWind and traditional turbine. This leads to LowWind turbines being much closer to each other in terms of distance in rotor diameters[4]; however, it ensures that the LowWind and traditional turbines have the same land cost per MW installed and are thus comparable in investment optimization. The resulting plant-level power curve for LowWind and several traditional turbines can be seen in Figure 6.

Using CorRES[4] with the plant-level power curves, time series simulations were carried out to model the generation patterns of the different technologies around Europe. CorRES simulates plant-level output. However, the time series were aggregated to regional level to give input to the energy system optimization described in the next subsection. The analyzed regions are shown in Figure 7. Each region was also split to three resource grades to model the variability in wind resources within the region[3]. One result from the simulation is that the impact of varying the cut-off wind speed of the LowWind design has different impacts in different regions around Europe Figure 8: high wind speed regions show a significant decrease in capacity factor (CF) when a lower (13 m/s) cut-off is used, whereas the in low wind speed regions the CF is only slightly reduced when comparing to a more standard cut-off value (25 m/s).

Looking at the resulting European scenarios (the scenarios are from[3] they are presented in the next subsection). It can be seen that LowWind has the potential to decrease variability of aggregate wind generation: Figure 9 shows that when LowWind is included, the CF (mean of the standardized generation) of the aggregate wind generation is higher and standard deviation (SD) is lower. This means that we can generate more energy (with the same installed capacity) with lower variability. The reduced aggregate variability is a result of LowWind generating more at low wind speeds, but also less on high wind speeds (when traditional turbines are generating a lot); examples of both cases can be seen in the time series plot in Figure 9. Note: the “with LW” scenario described in this paragraph is the “BASE +39%” scenario and the “no LW” the “BASE +50%” scenario from[3].

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[3] P. Swisher, J. P. Murcia Leon, Juan Gea-Bermúdez, M. Koivisto, H. Madsen, M. Münster, “Competitive-ness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050”, Applied Energy, vol. 306, part B, 118043, January 2022 (https://doi.org/10.1016/j.apenergy.2021.118043).

[4] J. P. Murcia, M. J. Koivisto, G. Luzia, B. T. Olsen, A. N. Hahmann, P. E. Sørensen, M. Als, “Validation of European-scale simulated wind speed and wind generation time series”, Applied Energy, vol. 305, 117794, January 2022 (https://doi.org/10.1016/j.apenergy.2021.117794).

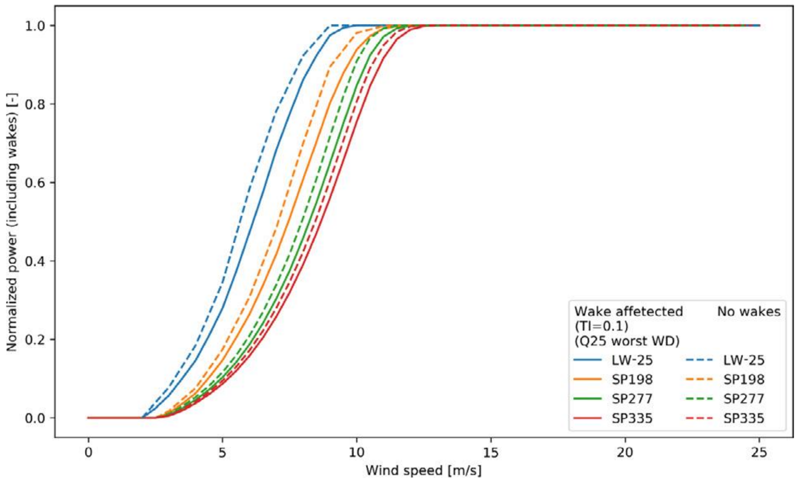


Figure 6. Plant-level power curvers for the LowWind (LW) technolgy and a selection of more tradiotonal turbines. Note that the shutdown procedure is not shown in this picture. The picture is from[3].

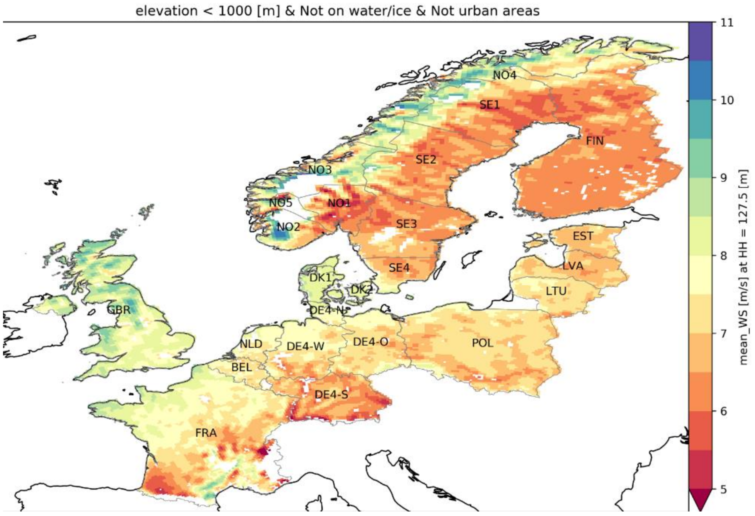


Figure 7. Regions simulated in CorRES. The picture is from[3].

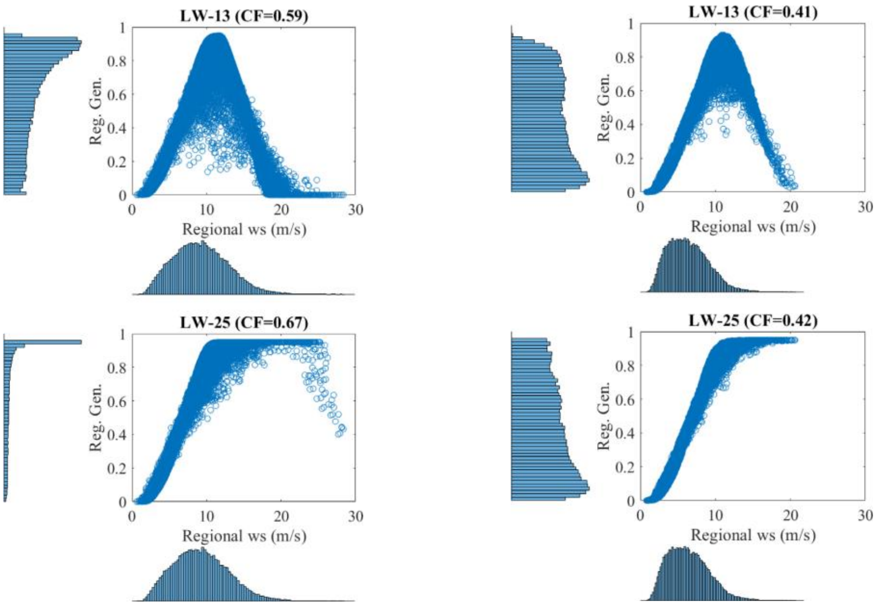


Figure 8. Wind speed vs. generation plots for two LowWind types: with cut-out at 13 m/s (top) and 25 m/s (bottom) for two regions: high wind Danish region (left) and low wind south German region (right). The picture is from[3].

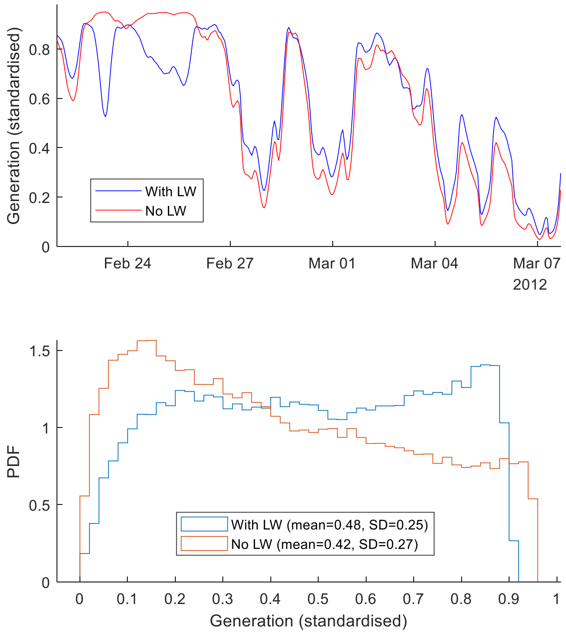


Figure 9. Time series plot of aggregate wind generation in Poland (top; zoom of a few days) and histogram of the generation (bottom; based on 10+ years of hourly simulations) for two 2045 scenarios: one with LowWind (LW) technology in the generation mix and one with only traditional turbines.

Energy system analyses

The performance of wind turbines have typically been assessed by the levelized cost of electricity (LCOE). With higher shares of wind power in the power market, the electricity price that a standard turbine can achieve at a given hour will decrease, as seen in Figure 10.

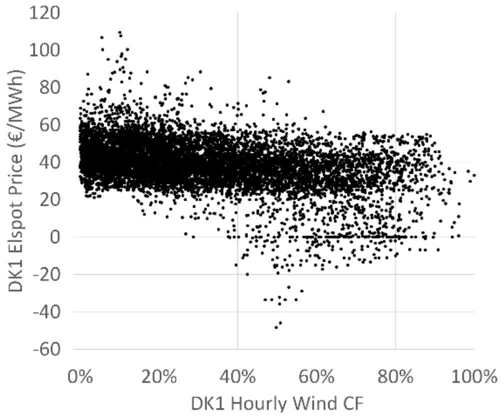


Figure 10. Impacts of high wind penetration on spot price in DK1 (2019)

In order to assess the revenue, which a LowWind turbine can make in different energy systems, the Balmorel model was applied. The Balmorel model is a partial equilibrium model, which covers electricity and district heating markets in North-West Europe. The model allows for least-cost optimization of investment and operation of conversion technologies as well as transmission and energy storages. The analysis, method, assumptions and results are documented in[3].

The results show high competitiveness of the LowWind turbine when price increases were less than 45% higher than comparable standard turbines (See Figure 11).

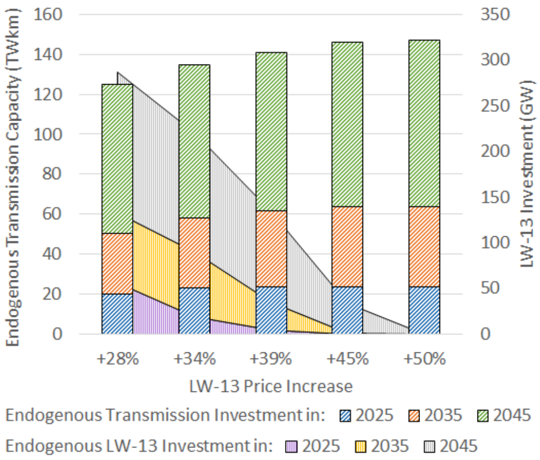


Figure 11 Investments in LW-13 and power transmission depending on LW-13 price increase

Results also show the correlation between transmission and LowWind turbines. With higher shares of LowWind turbines, less transmission capacity is required (See Figure 11). The impact can also be seen on the electricity prices in Figure 12.

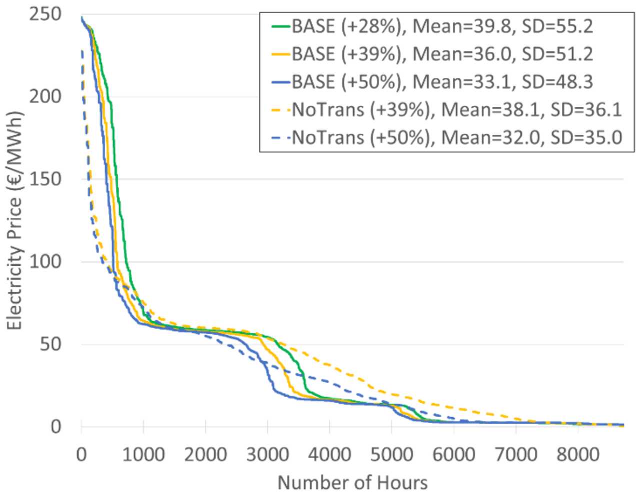
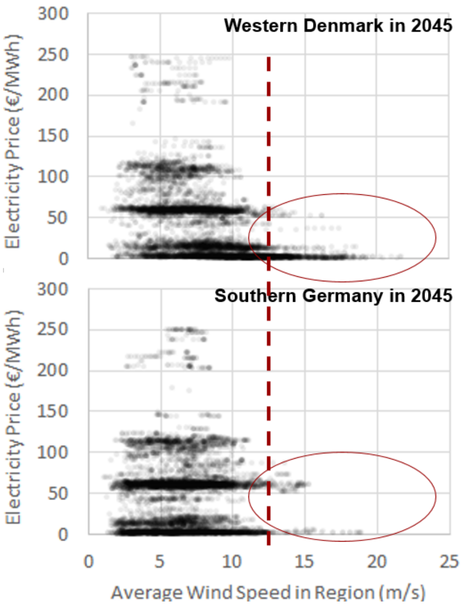
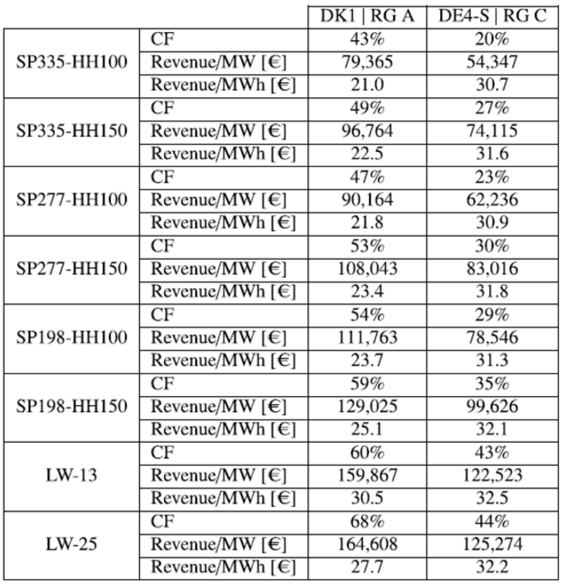


Figure 12 Electricity prices for different scenarios (2045)

In a situation with high share of LowWind (green curve and dotted yellow curve in Figure 12 there are more hours with higher prices. Wind production becomes more spread out across wind speeds and there are less hours of low net load.

When assessing the revenues of different turbine types as illustrated in Figure 13, it can be seen that even with similar capacity factors, the standard turbines cannot achieve the same revenue as the LowWind turbines. Furthermore, the LowWind turbine with cut off at 25 m/s is not found to be competitive with the LowWind turbine with cut off at 13 m/s even in high wind speed areas, due to low prices during the hours with high wind speeds.





		DK1 | RG A	DE4-S | RG C
SP335-HH100	CF	43%	20%
	Revenue/MW [€]	79,365	54,347
	Revenue/MWh [€]	21.0	30.7
SP335-HH150	CF	49%	27%
	Revenue/MW [€]	96,764	74,115
	Revenue/MWh [€]	22.5	31.6
SP277-HH100	CF	47%	23%
	Revenue/MW [€]	90,164	62,236
	Revenue/MWh [€]	21.8	30.9
SP277-HH150	CF	53%	30%
	Revenue/MW [€]	108,043	83,016
	Revenue/MWh [€]	23.4	31.8
SP198-HH100	CF	54%	29%
	Revenue/MW [€]	111,763	78,546
	Revenue/MWh [€]	23.7	31.3
SP198-HH150	CF	59%	35%
	Revenue/MW [€]	129,025	99,626
	Revenue/MWh [€]	25.1	32.1
LW-13	CF	60%	43%
	Revenue/MW [€]	159,867	122,523
	Revenue/MWh [€]	30.5	32.5
LW-25	CF	68%	44%
	Revenue/MW [€]	164,608	125,274
	Revenue/MWh [€]	27.7	32.2

Figure 13 Electricity prices in 2045, capacity factors and revenues for different turbines

In conclusion, the LowWind turbine with cut off at 13 m/s and below 45% higher prices is expected to be competitive both in areas with low wind speeds as well as in areas with high wind speeds and high shares of wind power. Finally, the LowWind turbine has a competitive advantage in areas with limited flexibility e.g. in terms of transmission capacities, where the joint timing of production and consumption has a high value. These results illustrate the value of assessing the performance of turbines in terms of their potential revenue generated in different energy systems or markets rather than in terms of a simple LCOE.

Work Package 3 Conceptual design development[5]

With the objective to determine the most promising innovations for further detailed design investigations in WP4 the concept exploration was initiated with design of a "Concept description card" where all LowWind project participants were encouraged to come up with concepts/inventions on a component or a full turbine concept described on just one page. In total 15 concepts were proposed and at a project, four of these concepts were chosen for further exploration up to the evaluation of the concepts after phase 1 of the project.

The four selected concepts are:

- LW-3b-dw-palm-tree
- LW-4b-dw-palm-t:ree
- LW-3b-dw-flapping-tip
- LW-3b-uw-smart-blade

LW-3b-dw-palm-tree

The downwind so-called palm tree rotor, LW-3b-dw-palm-tree, has been investigated thoroughly, Figure 14. The overall idea behind the concept is that with the downwind rotor the blades bend away from the tower up to rated wind speed and therefor potentially can be designed with lower stiffness and thus a lighter blade.

Several design iterations were carried out which led to version seven LWd7 which was configured to have a 15 degree downwind coning and with an upwind prebend on the outboard part, Figure 15. The design is primarily driven by flapwise moment, thrust and strain constraints, but notably not a flapwise deflection constraint. This results in a significantly more flexible design than the blade for the upwind LW reference turbine LW-RWT.

However, the blade was therefore also likewise a dynamically more challenging design and the first iteration of the LWd7 blade resulted in instability problems due to a collective edgewise vibration mode. As a consequence, the rev2 design featured a constraint on aeroelastic damping ratios of the first 20 modes as computed by HAWCStab2 to be positively damped.

When comparing the overall properties of the LWd7rev2 rotor with the LW upwind reference wind turbine LWu-RWT some important figures can be mentioned: 1) the AEP is 0.3% lower due to the reduced projected area. The rotor power coefficient is higher than that of the upwind design but this cannot compensate for the large reduction in rotor area due to the 15 degree coning. 2) The blades for the LWd7rev2 design are 2% longer but 5% lower weight. The design is constrained by the maximum thrust, and the flapwise moment of the off-design case (ex0), while the normal operation flapwise moment is 9% lower than for the upwind de-sign, which is due to the contribution of the centrifugal de-loading from the downwind coning.

However, the full load simulations did not show this reduction in flapwise moment, except during normal operation. The mean flapwise blade root moment is lower but the 1P variation of the moments from gravity for the coned/bended blade means that the max/min loads are on the same level as the flapwise loads on the upwind reference rotor LWu-RWT.

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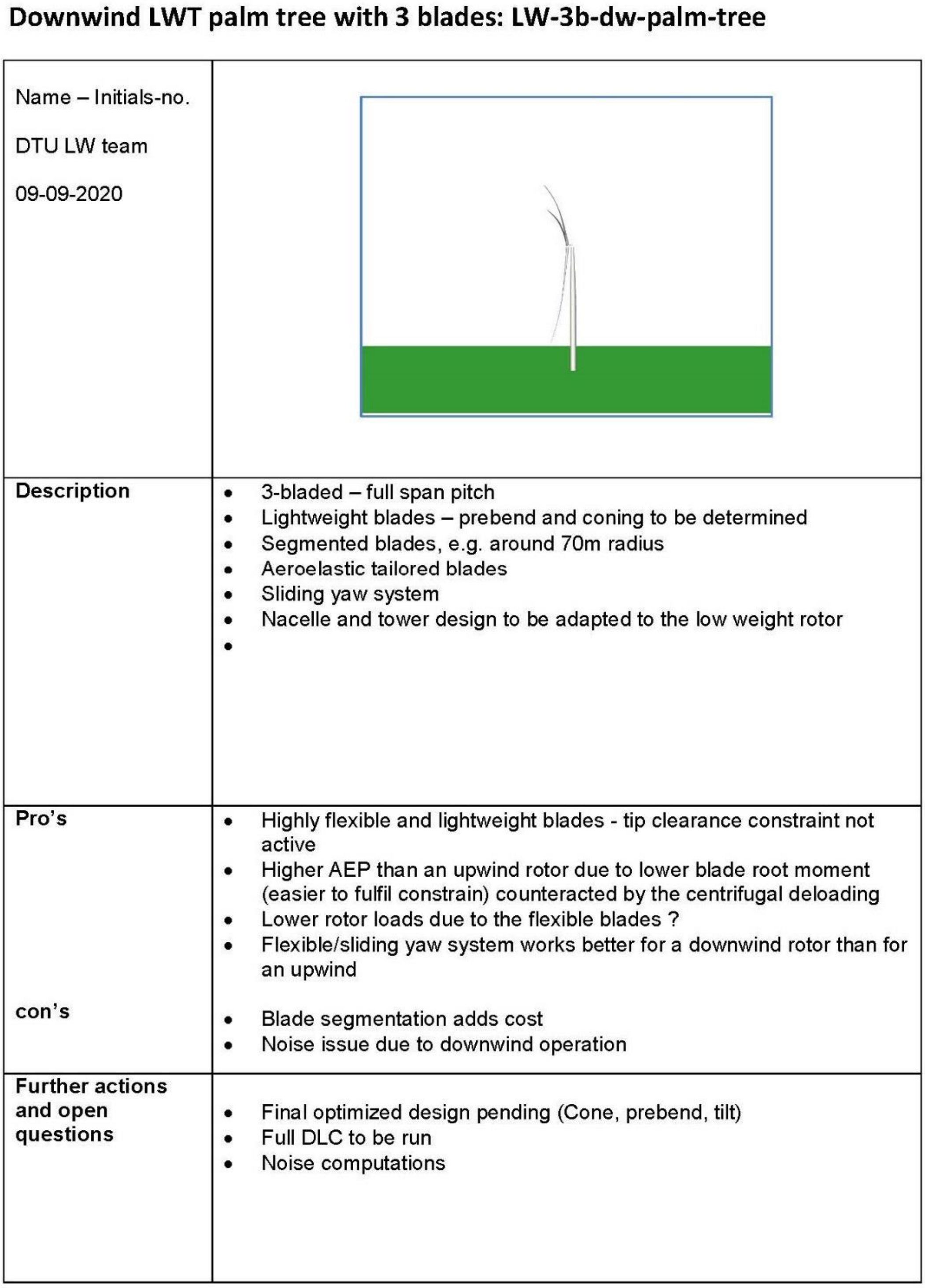
[5] From DTU: Helge Aagaard Madsen; Frederik Zahle; Athanasios Barlas; Flemming Rasmussen; Filippo Tre-visi; Fanzhong Meng; Riccardo Riva; Franck Bertagnolio. From Vestas: Thomas S. Bjertrup Nielsen; Torben Juul Larsen; Robert Thomas Rudolf. "Concept and innovation studies of a 208m diameter 3.4MW LowWind turbine". "DTU Wind Energy I-1274(EN)" July 2021.

Overall it appears challenging to obtain a downwind design with the same energy production compared to the upwind design, which is primarily due to the high cone angle. Therefore it should be investigated whether a reduced cone angle is feasible, combined with an investigation into how to avoid tower strike for such a design.



Downwind LWT palm tree with 3 blades: LW-3b-dw-palm-tree

Name – Initials-no. DTU LW team 09-09-2020	
Description	• 3-bladed – full span pitch • Lightweight blades – prebend and coning to be determined • Segmented blades, e.g. around 70m radius • Aeroelastic tailored blades • Sliding yaw system • Nacelle and tower design to be adapted to the low weight rotor •
Pro's **con's**	• Highly flexible and lightweight blades - tip clearance constraint not active • Higher AEP than an upwind rotor due to lower blade root moment (easier to fulfil constrain) counteracted by the centrifugal deloading • Lower rotor loads due to the flexible blades ? • Flexible/sliding yaw system works better for a downwind rotor than for an upwind • Blade segmentation adds cost • Noise issue due to downwind operation
Further actions and open questions	• Final optimized design pending (Cone, prebend, tilt) • Full DLC to be run • Noise computations

Figure 14 The concept card description of the three blade downwind palm tree concept

In the current design optimization setup, we do not give upwind deflection particular attention, since we do not evaluate cases where this occurs.

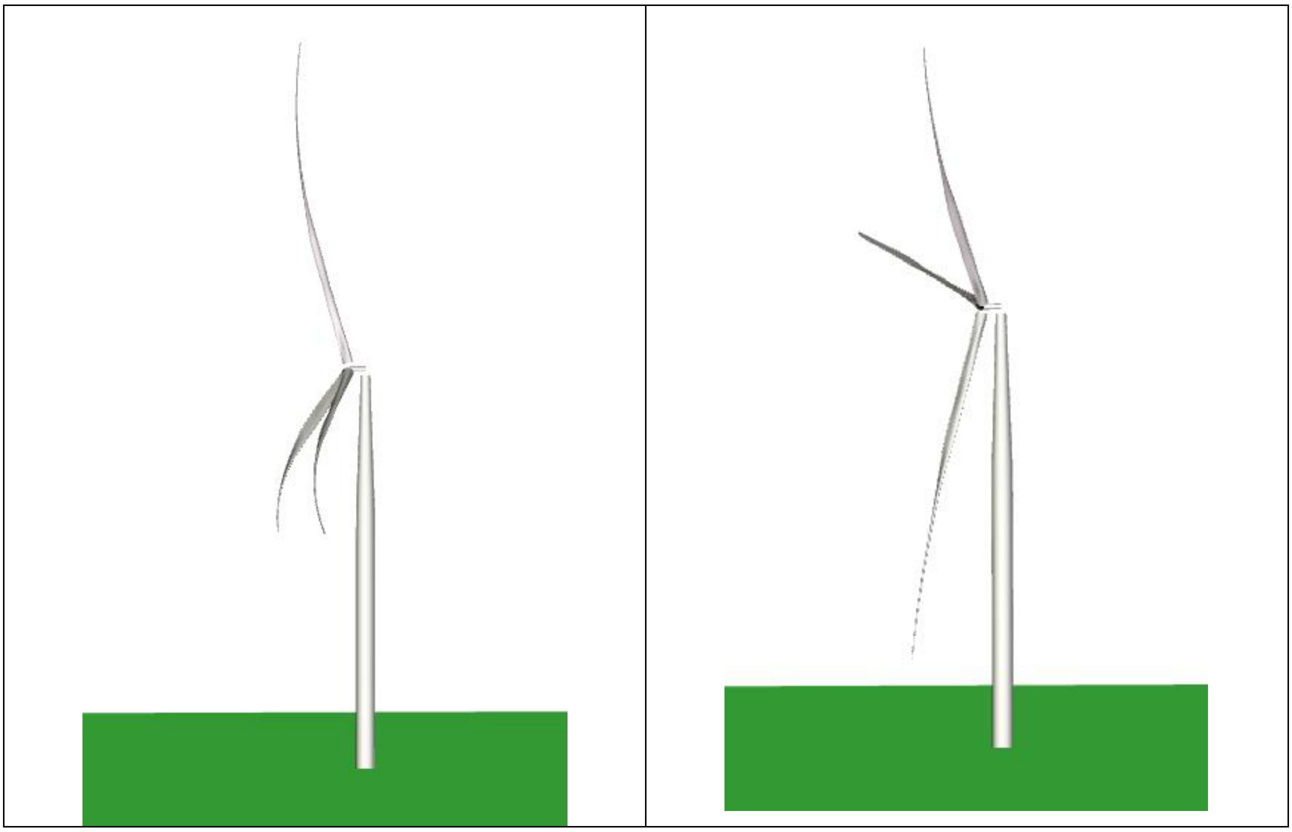


Figure 15 The downwind LWd7rev2 turbine was designed with 15 deg. downwind coning and with the outer part of the blades bend upwind. Its the turbine to the left at standstill. To the right the turbine is operating at 5m/s and the blades are now almost straight.

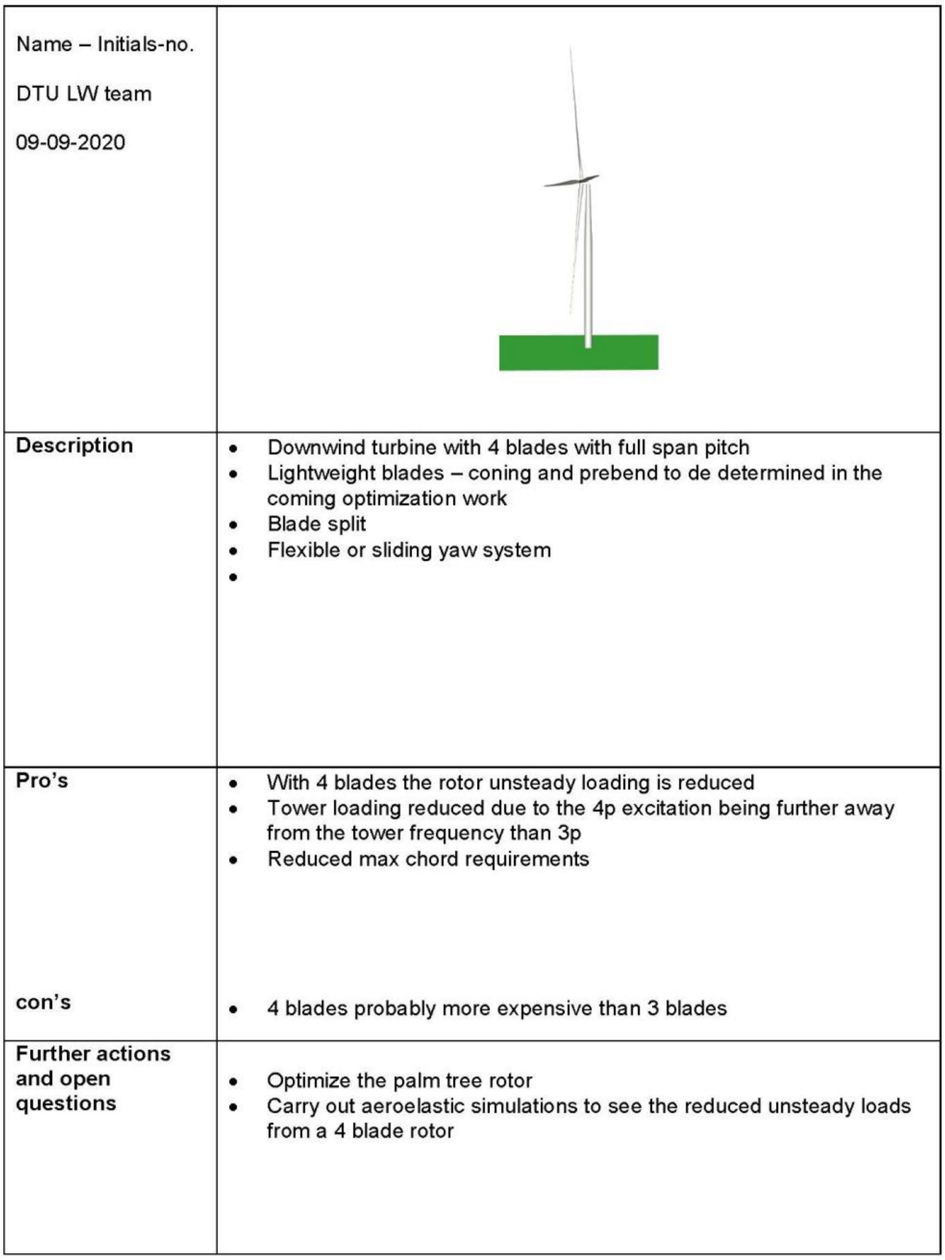
LW-4b-dw-palm-tree

The idea behind the four bladed, downwind palm tree rotor, Figure 16, is to reduce the rotor shaft loads (tilt and yaw loads) and tower loads as four blades will better out balance non-uniform loading over the rotor disc due to turbulence than a three bladed rotor and even more compared with a two-bladed rotor. As a downwind turbine design was not available at the first load analysis of the 4-bladed rotor, the LowWind reference turbine LWu-RWT was used as the baseline to compare with. The 4-bladed version of that rotor was simply designed by adding one additional blade and scaling the chord with 3/4 (0.75). In that way the 4-bladed rotor will aero-dynamically in steady, uniform wind behave almost as the 3-bladed rotor.

The comparison of power and thrust for the 3- and 4-bladed rotor confirmed that they aerodynamically behave similar. The comparison of the PSD of the dynamic thrust in turbulent wind and constant speed shows that the peaks are at 3p for the 3B rotor and at 4P for the 4B rotor. The peak is also lower for the 4B-rotor and comparing the fatt. counting of the thrust for the two rotors it is found to be 18.5% lower for the 4B rotor.

As the thrust is transferred as bending into the tower the same level of tower fatt can be expected in the tower bottom bending moments. On top of that for a similar tower for the 3B and 4B rotor the effect of the load input from the 4B rotor being on 4p and thus at a further distance from the tower frequency will lower the fatt loads even more for the 4B rotor in comparison with a 3B rotor.

Later in the concept studies a 4B downwind design as well as further load simulations on the 4B upwind version were carried out and compared with the load level of the three bladed reference turbine LWu-RWT. According to simple scaling rules the 4B blades were simply designed by assuming same mass of one blade for the 4-bladed turbine as for the 3-bladed turbine and the bending stiffness (EIx,EIy and GJ) simply scaled by a factor of 9/16.



Name – Initials-no. DTU LW team 09-09-2020	
Description	• Downwind turbine with 4 blades with full span pitch • Lightweight blades – coning and prebend to de determined in the coming optimization work • Blade split • Flexible or sliding yaw system •
Pro's	• With 4 blades the rotor unsteady loading is reduced • Tower loading reduced due to the 4p excitation being further away from the tower frequency than 3p • Reduced max chord requirements
con's	• 4 blades probably more expensive than 3 blades
Further actions and open questions	• Optimize the palm tree rotor • Carry out aeroelastic simulations to see the reduced unsteady loads from a 4 blade rotor

Figure 16 The concept card description of the four bladed downwind palm tree concept

The results from the aeroelastic simulations did not show an overall clear picture of the load level of neither the upwind, nor the downwind version of the 4-bladed rotors. This is partly due to the increased rotor weight by the mass of one blade which changes the system dynamics as well as influences the control. However, there are reduced extreme loads from operation on the tower and in particular tower top. Also decrease in main bearing loads are seen for the upwind4-bladed version. When it comes to fatt. loads a reduction is seen for the tower and in particular for the tower top fatt. loads. However, an increase is seen for the main bearing fatt. loads where we would expect a reduction

In conclusion, more simulations on a 4-bladed concept with optimized aeroelastic properties are needed to see the full load reduction potential on the 4-bladed concept.

LW-3b-dw-flapping-tip

The main idea with the 3-bladed downwind rotor with a flapping tip, LW-3b-dw-flapping-tip, is to combine the necessary blade split with a flexible joint so the flapwise, edgewise and torsional stiffness can be designed for optimal aeroelastic response.The main principle and physics were studied both analytically and numerically with HAWC2simulations. The equation for a moment free flapwise joint at a specific radial position were formulated. Using the blade mass data for the LWu-RWT and a split joint at 75% radius it was found that the coning angle is 77°for a moment free joint. Such a high local cone angle decreases the projected area considerably and thus the power production.

To decrease to reasonable values, there are three strategies::

- increase the centrifugal bending moment
- decrease the aerodynamic bending moment
- increase the moment in the joint, passive or active

The second option makes the power to drop so we investigated the first one. The centrifugal bending moment is increased by adding mass at the tip of the blade. Using a concentrated mass of one tonne placed at the blade tip the cone angle is reduced to 40°. This is still a high cone angle causing a considerable decrease in swept area and likewise reduced power. This example illustrates that flapwise stiffness has to be introduced in the joint to reduce the cone angle to a reasonable low value. This is future work.

LW-3b-uw-smart-blade

First the optimization setup has been modified to include steady flaps in the rotor design. Flaps are modelled as a modification of the airfoil polars. Therefore, the optimizer can utilize flaps in the design process to move the loads along the blade for each wind speed. Flaps are only used together with the 21% airfoil. It turned out that only a small AEP increase of 0.2% could be achieved.

Then the load alleviation potential of using flaps was investigated. In this case, the extreme load alleviation capability is explored, as the main focus is on improvement of the upwind optimized Wu-RWT rotor. One 10% chord trailing edge flap per blade is incorporated in the LWu-RWTrotor, covering the blade span from 65%-95% radius. The aerodynamic effectiveness of the flap used here is in the order of delta CL +/-0.5 for +/-15deg deflection. The ATEF flap dynamic stall model is utilized to model the unsteady aerodynamics of the flaps. The activation dynamics of the flap system are approximated by a first order model with a time constant of 0.1s. The integrated flap controller DLL is utilized, which is now part of the DTU wind energy controller (DTUWEC).

The ultimate load control feature is utilized in this study, which monitors the blade root flapwise moment signals and sets the flap angles to their min/max limits of +/-15degwhen the load exceeds a predefined threshold. The blade root flapwise moment threshold is chosen close to the maximum load level of normal operation (DLC 1.2), in order to react only to off-operation loads.

Load alleviation levels of interest are the 8% reduction in the minimum blade root flapwise moment (min MxBR), and the 10% reduction in the maximum blade root flapwise moment(max MxBR). Fatigue loads are not affected by this type of flap activation and optimal control or fatigue load reduction was not investigated.

Conclusion on WP3

The work has focused on exploring LowWind turbine concepts that might be even more competitive than the LowWind reference wind turbine LWu-RWT, that was designed and developed in WP1 of the project. The LWu-RWT has a conventional design with an upwind, three bladed rotor, pitch regulated and variable speed.

Fifteen concepts were proposed and four were studied in more details. In particular the so-called downwind palm tree rotor was developed in different versions. However, it has turned out that although a LowWind turbine has very long and flexible blades and thus potentially optimal in combination with a downwind rotor for better tower clearance than an upwind rotor, it has some drawbacks. The swept area decreases up to rated power due to downwind bending of the blades. Further, the 1p variation from gravity from the out of plane bending of the blades contributes to max flapwise blade loads that are close to the LWu-RWT load level.

Aeroelastic stability is found to potentially be problematic if not handled carefully in the design process. A major result is that the optimization tool HAWTOpt2 was further developed so that constraints on aeroelastic damping can be handled. Several other model developments and improvements have been carried during the work. Inparticular a noise simulation frame work for simulation of Infra-Sound (IS) and Low-Frequency Noise (LFN) has been developed. Also a new tower wake model for simulation of vortex shedding has been developed.

Summary of work in WP4 and WP5[6]

The detailed design of the selected concept involved a coordinated, multidisciplinary effort among experts within Vestas. Their first tasks were to adapt their tools to model the loads, aerodynamic performance, structure, installation/service activities and cost of the new turbine concept. Then they proceeded to iterate and optimize to arrive at a feasible and more optimal design. Finally, they planned and executed sub-scale component tests to validate these models.

One key activity in this validation effort is the wind tunnel test campaign which was conducted in collaboration with DTU in WP5. The testing involved both noise and force measurements, and it lead to the identification of geometry with the best performance in both categories.

Obtained commercial results

The concept is still under development and as such not commercialized. A potential commercialization would not happen before the next 4-5 years, as technology first needs to be matured, tested and implemented in product roadmaps.

Target group and added value for users

The target group for the technology is Vestas' customers globally, more specifically those with low-wind sites where a high capacity factor turbine has larger value. This is because of a significantly increased wind energy production during low wind, which itself has a value, but also because the electricity prices tend to be higher in these low-wind hours.

Dissemination

The first presentation of results from the project was at:

The Science of Making Torque From Wind 28 September - 2 October 2020, Delft, The Netherlands.

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[6] D4 & D5 Report: Experimental Study and detailed design of the LowWind concept EUDP LowWind Project, deliverable "D4 & D5" reporting on work package "WP4 & WP5" . Author: Vestas Wind Systems A/S

Frederik Zahle, Helge Aagaard Madsen, Filippo Trevesi, Fanzhong Meng, Thanasis Barlas, Flemming Rasmussen, Robert Thomas Rudolf. “Initial performance and load analysis of the Low Wind”.

The second presentation was at:

Wind Energy Science Conference 2021, 25-28 May, Hannover 2021.

Helge Aagaard Madsen, Philip Robert Swisher, Frederik Zahle, Flemming Rasmussen, Athanasios Barlas and Matti J. Koivisto. “The LowWind turbine concept for optimal system integration Impact on turbine design and the energy system”

The third presentation was at:

EERA - Low Specific Power and Low Wind Workshop September 22-23, 2021.

Helge Aagaard Madsen, Frederik Zahle, Athanasios Barlas, Flemming Rasmussen, Fanzhong Meng, Riccardo Riva, Franck Bertagnolio, Kenneth Lønbæk. “The LowWind project - an update”

Journal papers

Madsen, H. A., Zahle, F., Meng, F., Barlas, T., Rasmussen, F., & Rudolf, R. T. (2020). Initial performance and load analysis of the LowWind turbine in comparison with a conventional turbine. Journal of Physics: Conference Series, 1618(3), 032011. https://doi.org/10.1088/1742-6596/1618/3/032011

Swisher, P., Murcia Leon, J. P., Gea-Bermúdez, J., Koivisto, M., Madsen, H. A., & Münster, M. (2022). Competitiveness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050. Applied Energy, 304, 118043. https://doi.org/10.1016/j.apenergy.2021.118043

Conference papers

Franck Bertagnolio, Helge Aa. Madsen. ” A Tower Wake Model for Low-Frequency Noise of Downwind Turbine Rotors”. Paper presented at INCE EUROPE Conference on Wind Turbine Noise, Remote from Europe – 18th to 21st May 2021.

Publication

13-12-2021 ENERGIWATCH. Møller til ekstremt lav vind på tegnebordet hos DTU, Vestas og Goldwind

DTU Vindenergi undersøger med Vestas som partner de tekniske og kommercielle muligheder i en vindmølle til ekstremt lave vindhastigheder på helt ned til to meter i sekundet. ... Kinesiske lavvindsfordele Noget af det tætteste man kommer på DTU og Vestas’ koncept i eksisterende modeller, er Goldwinds nylige lancering af en mølle med en rotor på 191 meter og generatoreffekt på 4 MW.

Reports/deliverables

D1

Helge Aagaard Madsen; Filippo Trevisi; Athanasios Barlas; Fanzhong Meng; Frederik Zahle; Flemming Rasmussen; Riccardo Riva; Witold Robert Skrzypinski. ” Optimization, design and analysis of the 3.4MW LowWind reference turbine in comparison with the 3.4MW IEA onshore reference turbine”. DTU Wind Energy I-1048. July 2020.

D2

Above journal paper by Swischer, P et al.

D3

From DTU: Helge Aagaard Madsen; Frederik Zahle; Athanasios Barlas; Flemming Rasmussen; Filippo Trevisi; Fanzhong Meng; Riccardo Riva; Franck Bertagnolio. From Vestas: Thomas S. Bjertrup Nielsen; Torben Juul Larsen; Robert Thomas Rudolf. “Concept and innovation studies of a 208m diameter 3.4MW LowWind turbine”. "DTU Wind Energy I-1274(EN)" July 2021.

D4 & D5

Report “Experimental Study and detailed design of the LowWind concept EUDP LowWind Project”. Deliverable “D4 & D5” reporting on work package “WP4 & WP5”. Vestas Wind Systems A/S

D6

Polyneikis Kanellas; Matti Juhani Koivisto; Juan Pablo Murcia; Philip Robert Swisher. “Impact of Low Wind technology on the variability of the power system”. Deliverable D6 of the LowWind project, Department of Wind Energy, Technical University of Denmark, Risø, Denmark, December 3, 2021

D7

D7: Report on the Energy System Impacts of the LowWind Concept in the North Sea Region Towards 2050 Deliverable D7 of the LowWind Project Phil Swisher; Matti Juhani Koivisto; Marie Münster. Department of Management Engineering, Technical University of Denmark, Kongens Lyngby, Denmark, December 2021

D8

Present final report

6. Utilisation of project results

If the technology is found feasible and valuable, it may enter the product roadmap and be part of future Vestas offerings. In which case, Vestas would commercialize the technology. Development and testing are ongoing.

So far the project has not contributed to increased turnover, exports or employment, but if commercialized with success, it may open new markets especially low-wind sites.

All WTG OEMs are moving towards larger rotors and high-capacity turbines. The main competing rotor technology is standard blade and rotor development, aiming at cost-efficient scaling of existing technologies. Other competing technologies for providing high-capacity solutions are storage and hybrid projects (e.g. solar), where cost reductions could achieve similar high capacity offerings.

Tip height restrictions and noise may be entry barriers for low-wind turbines. Tip height restrictions need to be addressed in permitting and legislation, while noise can be dealt with by technology means to a certain extent, e.g. noise-reducing add-ons and aerodynamic design.

The project contributes to an increased share of wind energy production by enabling new markets (low wind) where wind energy with existing technologies would not be commercially feasible.

7. Project conclusion and perspective

The overall objective of the project was to explore the potentials of a completely new wind turbine concept – the Low-Wind turbine, designed for optimal integration in a power system with considerable amount of renewables. We succeeded in meeting this objective as the simulations of the LowWind turbine power curved characteristics in the Northern Europe energy system did confirm a big advantage of boosting the energy production at low wind speeds which is the characteristic of the LowWind turbine concept. Further we demonstrated with a design of the LowWind reference wind turbine of 3.4MW and a specific power of 100W/m^2 that it is possible on basis of conventional design approaches and technology to build such turbines. Further we investigated several other concepts with alternative designs.

The next steps for the developed technology is to increase the technical readiness level to TRL 6 by further verification activities in relevant operating environment. If TRL 6 is reached, the commercial attractiveness still needs to be evaluated further on existing products.

The project results have demonstrated that the technology can form a basis for future development of large wind turbine rotors. Demonstrating the technology in laboratory environment (wind tunnel) confirmed the working hypothesis.

8. Appendices

The dissemination material (articles, reports, presentations) can be downloaded from the projects share-point site:

https://share.dtu.dk/sites/LowWind_390250/Administration/Forms/AllItems.aspx?RootFolder=%2Fsites%2FLowWind%5F390250%2FAdministration%2FFinal%2Ddeliverables%2Ddissemination%2DEUDP&FolderCTID=0x0120000C271F3B4CAF0149BD7BE1A39A6AB4DF&View=%7BA1BAE266%2D6BA7%2D4887%2DB0BF%2DDC1F5FF85459%7D

HOWEVER – as some material is CONFIDENTIAL the access can only be given to EUDP employees after writing to project leader Helge Aagaard Madsen, hama@dtu.dk