EUDP 64011-0334 Final report

Project details:

Project title	Demonstration of Partial Pitch 2-Bladed
Project identification (program abbrev. and file)	64011-0334
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrationsprogram EUDP
Project managing company/institution (name and address)	Envision Energy (Denmark) ApS Torvet 11, 2.TV DK- 8600 Silkeborg
Project partners	Envision Energy (Denmark) ApS Risø DTU DONG Energy
CVR (central business register)	31492521
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Content

1. Project objective and results

The objective of the project was 1.)to demonstrate the cost saving potential of the Partial Pitch 2-bladed wind turbine technology, and 2.) through a measurements campaign to verify analysis and development tools, as absent of verified analysis and development tools for 2-bladed technology remains as the main barrier for Partial Pitch 2-bladed market acceptance.

In regards to objective 1.)
The project did not demonstrate a significant cost saving potential, nevertheless Envision is confident that the PP-2B technology have superior offshore competitiveness potential as the project have generated valuable learnings in regard how an even more efficient PP-2B wind turbine is to be designed.

In regards to objective 2.)
Today, in contrary to year 2012, the PP-2B technology is a mature and academically described technology. Needed analysis tools have been developed and successfully verified and project objective #2 is successfully fulfilled.

<u>Dansk version</u>
Formålet med projektet er 1.) at demonstrere omkostningsbesparende potentiale for Partial Pitch 2-bladet vindmølleteknologien, og 2.) gennem en måle kampagne at verificere analyse- og udviklingsværktøjer, da manglen på verificerede analyse og udviklingsværktøjer til 2-bladet teknologi forbliver som den største hindring for Partial Pitch 2-bladet teknologiens markedsaccept.

I forhold til mål 1.)
Projektet viste ikke signifikant omkostningsbesparende potentiale, alligevel er Envision overbevist om, at PP-2B har overlegen offshore konkurrenceevne, dette grundes i at projektet har genereret værdifulde læringer i forhold til hvordan en endnu mere effektiv PP-2B vindmølle skal designes.

I forhold til mål 2.)
I dag, i modsætning til år 2012, er PP-2B-teknologi en modnet og fagligt beskrevet teknologi. Analyse værktøjer er blevet udviklet og med succes verificeret og projekt objektive # 2 er blevet indfriet.

2. Executive summary

The Partial Pitch 2-Bladed demonstration, hereafter [PP-2B], gains to demonstrate a new modular 2-Bladed wind turbine concept for offshore applications, based on the innovative combination of a 2-bladed rotor, partial pitch control.

The technological target of the project was to demonstrate the load reduction potential on tower and foundation of the PP-2B enabling a 8-12% CAPEX cost reduction of an offshore wind farm, while simplifying manufacture and installation procedures and keeping up with the best efficiency achieved by today's commercially available turbines.

The main objective of the project is to demonstrate the potential of the PP-2B technology, with the extreme wind load reduction, and to develop and verify design and analysis tools for the PP-2B technology. Whereas conventional 3-Bladed upwind turbine technology today is well established supported by and handful of verified analysis and design tools, the missing verified analysis and design tools for 2-Bladed technology remains as one of the main barrier for market acceptance of the PP-2B technology.

The consortium organization structure including a R&D institute (DTU - Risø), a wind turbine developer and manufacturer (Envision) and a leading market representative (DONG) ensured an objective perspective and a trustworthy evaluation of the PP-2B market potentials and technology shortcomings.

To pursue the project objectives, the consortium behind the project did put together six Work Packages [WP], to ensure that all technological and market issues were strategically considered.

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3. Project objectives

The purpose of the PP-2B project is to demonstrate the operating performance, aerodynamic characteristics and structural dynamics of a new and groundbreaking wind turbine concept for offshore wind turbines. The turbine is based on a breakthrough conceptual design, which targets the solution to a number of specific challenges raised by offshore wind power installations.

Commercial offshore wind harvesting currently relies on turbines that have been adapted from the onshore wind industry, with a trend towards scaling onshore technology to build larger turbines. However, as offshore farms grow bigger – in number of installations and in rated power – and are located in deeper waters farther offshore, the potentials for a specific offshore wind industry based on novel concepts and with its own supply chain (components and logistics) is becoming increasingly evident.

The core of the new PP-2B wind turbine resides in its innovative rotor, whose conceptual design has resulted from extensive deliberations among highly skilled and experienced wind power engineers. During the development, it was concluded that a 2-bladed rotor with split blade partial pitch control and direct drive permanent magnet generator is favorable for the offshore industry. The design objectives for the PP-2B design has mainly been cost effectiveness, simplicity and reliability.

In addition, focusing on a holistic perspective, the turbine design is based on modular concepts, allowing for flexible component sourcing, manufacturing, transport and offshore installation. The main innovative aspects of the new rotor design are: the enabling of 2-blade technology dedicated for offshore; 30% reduction of extreme loads; split blade system and partial pitch; and turbine installation in one step.

The challenges faced by a novel offshore wind industry converge on the need to reduce the cost of energy – both CAPEX and OPEX. Hence, the PP-2B design concentrates on cost effectiveness, simplicity and reliability.

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The main innovative aspects of the new rotor design are: the enabling of two-blade technology for offshore wind energy harvesting; reduction of 30% extreme loads; split blade system and partial pitch; and turbine installation in one step.

Regardless of the trend towards larger turbines for the offshore environment – with 5-6 MW turbines already on the market and 10 MW turbines under development – the PP-2B has been designed for a standard rated power of 3.6 MW, since the largest components commercially available are for this power output.

This will permit the consortium to rely on well-established supply chains for the first generation of new turbines, accelerating serial production and marketing. Moreover, the split blade design is prone to scalable power: the blades consist of an outer part which is always at the same length and an inner part (blade extender) the length of which is adaptable for different wind regimes according to the farm location and individual offshore project specifications.

The split blade concept presents a number of other advantages, related to blade loading, aerodynamics and structure, as well as manufacturing, transport and installation methods. These advantages become even greater with the further scaling of turbines and blades.

Whereas partial pitch is a new technology, the split blade technology on which this concept is based relies on well-known methods. In this respect, the aerodynamic design of the blade is challenging but recent preliminary research into the concept points towards positive aerodynamic properties for this sectional blade technology. The main advantage of the partial pitch system is load reduction, particularly under extreme conditions, e.g. enabling protection during typhoon conditions. Calculations show that the two blade partial pitch rotor enables 30% extreme load reduction as compared to conventional three bladed concepts.

Building on the conceptual design, simulations and R&D work already performed by the project partners, which amounts to an initial verification of the, the activities planned specifically for PP-2B are designed to swiftly push the technology onto demonstration of a full-size pre-commercial prototype. The project, as such, deliberately aims at an accelerated demonstration in order to bring the concept to market.

The project consists of two main tracks: Development and implementation of an extensive measurement program and a calculation tools verification track.

Due to the novelty of the concept, adequate theory is absent, current calculation tools are underdeveloped, and compared to conventional turbine technology, 2-bladed technology lacks verification, the PP-2B project presents a unique opportunity to developer and verify a set of design tools for 2-bladed rotors and validated models and improved knowledge of the new technology serves a basis for benchmarking against existing products and demonstration of the expected CAPEX reduction

The work plan for PP-2B demonstration project consists of 6 work packages (WPs), which have been designed to ensure an accelerated demonstration of the performance of PP-2B and to verify the design tools for 2-Bladed concept

WP1 was planned to ensure smooth and successful progress throughout the different project phases as well as effective dissemination and exploitation of the results arising from the project. WP1 will deal with coordinating work between the consortium members, focusing on overall project management, including allocation of resources, work plan changes and flow scheduling, as well as general communication on the project. Envision took lead the project management WP1.

WP2: While both stall and pitch are well proven power regulation methods for wind turbines, the shift from the stall regulated inner part of the blade to the pitch regulated outer part of the blade challenge the classical aerodynamic blade element momentum (BEM) methods. Detailed CDF analysis of the transition from stall to pitch regulated blade part was validate by the BEM aerodynamic methodology and, this activity was managed by DTU.

WP3: To verify the stability of a 2-bladed turbine, a new stability tool based on Floquet theory was developed. Risø's nonlinear aeroleastic simulation tool HAWC2 was upgraded to handle the partial pitch operation. The stability tool and nonlinear time simulations tools was used to validate the 2-blade partial pitch concept. WP3 was managed by DTU.

WP4: The full scale prototype turbine was equipped with a full load measurement setup and a lidar for detailed inflow measurements. The measurements have been used to validate the 2-bladed turbine performance, both regarding power production and structural loads. The measurements campaign did work as reference data generator for the 2-Bladed design tools verification. WP4 was managed by DTU.

WP5 managed by Dong, Dong modified existing FLEX5 calculation tools and set up calculation model of the PP-2B turbine. They calculated the turbine for a reference offshore environment.
Relevant measure points and measure campaigns was defined to receive prototype measure data for evaluation of DONG's models and points of special interest from a commercial perspective.
After verification of the calculation model a generic turbine was made for benchmark purposes and a benchmark evaluated the impact of the COE from the PP-2B load reduction advantages.

WP6: Envision did set up the load calculation model for the prototype site and calculate loads according to the IEC standards. The commercial available BLADED aeroelastic calculation tool was used. Design driving load situations were identified and these conditions / situations were reflected in the definition of the instrumentation and the measurement campaigns. Sub system calculations models were compared to the measurement data. WP 6 were managed by Envision

4. Project results and dissemination of results

4.1 Introduction

This section discuss various element of the GC-1 wind turbine

4.1.1 Module concept for High voltage equipment and converters.

The concept is intended to enable easy sourcing and replacement of components. The idea is to allow local supplies, eg. if a customer wants a specific transformer, converter etc.

The transformer and converter module concept is used on the first Envision 4MW offshore turbine in China.

Figure 1 - GC1 - HV & Converter contept

4.1.2 Flexible main shaft

The flexible mainshaft produced by filament winding of carbon fiber, has proved its worth. The purpose was to eliminate bending loads going into the generator and hereby reducing the generator structural design to just focus on torque.

Other direct drive turbines like Siemens, Goldwind, Ahlstrom etc. has to consider the bending moments from the rotor loading into the generator design, which requires a huge calculation effort and turbine understanding from the generator supplier, which is increasing the generator cost.

Only challenge with the shaft has been to control the dynamic. The shaft is a huge torsional spring and in full loaded situation, the shaft will have 2.5 deg torsional deflection. When there is a torque drop, due to wind change, the energy storage in the spring is released and hence the generator system can go into vibration.
There has been initial challenges to reduce these vibrations, but a proper tuning of the controller by adding a drivetrain damper in the converter control, reduced the risk.

Normally the drivetrain damper is introduced in the control PLC, but as the frequency of the drivetrain was much higher than for traditional geared machines the PLC was not fast enough to reduce the vibration. Hence the drivetrain damper needed to be implemented in the converter SW. This was new to Envision and also a challenge to get the converter company to accept Envision control strategy in their converter.

There has not been any direct turbine spin off for the main shaft. Vestas has used a flexible Carbon coupling in their V164 turbine design, which is the technology that comes closed to the flexible shaft technology.

The Schäfler rolls company that produced the shaft has demonstrated the large filament winding technology and have proven to make 800mm diameter shafts of 7m which has been used for rudder shaft in large container ships. Traditionally the rudder shaft is forged steel and the production process could be several month. The transport is also easily 6 weeks to the location of use. With the filament winding in carbon they have been able to produce items with few weeks delivery time, cheaper price, easier installation and easy transport by plane etc. This new technology has been an eye opener for the ship industry.

4.1.3 Partial pitch

The partial pitch gave concern to the centrifugal forces acting on the pitch system and the bearing. The electrical components was tested in a test rig spinning the components to simulate 10 year life of the system during operation. No issues was encountered.

A concern was that the centrifugal forces would make the oil flow out of the bearing, but no leakage has been seen.

In general the turbine has worked above expectation with a very high availability. The partial pitch has not given any concerns or particular failure. The turbine has been hit by lightning several times and a non-optimum solution in the grounding resulted in a minor issue with one pitch drive during one of the lightning strikes.

Hence having the electrical pitch in radius 20m is feasible.

The main purpose for introducing the partial pitch was to reduce extreme loads during stand still of the turbine. The below plot shows the extreme overturning moment at the tower bottom – which is the design driver for fixed and floating offshore foundations. One curve is showing the expected loads for a 3 bladed turbine and for the 2 bladed partial pitch machine, which shows that the foundation loads can be expected to be approximately half of the traditional 3 bladed machine.

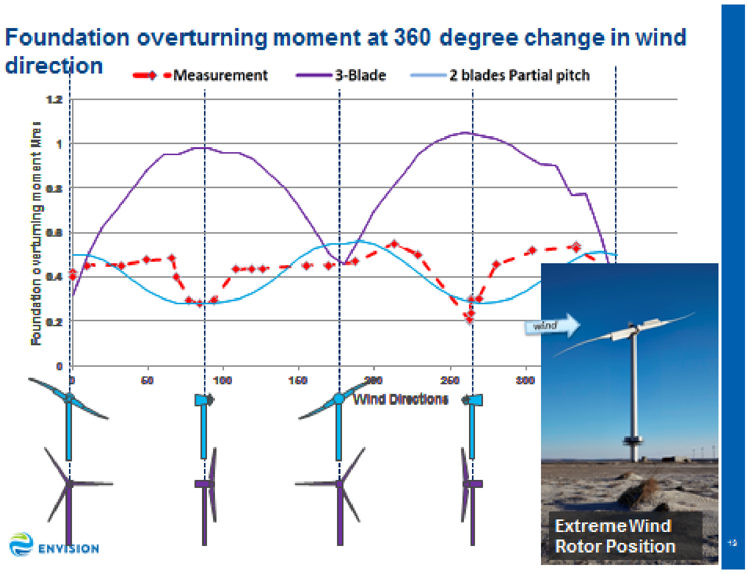


Figure 2 - PP-2B foundation loading

The red curve is showing the measured values and it can be seen that the turbine in side wind (at 90 deg and 270 deg flow angle) is having approx. 20% of the traditional turbines load.

The reason for the low foundation load at side wind, is that the rotor is floating in nearby horizontal position giving a very low projected area and therefore no loads. The rotor has shown to find an horizontal equilibrium position in side wind with one blade pointing towards the wind. During several periods it has been shown that the turbine can maintain this position and that the rotor will not start to rotate (and hereby give a larger projected area and larger loads).

During a storm period with 50h+ above 20 m/s the turbine maintained the wanted rotor position.

If the blade pointing towards the wind is pitched in direction to zero pitch, the rotor will act as a wind wane and hence always point towards the wind, finding the position with minimum drag on the rotor. With this strategy, the loading can be ensured for a larger range of wind directions.

During one of the storms the tower bottom loading was measured. The 10min average wind reached close to 38 m/s and the extreme gust was close to 53 m/s (3rd Dec 2013, 16.50h).

During this storm the average tower bottom load was approx. 15.000 kNm. This is approximately 1/3 of the normal tower bottom loading during normal production at 12 m/s. Further it is 6-7 times less than the extreme design load for the foundation. Hence the turbine is not sensitive to extreme high wind, which will enable the erection of this turbine in typhoon and hurricane areas without risk of the rotor and tower.

This makes the turbine concept interesting for South China sites, Taiwan, Japan, Philippines or US hurricane sites.

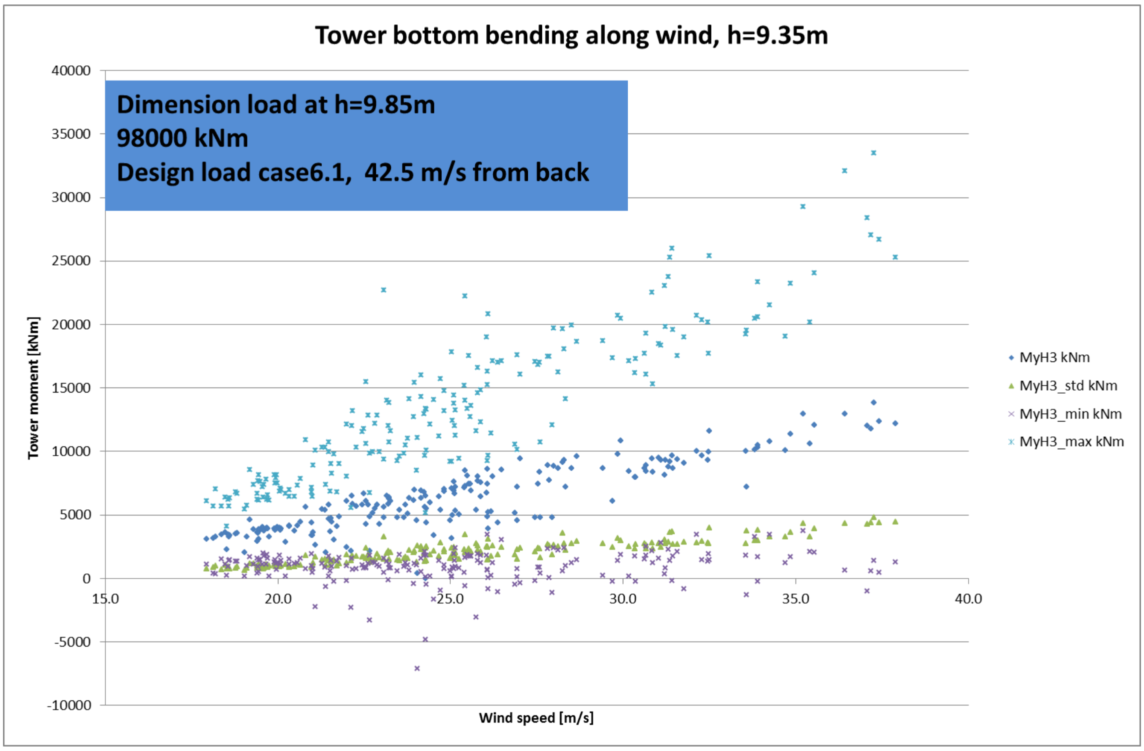


Figure 3 PP-2B foundation loading measurement during storm 3. Dec. 2013

Further the partial pitch has the advantage that the blade can be made in parts and hereby ease transportation, manufacturing, testing etc. Hence the technology will enable manufacturing of 200+m rotors.

Further the blade parts can be made in different material and manufacturing processes. The outboard part needs to be more perfect in the geometry and surface due to aerodynamics, whereas the inboard part needs to carry the loading and the aerodynamics is not so important for this section, allowing a more coarse manufacturing process.

Rumors tells that the partial pitch technology is considered in competitors + 200 rotors as transport, manufacturing and components sizes in general is becoming a problem, and by splitting the blades in more sections the challenges can be overcome.

Finally, by having the inboard blades fixed contrary than normal pitched rotors, the rotor overhang can be reduced. The reason is that for normal rotor the maximum chord of the rotor should not touch the tower when pithing the blades to feathered position.

For the partial pitch machine this is not a problem and hence the nacelle and load carrying structure can be made significant shorter and hereby cheaper. The nacelle of the turbine is actually only 1/3 of the length of a comparable size of turbine. This will also reduce the projected area of the nacelle and again reduce the extreme loads during high wind like typhoons.

4.1.4 2- bladed

The 2 bladed machine has approximately 2% less production than the traditional 3 bladed machine, compared on rotor size. But the 2 bladed machine will enable a lighter rotor. Each blade will be heavier than a traditional comparable 3 bladed blade, but is total the rotor blades will be 20-25% lighter than a traditional 3 bladed rotor. Further the hub and pitch system will be cheaper and lighter.

Hence the 2 bladed rotor will be cheaper and lighter.

The lighter rotor is especial very interesting for floating offshore as the tower top mass is directly linked to the dimension and cost of the floater.

Also the 2 bladed rotor can be transported for offshore sites as full assembled nacelle and rotor, which will reduce installation and vessel time offshore. As the installation cost is a huge part of an offshore park the technology is also interesting here.

The picture is demonstrating the full lift of assembled rotor and nacelle. And the graphics below is illustrating the installation concept

Figure 4 - GC1 THM single lift

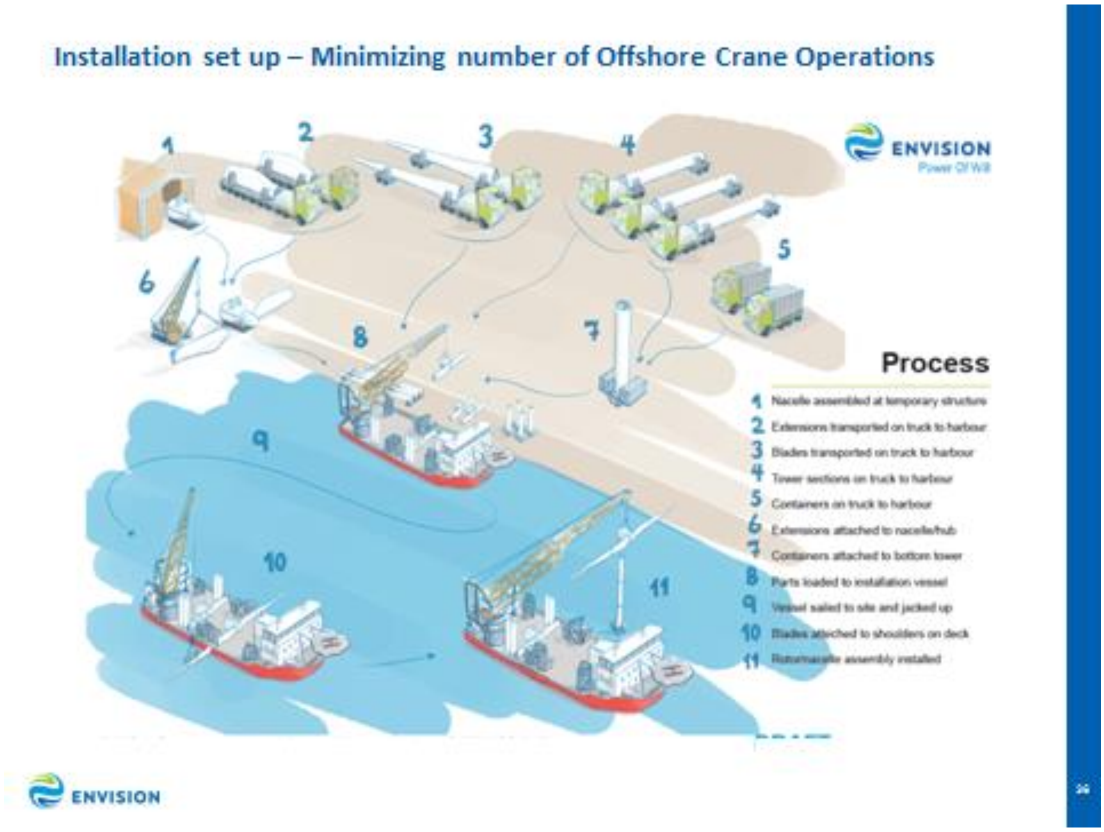
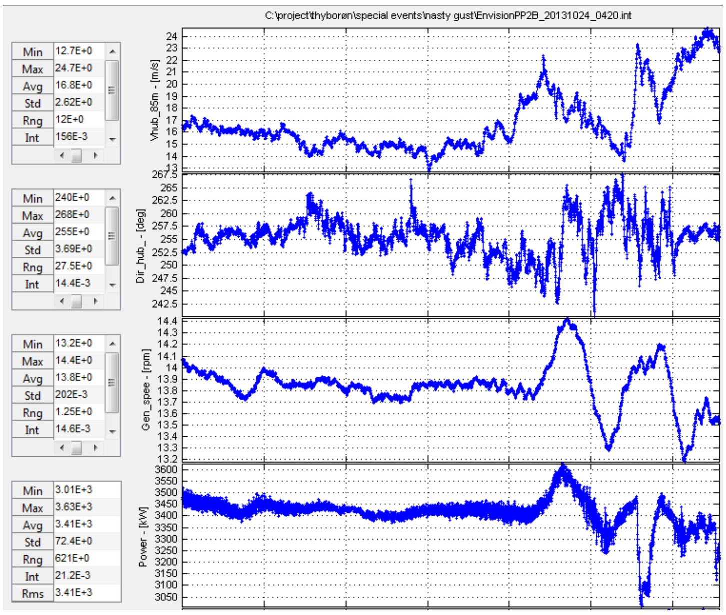


Figure 5 - PP-2B installation concept

4.1.5 Nasty gust – LVRT heavy rotor

By putting the pitch bearing to radius 20m the rotor will have a huge moment of inertia. Actually the rotor will have more than double inertia compared to similar rotor sizes. This means it can act as a fly-wheel which will prevent the rotor to speed up during gusts or to lose momentum during grid loss (Low Voltage Ride Through)



This effect was demonstrated during various gusts on the site.
The below plot is showing a gust with more than 10 m/s and 20 deg wind direction change. The rotor is only speeding up to 14.4 rpm from the original 13.8 rpm, which is an incredible low rpm step for this gust.

4.1.6 PP Blade

The aero shells on the inboard part of the blade started to crack in the assembly. The cracks grew with time and inspections finally revealed that the bonding of the shels to the beam was not according to the specification.

The aeroshells where removed from the inboard blade part and the turbine was operated in a period without the shells, until a new solution was found.

The rotor was taken down and the shells refurbished. The shells where made in sectional parts / modules whit a gab between each element, hereby preventing loads to be transferred from each element to the other and hereby removing the risk of cracks in the shells.

In the same work process the inboard blade part was reinforced to change the blade frequency and hereby remove a edge vibration issue.

The new blade edge frequency is 1.22Hz, hence a much stiffer blade.
The blade has performed satisfactory since and no cracks nor dynamic issues has been seen.

4.1.6.1 Mitigation for blade vibrations

To mitigate the blade vibration we should first be able to understand the problem, which we can now. Further we should be able to calculate the phenomena. Calculations in SW Bladed has shown same tendency and the measurement data can be reproduced.

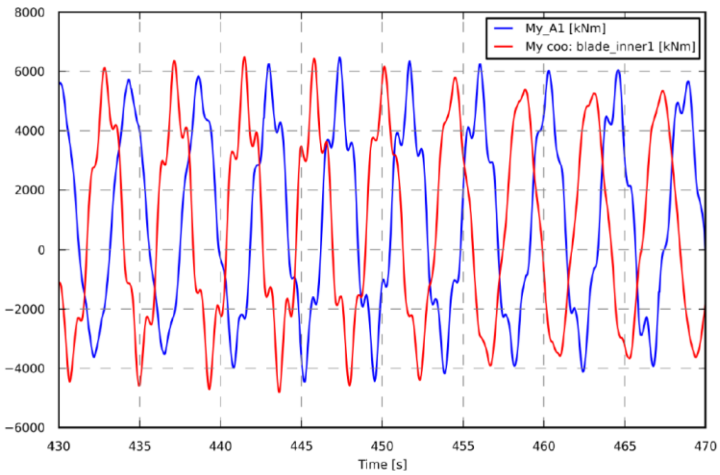


Figure 6 -Simulation and measurement of the blade edge vibration, blue measurement, red calculation

Risoe and LM has calculated the same dynamic as measured with their HAWC2 code.

LM's Flex5 design code and FAST has not been able to reproduce the problem as the torsional degree of freedom for the blades are not available in these codes
AN example on simulation and measurements are shown in below figure
Figure Simulation and measurement of the blade edge vibration, blue measurement, red calculation.

4.1.6.2 Structural design

Various calculation runs with different structural designs has shown that the blade can be made vibration free by increasing the edge stiffness so that the blade frequency is above the 5p frequency.

Further it has been seen that increasing torsional stiffness is also reducing blade vibrations.

Actual the LM66.5 blade designed for Envision SC-1 turbine, showed instability issues in some of the first iterations and luckily, Envision could claim that this was a real problem as the GC-1 turbine had this in the measurements. For same reason the blade design was changed.

4.2 DTU work packages

The main DTU objective for the project was to demonstrate the potential of the partial pitch two-bladed (PP-2B) technology. DTU Wind Energy took a responsibility for three work packages (WPs) among 6 WPs which were aerodynamic evaluation of partial pitch technology (WP2), aeroelastic analysis of two-bladed turbine (WP3) and On-site testing (WP4).

For the WP2, a comprehensive set of 3D CFD simulations including the gap between inner and outer part of the blade and vortex generators (VGs) of both cross-sections on the blade as well as fully resolved rotor simulations, and finally simulations coupling HAWC2 with EllipSys3D, investigating the behaviors of the rotor at standstill, has been performed.

For the WP3, the state-of-the art aeroelastic analysis tool, HAWC2, has been updated in order to consider the partial pitch concept and detailed load analyses were performed. Also the comparison studies between numerical results and experimental results were performed. Moreover stability analyses for the PP-2B turbine have been performed with HAWC2 and modal analysis using Hill's method was performed to calculate the mode shapes and modal frequencies.

For the WP4, the onsite measurements were successfully carried out at Harboøre Tange, Thyborøn, Denmark in the period 28th September 2012 to 14th of January 2016. The structural loads, produced power and turbine controller signals were measured and sampled together with detailed inflow information from the met mast nearby.

4.2.1 Aerodynamic Evaluation of Partial Span Pitch Technology (WP2)

The overall aim with the work was to improve the understanding of the complex aerodynamic characteristics of the Envision 2B-PP rotor, in particular the transition between the stall regulated inner part and the pitch regulated outer part of the blade.

This was achieved through a comprehensive series of high fidelity aerodynamic simulations using 3D Computational Fluid Dynamics (CFD).

The work had three primary branches:

- 3D airfoil sectional simulations: Simulations on the cross-section at the partial pitch junction to investigate the effect of VGs (both fully resolved and modelled using the BAY model), as well as the effect of the physically modelled gap.
- 3D rotor simulations: Simulations of the baseline rotor without the gap between the two wing sections, with and without VGs modelled using the BAY model; simulations of the rotor including the gap, but excluding VGs.
- HAWC2-CFD simulations of the rotor: Simulations under high wind standstill situations to investigate the aerodynamic characteristics in unusual inflow directions, not modelled well using aeroelastic codes.

The complete reporting of WP2 in (Taeseong Kim, 2016)

4.2.1.1 Discussion

In the results section it was shown that fully turbulent CFD predicted a general negative impact of the current VG layout on the power production of the turbine. The assumption of fully turbulent flow is of course not ideal because it implies a thicker boundary layer and hence the effectiveness of the VGs will be under-predicted. On the other hand the transitional simulations also showed that the VGs in the existing set-up did not always perform satisfactory. The reason was identified to be partly due to a gap in the row of VGs and partly because of too small VGs because their effectiveness was improved significantly when increasing their VG size and allowing them to be mounted on the PP junction.

The investigations also revealed that the fully turbulent simulations predicted the mechanical power of the turbine with VGs to be lower than the measured electrical power at moderate to high winds. At 14 m/s the power of the turbine without VGs was also under predicted by the fully turbulent simulations. On the other hand, when simulating with transition the power predicted by CFD was much higher than the measured electrical power - so much higher that the difference probably cannot be explained from losses in the generator. The "real" world is probably somewhere in between the transitional and fully turbulent simulations. All simulations showed that the performance of the blade region around the PP junction is very sensitive to both the operational conditions and computational parameters.

This indicates that the flow around the junction is probably either unstable or only marginally stable

4.2.1.2 Conclusion

The aerodynamic investigations done on the Envision 2B PP rotor consisted of a comprehensive set of 3D CFD simulations of both cross-sections on the blade as well as fully resolved rotor simulations, and finally simulations coupling HAWC2 with EllipSys3D, investigating the behavior of the rotor at standstill.

The Envision 2B PP rotor had a number of very challenging features to model aerodynamically.
Firstly, the inner stall regulated part of the blade, which extended 20 a radius of 22 m, consisted of very thick aerofoils of 56% relative thickness.
Secondly, the transition between the two blade sections had a physical gap (although this was partially covered by covers).
Thirdly, the rotor was equipped with vortex generators that were thought to be vital for the rotor to perform well.

The first set of 3D steady state rotor simulations in which the gap was not included suggested that the transition between the two blade sections gave rise to a large area of flow separation, which had a significantly adverse effect on power production. It was observed that the separated flow at the transition varied in strength, and at some wind speeds did not occur. Subsequent unsteady simulations indeed revealed that the flow phenomenon was highly unsteady in nature, fluctuating between two states, either fully attached or fully separated.
During the project, a new model was developed for including the effect of vortex generators without having to model them physically in the mesh (co-financed by other EUDP projects), referred to as the actuator BAY VG model. This type of model was necessary since each blade had 100s of VG vanes, which would require a prohibitive number of cells to include in the mesh. The model was firstly validated for

an aerofoil cross-section against wind tunnel measurements and fully resolved VG simulations.
Subsequently, the 56% aerofoil used at the PP junction was simulated for a 10 m section, including the physical gap as well as the VGs modelled using the above-mentioned model.
Including the partial pitch gap was initially thought to result in further deterioration of the flow quality, however, the contrary was in fact the case. The flow through the gap appeared to generate a stable counter-rotating set of vortices, which suppressed separation at the neighbouring sections.
The actuator BAY VG model was also applied to fully resolved rotor simulations of the 2B PP rotor. It was shown that fully turbulent CFD predicted a general negative impact of the current VG layout on the power production of the turbine. The assumption of fully turbulent flow is of course not ideal because it implies a thicker boundary layer and hence the effectiveness of the VGs will be under-predicted. On the other hand the transitional simulations also showed that the VGs in the existing set-up did not always perform satisfactory. The reason was identified to be partly due to a gap in the row of VGs and partly because of too small VGs because their effectiveness was improved significantly when increasing their VG size and allowing them to be mounted on the PP junction.
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Simulations were also carried out on the rotor comparing the original blade shape with the improved blade transition piece developed by Envision during the project period. Also, simulations were carried out including the physically modelled gap. The new transition piece marginally improved the flow quality, although the flow still appeared to be unstable. Simulation results including the gap led to the same conclusions as for the single cross-section simulations, in that the gap gave rise to a stable pair of vortices that suppressed separation inboard and outboard of the gap.
The final study carried out in this work package involved simulations at standstill to investigate the behavior of the rotor with variation of inflow angle and azimuthal position. Simulations with fixed azimuthal position of 90 degrees and a variation of inflow angle showed a fairly good agreement between HAWC2CFD and HAWC2 for the lateral tower bottom moment, whereas the foreaft moment was under-predicted by HAWC2. The second study aimed to investigate whether simulations could predict that the turbine would stabilize in a “T-position” during standstill. While the torque was reduced significantly for azimuth angles where the blade was close to horizontal, a rotor without any stick would not stabilize.

The overall conclusion to the aerodynamic analysis carried out in this project is that the aerodynamic characteristics of the rotor are associated with significant uncertainties due to its unconventional design. The combination of very thick aerofoils and abrupt transition at the partial pitch junction appears to make the flow unstable or only marginally stable in this region of the blade. It was shown that the gap itself may not be the root of the instability, but more likely the abrupt change in loading going from thick to thinner aerofoils across the junction.

4.2.2 Aeroelastic analysis of 2-bladed turbine (WP3)

The objective of WP3 is:

1. Develop design tools for two bladed turbines
2. Evaluate aeroelastic loads and stability for the particular 2-bladed partial pitch design

Four work streams have been identified to support WP3 objectives.

- Task 3.1. HAWC2 model validation (with different numerical codes and with measurement data)
    - Validation with FLEX5 and BLADED - (Cancelled based on the discussion with Envision)
    - HAWC2 model improvement (if necessary)
    - Validation with measurement data (selected data set only for HAWC2 model validation)
    - HAWC2 model improvement with the updated rotor design
    - More validation with measurement data (selected data set only for HAWC2 model validation)
- Task 3.2. Stability analysis with HAWC2
    - Stability analysis was developing Floquet theory into HAWCStab2
    - Stability analysis with HAWC2 (Campbell diagram)
- Task 3.3 Investigation of vibration problems
    - Blade edgewise vibration
    - Flexible shaft vibration – (cancelled due to solving the problem by communication between DTU Wind Energy and Envision)
- Task 3.4. Loads investigations (extreme and fatigue loads)
    - Selection of load cases for load analysis (both for numerical and measurement)
    - Numerical investigation (only HAWC2 simulation)
    - Validation with selected measurement data set (HAWC2 and Measurement data)
    - Numerical HAWC2 investigation with airfoil data with and without VG's

The complete reporting of WP3 in (Taeseong Kim, 2016)

4.2.2.1 Conclusions

The numerical analysis tool, HAWC2, was successfully updated to consider the innovative partial pitch concept by introducing a multi-rotor concept. General dynamics of wind turbines with two- and three-blades were compared.

Several load cases were investigated to illustrate some key differences. Normal power production with normal turbulence (DLC 1.1) and extreme turbulence (DLC 1.3), power production with loss of electrical network (DLC 2.4) and parked with a loss of grid connection (DLC 6.2) are considered as the main design load cases. The blade load level is about 1.5 times higher for the PP-2B turbine directly caused by the 50% increased chord due to the solidity similarity, by handling the same amount of loads with one blade less rotor, and by considering a rigid hub system. Larger tower load variations during operations were observed for the PP-2B turbine due to the 2P excitation from the rotor being closer to the tower frequency than 3P of a three bladed turbine.

The extreme tower loads during parked situation in a storm were reduced with around 20% and 18% for the PP-2B and the PP-3B compared to the 3B. Moreover, a huge potential of reducing the extreme load of 60% for the PP-2B could be obtained if the blades are placed in a T-configuration and perpendicular to the wind (wind direction of ±90°). Also, less blade root bending moments were observed from the PP-2B turbine for the stand-still storm condition. In conclusion, the partial pitched blade is able to reduce an extreme load at the stand-still storm situation when all wind directions are taken into account. Also the partial pitched blades experience less loading than the 3B turbine at the stand-still condition. Moreover the loading on the partial pitched blades are less affected by changes in wind direction during stand-still condition.

Detailed stability analysis with HAWC2 has been performed. From the analysis it has been shown that for low rotor speeds matching idling conditions the rotor modes changes with azimuth positions, matching either stand still frequencies for the rotor in either vertical or horizontal mode or a mix of the two states. For higher rotor speeds matching normal operation conditions the asymmetric flap and edge rotor mode frequencies does not split with ±1P as known from three bladed turbines, but instead with multiple n times ±2P frequency, i.e. ±2P, ±4P, ±6P, and so on. The tower frequency is for the two-bladed turbine seen to be significantly affected by the rotor speed of the turbine. The tower frequency keeps a base frequency, which is constant for all rotor speeds, but at the same time splits up into a +2P and -2P mode, causing a total of three frequencies to be aware of in the design phase.

From the Campbell diagram of the PP-2B, it seems that there are many frequencies covered at the operation RPM. However it does not mean that all frequencies are critical because it depends on the correct amount of damping for the individual frequency. When the aerodynamic effects are considered the most of flap related modes are damped out. More validations with measurement data will be performed.

A modal analysis of the turbine at zero pitch in the rotor speed range from 3 – 15 rpm has been performed using Hill's method on a simple turbine model able to capture the turbine modes below 2 Hz. Hill's method provides the periodic mode shapes of each principle turbine mode which for a two-bladed turbine consists of the tower bending, drivetrain torsion, and the symmetric and asymmetric rotor modes. Note that the rotor modes are either symmetric or asymmetric modes related to a blade mode. Even though the response of the 1st asymmetric edgewise mode seen from the tower seems to split by ±1P, the concept of a backward and forward whirling mode pair corresponding to a blade mode known from three-bladed turbines does not exist for two-bladed turbines.
These terms for the order of blade vibrations have simply no meaning for a two-bladed rotor because there is no difference in order of vibration for only two blades. The ±1P frequency splitting of the tower response of the 1st asymmetric edgewise mode can be interpreted from time simulations as two separate modes, but they are due to a single mode. Hence, it is not possible to excite the +1P response without also exciting the -1P response because the responses at the two frequencies are caused by the same mode.

The numerical simulation results of the PP-2B are compared with the full-scale measurement data set during normal operations and an extreme wind gust case. In order to select a high quality measured data set the selection criteria are defined such as the wind direction, the yaw error, generator speed etc. For the normal operation case statistic loads (Max-Mean-Min) are compared. Especially, blade bending moments and tower top bending moments are compared with the first wind turbine model. A very fine agreement is seen between simulated and measured loads. An extreme wind gust case was measured at Thyborøn where the wind speed jumped from 13.6 to 23.3 m/s during three seconds. In order to reproduce the measured gust wind for the numerical simulation a stochastic Mann turbulence wind field was modified by constraint limitation to match the wind speeds measured by two cup anemometers at 21m and 85m from the ground. From the measured and the simulated response comparisons, it was found that the rotor speed, the blade pitch angle, and the blade loads are not quickly reacted to the wind gust. One explanation of this is the enlarged rotor inertia caused by the blade pitch bearings placed 20m from the blade root.

In July 2014 the shell of the inner part of the blades of the E128-3.6MW Envision turbine were replaced with a new set. To reflect the properties of the new shells, the numerical model of the blades has been updated. Using the updated turbine model, a study comparing measurements and simulations has been performed. The study compares statistics and fatigue levels of 9636 data files of 10 min measurements with the statistics and fatigue levels of 171 simulations. The selected measurements are the result of applying a combination of filters that extracts normal standard operation situations where all sensors of interest have reasonable values.
When looking at the overall comparison it can be concluded that measurements and simulations are within the same order of magnitude, and that fundamental trends are captured in the same way. However, when looking into more detail, it has to be noted that the current representation of the measurement data and simulation results shows a number of noticeable differences:

- Not all measurement ambiguities and faulty artefacts have been completely removed from the measurements. This requires us to be cautious when trying to explain why the simulations show lower spreads or have very different extreme values.
- The power, pitch and rotor speed curves match reasonably well, but some noticeable differences remain at very low wind speeds due to a 1 degree difference in minimum pitch angle, and this affects the rotor speed at those wind speeds, and also might alter how the controller goes through the rotor speed exclusion zone.
- The measurements show a tower side-side vibration in above rated conditions that is not present for the simulations. It is not clear what effectively drives this vibration in the measurements, or why it is absent from the simulations.
- There are non-negligible differences in mean values for the tower top/bottom bending moments and shaft torque channels, however, the results do indicate that some of the main aerodynamic characteristics (with respect to lift and drag) of rotor are modelled correctly. However, due to the aerodynamic complexity of this 2 bladed partial pitch wind turbine, a lot of uncertainties are introduced when using the current models, such as the root vortex on the inner/outer blade interface and the 3D corrections for the 2D airfoil data. This could partly explain why the mean values of the measurements are not matched as well as one could expect with the measurements. Additionally, due to the controller black box approach, it cannot be guaranteed that both the measurement and simulation controllers are exactly the same (as is illustrated with the minimum pitch angle difference).
- The blade edge-wise loads compare well from a mean/max/min perspective. However, it is interesting to note that the 1 Hz equivalent representation show a difference, where the simulated values are higher compared to the measurements. This could indicate that the simulations have a higher vibration level compared to the simulations. It is interesting to note that the reverse trends is shown for the tower side-side loading and the shaft torsion 1 Hz equivalent loads: higher values for the measurements compared to the simulations.

4.2.3 On site testing, Certification and evaluation (WP4)

The objective of WP4 is:

1. Measure power performance
2. Measure loads and analyse data
3. Make reports for certification

Three work streams have been identified to support WP4 objectives.

- Task 4.1 – Power
    - Mount meteorological mast, equipment and carry out measurements
- Task 4.2 – Loads
    - Mount strain gauges in blade, blade extender, main shaft and tower
    - Carry out measurements of loads and metrological data
    - Analyse data and work out load envelope for the turbine
- Task 4.5 – Aeroelastic load analysis
    - Model validation against measurements
    - Aeroelastic analyze of special cases or problems based on measurements and simulations

The measurement system consists basically of a number of sensors, 5 data acquisition units (DAU's) and a measurement PC running the samplings program Daqwin. The DAU's and the PC are connected in a local network via optically fibers and via WLAN from the hub to the nacelle. Most sensors are connected to DAU's via cables but some with serial output are connected directly to the PC via the LAN such as yaw sensor and Sonic anemometer.

A DAU have 16 analogue (±5V) and 6 digital inputs. These signals are converted in to a values between 0 to 65535 (16 bit integer) at 35 Hz and send to measurement PC. Daqwin uses a setup file with gain and offsets to convert the values in to physical units again, samples the data in 35 Hz and saves in 10-minute time serial files (in tim-file format).

All Daqwin time serial files are time stamped at the starting time of the time serial (example: EnvisionPP2B_20151201_1140_000035.tim). The measurement PC is synchronized to an external time server every 20 minutes.

Some signals such as loads signals are sampled in voltage and needs to be calibrated to kNm. This is done by post processing data at time serial level and creating new time serials in flex4 format (int-files). Here are also added calculated channels such as tower bending moments with reference to the yaw direction.

The measurement system inclusive all installed sensors are described in details (Taeseong Kim, 2016)

4.2.3.1 Conclusion:

Onsite measurements on the Envision PP-2B prototype turbine were carried out at Harboøre Tange, Thyborøn, Denmark by DTU in the period 28th September 2012 to 14th January 2016.

In a period of more than 3 years simultaneously signals such as structural loads, produced power and turbine controller signals were measured and sampled together with detailed inflow information from the met mast nearby. The total data base includes 167198 10-minutes time serials (27866 hours or approximately 3.2 years) and the system has been logging data 96.5% of the full period.

The measurement system where specifically designed to be able to measure exact rotor position and loads during parking in high wind situations which is an important feature for the turbine concept and several high wind tests were performed during the campaign.

4.3 Envision work packages

4.3.1 Aeroelastic analysis of 2-bladed turbine

The objective of WP6 is:

1) Update the load simulation model for the specific site conditions
2) Load simulation for the turbine for the specific site
3) Definition of measurement need for the demonstration turbine
4) Measurement setup
5) Measurement analysis and calculation verification

Six work streams have been identified to support WP4 objectives.

Task 6.1 – Update the load simulation model for the specific conditions
Envision will based on the actual site conditions and turbine configuration build the simulation model in Bladed for the site specific load calculations

Task 6.2 – Load simulation for the turbine for the specific site conditions
The site specific loads will be calculated and reported.

Task 6.3 - Definition of measurement need for the demonstration turbine
The data amount and measurement points should be defined and specific operation modes of the turbine should be defined. The PP-2B concept has some advantages in high wind conditions at stand still and test to demonstrate these conditions should be defined. Further shut down procedures with failure in the control system are calculated to be less severe for the PP-2B compared to 2 blades and hence these situations should also be addressed.

Task 6.4 - Measurement setup
Organise the permissions, purchase and practical issues about the measurement mast at the prototype site. Organise the practical issues and electrical installations in the nacelle at the prototype assembly site at MAN Diesel & Turbo facilities in Fredrikshavn / perform the installation. Organise the instrumentation of the blade at LM facilities in Lunderskov.

Task 6.5 - Measurement analysis and calculation model validation
Envision will receive necessary measurement data from the measurement campaign for the demonstration turbine. Risø will deliver the data in the requested format. Based on the actual measured site conditions Envision will modify the calculation environment model and calculation files to fit the actual site data. The structural frequencies in the calculation model should be adjusted to fit the measurements. A new load calculation will be made and the measured and calculated data will be compared. This will be done on specific turbine behaviour such as frequencies and modal shapes but also on fatigue load and general load level.

4.3.1.1 Conclusion

Objectives have been fulfilled where the turbine has been modelled in different calculation tools. The model and the performance were shown by the measurements and a validation of the different parts of the turbine has been done.
Good agreement was found with the Risø calculation and also foundation calculation by DONG.

Outside of the EUDP project differences where seen in the results from the tools used by Envision and the tools used by the blade supplier. The envision tools had included torsional degree of freedom of the blades in the simulation and the blade shown edgewise unstable behavior in the simulations.
As the tools where new and not validated properly it was agreed to proceed with the erection of the turbine, but monitor the blade edgewise dynamic carefully. Unfortunately the blade showed edgewise unstable behavior during operation at high turbulence.

This had led to many investigations on the root cause for this vibration and has been a learning process for both Envision and the blade manufacturer.

As the blade extender had structural damages during the year, due to manufacturing failures, the rotor was taken down for an upgrade. During this upgrade the blade frequency and stiffness was changed and a good performance of the blade was obtained.

The upgraded blade has a new aerodynamic design for the inboard section and a validation also in high wind is essential to document the low loads at extreme high wind.

During the measurement campaign it has shown that the method used for passing the tower frequency with the rpm can be improved. Different strategies for avoiding this frequency collision have been identified and some already tested.
Similar it has been seen that the tower measurements can be used to measure blade vibrations and imbalances in the rotor and these methods have been generally adopted in Envision controlling strategies.

4.4 DONG work package

The goal of the project is to evaluate the turbine and its feasibility for offshore installation.
Figure 2-1 The 2 bladed partial pitch envision E128 3.6 MW wind turbine.
Focus has been on design loads which differs from e.g. statistical max values of calculated loads. This is considered the best comparison basis as it represents the actual loads to be certified and used for design of offshore foundations.

Supporting the above objective 5 individual deliverables are delivered by DONG

- Building Aeroelastic simulation model of the turbine in the DONG calculations environment and update calculation tools for the two bladed partial pitch model.
- Load simulation for the turbine in an offshore environment.
- Definition of measurement need for the demonstration turbine
- Measurement analysis and calculation model validation
- Result benchmark with generic 3 bladed wind turbine

4.4.1 Building Aeroelastic simulation model of the turbine in the DONG calculations environment and update calculation tools for the two bladed partial pitch model.

DONG Energy received the necessary data and control software early in the project. The turbine model was implemented in the DONG energy internal calculation software based on FLEX5, which among other things required modifications to the FLEX5 code in order to handle partial pitch.

The controller is an important part of the calculation environment. However, it turned out to be difficult to implement a stable version of the DLL provided by Envision Energy 1. This was also a problem for other project participants. As a solution, DONG's internal controller (EEController) was used instead. This required software changes in order to handle the RPM ramp down at high wind speeds below cut-out, which is a special feature for this turbine. The controller settings are defined based on turbine settings (max RPM etc.) and fine-tuned to match loads resulting from the use of the Envision DLL control.

The model structural properties have been validated through comparison of system frequencies and mode shapes to reference data. The basic aerodynamics and operational settings have been validated by comparing power curve and time signal of pitch and RPM.

The dynamic control behaviour of the DONG internal controller is validated by comparing 1 Hz equivalent tower bottom fatigue loads for wind speeds of 5, 11, 15 and 20 m/s for 6 different turbulence seeds (for a land based turbine). Figure 6-1 and Figure 6-2 show the result – except for side-side loads at 5 m/s the load groups are close to the results of the DLL control.

Based on this it is decided to use EEController as it results in correct foundation design loads for wind speeds greater than or equal to 10 m/s. It has been validated that the unrealistic high fatigue loading at 5 m/s has a negligible impact on design loads.

4.4.2 Load simulation for the turbine in an offshore environment.

Both extreme and fatigue loads will be discussed based on the design load cases (DLC's) in Table 6-1. The design giving load will depend on various issues, but it is noted that both extreme and fatigue loads are important for offshore turbines and foundations.

	DLC(s)	Safety factor (PSF)	
Extreme	6.1	1.35	Parked at optimum yaw angle
Extreme (abnormal)	6.2	1.1	Parked at 0-360 deg. angles relative to wind.
Fatigue	1.2	1.00	Normal power production

Figure 7 - Investigated IEC design load cases

The Extreme design loads are found as the mean of max of load groups:

Design value = Max(Mean of max; DLC 6.1 incl. PSF, DLC 6.2 incl. PSF))

In this investigation care was taken to ensure that the turbine foundations has the same sensitivity to wave loading. This includes attention to:

1. Foundation outer diameter
2. Orientation of appurtenances (boat landing etc.)
3. Dynamic behaviour at point of wave impact (system frequency and deflection magnitude).

4.4.2.1 Site 1. Hard wave climate

The calculations are based on actual foundation and transition piece (TP) for an offshore wind turbine park. Soil, wind and wave properties are also according to the actual site. Calculations for the E128 turbine have been compared to the installed 3 bladed turbine.

The water depth is approximately 30 m. Extreme wind speed is approximately 45 m/s at hub height. The site has large extreme waves. The maximum gust wind speeds are approx. 60 m/s.

It was erroneously expected that this site, which represents hard met-ocean conditions, will reduce the benefits of the partial pitch 2 bladed technology. However, the conditions are typical for many offshore sites and it eventually turned out that the load reduction potential was larger for this site than for a site with milder wave loads.

4.4.2.1.1Extreme loads

The Envision turbine was parked at high wind speeds with horizontally fixed rotor and 90 degree yaw relative to the incoming wind direction, whereas the 3 bladed reference turbine was parked with 0 degree yaw error. This represents the actual normal conditions (DLC 6.1). Abnormal conditions(DLC 6.2) was also taken into account, in which case the turbine cannot yaw and thus is subjected to wind from all directions.

The calculated extreme loads are given in Table 1 (relative to values for the 3-bladed reference turbine). The load reduction using 2 bladed partial pitch technology is 3% at seabed and 11% at tower-foundation interface.

	3,6 MW 3-Bladed turbine	3.6 MW Envision 2-Bladed partial pitch.
Resulting Moment at foundation- tower interface [kNm]	100 %	89%
Resulting Moment at seafloor [kNm]	100 %	97%

Table 1 - Comparison of design extreme loads relative to values for the 3-bladed reference turbine. PSF included

4.4.2.1.2 Fatigue loads

Note: The fatigue loads are controller dependant. As the DONG controller is used instead of the Envision controller, the loads reported here may be too large by an estimated 0-5%.

The design fatigue loads are seen in Table 2 (relative to values for the 3-bladed reference turbine). The fatigue loads are higher using the 2 bladed partial pitch technology. They are increased by 32% at seabed and 23% at tower-foundation interface.

	3,6 MW 3-Bladed turbine	3.6 MW Envision 2-Bladed partial pitch.
Side-Side Moment Foundation- tower interface [kNm]	100 %	132 %
Fore-aft Moment Foundation-tower interface [kNm]	100 %	108 %
Side-Side Moment Seabed [kNm]	100 %	123 %
Fore-aft Moment Seabed [kNm]	100 %	111 %

Table 2 - Comparison of design fatigue loads relative to values for the 3-bladed reference turbine. PSF included

It has been validated that the relative difference between the loads is the same when wind speeds below 10 m/s are omitted. This is important as the DONG Controller may perform poorly at low wind speeds due to special issues related to critical rotor RPM.

4.4.2.1.3 Extreme loads with extreme wave excluded

In this section the loading is compared to smaller waves at the same site. This has been done in order to obtain a better understanding of the design loads and to obtain results for sites with small waves. This section also illustrate aspects regarding DLC 6.1 and DLC 6.2, and their PSF values. Two cases are compared, where the first is exactly the same as in the previous sections:

- Case 1 - 50 year extreme wave included (same as Sections 4.4.2.1.1
- Case 2 - No extreme wave (representative for extreme wave loads at sites with mild wave climate).

Figure 8 shows the normalised extreme loads at tower-foundation interface as function of wind direction. Note: partial safety factors not included as both DLC 6.1 and DLC 6.2 loads can be deduced from the plot.

A list of the design points for extreme loads are given in Table 6-4. It is noted that the design extreme load is found in DLC 6.1 for Case 1 - Envision turbine. All other design extreme loads are found for DLC 6.2.

Case	Design point	Turbine	DLC	PSF
1	A B	Envision 3 Bladed Ref.	6.1 6.2	1.35 1.10
2	C D	Envision 3 Bladed Ref.	6.2 6.2	1.10 1.10

Table 3 - Design points for extreme loads with reference to Figure 8

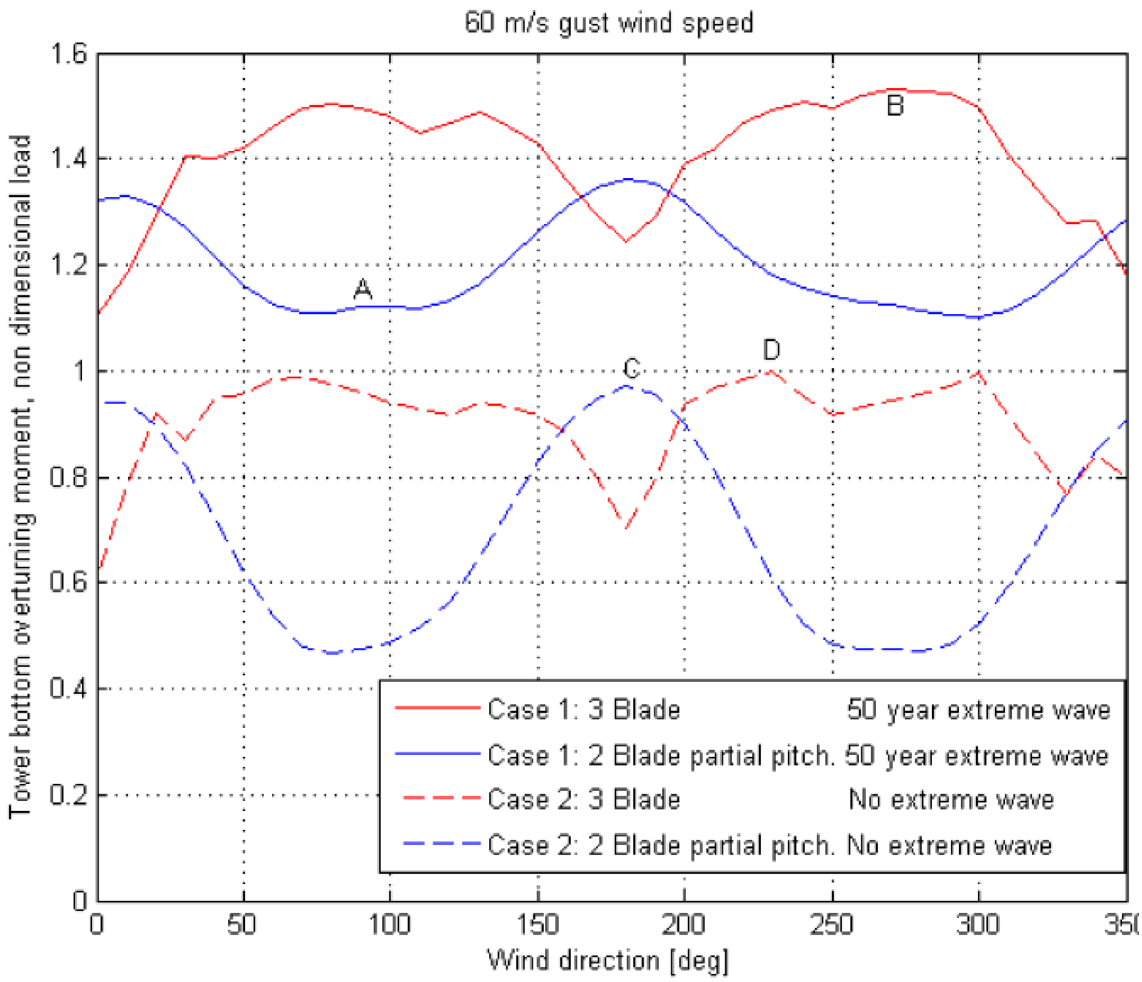


Figure 8 - Extreme loads for 2 different types of wave loading. PSF excluded

Table 4 shows the normalised design loads including PSF. For Case 2 the design extreme loads are 3% smaller for the Envision turbine compared to the 3 bladed turbine.

It may intuitively seem unrealistic that the load reduction using 2 Bladed partial pitch is not larger when extreme wave loading is omitted (Case 2). The reason is that the "extreme load" design driving load case changes from DLC 6.1 to DLC 6.2, where the turbine is subjected to incoming wind from all directions which is not favourable for the partial pitch turbine.

	3,6 MW 3-Bladed turbine	3.6 MW Envision 2-Bladed partial pitch.
Case 1 [kNm]	100 %	89%
Case 2 [kNm]	100 %	97%

Table 4 - Comparison of design extreme loads relative to values for the 3-bladed reference turbine. PSF included

4.4.2.2 Site 2 Mild wave climate

This section differs from Section 4.4.2.1 in having a milder wave climate. Extreme wind speed is approximately 40 m/s. The site has small extreme waves. Water depth is approx. 20m.

Results are calculated as described in Section 4.4.2.1 using actual foundations etc. for this site.

4.4.2.2.1Extreme loads

Table 6-6 shows the normalised design loads. The load reduction potential of 3% for E128 is exactly the same as was found for the equivalent Case 2 in Section 4.4.2.1.3.

	3,6 MW 3-Bladed turbine	3.6 MW Envision 2-Bladed partial pitch.
Resulting Moment at foundation- tower interface [kNm]	100 %	98%
Resulting Moment at seafloor [kNm]	100 %	97%

Table 5 - Comparison of design extreme loads relative to values for the 3-bladed reference turbine. PSF included

4.4.2.3 Conclusions

For a site with extreme wave climate the design extreme load reduction potential is 11% at tower foundation interface and 3% at seafloor.
For a site with mild wave climate the design extreme load reduction potential is 3% at both tower foundation interface and seafloor.

4.4.3 Definition of measurement need for the demonstration turbine

The measurement needs were defined early in the project and the sensor list was approved by DONG Energy.

4.4.4 5.4) Measurement analysis and calculation model validation

Due to the various issues it is decided between DONG and Envision not to base the model validation on measurements. These issues include the use of DONG's controller and that aerodynamic shells are removed from the blade extenders. Also, the aeroelastic models have been tested and compared by the project participants.

4.4.5 Result benchmark with generic 3 bladed wind turbine

Public known data is not easily available for a 3.6 MW 3 bladed wind turbine and therefore it has been decided to base this investigation on the loads found in Section 4.4.2 where offshore sites were considered. The relative change in loads compared to the reference 3 bladed turbine is used to estimate the change in weight of primary steel for both foundation and tower.

It will be assumed that the choice of site and foundation is such that fatigue loads are not design driving. This is a major simplification and in general the high fatigue loads on the E128 will increase the tonnage for parts where fatigue loads are design driving. A case has also been studied where certain parts of the tower and foundation are not affected by extreme load reductions. This represents a more realistic design case.

Besides from manufacturing costs, the following is also considered: Installation, O&M, AEP and decommissioning.

4.4.5.1 Baseline for generic 3 bladed wind turbine

Based on results from Section 4.4.2 the generic 3 bladed wind turbine is assumed to have 12% larger design extreme loads. This represents a site for which E128 is a suitable choice.

The turbine price (incl. tower, excl. foundation) is assumed to be the same between the turbines.

4.4.5.2 Manufacturing

If the reduction in extreme loads is applied everywhere it leads to an equivalent reduction in primary steel tonnage of 12% for foundation and tower.

This is based on an assumption of thin walled primary steel and a 12% reduction in required stiffness.

The baseline steel tonnage for the reference 3 bladed turbine foundation and tower shall be 700mT (700000kg). The reduction in steel tonnage when using the Envision turbine is then 84mT (12%).

The cost savings has been determined in cooperation with the Foundations Project Management department. The savings will optimistically be taken as 151.000 euro per turbine.

4.4.5.2.1 Manufacturing – Fatigue included

Certain parts of the tower and foundation are usually designed for fatigue. Omitting these parts the tonnage which is driven by extreme loads is reduced to approximately 50%.

The saving is then between 63.000 to 75.500 euro per foundation and tower.

This is not taking into account increases in tonnage for E128 due to higher fatigue loads.

4.4.5.3 Installation

The savings in installation costs for E128-2BPP shall be determined based on the following properties of the 2 bladed partial pitch technology:

1. Rotor-Nacelle (RNA) can be assembled in harbour (requires 128m of space for rotor) or on board the installation vessel. In any case it can be done before the installation lifting operation.
2. The 2 bladed RNA is a heavy and stable structure which may be less wind sensitive than a 3 bladed rotor. Therefore, there may be more weather windows available.
3. Possibly, RNAs can be transported faster to site as they take up less space on installation vessel allowing more units to be transported simultaneously (note: only if compared to 3 bladed rotors preassembled in harbour).
4. The hub-nacelle weight for the 3 bladed turbine must be compared to the total rotor-hub-nacelle (RNA) weight for the 2 bladed when considering the price of installation vessel.
5. If single blade mounting is used the number of heavy lift operations is reduced by 1 for the 2 bladed rotor.

These issues have been clarified at meetings with DONG Energy offshore installation experts:

1. Previous experience with assembling entire rotors in harbour has shown that this is a complicated task which should be avoided. Challenges are related to the available space on harbour and installation ship. Also, the rotor/nacelles must be mounted high on deck to ensure clearance between blade tips and sea. This requires special equipment/structures on deck.
2. Previous experience has shown that installation of whole rotors (ex. nacelle) is only possible at wind speeds well below 10 m/s. For comparison, single blade mounting is possible at wind speeds of 12-14 m/s. Even though the E128 Rotor Nacelle Assembly (RNA) is much heavier than just a rotor, it is unlikely that it can be installed at wind speeds higher than for single blade mounting.
3. It is possible to transport the assembled E128 RNA allowing more units to be transported. But it is not recommended and single blade mounting is preferred.
4. As single blade mounting is preferred, there is no weight issues with the Envision turbine. All component weights are comparable to other turbines of the same rated power.
5. The best installation concept is single blade mounting. This process only differs from 3 bladed rotors in the number of installation lifts which is 4 instead of 5 (one blade less installed).

In conclusion, the best installation method is single blade mounting. However, this procedure requires one (1) of the following to be fulfilled:

- The turbine must have turning gear.
- The turbine can yaw 180 degrees during installation.
- Special lifting gear must be available, which can install blades both when the suction side is up and when it is down.

It will be assumed that single blade mounting is possible, thus saving 1 hour of installation time. For a charter price of 130.000 euro per day this amount to 5.500 euro saved per installed turbine.

4.4.5.4 Decommissioning

This shall be based on the same properties as listed in Section 4.4.5.3.

It will be assumed that the decommissioning savings are the same as for installation, i.e. 5.500 euro saved per decommissioned turbine. Even though decommissioning is in 25 years the 5.500 euro will be taken as net present value. This is assumed because the future cost is difficult to determine.

4.4.5.5 Operations & Maintenance (O&M)

The savings in O&M for E128-2BPP shall be determined based on the following properties:

1. Drivetrain may be changed without removal of rotor and hub (special feature of Envision design).
2. General costs are assumed to be equivalent to that of a 3 bladed turbine.
3. The turbine uses a special direct drive concept where the torque is transferred from the rotor to a permanent magnet generator (PMG) through a shaft which is highly flexible in bending. Thereby, damaging bending moments are not transferred into the generator reducing the risk of damage and increasing the efficiency.

These issues have been discussed:

1. It is unlikely that the drivetrain in any competing turbines will fail. Therefore it is not a significant advantage that the drivetrain can be easily replaced.
2. –
3. This is a clear advantage of the turbine. The risk of generator failure is reduced but for competing turbines the actual risk is unknown and it is not possible to estimate cost savings for E128. The fact that risk of gearbox failure is avoided by the direct drive concept is not considered as well as the higher risk associated with the more advanced electronics of the PMG is not considered.

The O&M costs are difficult to determine and will be assumed to be the same as for the reference turbine.

4.4.5.6 Annual energy production (AEP)

The comparison is based on a 3 bladed turbine with the same rated power and wind speed as the 2 bladed partial pitch turbine. However, due to a ramp down of power at high wind speeds the Envision E128 turbine has less annual energy production.

For a typical offshore site (capacity factor=61%) the AEP is reduced by 1.9% for the E128-3.6MW. I.e. an annual reduction in produced energy of 361000 kWh.

Assuming a fixed price of 1 DKK/kWh the net present value of the income loss per turbine during 25 years is -5.087.914 DKK = 678.388 euro (5% discount rate).

4.4.5.7 6.5.8 Final business case and cost of energy

The following case assumes 100 x 3.6MW turbines. It is for the special case where fatigue loads are not design driving in any part of tower/foundation. The change in Cost of energy can be assumed to be equivalent to the change in invested capital described below.

All values are net present value in euro.

Table 6 show the expense changes compared to the reference 3 bladed turbine based on the previous sections. The baseline case shows an increase in total expenses of 4.0% for an assumed reference total investment of 1.3 Billion euro. This increase is driven by the AEP losses. Assuming the AEP losses may be omitted, the expenses are decreased by 1.2%. The typical case where only 50% of the tower-foundation is designed for extreme loading shows a 0.7% reduction in total expenses.

Expenses / tEuro		Baseline 100% ULS	No AEP loss. 100% ULS	No AEP loss. 50% ULS
Reference off-shore park	Total investment	1.300.000	1.300.000	1.300.000
Absolute difference to reference 3 bladed rotor.	Manufacturing	-15.100	-15.100	-7.550
	Installation	-550	-550	-550
	Decommissioning	-550	-550	-550
	O&M	0	0	0
	AEP loss	67.839		
	SUM	51.639	-16.200	-8.650
% change in investment using E128	SUM / Yotal investment	4,0%	-1,2%	-0,7%

Table 6 - Expense sheet comparing differences to 3 bladed rotor. % ULS refer to the fraction of foundation and tower tonnage which is designed for extreme loads. Tonnage increases due to high fatigue load is omitted.

4.4.6 Conclusions

Foundation design loads have been calculated for the Envision 2 Bladed partial pitch turbine (E128) and for a reference 3 bladed turbine. This has been done for 2 sites:

1. Hard wave climate
2. Mild wave climate

For the site with hard wave climate The design extreme loads are decreased by 3-11% for E128. The fatigue design loads are increased by 23-32%.

For the site with mild wave climate the design extreme loads are decreased by 2-3%.

Based on the above the potential cost savings has been analysed for an offshore park consisting of 100 turbines. The baseline result is an increase in total expenses of 4% when using E128.

This is associated with less power production and if this loss is omitted the total expenses are reduced by 0.7-1.2%.

I must be emphasized that the higher costs associated with increased fatigue loading is completely omitted.

5. Utilization of project results

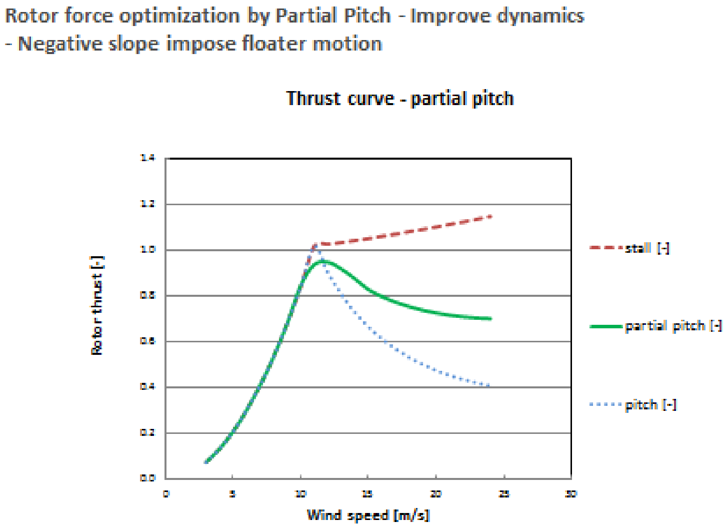
The project have generated valuable learnings for the involved participants and in particular the learning that the PP-2B technology holds strong competiveness in respect to wind turbines on floating foundations is unexpected, but highly appreciated by Envision.

5.1 Floating wind

For floating wind turbines one critical design situation is the extreme wind situation. Here there will typically not only be high wind but also tall waves. The critical for the floater design is the overturning moment. This moment is defined by the height of the tower and the load from the turbine.

For offshore turbines in general there is not gain in having a high tower as the wind shear is so low that there is no real wind increase by having a higher tower. Hence the lower the tower the lower price for the offshore installation. One limiting factor is the distance from blade tip to water surface. Here there are rules in various countries that there should be a minimum distance from blade tip to water surface, to ensure safe passage for ship traffic and service vessels in general. This height is between 20-30m depending on the offshore park and the local rules. The two bladed turbine can be parked in horizontal position and hereby the blade to water distance can be lowered and still maintain a safe distance to the vessels.

In floating wind will 10% tower height reduction result in 10% less overturning moment and more or less 10% smaller floater, which is a very interesting business case.



Further the extreme load can be very low with the 2 bladed partial pitch machine which is also very interesting for the floater design.

Finally the 2 bladed partial pitch machine has a great advantage in the dynamic of the turbine when installed on a floater.

For a pitch turbine the rotor thrust is increased until rated power is reached. Hereafter the blades are pitched to let the air flow through the rotor. Hereby the thrust is decreased. For a floating wind turbine a wind gust at high wind will result in lower thrust that will make the floater and turbine move forward – and hereby inducing more wind. Similar if the wind drops the thrust will increase and therefore the machine will move backward and hereby reducing the wind by the movement of the nacelle. This increase and reduction of thrust will make the control of the turbine instable.

For a stall turbine the thrust will increase at higher wind and hence the floater will incline more at higher wind. A partial pitch machine is a combination of stall and pitch turbine and hence the thrust curve will be a mix of the stall and pitch machine. This will make the controller more stable and therefore easier to control the turbine and the floater inclination, see below figure with the thrust differences for the different turbines.

Various floating offshore projects in France, Japan and US has been investigated and business negotiation has been made with some of the partners and utilities. The below is an example on a ring floater that will be used in projects in Japan and France in the near future – unfortunately not with Envision technology due to commercial reasons.

6. Project conclusion and perspective

The objective of the project was:

1.) To demonstrate the cost saving potential of the Partial Pitch 2-bladed wind turbine technology, and
2.) Through a measurements campaign to verify analysis and development tools for the technology, the currently absent of verified analysis and development tools for 2-bladed technology remains as the main barrier for Partial Pitch 2-bladed market acceptance.

In regards to objective 1.)
The project, DONG Work Package, did not demonstrate a significant cost saving potential, nevertheless Envision is confident that the PP-2B has superior offshore competitiveness potential as the project have generated valuable learnings in regard how an even more efficient PP-2B wind turbine is to be scoped and designed.

In regards to objective 2.)
Today, in contrary to year 2012, the PP-2B technology is a mature and academically described technology. Need analysis tools have been developed and successfully verified and project objective #2 is 100% fulfilled.

Perspective:
As discussed in this report, Envision had initial technical problems with the blades, the nature of the problem is fully understood and solve, nevertheless this incident affected the PP-2B demonstration timeline negatively and the market opportunity for 3-4MW offshore wind turbine was lost. Reviewing market tendencies, Envision have concluded that next high volume offshore wind turbines size to be +8MW and not as previously anticipated a 6MW size.

In this context Envision is presently scoping next global offshore wind turbine platform to compete with known market leaders such as Siemens Wind Power & MHI Vestas based on PP-2B technology.

7. Annex

8. Referencer

Taeseong Kim, F. Z. (2016). *Demenstraion of partial pitch 2-bladed wind turbine.* DTU Wind Energy I-0447 (EN).

9. Relevant links