DeepWind Deliverable

Grant Agreement number: 256769

Project title: Future Deep Sea Wind Turbine Technologies

Deliverable No.: D8.4

Deliverable title: Evaluation (R)

Deliverable status: closed

Name of lead beneficiary: DTU

Nature of deliverable: R

Dissemination level: PU

Due date from Annex 1: M48

Actual submission date: M48

Quality check approval by: Will be reviewed by Torben J. Larsen, DTU

Evaluation of the DeepWind concept
Deliverable D8.4

Uwe Schmidt Paulsen, Michael Borg, Luis Seabra, Davis Verelst, Helge A. Madsen, Troels F. Pedersen, Per Hørlyck Nielsen, Signe Schløer, Charles Smadja (NenuPhar), Jesper Hattel, Stefan Carstensen, Knud Kragh, Ismet Baran, Gerard van Bussel (TUDelft), Carlos Fereira (TuDelft), Ewen Ritchie (AAU), Krisztina Leban, Harald Svendsen (Sintef), Ole Svenstrup (DHI), Petter Andreas Berthelsen (MARINTEK), Erik-Jan de Ridder(MARIN), Lorenzo Battisti (UniTrento),Wei He(Statoil), Paul Veers (NREL)

DTU Wind Energy E-0060(EN)

September 2014

PP26

Deepwind Floating Offshore Vertical Wind Turbine-From Concept to Design(DWII)

Uwe Schmidt Paulsen

PP8

Evaluation of the DeepWind concept Deliverable D8.4

Department of Wind Energy E Report 2014

Uwe Schmidt Paulsen, Michael Borg, Luis Seabra, Davis Verelst, Helge A. Madsen, Troels F. Pedersen, Per Hørlyck Nielsen, Signe Schløer, Charles Smadja (NenuPhar), Jesper Hattel, Stefan Carstensen, Knud Kragh, Ismet Baran, Gerard van Bussel (TUDelft), Carlos Fereira (TuDelft), Ewen Ritchie (AAU), Krisztina Leban, Harald Svendsen (Sintef), Ole Svenstrup (DHI), Petter Andreas Berthelsen (MARINTEK), Erik-Jan de Ridder(MARIN), Lorenzo Battisti (UniTrento),Wei He(Statoil), Paul Veers (NREL)

DTU Wind Energy E-0060(EN)

September 2014

DTU Wind Energy
Department of Wind Energy

Authors: Uwe Schmidt Paulsen, Michael Borg, Luis Seabra, Davis Verelst, Helge A. Madsen, Troels F. Pedersen, Per Hørlyck Nielsen, Signe Schløer, Charles Smadja (NenuPhar), Jesper Hattel, Stefan Carstensen, Knud Kragh, Ismet Baran, Gerard van Bussel (TUDelft), Carlo

DTU Wind Energy E-0060(EN)
September 2014

ISBN 978-87-92896-99-5

Summary (max 2000 characters):

The report describes the DeepWind 5 MW conceptual design as a baseline for results obtained in the scientific and technical work packages of the DeepWind project.
A comparison of DeepWind with existing VAWTs and paper projects are carried out and the evaluation of the concept in terms of cost, as well as the technical and scientific recommendations are performed.
The work is a result of the contributions within the DeepWind project which is supported by the European Commission, Grant 256769 FP7 Energy 2010-Future emerging technologies, and by the DeepWind beneficiaries: DTU(DK), AAU(DK), TUDELFT(NL), TUTRENTO(I), DHI(DK), SINTEF(N), MARINTEK(N), MARIN(NL), NREL(USA), STATOIL(N), VESTAS(DK) and NENUPHAR(F).

Contract no.:
EC-256769

Project no.:
43057

Sponsorship:
European Commission-FP7
under contract 256769

Front page:
DeepWind Baseline 5MW
conceptual design

Pages: 26
Tables: 4
Referencer: 22

Technical University of Denmark
Department of Wind Energy
Frederiksborgvej 399
Building 118
4000 Roskilde
Denmark
Phone 21329405

uwpa@dtu.dk
www.vindenergi.dtu.dk

Preface

The hypothesis of DeepWind is that this concept is developed specifically for offshore application and has potentials for better cost efficiency than existing offshore technology. Based on this hypothesis the objectives are:

i. to explore the technologies needed for development of a new and simple floating offshore concept with a vertical axis rotor and a floating and rotating foundation,
ii. to develop calculation and design tools for development and evaluation of very large wind turbines based on this concept and
iii. evaluation of the overall concept with floating offshore horizontal axis wind turbines.

Upscaling of large rotors beyond 5MW has been expressed to have more cost potentials for vertical axis wind turbines than for horizontal axis wind turbines due to less influence of cyclic gravity loads. However, the technology behind the proposed concept presents extensive challenges needing explicit research, especially:

- dynamics of the system,
- pultruded blades with better material properties,
- sub-sea generator,
- mooring and torque absorption system, and
- torque, lift and drag on the rotating and floating haft foundation.

In order to be able in detail to evaluate the technologies behind the concept the project comprises:

1. numerical tools for prediction of energy production, dynamics, loads and fatigue,
2. tools for design and production of blades
3. tools for design of generator and controls,
4. design of mooring and torque absorption systems, and
5. knowledge of friction torque and lift and drag on rotating tube.

The technologies need verification, and in the project verification is made by:

6. proof-of concept testing of a small, kW sized technology demonstrator, partly under real conditions, partly under controlled laboratory conditions,
7. integration of all technologies in demonstration of the possibility of building a 5 MW wind turbine based on the concept, and an evaluation of the perspectives for the concept.

The results of WP01, WP02, WP03, WP04, WP05, and WP06 are integrated into a conceptual study of a new 5 MW design for comparison and evaluation against existing 5MW offshore horizontal axis wind turbine technology. Upscaling is explored against scaling trends from a 5 MW prototype towards a final 20 MW 'exercise'. Cost elements affecting the distribution of cost are surveyed, and effects with cost advantage potential are considered and the exercise accentuates differences of the concept compared to a 5 MW/ 20 MW offshore horizontal – axis turbine technologies. The results from the technical work packages are readdressed in terms of capitalised knowledge in the new technology field embracing compliance, safety and standards for offshore wind energy converters and the cost projections for upscaling are estimated by different levels of complexity. The conditions at site are discussed and explained for the final design layout calculations in WP01, Task 1.2. Applications of code, standards and regulations as well as decommissioning are surveyed into the calculations of the 5 MW design layout. This report describes site conditions which are relevant to apply for the present design.

In the present report, technical and cost evaluation of the 5 MW DeepWind is made, and the concept is compared to other VAWT concepts.

Risø, September 2014

Uwe Schmidt Paulsen
Project manager and Co-ordinator of DeepWind

Content

Summary

In section 1 a brief presentation of the concept is provided, followed by section 2 with going through lessons learned from the design process of the concept. In the process several iterations have been carried out and we analyse how this process performed.
In section 3 an assessment of the main component parts in the concept is described on the advantages, disadvantages of the concept and what future potential for work might be identified.
In section 4 a qualitative and quantitative comparison of the DeepWind concept is carried against other floating VAWT concepts seen in literature, either existing or on paper. The different concepts are discussed on main commonalities /differences.
In section 5 the concept is evaluated briefly on the costs.
In section 6 an outlook is provided for next steps of the concept.
Section 7 concludes the project goals and results.

1. Introduction

Figure 1 provides a schematic diagram of the second iteration of the floating DeepWind concept, obtained from [1]. This document aims to assess the design of DeepWind concept, highlighting advantages, disadvantages and potential for future work in cost reduction.

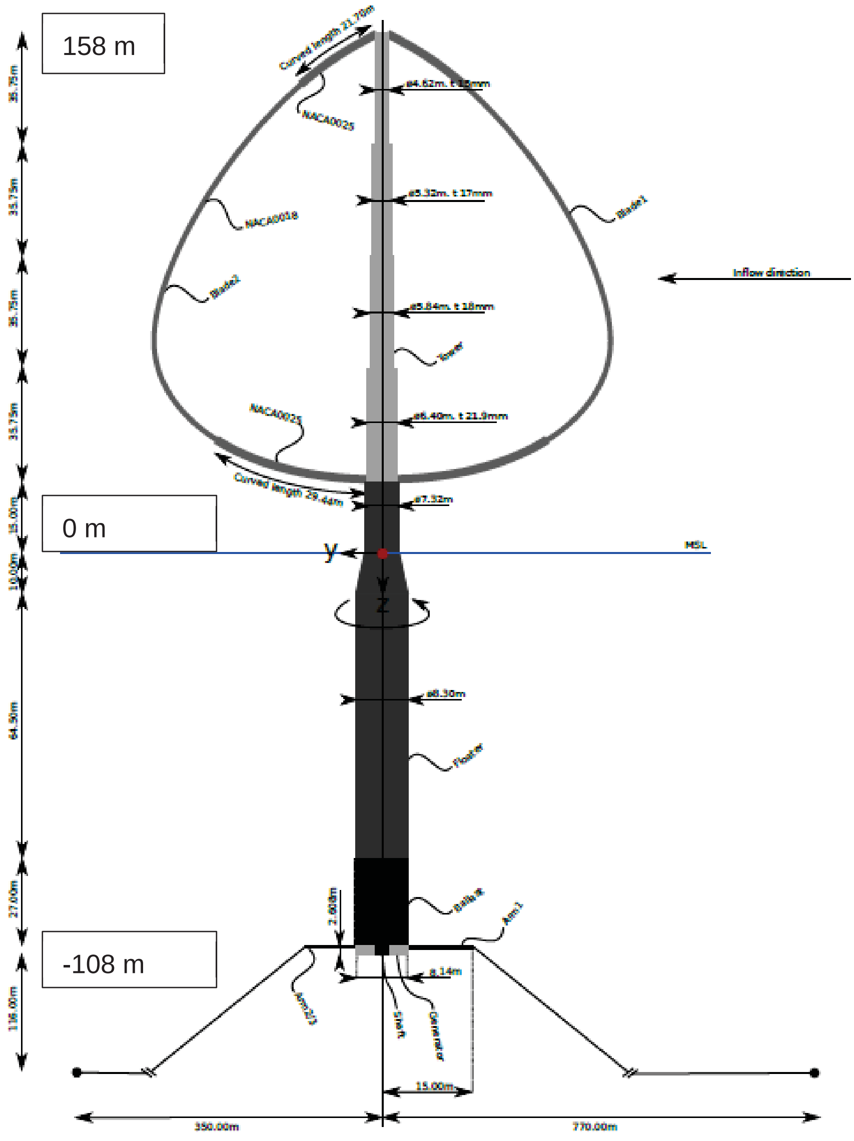


Figure 1 Schematic of the DeepWind concept, obtained from [1]

2. Designing DeepWind: Lessons Learnt & Future Recommendations

The hydro-servo-aero-elastic computations[1.] showed that the DeepWind concept had diverse tuning instability problems originating from a combination of parameters but not least that the basic design is a stall regulated rotor which is known for its instability problems when operating at high wind speeds. Without going into the details of the nature of these instabilities, one should stress out that for these simulation five distinct engineering fields are closely interacting with each other:

- hydrodynamics (floater),
- structural dynamics (tower, blades, floater, mooring lines),
- aerodynamics (blades),
- electro-mechanics (generator), and
- control (generator).

During the DeepWind project, each component was initially designed independently from each other (apart from the obvious design specifications). However, the different design models as used for the controller, floater, generator and blades did use some simplified models to account for the some of the most relevant interactions with the other components.

When in the final stage of the project all different sub components were integrated in the aeroelastic model the results showed the DeepWind concept did work, but it only operated in a stable fashion at some of the predefined load cases. These instability problems did not show up at the same level in the earlier stage of the project due the necessary modelling simplifications required to actually make a first design draft of the respective components. Once the different components had been designed with a certain level of detail, an integrated hydro-servo-aero-elastic HAWC2 model could be drafted and evaluated. Due the amount of manual work involved in the different design processes (which was carried out by different partners), it was difficult to re-evaluate the final design considering the results from the stability analysis with the HAWC2 model. Note that the final integration of the components only took place at a late stage in the project, and therefore only a limited amount of time and resources were available to address the complicated dynamic issues of the system. Also that for dynamic VAWT analysis there is not the at all the same level of experiences from literature to build upon as for HAWT´s.

The conclusion from this design exercise is that when simulating such a complicated dynamical and integrated structure one should consider the different physical interactions in more detail at an earlier stage of the design. In doing so, an integrated design procedure can be carried out, and that will help identifying those operational conditions and design parameters at which stability can be problematic. Consequently, a tough requirement arises from a modelling and design perspective: all different simulation and design models should be able to interact with each other. This is not a trivial requirement, and puts significant emphasis on the software implementation of the different design and analysis models. Additionally, from a design perspective, the design variables that have to be exchanged between the different models have to be carefully planned and defined beforehand. Such future work will significantly benefit from the fact that the analysis now can be carried out with a fully developed and validated hydro-servo-aero-elastic model for floating VAWT´s established in this project.

3. Subsystems Assessment

This section presents a brief overview of the advantages, disadvantages and potential of future work for the subsystems of the DeepWind concept, mainly from the perspective of dynamics, loads and considerations for costs.

	Advantages	Disadvantages	Future work potential
Rotor & Tower	**Rotor**: Reduced blade manufacturing costs, Less complex load regimes on components resulting in simpler and more cost effective structure less prone to failure. The big advantage of the present design is that it does not use any struts and in general no supports perpendicular to the blades. This eliminates the stress concentrations that have been the main cause of failure on VAWT´s. Another major advantage is that there is no loss of power from the struts/blade connections. A third major advantage is that the modal shapes of the blades are fewer and thus less eigenfrequencies that can interact with the 2p load input. **Tower**: connection to both ends of blades reduces bending loads on components	**Rotor**: - Significant sections of blades not at optimal radius (i.e. generate less torque). - Simulations predict blade edgewise instability with flexible blades, still has to be seen whether this occurs in reality. Possible solution to use higher edgewise blade stiffness, stall strips and aeroelastic tuning-In comparison to other VAWT types, this rotor does not perform as well (power generated) when inclined. **Tower**: - Induces wake along full length of blades, reducing extracted power.	Further design cycles utilizing multidisciplinary optimization, with key objectives including: minimize centre of gravity height, maximize shaft torque, minimize thrust line of action & overturning moment, minimize tower and blade connections stresses, maximizing annual energy yield. With regards to aerodynamic rotor design, particular details that may improve rotor performance include: modifying the cant angle of the lower blade root to induce a more aerodynamically efficient design considering self-weight and gyroscopic effects. Consider applying compliant structure strategies to the turbine design to maximize structural capacity whilst reducing loads and CAPEX/OPEX costs.

Transmission /Generator /Controller	- Located at base of support structure, lowering centre of gravity (increasing stability) - Direct drive (no gearbox), reduction in number of components and probability of failure, lower O&M.	- Situated at the bottom of support structure, producing safety issues for maintenance personnel and have similar issues as HAWTs with regards to weather windows (motions at bottom of spar may be significant due to large distance from centre of rotation).	Investigation the potential of using the generator controller to actively reduce mooring line forces and fatigue. Tune controller to damp the edgewise vibrations as has been used on HAWT´s.
Support Structure	- Simplified geometry reduces manufacturing and installation costs -Rotating spar utilizes surrounding fluid as roller bearing, eliminating a major design challenge seen with other floating VAWT concepts (e.g. NOVA) - Rotating spar with ballast is a very efficient damper of the 2P aerodynamic loads variations.	- Power losses through fluid friction with rotating spar. - Requires minimum water depth (>150m), limiting potential sites	-
Mooring System	- Proven technology	- Very low position of fairleads induced greater inclining moments. - Torque arms subject to very large bending moments - In very deep waters catenary lines may incur large capital costs	- Investigate designs to reduce torque arm root bending moments (potentially through the use of interconnecting arms/cables) - Assess taut mooring systems as alternative to reduce global platform motions -Investigate optimization of torque arm positions along spar to reduce inclining moments whilst maintaining desirable centre of gravity (generator assembly would be situated at same position as torque arms)

4. Comparison with other Floating VAWT Concepts

In this section a qualitative and quantitative comparison of the DeepWind concept is carried against other floating VAWT concepts seen in literature. The other concepts considered are:

- NOVA semi-submersible [2] (Figure 2a)
- OC4-DeepWind semi-submersible [3] (Figure 2b)
- VertiWind semi-submersible [4] (Figure 2c)
- Floating axis wind turbine [5] (Figure 2d)
- Spinfloat Tri-Floater [6] (Figure 2e)
- Gwind [7] (Figure 2f)
- SeaTwirl [8] (Figure 2g)

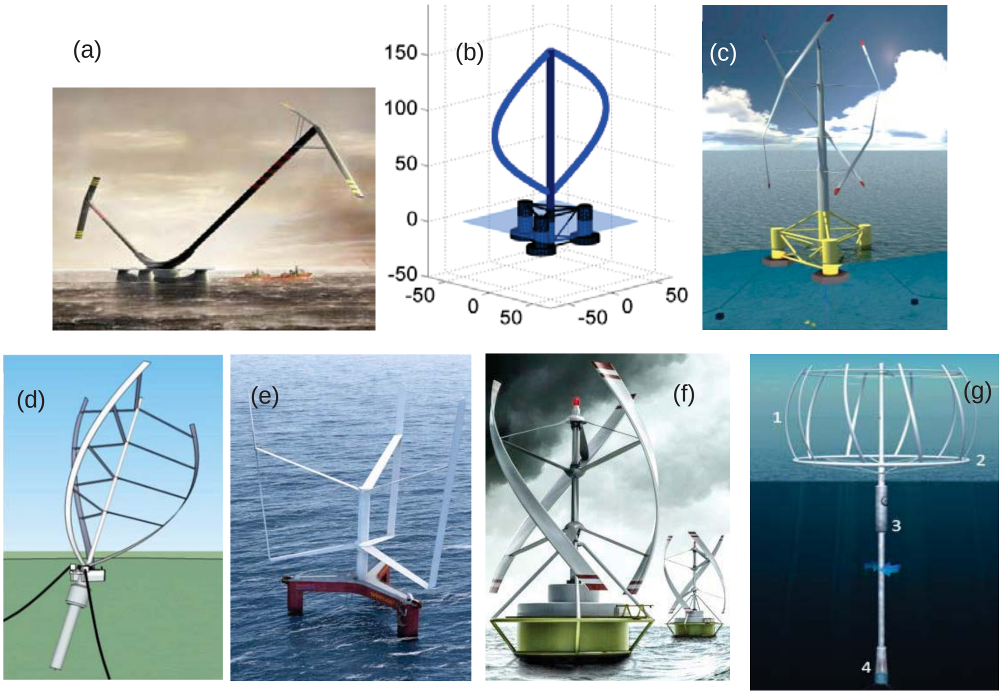


Figure 2 - Other floating VAWT concepts: (a) NOVA semi-submersible; (b) OC4-DeepWind semi-submersible; (c) VertiWind semi-submersible; (d) Floating axis wind turbine; (e) Spinfloat Tri-Floater; (f) Gwind; (g) SeaTwirl

Table 1 - Comparison of floating VAWT concepts characteristics

	DeepWind 1st iteration	DeepWind 2nd iteration	NOVA	OC4-DeepWind	VertiWind	Floating Axis WT	Spinfloat	Gwind	SeaTwirl
Support structure type	Rotating spar	Rotating spar	Semi-sub	Semi-sub	Semi-sub	Rotating spar	Semi-sub	Spar	Rotating spar
Rotor type	Darrieus	Darrieus	V-type	Darrieus	Helical H-type	Truncated Darrieus	H-type	Helical H-type	Helical H-type
Rated capacity (MW)	5.0	5.0	10.0	5.0	2.0	3.0	6.0	-	10.0

Rated wind speed (m/s)	14.0	14.0	12.9	14.0	12.0	15.0	-	-	-
Rated RPM	5.26	6	3.7	5.26	-	17.0	-	-	-
Total Mass, excluding mooring (tonnes)	5640.0	5133.0	11800.0	13353.7	-	602.0	-	-	-
Displacement (tonnes)	6175.0	5321.8	11900.0	14108.0	-	-	-	-	-
Draft (m)	108.0	108.0	15	20	-	-	-	-	-
CM below SWL (m)	80.16	82.5	5.76	8.66	-	-	-	-	-
Pitch Stiffness (Nm/rad)	1.08E+9	1.66E+09	2.65E+9	8.08E+9	-	-	-	-	-

The majority of the other floating VAWT concepts utilize a semi-submersible support structure, except for the Floating Axis Wind Turbine and SeaTwirl concepts, that make use of the same type of support structure as the DeepWind concept and the Gwind concept that makes use of a non-rotating spar. Whilst the semi-submersible expands the operational water depth range into shallower waters than the spar, semi-submersibles are more complex structures increasing CAPEX costs and experience large global platform motions (inducing larger inertial loads on turbine components). The limited draft of the semi-submersibles also implies mooring fairlead position further away from the anchor positions, resulting in longer and more costly mooring lines than the DeepWind concept for a given water depth. Further to this, the semi-submersible does not make use of the surrounding fluid as a supporting roller bearing for the turbine shaft, and hence requires high capacity bearings to connect the turbine shaft to the support structure, undergoing complex load regimes and increasing the cost of the floating wind turbine.

The centre of gravity of the DeepWind concept is also significantly lower than those of the semi-submersible concepts, implying greater stability and reduced rotational platform motions. Whilst the semi-submersibles have larger hydrostatic pitch stiffnesses than the DeepWind concept, the significantly larger waterplane area and submerged volume near the sea surface (and hence in the range of significant wave particle motion) results in larger wave excitation forces than the latter concept.

Whilst the OC4-DeepWind concept makes use of the same rotor geometry as the 1st iteration of the DeepWind concept, the NOVA, VertiWind and Floating Axis Wind Turbine concepts utilize different VAWT rotor configurations. In the NOVA project, one of the main aims was to minimize the overturning moment of the turbine, resulting in a V-type rotor that has a larger radius but lower maximum blade height. The VertiWind and Gwind concepts use a helical H-type rotor that aims to reduce the 'torque ripple' effect on the turbine shaft and powertrain by staggering each blade along its length (cf. Figure 2(c)). Whilst this is envisaged to reduce the loads and stresses on generator and electrical equipment, the more complex blade shape requires support struts that undergo more complex loading regimes, and hence larger struts would be needed that reduce turbine aerodynamic performance and increase cost. The DeepWind turbine is seen to be cheaper to manufacture and less prone to mechanical failures.

Lastly, the rated power capacities vary somewhat between the concepts, mainly due to the time frame of bringing the concept to realization. The VertiWind concept has the smallest power capacity as it is already in the prototype stage, with a full scale onshore turbine currently under construction. The NOVA concept has a capacity of 10MW, significantly larger than the other concepts and currently floating HAWT designs as the project, concluded in 2011, aimed to investigate very large concepts for long-term deployment of floating offshore wind turbines. The OC4-DeepWind was mainly proposed as a reference design for research purposes, adapting the DeepWind 1st iteration rotor to a large, un-optimised semi-submersible originally designed to accommodate a 5MW HAWT that is significantly oversized for the VAWT.

5. Concept Cost Evaluation

The Concept is described on the principle, the technology and the cost in the literature [8,9,10,11,12,13,14, 15,16,17,18] and from other studies more general comparisons are found[19,20,21,22].
The DeepWind 5 MW cost analysis carried out in the project shows a cost of the turbine of 1790 €/kW which is comparable to onshore installations summarized in a comparative study of onshore and offshore wind energy[22.] , and the breakdown into cost of components is shown in. With the present choice for the floater materials, even the rotating spar is relatively expensive.
On the production the wind turbine produces 20 GWh, at the selected site same as Hywind site, which gives with a simplified cost model the cost of energy as 0.46 €/kWh, and discounted 0.065€/kWh for a 100MW windfarm (20 years of operation). A simplified calculation of interest gives 14% on the assumption that the capital costs are loans at 7% interest. The cost differentiation of posts is shown in Figure 3, right. With increasing units a cost model provided by the industrial partner gives for 500 units a LCOE of 0.073€/kWh, and interpolated for 20 units LCOE of 0.130€/kWh. In another study LCOE is reported as 0.087€/kWh. The difference of LCOE results needs to be addressed and elaborated on the models assumptions in detail.

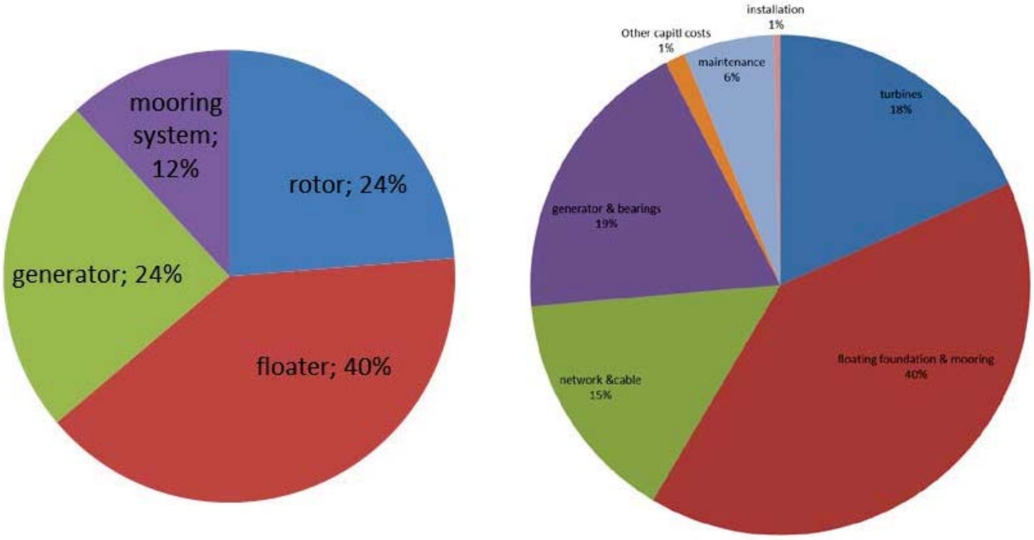


Figure 3 Cost break down of concept: Left-1 unit. Right-20 units in wind farm

For the 20 MW cost of energy is calculated as low as 0.21€/kWh, but now with new materials (concrete) in the rotating spar. This exercise show that changing the floater technology with respect to materials selection it will have substantial influence. This conclusion is also supported in the conceptual study phase[10,11]. The LCOE has not been computed.

6. Recommendations

Based on project experiences, the following recommendations cover the scientific and technical aspects of pursuing the DeepWind concept technology further, and the incitement for the industry to participate in the development.

6.1 Recommendations for scientific programs

To strengthen the technological development and demonstration programs within the floating offshore VAWT it is suggested to set up programs for detailed studies on several topics.

Identified areas for studies are:

- Suggestions for development on new design and research areas in floating offshore foundations, in particular on:
  - blade technologies(pultrusion)
  - integration of blades with rotor(joints)
  - foundation
  - water brake/air brake
  - shaft sealing
  - control systems
  - anchoring systems
  - present and new generator technology

Studies of the Integration of wind turbines:

- Wind farm site assessment of potential offshore positions
- Wind farm detailed case simulations
- Cost assessment of technology
- Cost analysis of wind farm projects (lifetime, materials, sustainability)

Integrated approaches are:

- implementation of vortex model for detailed loads calculations
- research in advanced flow modeling of VAWT rotors
- use of optimisations tools(MDaO)

6.2 Recommendations for technology development

The present overview details on key issues and objectives to be dealt with, and the indication of the time for maturing the technology expressed briefly as an indicator and the need for research and development, seeTable 2.

Table 2Technology development overview

Technology	Objectives	Technology perspective I/II/III	R&D perspective	Industrial perspective
Rotor technology	Profile optimization Blade integration Optimisation	I	Yes	Yes
Foundation technology	Development of cost effective structures (materials)	I-II	Yes	Yes
Generator technology	Permanent magnet multi-pole generators	I-II	Yes	Yes
Transition of concept	Up-scaling, Optimizations	I-III	Yes	Yes
Bearing	Industrial optimization	I-II		Yes

technology				
Shaft sealing	Transition of present ship or submarine technology	I-II	Yes/No	Yes
Safety Systems	Transition of present Safety technology	I-II	Yes	Yes
Anchoring& Seabed	Anchoring technology Seabed assessment	I-III	Yes	Yes

Key

I: short period 1-3 years, II: medium period 5-8 years and III: long period 10-15 years

6.3 Rotor technology

The development of efficient rotors is an overall key objective for efficient and economical wind turbine rotors. Codes have to be designed to deal with bottlenecks from manufacturing process of rotor parts (blades, blade fixing, materials physics and - technology, etc). The code makes it possible to encounter profile optimization, for which the development has to be implemented on larger blades made of pultruded GRP, GRE or CRP. The research on scaled kW-MW rotors enhances the concept development by application of rotor aero-elasticity, and by building, testing and evaluating demonstration wind turbines. The verification of codes is made in a demonstration development program with scaled rotors. Large flexible blades are likely to induce vibrations if not designed well; a thorough investigation of the rotor and the other parts are needed to assure a feasible structure. MDAO has been used to obtain good solutions.

6.4 Foundation technology

As indicated in the reports the rotating spar is a structural important part of the entire concept. The rotor part, its weight(eg materials selection) and counter-weight will be in interaction, and studies have to be carried out in order to account cost sensitivity. Research and development at this stage will be a precondition for exploring the techno-economical perspectives of the concept. Optimization of foundations used for this offshore application is developed with emphasis on looking into more detail on specific materials like pre-tensioned concrete or fibre reinforced concrete, steel, GRP and similar materials; thus providing a basis for durable and cost effective foundations (rotor tube, transition part, floating rotating spar). Also the marine life has to be incorporated.

6.5 Shaft sealing and deep sea bearings technology

The sealing of electrical components against water ingress is of major importance. The verification at more deep sea places with generator module penetration/equilibrium of sea-water under high pressure in the area of roller bearings or similar is an area of research. Sealings and bearings technologies known from ships, submarines and from tidal turbines are presently the state of the art technology. Bearings made with magnetic material are promising, but needs demonstration.

6.6 Generator technology

Promising direct-drive permanent magnet (PM) machines are perhaps attractive with higher efficiency but with lower power to weight ratio compared to electrically excited machines. In the case with the DeepWind concept with the floating and rotating offshore foundation, it might be advantageous due to the stability of the structure to place it even higher up than at the end of the rotating spar.

6.7 Safety Systems

The suggestions incorporate development of a safety system which has a known function within the wind energy community, except that the technology has to be developed for efficient operation under submerged sea-water conditions. Air-brakes might be an alternative option. The permanent magnet generator technology allows to use electrical braking as well to assist in in safety strategies.

6.8 Anchoring and sea-bed

Presently the torque leveler of the lowest part of the rotating spar is interconnected with an anchor part and a cable system descending to the sea-bed and fixed there. Mooring systems(mooring lines and anchoring) costs are representing a substantial cost share and needs cost reduction by looking into new materials selections for the mooring lines and into anchoring technology. New conceptual mooring systems have to be developed.

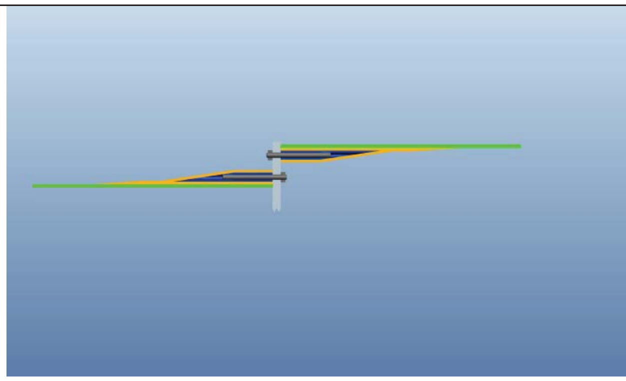
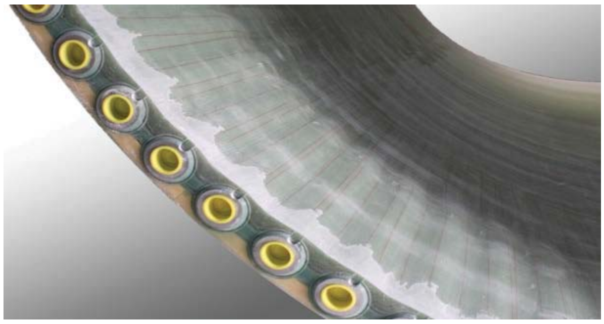
6.9 Risk assessment

During the project, potential technical risks were identified, and now at the end of this project we have compiled the list against the achievements, see Table 3.

Table 3 Technical risks assessed in DeepWind

Risk identified	Status from conceptual design
Structural Resonance of the elastic modes of the rotor can cause destructive vibrations if they are coincident with the per rev excitations of the aerodynamic loads. All these resonances must be avoided. The best (but perhaps too expensive) solution is to put all the elastic modes above the first three harmonics of the loading in the operating range.	A servo–aero-elastic tuning instability seems to occur by an interaction of the combined shaft and blade torsional mode and the controller. This only showed up at stalled conditions at high wind. Therefore a fixed rotational speed operation was investigated and worked fine below stall. During stall operation instability in the yaw degree of freedom of the mooring system was found. This instability seemed to influence the forces on e.g. the blades to a major extend.
Instability: Flutter (aeroelastic instability) and whirl (divergence instability) must be predicted and avoided. These are instabilities that are independent of wind excitation (are self-excited) and will depend only on operating speed.	The tip speed is so low (less than 50m/s) that flutter instability has not been a problem. The main instability or low damped mode on the blades has been for the edgewise vibration at high wind where the flow over the airfoil is stalled. Increase of the edgewise stiffness has been found to decrease the problem.
The durability of the new manufacturing approach to blades including pultrusion and the joining of pultruded parts into an integrated whole. These blades need to limit the built in stresses due to making curved sections out of straight pultrusion.	Having an advanced numerical simulation tool for the pultrusion process is a challenging issue. Nevertheless, we have developed this and the simulation tool is capable of predicting the temperature, degree of cure as well as the residual stresses. (See D2.3 and D2.4). Alternative to the straight pultrusion, a “curved” pultrusion can be used which is a developing technology and patented in 2008. Using this manufacturing technique, the blades or blade parts can be produced in “arched” shape. This would

	prevents the bent-in place process and internal stresses.
The ability to pultrude very large chord length blades with multiple open cells has not been demonstrated. It is not likely to be possible. Even if it is, such blades are likely to have built in strains that are too high when bent into place. A solution that relies on pultruding portions of the blade separately and then joining them along the length should be pursued.	Technically it is possible to pultrude 10-15 m cross section for 20 MW design. A 3 m long cross section has already been manufactured in the industry. A forming die with 1-2 m length would be sufficient to have a fully cured blade at the die exit. Polyester could be used since it is cheaper than epoxy. The combination of unidirectional fiber, continuous filament mat and woven fabrics can be used as a fiber reinforcement. 100 mm thick glass/polyester product has already been pultruded in the industry (source: Fiberline) The alignment of the reinforcements would have high risk for a chord length of 10-11 m. The initial tool cost would be so high: 10-15 m by 1-2 m steel block. A custom made pulling device should be planned with a pulling capacity of ~150-200 tons. The alignment of the mandrel would be one of the main challenging issues. Mandrel is used to manufacture the hollow sections inside blade profile. A huge resin bath or resin injection chamber will be needed which would be expensive (but only for the initial pultrusion set-up). The required space of facility to make a production for lengths of couple of hundred meters. Technically it is possible to pultrude very large blades with cavities. However, the capacity of the pultrusion line would be a challenging issue to be considered. A custom made pulling device can be design to pull the large section. The forming die which is made of a steel block will be relatively expensive, on the other hand a 1-2 m long die would be sufficient to cure the blade completely. The alignment of the reinforcement will be the main challenge during processing.
The connections from the blades to the tower and between different tower sections are highly susceptible to fatigue weakness. Adhesives are susceptible to the large variation in thickness due to the large sizes of the parts. Welds are susceptible to the skill of the welder. Both will require inspection of some sort.	In parallel with the aerodynamic and structural design of the present 5MW design, novel asymmetrical airfoils have been developed at TUDelft, which provide very interesting opportunities to improve both the structural and aerodynamic properties of the Deepwind design In DeepWind, the sectionized rotor concept has been developed in which three pultruded blade profiles are connected to each.

	 Several solutions for this connection are available such as using an adhesive for bonding the sections together. However, there is no available reference in the literature related to this bonding process. Another solution is to co-cure a mechanical connection to the pultruded blade profile. An example is shown below, where a root section is pre-manufactured and co-cured with the blade for a large horizontal wind turbine.  This type of connection can be combined with a similar connection on the accompanying blade part. For the Deepwind project the inner blade part may be manufactured with other techniques or materials as the outer blade part for lower costs or ease of assembly. The concept of assembly of blade sections with bolted connection is also known for large horizontal wind turbines
If there are negative drag coefficients due to tower rotation (as the CFD suggests), the possibility of transferring rotational energy into translational energy could cause problems. If the elastic motions of the tower are fed by energy of rotation it could lead to elastic instability.	Constant current would only result in constant Magnus forces on the platform. Considering the oscillatory wave particle motion, the oscillatory component of the Magnus force would have the same frequency range as the wave excitation forces, albeit in different directions. As the platform natural frequencies have been established beyond this range, there should not be instabilities arising from this source.
Calculated extreme values need to be based on simulation of several stochastic load cases. The estimated extreme values will depend on	With the tools developed in DeepWind, detailed investigations can be studied analyzed for different scenarios.

extrapolation to the extreme expected for the life of the turbine.	
Turbine performance depends on the stall regulation of power. VAWTs are always exposed to dynamic stall, which is also influenced by whether the airfoil is clean or soiled. Loads are also highly affected by the nature of the dynamic stall.	Dynamic stall is standard option in the aeroelastic simulation tool. However, deep stall and dynamic stall effects are still lagging to be explored and validated experimentally in full scale testing. It has been shown during the simulations that the maximum power depends strongly on the maximum rotational speed and it is foreseen that the control system for a final design must be design for some feedback from power level to set rpm when approaching rated power.
The must be some method of stopping the turbine without the generator is essential. It must also be able to lock the rotor for service and maintenance.	Different concepts for a safety system for stopping the system independently of the control system have been investigated on a conceptual level without a firm conclusion. Alternatives include hydrodynamic braking "wings", sinking the turbine into the water, and aerodynamic braking flaps. The issue is important and needs further investigation.
There must be a feasible approach to simply and easily accessing and maintaining the generator and main bearing. The best solutions would allow you to remove, replace and carry the combined generator/bearing unit to shore for service. Minor serviced should be easily done at sea.	Alternative layouts for generator and electrical equipment offering different access options have been considered on a high level. Some electrical equipment may be moved above the sea surface. Access to generator and main bearing may be simplified by flipping the turbine to horizontal position on the sea surface, in a way similar to concepts for installation. This or other alternatives have not been investigated in any detail. However, the issue is important and needs further investigation.

7. Conclusion

DeepWind has elaborated in eight work packages on technical challenges and obstacles, as shown in the figure -overview of elaborated work packages, and partners:

- Work Packages:
    1. Aero-elastic fully coupled code implementation and simulation
    2. Blade technology and blade design
    3. Generator concepts
    4. Turbine system controls
    5. Mooring, floating and torque absorption systems
    6. Exploration of torque, lift and drag on a rotating tube
    7. Proof-of-principle experiments
    8. Integration of technologies and upscaling

Figure 4 Overview of elaborated work packages in project

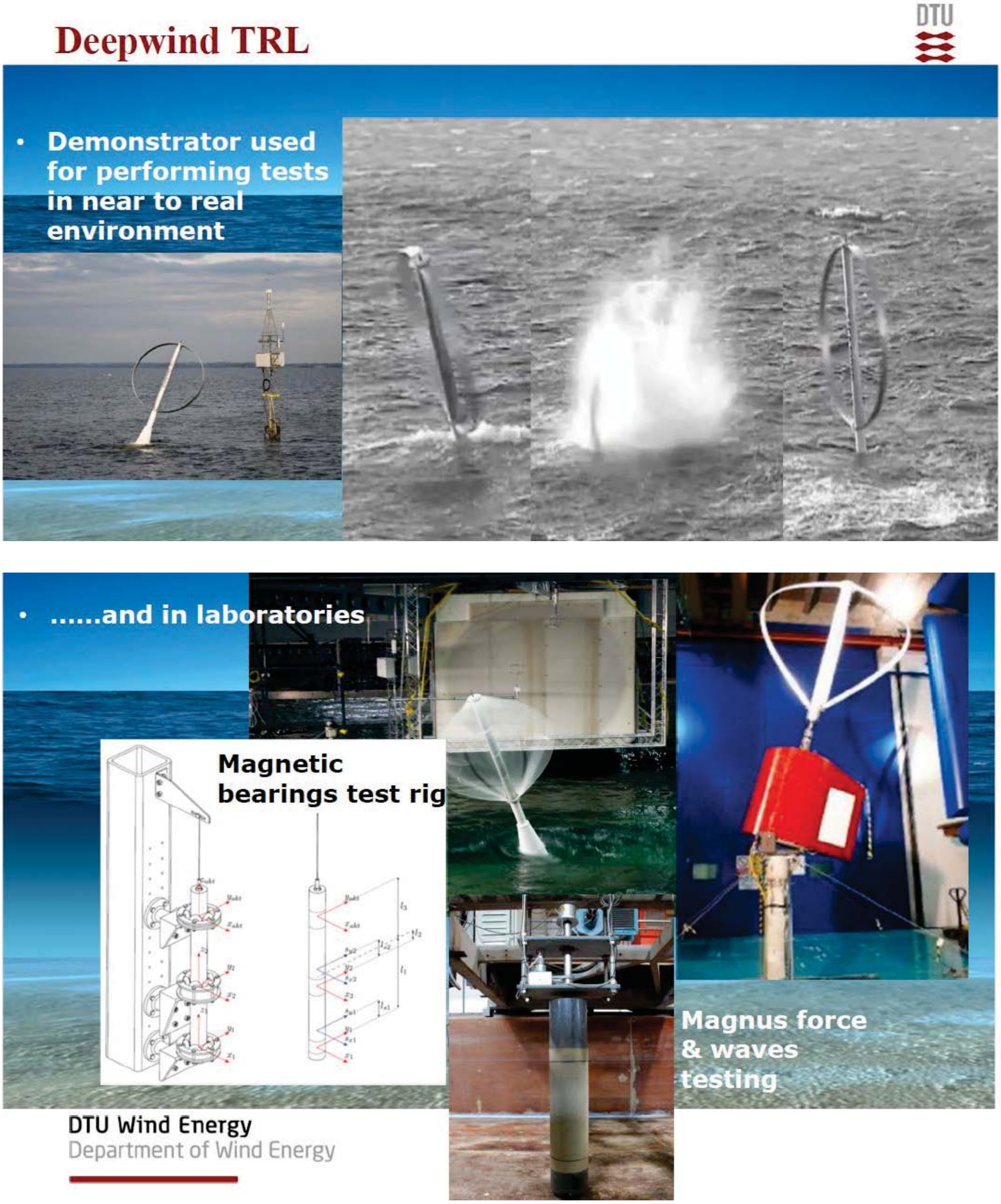


Figure 5 Activities elevating technology readiness level(TRL)

DeepWind has, based on state on-the art conceptual design, the potential for substantial cost reduction in production, installation and O&M for deep sea conditions. Particular emphasis is placed on the system integration of main components (rotor including blades and reliable joints, shaft and mooring system, generator and controls etc.) into a complete design developing optimised solutions for manufacture and production that move closer to market. Future actions would be to refine tools developed, to confirm that the low part count leads to substantially lower production costs and high reliability and also to improve the present 5 MW (and 20 MW) concept into an optimised cost effective design. The aim is to achieve TRL progression through testing, not only of the hydrodynamic system behaviour but through developing procedures or insight into procedures for installation and O&M. A number of technical papers and reports have been produced and in this way proper documentation has been carried out.

In conclusion, the work packages conducted in the project have resulted in simulation tools, activities and results that have elevated the DeepWind concept into a technology that is tangible from an industrial point of view. Initiatives have been done to describe how a business plan should be engineered.

8. References

[1.] Detailed Load Analysis of the baseline 5MW, Verelst D., Madsen H., Kragh K. Belloni, F.DTU Wind Energy E-0057 September 2014

[2.] DeepWind Concept Collu, M., Brennan, F.P., Patel, M.H. (2012): Conceptual design of a floating support structure for an offshore vertical axis wind turbine: the lessons learnt, Ships and Offshore Structures, Vol. 9, No.1, 3-21.

[3.] Borg, M., Wang, K., Collu, M. and Moan, T. (2014), Comparison of two coupled model of dynamics for offshore floating vertical axis wind turbines, ASME 33rd International Conference on Ocean, Offshore and Arctic Engineering, 8-13 June, 2014, San Francisco, USA.

[4.] Cahay, M., Luquiau, E., Smadja, C., Silvert, F. (2011), Use of a vertical wind turbine in an offshore floating wind farm, Offshore Technology Conference, 2-5 May, 2011, Houston, Texas, USA.

[5.] Akimoto, H., Tanaka, K., Uzawa, K. (2011), Floating axis wind turbines for offshore power generation – a conceptual study, Environ. Res. Lett., Vol. 6.

[6.] http://www.spinfloat.com/ressources/documents/1/190,3_SF_20140411-PR-Spinfloat-Consortiu.pdf

[7.] http://www.gwind.no/

[8.] Paulsen U. ,Pedersen TF, Vita L. 2007. Vawt Litterature Survey Risø-2612(EN)

[9.] Paulsen U., Pedersen TF, Vita L. 2007. Existing VAWT Technologies Risø-2613(EN)

[10.] Paulsen U. ,Pedersen TF, Vita L. 2008. Floating VAWT Concepts Risø-2614(EN)

[11.] Paulsen U. ,Pedersen TF, Vita L. 2008. Floating VAWT wind farm concepts Risø-2615(EN)

[12.] Paulsen U. ,Pedersen TF, Vita L. 2008. Recommendations for floating VAWT technology demonstration and development Risø-2616(EN)

[13.] Sarwar K. Cost Model for Floating offshore Vertical Axis Wind Turbines, TuDelft, DTU EWEM MSC thesis 2014

[14.] Paulsen Uwe S., Madsen Helge Aa,Kragh Knud,Nielsen, P.H.,Baran I.Rietchie E.,Leban Krisztina M.,Svendsen Harald,Berthelsen Petter A.,van Bussel Gerard J.W.,Fereira, Carlos S.,Chrysochoidis-Antsos Nichos The 5 MW DeepWind floating offshore vertical wind turbine concept design - status and perspective part of: Proceedings - EWEA 2014, 2014, European Wind Energy Association (EWEA), Presented at: European Wind Energy Conference & Exhibition 2014, 2014, Barcelona Article in proceedings (Peer reviewed)

[15.] Vita. L. 2011 Offshore Floating vertical Axis Wind Turbines with Rotating Platform. Risø-PhD-80(EN) August 2011.

[16.] Berthelsen Petter Andreas 2014 Conceptual design of a floating support structure and mooring system for the DeepWind project. D5.2 September 2014.

[17.] Leban, K. 2014 Design Tool for Direct Drive Wind Turbine Generators PhD Thesis AAU 2014

[18.] Paulsen. U.S. et al DeepWind-from idea to 5 MW concept EERA DeepWind'2014, 11th Deep Sea Offshore Wind R&D Conference

[19.] Griffith T. 2014 Innovative Offshore Vertical-Axis Wind Turbine Rotors Project. SANDIA, Presented at VAWT Workshop at DTU Risø 16-17 June 2014.

[20.] Schelbergen, M. 2013 Structural Optimization of Multi-Megawatt, Offshore Vertical Axis Wind Turbine Rotors. Identifying Structural Design Drivers and Upscaling of Modern, Large Vertical Axis Wind Turbine Rotors MSc Thesis TUDelft

[21.] Berthelsen Petter Andreas, Fylling Ivar 2014 Conceptual design of a floating support structure and mooring system for a vertical axis wind turbine Omae Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering 2012.

[22.] Kost C. 2013 Levelized Cost Of Electricity Renewable Energy Technologies Study Frauenhofer ISE November 2013

Acknowledgements

I would like to thank the European Commission for letting science being the leverage in narrowing the gap between research and applied technology for the industry. Also I want to thank DTU for support and colleagues in DTU Wind Energy for constructive feedback, discussions and technical help wherever needed.

I would particularly like to thank Lorenzo Battisti and his team from Trento University to contribute with wind tunnel measurement results, and Trento University and DTU also for sponsoring the documenting testing of the rotor in the wind tunnel of Polytechnico Milano and allowing me to explain the concept upfront.

I am also thanking Dr. Daniel Griffith, SNL (USA) for interesting and fruitful exchange of ideas, papers and support during the project.

The material being released is based on reports provided for the DeepWind project, all provided under EU actions.

The work is a result of the contributions within the DeepWind project which is supported by the European Commission, Grant 256769 FP7 Energy 2010- Future emerging technologies, and by the DeepWind beneficiaries: DTU(DK), AAU(DK), TUDELFT(NL), TUTRENTO(I), DHI(DK), SINTEF(N), MARINTEK(N), MARIN(NL), NREL(USA), STATOIL(N), VESTAS(DK) and NENUPHAR(F).

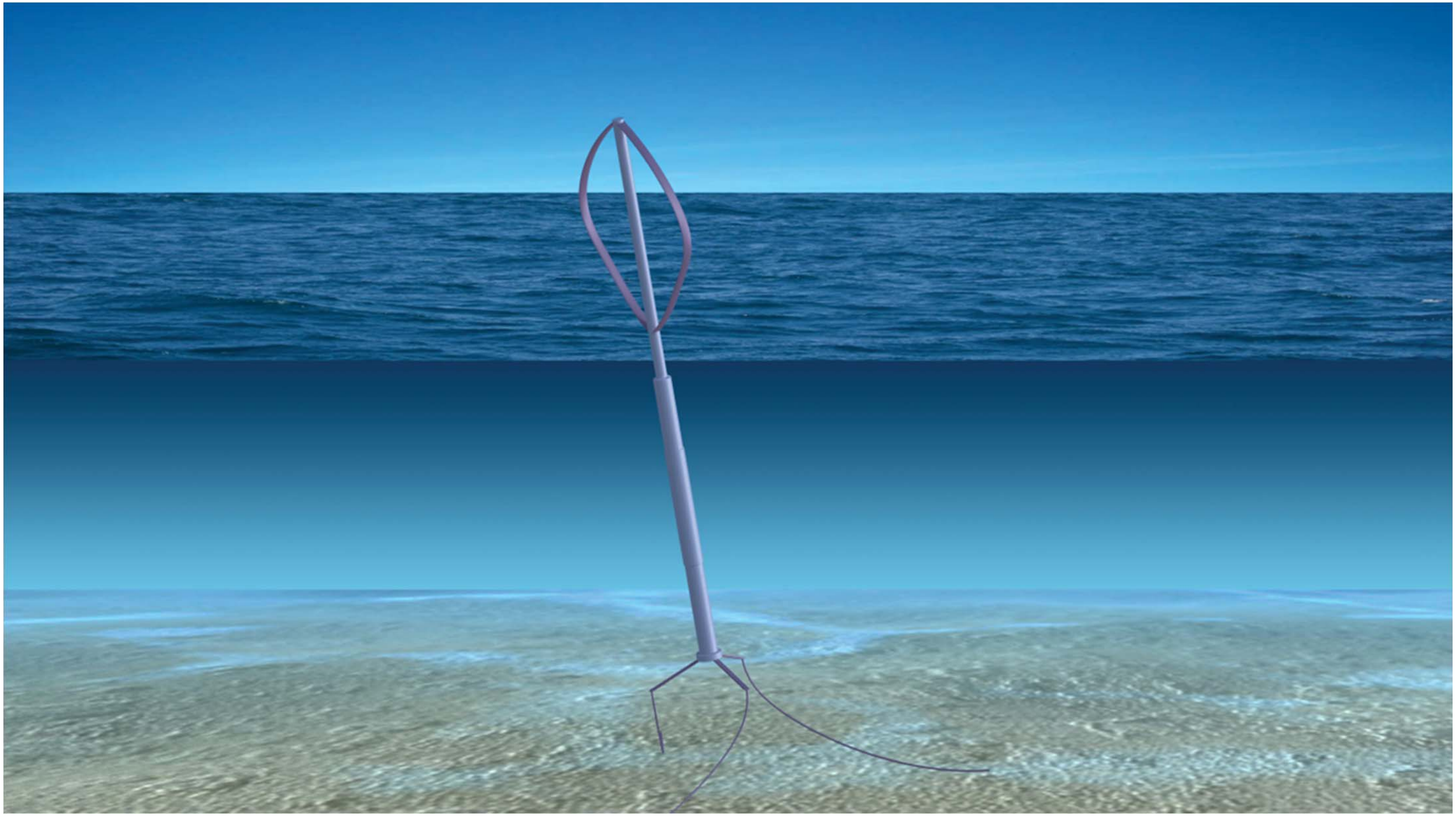
DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

Technical University of Denmark
Department of Wind Energy
Frederiksborgvej 399
Building 118
4000 Roskilde
Denmark
Phone 46 77 50 85

info@vindenergi.dtu.dk
www.vindenergi.dtu.dk

Deepwind Floating Offshore Vertical Wind Turbine-From Concept to Design(DWII)



DTU Wind Energy
Department of Wind Energy

Uwe Schmidt Paulsen (uwpa@dtu.dk)

DeepWind (2010-2014)

- A radical new design- aiming for better COE and a more reliable wind turbine
  - Few components-less failures at less cost
  - Pultrusion-less failures; cost approximately 30% of conventional blade
  - Operation not influenced by wind direction
  - New airfoil profiles available for better efficiency
  - Simple stall control with overspeed protection
- Rotating spar with high Aspect ratio-Less displacement than existing concepts
- No nacelle-low center of gravity - high stability
- Upscaling potential

Paulsen et al. *The 5 MW Deepwind Floating Offshore Vertical Wind Turbine Concept Design - Status And Perspective* Proceedings of EWEA 2014,Barcelona

DeepWind (2010-2014)

- Work Packages:
  1. Aero-elastic fully coupled code implementation and simulation
  2. Blade technology and blade design
  3. Generator concepts
  4. Turbine system controls
  5. Mooring, floating and torque absorption systems
  6. Exploration of torque, lift and drag on a rotating tube
  7. Proof-of-principle experiments
  8. Integration of technologies and upscaling

Partners:

- ✓ Risø-DTU, MEK-DTU, TUDelft, Aalborg University, DHI, SINTEF, Marintek, Università di Trento, NREL
- ✓ Vestas, Nenuphar, Statoil

Deepwind TRL

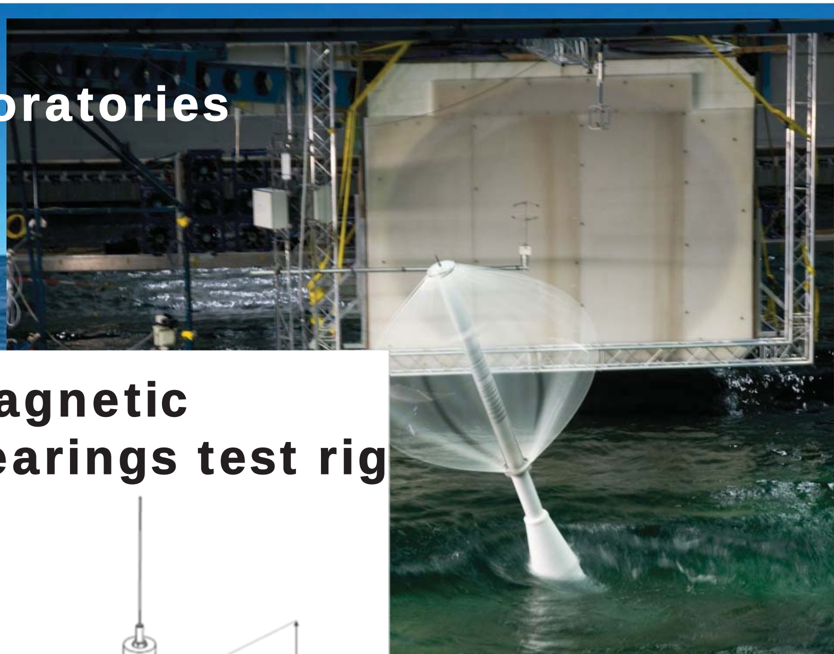
- Demonstrator used for performing tests in near to real environment

DTU Wind Energy
Department of Wind Energy

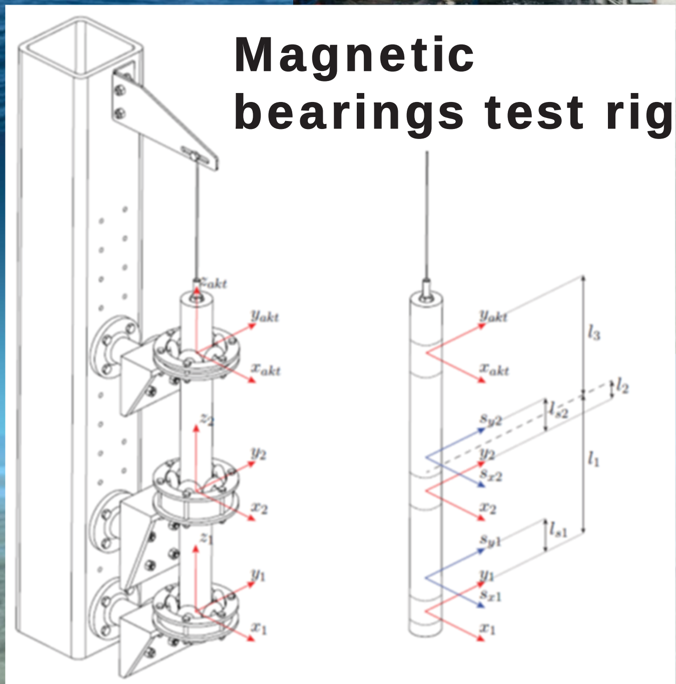
Uwe Schmidt Paulsen (uwpa@dtu.dk)

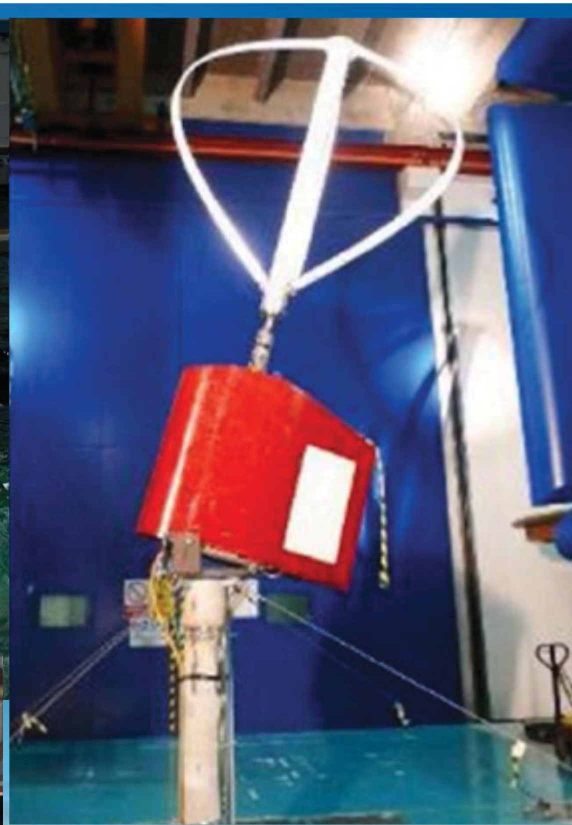
Deepwind TRL

- ……and in laboratories



Magnetic bearings test rig





Magnus force & waves testing

DTU Wind Energy
Department of Wind Energy

Deepwind Floating Offshore Vertical Wind Turbine-From Concept to Design(DWII)

1. to transform the DeepWind floating vertical axis turbine concept into a robust competitive offshore power system, through significant reduction of production, installation, and O&M costs with an affordable COE target below 100 €/MWh

2. to exploit the simple DWII design with yard assembly, towing to site and final installation without use of expensive lifting equipment

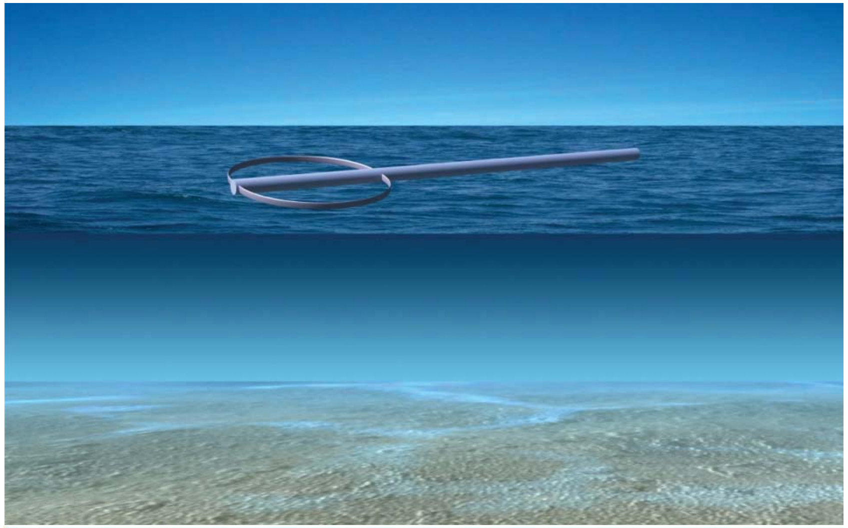
3. to bring the current state-of-the art 1 kW DeepWind lab tested proof-of-concept into more realistic environments and thereby lift the TRL from 3-4 to TRL 4-5.

4. to utilize strong synergy of knowledge acquired from DeepWind consortium, from experienced partners with particular competences and industry to accelerate development of a radical new energy technology with upscaling potentials

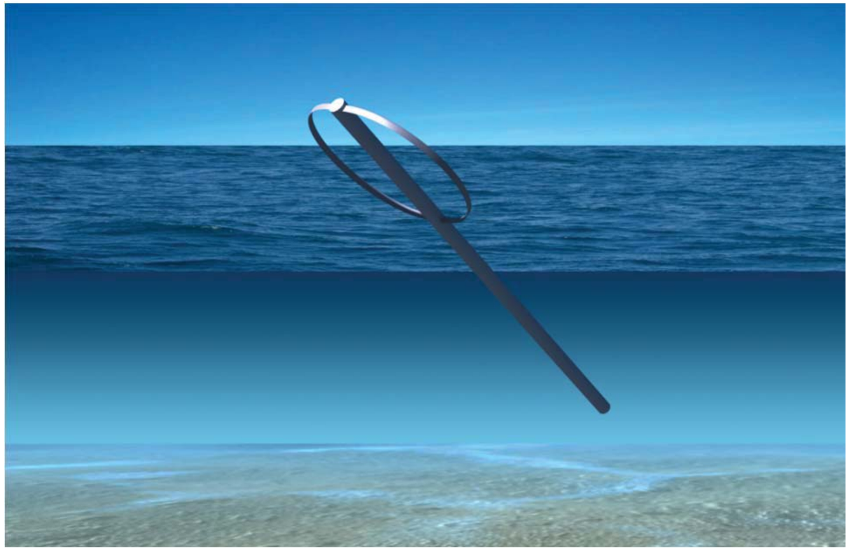
DWII Design

Installation, Operation and Maintenance

- INSTALLATION
  - ✓ Using a two bladed rotor, the turbine and the rotor can be towed to the site by a ship. The structure, without counterweight, can float horizontally in the water. Ballast can be gradually added to tilt up the turbine.

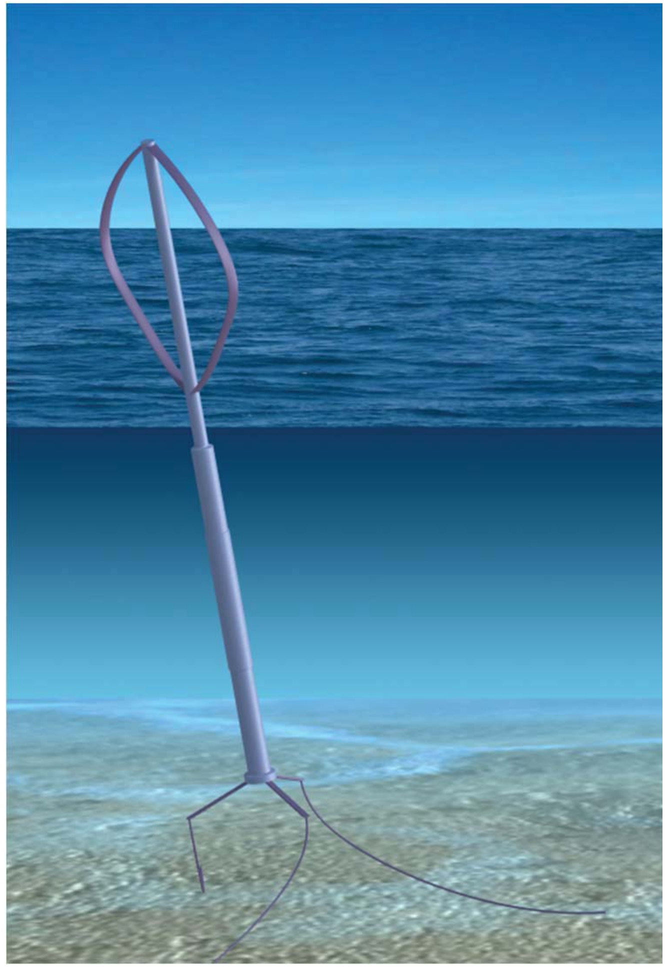


- O&M
  - ✓ Moving the counterweight in the bottom of the foundation is possible to tilt up the submerged part for service.
  - ✓ It is possible to place a lift inside the tubular structure.



DWII Design & Project contributions

- Pultrusion technology allows for reliable low cost blades with extraordinary material properties and high quality
- Concept simplicity
- Few components with less down time failures
- Cost-effective different materials for large structure
- Specific requirements to maintain the underwater components



1. **Review of DeepWind concept and design tools**
2. **Topology optimization of subcomponents and integrated design into a MW design**
3. **Technology validation in relevant environment**
4. **Cost of production, installation, O&M for MW design**
5. **Closer to market actions**