Retrospective aspects of DeepWind (ANFSCD)

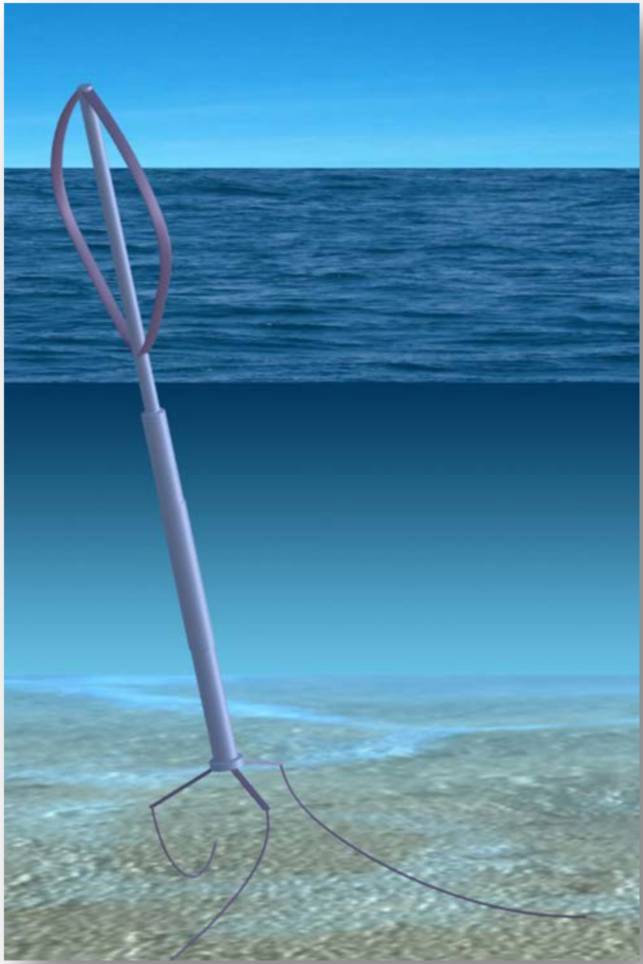
Presented at SuperGen Wind Hub General Assembly meeting, Cranfield, UK

23 November 2016

Uwe Schmidt Paulsen uwpa@dtu.dk
Loads and Control section

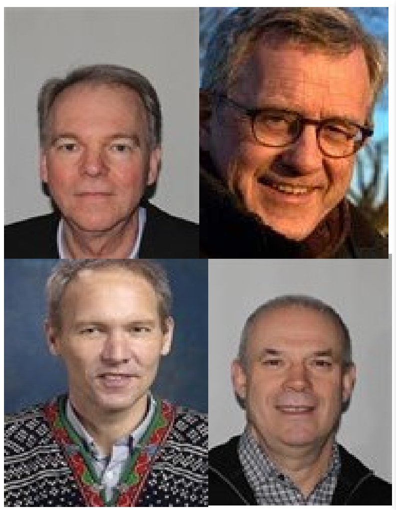
Contents

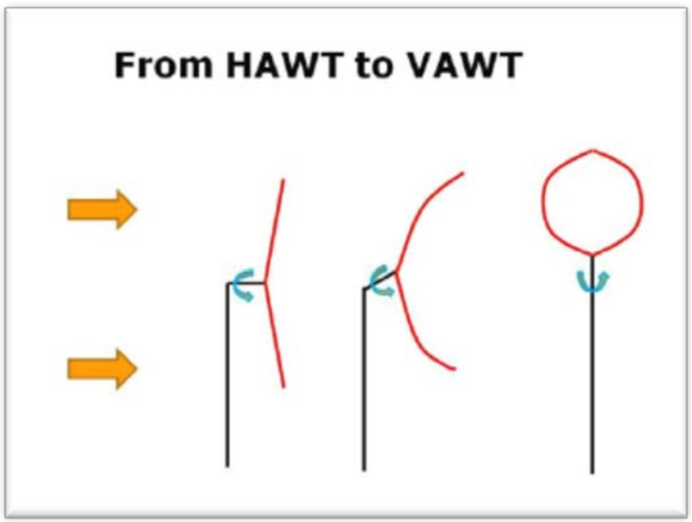
- What is DeepWind
  - Motivation and Background
  - Concept
- Design Status
  - Design tools
  - Rotor
  - Floater
  - Generator and Bearing technology
  - Controls
- Conclusions



What is DeepWind?

- How was it identified?-A creation of concept?-Creative art?





Creators

Back in 2009:

..The installed wind power in Europe is expected to reach 230GW in 2020(it was 120GW at the end of 2008)...

..40GW are expected to come from off-shore wind power, meaning a growth of 28% in the annually new offshore power installation for the next 10 years...

..Offshore wind power is more than 2x costlier than onshore power..

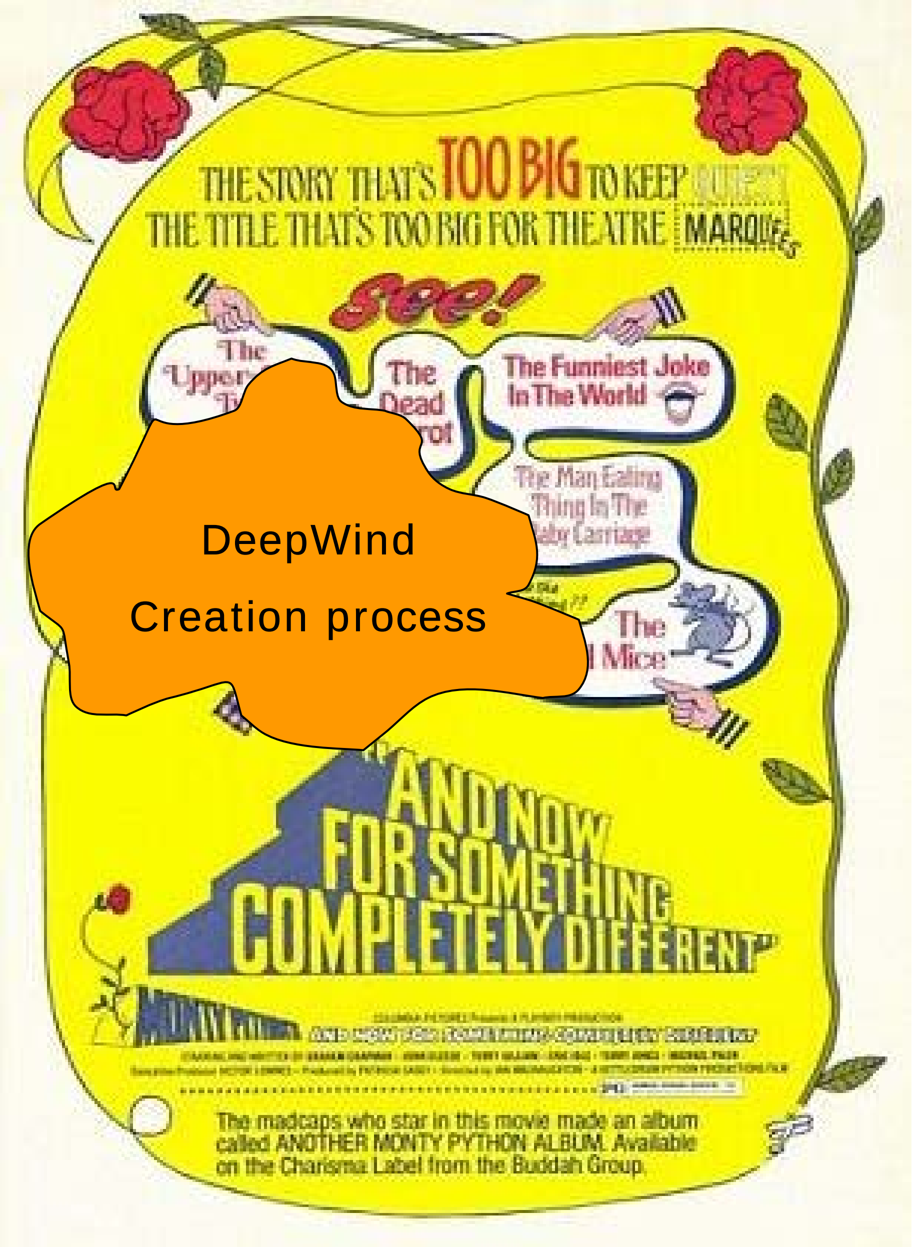
=>new low COE solutions are required

Hypothesis

..offshore wind energy needs new concepts specifically designed for offshore conditions

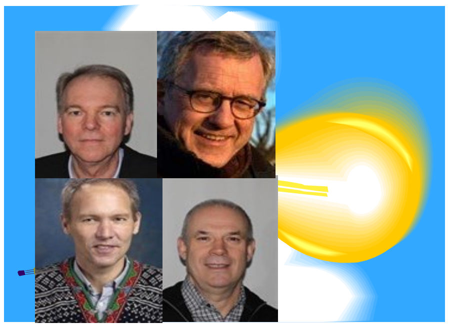
What is DeepWind?

- How was it identified?-A creation of concept?-Creative art?



What is DeepWind?

- How was it identified?-A creation of concept?-Creative art?



Our experience

- Hard work pays
- Jogging is a state of mind
- R&D environment and enthusiastic PhDs
- Team work, also in consortium
- Idea right on time

CREATIVITY ACCORDING TO J. CLEESE

Creativity is a state of operating

1)sleeping on a problem over night-unconscious effects helpful in creativity

2)go over your concept again (rewrite the manuscript from memory) unconscious part helps in working out faster, and more clear

3)no interruptions allowed in the course of creative state.

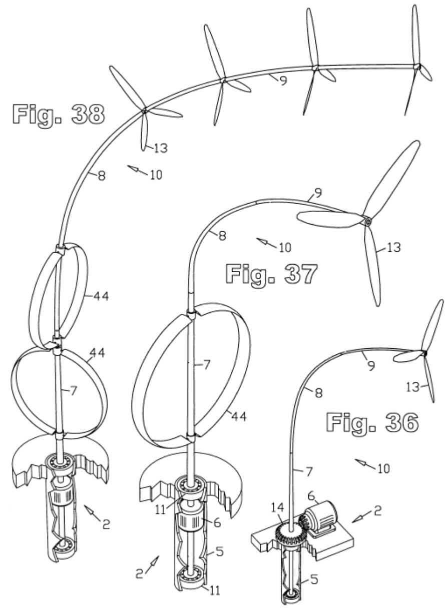
the origin of ideas is diffuse (-not from our laptops))

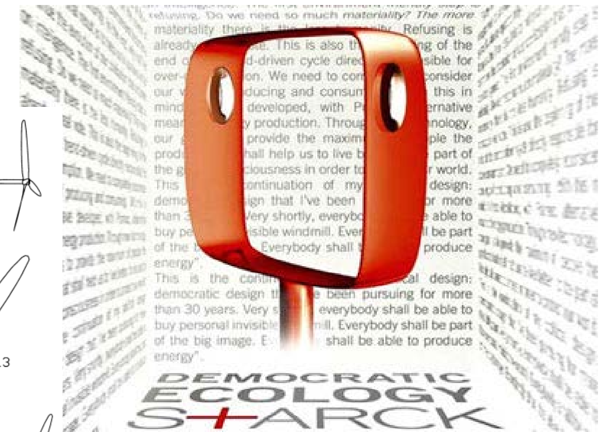
What is DeepWind?

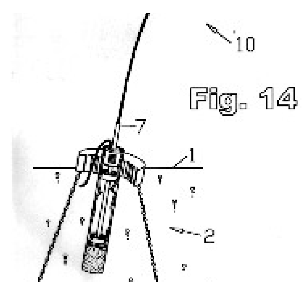
- How was it identified?-A creation of concept?-Creativ art?
- Patent applicable?

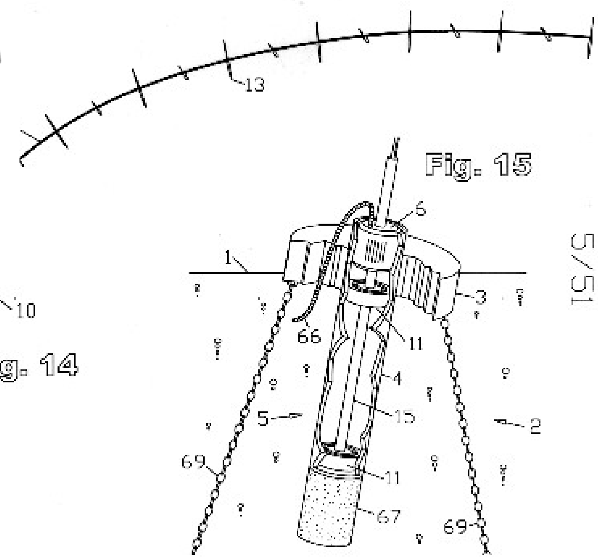
US 6616402 B2 SELSAM™

Priority date Jun 14, 2001









SELSAM™

Scientific contents

DeepWind (2010-2014)

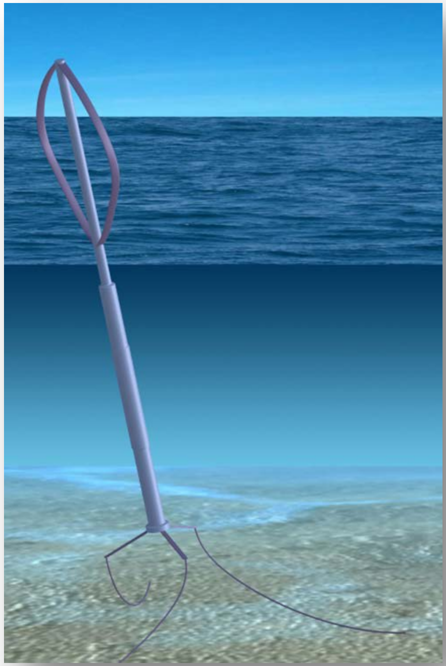
- Work Packages:
  1. Aero-elastic fully coupled code implementation and simulation
  2. Blade technology and blade design
  3. Generator concepts
  4. Turbine system controls
  5. Mooring, floating and torque absorption systems
  6. Exploration of torque, lift and drag on a rotating tube
  7. Proof-of-principle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

Partners:

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

DeepWind

- A radical new design- genuine offshore concept 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 for better efficiency
  - Simple stall control with overspeed protection



Vita L, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F *A Novel Floating Offshore Windturbine Concept* in Proceedings of the European Wind Energy Conference (EWEC), Marseille, France,2009

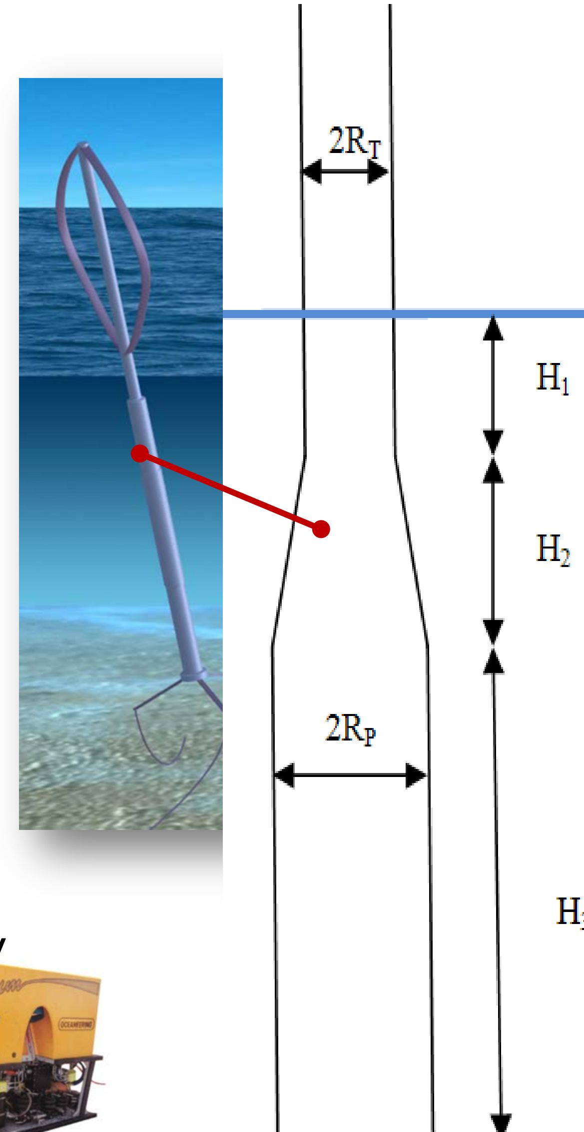
Vita L, Zhale F, Paulsen US Pedersen TF, Madsen HA, Rasmussen F. *Novel Concept For Floating Offshore Wind Turbines: Concept Description And Investigation Of Lift, Drag And Friction Acting On The Rotating Foundation* in Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, June 6 Shanghai 2010 **OMAE2010-20357**

Larsen TJ, Madsen HA. On The Way To Reliable Aero-elastic Load Simulation On VAWT's. Proceedings of EWEA 2013 Wind Energy conference Vienna;2013

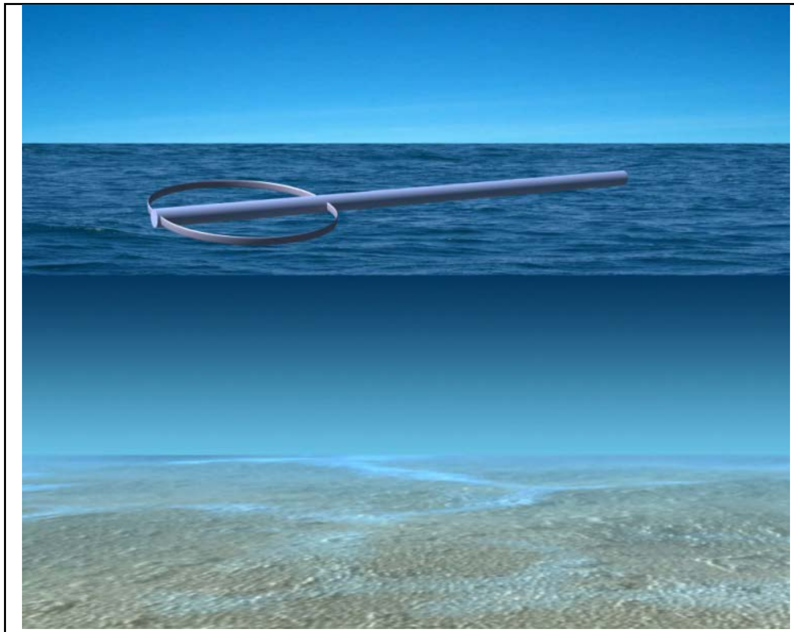
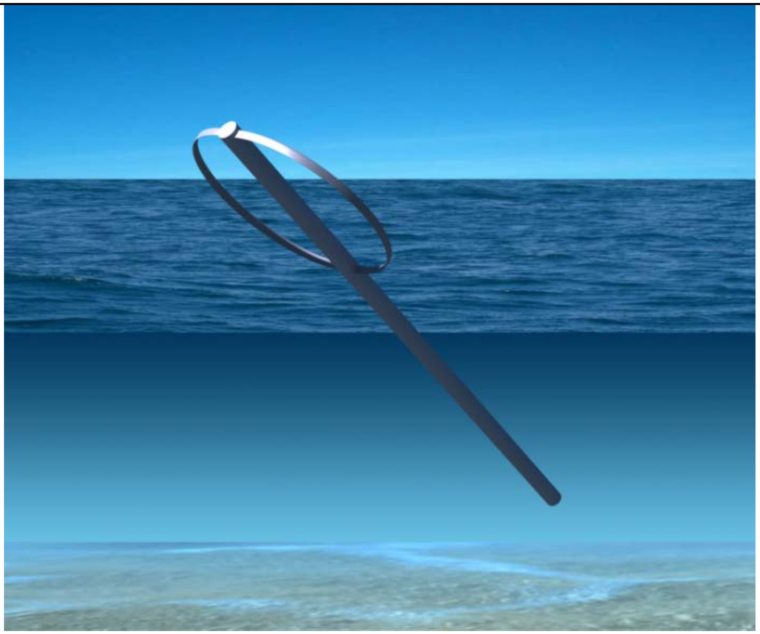
Vita L *Offshore floating vertical axis wind turbines with rotating platform* Risø DTU, Roskilde, Denmark, PhD dissertation PhD 80, 2011

DeepWind

- A radical new design- aiming for better COE and a more reliable wind turbine
- Rotating slender spar
  - Slender, long floater with high inertia and large natural period $T_{roll} > T_{wave}$
  - Material steel, but also concrete suitable (1/3 of steel cost)
  - Technology feasible for 100-1000m water depths
  - No big cranes or installation vessels needed
  - Underwater technology business opportunity

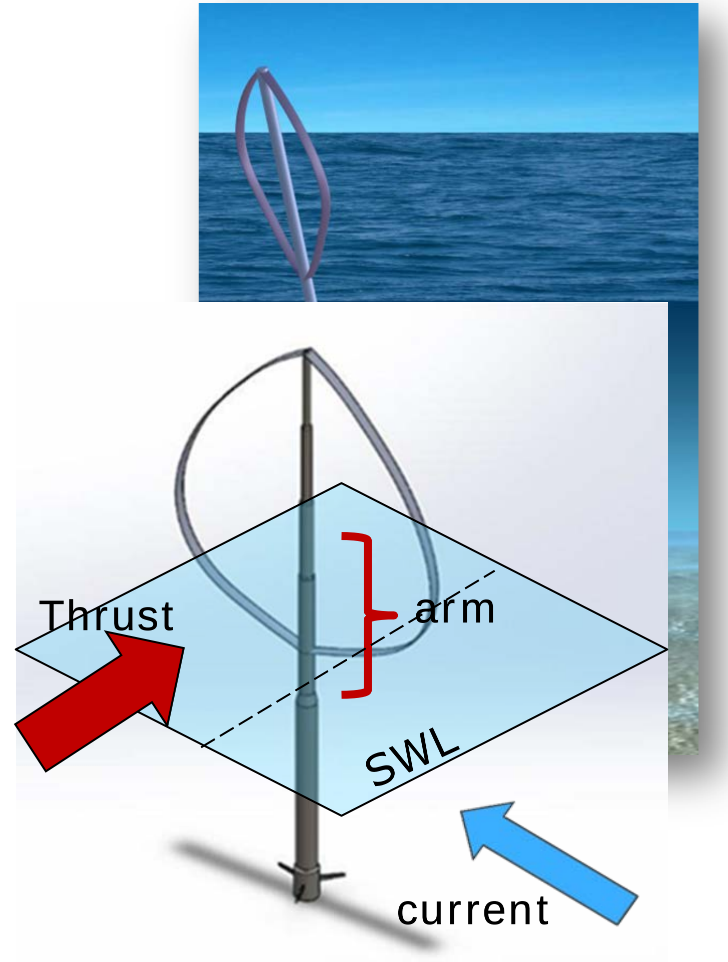


Installation, O&M

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

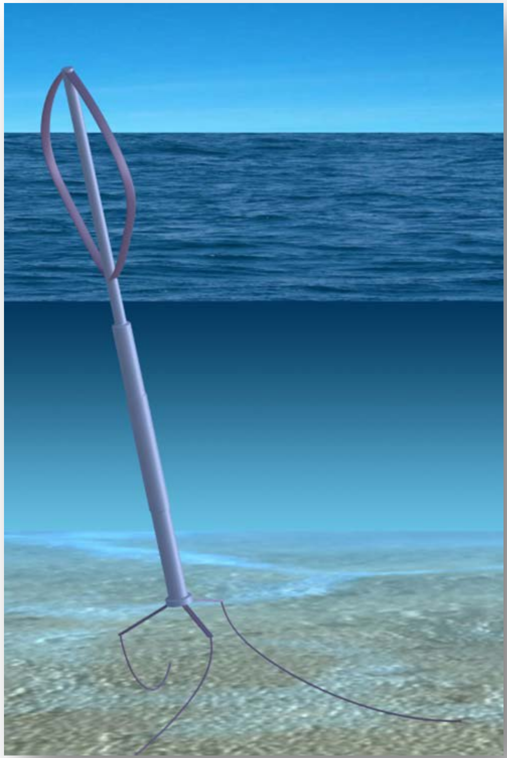
DeepWind

- A radical new design- aiming for better COE and a more reliable wind turbine
- Rotating spar with high Aspect ratio-Less displacement than existing Floating concepts
- No nacelle-low center of gravity - high stability
  - Low over-turning moment, with lesser torque arm than HAWT
  - No yaw-no pitch: Lesser components failure
- BUT
  - Transverse forces (Magnus force)
  - Less stiff against heave motion



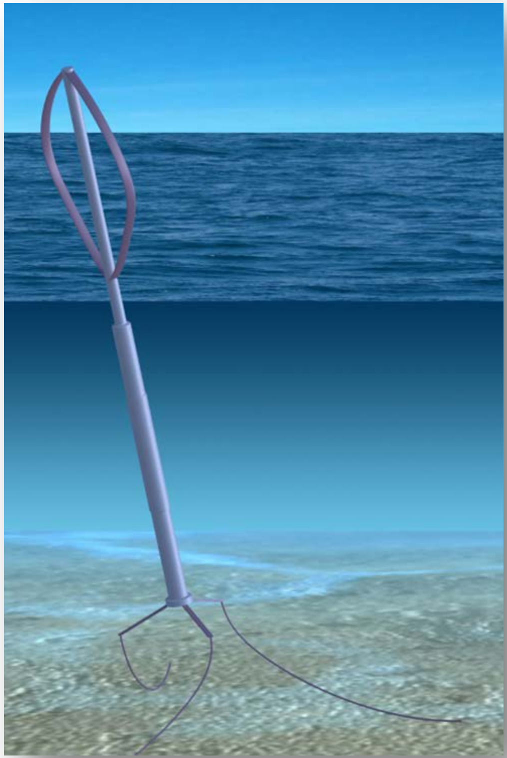
DeepWind

- A radical new design- aiming for better COE and a more reliable wind turbine
- Rotating spar with high Aspect ratio-Less displacement than existing Floating concepts
- No nacelle-low center of gravity - high stability
- Upscaling potential
  - Pultrusion at any scale(ideally)
  - Gravity lesser significant for cyclic loadings than HAWTs
  - High stability with heavy parts at ‘low end’
  - PMG upscaling realistic for 20 MW



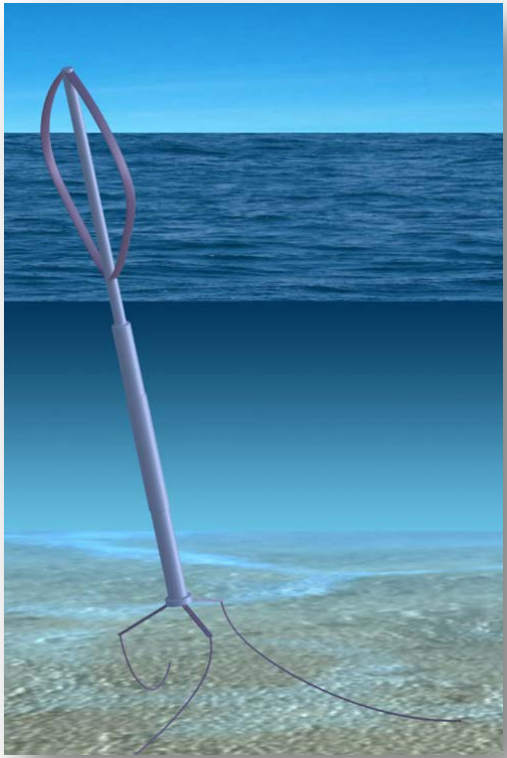
DeepWind

- A radical new design- aiming for better COE and a more reliable wind turbine
- Rotating spar with high Aspect ratio-Less displacement than existing Floating concepts
- No nacelle-low center of gravity - high stability
- Upscaling potential
- Insensitivity for dynamic wind loads
  - wind turbulence
  - gusts
  - wind direction changes
- BUT:
  - Aerodynamic loads pulsation
  - Load variations on tower(2 bladed)

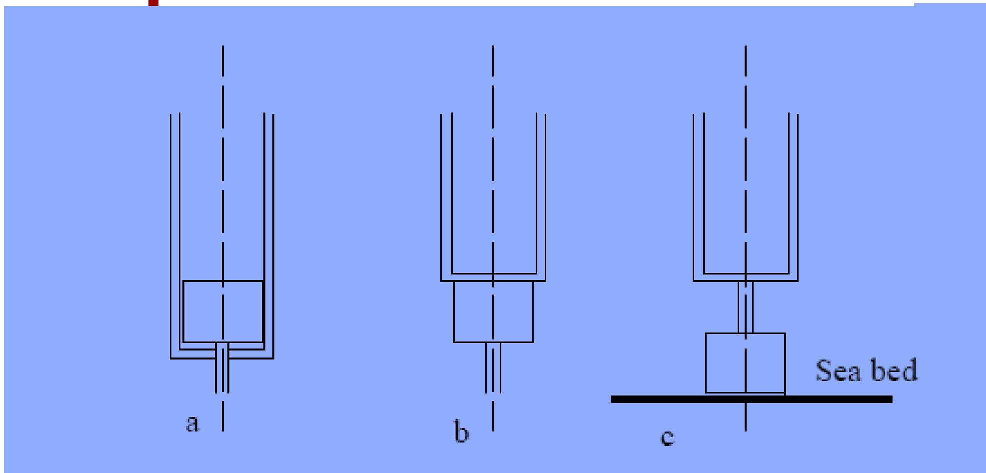


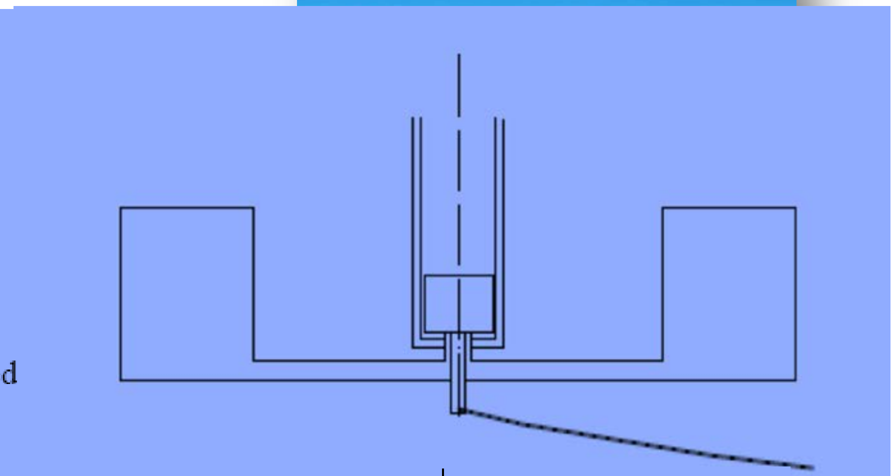
DeepWind

- A radical new design- aiming for better COE and a more reliable wind turbine
- Rotating spar with high Aspect ratio-Less displacement than existing Floating concepts
- No nacelle-low center of gravity - high stability
- Upscaling potential
- Insensitive to wind turbulence
- Insensitive to wind direction change
- Subsea Generator technology
  - Generator state of the art :Transverse flux PM
  - Several design proposals

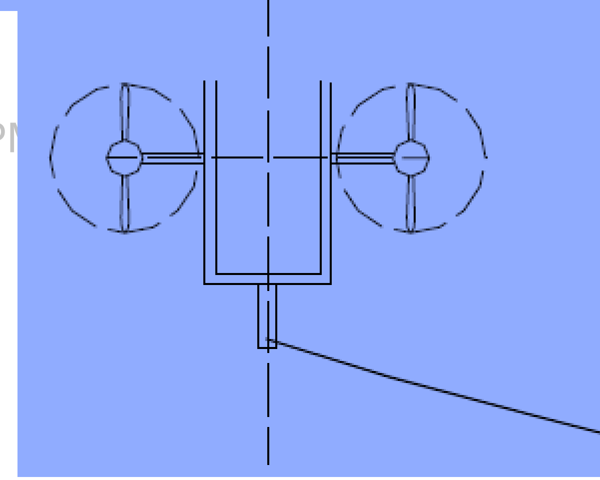


DeepWind



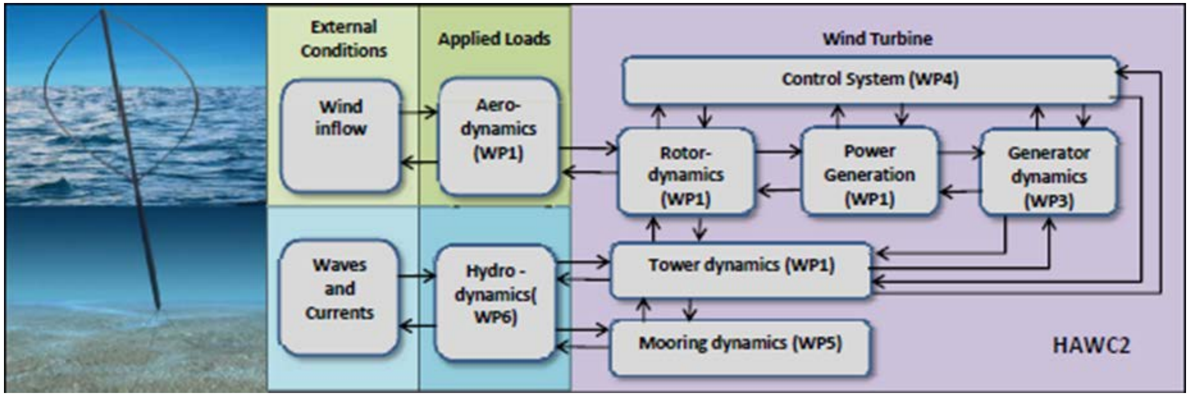


- Insensitive to wind direction change
- Subsea Generator technology
  - Generator state of the art :Transverse flux P
  - Several design proposals: inside/outside/shrouded/with vane



Design suites(1)

- General FE model
- Wind
  - ✓ Atmospheric Turbulence
  - ✓ Shear
- Aerodynamics
  - ✓ Dynamic stall
  - ✓ Actuator Cylinder
- Hydrodynamics
  - ✓ Magnus force
  - ✓ Morrison forces
  - ✓ Friction
- Mooring lines
- Generator control

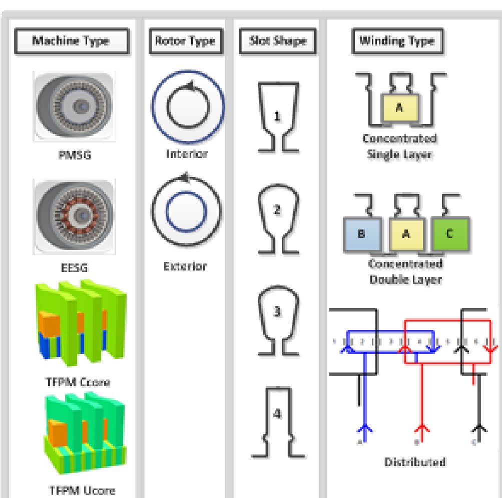


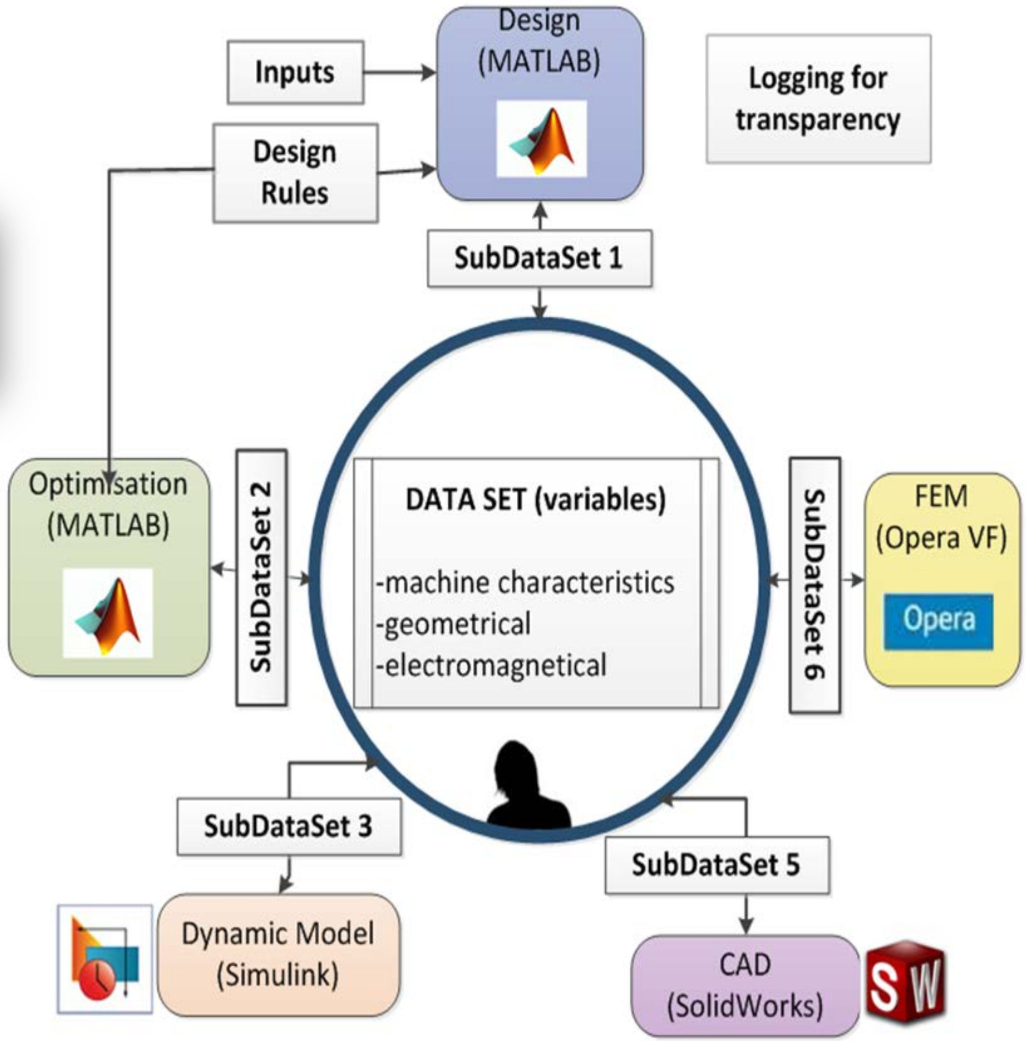
Design suites(2)

- Generator design tool
- CAD design tool

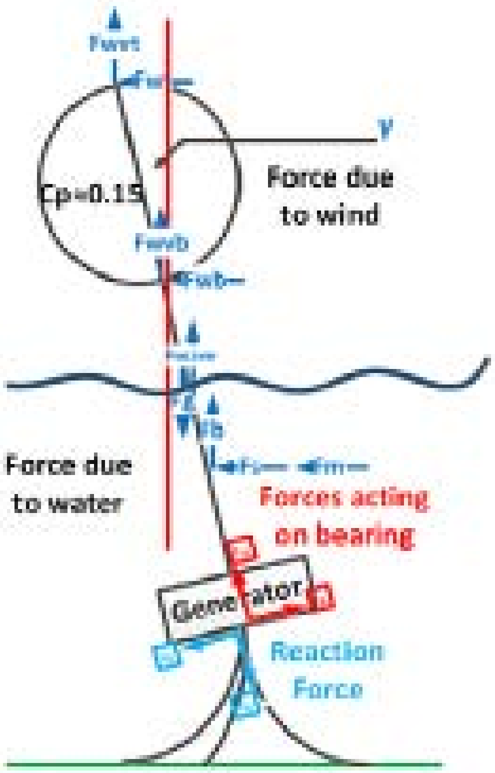
Leban K, Ritchie E, Argeseanu A .Design Tool for Large Direct Drive Generators: *14th International Conference on Optimization of Electrical and Electronic Equipment - OPTIM 2014 -*

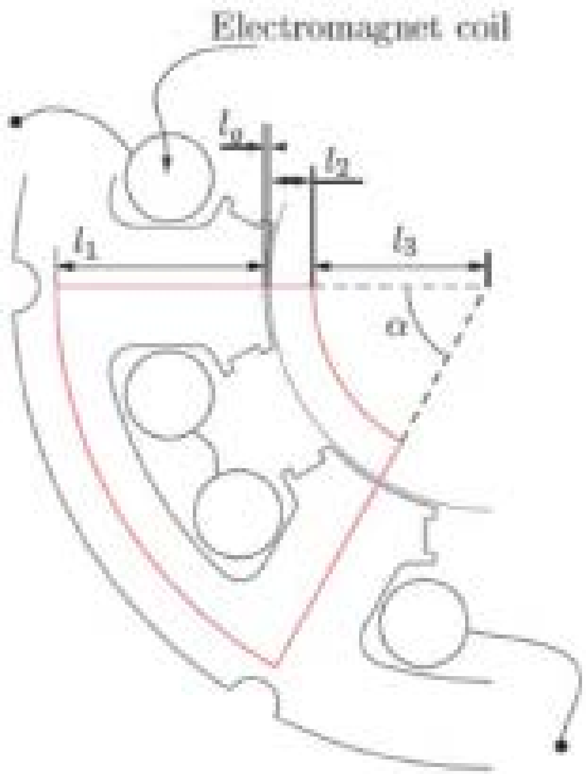
✓ Optimization
✓ Simulation
✓ Visualization



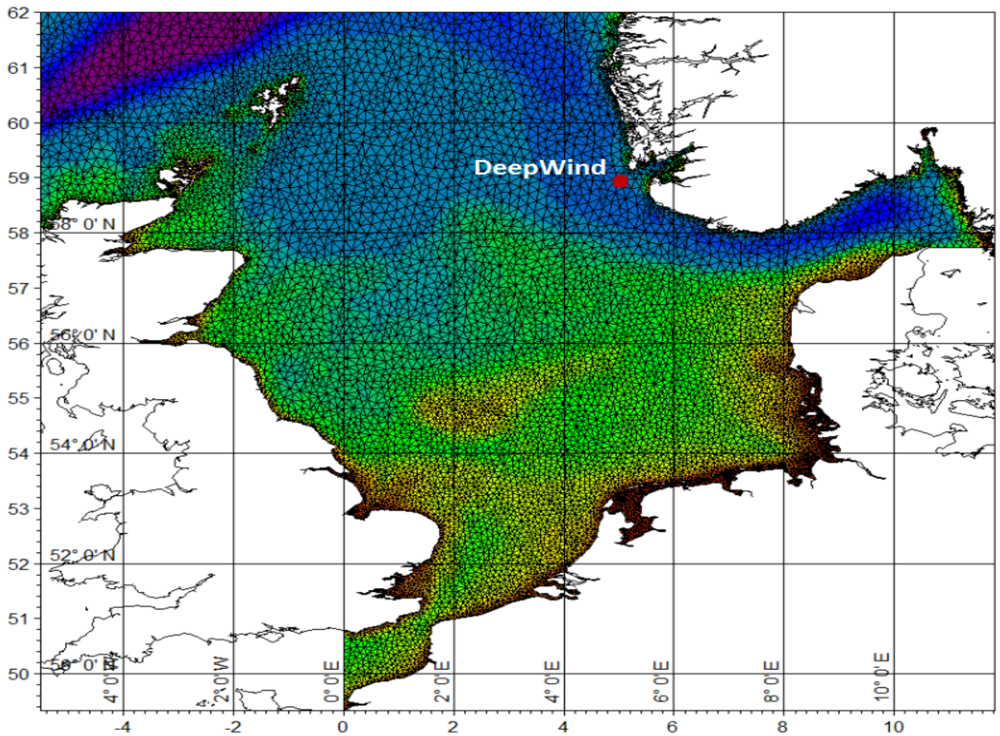


Bearing design tool(3) and test rig





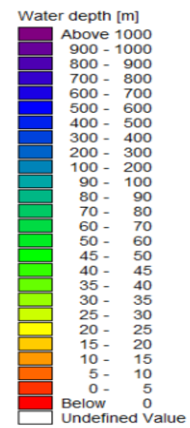
Preconditions-Site(Karmøy, No)



Latitude: 59° 8'44.88"N,

Longitude: 5° 1'25.66"E

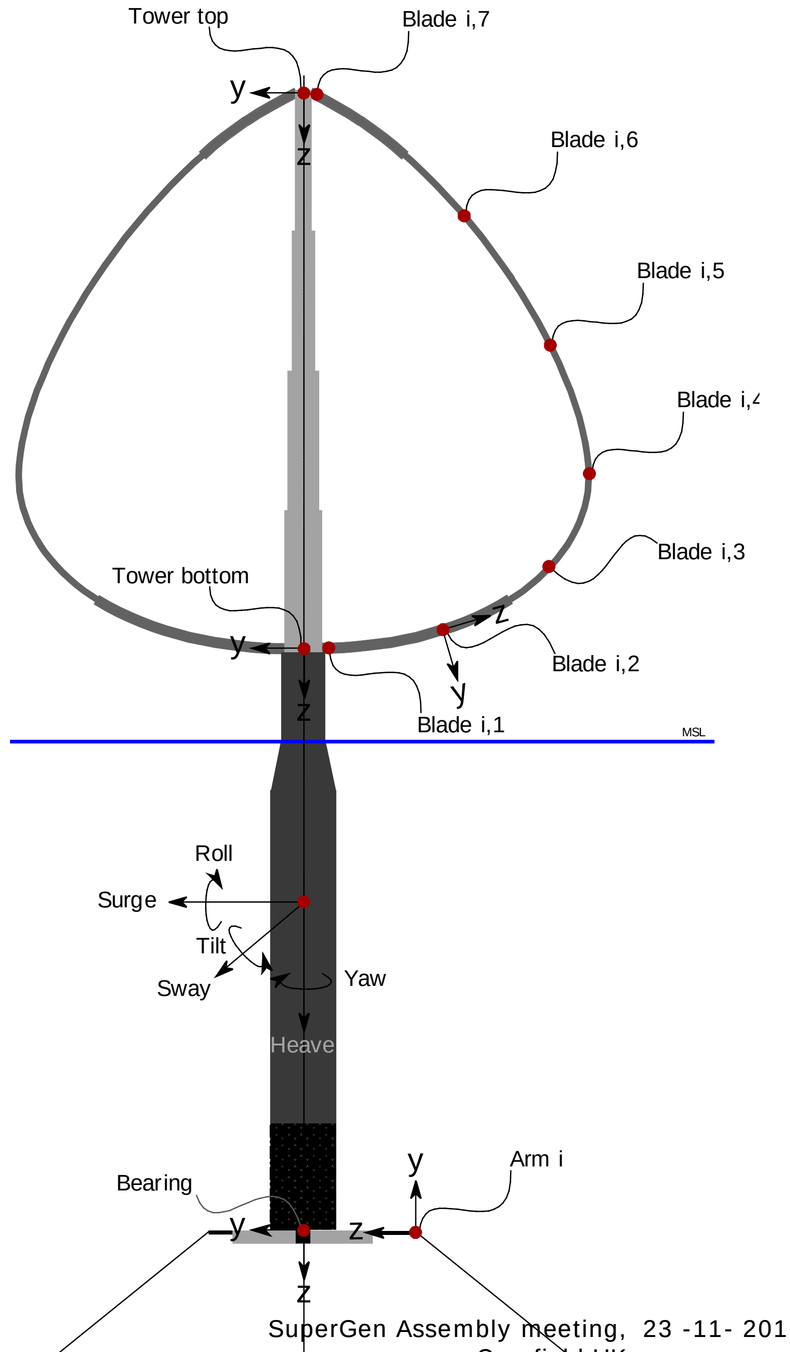
DHI's Hindcast model



Velocity of the water currents at the surface	[m/s]	0, [0.35,0.7]
Maximum significant wave height H_s	[m]	14
Maximum peak wave period T_P	[s]	16
Wind speed (limit wind speed of the design)	[m/s]	<25

Sketch of the concept

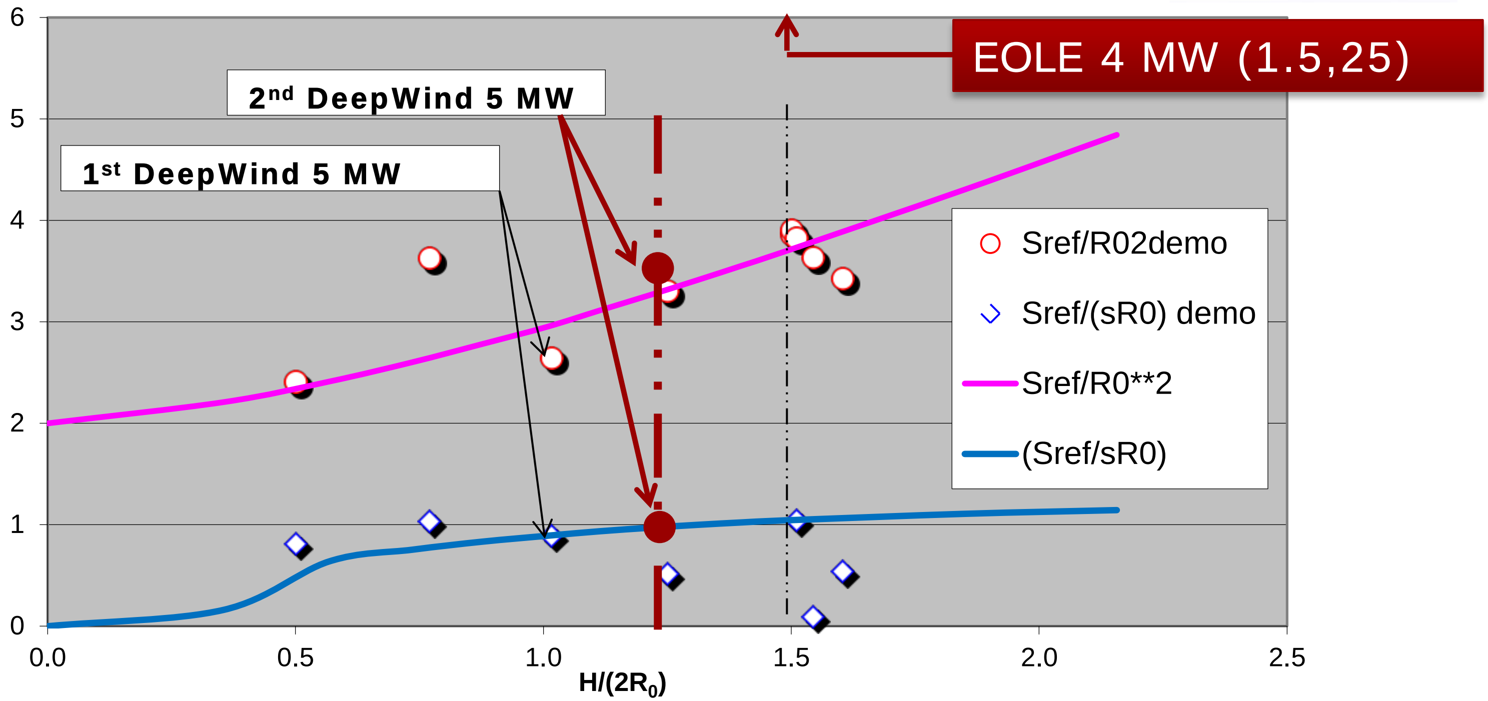
Rated Power	$[MW]$	5
Rated Rotation Speed	$[rpm]$	5.95
Rated Wind Speed	$[m/s]$	14
Wind Speed Range	$[m/s]$	4-25
Rotor Radius	$[m]$	60.49
Rotor Height	$[m]$	143
Chord	$[m]$	5
Solidity	[-]	0.16583
Swept Area	$[m^2]$	11996



DeepWind
5 MW Design Rotor

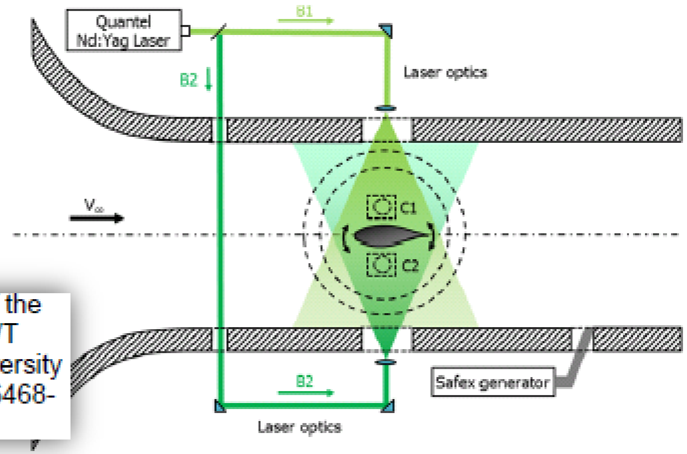
Geometry

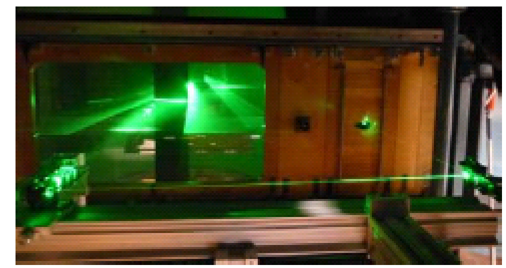
Rotor radius (R_0)	[m]	60.5
$H/(2R_0)$	[-]	1.18
Solidity ($\sigma = Nc/R_0$)	[-]	0.165
Swept Area (S_{ref})	[m^2]	11996



Airfoil development

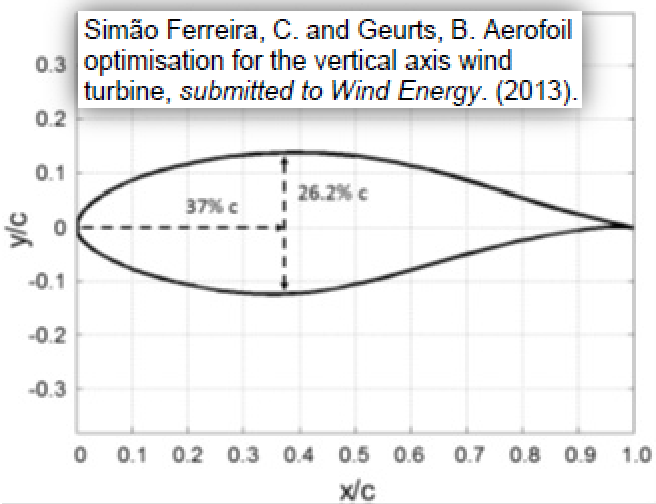
LTT WT TUDelft

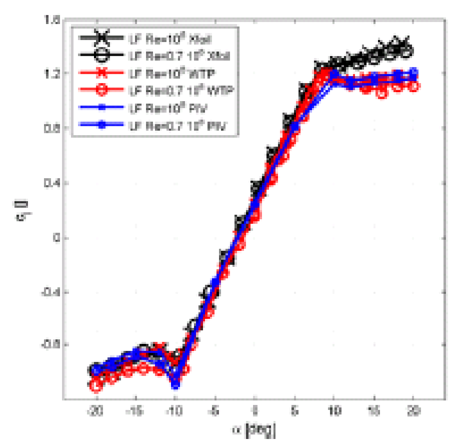


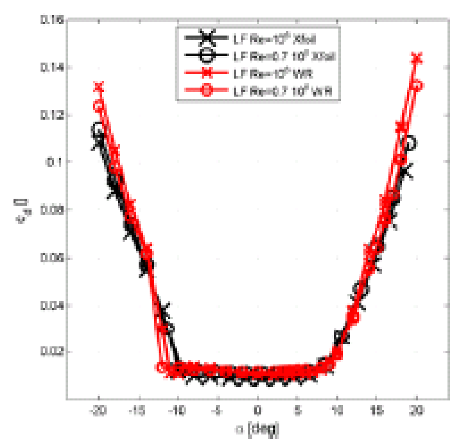


Simao Ferreira, C. The near wake of the VAWT: 2D and 3D views of the VAWT aerodynamics. PhD thesis,Delft University of Technology. ISBN/EAN:978-90-76468-14-3. (2009).

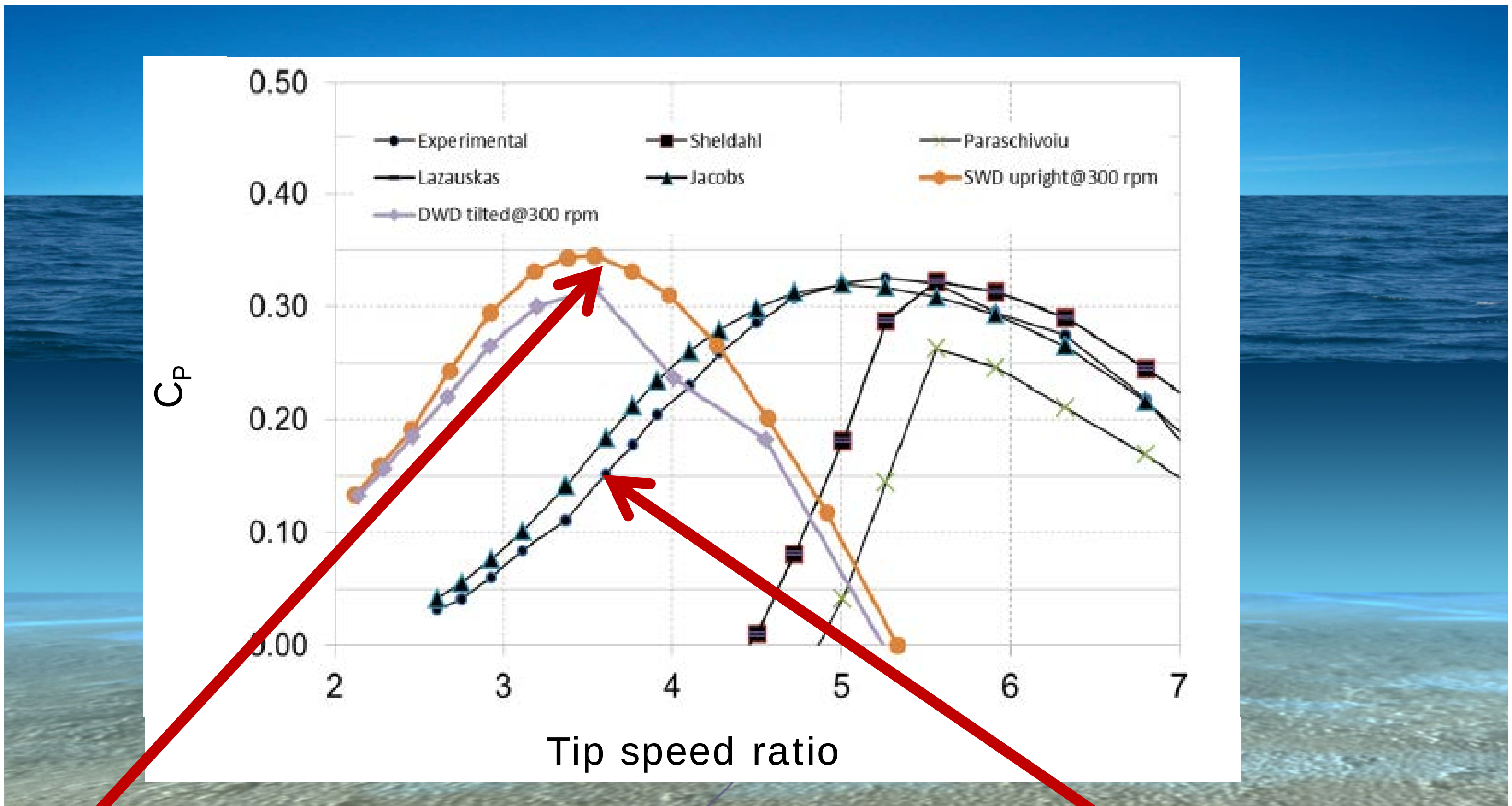
Simão Ferreira, C. and Geurts, B. Aerofoil optimisation for the vertical axis wind turbine, *submitted to Wind Energy*. (2013).







Airfoil development DeepWind



Milano wind tunnel Ø2m rotor(DeepWind) upright

SNL Ø2m rotor-free field measurements

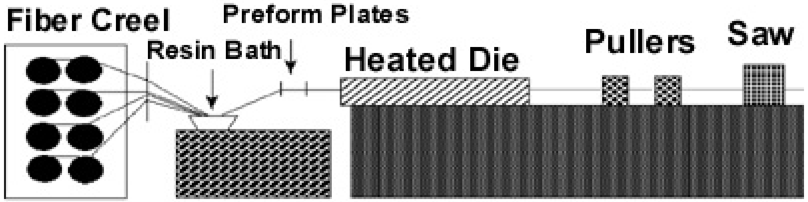
Blade Design

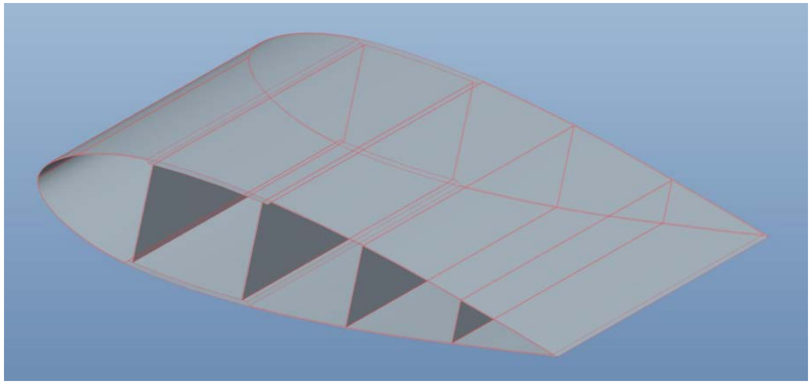
Pultrusion:

Constant chord over length

Low manufacturing cost +

Structural strength for thin profiles -



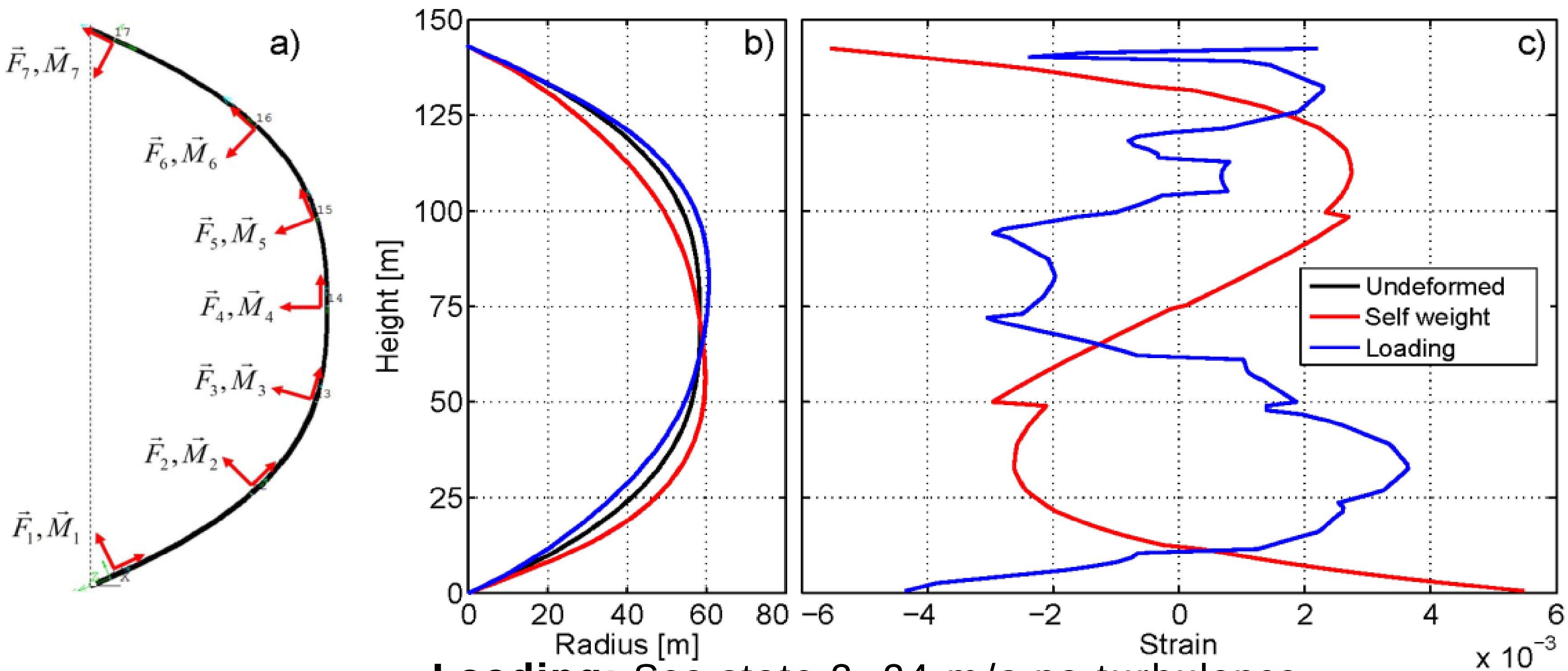


5 MW blade section, 1st baseline

Blade Weight:

1st baseline	2nd baseline	present	RePower5M
157T	95T	105T	54T
7.45m →	5m →	5m	
376m	400m	400m	185m

Blade shape optimization

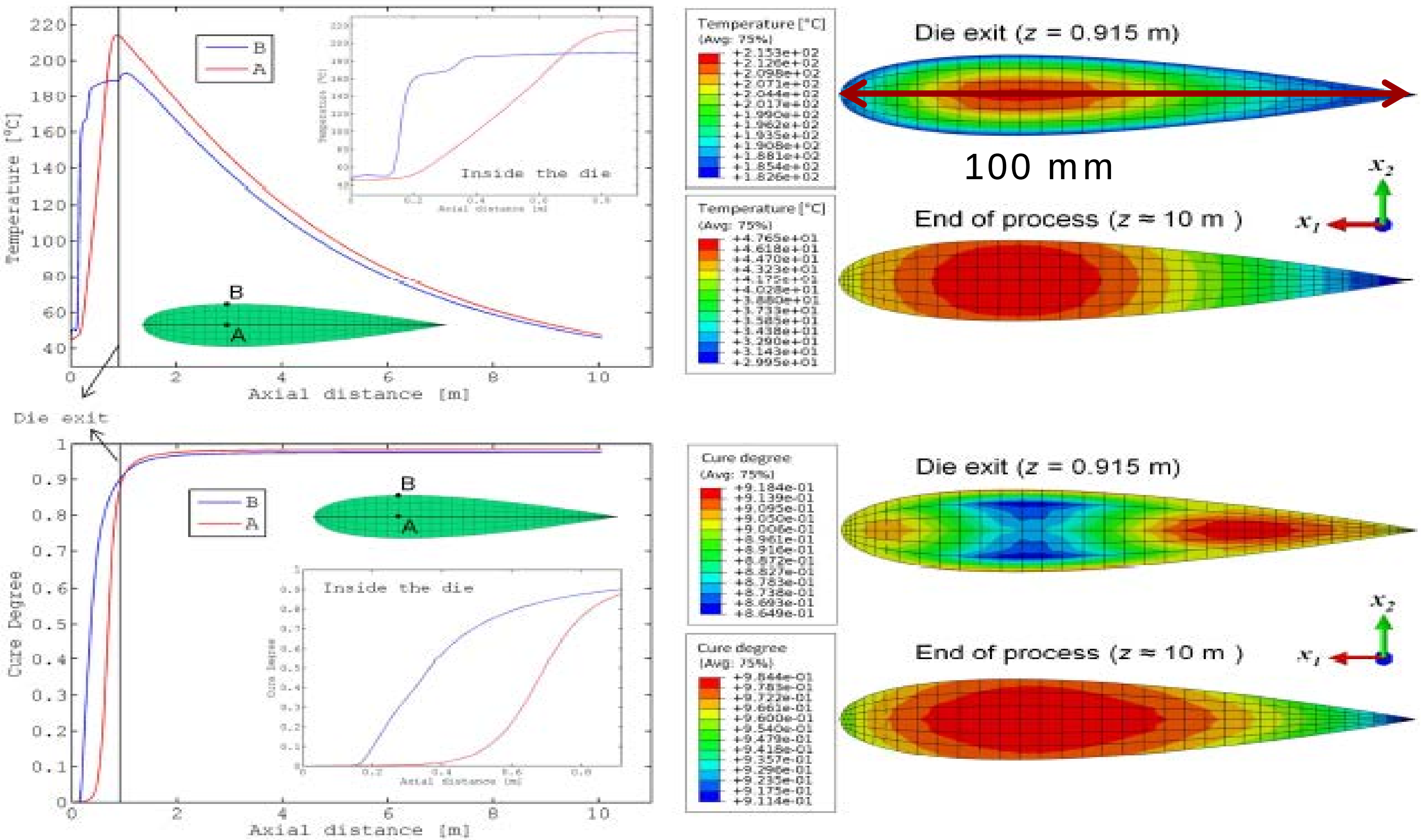


Loading: Sea state 3, 24 m/s no turbulence

"Pultrusion is one of the most cost-efficient composite manufacturing methods to produce constant cross sectional profiles at any length".

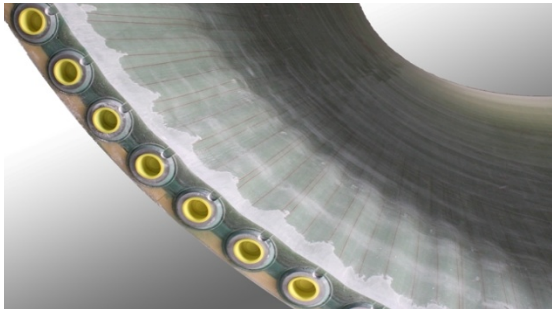
- U.S.Paulsen DeepWind-from idea to 5 MW concept Energy Procedia (2014)

Pultrusion manufacturing

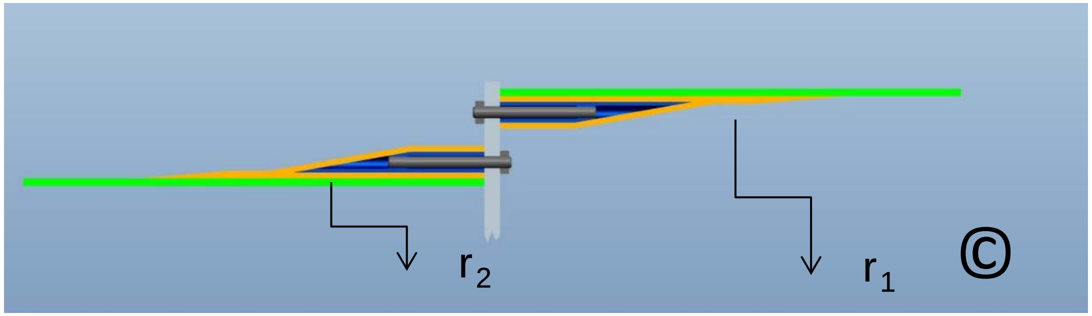


- Baran I, Tutum CC, Hattel JH. The internal stress evaluation of the pultruded blades for a Darrieus wind turbine. Key Eng. Mat. 2013; 554-557: 2127-2137

Industrial joints solution



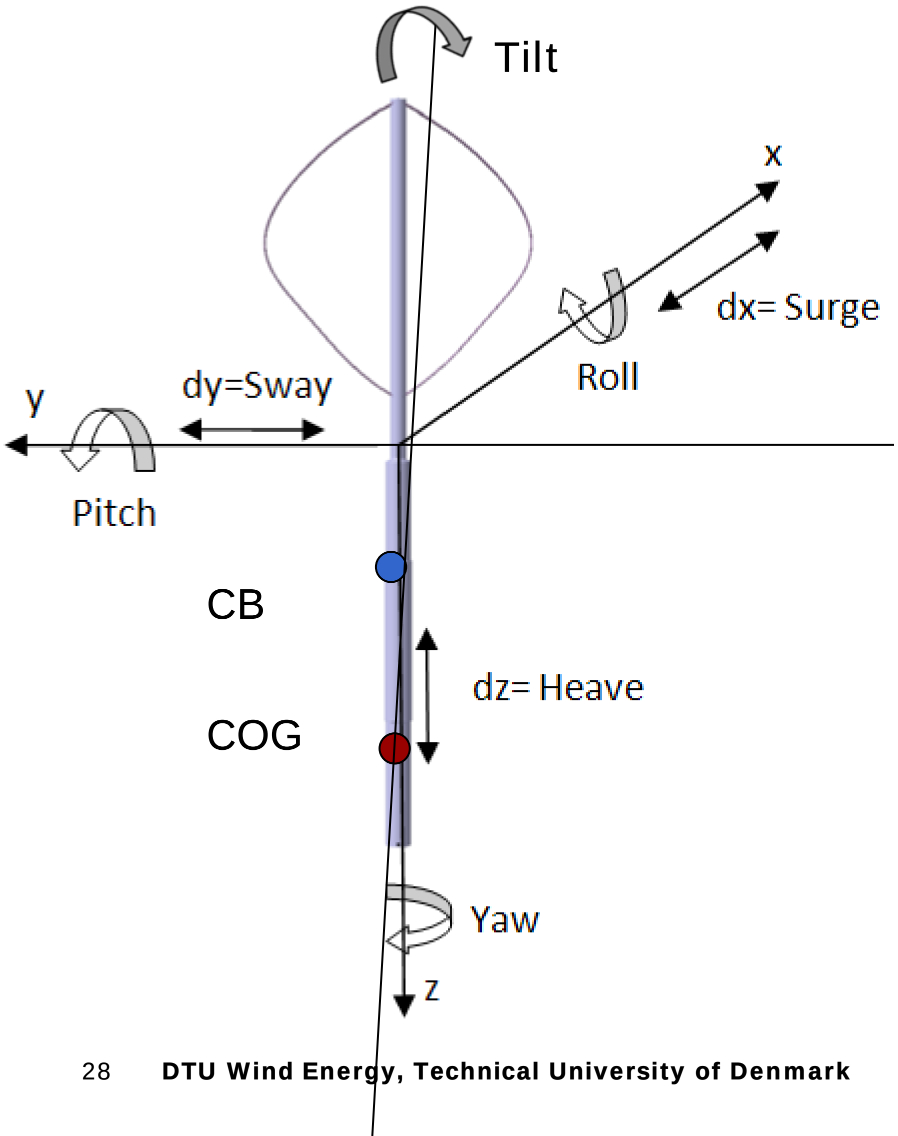
Courtesy of SSP Technology A/S



Slim profile-------Joint------Thick profile

- ❑ Investigation of potential extreme load reduction for a two-bladed upwind turbine with partial pitch," Taeseong Kim, Torben J Larsen, and Anders Yde, Wind Energy, submitted 2013.

Floater

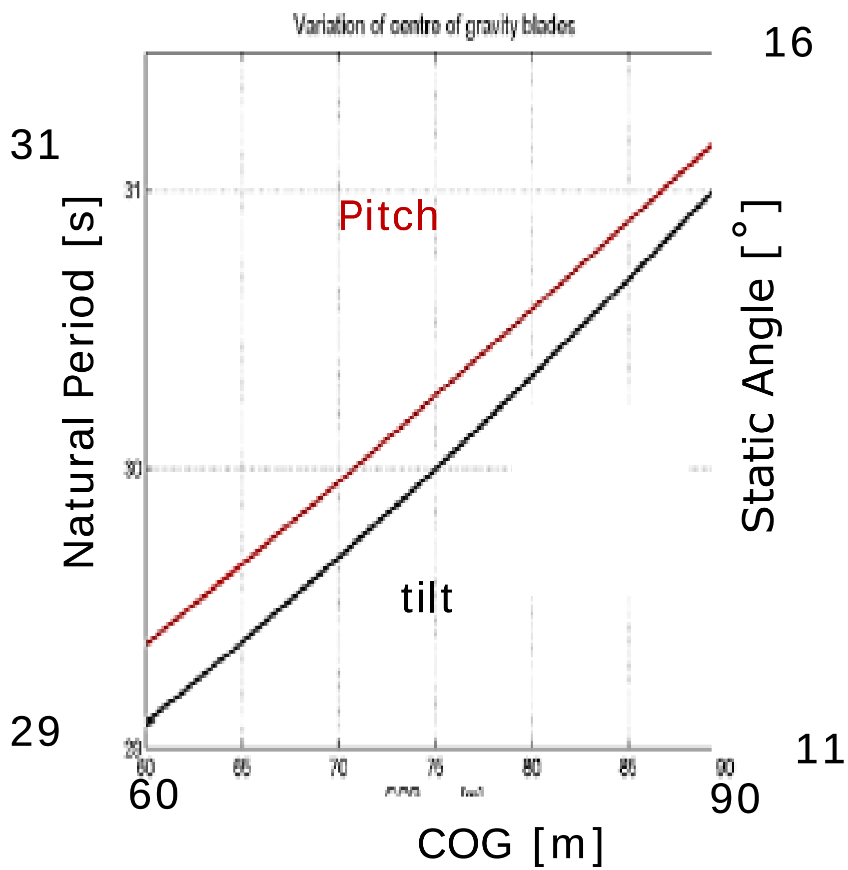


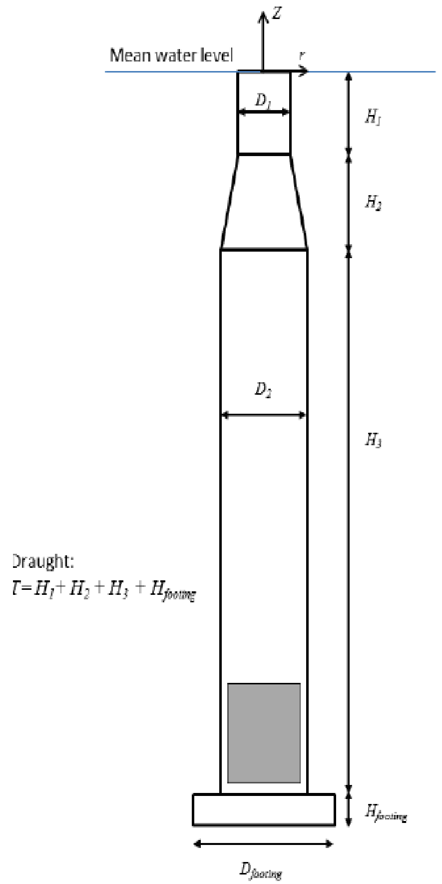
- Gravity stability: vertical distance between COG and BC
- If Rotation around COG and weak Pitch-Surge coupling :

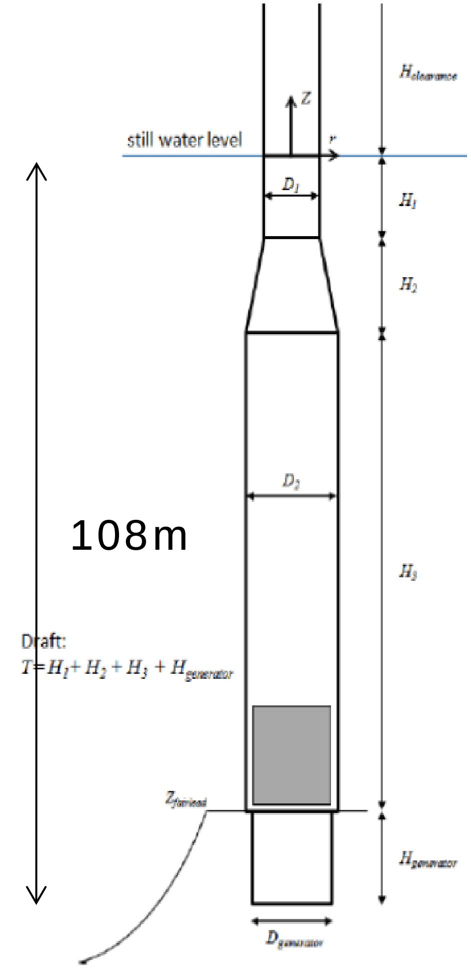
  .:. T_{n5}=2Pi $\sqrt{(I_{55}+a_{55}/k_{55})}$

- Avoid resonance
  - Tn> wave periods with significant energy contents
  - (I55 + a55) increase or decreasing k55
- Avoid large generator accelerations

Floater





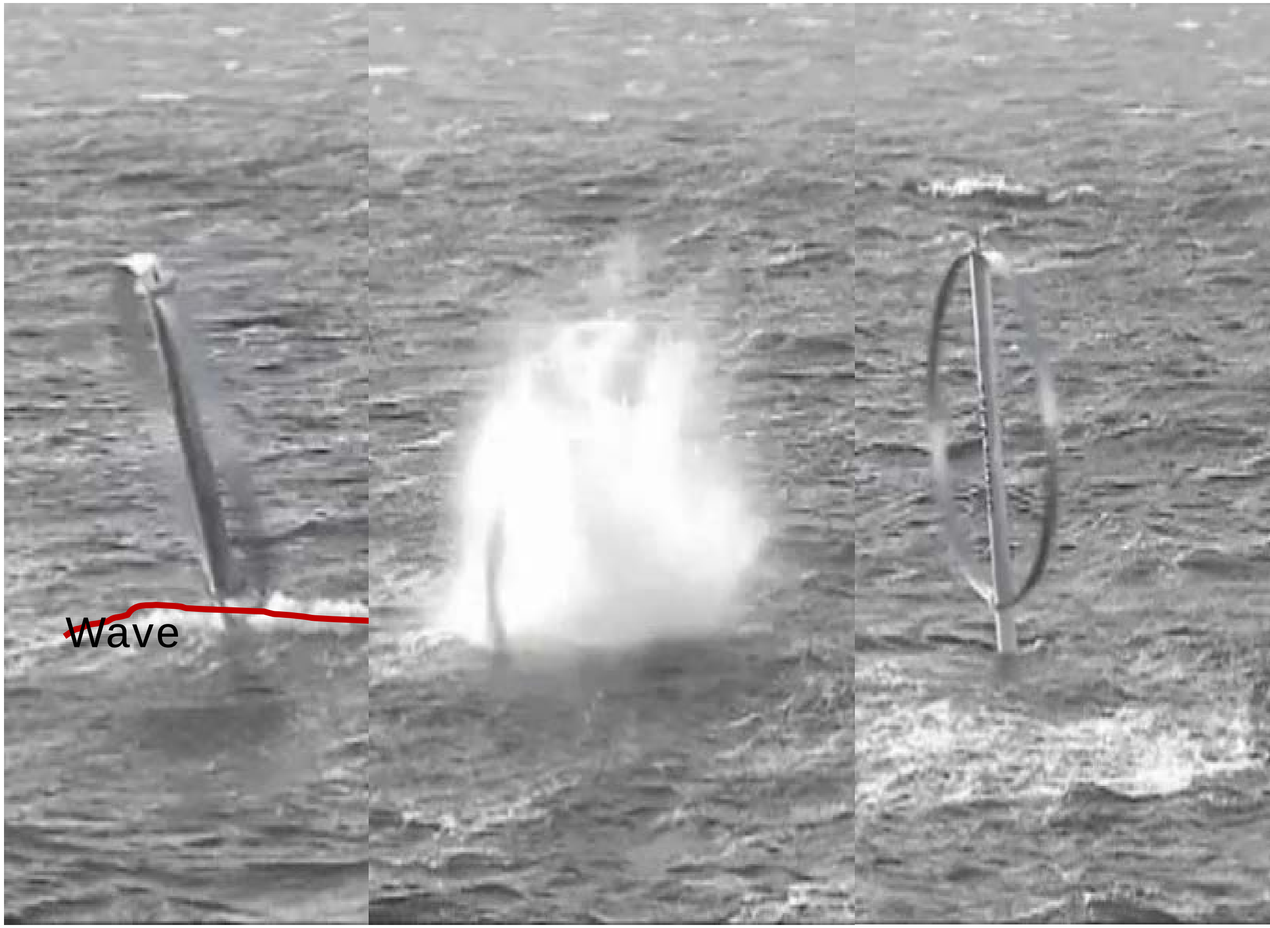


1st floater design 2nd floater design

Safety system

Demonstrator testing

blades hitting water



Before hit after

Safety system

Idea from
Demonstrator testing

blades hitting water

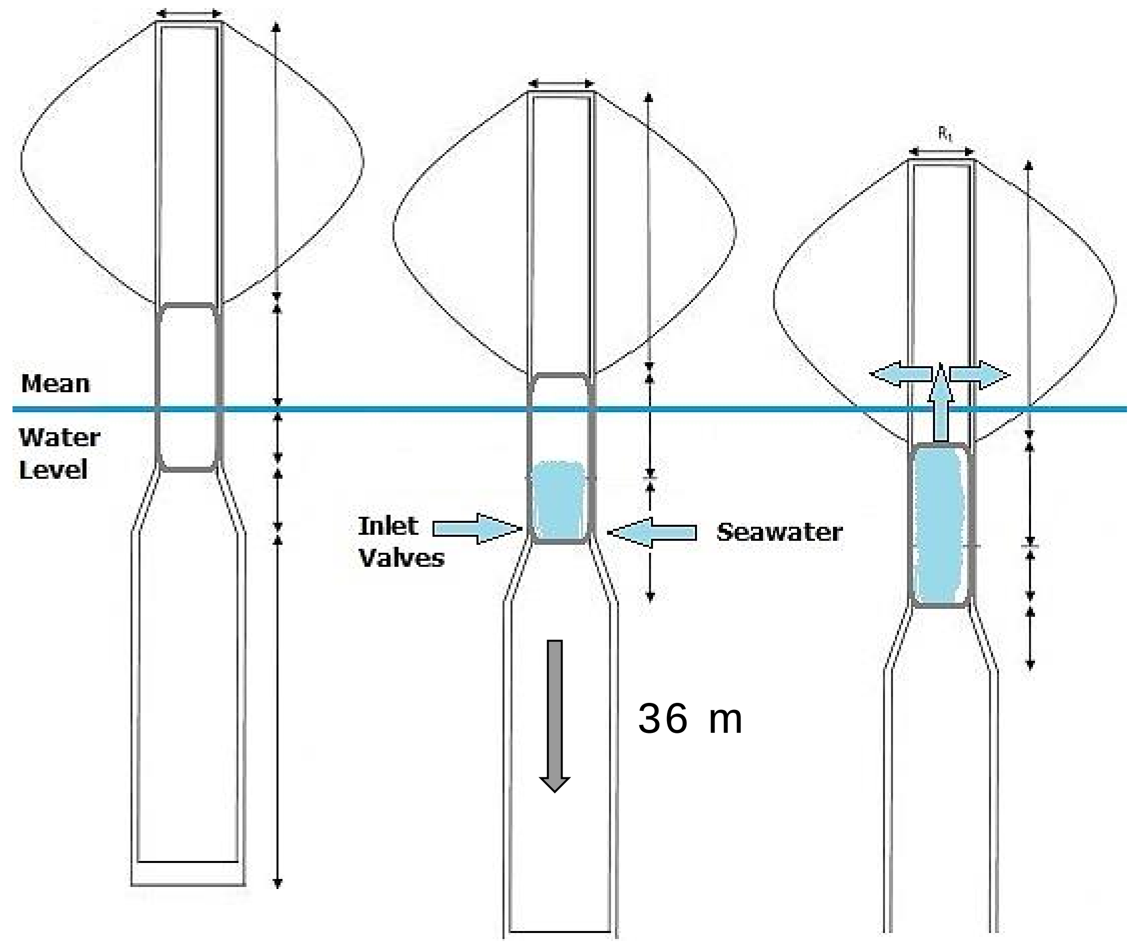
Huge Rotor Inertia

Slow rpm 0.6 rad/s

Max sinking depth to
avoid mooring line
twisting is 65 m

≈ 50 deg twist

.:. To be verified



Electrical design

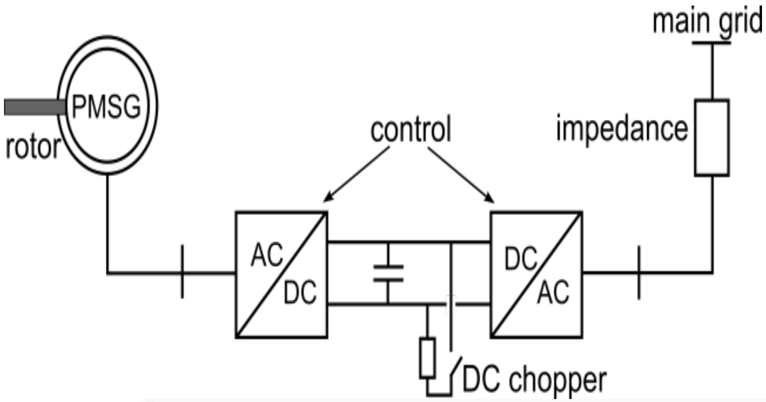
Direct Drive

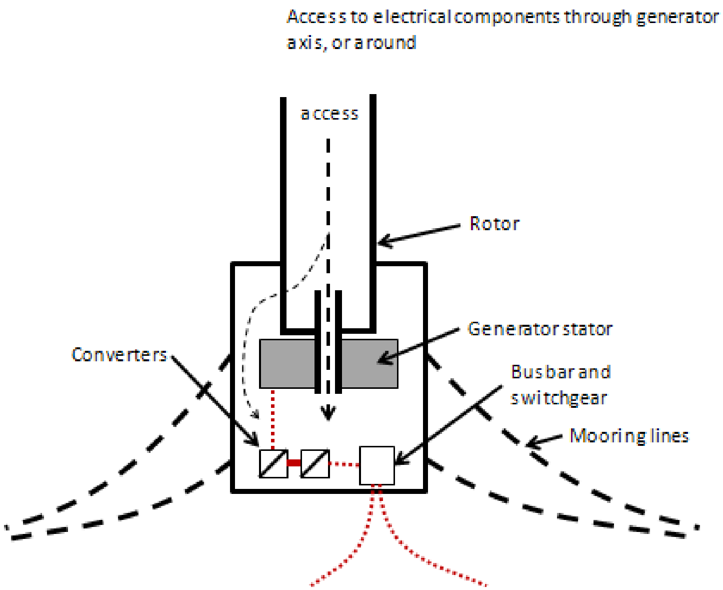
Permanent Magnet

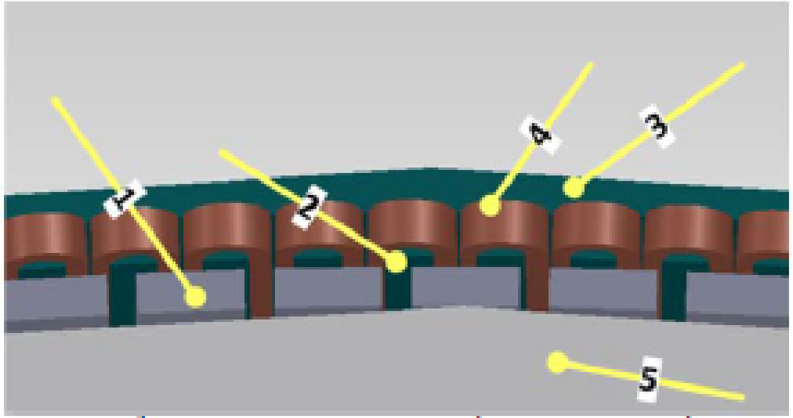
Radial Flux

Height x Dia ≈3m x 6m

Weight (core material) ≈ 90 T





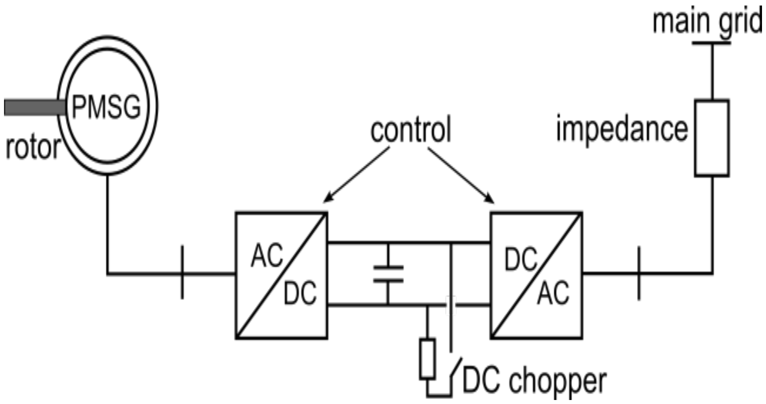


Legend: [1]Permanent magnet [2]Stator tooth [3]Stator back iron [4]Winding coil [5]Rotor back iron

Results-Electrical system

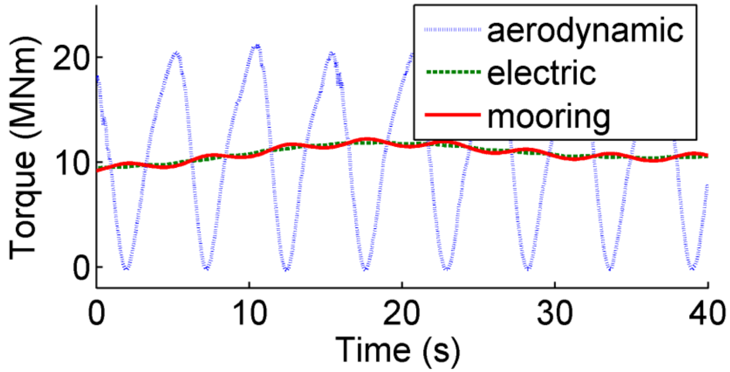
Grid integration

4 quadrant inverter

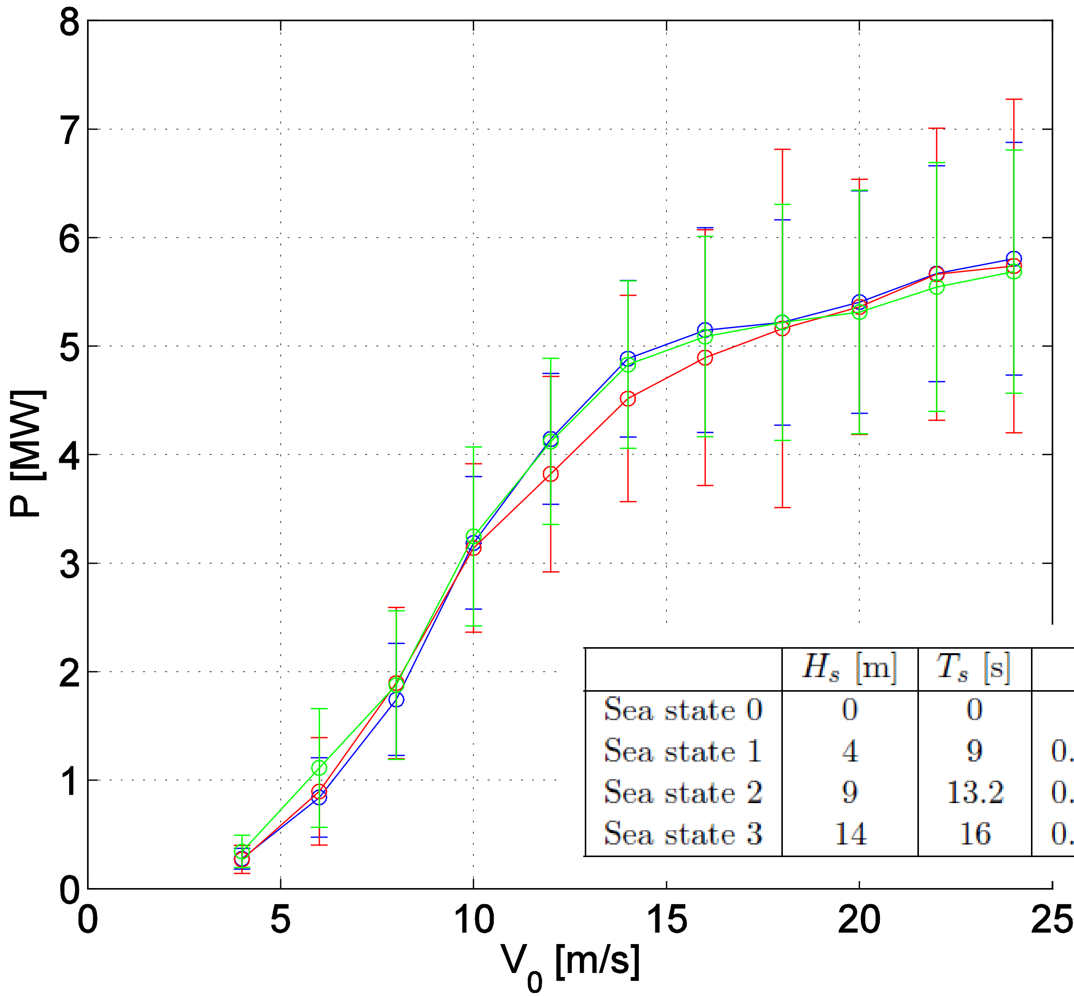


All active turbine control via generator torque

2p damping with notch filter and PI controller



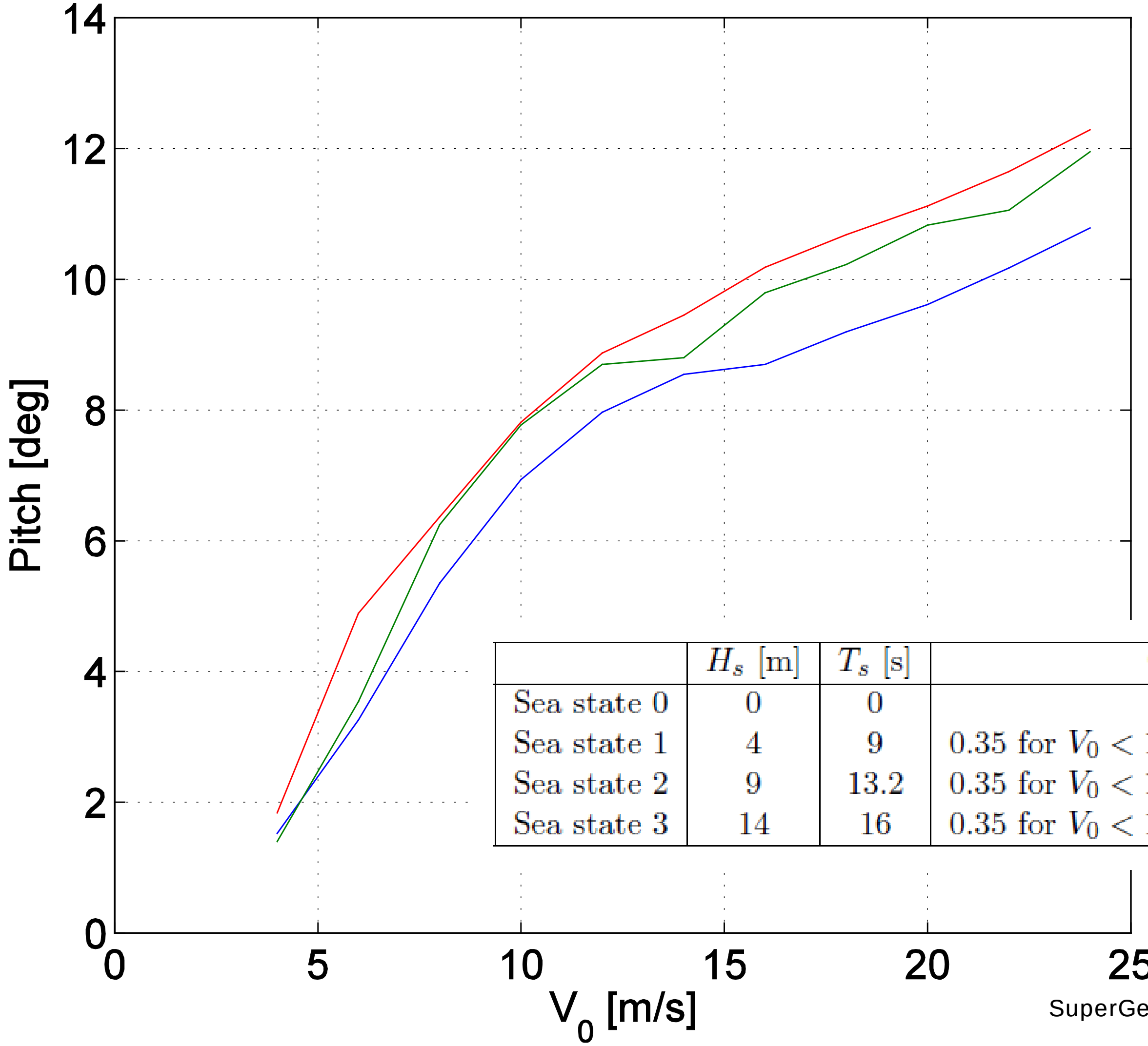
Power curve(2nd baseline)



Blue SS1 Red SS2 Green SS3

	H_s [m]	T_s [s]	Current [m/s]
Sea state 0	0	0	0
Sea state 1	4	9	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s
Sea state 2	9	13.2	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s
Sea state 3	14	16	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s

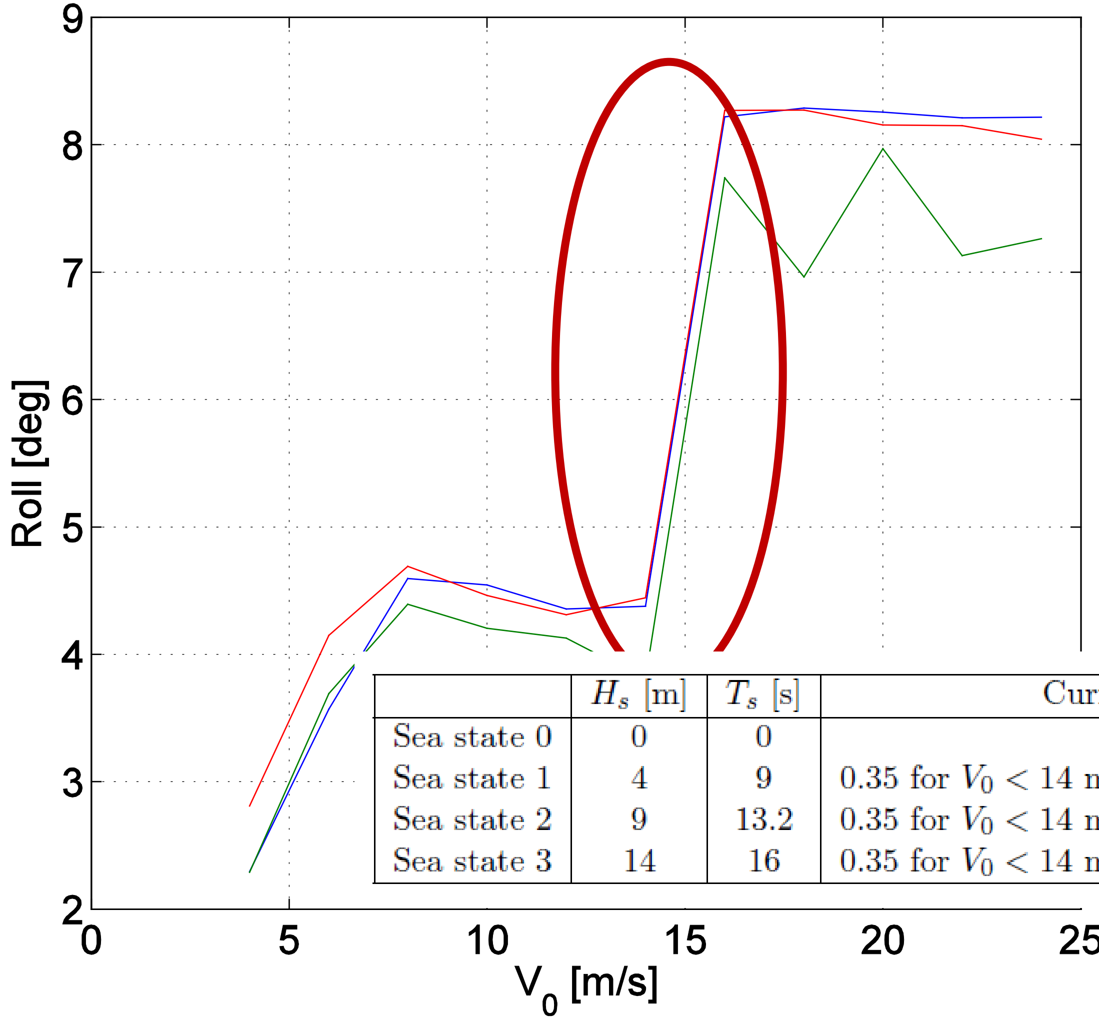
Pitch



Blue SS1 Red SS2 Green SS3

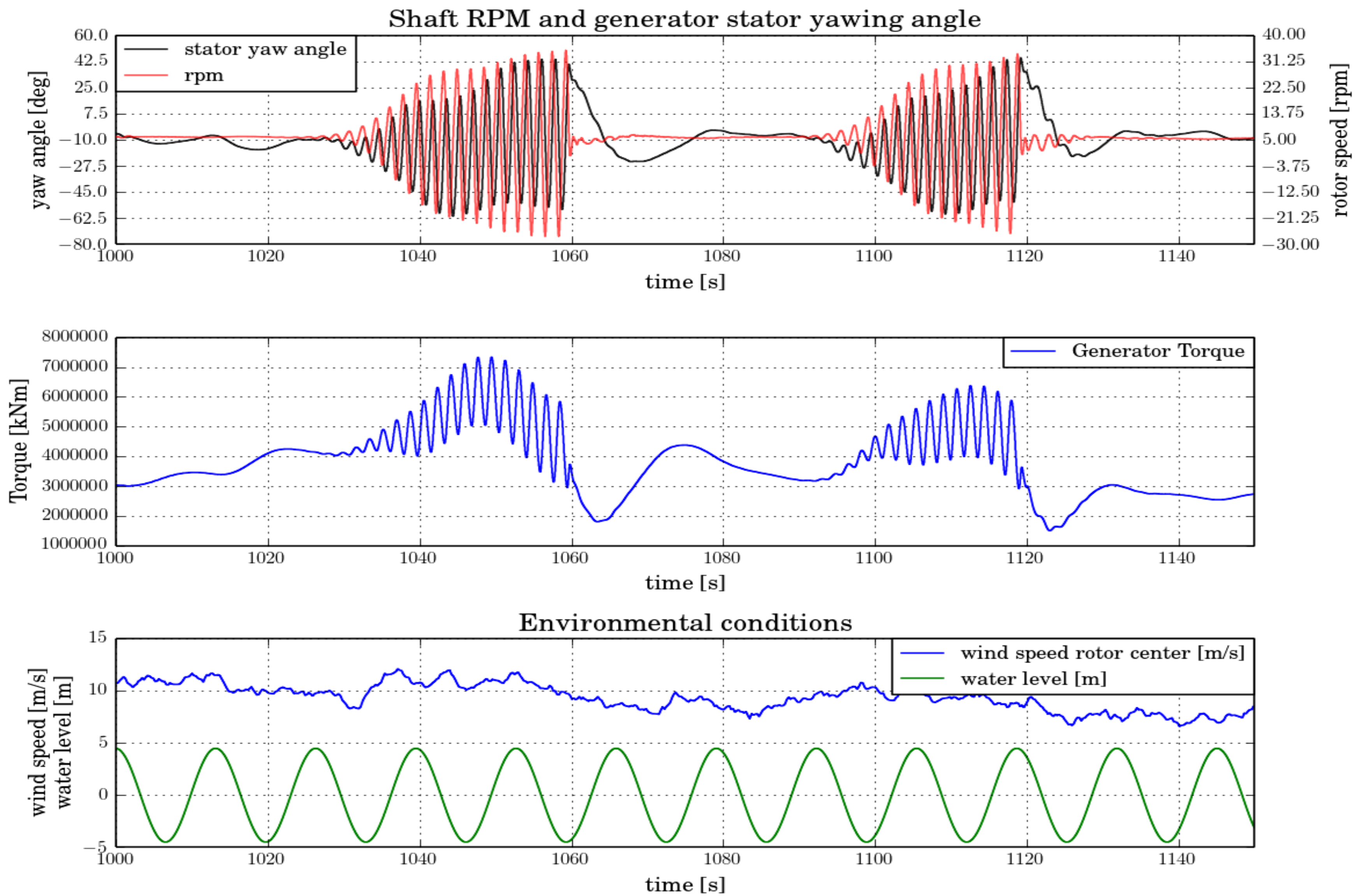
	H_s [m]	T_s [s]	Current [m/s]
Sea state 0	0	0	0
Sea state 1	4	9	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s
Sea state 2	9	13.2	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s
Sea state 3	14	16	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s

Roll



Blue SS1 Red SS2 Green SS3

	H_s [m]	T_s [s]	Current [m/s]
Sea state 0	0	0	0
Sea state 1	4	9	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s
Sea state 2	9	13.2	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s
Sea state 3	14	16	0.35 for $V_0 < 14$ m/s, 0.7 for $V_0 > 14$ m/s



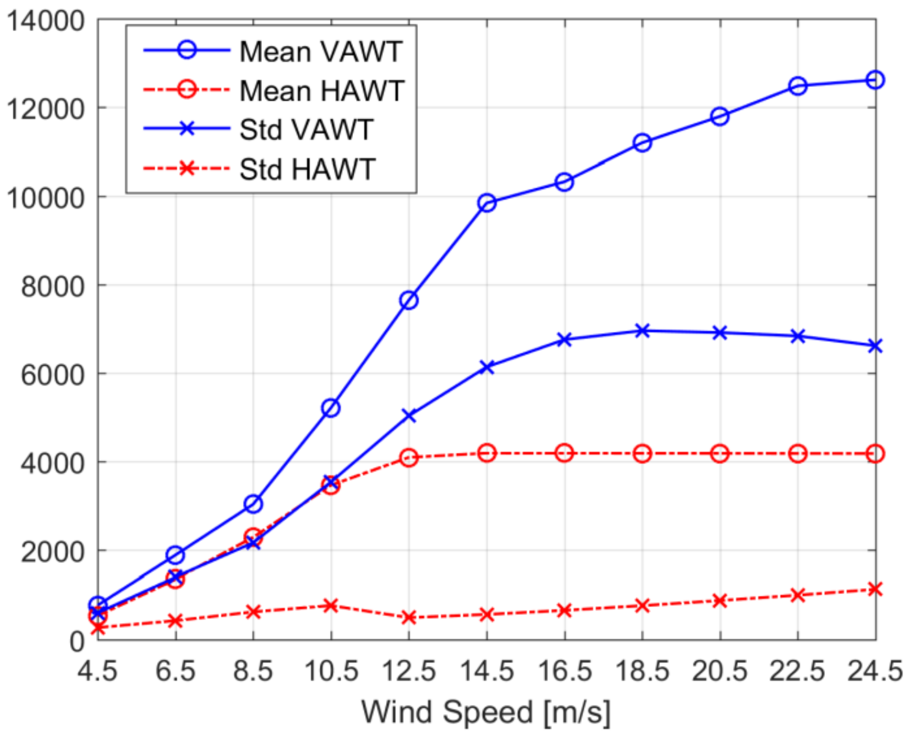
- **Detailed Load Analysis of the baseline 5MW. DeepWind Concept.** David R.S. Verelst, Helge A. Madsen, Knud A. Kragh and Federico Belloni(DTU Wind Energy E; No. 0057)

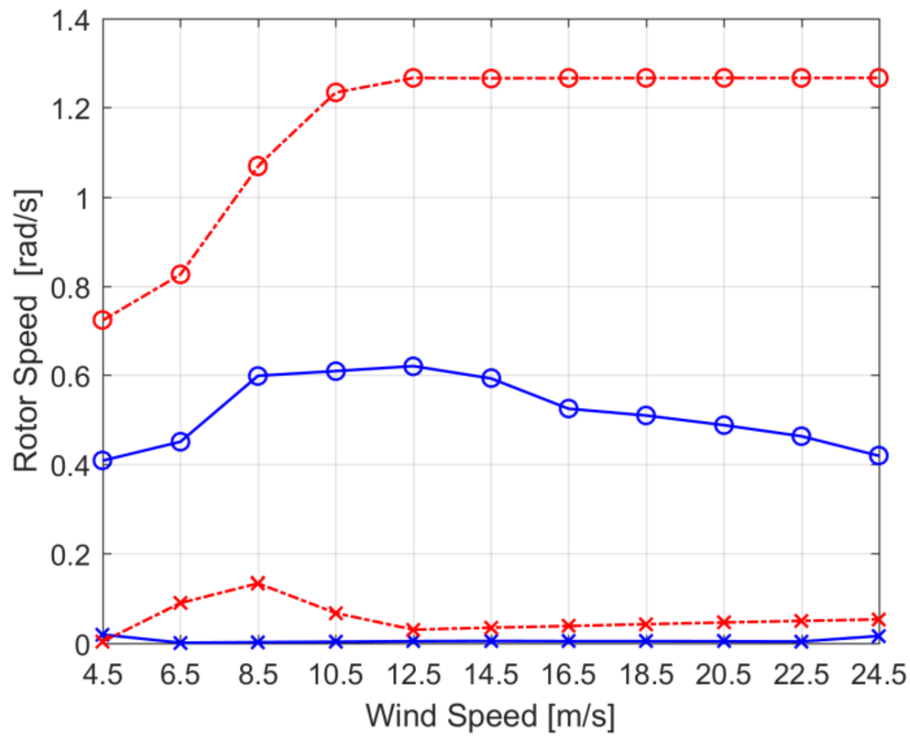
So…..

After a redesign of the rotor which increased both the stiffness and mass, <u>and</u> simplifying generator control- *edgewise instability was no longer observed*.

- Christos Galinos, Torben J. Larsen, Helge A. Madsen Uwe S. Paulsen Vertical axis wind turbine design load cases investigation and comparison with horizontal axis wind turbine 13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway Energy Procedia (2016)
- Meyer, R. E.: Stability Analysis of Multi-Megawatt Darrieus- Type Floating Vertical Axis Wind Turbines . DTU Wind Energy-M-0099, 2016

Power curve(after redesign of 2nd baseline)



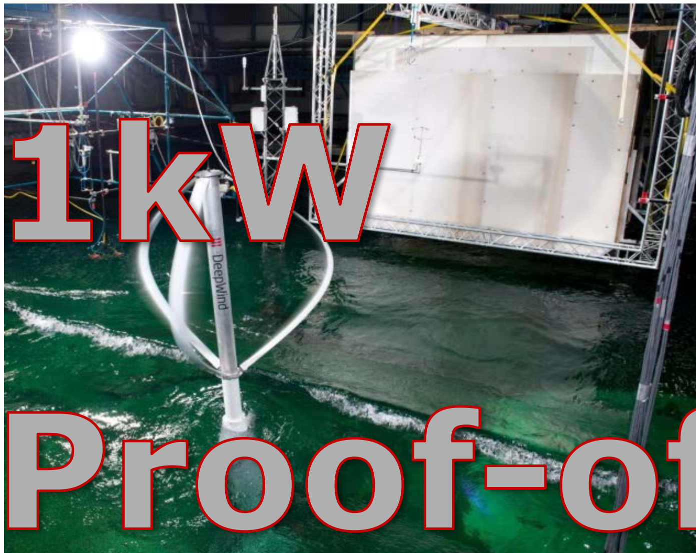


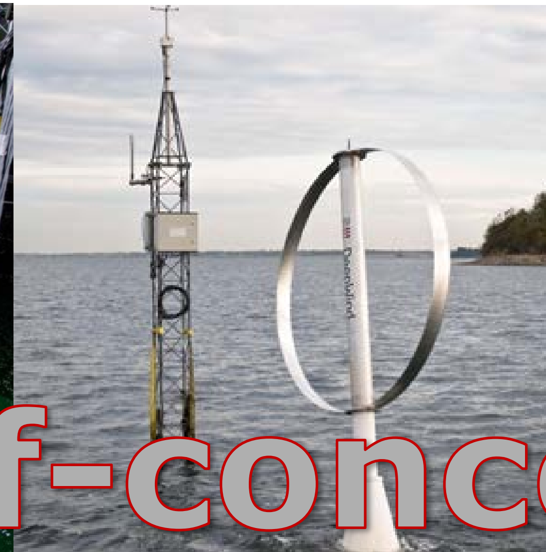
- Christos Galinos, Torben J. Larsen, Helge A. Madsen Uwe S. Paulsen Vertical axis wind turbine design load cases investigation and comparison with horizontal axis wind turbine 13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway Energy Procedia (2016)

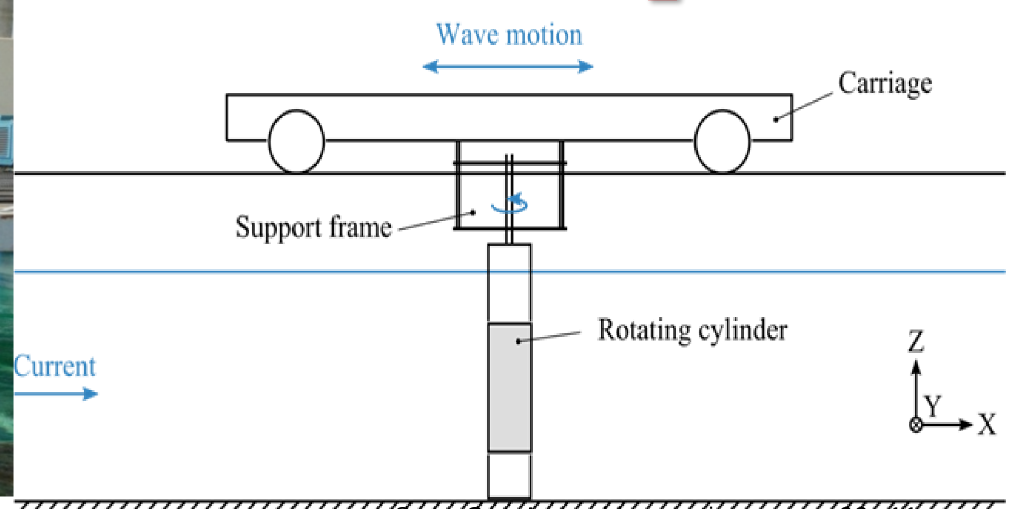
Demonstration

1kW

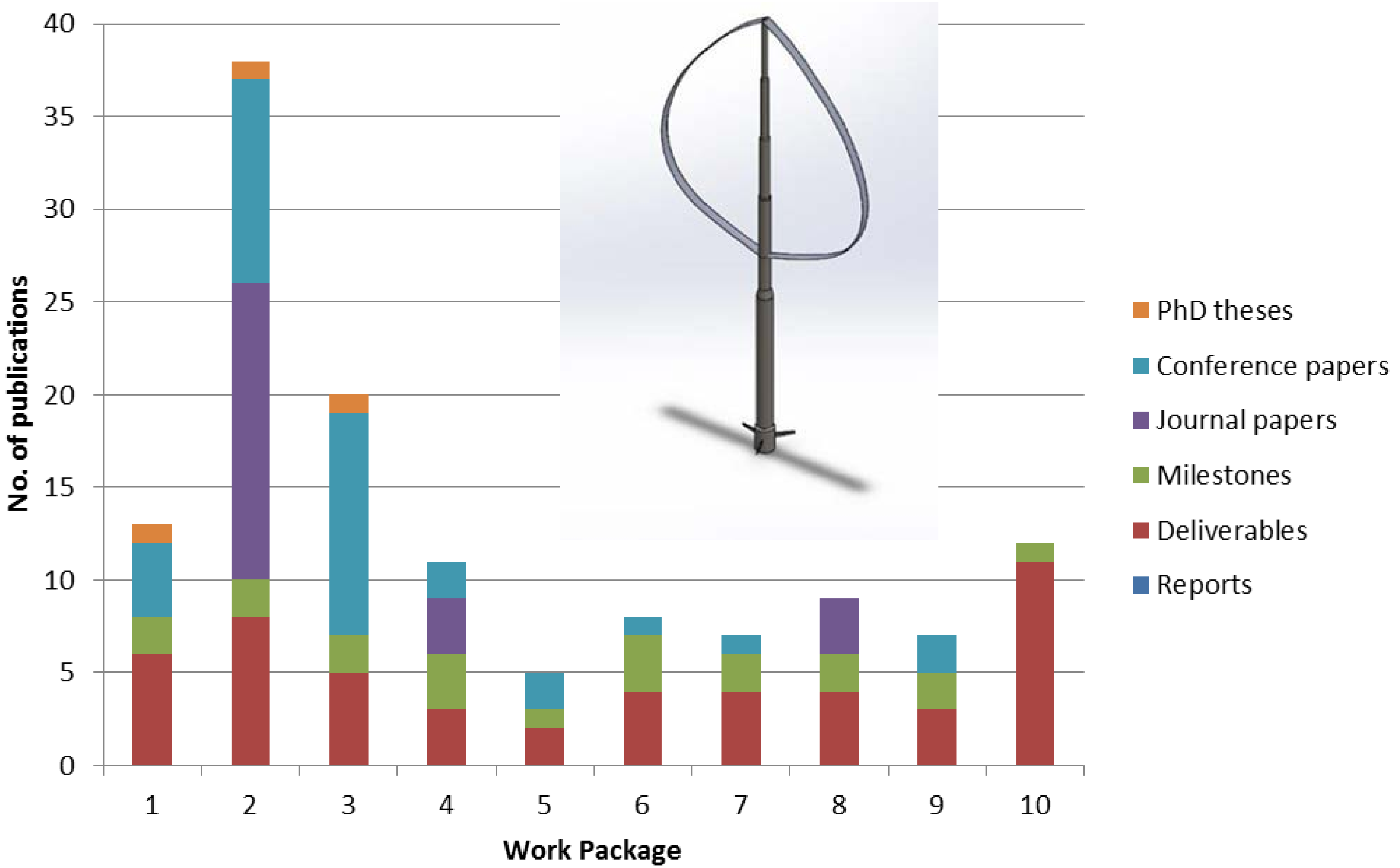
Proof-of-concept



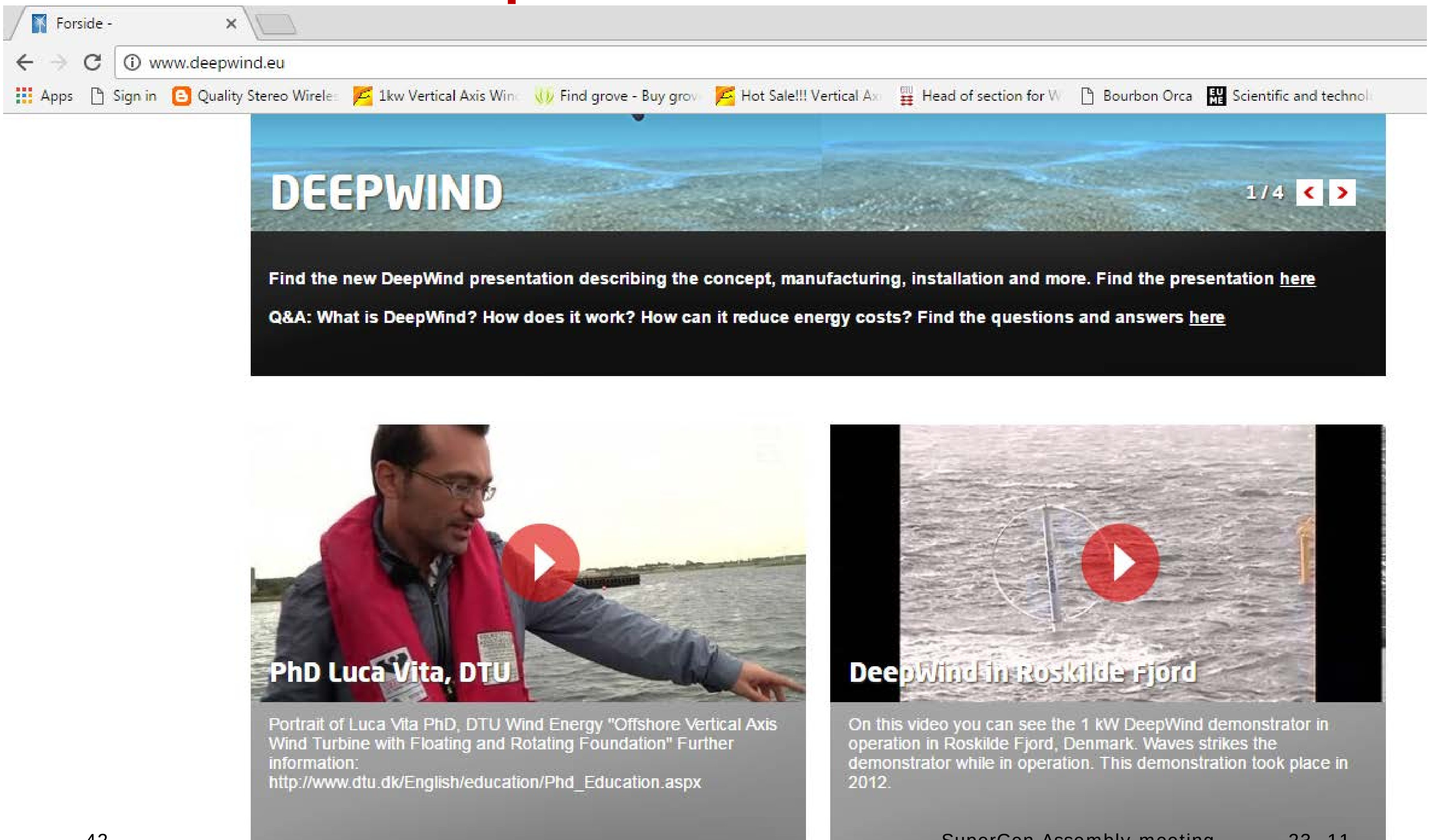




Dissemination pr WP



Dissemination pr WP



Exploitation planning

- Preparation of a business plan
  - ➢ NENUPHAR
  - ➢ VESTAS
- Report finished by February 2014
  - Commented by VESTAS
  - Commented by IPR(DTU)
- Real market assessment(NENUPHAR) + report on planning the business plan

Conclusions

CONCEPT

Rotor

- ✓ Demonstration of a optimized rotor design with pultruded, sectionized GRP blades
- ✓ Aerodynamic stall control, a robust and simple electrical controls
- ✓ 2 Blades with 2/3 less weight than 1st baseline 5MW design, and Less bending moments in root, and tension during operation
- ✓ Potential for less costly light weight rotor
- ✓ Use of moderate thick airfoils of laminar flow family with smaller CD_0 and good C_P increase efficiency and increase structural rigidity

Floater

- ✓ Successful design for harsh deep sea environment

Conclusions

INDUSTRY READYNESS

- ✓ Concept elevated to TRL4-5
- ✓ Solutions available for joints, underwater generator and mooring system

BUSINESS CASE

- ✓ No show stopper- the concept can be developed further in an industrial optimization process

DeepWind is in a steep learning curve (LCOE: ~20 €/MWh)

The 20 MW is far beyond current wind turbine sizes

DeepWind reduces or eliminates step changes in project costs that can provide significant cost savings.

Floating: State of the art?

Lower O&M Requirements

Lower Floater Stability Requirements

Lower moment arm / overturning moment

- Higher allowable pitch angle
- Possibility for alternative anchoring configuration

Main expectations:

- No maintenance of and **no** cost of yaw and pitch mechanism(+)
- Lower foundation cost (+)
- Aerodynamic efficiency (+)
- Rotor and generator cost (+-?)
- Lower bearing cost (+)

Differing opinions:

- VAWT Developers; Extremely positive
- HAWT Developers; Extremely negative

- Uwe Schmidt Paulsen A review of state-of-the-art in torque generation and control of floating vertical-axis wind turbines Euromech 2016 TUDelft

Acknowledgement

Peter Jamieson for inviting

DTU WE

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).

Thank You for your Attention

This project has received funding from the European Union’s Seventh Programme for research, technological development and demonstration under grant agreement No 256769