Deliverable 5.21

Workshop: dissemination of results and feedback from participants

Agreement n.:	308974
Duration	November 2012 – October 2017
Co-ordinator:	DTU Wind

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7-ENERGY-2012-1-2STAGE under grant agreement No. 308974 (INNWIND.EU).

Document information

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Author:	**Emanuela Giovannetti (EWEA)**
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1 TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background and objectives

This report has been drafted in the framework of Task 5.3 (Dissemination of the results) of the INNWIND.EU project.

It summarises the outcomes of the external dissemination workshop held on the 18th November 2015 within the EWEA Annual Conference – EWEA Annual 2015 in Paris.

Due to the complementarities of the treated subjects, the event was organised in cooperation with AVATAR, another project co-funded by the FP7 Programme of the European Commission.

1.2 SMART description

Deliverable No: 5.21	Title : Workshop: dissemination of results and asking feedback from participants on exploitation of results
Month Due: 24	**Participants:** EWEA, DTU Wind Energy, University of Oldenburg, NTUA
Brief Description (3 lines): Brief Description (3 lines): The workshop has two main goals. Firstly the results achieved in the months of the project will be disseminated. And secondly the audience will be asked to provide regarding the exploitation of the project results. The technology roadmap will form the basis for this discussion on exploitation.	
Specific targets: Specific targets: 1) The focus of this event is on the definition of reference wind turbine, the technology roadmap and the cost models.	
Measure of success: 1) Good attendance of the workshop and efficient exchange of information between partners, 2) Ideas on how to improve the time-to-market	
Participant contributions **GL-GH:** coordination **DTU:** review and advisory role **CRES:** review and advisory role **EWEA:** logistics of the workshop	

1.3 Participants

A total number of 53 participants signed the participant list:

Matthijs Soede (European Commission), James Ahlgrmm (U.S. Department of Energy), Ozlem Ceyhan (ECN Wind Energy), Nadine Chapalain (Mitsubishi Electric), Takis Chaviaropoulos (NTUA), Philippe Couturier (Technical University of Denmark), Dariusz Dabrowski (Technical University of Denmark), David Delgado (Siemens Wind Power), André Schäfer (HBM), Lene Eliassen (NTNU), Álvaro Gonzales (CENER), Marc Guyot (EOLINK), Martin Hartvelt (ECN/TU Delft/DTU), Jason Jonkman (NREL), Per Hessellud Lauritsen (Siemens Wind Power), Jesper Madsen (LM Wind Power), Anand Natarajan (DTU), Oscar Pires (CENER), Peter Rosenbusch (Laboratoire National de Metrologie et d'Essais), Gerard Schepers (ECN), Emilien Simonot (KIC InnoEnergy), Andreas Vath (Bosch Rexroth), Jens Sorensen (DTU Wind Energy), Laurent Beandet (EDF-R&D), Asger Abrahamsen (DTU Wind Energy), Giorgios Seros (CRES), Bodo Richert (Siemens), Soren Norlberg (Siemens), Habiba Boulharts (IFP Energies Nouvelles), Ali Sfar (Adwen Offshore), Franck Pellecchia (Adwen Offshore), Subhadip Biswas (Adwen Offshore), Paul Deglaire (Adwen Offshore), Jur Elzinga (ALE – HEAVYLIFT), Emanuela Giovannetti (EWEA), Christian Lambert (EKF),Christian Pavese (DTU Wind Energy), Michele Restuccia (Adwen Offshore), Habiba Boulharts (IFP Energies Nouvelles), Gabriele Bedon (University of Padoua), Wilfried Njomo W. (DTU Wind Energy), Jan-Willem van Wingordon (TU Delft), Hans Dürv (Senvion GmbH), Stefan Schrader (Senvion GmbH), Ralf Spolz (Senvion GmbH),Tony Burton (DNVGL), Peter Essmann (Siemens), Peters Jamienson (University of

Strathclyde), Daniel Román (Gamesa), Gerard van Bussel (TU Delft), Bernhard Stoevesandt (Fraunhofer IWES).

1.4 Agenda

3.00 - 3.05	**Welcome note** (Peter Hjuler Jensen, Deputy Head of DTU Wind Energy)
3.05 – 3.15	**Introduction to the projects INNWIND.EU and Avatar** (Peter Hjuler Jensen)
3.15 – 3.25	**Design of 10+ MW offshore wind turbines at 50m water depths** (Anand Natarajan, Senior Scientist at DTU Wind Energy)
3.25 – 3.45	**"Soft or tough – when growing rotor size?"** (Flemming Rasmussen, Head of Aeroelastic Design Section – DTU Wind Energy)
3.45 – 4.05	**Superconducting versus pseudo direct drive generators - test results and perspectives** (Asger Abrahamsen, Senior Researcher at DTU Wind Energy)
4.05 – 4.25	**Novel experiment results enabling new 10 MW support structures designs** (Martin Kühn, Professor Wind Energy Systems at University of Oldenburg)
4.25 – 4.45	**Assessment of Innovations and Integration** (Takis Chaviaropoulos, Senior research associate, NTUA)
4.45 – 5.10	*break*
5.10 – 5.20	**Low induction reference rotor design** (Giorgios Sieros, Senior research associate, CRES)
5.20 – 6.05	**Wind tunnel measurements** (Ozlem Ceyhan, Researcher ECN and Oscar Pires, Research Specialist CENER)
6.05 - 6.25	**Discussion** Chaired by Peter Hjuler Jensen, Deputy Head of DTU Wind Energy
6.25 -6.30	**Closing remarks** Peter Hjuler Jensen, Deputy Head of DTU Wind Energy

1.5 Presentations

The event included the 5 following presentations on the INNWIND.EU project:

1. **Introduction to the projects INNWIND.EU and Avatar**
2. **Design of 10+ MW offshore wind turbines at 50m water depths** (Anand Natarajan, Senior Scientist at DTU Wind Energy)

3. **“Soft or tough – when growing rotor size?”** (Flemming Rasmussen, Head of Aeroelastic Design Section – DTU Wind Energy)
4. **Superconducting versus pseudo direct drive generators - test results and perspectives** (Asger Abrahamsen, Senior Researcher at DTU Wind Energy)
5. **Novel experiment results enabling new 10 MW support structures designs** (Martin Kühn, Professor Wind Energy Systems at University of Oldenburg)
6. **Assessment of Innovations and Integration** (Takis Chaviaropoulos, Senior research associate, NTUA)

The presentations can be found in the Appendix.

1.6 Measure of success

As it is possible to see under section 1.2 above, the SMART deliverables to determine the success of this event are:

1) Good attendance of the workshop and efficient exchange of information between partners.
2) Ideas on how to improve the time-to-market.

The first SMART indicator was fulfilled due to the following factors:

- Organising the event in the framework of the EWEA Annual Conference, EWEA 2015, probably helped in reaching out the desired stakeholders, both in terms of logistical facilities and advertisement, and for the audience attending the EWEA conference. As already mentioned, 53 people participated representing, among others, universities, wind turbine manufacturers, O&M suppliers, certification bodies, research institutes, test and measurements bodies.

- Thanks to the complementarity of the issues tackled, it was decided to organise the workshop in cooperation with the AVATAR project. This was also an added value in terms of a broader offer of the themes proposed.

- Several discussions were had between members of the audience and the speakers on topics such as the scope of a 20 MW wind turbine and its component size, the different innovations being developed as well as access to the project results.

- A core team composed by EWEA, DTU, DNV-GL, NTUA coordinated the organisation of the event in collaboration with the colleagues of the AVATAR project. More in particular, other than via an exchange of emails, a few conference calls helped the group to: fine-tune the definition of the agenda of the event; harmonise the presentations so as to have a smooth flow of coherent issues addressing the targeted audience; monitor the state of advancement of the logistics; set-up invitation systems and coordinate invitations and reminders spreading among the respective networks of contacts; send weekly updates of registerees.

The second SMART indicator was fulfilled as follows:

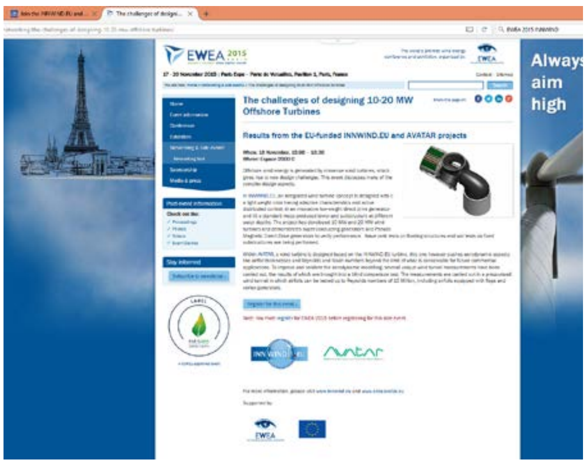
The main innovations of the INNWIND.EU project are disseminated to potential end users who are themselves building large offshore wind turbines and who stand to benefit from the knowledge gained at this event. Raising the awareness and understanding of the INNWIND.EU innovations has been achieved, which enables a wider focus on innovations with other players possibly furthering their technology readiness levels.. Moreover, the presence of several persons from the offshore wind industry such as from Senvion and Adwen helped in conveying the project results to industrial key actors outside the project consortium. This was evident in this workshop which further brought together the academia and industry players and involved them in a fruitful discussion.

Registration system under the INNWIND.EU website /

http://www.innwind.eu/News/Nyhed?id=DD5FA9B3-123B-45C3-8558-189AC726C3B9

Registration system under the EWEA 2015 website

http://www.ewea.org/annual2015/networking/the-challenges-of-designing-10-20-mw-offshore-turbines



2 MINUTES

A brief summary of each session is presented herewith. This also included the AVATAR's presentations in order to provide with a better overview of the content of the workshop.

2.1 Introduction to the projects INNWIND.EU and Avatar

Peter Juler Hansen (DTU) and Gerard Schepers (ECN) introduced the INNWIND.EU and AVATAR projects respectively, in their quality of project coordinators.

2.2 Design of 10+ MW offshore wind turbines at 50m water depths (Anand Natarajan, Senior Scientist at DTU Wind Energy)

This presentation introduced the reference turbines used in the Avatar and INNWIND.EU projects.

2.3 "Soft or tough – when growing rotor size?" (Flemming Rasmussen, Head of Aeroelastic Design Section – DTU Wind Energy)

This presentation highlighted the challenges, barriers and perspectives for further upscaling of rotors from 8 towards 20 MW. It also described innovations from the INNWIND.EU project that facilitate this development covering new high speed aerodynamic concepts, thick and dedicated airfoils, light weight structural design, flexibility, long slender blades, aeroelastic tailoring, stability, and passive and active load control and alleviation.

2.4 Superconducting versus pseudo direct drive generators - test results and perspectives (Asger Abrahamsen, Senior Researcher at DTU Wind Energy)

The presentation focused on test results of superconducting direct drive generators and magnetic pseudo direct drive generators for wind turbines and the perspectives these results give for the wind industry.

2.5 Novel experiment results enabling new 10 MW support structures designs (Martin Kühn, Professor Wind Energy Systems at University of Oldenburg)

The presentation focused on results from new experiments on a floater in a wave tank. Innovations to reduce cost of energy for bottom mounted structures were shown.

2.6 Assessment of Innovations and Integration (Takis Chaviaropoulos, Senior research associate, NTUA)

More than 10 innovative component designs for blades, drive trains and deep offshore support structures are comparatively assessed using INNWIND.EU key performance indicators and cost models. The potential of individual designs and their combination in reducing the levelised cost of electricity is justified and quantified.

2.7 Low induction reference rotor design (Giorgios Sieros, Senior research associate, CRES)

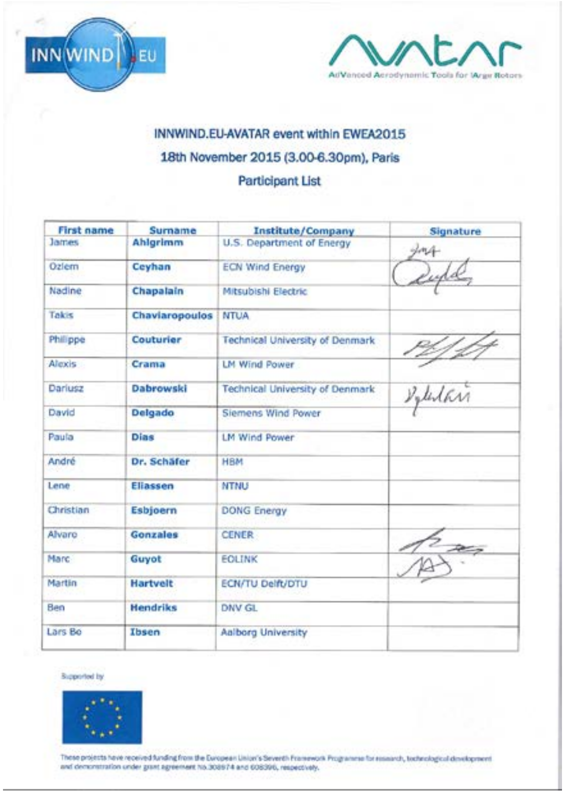
The reference turbines used in the Avatar and INNWIND.EU projects were already presented in general. This presentation focused on the low induction rotor. A low weight rotor design.

2.8 Wind tunnel measurements (Ozlem Ceyhan, Researcher ECN and Oscar Pires, Research Specialist CENER)

The small wind tunnel size generally leads to Reynolds numbers in the order of 3-6M, much lower than the Reynolds number on a large wind turbine (15M). Measurements were presented taken in a pressurised tunnel in which Reynolds numbers of 15M could be reached. The measurements have been compared with calculations which are carried out under 'blind conditions' i.e. without knowledge of the measurements.

3 ANNEXES

3.1.1 Signed List of participants



INNWIND.EU-AVATAR event within EWEA2015

18th November 2015 (3.00-6.30pm), Paris

Participant List

First name	Surname	Institute/Company	Signature
James	Ahlgrimm	U.S. Department of Energy	
Ozlem	Ceyhan	ECN Wind Energy	
Nadine	Chapalain	Mitsubishi Electric	
Takis	Chaviaropoulos	NTUA	
Philippe	Couturier	Technical University of Denmark	
Alexis	Crama	LM Wind Power	
Dariusz	Dabrowski	Technical University of Denmark	
David	Delgado	Siemens Wind Power	
Paula	Dias	LM Wind Power	
André	Dr. Schäfer	HBM	
Lene	Eliassen	NTNU	
Christian	Esbjoern	DONG Energy	
Alvaro	Gonzales	CENER	
Marc	Guyot	EOLINK	
Martin	Hartvelt	ECN/TU Delft/DTU	
Ben	Hendriks	DNV GL	
Lars Bo	Ibsen	Aalborg University	

Supported by

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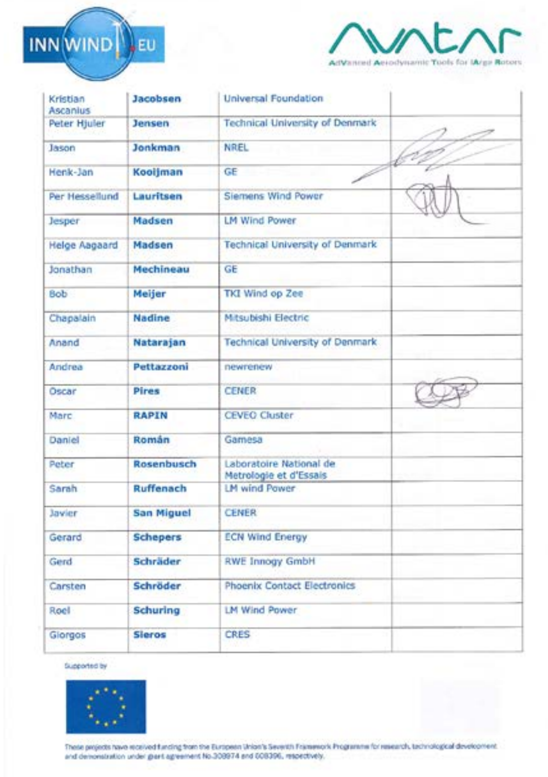

Kristian Ascanius	Jacobsen	Universal Foundation	
Peter Hjuler	Jensen	Technical University of Denmark	
Jason	Jonkman	NREL	
Henk-Jan	Kooijman	GE	
Per Hessellund	Lauritsen	Siemens Wind Power	
Jesper	Madsen	LM Wind Power	
Helge Aagaard	Madsen	Technical University of Denmark	
Jonathan	Mechineau	GE	
Bob	Meijer	TKI Wind op Zee	
Chapalain	Nadine	Mitsubishi Electric	
Anand	Natarajan	Technical University of Denmark	
Andrea	Pettazzoni	newrenew	
Oscar	Pires	CENER	
Marc	RAPIN	CEVEO Cluster	
Daniel	Román	Gamesa	
Peter	Rosenbusch	Laboratoire National de Metrologie et d'Essais	
Sarah	Ruffenach	LM wind Power	
Javier	San Miguel	CENER	
Gerard	Schepers	ECN Wind Energy	
Gerd	Schräder	RWE Innogy GmbH	
Carsten	Schröder	Phoenix Contact Electronics	
Roel	Schuring	LM Wind Power	
Giorgos	Sieros	CRES	

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INNWIND.EU

AVATAR
AdVanced Aerodynamic Tools for IArge Rotors

Emilien	**Simonot**	KIC InnoEnergy	
John	**Skiller**	SKF	
Darius	**Snieckus**	Recharge	
Alf	**Trede**	SENVION	
Igone	**Ugalde**	TECNALIA	
Andreas	**Vath**	Bosch Rexroth	
Isao	**Yoshino**	Mitsui Zosen Europe Ltd.	
Habiba	BOULHARTS	IFP Energies nouvelles	
Gabriele	Bedon	University of Padua	
Wilfried	NJOMO W.	DTU Wind Energy	
Jan-Willem	van Wingerden	TU Delft	
Hans	Dörr	Senvion GmbH	
Stefan	Schrader	— " —	
Ralf	Spitz	— " —	
Tony	BURTON	DNVGL	
PETER	EGGMANN	SIEMENS	
Peter	JAMIESON	UNIVERSITY OF STRATHCLYDE	
DANIEL	ROMÁN	GAMESA	
Gerard	van Bussel	TU Delft	
Bernhard	Stoevesandt	Fraunhofer IWES	

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Igone	**Ugalde**	TECNALIA	
Andreas	**Vath**	Bosch Rexroth	A. Vath
Isao	**Yoshino**	Mitsui Zosen Europe Ltd.	
Jens	Sørensen	DTU	
Laurent	Beaudet	EDF - R&D	
ASGER	ABRAHAMSEN	DTU Wind Energy	
Flemming	Rasmussen	DTU	
Giorgos	Sieros	CRES	
Bodo	RICHERT	SIEMENS	
Søren	Nordborg	Siemens	S. Nordborg
Habiba	BOULHARTS	IFP Energies Nouvelles	
ALI	SFAR	Adwen Offshore	
FRANCK	PELLECCHIA	Adwen Offshore	
SUBHADIP	BISWAS	Adwen Offshore	
DEGLAIRE	PAUL	Adwen Offshore	
JUR	ELZINGA	ALE - HEAVYLIFT	
Emanuela	GIOVANNETTI	EWEA	
Christian	Lambert	EKF.	

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CHRISTIAN	PAVESE	DTU WIND ENERGY	
MICHELE	RESTUCCIA	ADWEN OFFSHORE	

3.1.2 Presentations

Introduction to the projects INNWIND.EU and Avatar (Peter Hjuler Jensen, Deputy Head of DTU Wind Energy and Gerard Schepers, Project coordinator at ECN Wind Energy)

Program: INNWIND.EU and Avatar

3.00 - 3.05	**Welcome (Peter Hjuler Jensen, Deputy Head of DTU Wind Energy)** **Welcome introduction by EU Scientific Officer Matthijs Soede**
3.10– 3.15	Introduction to the projects INNWIND.EU and Avatar (Peter Hjuler Jensen)
3.15 – 3.25	Design of 10+ MW offshore wind turbines at 50m water depths (Anand Natarajan, Senior Scientist at DTU Wind Energy)
3.25 – 3.45	"Soft or tough – when growing rotor size?" (Flemming Rasmussen, Head of Aeroelastic Design Section – DTU Wind Energy)
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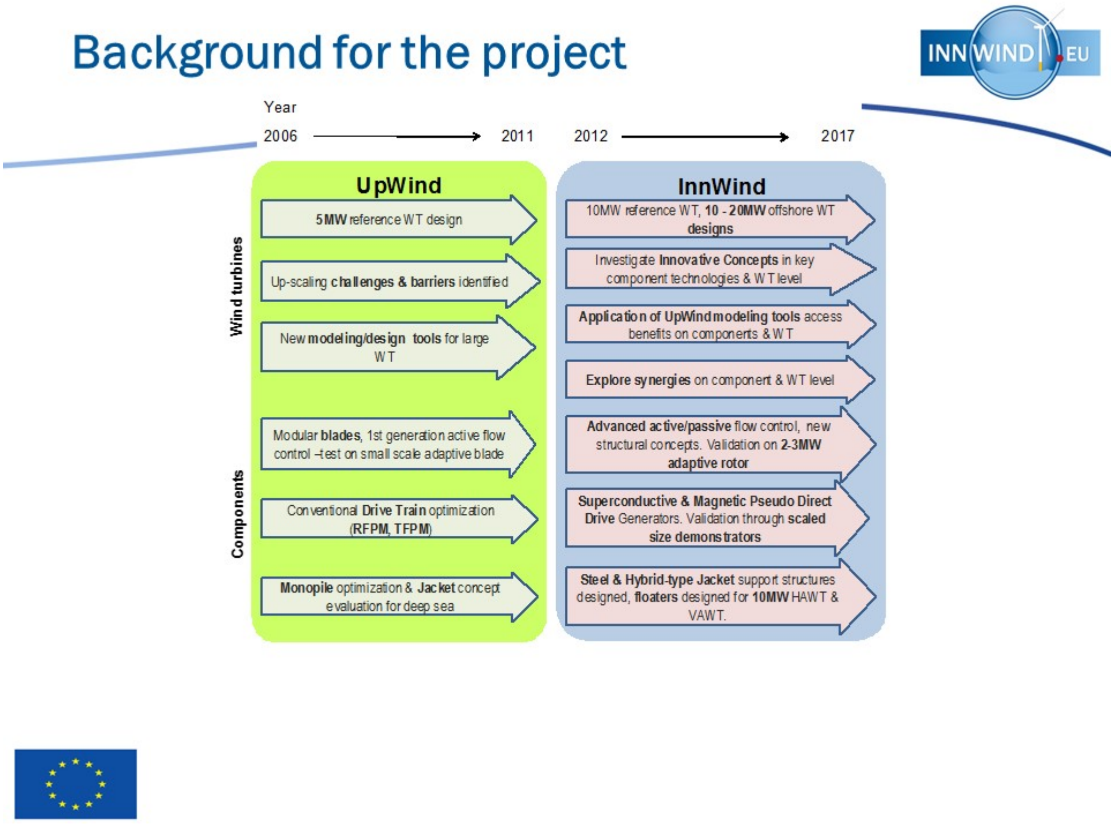
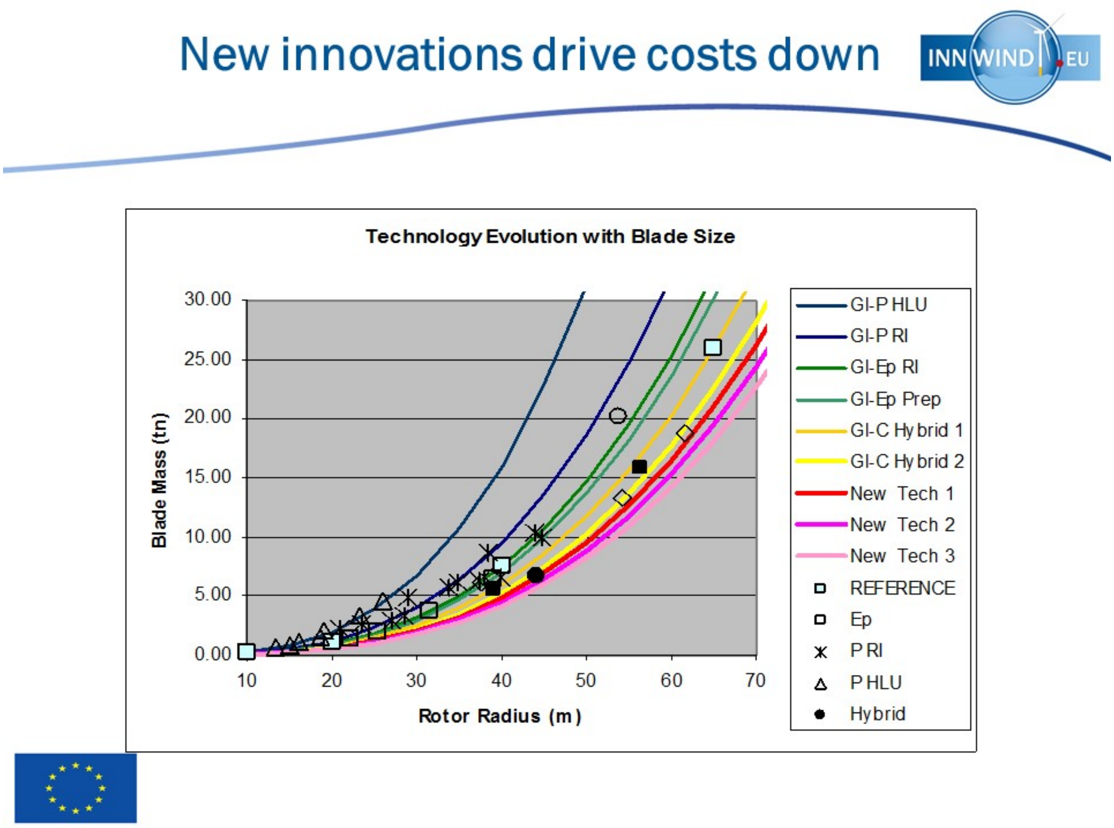
6.05 – 6.25	Discussion Chaired by Peter Hjuler Jensen, Deputy Head of DTU Wind Energy
6.25-6.30	Closing by Peter Hjuler Jensen

INNWIND.EU Overview and the Consortium

- INNWIND.EU started 1. November 2012
- 5 year project, 19.6M€ overall budget
- 27 Participating organizations
- 7 Leading wind energy industries, 19 leading Universities/Research organizations, 1 trade institution
- Demonstrations of Innovative Components

Work Package	Innovation Demonstration	Size/ Capacity	Task Leader
WP3	Superconducting direct drive generator pole pair	3-6 MW	Siemens wind power
WP3	Magnetic pseudo direct drive generator (Magnetic gear + generator)	150 kW – 2.5 MW	Magnomatics
WP2	Smart blades	Scaled down tests	DTU





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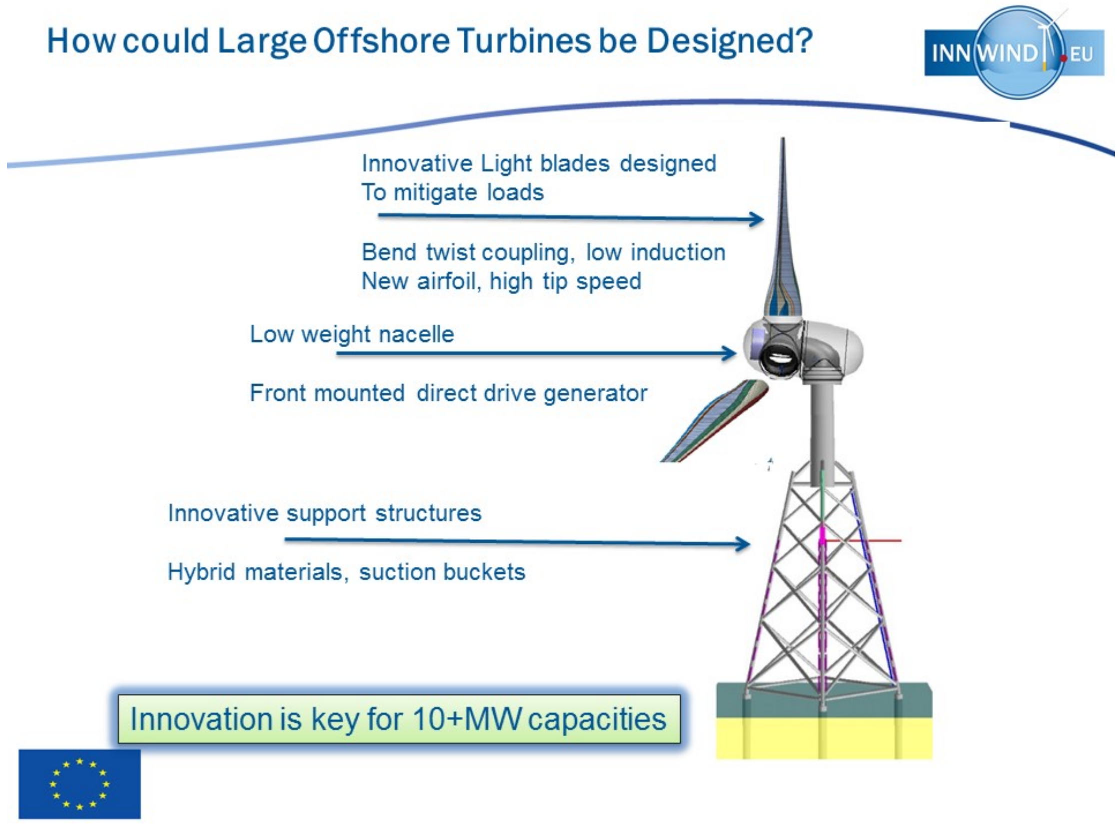

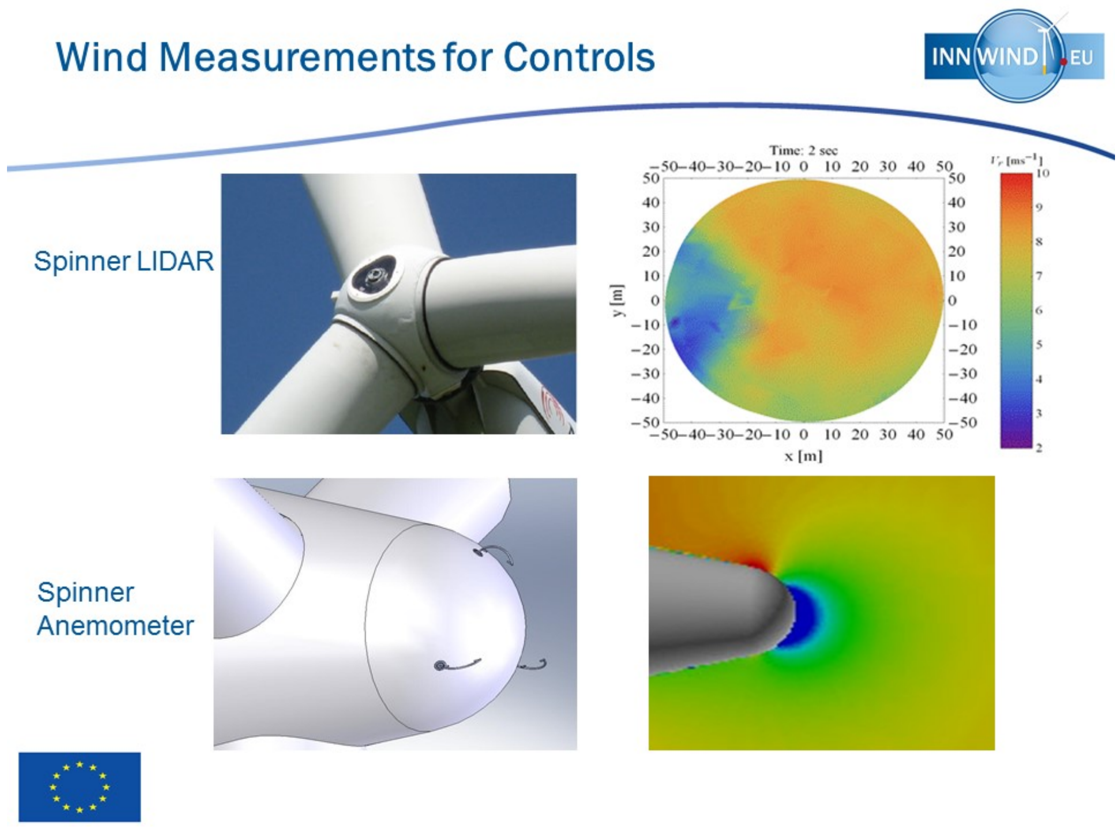

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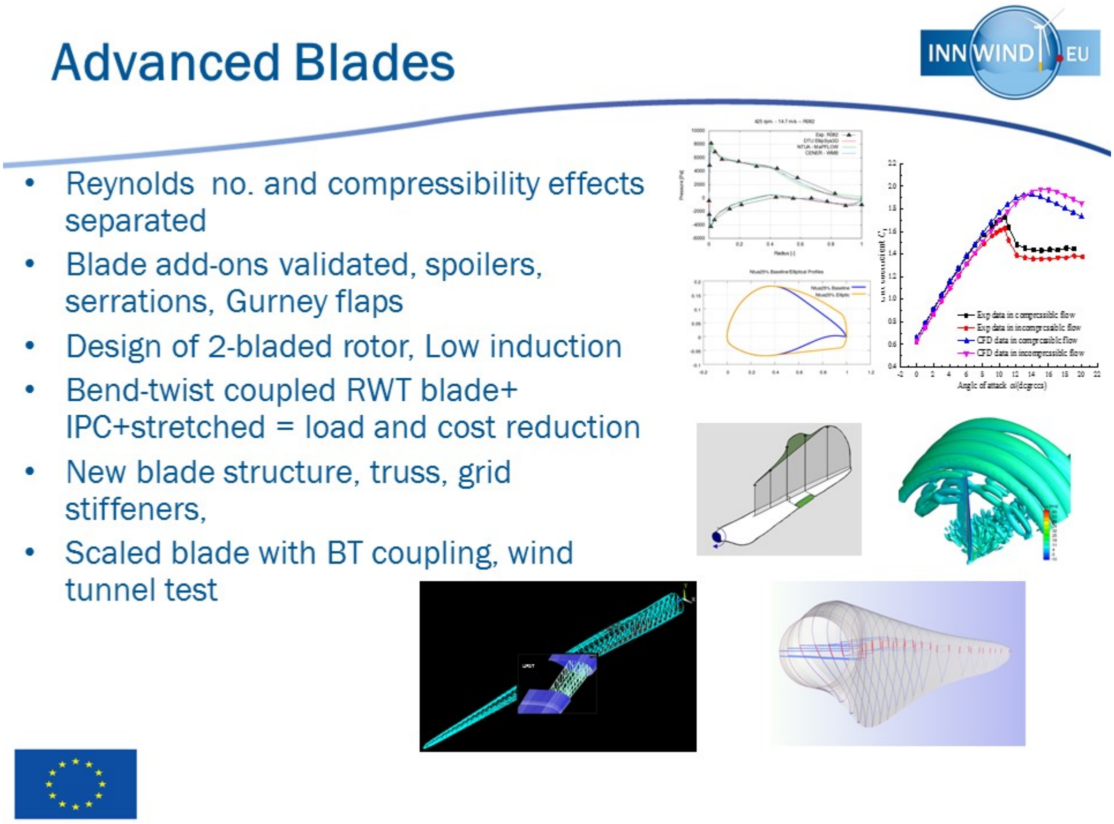
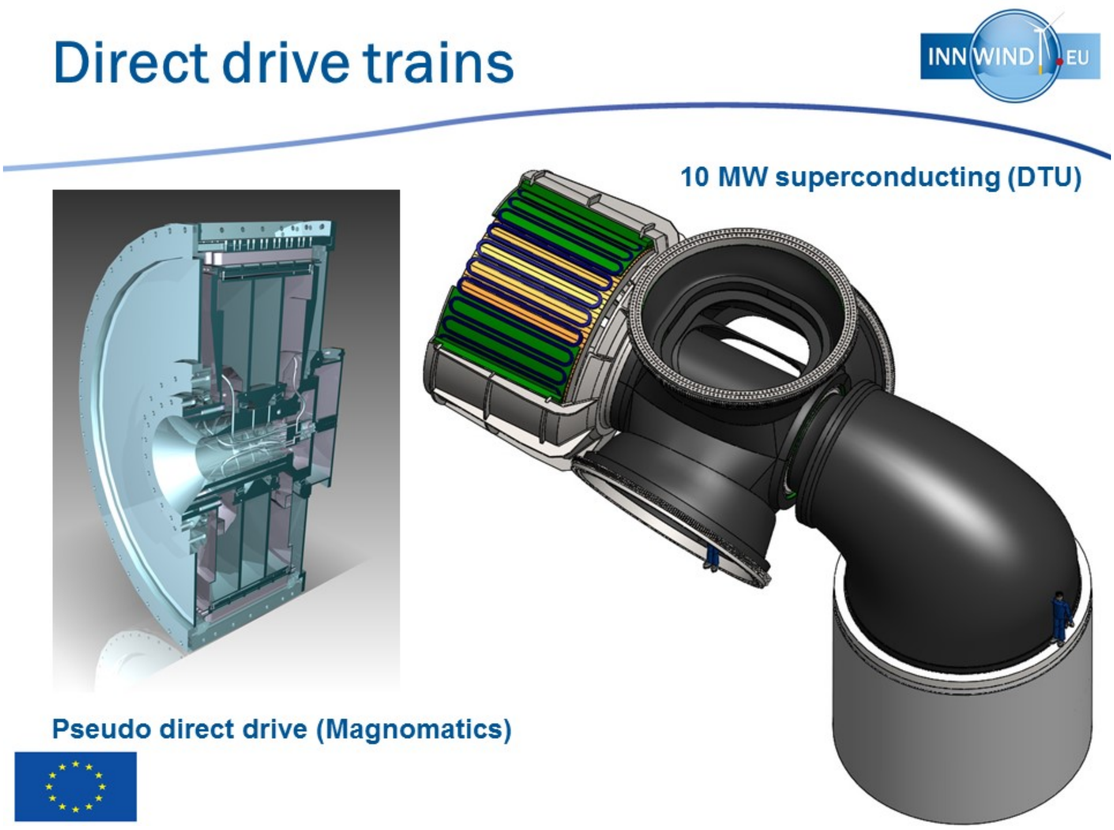
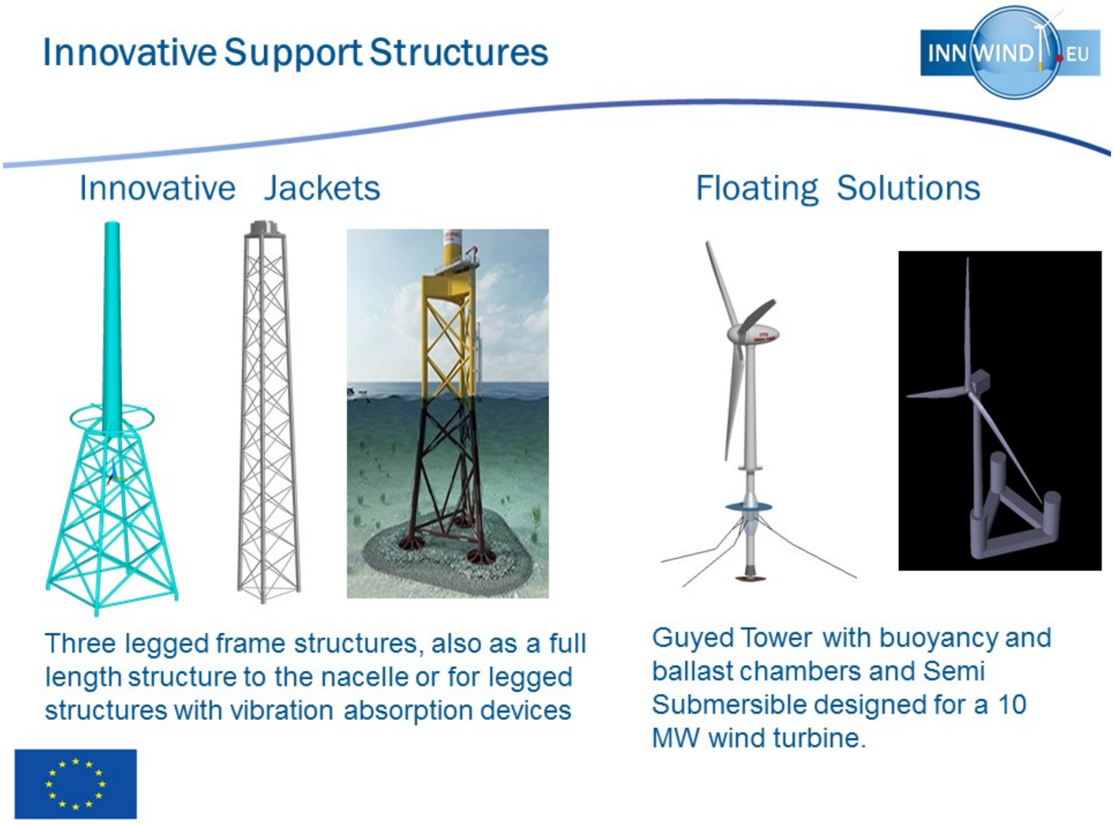

Advanced Blades
• Reynolds no. and compressibility effects separated
• Blade add-ons validated, spoilers, serrations, Gurney flaps
• Design of 2-bladed rotor, Low induction
• Bend-twist coupled RWT blade+ IPC+stretched = load and cost reduction
• New blade structure, truss, grid stiffeners,
• Scaled blade with BT coupling, wind tunnel test


Direct drive trains
10 MW superconducting (DTU)
Pseudo direct drive (Magnomatics)


Innovative Support Structures
INNWIND.EU
Innovative Jackets
Floating Solutions
Three legged frame structures, also as a full length structure to the nacelle or for legged structures with vibration absorption devices
Guyed Tower with buoyancy and ballast chambers and Semi Submersible designed for a 10 MW wind turbine.

Design of 10+ MW offshore wind turbines at 50m water depths (Anand Natarajan, Senior Scientist at DTU Wind Energy)

Design of 10+ MW offshore wind turbines at 50m water depths

Anand Natarajan with contributions from INNWIND.EU and AVATAR team
DTU Wind Energy

The 10 MW Reference Wind Turbine

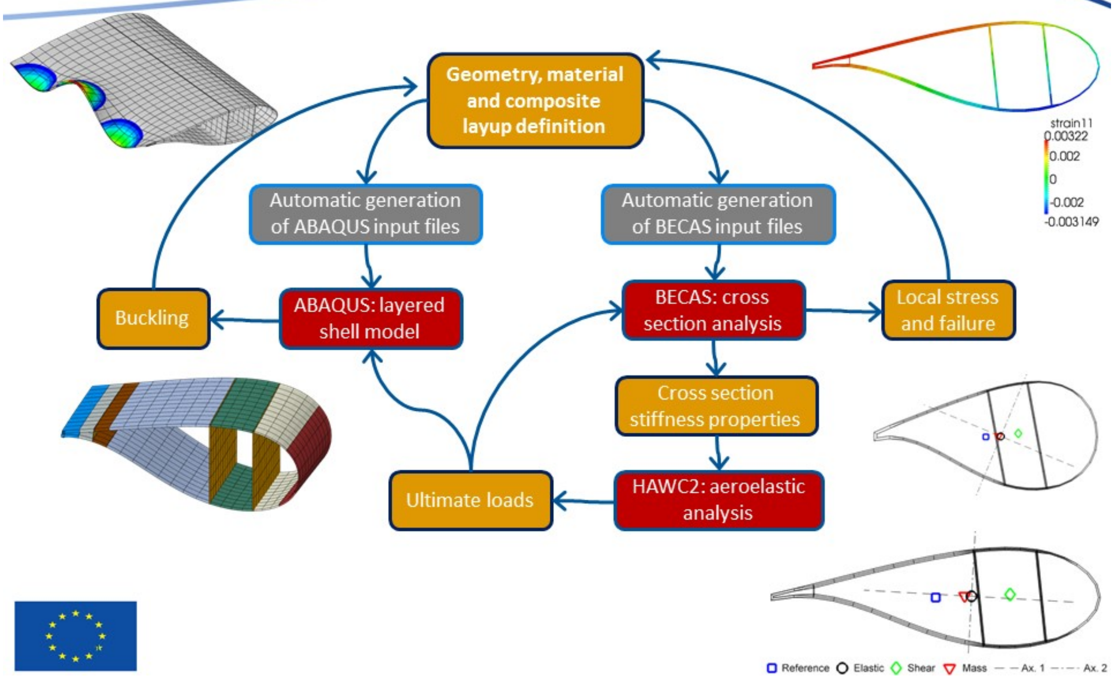
- **The objective is:**
  - To provide a publicly available representative design basis for next generation of large offshore wind turbines.
  - To achieve a design made with traditional design methods consistent with design standards
  - Good aerodynamic performance and fairly low weight rotor
  - To provide a design with high enough detail for use for comprehensive comparison of both aero-elastic as well as high fidelity aerodynamic and structural tools.
- **The objective is not:**
  - To design a rotor pushed to the limit with lowest weight possible,
  - To design a light weight support structure,
  - To provide a design ready to be manufactured; the manufacturing process is not considered.

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

The DTU 10 MW Reference Wind Turbine Design Summary

Description	Value
Rating	10MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Medium speed, Multiple stage gearbox
Rotor, Hub diameter	178.3m, 5.6m
Hub height	119m
Cut-in, Rated, Cut-out wind speed	4m/s, 11.4m/s, 25m/s
Cut-in, Rated rotor speed	6RPM, 9.6RPM
Rated tip speed	90m/s
Overhang, Shaft tilt, Pre-cone	7.07m, 5°, 2.5°
Pre-bend	3m
Rotor mass	225tons (each blade ~40tons)
Nacelle mass	446tons
Water Depth	50 m

Reference Wind Turbine Rotor Design loop



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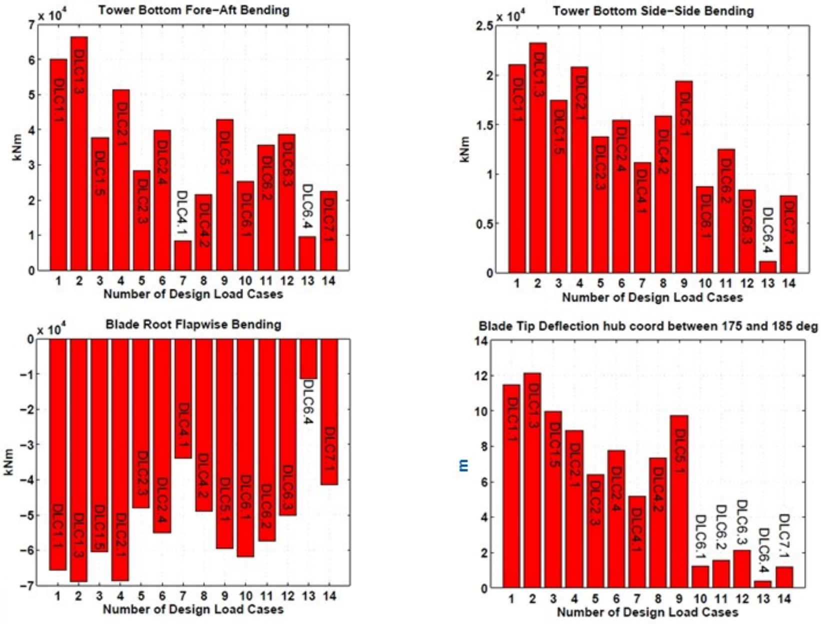
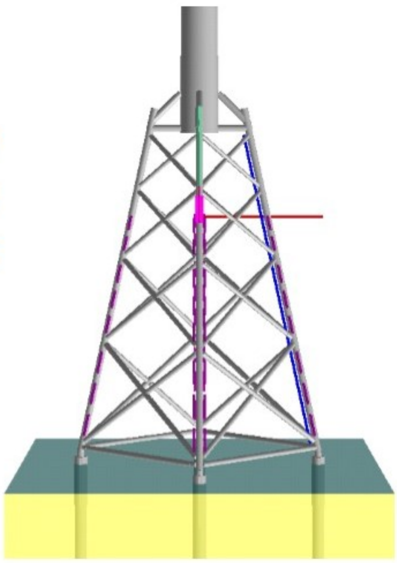
Load calculations



Reference Jacket

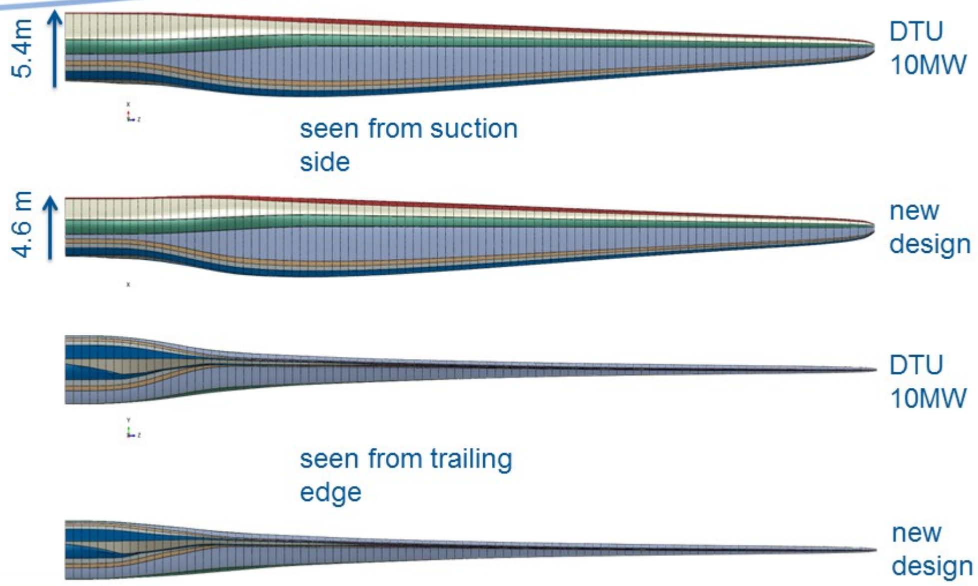
- Top width: 14m
- Bottom width: 34m
- Leg Diameter: 1400mm
- Brace Diameter: 880-1090mm
- Wall thicknesses: 22-120mm

- Tower mass: 430 tons
- Jacket mass: 1210 tons
- TP mass: 330 tons
- Pile mass: 380 tons



(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Re-design the Blade Root – Smaller Pitch Bearing

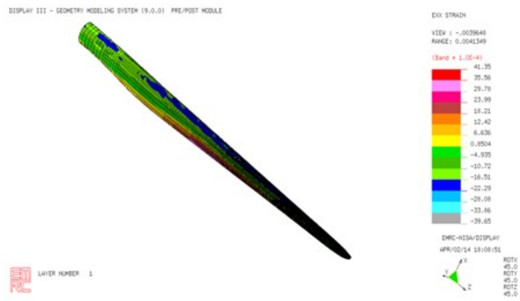


AVATAR Reference Turbine

- Increase blade tip speed to > 100m/s
- Increased Hub Height to 132m
- Increase rotor diameter to ~205m
- Power Density drastically reduced (400W/m^2 → 300W/m^2) by increasing rotor diameter with same rated power.
- Coefficient of Power Reduced
- Limitations on thrust and blade root bending moment
  - Thrust decreased, so that bending moment at tower bottom remains similar to INNWIND.EU RWT
  - Blade Root Bending moment increases slightly

AVATAR Blade Structural Design

- Carbon reinforcements introduced
  - Changes philosophy of design
  - No longer driven by stiffness concerns
- Weight of 46t (up slightly from INNWIND.EU blade)
- Flapwise deflection reduced
- Edgewise deflection increased



1st Eig.: 0.639Hz (Edge)
2nd Eig.: 0.820Hz (Flap)
3rd Eig.: 1.904Hz (Edge)
4th Eig.: 2.198Hz (Flap)
5th Eig.: 4.045Hz (Possibly coupled)

Moving from 10 MW to 20 MW RWT Upscaled *Design Summary*

Rated Power [MW]	10	20
Number of blades [-]	3	3
Rotor Diameter [m]	178.33	252.2
Hub Height from m.s.l. [m]	119	155.9
Blade Length [m]	86,36	122.14
Blade Root Diameter [m]	5.4	6.5
Rated Wind Speed [m/s]	11.4	11.4
Design Extreme Thrust Value [kN]	4600	9600
Minimum Rotor Speed [RPM]	6	4.25
Rated Rotor Speed [RPM]	9.6	6.79
Optimal TSR [-]	7.5	7.5
Gear Ratio [-]	50	50
Blade Mass [tons]	41.7	118
Hub Mass [tons]	105.5	251
Nacelle mass [tons]	446	1061
Tower mass [tons]	628.4	1629.3
Tower Top Mass, RNA [tons]	676.7	1665.8
Water depth (mean sea level - m.s.l.) [m]	50	50
Access Platform a.m.s.l. [m]	25	25
Jacket Mass [Tons]	1210	?

Natural frequencies of 10 MW to 20 MW designs
Design Summary

Mode	Description	10 MW HAWC2 (Hz)	20 MW Classical Upscaling (Hz)	Adjusted 20 MW GAST (Hz)
1	*1st Tower SS*	0.248672	0.17584	**0.20532**
2	*1st Tower FA*	0.251432	0.17779	**0.20848**
3	*1st Drive Train*	0.502233	0.35513	0.35259
4	*1st Blade Asym. Flapwise Yaw*	0.547028	0.38681	0.36848
5	*1st Blade Asym. Flapwise tilt*	0.590138	0.41729	0.38340
6	*1st Blade Collective Flap*	0.633966	0.44828	0.45281
7	*1st Blade Asym. Edgewise 1*	0.922035	0.65198	0.62916
8	*1st Blade Asym. Edgewise 2*	0.935768	0.66169	0.64171
9	*2nd Blade Asym. Flapwise Yaw*	1.376250	0.97316	0.91563
10	*2nd Blade Asym. Flapwise tilt*	1.550470	1.09635	0.97583
11	*2nd Blade Collective Flap*	1.763300	1.24684	1.24052
12	*2nd Tower SS*	1.969450	1.39261	1.43239
13	*2nd Tower FA*	2.246720	1.58867	1.74721

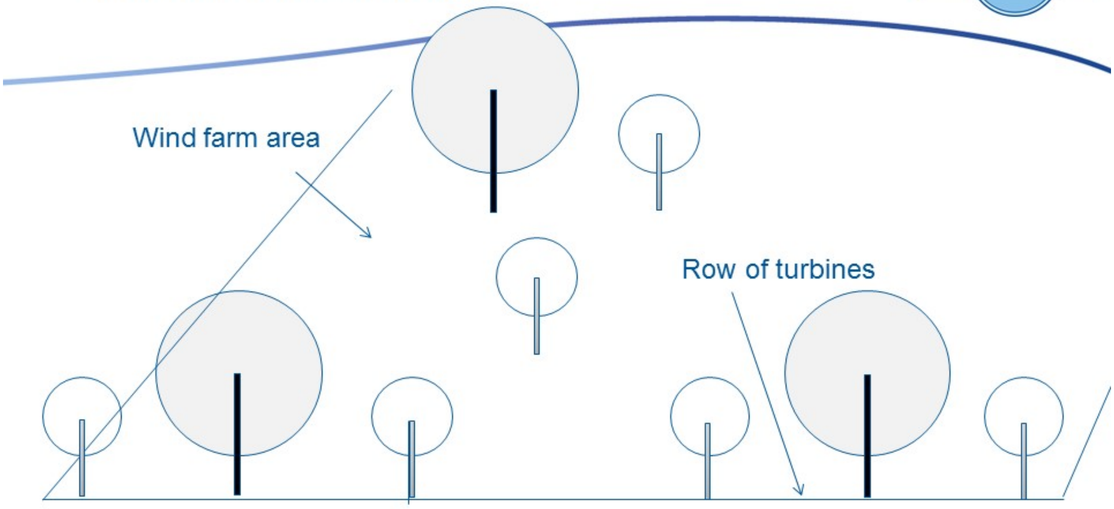
20 MW turbine
1P : 0.071 to 0.113 Hz
3P : 0.212 to 0.339 Hz

Summary

- 10 MW offshore wind turbines designed based on aeroelastic iterations and load mitigation
- Both glass and carbon fiber blade designs
- Sufficient design margins in rotor for further mass reduction.
- Upscaled to 20 MW capacity with reduced blade root diameter.
- Re-designed tower for offshore purposes.
- Offshore sub structure design is a challenge based on the reduced natural frequencies of the large turbine and due to stiff structural characteristics of the jacket.

“Soft or tough – when growing rotor size?” (Flemming Rasmussen, Head of Aeroelastic Design Section – DTU Wind Energy)

Implication of size on siting



Distance between turbines in fixed diameters:

Total swept area independent of turbine size for a wind farm
Total swept area proportional to turbine size for a row of turbines

Towards large wind turbines in rows

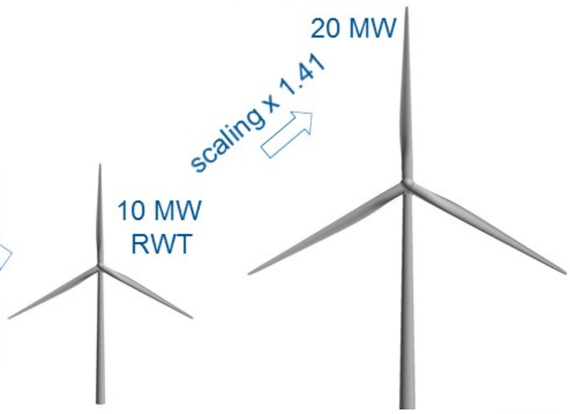
(*INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results*)

DTU 10 MW RWT and upscaled 20 MW

Size	10	20	MW
Rated wind speed	11,4	11,4	m/s
Rated power	10	20	MW
Number of blades	3	3	-
Rotor Diameter	178,3	252,2	m
Hub Diameter	5,6	7,9	m
Hub Height	119	155,9	m
Min Rotor Speed	6	4,2	rpm
Max Rotor Speed	9,6	6,8	rpm
Max Generator Speed	480	339,4	rpm
Gearbox Ratio	50	50	-
Maximum Tip Speed	90	90	m/s
Hub Overhang	7,1	10	m
Shaft Tilt Angle	5	5	º
Rotor Precone Angle	-2,5	-2,5	º
Sweep angle	0	0	º

Mass in tons	10 MW	20 MW
Blade	42	118
Hub	105	298
Rotor (Blades + Hub)	230	652
Nacelle	446	1.060
Tower	628	1.985
Overall	1.305	3.698

(Ref. Anand Natarajan, DTU)



Implications of upscaling

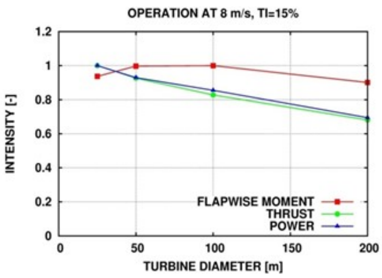
Advantages:

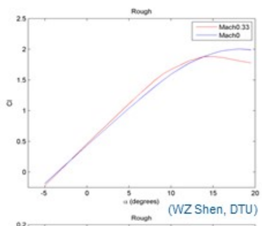
- Increased wind resources
- Increased Reynolds no. (speed and size)
- Rotational sampling of turbulence concentrates energy at 1p
- Filtering of turbulence (lower fatigue loads, less fluctuations)

Challenges:

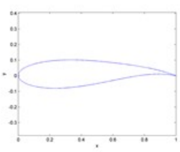
- The flexibility increases
- Self induced loads and stability issues
- Increased tip speed (Mach no. effects after 90 m/s and erosion, noise)

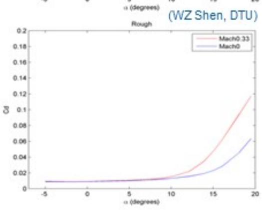
Std. dev. relative to the mean value



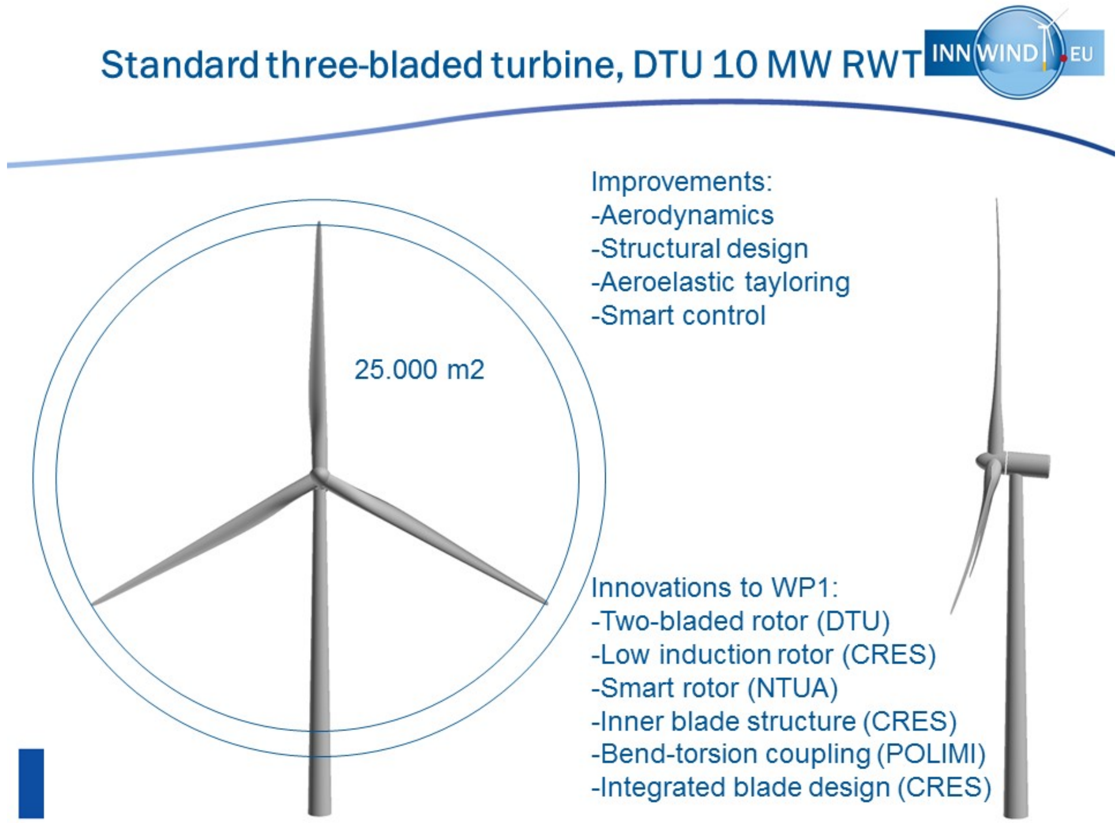


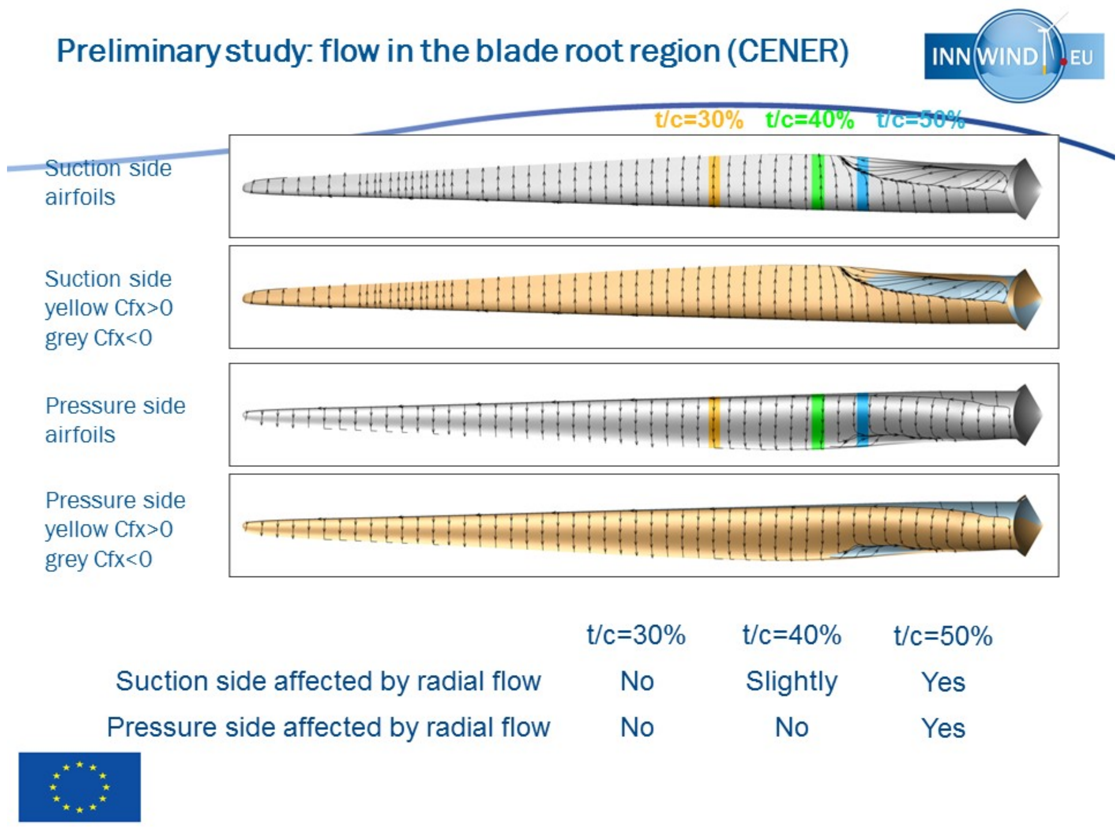
(WZ Shen, DTU)





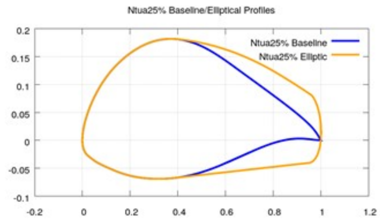
(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)



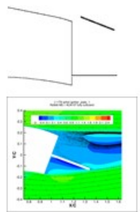


(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Improved thick inboard airfoils (NTUA, CENER)



Flap + Offset cavity:
L/D increase (28%)



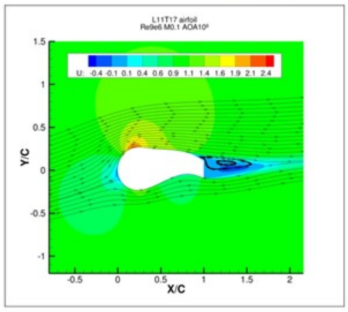
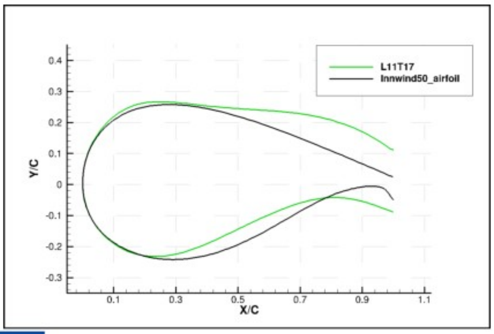
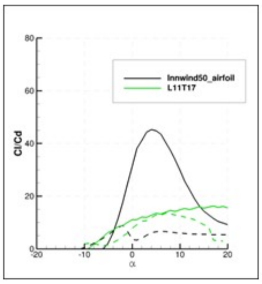


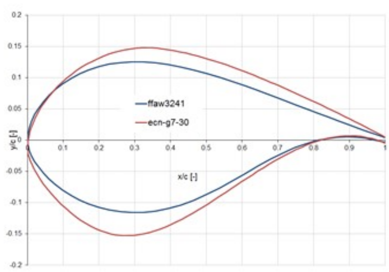
Figure 3.6-23 U velocity contour and streamtraces. L11T17 reference airfoil. Transitional.

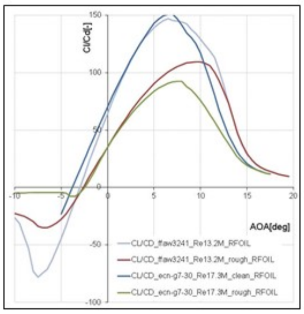




Slender blades by thick airfoils outboard

New ECN 30%thick airfoil compared with FFA 24% airfoil



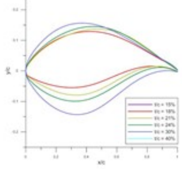


- Apply ECN 30% outboard

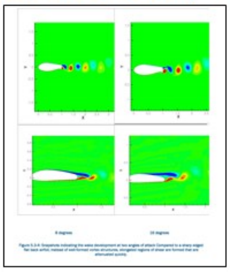
-Higher lift and drag, similar Cl/Cd (clean)

-Roughness sensitivity is worse than FFA 24% (Cl/Cd and Cl_max)

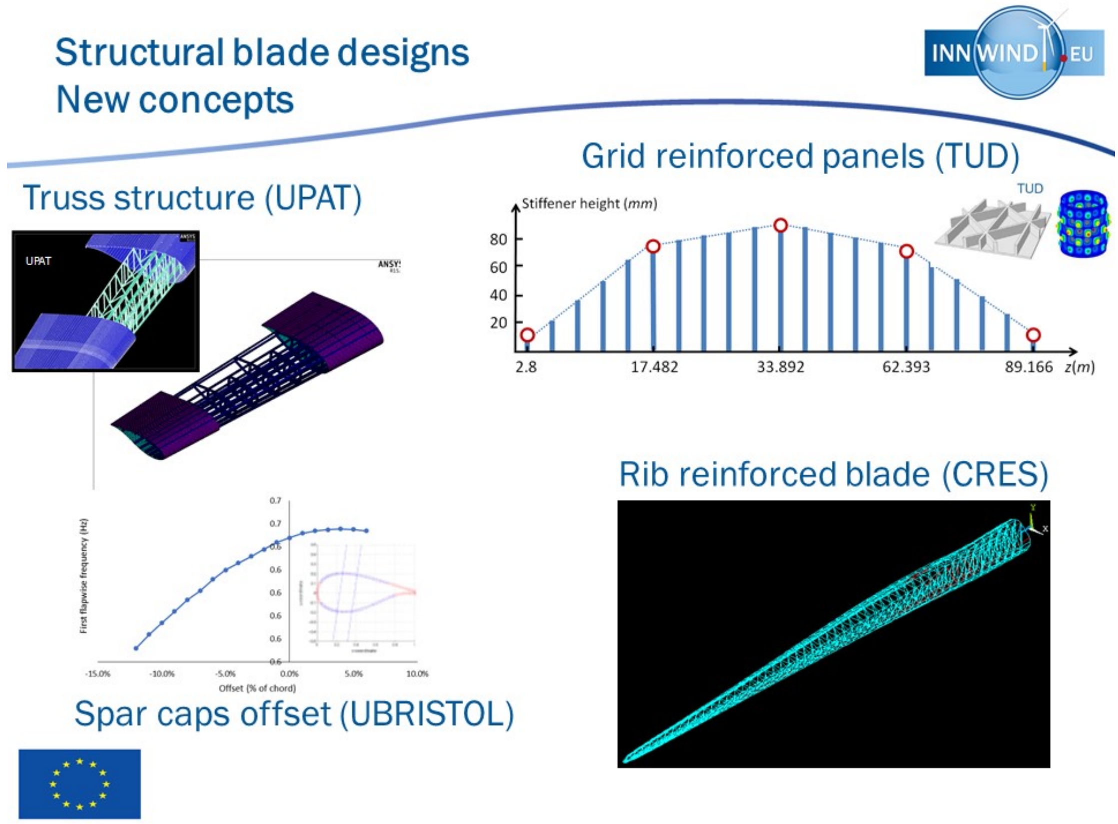
Low lift airfoils (CRES)

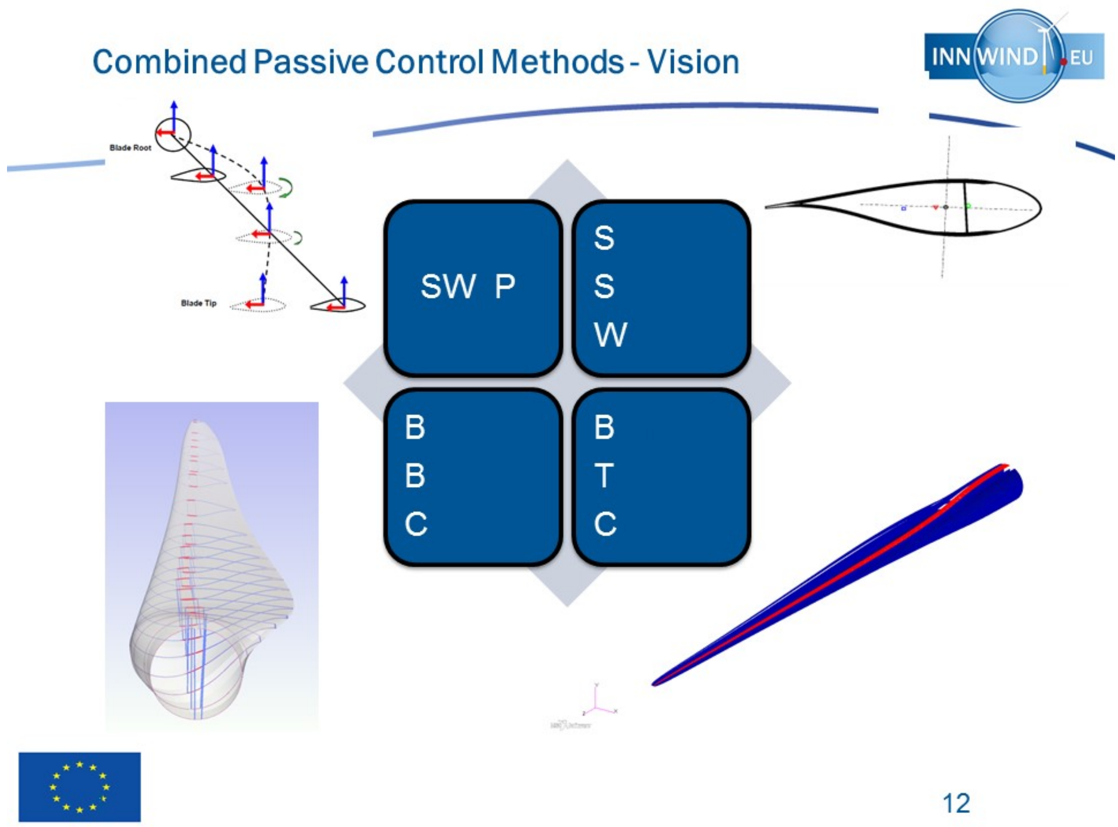


Elliptical airfoils (NTUA)



(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)



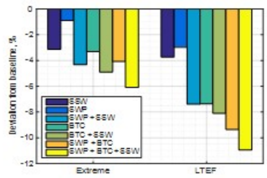


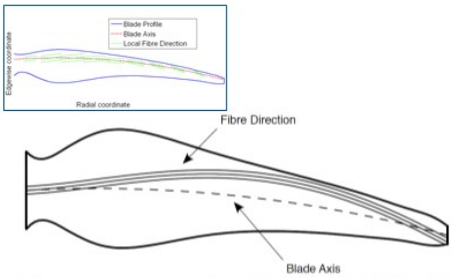
(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Structural blade designs
Build-in coupling

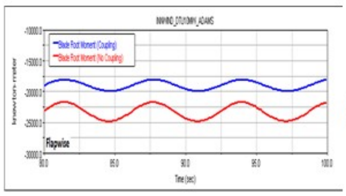
BTC (PoliMi)

BTC/SSW/SWP (DTU)





Variable tow BTC (UBRISTOL)



BTC (CENER)

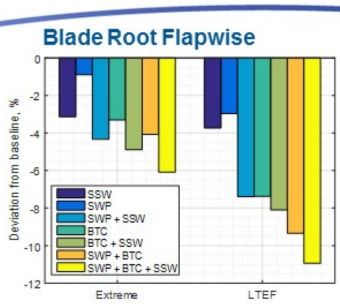
Structural blade designs
Integrated design

BTC+IPC/Long (PoliMi)

	RWT	BTC	182m BTC	BTC IPC	188m BTC + IPC
Rotor Diam.	178.3 m	178.3 m	182 m	178.3 m	188 m
Blade Mass	42422 kg	-3.7%	+5.0%	-4.8%	+16.2%
AEP	45.760 GWhy	+0.9%	+2.2%	+0.7%	+4.2%
CoE	75.911 $/kWh	-1.0%	-1.7%	-0.9%	- 2.8%
Tower Bottom	495794 kNm	-6.4%	-1.8%	- 6.4%	+1.7%
DEL Hub Nodding	27950 kNm	-3.8%	+4.1%	- 5.6%	+15.0%

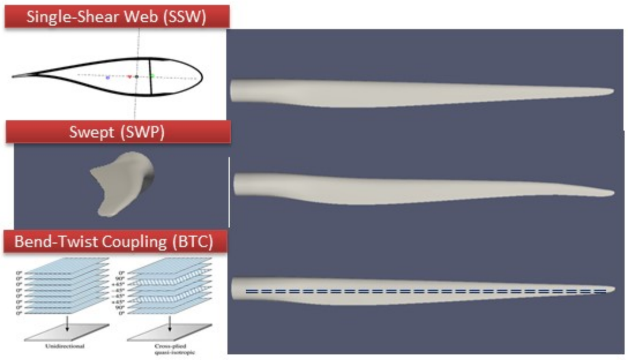
Combined Passive Control Methods – Preliminary Study

Blade Design	AEP	Tower clearance
Baseline	48.564 GWh	3.656 m
SSW	– 0.3%	+ 1.3%
SWP	– 0.1%	+ 4.9%
SWP + SSW	– 0.4%	+ 8.6%
BTC	+ 0.04%	– 5.7%
BTC + SSW	+ 0.3%	– 11.6%
SWP + BTC	– 0.1%	– 4.0%
SWP + BTC + SSW	– 0.3%	– 1.0%



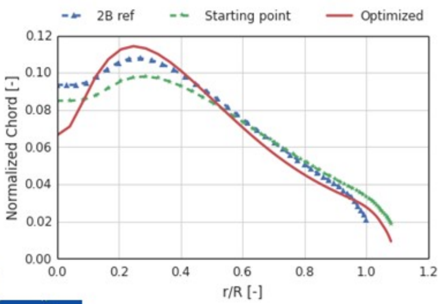
Flap load reduction potential:

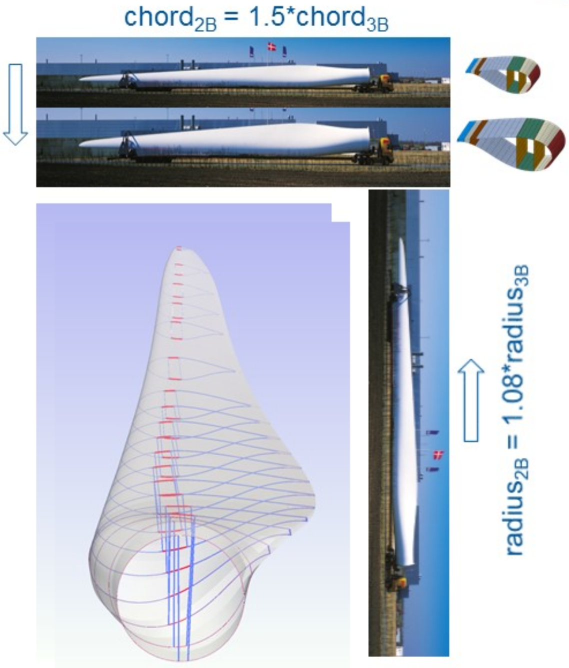
Swept: 16 %
Three passive: 24 %



Aero-structural Optimization of a Two-Bladed Downwind 10 MW Turbine

- $EI_{x\text{-}2B} = 2.25 \cdot EI_{x\text{-}3B}$
- Blade $Loads_{2B} = 1.5 \cdot Loads_{3B}$
- Downwind rotor configuration allows for greater flapwise tip deflections
- The 2B design can be stretched
- Example 10 MW blade with 8% increase in R: R=96m





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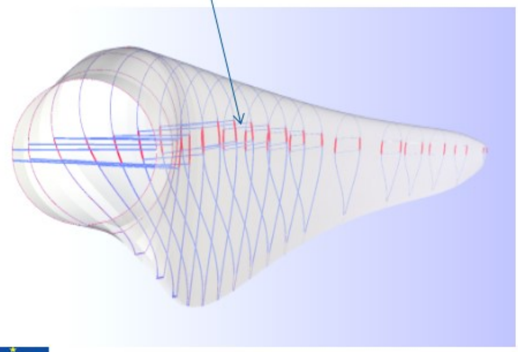
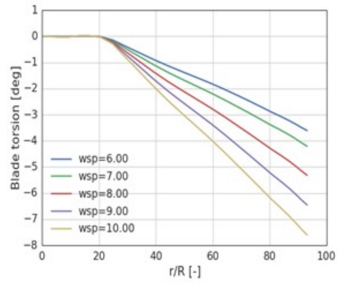
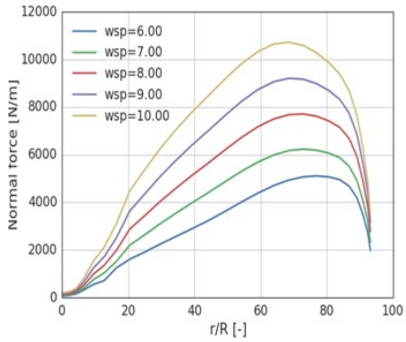
Stretched two-bladed 10 MW Ref. Rotor -downwind

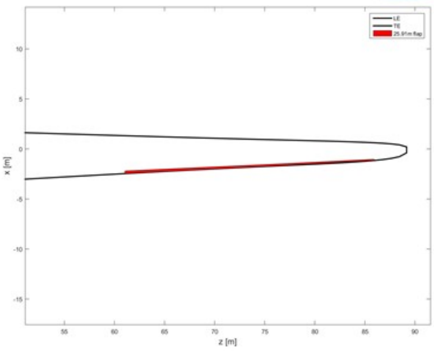
- 96 m radius
- 34 tons blade weight (42 for 3B)
- 12 % increase in power below rated
- 13 % decrease in fatigue loads
- 8 deg. blade torsion at 10 m/s
- Curved spar caps

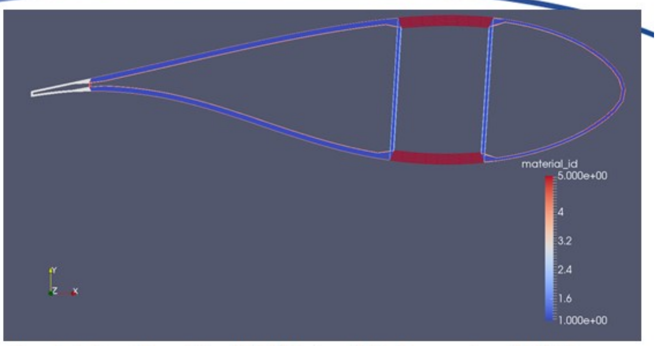






10 MW RWT blade with trailing edge flap

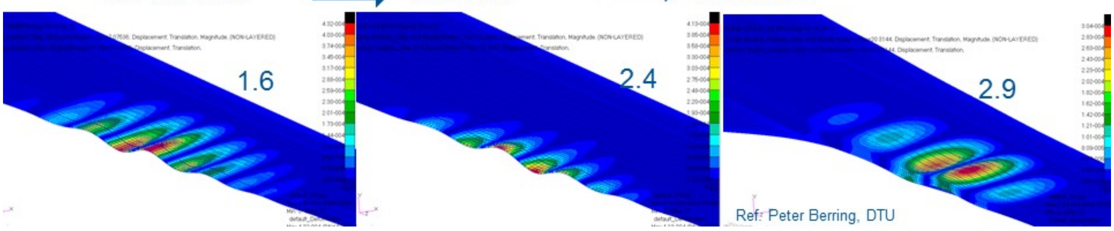


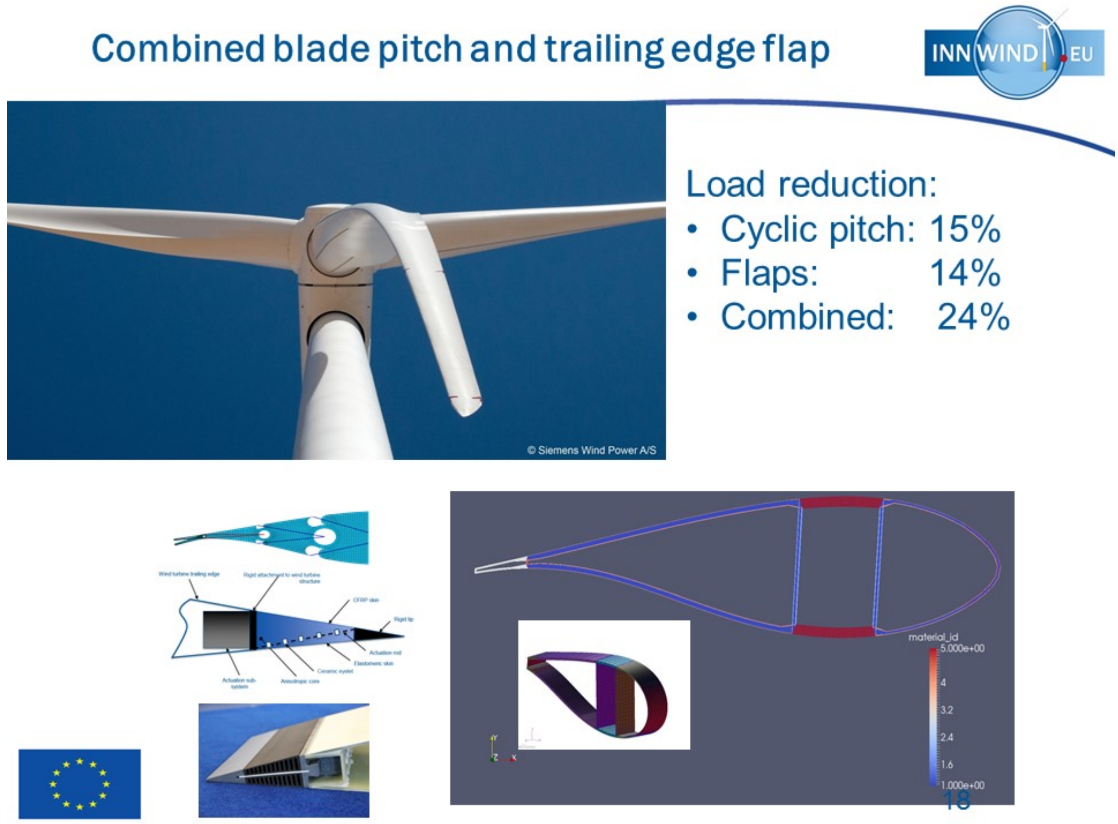


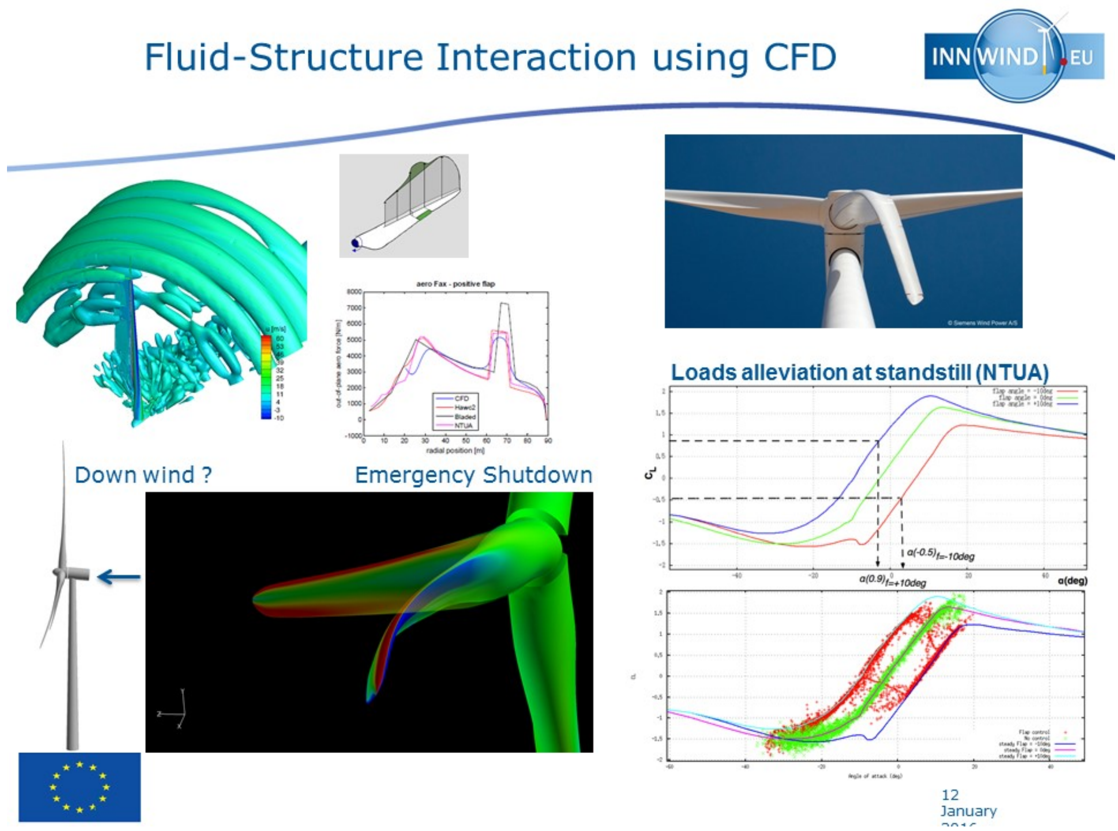
Internal structure of the optimized 10 MW design with the flap geometry - 85% blade span section. (Carlo Tibaldi)

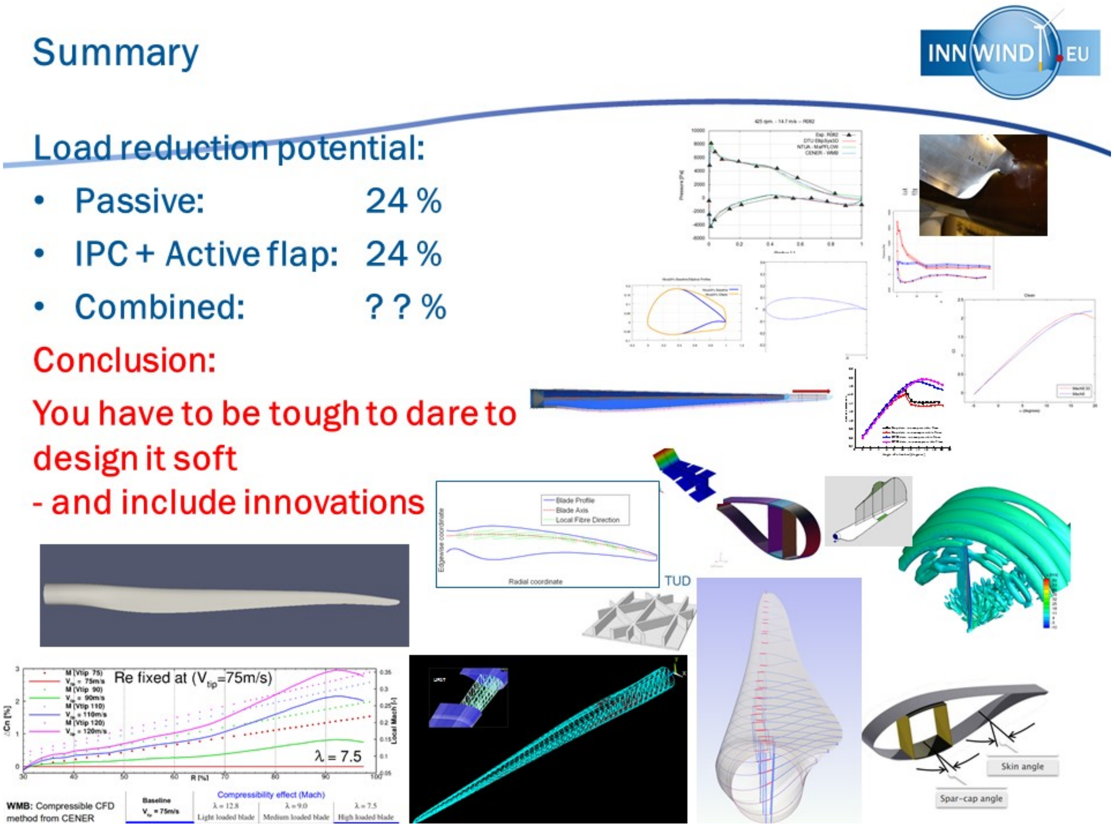
Improved buckling resistance:

No 3rd web → 3rd web → blunt T.E.




Combined blade pitch and trailing edge flap
INNWIND.EU
Load reduction:
• Cyclic pitch: 15%
• Flaps: 14%
• Combined: 24%
© Siemens Wind Power A/S
material_id
5.000e+00
4
3.2
2.4
1.6
1.000e+00
18


Fluid-Structure Interaction using CFD
INNWIND.EU
aero Fax - positive flap
CFD
Hawc2
Bladed
NTUA
radial position [m]
Down wind ?
Emergency Shutdown
Loads alleviation at standstill (NTUA)
α(0.9)f=+10deg
α(-0.5)f=-10deg
α(deg)
12
January



Superconducting versus pseudo direct drive generators - test results and perspectives (Asger Abrahamsen, Senior Researcher at DTU Wind Energy)

INNWIND.EU and AVATAR event @ EWEA 2015
18th November 2015 (3.00 - 6.30 pm)
Paris Expo, Porte de Versailles Pavilion 1, Paris.

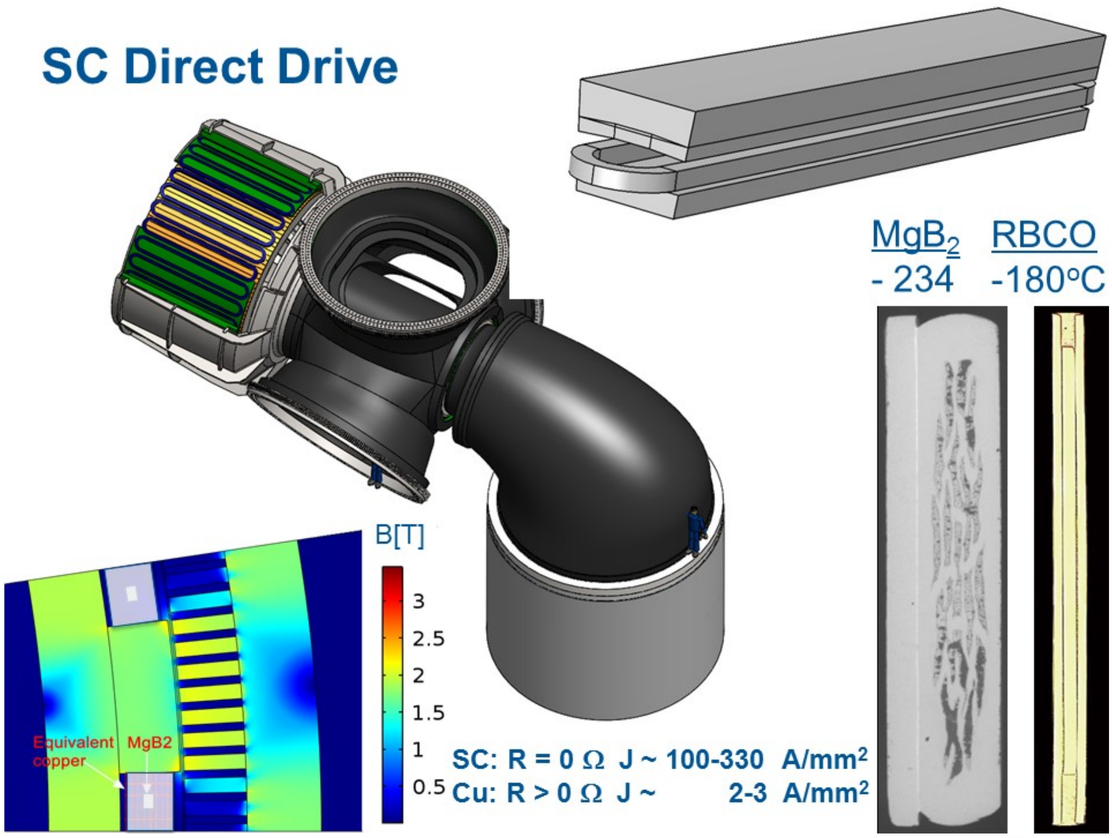
Superconducting versus pseudo direct drive generators - test results and perspectives

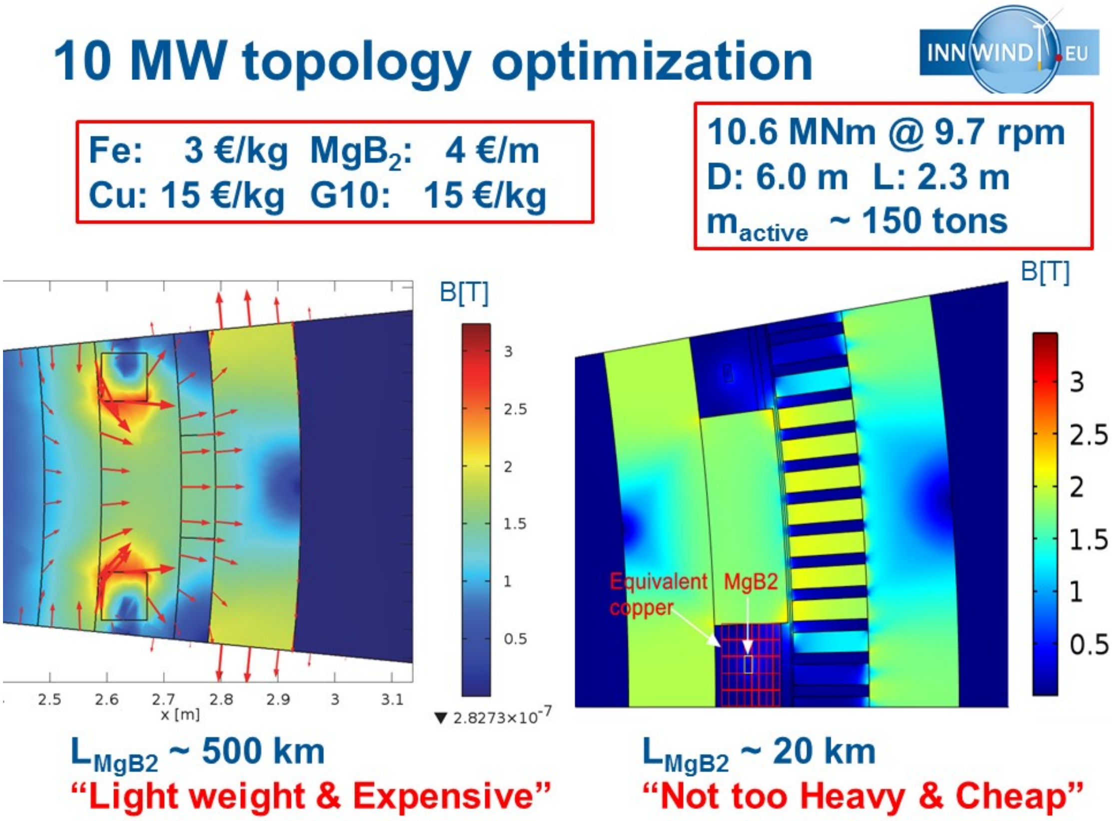
Asger B. Abrahamsen, Senior Research Scientist
DTU Wind Energy. DTU Risø Campus, Technical University of Denmark

Outline

- **Non-contact and as compact as permanent magnet direct drive**
- Superconducting Direct Drive generators
  – RBCO pole pair & MgB_2 coil
- Magnetic Pseudo Direct Drive generator
  – T = 5 → 16 → 110 kNm Demo
- Cost Of Energy

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

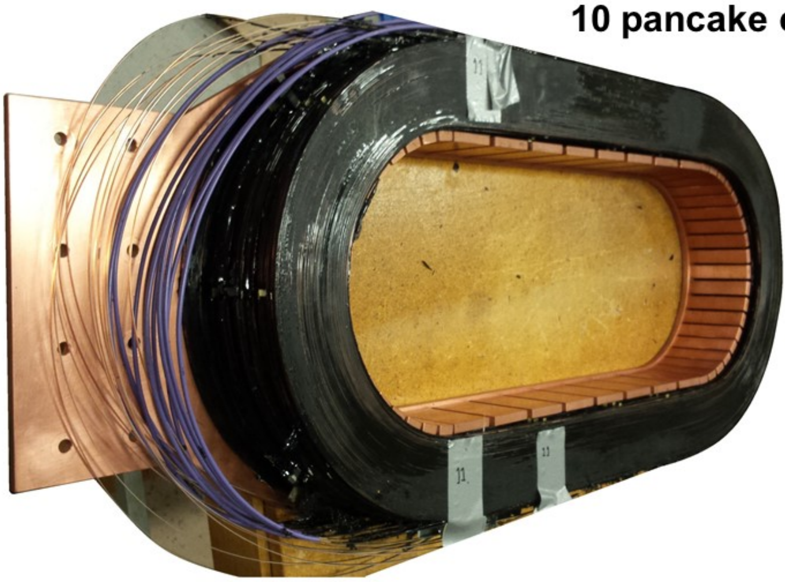




(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

MgB_2 coil demo

SINTEF



Columbus Superconductors
10 pancake coils stacked

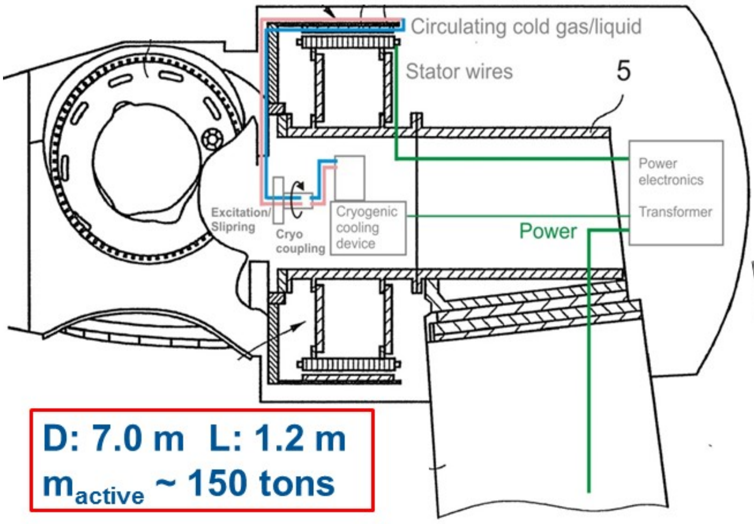
Test in 2016

L ~	0.8 m
W ~	0.4 m
Turns:	2080
L_{MgB2}:	4.5 km
Height:	81 mm
Width:	87 mm

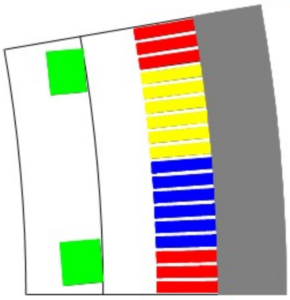
SC pole pair demo

SIEMENS

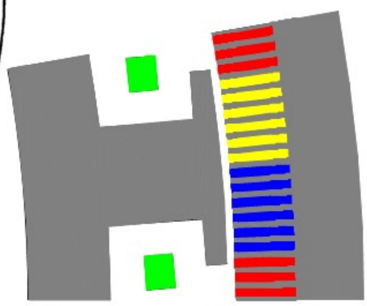
"As high operation temperature as possible → HTC"



D: 7.0 m L: 1.2 m
m_{active} ~ 150 tons

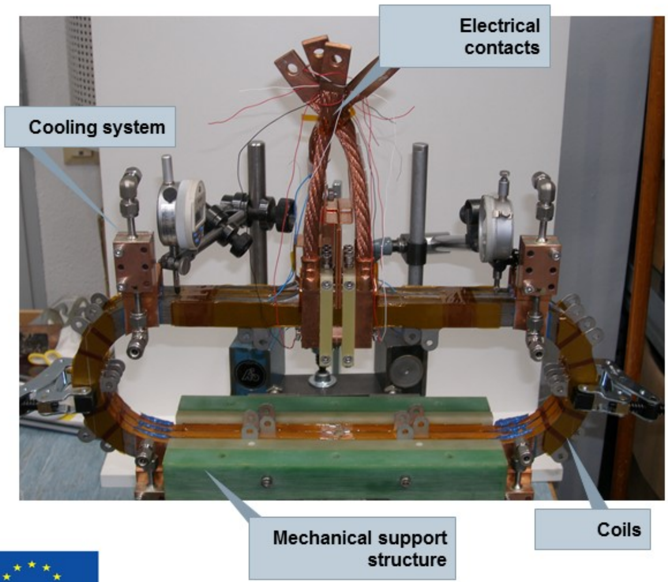


Air-core stator, air-core rotor



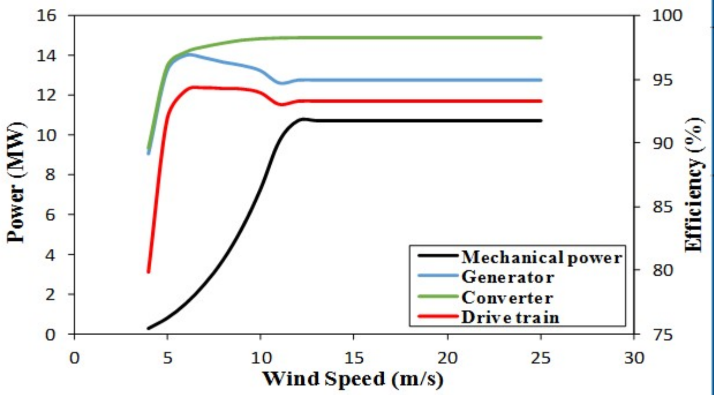
Iron-core stator, iron-core rotor

RBCO HTC coil demo SIEMENS



- High temperature superconductor tapes
- 3 pancake stacked
- T = - 243 °C (LNe)
- I = 474 A
- AC losses determined
  @ I_{AC} < 100 A &
  I_{DC} < 300 A
- Industrialization of coil manufacturing needed

10 MW HTC SC direct drive SIEMENS



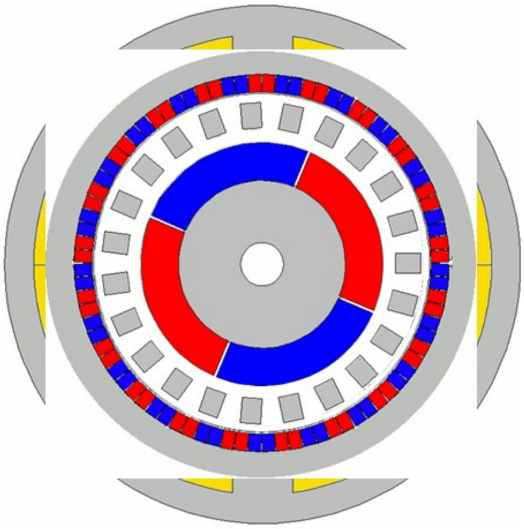
L_{SC} = 5.3 km

Component	Material	Cost (€)
Generator	Stator iron	58188
	Rotor iron	53735
	Copper	117480
	SC	534896
	Total	764299*
Converter	Switches	160314
	Generator filter	58084
	DC Link	152000**
	Grid filter	89000**
	Cooling system	143000**
	Mechanical support	184000**
	Total	786398
Total drive train	Total	1550697

* Without cooling system cost.
**Deliverable 3.3.2 - Converter designs based on new components and modular multilevel topologies.

Magnetic Pseudo Direct Drive (PDD)

Magnomatics®



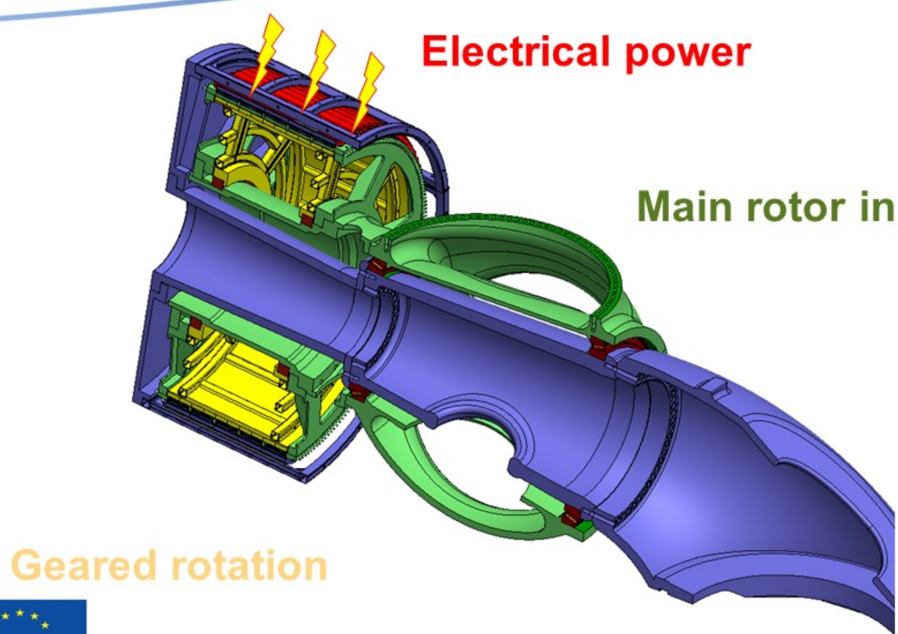
PDD =
Magnetic gear
+
Armature

- Compact
- No contact
- High efficiency

Kirby, Calverley, Stehouwer & Hendriks EWEA 2014

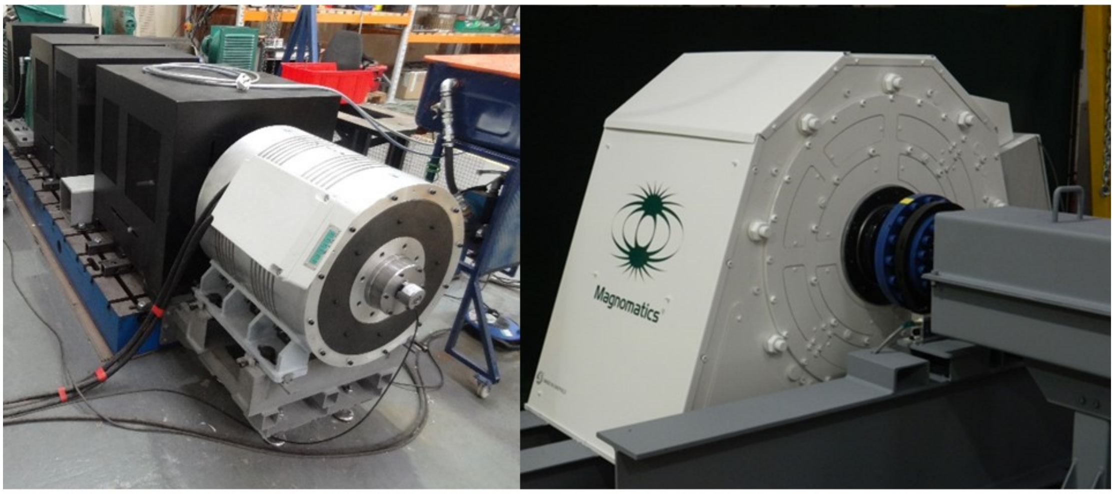
Integration into King-Pin nacelle

DNV·GL Magnomatics®



Kirby, Calverley, Stehouwer & Hendriks EWEA 2014

PDD demonstrators

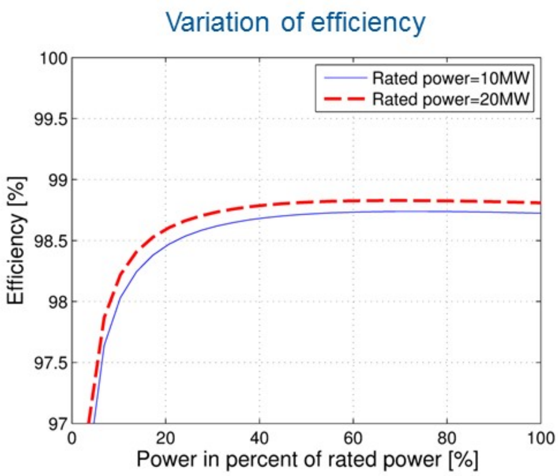


a) T = 5 kNm (INNWIND) **b) T = 16 kNm (Upgrade)**

c) T = 110 kNm (Commercial) → Feedback to INNWIND

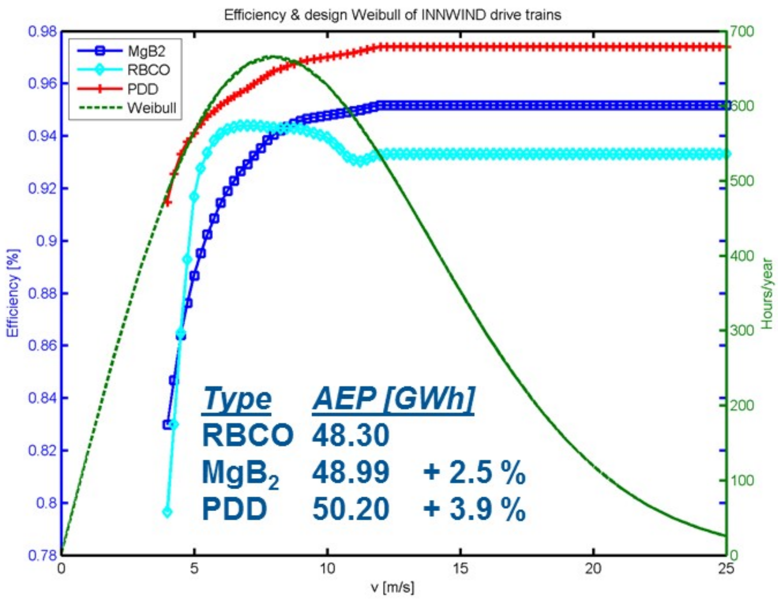
PDD optimized for 10 and 20 MW

Parameter	10MW	20MW
Airgap diameter	6.0m	8.5m
Active axial length	1.66m	2.35m
Permanent magnet mass	13.5tons	38.2tons
Copper mass	7tons	14tons
HS and PP rotor laminated steel mass	14tons	39.6tons
Stator laminated steel mass	15.5tons	45tons
Structural mass	100tons	383tons
Total mass	150tons	520tons
Cost of permanent magnets	58.1 k€/ton	
Cost of copper material	4.59 k€/ton	
Cost of laminated steel	1.61 k€/ton	
Cost of structural material	0.32 k€/ton	
Total material cost	896 k€	2542 k€



(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Cost of Energy (CoE) @ 10 MW



$$CoE = \frac{C_D + C_R + O}{AEP \cdot LT}$$

$$\sim \frac{C_R + O}{AEP \cdot LT}$$

Type	Cost* [M€]
PDD	0.9
RBCO	1.6 + 78 %
MgB_2	2.3 + 156%

Type	ΔCoE [%]
PDD	~ - 3.9
RBCO	~ + 1.15
MgB_2	~ + 1.0

*Preliminary
C_R ~ 30 M€, O ~ 35 M€
LT = 25 years

Conclusions

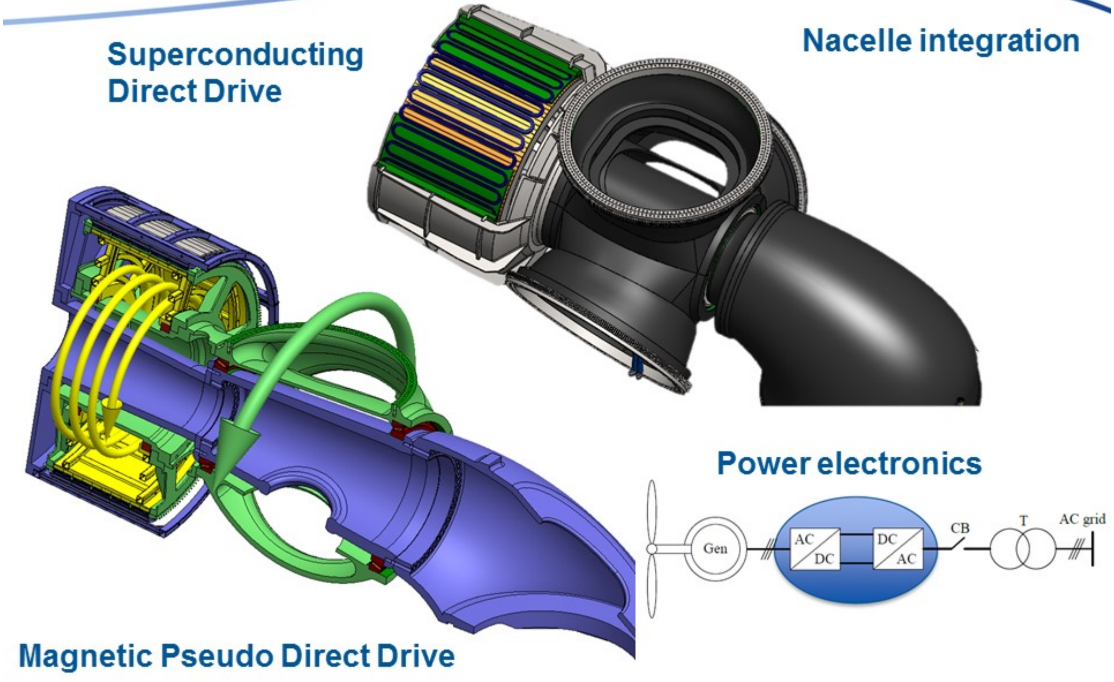
- Innovative non-contact drive trains investigated
- Superconducting Direct Drive
  - RBCO: Race track coil demonstrated. ΔCoE ~ + 1 %
  - MgB_2: Race track coil under construction ΔCoE ~ + 1 %
  - Both will remove dependency of Rare Earth Elements
- Magnetic Pseudo Direct drive
  - Demonstrated: T = 5 kNm. Next: 6 & 110 kNm
  - Superior in term of efficiency and cost. ΔCoE ~ - 3-4 %
  - Increased Rare Earth Elements dependency compared to permanent magnet direct drive

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Contributions

D. Liu & Henk Polinder, Delft University of Technology (NL)
N. Magnuson, SINTEF (N)
A. Thomas & Z. Azar, Siemens Wind Power (DK / UK)
E. Stehouwer & B. Hendriks, DNV GL (NL)
A. Penzkofer & K. Atallah, University of Sheffield (UK)
R. S. Dragan & A. Meyers, Magnomatics (UK)
F. Deng & Z. Chen, Aalborg University (DK)
D. Karwatzki & A. Mertens, University of Hannover(D)
M. Parker & S. Finney, University of Strathclyde
Asger B. Abrahamsen (asab@dtu.dk), DTU Wind Energy (DK)
Project website: www.innwind.eu

Electro-mechanical conversion WP



Novel experiment results enabling new 10 MW support structures designs (Martin Kühn, Professor Wind Energy Systems at University of Oldenburg)

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Novel experiment results enabling new 10 MW support structures designs

Martin Kühn
ForWind – University of Oldenburg

INNWIND.EU-AVATAR event within EWEA2015

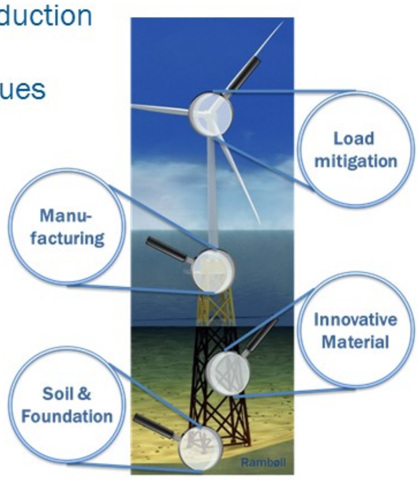
Content

- Design of bottom-mounted support structures
- Design of floating foundations
- Conclusions

Design of bottom-mounted support structures

Innovations on component level for cost reduction

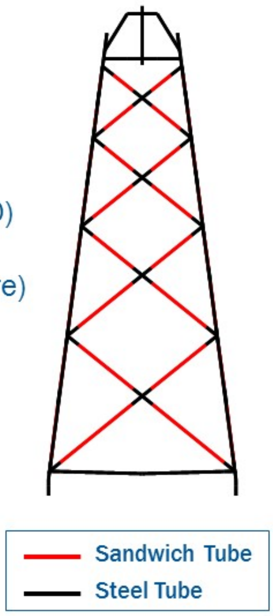
- **Innovative materials**
  - Sandwich tubes and joining techniques
- **Soil & foundation**
  - Soil structure interaction
  - Suction buckets
  - Semi-floater
- **Load mitigation**
  - Structural control and loads
  - Vibration absorbers
  - Effect of load mitigation controls
- **Manufacturing**
  - Mass-producible Jackets



RAMBØLL DTU AALBORG UNIVERSITY Fraunhofer IWES
Carl von Ossietzky Universität Oldenburg | Leibniz Universität Hannover | Knowledge Centre WMC Wind turbine Materials and Constructions | GL

Sandwich materials for jacket tubes

- Sandwich tubes
  - two relatively thin steel tubes
  - core (made of UHPC or Elastomer)
- Cost reduction potential:
  - buckling and wrinkling are mitigated
  - possible use of high strength steel (S460 and S690)
  - faster welding of the steel tubes
  - cost reduction potential: ~7,5% (whole substructure)
- Tubes: TRL 3, Structure: TRL: 1-2



Test specimen

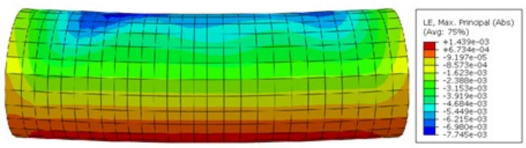
Leibniz Universität Hannover

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

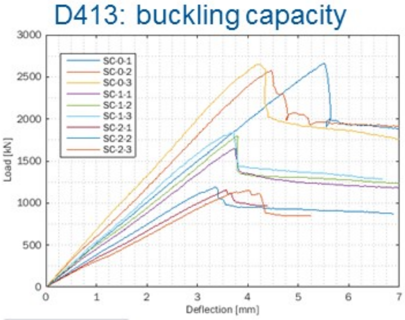
Testing of sandwich tubes

Measurement
- centric
- eccentric loading

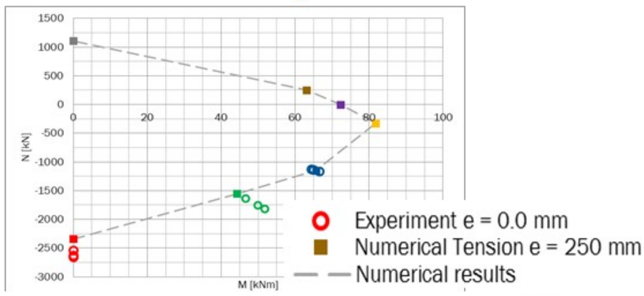
Numerical calculations
- nonlinear material models for core and steel sheets



D413: buckling capacity

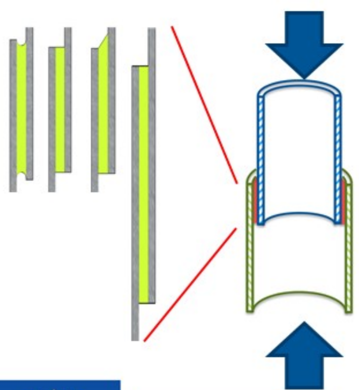


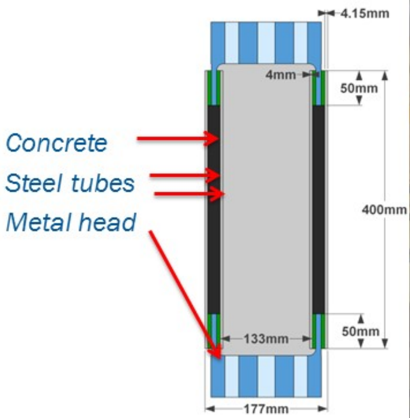
D414: eccentric loading

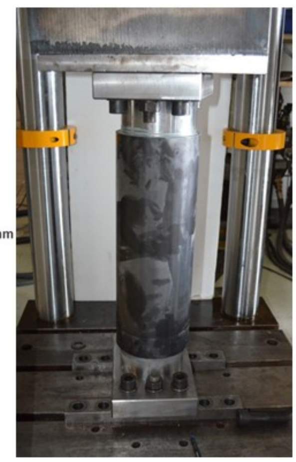


Testing of hybrid joints

Substructure – Joint tests
- tension and compression
- static test
- fatigue test





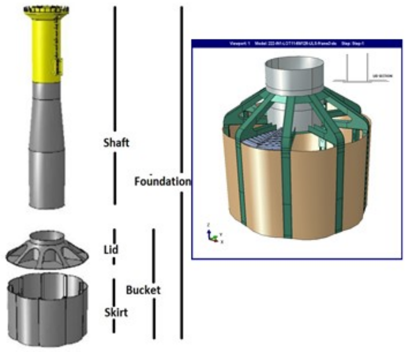


(*INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results*)

Soil & foundation: Suction buckets

Design of a Mono Bucket for the 10 MW turbine

- Based on DLC 1.2 for FLS and 6.2a for ULS as used for the ref. jacket
- Cost estimate for 80 WTGs considering fabrication and installation
    - Weights: shaft 848 t, bucket incl. CC 384 t, secondary steel 50 t
    - Lump sum cost: 4.4 M€



Outlook: Design of bucket foundations for 10 MW & 20 MW jacket

Support by:

UNIVERSITY

Soil & foundation: Vibro-driven piles

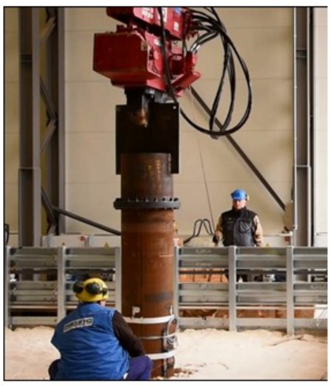
Cost reduction potential

- lower installation time and subsea noise

Validation of numerical modelling with experiments

- supply of a validated tool for the extrapolation of a single pile behaviour to larger diameters
- pre-loading effect

Successful installation of 2 vibro-driven piles



Tensile static test of Pile 2

Fraunhofer IWES

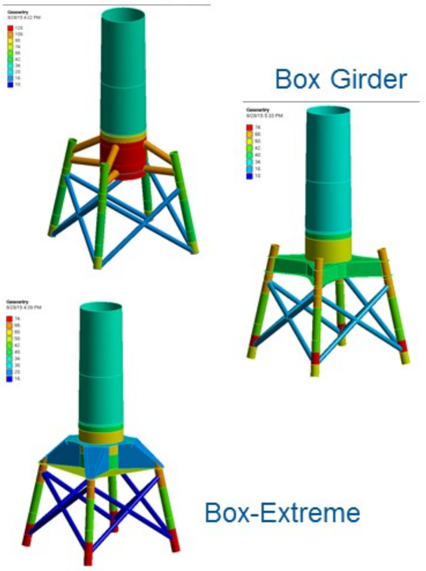
(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

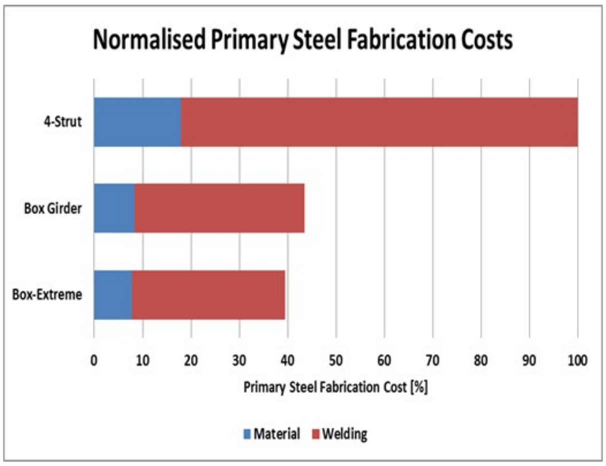
Manufacturing cost: Transition piece

4-Strut

Box Girder

Box-Extreme





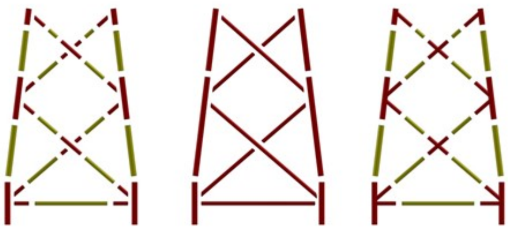
RAMBOLL

Manufacturing cost: Jacket

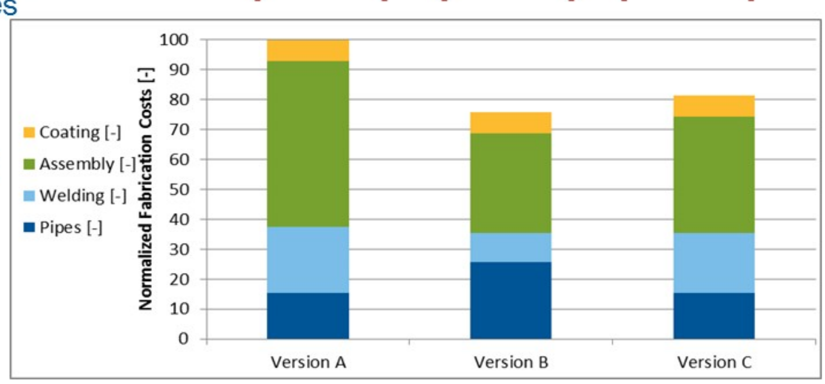
A: classical solution, aiming at a mass reduction

B: reduce the number of welds and tubular members in order to reduce assembly costs.

C: Similar to A, but prefabricated standard tubes

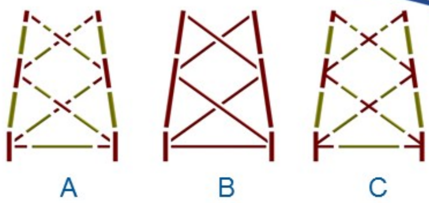


Coating
Assembly
Welding
Pipes



(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Manufacturing cost: Jacket



- Cost minimization mainly through material, welding and assembly costs (since coating cost is smallest share)
- Pure mass reduction not necessarily effective
  ⇒ large number of different cross-sections
  ⇒ higher assembly and welding costs.
- In general, it is not possible to minimize all of the cost contributors by choosing one assembly strategy.
- Reduction of the number of tubular members and welds (version B) is the less expensive strategy, but penalty on structural mass of the jacket.
- Sandwich materials could offer a further cost-saving solution

Design of floating foundations

- Finalize model innovations in the codes for FOWT
- Validate numerical models with water tank tests results
- Define wave tank scale testing procedures
- Design of control strategies

University of Stuttgart Germany

CENER

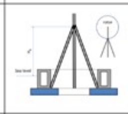
National Technical University of Athens

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Review of Revised Deliverables: D4.33 (3)

Summary of improvements:

- An general introduction with explanations to the selections made is added
- More detailed design analysis of semi-sub #1
- A new version of the semi-sub #2 is included
- A concluding section with a comparison of the main parameters and costs is added.
- Hybrid version of concrete floater and semi-sub #1 is selected.

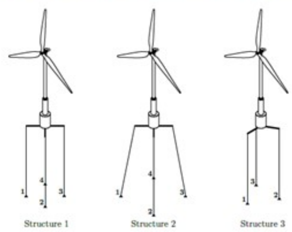
	Semi-floater	Concrete Floater	Semi-sub #1	Semi-Sub #2
				
Floater mass [t]	542 (excluding mooring system)	39000	23460 with ballast, 3745 steel & moorings	28434
Tower mass [t]	426 (without RNA)	see [14].	467.6	534
Draft [m]	(-)	45 (outer radius, 18.2, inner radius 7.7)	25.5	30
Max pitch @ Rated wind	5.5°	3.5°	3.5°	3.5°
Max pitch @ ULS	7.5°	-		
1st Eigenperiod [s]	37.6 (tower)	44.0	20.7s [heave] 24.4s [pitch]	14.3s [heave] 18.3s [pitch]
Overall Cost [€]	2.7 million	7 millions	12.5 millions	4.8 millions

10MW INNWIND WT Wave Tank Tests

2 test campaigns performed with INNWIND 10MW WT

10 MW Semisumersible
ECNantes (France), Fall 2014

10 MW TLP
DHI (Denmark), January 2015



Video on wave tank testing

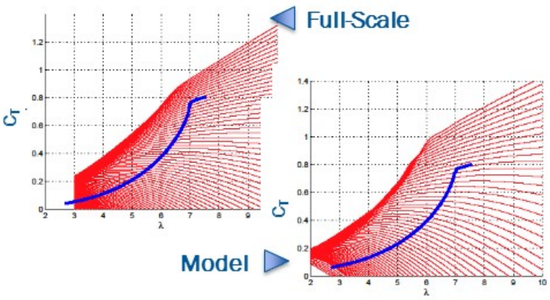
Semi-sumersible test campaign at ECNantes (France), Fall 2014

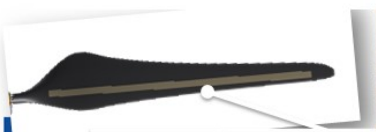
10MW INNWIND WT Wave Tank Tests

2 different methods to include aerodynamics:

Low Reynolds rotor redesign

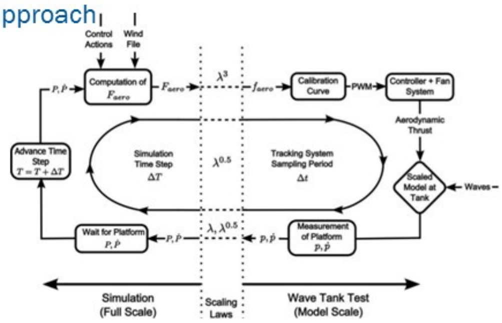
- Higher rotor solidity (increase blade chord, i.e. airfoils Reynolds)
- Airfoil selection





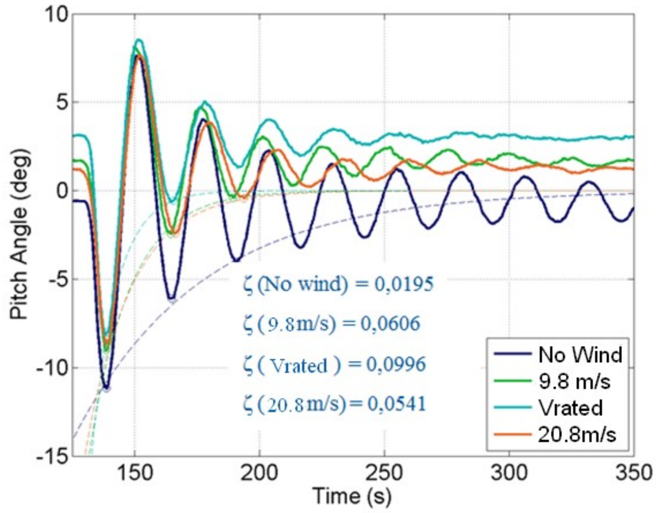
Low Reynolds, low cambered RG-14 airfoil

Ducted fan and Software-in-the-Loop approach

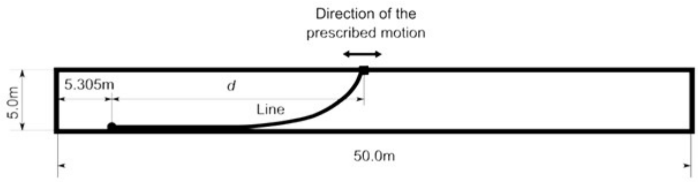


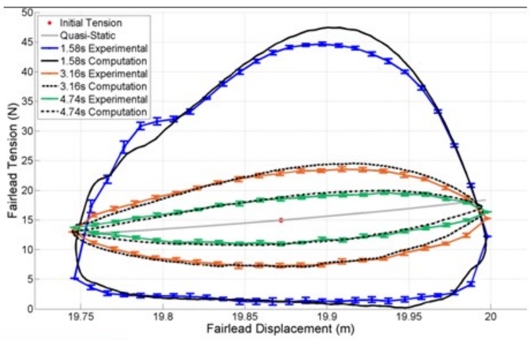
Semi-sumersible test campaign (#1 Tests Series)

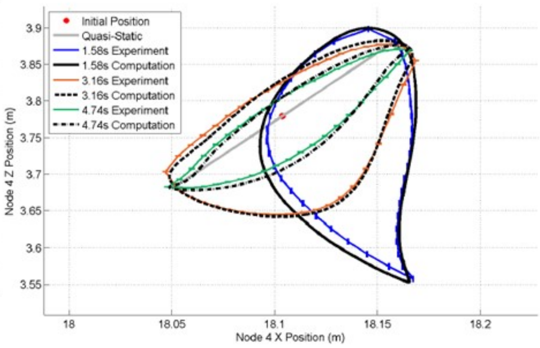
Pitch free decays: Aerodynamic damping with ducted fan



Experimental Validation of Mooring Lines Code (CENER)







(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Results of Wave Tank Tests (#1 Tests Series)

- Database with Experimental Results
  - Free access after regstration
  - Description of the test (pdf) and the structure of the database
  - Excel file containing the database information
  - Data in binary Matlab format
  - Calibration functions in Matlab format
  - Matlab scripts to handle data
  - Graphs giving an overview of tests

(http://www.ifb.uni-stuttgart.de/windenergie/download_messdaten.html)

Index of /windenergie/innwind/DataBase

Name	Last modified	Size	Description
Parent Directory		-	
CalibrationFunctions/	15-Apr-2015 15:00	-	
CollectedData/	15-Apr-2015 15:00	-	
DataBase.zip	17-Apr-2015 15:04	3.8G	
DataIndex_INNWIND_ECN1409.xlsx	02-Apr-2015 15:46	93K	
INNWINDExportData.m	15-Apr-2015 14:59	2.3K	
INNWINDPlotTestData.m	15-Apr-2015 14:59	4.1K	
INNWINDReadData.m	15-Apr-2015 14:59	8.0K	
INNWINDReadDataIndex.m	15-Apr-2015 14:59	6.8K	
ReadASCIIFile.m	15-Apr-2015 14:59	1.0K	
ReplaceString.m	15-Apr-2015 14:59	1.5K	
figures/	15-Apr-2015 15:00	-	

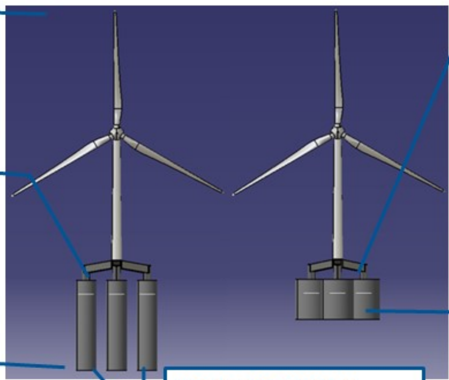
Apache Server at www.ifb.uni-stuttgart.de Port 80

Outlook: INNWIND.EU *TripleSpar* concept

Extended *lifetime of parts of the foundation* (2-3 x turbine)

Modularization (mass production of columns, variable draft)

Sites: Shallow and deep (suitable for European waters)



High *stability* & wave force attenuation through damping plates

Manufacturing: 3 independent concrete columns (spars), connected by steel interface

Low CAPEX due to pre-stressed concrete

(INNWIND.EU, Deliverable 5.21, Workshop: dissemination of results and asking feedback from participants on exploitation of results)

Conclusions

- Design of bottom-mounted support structures
  - Innovations on component level *and*
  - Design integration in innovative 10 & 20 MW structures

⇒ Facilitated by comprehensive numerical & experimental studies: hybrid tubes and joints, suction buckets, vibro-driven piles, etc.

- Design of floating foundations
  - Further development of models, control and testing methods
  - Development of an innovative floater design
  - Design integration with 10 MW turbine

⇒ Facilitated by validation of numerical models with wave tank tests