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Report

EERA DeepWind'2020 Conference
15 - 17 January 2020

Radisson Blu Royal Garden Hotel, Trondheim

John Olav Tande (editor)

SINTEF Energy Research AS
Power Conversion and Transmission
2020-02-13

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ABSTRACT

This report includes the presentations from the 16th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2020, 15 – 17 January 2020 in Trondheim, Norway.

Presentations include plenary sessions with broad appeal and parallel sessions on specific technical themes:
a) New turbine and generator technology
b) Grid connection and power system integration
c) Met-ocean conditions
d) Operations & maintenance
e) Installation & sub-structures
f) Wind farm optimization
g) Experimental Testing and Validation
h) Wind farm control systems

Plenary presentations include frontiers of science and technologies and strategic outlook. The presentations and further conference details are also available at the conference web page: https://www.sintef.no/projectweb/eera-deepwind/previous-conferences/

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E2 Installation and sub-structures

F Wind farm optimization

G1 Experiment testing and validation

G2 Experimental testing and validation

H Wind farm control systems

Closing session - Strategic Outlook

Wednesday 15 January		
09.00	Registration & coffee	
	Opening session – Frontiers of Science and Technology Chairs: John Olav Tande, SINTEF and Prof Trond Kvamsdal, NTNU	
09.30	Opening and welcome by chair	
09.40	*Bringing offshore wind forward through R&I*, Head of EERA JP wind, Peter Eecen, TNO	
10.00	*The grand challenges in the science of wind energy*, Katherine Dykes, DTU	
10.20	*How offshore wind will help Europe go carbon-neutral*, Lizet Ramirez, WindEurope	
10.40	*Introduction to the 1.2 GW Floating Offshore Wind Farm Project in Korea*, Hyunkyoung Shin, University of Ulsan	
11.00	*Offshore wind status and outlook for China*, Dr. Liu Yongqian, Renewable Energy School, North China Electric Power University	
11.20	*How technology is driving global offshore wind*, Chair ETIPwind, Aidan Cronin, SiemensGamesa	
11.55	Closing by chair	
12.00	Lunch	
	Parallel sessions	
	A) New turbine and generator technology Chairs: Karl Merz, SINTEF Prof Gerard van Bussel, TU Delft	**C1) Met-ocean conditions** Chairs Joachim Reuder, University of Bergen (UiB), Erik Berge, The Norwegian Meteorological Institute
13.00	Introduction by Chair	Introduction by Chair
13.05	*Introduction to the FARWIND concept for sustainable fuel production from the far-offshore wind energy resource,* C.Gilloteaux, Centrale Nantes - CNRS	*Evaluation of different methods for reducing offshore wind measurements at oil platforms to 10 m reference height,* E.Berge, Norwegian Meteorological Institute
13.30	*Comparison of Electrical Topologies for Multi-rotor System Wind Turbines,* P.Pirrie, University of Strathclyde	*Ship-based multi-sensor remote sensing and its potential for offshore wind research,* C.A.Duscha, UiB
13.50	*An Aerospace Solution to Leading Edge Erosion,* P.Greaves, ORE Catapult	*Taking the motion out of floating lidar: A method for correcting estimates of turbulence intensity,* F.Kelberlau, NTNU
		Framework for optimal met-ocean sensor placement in offshore wind farms, E.Salo, University of Strathclyde
14.30	Closing by Chair	Closing by Chair
14.35	Refreshments	
	H) Wind farm control systems Chairs: Karl Merz, SINTEF and Xabier Munduate, CENER	**C2) Met-ocean conditions (cont.)**
15.05	Introduction by Chair	Introduction by Chair
15.10	*Model predictive control on a wind turbine using a reduced order model based on STAS,* A.Skibelid, NTNU	*Dynamic response of bottom fixed and floating wind turbines. Sensitivity to wind field models, F.G.Nielsen*, UiB
15.30	On the Stochastic Reduced-Order and LES-based Models of Offshore Wind Farm Wake, M.B.Paskyabi, UiB	*Relevance of sea waves and farm-farm wakes for offshore wind resource assessment,* J.Fischereit, DTU Wind Energy
15.50	*Consequences of load mitigation control strategies for a floating wind turbine*, E.Bachynski, NTNU	*Dependence of Floating Lidar Performance on External Parameters – Results of a System Classification Focussing on Sea States, G.Wolken-Möhlmann, Fraunhofer IWES*
16.10	Closing by Chair	Closing by Chair
18.00	Conference reception at To Tårn	

Side events

Wednesday 15 January, 1300-1530: Havvind haster: Hvordan skal vi lykkes? (Norwegian only, read more here)

Thursday 16 January: 1300 – 1430: Offshore wind lighthouse initiative
The EU funded SETWind project has a vision of creating an ambitious pan-European effort in offshore wind energy research that will contribute to achieving the targets set in the Paris Agreement. Fostering international collaboration in offshore wind energy is crucial to reach the ambitious goals, but also makes economic sense.

This workshop is organized by the SETWind project together with ETIPwind and EERA JPwind to support the development of offshore wind energy. The workshop is at the venue of the EERA DeepWind R&I conference and is open for all registered conference participants.

Read more about the ocean of opportunities at https://www.eerajpwind.eu/offshore-wind-an-ocean-of-opportunities/.

Thursday 16 January		
	D1) Operation & maintenance Chairs: Iver Bakken Sperstad, SINTEF Volker Berkhout, Fraunhofer IWES	**E1) Installation and sub-structures** Chairs: Prof Arno van Wingerde, Fraunhofer IWES Prof Michael Muskulus, NTNU
09.00	Introduction by Chair	Introduction by Chair
09.05	*Potential of machine learning algorithms for the identification of structural damages in offshore jacket structures,* D.Cevasco, University of Strathclyde	*Nonlinear hydroelastic responses of monopile and spar wind turbines in regular waves,* V.Leroy, LHEEA Lab, Centrale Nantes
09.30	*Automated inspection of offshore wind turbine foundation using complementary NDT and defect detection techniques,* S.Subramaniam, Brunel Innovation Centre	*From pre-design to operation: Outlook and first results of the FloatStep project,* H.Bredmose, DTU Wind Energy
09.50	*Load Estimation for Condition Monitoring in Wind Turbines Based on Physical Modeling,* M.Pagitsch, RWTH Aachen Univ.	*Structural Design of a Prestressed-Concrete Spar-type floater for 10 MW wind turbines,* S.Oh, ClassNK
10.10	*Digital Assistance in the Maintenance of Offshore Wind Parks,* M.Stepputat, Fraunhofer	*Mooring line dynamics of a semi-submersible wind energy platform. Cross validation of two commercial numerical codes with experimental data, R.Chester,* University College Cork
10.30	Refreshments	
	D2) Operation & maintenance (cont.)	**E2) Installation and sub-structures (cont.)**
11.00	*Life Extension of Offshore Wind Farms: A Decision Support Tool,* M.Shafiee, Cranfield University	*Wave-induced collision loads and moments between a spar-buoy floating wind turbine and an installation vessel,* D.Lande-Sudall, Western Norway University of Applied Sciences
11.20	*A versatile and highly accurate sensor technology for load measurements*, T.Veltkamp, TNO Energy Transition	*Implementation of Substructure Flexibility and Member-Level Load Capabilities for Floating Offshore Wind Turbines in OpenFAST,* J.Jonkman, NREL
11.40	*Are seakeeping simulations useful for the planning of offshore wind O&M?* S.Gueydon, MARIN	*Levelized Cost of Energy and Life Cycle Assessment of IDL Tower,* N.Saraswati, TNO
12.00	Closing by Chair	Closing by Chair
12.05	Lunch	
	B1) Grid connection and power system integration Chairs: Prof Kjetil Uhlen, NTNU Prof Olimpo Anaya-Lara, Strathclyde University	**G1) Experimental Testing and Validation** Chairs: Tor Anders Nygaard, IFE Ole David Økland, SINTEF, Amy Robertson, NREL
13.05	Introduction by Chair	Introduction by Chair
13.10	*VIKINGS: Offshore Wind Integration within the Stand-alone Electric Grid at Oil and Gas Offshore Installations,* W.He, Equinor	*RAVE (Research at alpha ventus) offers its 10 years of measurement data to support research in offshore wind power,* B.Lange, Fraunhofer IWES
13.35	*Feasibility assessment of wireless series reactive compensation of long submarine AC cables,* G.Lugrin, SINTEF	*Managing data to develop digital twins, demonstrate new technology and provide improved wind turbine/wind farm control during operation,* P.McKeever, ORE Catapult
13.55	*Power Oscillation Damping from Offshore Wind Farms Connected to HVDC via Diode Rectifiers,* O.Saborio-Romano, DTU Wind Energy	*Experimental Investigations on the Fatigue Resistance of Automatically Welded Tubular X-Joints for Jacket Support Structures,* K.Schürmann, Leibniz University Hannover
14.15	*Dynamic Analysis of Power Cable in Floating Offshore Wind Turbine,* M.Sobhaniasl, University of Rome	*Determination of the Yaw Moment of a Downwind-coned Rotor under Yawed Conditions: Limitations of a Blade Element Momentum Theory Method*, C.W.Schulz, Hamburg University of Technology
14.35	Refreshments	
	B2) Grid connection and power system integration (cont.)	**G2) Experimental Testing and Validation (cont.)**
15.05	*Can levelised revenues from auctions be used to deduct levelised cost of offshore wind farms? The case of Kriegers Flak,* L.Kitzing, DTU	*Hydrodynamic testing of a flexible, large-diameter monopile in regular and irregular waves: observations and effects of wave generation techniques,* E.Bachynski, NTNU
15.25	*Measuring cost reductions of offshore wind using European offshore auctions,* L.Kitzing, DTU	*Validation of Drift Motions for a Semi-submersible Floating Wind Turbine and the Associated Challenges,* M.Y.Mahfouz, Stuttgart Wind Energy
15.45	*Forecasting Wind Power as a Dispatchable Generation Source for Grid Frequency Control,* L.May, Strathclyde University	*Hybrid Modelling for Engineering Design of Floating Offshore Wind Turbine Foundations – Model Coupling and Validation,* P.D.Tomaselli, DHI
16.05	*Surrogate model of offshore farm to farm wake effects for large scale energy system applications,* J.P.Murcia, DTU	*On the real time hybrid modelling of floating offshore wind turbine using ducted fan(s),* F.Petrie, Oceanide
16.25	Closing by Chair	Closing by Chair
16.30	Refreshments	
17.00	Poster session	
19.00	Conference dinner	

Poster session with refreshments (17.00-19.00 Thursday 16 January)

1. *Multi-objective model predictive control for a multi-rotor wind turbine*, J.Urdal, NTNU
2. *Introducing wake effects from offshore wind farm clusters to Danish power integration system,* X.G.Larsén DTU Wind Energy
3. *Evaluation of different wind fields for the investigation of the dynamic response of offshore wind turbines,* A.Nybø, UiB
4. *Wave-modified two-equation model to study wave-wind interaction in shallow waters,* M.B.Paskyabi, UiB
5. *Comparison of long-term and short-term wind power forecasting methods,* C. Lau, Industrial Technology Research Inst.
6. *Vertical profiles of wind velocity, turbulence intensity and temperature beyond the surface layer,* P.Domagalski, WindTak
7. *COTUR – estimating the COherence of TURbulence with wind lidar technology,* M.Flügge, NORCE
8. *Polymorphic uncertainty in met-ocean conditions and the influence on fatigue loads,* C.Hübler, ForWind
9. *Evaluation of Gaussian wake models under different atmospheric stability conditions: comparison with large eddy simulation results, M.Krutova, UiB*
10. *A novel approach to computing super observations for probabilistic wave model validation,* P.Bohlinger, Norwegian Meteorological Inst.
11. *Hub-based vectoral reduction of turbulent wind fields for actuator-disc wind turbine models,* V.Chabaud, SINTEF
12. *Comparison of Weather Window Statistics and Time Series Based Methods Considering Risk Measures, J.Lübsen, Fraunhofer IWES*
13. *A Conceptual Framework for Data-driven Reliability-centred Evolutionary and Automated Maintenance of Offshore Wind Farms,* K.Aslansefat, University of Hull
14. *Applications and platforms in digitalisation of wind farm O&M – community feedback and survey results,* V.Berkhout, Fraunhofer IEE
15. *Identification and prioritization of low performing wind turbines using a power curve health value approach, S.Pfaffel, Fraunhofer IEE*
16. *Innovative, Low Cost, Low Weight and Safe Floating Wind Technology Optimized for Deep Water Wind Sites: The FLOTANT Project,* A.Castro, The Oceanic Platform of the Canary Islands
17. *Short-term Offshore Wind Speed Forecasting with an Efficient Machine Learning Approach*, M.B.Paskyabi, UiB
18. *Vortex interaction in the wake of a two- and three-bladed wind turbine,* L.Kuhn, NTNU
19. *Sensitivity analysis of cost parameters for floating offshore wind farms,* C.Maienza, Univ of Campania
20. *Flow model integration into the STAS framework for optimal control of wind power plants,* S.Dankelman, SINTEF
21. *Optimization of reactive power dispatch in offshore wind power plants,* K.Das, DTU Wind Energy
22. *Simulation of wind turbine wake meandering pattern,* B.Panjwani, SINTEF
23. *A Numerical Study on the Effect of Wind Turbine Wake Meandering on Power Production of Hywind Tampen,* B.Panjwani, *SINTEF*
24. *Surge decay CFD simulations of a Tension Leg Platform (TLP) floating wind turbine,* A.Borràs Nadal, IFP Energies Nouvelles
25. *Hydrodynamic Investigation of Large Monopile for Offshore Wind Applications: Numerical and Experimental Approaches,* A.Moghtadaei, Queens University of Belfast
26. *Optimization-based calibration of hydrodynamic drag coefficients for a semi-submersible platform using experimental data of an irregular sea state,* M.Böhm, ForWind
27. *Laboratory test setup for offshore wind integration with the stand-alone electric grid at oil and gas offshore installations,* O.Mo, SINTEF
28. *Friction coefficients for steel to steel contact surfaces in air and seawater*, R.J.M. Pijpers, TNO
29. *Numerical and Experimental Investigation of MIT NREL TLP under regular and irregular waves,* M. Vardaroglu, Università della Campania
30. *Load Estimation and Wind Measurement Considering Full Scale Floater Motion*, A.Yamaguchi, University of Tokyo
31. *A study on dynamic response of a semi-submersible floating wind turbine considering combined wave and current loads,* Y.Liu, University of Tokyo
32. *GANs assisted super-resolution simulation of atmospheric flows,* D.T.Tran, NTNU
33. *Liner parameter-varying model of wind power plant for power tracking and load reduction,* K.Kölle, SINTEF
34. *Fast divergence-conforming reduced basis methods for stationary and transient flow problems,* E.Fonn, SINTEF
35. *State of the art and research gaps in wind farm control. Results of a recent workshop,* G.Giebel, DTU
36. *Optimization of wind turbines using low cost FBG shape sensing technology*, C.M. da Silva Oliveira, Fibersail
37. *SpliPy – Spline modelling in Python,* K.Johannessen, SINTEF

19.00	Dinner

Friday 17 January	
	F) Wind farm optimization. Chairs: Yngve Heggelund, NORCE and Henrik Bredmose, DTU Wind Energy
09.00	Introduction by Chair
09.05	*Effect of wind direction on wind park performance using Actuator Surface Modelling (ASM) with and without nacelle effects,* B.Panjwani, SINTEF
09.25	*Design Optimization of Spar Floating Wind Turbines Considering Different Control Strategies*, J.M.Hegseth, NTNU
09.45	*Far off-shore wind energy-based hydrogen production: Technological assessment and market valuation designs,* M.Woznicki, CEA
10.05	*Optimising the utilisation of subsea cables in GW scale offshore wind farm collector networks using energy storage*, P.Taylor, University of Strathclyde
10.25	Closing by Chair
10.30	Refreshments
	Closing session – Strategic Outlook Chairs: John Olav Tande, SINTEF and Prof Michael Muskulus, NTNU
11.00	Introduction by Chair
11.05	*Offshore wind is going big,* Kristian Holm, Head of wind turbine technology, Equinor
11.35	*Zero Emission Energy Distribution at Sea (ZEEDS),* Jim Stian Olsen, Innovation Program Manager, Aker Solutions
12.05	*Status and outlook of European offshore wind research and innovation*; Dr. Carlos Eduardo Lima Da Cunha, Policy Officer, European Commission, DG Research & Innovation
12.35	Poster award and closing
13.00	Lunch

Scientific Committee and Conference Chairs

An international Scientific Committee is established with participants from leading institutes and universities. These include:

Anaya-Lara, Olimpo, Strathclyde University
Berge, Erik, Meteorologisk institutt
Berkhout, Volker, Fraunhofer IEE
Bredmose, Henrik, DTU
Cutululis, Nicolaos, DTU
Eecen, Peter, ECN
Heggelund, Yngve, CMR
Kvamsdal, Trond, NTNU
Madsen, Peter Hauge, DTU
Merz, Karl, SINTEF Energi
Munduate, Xabier, CENER
Muskulus, Michael, NTNU
Nielsen, Finn Gunnar, UiB
Nygaard, Tor Anders, IFE
Reuder, Joachim, UiB
Robertson, Amy, NREL
Sperstad, Iver Bakken, SINTEF Energi
Tande, John Olav, SINTEF Energi
Uhlen, Kjetil, NTNU
Van Wingerde, Arno, Fraunhofer IWES
Van Bussel, Gerard, TU Delft
Økland, Ole David, SINTEF

The Scientific Committee will review submissions and prepare the programme. Selection criteria are relevance, quality and originality.

The conference chairs were:

- John Olav Giæver Tande, Chief scientist, SINTEF Energi AS
- Trond Kvamsdal, Professor NTNU
- Michael Muskulus, Professor NTNU

Opening session – Frontiers of Science and Technology

Opening and welcome by chair, John Olav Tande, SINTEF Energi

Bringing offshore wind forward through R&I, Head of EERA JP wind, Peter Eecen, TNO

The grand challenges in the science of wind energy, Katherine Dykes, DTU

How offshore wind will help Europe go carbon-neutral, Lizet Ramirez, WindEurope

Introduction to the 1.2 GW Floating Offshore Wind Farm Project in Korea, Hyunkyoung Shin, University of Ulsan

Offshore wind status and outlook for China, Dr. Liu Yongqian, Renewable Energy School, North China Electric Power University

How technology is driving global offshore wind, Chair ETIPwind, Aidan Cronin, SiemensGamesa

EERA DeepWind'2020
17th Deep Sea Offshore Wind R&D Conference,
Trondheim, 15 - 17 January 2020

› BRINGING OFFSHORE WIND FORWARD THROUGH R&I

Peter Eecen
Coordinator EERA Joint Programme on Wind Energy
R&D Manager TNO Wind Energy

EERA – EUROPEAN ENERGY RESEARCH ALLIANCE

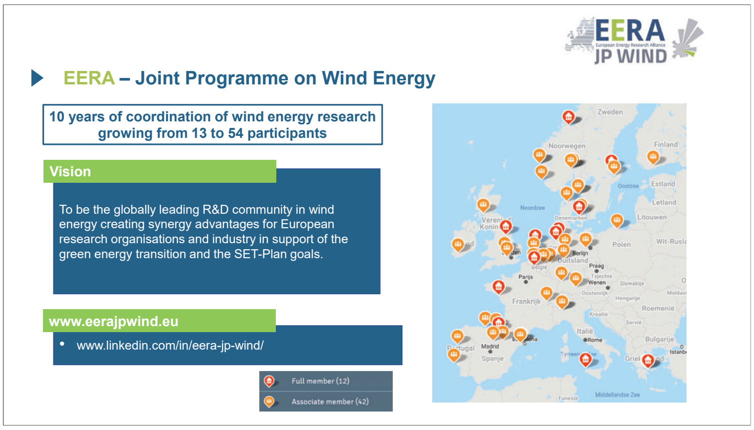
› The European Energy Research Alliance (EERA) is an association of European public research centers and universities active in low-carbon energy research. Wind Energy is one of 15 Joint Programmes.

- 250+ organisations
- 50,000+ researchers
- 30 countries

Catalysing European energy research for a climate-neutral society by 2050

- Advanced Materials and Processes for Energy Application (AMPEA)
- Bioenergy
- Carbon Capture and Storage
- Concentrated Solar Power (CSP)
- Economic, Environmental and Social Impacts (JP e3s)
- Energy Efficiency in Industrial Processes
- Energy Storage
- Energy Systems Integration
- Fuel Cells and Hydrogen
- Geothermal
- Hydropower
- Nuclear Materials
- Ocean Energy
- Photovoltaic Solar Energy
- Shale Gas (discontinued)
- Smart Cities
- Smart Grids
- Wind Energy

Bringing offshore wind forward through R&I



EERA – Joint Programme on Wind Energy

10 years of coordination of wind energy research growing from 13 to 54 participants

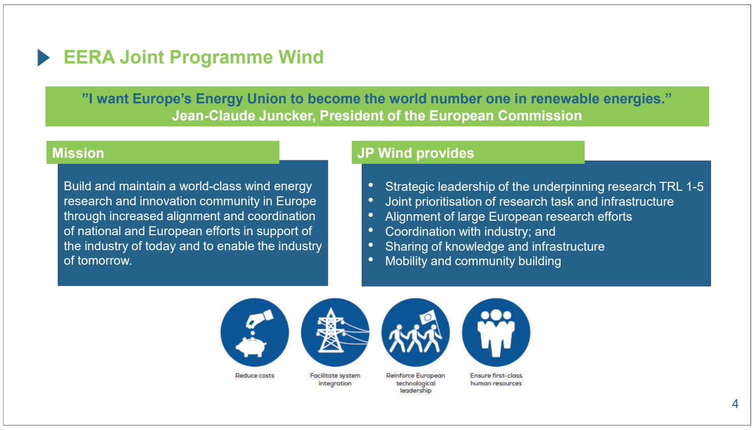
Vision

To be the globally leading R&D community in wind energy creating synergy advantages for European research organisations and industry in support of the green energy transition and the SET-Plan goals.

www.eerajpwind.eu

- www.linkedin.com/in/eera-jp-wind/

- Full member (12)
- Associate member (42)



EERA Joint Programme Wind

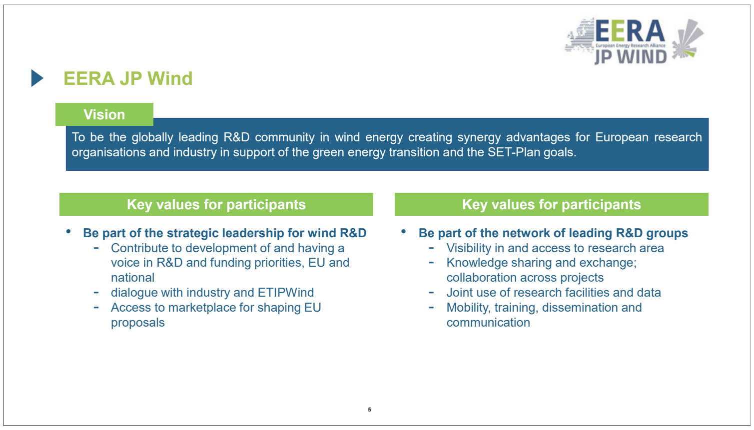
"I want Europe's Energy Union to become the world number one in renewable energies."
Jean-Claude Juncker, President of the European Commission

Mission

Build and maintain a world-class wind energy research and innovation community in Europe through increased alignment and coordination of national and European efforts in support of the industry of today and to enable the industry of tomorrow.

JP Wind provides

- Strategic leadership of the underpinning research TRL 1-5
- Joint prioritisation of research task and infrastructure
- Alignment of large European research efforts
- Coordination with industry; and
- Sharing of knowledge and infrastructure
- Mobility and community building



EERA JP Wind

Vision

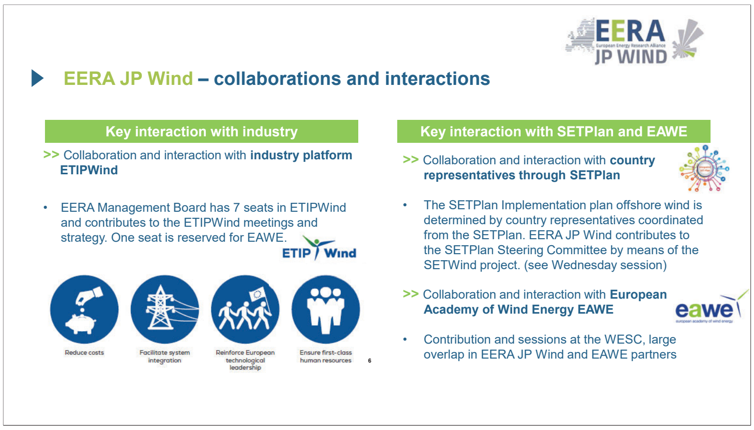
To be the globally leading R&D community in wind energy creating synergy advantages for European research organisations and industry in support of the green energy transition and the SET-Plan goals.

Key values for participants

- **Be part of the strategic leadership for wind R&D**
  - Contribute to development of and having a voice in R&D and funding priorities, EU and national
  - dialogue with industry and ETIPWind
  - Access to marketplace for shaping EU proposals

Key values for participants

- **Be part of the network of leading R&D groups**
  - Visibility in and access to research area
  - Knowledge sharing and exchange; collaboration across projects
  - Joint use of research facilities and data
  - Mobility, training, dissemination and communication



EERA JP Wind – collaborations and interactions

Key interaction with industry

>> Collaboration and interaction with **industry platform ETIPWind**

- EERA Management Board has 7 seats in ETIPWind and contributes to the ETIPWind meetings and strategy. One seat is reserved for EAWE.

Key interaction with SETPlan and EAWE

>> Collaboration and interaction with **country representatives through SETPlan**

- The SETPlan Implementation plan offshore wind is determined by country representatives coordinated from the SETPlan. EERA JP Wind contributes to the SETPlan Steering Committee by means of the SETWind project. (see Wednesday session)

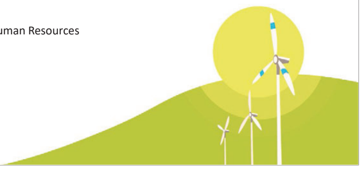
>> Collaboration and interaction with **European Academy of Wind Energy EAWE**

- Contribution and sessions at the WESC, large overlap in EERA JP Wind and EAWE partners

EERA JP Wind *R&I strategy* 2019

Research Agenda topics:

1) Next generation wind turbine technologies and disruptive concepts
2) Grid integration and energy systems
3) Sustainability, Social Acceptance, Economics and Human Resources
4) Offshore wind (bottom-fixed and floating)
5) Operation and maintenance
6) Fundamental Wind Energy Science



R&I priorities – process

- The Management Board of EERA JP Wind delivered **end 2017** a strategy for EERA JP Wind.
- At the same time, the R&I priorities were defined and delivered. These were used for:
  - Input to EU requests
  - Input to ETIPWind
  - Input and basis for SETPlan Implementation plan offshore wind

- In 2019 EERA JP Wind decided to update, refine and publish the R&I strategy
  - EU is requesting guidance on R&D priorities from different organisations (a.o. EERA).
  - EERA JP Wind aims to support EU by setting the R&I priorities for wind energy.
  - Assist the development of the H2020 programme and refinement of the HorizonEurope calls

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The EERA JPWind R&I strategy – connections

- ETIPWIND R&I agenda

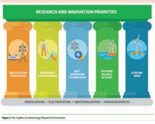
EERA R&I strategy 2019 – topics

Six urgent and important **topics** have been identified:

1. **Next generation wind turbine technology & disruptive concepts**
2. **Grid integration and energy systems**
3. **Sustainability, social acceptance and human resources**
4. **Offshore wind (bottom fixed + floating)**
5. **Operation and maintenance**
6. **Fundamental wind energy science**

For each topic EERA JP Wind has defined
- priority topics
- Challenges
- key action areas.

R&I priorities – connection to other agenda's

ETIPWind 2017	ETIPWind 2019	EERA 2017 strategy	EERA 2019 strategy
Next generation technology	Next generation technologies	Next generation technology	**Next generation wind turbine technology & disruptive concepts**
Grid systems, integration and infrastructure	Grid & system integration	Grid systems, integration and infrastructure	**Grid integration and energy systems**
Offshore balance of plants	Offshore balance of plants	Offshore balance of plants	**Offshore wind (bottom fixed + floating)**
Operation and maintenance	Operation and maintenance	Operation and maintenance	**Operation and maintenance**
From R&I to deployment	Digitalisation, electrification, industrialisation and human resources	From R&I to deployment	**Sustainablity, social acceptance, economics and human resources**
Industrialisation	Floating Wind	Industrialisation	
		Basic wind energy science	**Fundamental wind energy science**

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1. Next generation wind turbine technologies and disruptive concepts

❖**Large technology developments are being realised and foreseen while wind energy is being implemented in large numbers (6000GW wind power worldwide implementation). EERA partners work on next generation wind turbines, the outcome is used by industry for product development. New concepts require major support at higher TRLs (demonstration at full scale in R&D context) to overcome the inertia of existing concepts.**

Key action areas
- **Develop next generation test and validation methods**
- **Investigate smart turbine design**
- **Removing barriers towards 20+MW turbines**
- **Develop disruptive technologies**
- **New materials and optimized structures**

2. Grid integration and energy systems

R&I must contribute to the transition towards 100% RES power systems, understanding the challenges and developing the required technical capabilities. This includes aspects such as offshore grid development and operation at North Sea scale, dynamic stability of electricity systems with very large penetration of power-electronic converters and maintaining a secure and affordable energy provision through developing markets and ancillary services, hybrid renewable energy systems, sector coupling and energy conversion and storage.

Key action areas

- Design and control of wind power plants for 100% RES power system
- Power market design, energy management and balancing
- Sustainable hybrid solutions, storage and conversion
- Increased performance of wind power via digitalization

3. Sustainability, Social Acceptance, Economics and Human Resources

Massive deployment of wind power must be done in a sustainable manner, creating maximum value for stakeholders, including citizens, users and investors with respect to the Sustainable Development Goals. This is achieved by taking away barriers to massive deployment and ensuring sufficiently qualified human resource.

Key action areas

- Identify the most promising areas for value creation by wind energy in the future
- Standardised methods for quantitative impact assessments in research projects
- Research-based and targeted continuing education and training
- Recycling and circular economy
- Show-case best practices to empowering citizens and public engagement in wind power projects

4. Offshore wind (bottom fixed + floating)

Massive offshore implementation of wind power requires R&I to further reduce risks and costs, thus accelerate deployment. Developments will occur further offshore and in deeper water requiring floating wind power. Integrated design methods needs to be developed which includes wind and waves, electrical infrastructure, environment, substructures, control, logistics and risks.

Key action areas

- Enabling floating wind
- Experiment for validation of design and multi-disciplinary optimization models for offshore wind farms (floating and fixed). Creating open access data sets.
- Understanding and modelling offshore physics for wind farm design and operation
- Understanding the mechanical and electrical design conditions for electrical infrastructure for floating wind farms

5. Operation and maintenance

In order to reduce the cost of wind power, operation and maintenance must be optimized. Robotics solutions should reduce the required human intervention and sensor system provide the information for improved monitoring and control to increase life. The abundance of data and information should be used in big-data analytics technologies to improve O&M.

Key action areas

- Development and validation of models of component and structural damage and degradation as functions of loads and environment
- Next generation of Wind farm control
- Enable digital transformation in wind energy system O&M
- Sensor systems and data analytics for health monitoring
- Robotics

6. Fundamental Wind Energy Science

Research in the fundamental wind energy sciences is required to develop the research competences and the underpinning scientific knowledge to improve standards, methods and design solutions. Also models and experimental data are needed for complex sites and extreme climates, larger and relatively lighter turbines, more efficient wind farms and large-scale penetration in the energy system. The research leads to updated standardized design criteria and standardized methods for testing and validation.

Key action areas

- Efficient multi-disciplinary optimization and system engineering
- Multi-scale flow modelling
- Large rotor aerodynamics
- Digitalization and data analytics
- Materials science
- Construction and manufacturing
- Open access database for research validation
- Integrated Multi fidelity system

THANK YOU

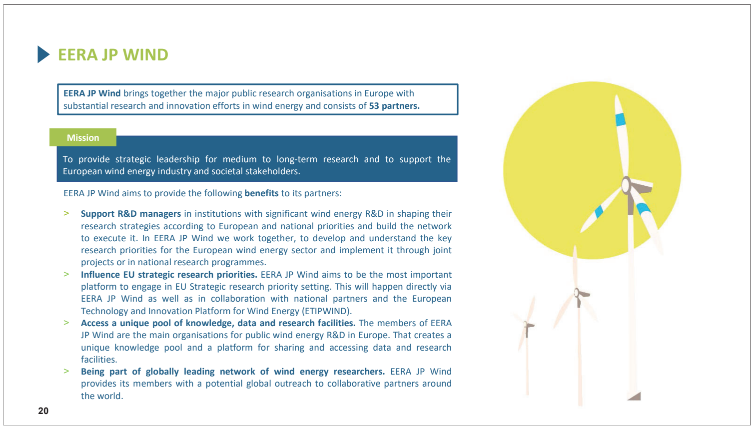
PETER EECEN
COORDINATOR EERA JP WIND

For more inspiration:
TNO.NL/TNO-INSIGHTS

EERA JP Wind *R&I strategy* 2019

I. Introduction to the EERA JP Wind R&I Strategy 2019

II. Research Agenda topics:
  1) Next generation wind turbine technologies and disruptive concepts
  2) Grid integration and energy systems
  3) Sustainability, Social Acceptance, Economics and Human Resources
  4) Offshore wind (bottom-fixed and floating)
  5) Operation and maintenance
  6) Fundamental Wind Energy Science



EERA JP WIND

EERA JP Wind brings together the major public research organisations in Europe with substantial research and innovation efforts in wind energy and consists of **53 partners.**

Mission

To provide strategic leadership for medium to long-term research and to support the European wind energy industry and societal stakeholders.

EERA JP Wind aims to provide the following **benefits** to its partners:

> **Support R&D managers** in institutions with significant wind energy R&D in shaping their research strategies according to European and national priorities and build the network to execute it. In EERA JP Wind we work together, to develop and understand the key research priorities for the European wind energy sector and implement it through joint projects or in national research programmes.

> **Influence EU strategic research priorities.** EERA JP Wind aims to be the most important platform to engage in EU Strategic research priority setting. This will happen directly via EERA JP Wind as well as in collaboration with national partners and the European Technology and Innovation Platform for Wind Energy (ETIPWIND).

> **Access a unique pool of knowledge, data and research facilities.** The members of EERA JP Wind are the main organisations for public wind energy R&D in Europe. That creates a unique knowledge pool and a platform for sharing and accessing data and research facilities.

> **Being part of globally leading network of wind energy researchers.** EERA JP Wind provides its members with a potential global outreach to collaborative partners around the world.

EERA R&I strategy 2019 – topics

EERA JP Wind has defined the priority topics, challenges and key action areas for wind energy research. The resulting R&I strategy is the result of discussions with the **53 major European research groups** organized in EERA JP Wind. Six urgent and important **topics** have been identified:

1. **Next generation wind turbine technology & disruptive concepts** - Large technology developments are being realised and foreseen while wind energy is being implemented in large numbers. The wind sector requires a strong scientific knowledge base to develop wind energy generators beyond its capabilities of today and tomorrow. New concepts contribute to the massive deployment but require major support at higher TRLs to overcome the inertia of existing concepts.
2. **Grid integration and energy systems** - R&I must contribute to the transition towards 100% RES power systems, understanding the challenges and developing the required technical capabilities. This includes aspects such as dynamic stability of systems with very large penetration of converters, market designs and interactions with other energy systems, sector coupling, energy conversion and storage.
3. **Sustainability, social acceptance and human resources** - Massive implementation of wind power must be done in a sustainable manner, creating maximum value for stakeholders, including investors, users and citizens with respect to the Sustainable Development Goals. This is achieved by taking away barriers to massive deployment and ensuring sufficient qualified human resource.
4. **Offshore wind (bottom fixed + floating)** - Massive offshore implementation of wind power requires R&I to further reduce risks and costs, thus accelerate deployment. Developments will occur further offshore and in deeper water requiring floating wind power. Integrated design methods needs to be developed which includes wind and waves, electrical infrastructure, environment, substructures, control, logistics and risks.
5. **Operation and maintenance** - In order to reduce the cost of wind power, operation and maintenance must be optimised. Robotics solutions should reduce the required human intervention and sensor system provide the information for improved monitoring and control to increase life. The abundance of data and information should be used in big-data analytics technologies to improve O&M.
6. **Fundamental wind energy science** - Research in the fundamental wind energy sciences is required to develop the research competences and the underpinning scientific knowledge. This leads to improved standards, methods and design solutions. Models and experimental data are needed for complex sites and extreme climate, larger and lighter turbines, more efficient wind farms and large-scale penetration in the energy system.

EERA R&I strategy 2019 – Contribution to SET Plan and SDGs

The EERA JP Wind R&I strategy contributes to the **European Strategic Energy Technology Plan (SET Plan**) as well as to the **Sustainable Development Goals (SDGs).**

SET Plan: The EU is committed to becoming the global leader in renewable energy technology and realise an CO2-free energy system. The EU Energy Roadmap 2050 aims to ensure a clean, competitive and reliable energy supply. The SET Plan aims to accelerate the development and deployment of low-carbon technologies. It promotes research and innovation efforts across Europe by supporting the most impactful technologies in the EU's transformation to a low-carbon energy system.

SDGs: The 2030 Agenda for Sustainable Development was adopted by all United Nations Member States in 2015, providing a shared blueprint for peace and prosperity for people and the planet, now and into the future. The 17 SDGs are an urgent call for action by all countries - developed and developing - in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.

EERA R&I strategy 2019 – Connection to other strategies

The partners in EERA JP Wind are working on wind energy research and development that will keep Europe in the forefront of the world's pre-competitive wind energy research and maintain Europe's innovative wind industry.

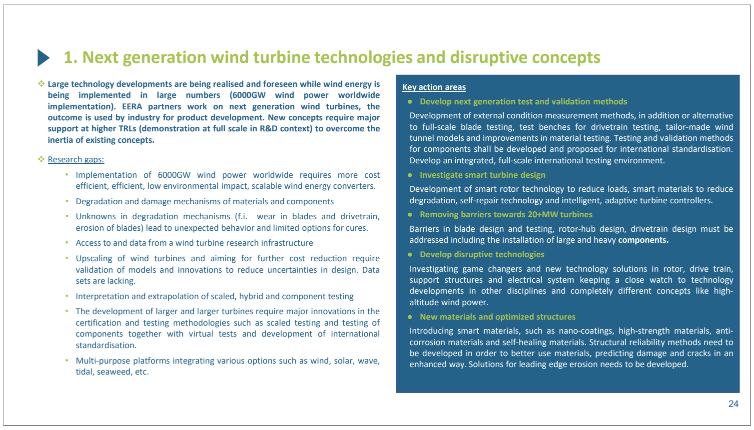
EERA JP Wind works closely with ETIPWind, the industry platform that connects Europe's wind energy community, and EAWE, the European Academy of Wind energy, an academic research community of research institutions and universities in Europe.

Both **ETIPWind** as **EAWE** have published their research strategies. The R&I strategy of EERA JPWind is strongly connected. However, each strategy has its own purpose and application: where the ETIPWind strategy primarily aims at higher technology readiness levels (TRL), the EAWE strategy primarily focusses on fundamental research topics at low TRL.

The EERA JP Wind strategy aims at research that is required to bring the results of more fundamental research into applications. The result is a research scope on TRL3 to TRL8 with strong focus on applicability to industry and product development. The innovations that are the result support the industry. A successful and leading European wind industry requires the support from expert groups in short, medium and long-term research activities and requires a research strategy at all three levels.

ETIP Wind
EUROPEAN TECHNOLOGY & INNOVATION PLATFORM ON WIND ENERGY

eawe
european academy of wind energy



1. Next generation wind turbine technologies and disruptive concepts

- **Large technology developments are being realised and foreseen while wind energy is being implemented in large numbers (6000GW wind power worldwide implementation). EERA partners work on next generation wind turbines, the outcome is used by industry for product development. New concepts require major support at higher TRLs (demonstration at full scale in R&D context) to overcome the inertia of existing concepts.**
- Research gaps:
  - Implementation of 6000GW wind power worldwide requires more cost efficient, efficient, low environmental impact, scalable wind energy converters.
  - Degradation and damage mechanisms of materials and components
  - Unknowns in degradation mechanisms (f.i. wear in blades and drivetrain, erosion of blades) lead to unexpected behavior and limited options for cures.
  - Access to and data from a wind turbine research infrastructure
  - Upscaling of wind turbines and aiming for further cost reduction require validation of models and innovations to reduce uncertainties in design. Data sets are lacking.
  - Interpretation and extrapolation of scaled, hybrid and component testing
  - The development of larger and larger turbines require major innovations in the certification and testing methodologies such as scaled testing and testing of components together with virtual tests and development of international standardisation.
  - Multi-purpose platforms integrating various options such as wind, solar, wave, tidal, seaweed, etc.

Key action areas

- **Develop next generation test and validation methods**

  Development of external condition measurement methods, in addition or alternative to full-scale blade testing, test benches for drivetrain testing, tailor-made wind tunnel models and improvements in material testing. Testing and validation methods for components shall be developed and proposed for international standardisation. Develop an integrated, full-scale international testing environment.
- **Investigate smart turbine design**

  Development of smart rotor technology to reduce loads, smart materials to reduce degradation, self-repair technology and intelligent, adaptive turbine controllers.
- **Removing barriers towards 20+MW turbines**

  Barriers in blade design and testing, rotor-hub design, drivetrain design must be addressed including the installation of large and heavy **components.**
- **Develop disruptive technologies**

  Investigating game changers and new technology solutions in rotor, drive train, support structures and electrical system keeping a close watch to technology developments in other disciplines and completely different concepts like high-altitude wind power.
- **New materials and optimized structures**

  Introducing smart materials, such as nano-coatings, high-strength materials, anti-corrosion materials and self-healing materials. Structural reliability methods need to be developed in order to better use materials, predicting damage and cracks in an enhanced way. Solutions for leading edge erosion needs to be developed.

2. Grid integration and energy systems

- **R&I must contribute to the transition towards 100% RES power systems, understanding the challenges and developing the required technical capabilities. This includes aspects such as offshore grid development and operation at North Sea scale, dynamic stability of electricity systems with very large penetration of power-electronic converters and maintaining a secure and affordable energy provision through developing markets and ancillary services, hybrid renewable energy systems, sector coupling and energy conversion and storage.**
- Research gaps:
  - **Adaptation of electricity markets for a 100% RES power systems.** When production of wind and solar will dominate the markets, their production characteristics must be matched by market design, including more local and short-term flexibility markets, with faster dispatch and adequate pricing
  - **Validated energy systems models for assessing the value of wind power** with 100 % variable renewable energy supply. Various scenarios / hourly timestep models exist, but with more or less crude assumptions, e.g. on wind variations, balancing capabilities, regional transportation bottlenecks, etc.
  - **Degradation and failure mechanisms of cables, transformers and power electronic converters** call for extensive research and testing to be fully understood and enable reliable grid solutions, including mitigating measures.
  - **Behavior and control of large HVDC connected clusters** is vital for enabling future development of large interconnected offshore grids, serving to connect wind farms to different national markets and offshore loads, as well as power/energy exchange between regions. Essential aspects are strategic grid planning, optimal power flow, reliable operation and protection schemes and supporting the interconnected terrestrial grids.
  - **Dynamic performance of very large wind power clusters** need to maintain power quality and stability in offshore wind farm grids that are fully based on power-electronic converters in order to guarantee reliable and efficient wind farm operation.
  - **Advanced system services from wind power**, providing reserve power for frequency support, reactive power for (dynamic) voltage support, mitigate or actively compensate harmonics for maintaining power quality and providing black start (grid forming operation) for increasing security of supply and helping system restoration, etc.

Key action areas

- **Design and control of wind power plants for 100% RES power system**

Technical solutions to enable wind power plants to enabling safe and efficient power system operation with 100% renewable generation

- **Power market design, energy management and balancing**

The energy system transition requires development of tools for energy management, taking into account wind forecast uncertainty, and supporting the interaction between wind power, other generation, conversion and storage, demand-response and grid capacity limitations.

- **Sustainable hybrid solutions, storage and conversion**

Combining offshore wind with other renewables, utilizing complementary generation patterns, contributes to improving the security of supply and lowering grid integration costs. Conversion and storage is essential to realize the required generation flexibility and security of supply, both on the short term as well as seasonal. Furthermore, integrating of these solutions in offshore wind farms is needed to facilitate their large-scale and economic integration, including off-grid approaches, i.e. using gas or other alternative energy carriers.

- **Increased performance of wind power via digitalization**

Use of field data, big data analytics and AI combined with system modelling for monitoring, control and performance optimization of wind power in the energy system.

3. Sustainability, Social Acceptance, Economics and Human Resources

- **Massive deployment of wind power must be done in a sustainable manner, creating maximum value for stakeholders, including citizens, users and investors with respect to the Sustainable Development Goals. This is achieved by taking away barriers to massive deployment and ensuring sufficiently qualified human resource.**
- Research gaps:
  - Wind can create higher value for society, both on the market side (high value energy at low cost), on the societal side (socio-economic benefits, avoiding negative impacts), depending on the interactions between market, technological, environmental issues within the overall policy and regulatory framework
  - Contribution of wind energy to the UN Sustainable Development Goals (SDG)
  - Applying life-cycle assessment and estimating requirements of resources for the energy transition, including the availability of resources in power systems with very high shares of wind energy
  - Assessing the economic and societal impact of research and innovation projects for wind energy
  - Technologies and designs to improve recycling and end-of-life solutions
  - Transfer understanding of mechanisms behind social acceptance into implementable approaches and demonstrate their value for project realisation
  - Identify skills and training needs required for developing and handling future wind turbine designs and develop best practices for high quality training programs

Key action areas

- **Identify the most promising areas for value creation by wind energy in the future**

Assessment of new ideas such as alternative routes to market (e.g. through hydrogen production), regulation and market design (e.g. to reduce barriers, financial mechanisms to support wind investment…), new business models (e.g. aggregator services), profit-sharing mechanisms (e.g. local ownership schemes).

- **Standardised methods for quantitative impact assessments in research projects**

Development Develop a method for broader socio-economic impact assessments in project proposals (including cost indicators and value creation indicators).

- **Research-based and targeted continuing education and training**

Adequate human resources with the right skills and competences are key to Europe's continued global leadership in wind energy. New skills are required as the technology evolves.

- **Recycling and circular economy**

As wind power increases its share in the energy mix, it needs to address issues related to its environmental and social footprints. An environmental and community friendly design also includes the 'afterlife' of a turbine. We need to develop technologies that are easily recyclable, create designs that are good for recycling and embrace circular economy concepts in our research and development.

- **Show-case best practices to empowering citizens and public engagement in wind power projects**

Extensive wind onshore deployment is increasingly impacting citizens, who need be included in the planning and design process. During the past years, we have started to understand mechanisms and solutions for effective participatory processes and create acceptability. We now need demonstration projects on how to build the 'acceptable' onshore wind plant.

4. Offshore wind (bottom fixed + floating)

- **Massive offshore implementation of wind power requires R&I to further reduce risks and costs, thus accelerate deployment. Developments will occur further offshore and in deeper water requiring floating wind power. Integrated design methods needs to be developed which includes wind and waves, electrical infrastructure, environment, substructures, control, logistics and risks.**
- Research gaps:
  - **Validation of integrated design models for floating wind plants** is needed to ensure cost effective designs and to maximize the opportunities for floating foundations optimization based on wind turbine load control technology.
  - **Efficient multi-disciplinary optimization** offers to achieve cost effective and reliable foundations, accounting for a wide range of design parameters and needs research and maturing. Platform and mooring lines maintenance strategy.
  - **Offshore physics (soil damping, breaking waves, soil-structure-fluid interaction, air-sea interaction).** The limited understanding of physics phenomena and model uncertainties affecting offshore balance of plant technology prevents accurate design models and optimal cost-effective designs. Proper data sets are lacking.
  - **Site-specific structural and electrical design conditions for electrical infrastructure** are lacking to better understand the loading and operational conditions of key electrical components like cables or power converters, enabling improvements in reliability.

Key action areas

- **Enabling floating wind**

Develop design model for integrated aero-hydro-elastic optimisation including cost optimisation. Develop technology to enhance mass-production and installation of floating platforms. Develop smart and disruptive solutions for (dynamic) mooring.

- **Experiment for validation of design and multi-disciplinary optimization models for offshore wind farms (floating and fixed). Creating open access data sets.**

Execute large-scale floating experiment to create open access experimental datasets for effective design model validation and uncertainty calculations, leading to faster improvements of design tools and more accurate designs. Develop an effective coupling of offshore design models (i.e. balance of plant - wind turbine) and metocean models to enable overall system optimization.

- **Understanding and modelling offshore physics for wind farm design and operation**

The improvement of models focused on key physical phenomena (i.e. soil-structure-fluid interaction) is needed to develop better design tools for industry, able to capture a broader spectrum of failure modes.

- **Understanding the mechanical and electrical design conditions for electrical infrastructure for floating wind farms**

Develop more accurate and site-specific load models accounting for metocean conditions (i.e. hydrodynamic forces on dynamic cables) as well as the electrical operational conditions and interactions for improved layout including connections, transformers and inter-array cables.

5. Operation and maintenance

- **In order to reduce the cost of wind power, operation and maintenance must be optimized. Robotics solutions should reduce the required human intervention and sensor system provide the information for improved monitoring and control to increase life. The abundance of data and information should be used in big-data analytics technologies to improve O&M.**
- Research gaps:
  - **Accurate reliability models of components as functions of operation and loads.** Condition based maintenance or replacement of (sub)components relies on accurate reliability models that can predict remaining lifetime or probability of failure for a given load history.
  - **Degradation mechanisms of surfaces (wear, erosion and corrosion).** Unknowns in degradation mechanisms (f.i. wear in blades and drivetrain, erosion of blades and corrosion of support structures) lead to unexpected behaviour and limited options for cures.
  - **Lifetime extension** – is an effective solution for reduction of LCOE reduction as well as impact to environment and resources.
  - **Data analytics for O&M purpose and lifetime health prediction for predictive maintenance.** Abundant information and data are available from wind farms, for which processing by big-data analytics technology needs to be developed.
  - **Robotics –** Reduction to human presence at offshore platforms at large height to improve health and safety by automated and remote inspections and repair inside the nacelle as outside the turbine.

Key action areas

- **Development and validation of models of component and structural damage and degradation as functions of loads and environment**

The fundamentals and results of damage and degradation need to be developed from micro-scale to macro-scale level. Validation requires extensive testing programmes.

- **Next generation of Wind farm control**

Advanced (including data-driven, model-free, AI, etc) and holistic multi-objective wind farm control optimizing overall performance.

- **Enable digital transformation in wind energy system O&M**

The abundance of available data requires big data analytics and applying real time testing and "digital twins" to be developed to recognize patterns and improve energy yield and control degradation.

- **Sensor systems and data analytics for health monitoring**

Robust, reliable, accurate and durable sensors need to be developed to monitor the condition and degradation of the most critical components and external conditions against lowest costs. Self-diagnostic systems and multi-sensor constructions may include remote sensing of external conditions and damage such as lidars, drones etc.

- **Robotics**

Remote and automated repair technology and strategy requires the development of sensor technology and robotic solutions. These should be tested in safe demonstration environments as well as in the dynamic wind turbine environment.

6. Fundamental Wind Energy Science

- **Research in the fundamental wind energy sciences is required to develop the research competences and the underpinning scientific knowledge to improve standards, methods and design solutions. Also models and experimental data are needed for complex sites and extreme climates, larger and relatively lighter turbines, more efficient wind farms and large-scale penetration in the energy system. The research leads to updated standardized design criteria and standardized methods for testing and validation.**
- Research gaps:
  - **Climate change and extreme** climate affect the design, performance and operation. The development in critical geo-physical condition in the future needs to be modelled and assessed.
  - **Atmospheric multi-scale flow from meso-scale to wind farm flows** i.e. accurate and validated model predicting properties of flow in complex terrain regions down to wind farm flow affected by wakes and turbine control.
  - **Physics of large rotor aerodynamics: inflow, blade and wake aerodynamic characterization** i.e. accurate model development for the flow around large blades including add-ons and active flow devices and wake models.
  - **High performance computing and digitalization** call for extensive research and testing to be fully applied and enable accurate and reliable solutions.
  - **Materials, including better knowledge of properties, new and improved materials and their degradation and failure mechanisms,** provide new opportunities for weight and cost reductions, higher reliability and improved manufacture of wind energy systems.
  - **System engineering models, including detailed fluid-structure, soil-structure and electro-mechanical interaction** needs development in order to allow optimal design and operation for reduced LCOE and system compliance

Key action areas

- **Efficient multi-disciplinary optimization and system engineering**

Optimisation of wind farm design requires a multi-disciplinary, system engineering approach including rotor, nacelle, tower, support structure, electrical infrastructure, soil, environment, markets and regulations and includes public acceptance as well as societal costs and benefits. Tools needs to be developed and matured, taking into account the complete lifecycle.

- **Multi-scale flow modelling**

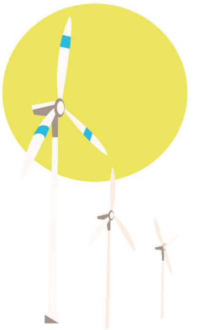
Multi-scale modelling using high fidelity and high-performance computing to provide accurate estimates for siting, control, performance and operation of wind farms as well as predictions of effects from climate change and extreme climates.

- **Large rotor aerodynamics**

Aerodynamic modelling at High Reynolds number, from high fidelity to engineering tools. Subsystem validation in wind tunnels and real-full scale wind turbine aerodynamic experiment measuring inflow, blade flow and the wake for model validation. This provides accurate power performance, loads and input for control.

- **Continued on next page**

6. Fundamental Wind Energy Science – Key action areas



Key action areas continued

- **Digitalization and data analytics**

New sensors, data processing, machine learning and data analytics and methods for implementation in data-driven design, digital twins, control and monitoring for O&M needs development for increased reliability and reduced costs in wind energy.

- **Materials science**

Better and more accurate knowledge of properties, behavior, degradation and damage mechanisms of materials as well as development of new materials or treatments to offer less conservative and more reliable designs needed for upscaling, cost reduction, circularity and lifetime extension. Material science is needed directed towards fracture mechanics, composite blades, structural elements, corrosive and erosive environment, mechanical and electrical components such as generators and magnets, subsea cables.

- **Construction and manufacturing**

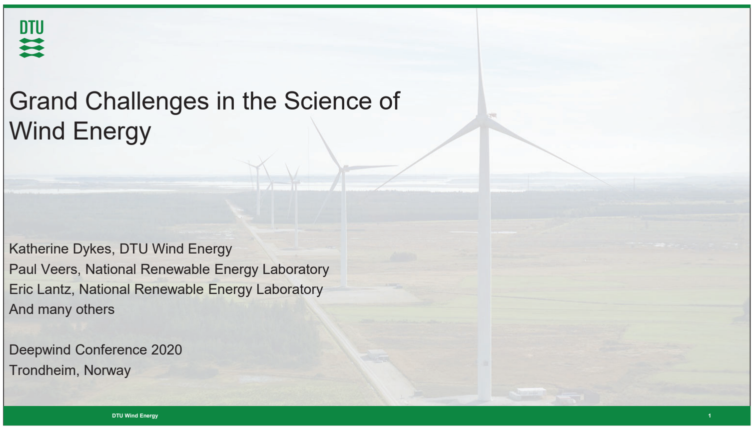
Relevant experiments need to be developed and implemented to create open access databases involving industry.

- **Open access database for research validation**

Remote and automated repair technology and strategy requires the development of sensor technology and robotic solutions. These should be tested in safe demonstration environments as well as in the dynamic wind turbine environment.

- **Integrated Multi fidelity system**

Global high fidelity system models provide insights in critical interaction between system components, i.e. for the drive train components and engineering tools offer total system optimization of wind energy plants, while being essential for the development of reduced order engineering design tools for technology and plant design.



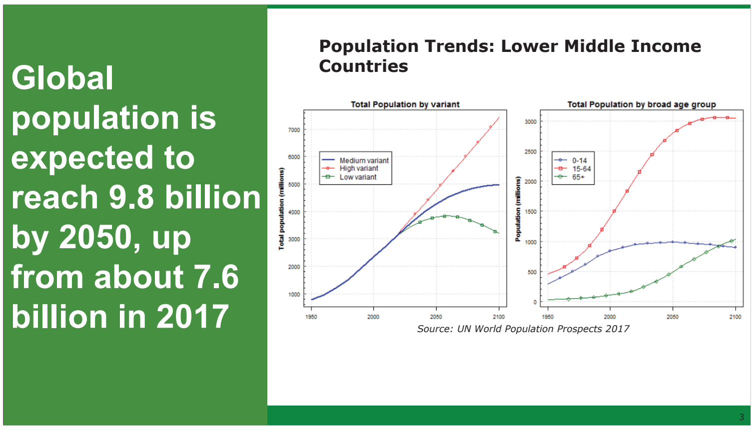
Grand Challenges in the Science of Wind Energy

Katherine Dykes, DTU Wind Energy
Paul Veers, National Renewable Energy Laboratory
Eric Lantz, National Renewable Energy Laboratory
And many others

Deepwind Conference 2020
Trondheim, Norway

Overview

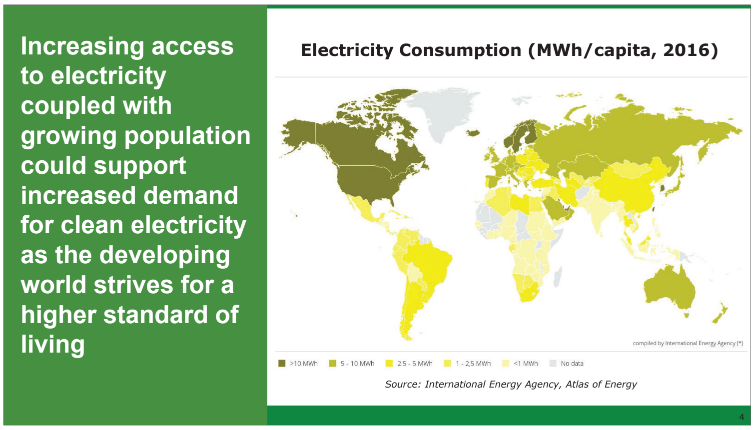
1 Global Trends and Energy Use
2 Changing Paradigms and Needs for Wind Energy
3 Grand Challenges in the Science of Wind Energy
4 Expertise to Achieve Success



Global population is expected to reach 9.8 billion by 2050, up from about 7.6 billion in 2017

Population Trends: Lower Middle Income Countries

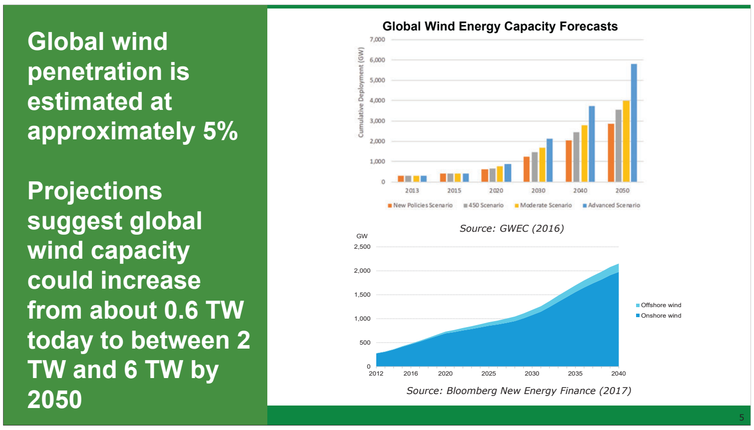
Source: UN World Population Prospects 2017



Increasing access to electricity coupled with growing population could support increased demand for clean electricity as the developing world strives for a higher standard of living

Electricity Consumption (MWh/capita, 2016)

Source: International Energy Agency, Atlas of Energy



Global wind penetration is estimated at approximately 5%

Projections suggest global wind capacity could increase from about 0.6 TW today to between 2 TW and 6 TW by 2050

Global Wind Energy Capacity Forecasts

Source: GWEC (2016)

Source: Bloomberg New Energy Finance (2017)

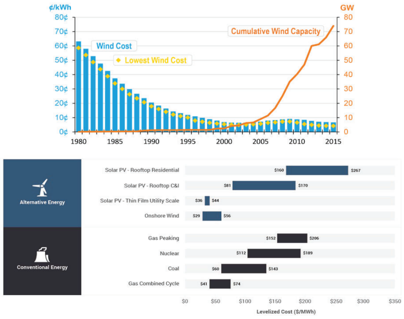
What will it take to achieve 50% or more of the global electricity supply?

IEA Wind TCP Topical Experts Meeting #89: A Grand Vision for Wind Energy

- **Purpose:** Explore the question of how to enable a future in which wind energy achieves its full potential as global energy resource
- **Participants:** Over 70 experts representing 15 different countries
- **Outcomes:** *Grand Challenges of Wind Energy Science*

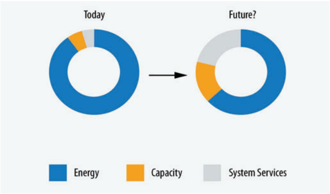
To Realize the Potential of the Resource, Costs Will Need to Continue to Fall

- Wind energy competitive in many places globally
- Costs of other technology (especially solar) also still falling



A Grand Vision for Renewables

- IEA Wind Grand Vision for Wind Energy explores a future scenario of 80% of the world electricity supply coming from renewables – a paradigm shift in system architecture, technologies and markets

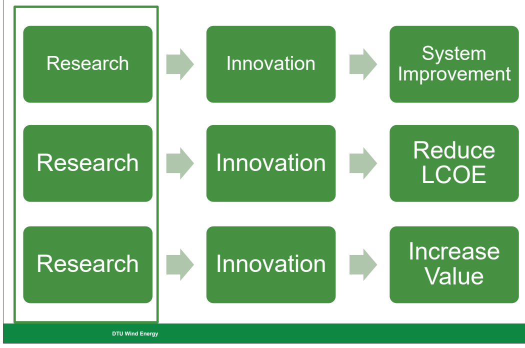


Future electricity system market structure (Source: Dykes et al 2019 based on Ahlstrom et al 2015)

Options for wind energy in a changing environment

- Success of wind energy in the future:
  - –If storage, power-to-x ubiquitous, highly elastic demand, then do nothing, focus on cheap electrons (**LCOE**)
  - –If dispatchability, capacity value dominate revenue, then rethink options and increase value of wind energy (**Beyond LCOE**)

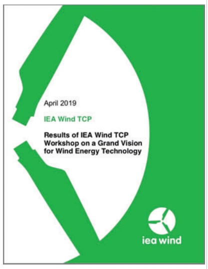
Realizing the future Grand Vision for Wind Energy



Research → Innovation → System Improvement

Research → Innovation → Reduce LCOE

Research → Innovation → Increase Value



April 2019

IEA Wind TCP

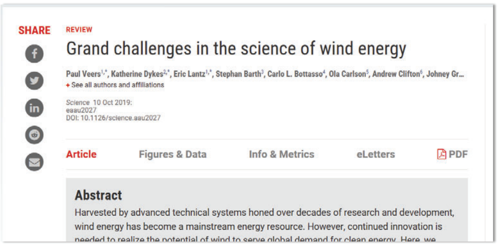
Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology

iea wind

The grand challenges in wind energy science and engineering to enable the wind-based future energy system

Realizing and Passing 6 TW Will Require New Fundamental Knowledge and Integration of Ideas across Several Domains

- The Grand Challenges of Wind Energy Science include:
  - –The **physics of atmospheric flow**, especially in the critical zone of wind power plant operation
  - –The **system dynamics and materials** of the largest, most flexible machines that have yet to be built
  - –**Optimization and control of fleets of wind plants** made up of hundreds of individual generators working **to support the electric grid**



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REVIEW

Grand challenges in the science of wind energy

Paul Veers[1,*], Katherine Dykes[2,*], Eric Lantz[1,*], Stephan Barth[3], Carlo L. Bottasso[4], Ola Carlson[5], Andrew Clifton[6], Johney Gr...

+ See all authors and affiliations

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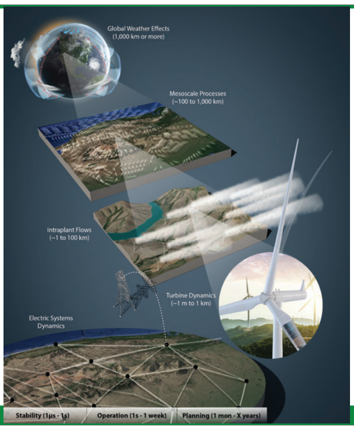
Abstract

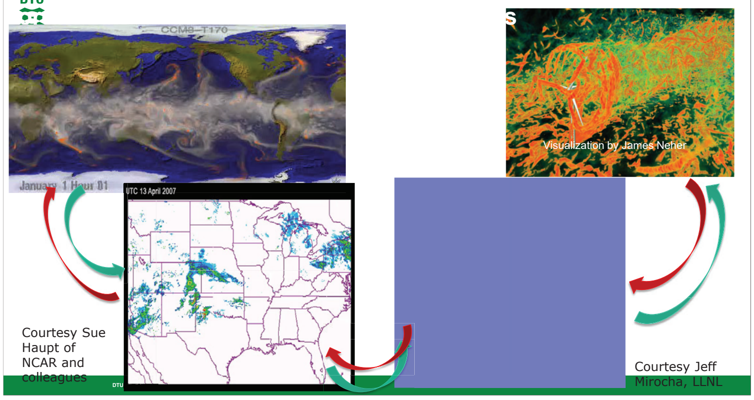
Harvested by advanced technical systems honed over decades of research and development, wind energy has become a mainstream energy resource. However, continued innovation is needed to realize the potential of wind to serve global demand for clean energy. Here, we

https://science.sciencemag.org/content/early/2019/10/09/science.aau2027

The Grand Challenges extend from the global weather system to the minutiae of materials science to sub-second power system stability



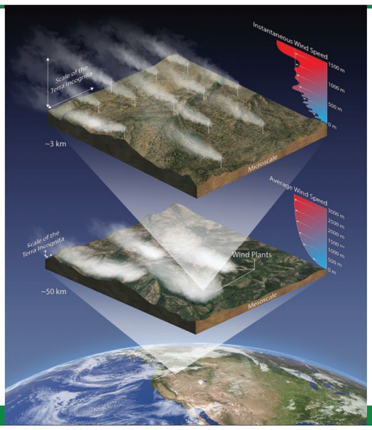
Source: NREL



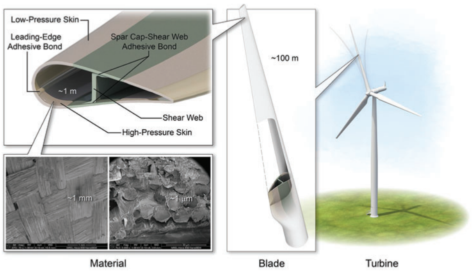
Courtesy Sue Haupt of NCAR and colleagues

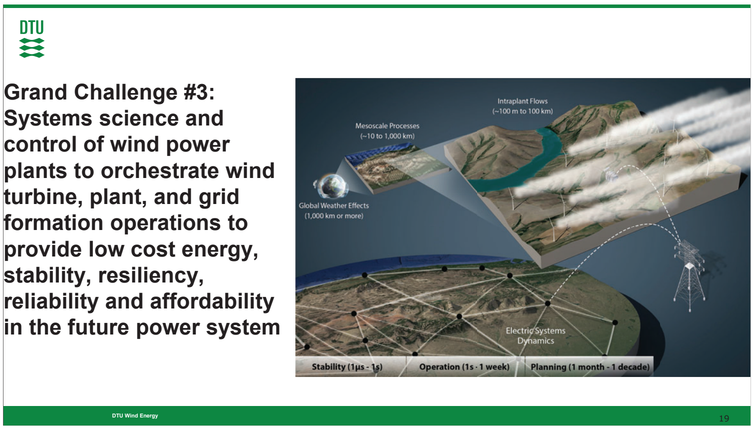
Courtesy Jeff Mirocha, LLNL

Grand Challenge #1: Mastering the physics of resource from the atmosphere to the intra-plant flows

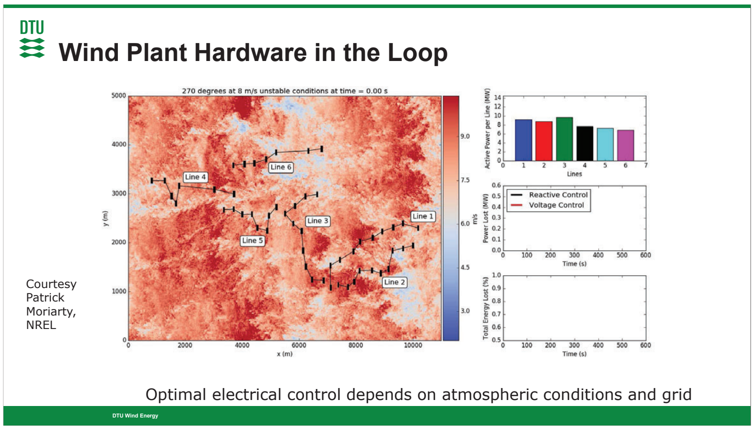


Grand Challenge #2: Characterizing the structural, aero and hydrodynamics of some of the largest standing structures ever built coupled with access to the most advanced material properties at commodity prices





Grand Challenge #3: Systems science and control of wind power plants to orchestrate wind turbine, plant, and grid formation operations to provide low cost energy, stability, resiliency, reliability and affordability in the future power system

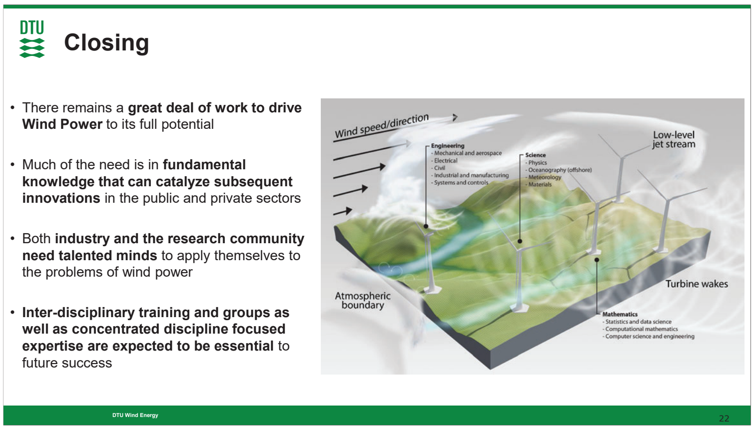


Wind Plant Hardware in the Loop

Courtesy
Patrick
Moriarty,
NREL

Optimal electrical control depends on atmospheric conditions and grid

The wind energy research and technology pathway forward



Closing

- There remains a **great deal of work to drive Wind Power** to its full potential
- Much of the need is in **fundamental knowledge that can catalyze subsequent innovations** in the public and private sectors
- Both **industry and the research community need talented minds** to apply themselves to the problems of wind power
- **Inter-disciplinary training and groups as well as concentrated discipline focused expertise are expected to be essential** to future success

Thank You

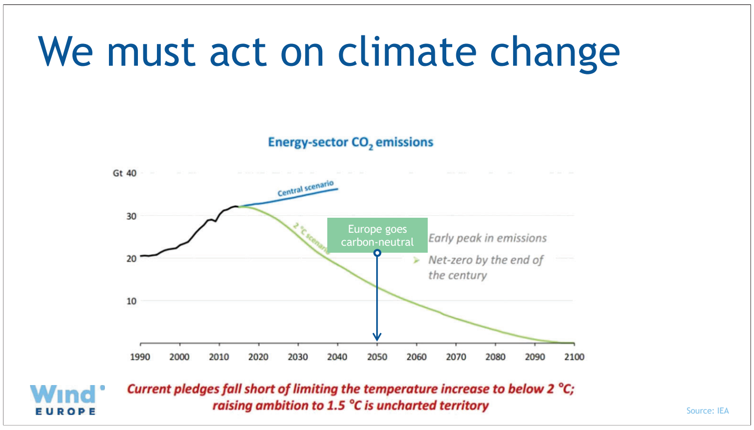
HOW OFFSHORE WIND WILL HELP EUROPE GO CARBON-NEUTRAL

Lizet Ramírez

Offshore Analyst, WindEurope

windeurope.org

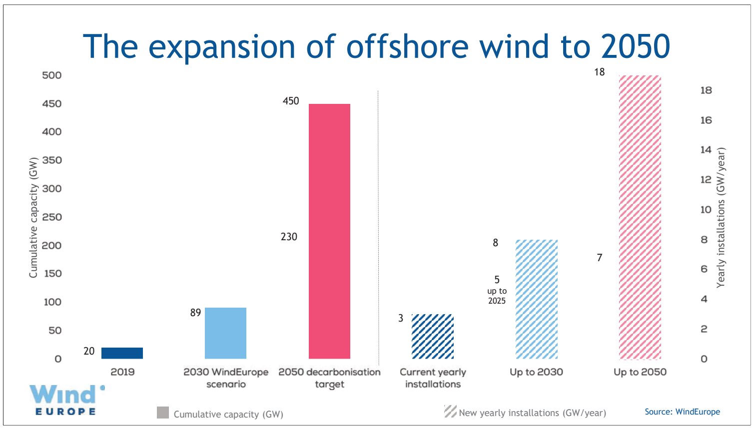
January 2020



We must act on climate change

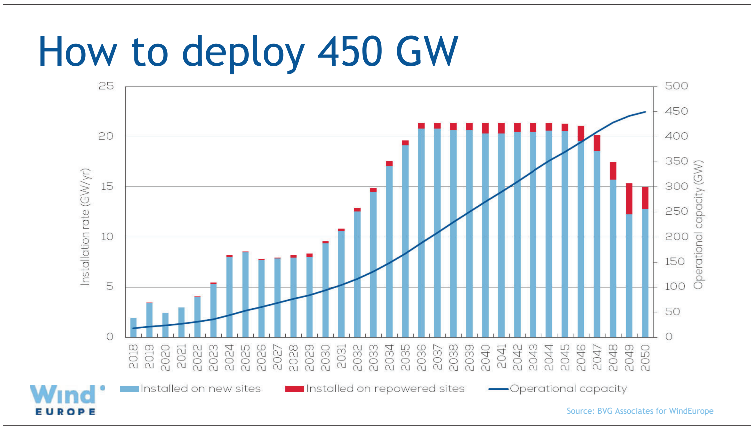
Current pledges fall short of limiting the temperature increase to below 2 °C; raising ambition to 1.5 °C is uncharted territory

Source: IEA



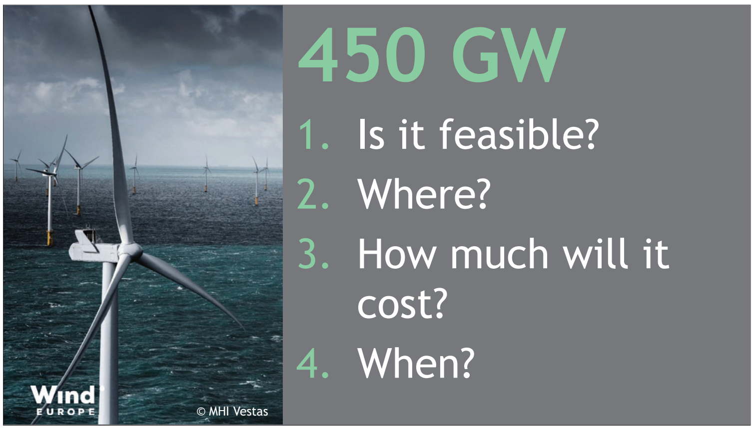
The expansion of offshore wind to 2050

Source: WindEurope



How to deploy 450 GW

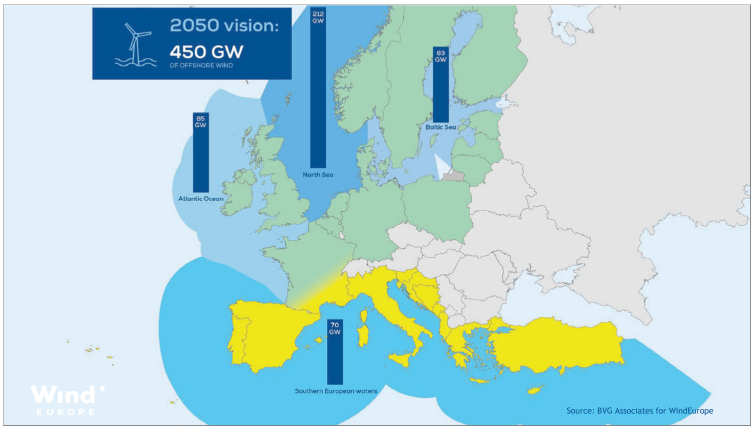
Source: BVG Associates for WindEurope



450 GW

1. Is it feasible?
2. Where?
3. How much will it cost?
4. When?

© MHI Vestas



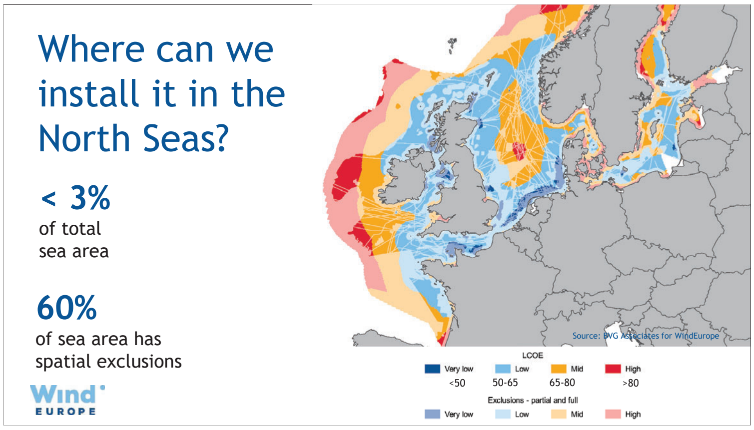
Source: BVG Associates for WindEurope

We can do it together

80 GW
60 GW
57 GW
36 GW
35 GW
30 GW
28 GW
22 GW
20 GW
15 GW
6 GW
4 GW
Rest of Mediterranean
31 GW
3 GW
1 GW
13 GW
9 GW

WindEurope

Source: BVG Associates for WindEurope

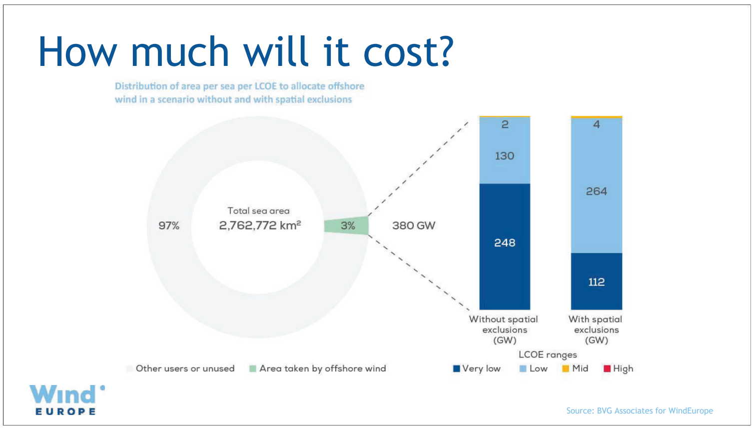


Where can we install it in the North Seas?

< 3%
of total
sea area

60%
of sea area has
spatial exclusions

WindEurope



How much will it cost?

Distribution of area per sea per LCOE to allocate offshore wind in a scenario without and with spatial exclusions

WindEurope

Source: BVG Associates for WindEurope

Happy coexistence

WindEurope

1. Get your maritime spatial planning right

2. Beef up your permitting authorities

3. Accelerate grid development -on and offshore

4. EU regulatory framework for hybrid projects

5. Electrify transport, heating and industry

6. Visibility on volumes and revenues

European Green Deal

> "I want Europe to strive for more by being the first climate-neutral continent"
>
> -Ursula von der Leyen

WindEurope

Wind
EUROPE

windeurope.or

WindEurope, Rue Belliard 40
1040 Brussels, Belgium

Introduction to the 1.2 GW Floating Offshore Wind Farm Project in the East Sea, Ulsan, Korea

Hyunkyoung SHIN
Trondheim, Norway
January 15, 2020

Convenor
IEC TC88 MT3-2 (for Revision of IEC 61400-3-2)

Professor
Department of Floating Offshore Wind Energy Generation Systems, Graduate School
School of Naval Architecture and Ocean Engineering, College of Engineering
University of Ulsan, KOREA

Outline

0. Introduction to the University of Ulsan, Ulsan, Korea
1. Why Offshore Wind ? Why FOWTs ?
2. Critical Needs for FOWTs in Korea
3. Floating Offshore Wind Farm Projects Planned in the East Sea, Korea
   - 3.1 Korea's RE 3020
   - 3.2 Ulsan Shin-Gori 750kW FOWT Pilot Project
   - 3.3 Plan of Floating Offshore Wind Farms in Ulsan
   - 3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)
   - 3.5 Comparison with Measured Data and Reanalysis Data

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0. Introduction to the University of Ulsan, Ulsan, Korea

Ulsan, KOREA

Wikipedia

Source : Explore Korea through Statistics 2018

Kim Yuna,
Figure skating Queen
Gold medalist,
at the Vancouver 2010 Winter Olympics
Silver medalist,
at the Sochi 2014 Winter Olympics

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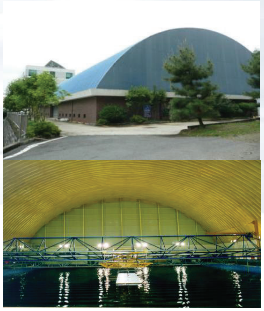
0. Introduction to the University of Ulsan, Ulsan, Korea

Floating Airport Model Test
Ocean Engineering Wide Tank, UOU, Korea



LxBxDxDw=30x20x3x2.5 m

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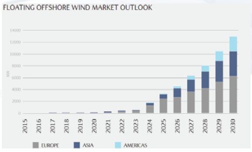
1. Why Offshore Wind ? Why FOWTs ?

Industry	Compound annual growth rate for GVA between 2010 and 2030	Total change in GVA between 2010 and 2030	Total change in employment between 2010 and 2030
Industrial marine aquaculture	5.69%	303%	152%
Industrial capture fisheries	4.10%	223%	94%
Industrial fish processing	6.26%	337%	206%
Maritime and coastal tourism	3.51%	199%	122%
Offshore oil and gas	1.17%	126%	126%
Offshore wind	24.52%	8 037%	1 257%
Port activities	4.58%	245%	245%
Shipbuilding and repair	2.93%	178%	124%
Maritime equipment	2.93%	178%	124%
Shipping	1.80%	143%	130%
Average of total ocean-based industries	**3.45%**	**197%**	**130%**
Global economy between 2010 and 2030	**3.64%**	**204%**	**120%[1]**

[1] Based on projections of the global workforce, extrapolated with the UN medium fertility rate.

Source: Authors' calculations based on OECD STAN, UNIDO INDSTAT, UNSD; Lloyd's Register Group (2014; 2013); World Bank (2013); IEA (2014); FAO (2015).



https://www.statoil.com/en/what-we-do/hywind-where-the-wind-takes-us.html

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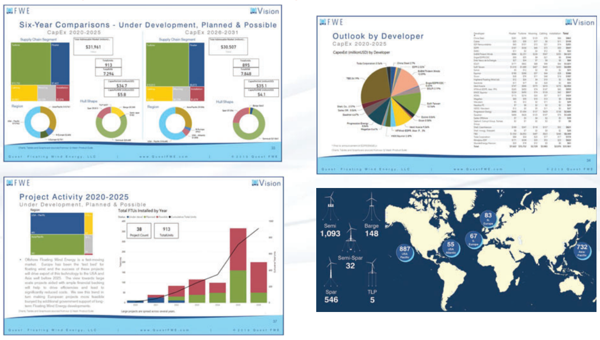
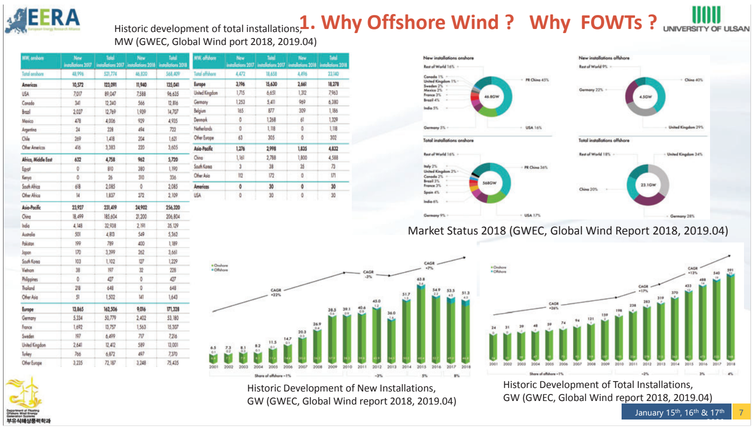
1. Why Offshore Wind ? Why FOWTs ?



Global Floating Wind Energy Market & Forecast 2019~2031
(Source : Quest Floating Wind Energy 2019)



1. Why Offshore Wind ? Why FOWTs ?

Historic development of total installations, MW (GWEC, Global Wind port 2018, 2019.04)

MW, onshore	New installations 2017	Total installations 2017	New installations 2018	Total installations 2018
Total onshore	48,996	521,774	46,820	568,409
Americas	**10,572**	**123,091**	**11,940**	**135,041**
USA	7,017	89,047	7,588	96,635
Canada	341	12,240	566	12,816
Brazil	2,027	12,769	1,939	14,707
Mexico	478	4,006	929	4,935
Argentina	24	228	494	722
Chile	269	1,418	204	1,621
Other Americas	416	3,383	220	3,605
Africa, Middle East	**632**	**4,758**	**962**	**5,720**
Egypt	0	810	380	1,190
Kenya	0	26	310	336
South Africa	618	2,085	0	2,085
Other Africa	14	1,837	272	2,109
Asia-Pacific	**23,927**	**231,419**	**24,902**	**256,320**
China	18,499	185,604	21,200	206,804
India	4,148	32,938	2,191	35,129
Australia	501	4,813	549	5,362
Pakistan	199	789	400	1,189
Japan	170	3,399	262	3,661
South Korea	103	1,102	127	1,229
Vietnam	38	197	32	228
Philippines	0	427	0	427
Thailand	218	648	0	648
Other Asia	51	1,502	141	1,643
Europe	**13,865**	**162,506**	**9,016**	**171,328**
Germany	5,334	50,779	2,402	53,180
France	1,692	13,757	1,563	15,307
Sweden	197	6,499	717	7,216
United Kingdom	2,641	12,412	589	13,001
Turkey	766	6,872	497	7,370
Other Europe	3,235	72,187	3,248	75,435

MW, offshore	New installations 2017	Total installations 2017	New installations 2018	Total installations 2018
Total offshore	4,472	18,658	4,496	23,140
Europe	**3,196**	**15,630**	**2,661**	**18,278**
United Kingdom	1,715	6,651	1,312	7,963
Germany	1,253	5,411	969	6,380
Belgium	165	877	309	1,186
Denmark	0	1,268	61	1,329
Netherlands	0	1,118	0	1,118
Other Europe	63	305	0	302
Asia-Pacific	**1,276**	**2,998**	**1,835**	**4,832**
China	1,161	2,788	1,800	4,588
South Korea	3	38	35	73
Other Asia	112	172	0	171
Americas	**0**	**30**	**0**	**30**
USA	0	30	0	30

Market Status 2018 (GWEC, Global Wind Report 2018, 2019.04)

Historic Development of New Installations, GW (GWEC, Global Wind report 2018, 2019.04)

Historic Development of Total Installations, GW (GWEC, Global Wind report 2018, 2019.04)

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2. Critical needs for FOWTS in Korea

- ◘Quantum Jump for Korea Wind Industry

  (System & Supply Chain: ~~HHI, SHI, DSME, STX,~~ Doosan, Hyosung, UNISON, Hanjin, etc.)
- ◘Jobs & the 4th Industrial Revolution
- ◘LCOE (6cent/kWh)
- ◘Energy Poverty in North Korea

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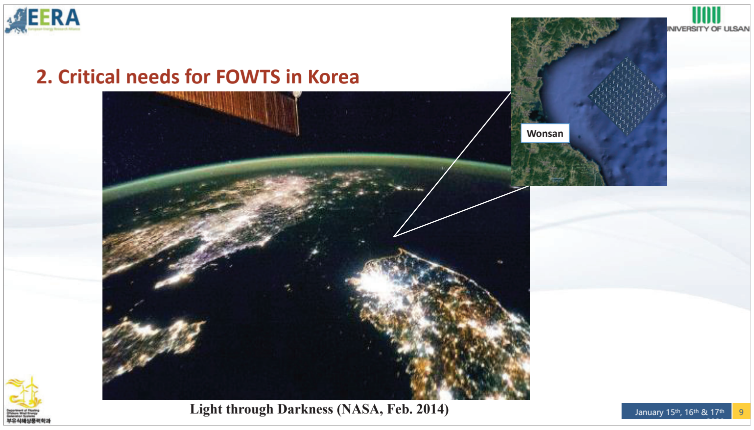

2. Critical needs for FOWTS in Korea

Light through Darkness (NASA, Feb. 2014)

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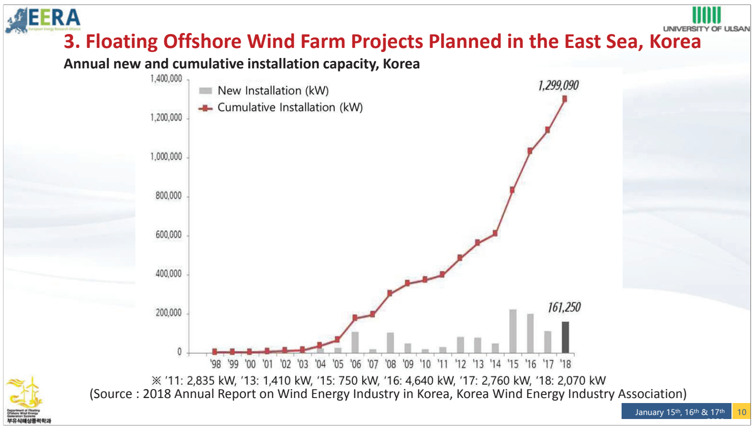

3. Floating Offshore Wind Farm Projects Planned in the East Sea, Korea

Annual new and cumulative installation capacity, Korea

※ '11: 2,835 kW, '13: 1,410 kW, '15: 750 kW, '16: 4,640 kW, '17: 2,760 kW, '18: 2,070 kW

(Source : 2018 Annual Report on Wind Energy Industry in Korea, Korea Wind Energy Industry Association)

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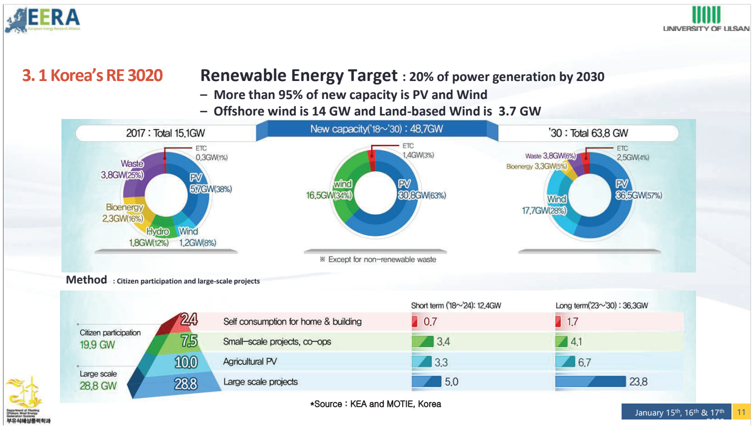

3. 1 Korea's RE 3020

Renewable Energy Target : 20% of power generation by 2030

- More than 95% of new capacity is PV and Wind
- Offshore wind is 14 GW and Land-based Wind is 3.7 GW

※ Except for non-renewable waste

Method : Citizen participation and large-scale projects

			Short term ('18~'24): 12.4GW	Long term('23~'30) : 36.3GW
Citizen participation 19.9 GW	2.4	Self consumption for home & building	0.7	1.7
	7.5	Small-scale projects, co-ops	3.4	4.1
Large scale 28.8 GW	10.0	Agricultural PV	3.3	6.7
	28.8	Large scale projects	5.0	23.8

*Source : KEA and MOTIE, Korea

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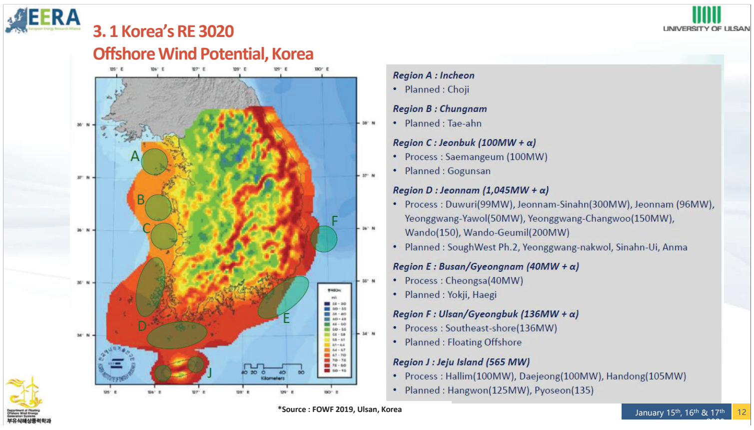

3. 1 Korea's RE 3020

Offshore Wind Potential, Korea

Region A : Incheon
- Planned : Choji

Region B : Chungnam
- Planned : Tae-ahn

Region C : Jeonbuk (100MW + α)
- Process : Saemangeum (100MW)
- Planned : Gogunsan

Region D : Jeonnam (1,045MW + α)
- Process : Duwuri(99MW), Jeonnam-Sinahn(300MW), Jeonnam (96MW), Yeonggwang-Yawol(50MW), Yeonggwang-Changwoo(150MW), Wando(150), Wando-Geumil(200MW)
- Planned : SoughWest Ph.2, Yeonggwang-nakwol, Sinahn-Ui, Anma

Region E : Busan/Gyeongnam (40MW + α)
- Process : Cheongsa(40MW)
- Planned : Yokji, Haegi

Region F : Ulsan/Gyeongbuk (136MW + α)
- Process : Southeast-shore(136MW)
- Planned : Floating Offshore

Region J : Jeju Island (565 MW)
- Process : Hallim(100MW), Daejeong(100MW), Handong(105MW)
- Planned : Hangwon(125MW), Pyoseon(135)

*Source : FOWF 2019, Ulsan, Korea

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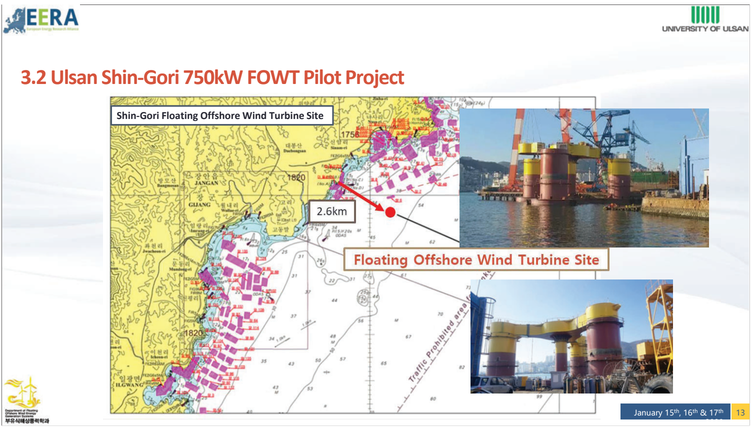
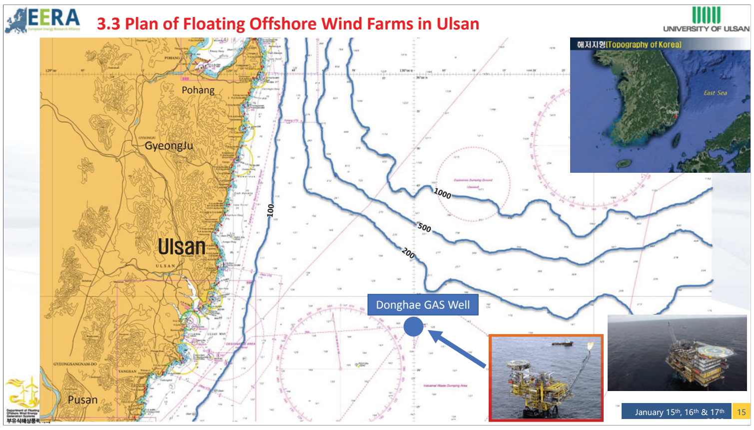


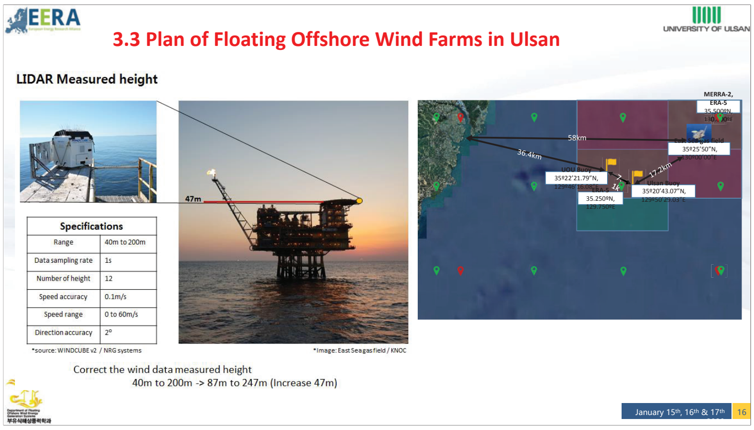
3.2 Ulsan Shin-Gori 750kW FOWT Pilot Project

3.2 Ulsan Shin-Gori 750kW FOWT Pilot Project

- Demonstration Project of a Pilot (750kW) Floating Offshore Wind Turbine in 50m deep



3.3 Plan of Floating Offshore Wind Farms in Ulsan



3.3 Plan of Floating Offshore Wind Farms in Ulsan

LIDAR Measured height

Specifications	
Range	40m to 200m
Data sampling rate	1s
Number of height	12
Speed accuracy	0.1m/s
Speed range	0 to 60m/s
Direction accuracy	2°

*source: WINDCUBE v2 / NRG systems

*Image: East Sea gas field / KNOC

Correct the wind data measured height
40m to 200m -> 87m to 247m (Increase 47m)

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

- Project Progress
- Supporting Technology, Research & Development
- Building Floating Offshore Wind Farm Roadmap
- Resolving Issue of Navy's Operation Area Overlapping
- Arbitrating between Developers and Fishermen
- Cooperating with Ministries to Amend Irrational or Excessive Regulations

- Plan and schedule
- Site selection, LIDAR deployment, Wind Turbine Conceptual Design (Jul 2018~2020)
- SPC Establishment, licenses acquisition, Financing, etc. (2021~2022)
- EPC of Floating Offshore Farm (2023~2024)
- Demonstration and Operation (2025~)
- Supporting Technology, Research & Development

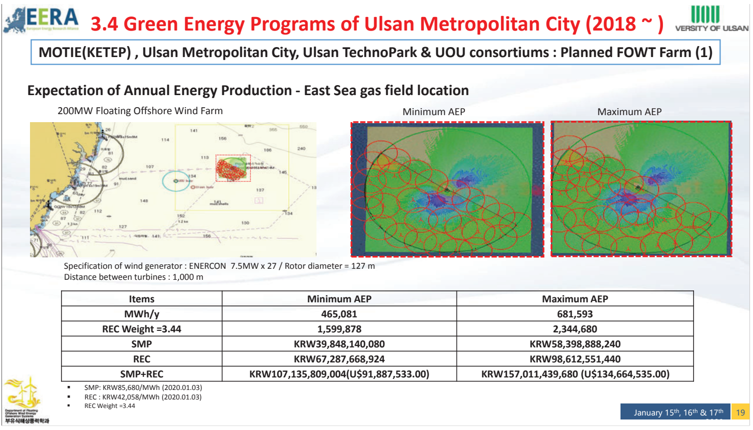
3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

EEZ off the coast, Ulsan, Korea is the best offshore for floating offshore farms

- Environmental conditions for Floating offshore wind farms
- Well-developed shipbuilding and offshore industry
- Grid accessibility
- Possible utilization of Donghae gas field infrastructure
- Public acceptance (EEZ)
- Lots of ports

o MOTIE(KETEP) , Ulsan Metropolitan City, Ulsan TechnoPark and UOU consortium : 200 MW
o KNOC consortium : 200 MW
o Five international consortiums

- CIP : 200 MW, Ulsan White Heron Project
- GIG : 200 MW, Project Gray Whale
- Shell : 200 MW, Donghae TwinWind Project
- EDPR, PPI, Aker : 200 MW, KFWind Project
- Equinor : 200 MW, Donghae 1 project
- NAVAL Energies : 200MW (?)



3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

MOTIE(KETEP) , Ulsan Metropolitan City, Ulsan TechnoPark & UOU consortiums : Planned FOWT Farm (1)

Expectation of Annual Energy Production - East Sea gas field location

200MW Floating Offshore Wind Farm

Minimum AEP

Maximum AEP

Specification of wind generator : ENERCON 7.5MW x 27 / Rotor diameter = 127 m
Distance between turbines : 1,000 m

Items	Minimum AEP	Maximum AEP
MWh/y	465,081	681,593
REC Weight =3.44	1,599,878	2,344,680
SMP	KRW39,848,140,080	KRW58,398,888,240
REC	KRW67,287,668,924	KRW98,612,551,440
SMP+REC	KRW107,135,809,004(U$91,887,533.00)	KRW157,011,439,680 (U$134,664,535.00)

- SMP: KRW85,680/MWh (2020.01.03)
- REC : KRW42,058/MWh (2020.01.03)
- REC Weight =3.44

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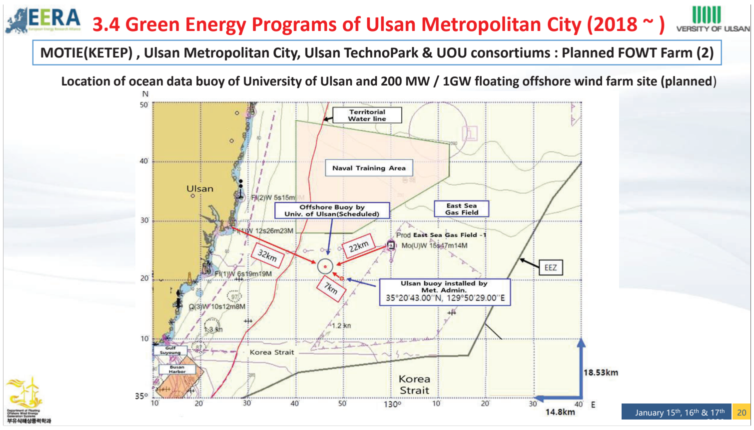

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

MOTIE(KETEP) , Ulsan Metropolitan City, Ulsan TechnoPark & UOU consortiums : Planned FOWT Farm (2)

Location of ocean data buoy of University of Ulsan and 200 MW / 1GW floating offshore wind farm site (planned)

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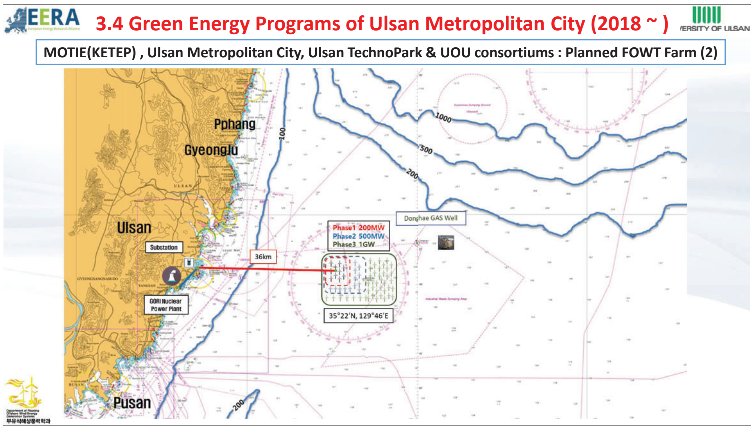
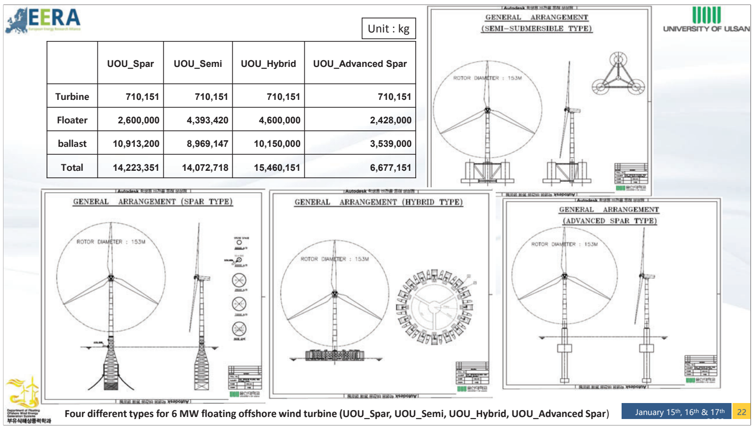


3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

MOTIE(KETEP) , Ulsan Metropolitan City, Ulsan TechnoPark & UOU consortiums : Planned FOWT Farm (2)



Unit : kg

	UOU_Spar	UOU_Semi	UOU_Hybrid	UOU_Advanced Spar
Turbine	710,151	710,151	710,151	710,151
Floater	2,600,000	4,393,420	4,600,000	2,428,000
ballast	10,913,200	8,969,147	10,150,000	3,539,000
Total	14,223,351	14,072,718	15,460,151	6,677,151

Four different types for 6 MW floating offshore wind turbine (UOU_Spar, UOU_Semi, UOU_Hybrid, UOU_Advanced Spar)

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3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

Five international consortiums

- Five international consortiums (CIP, Shell, GIG, EDP, Equinor) will take part in the project to build floating wind farms through cooperation with the city of Ulsan, South Korea.
- The city has been involved in green energy programs with government support.

*Source : Ulsan Metropolitan Government, Korea

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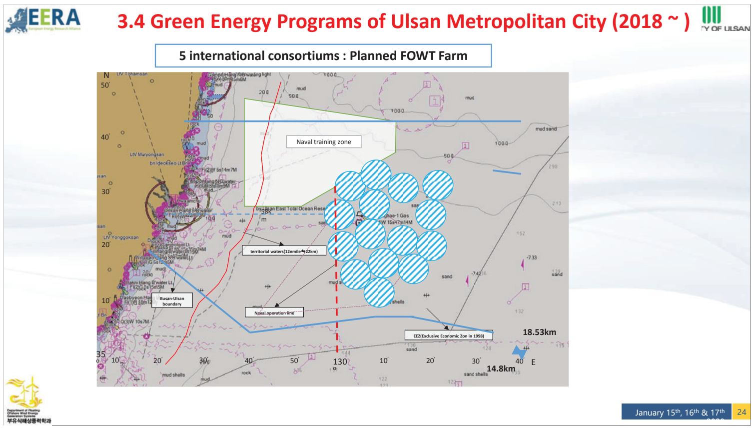

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

5 international consortiums : Planned FOWT Farm

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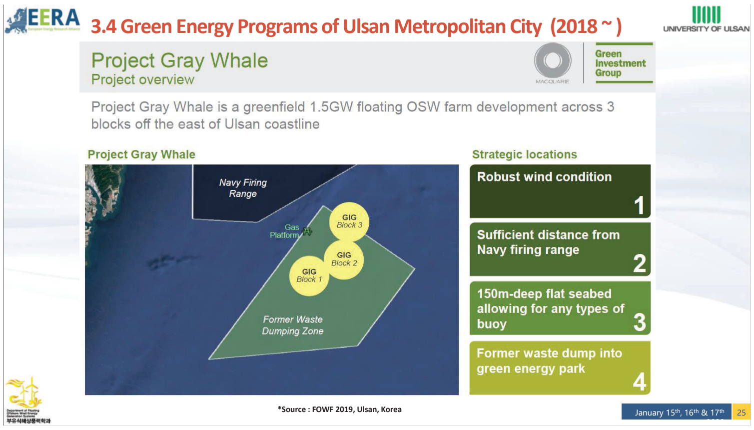

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

Project Gray Whale
Project overview

Project Gray Whale is a greenfield 1.5GW floating OSW farm development across 3 blocks off the east of Ulsan coastline

Project Gray Whale

Strategic locations

1. Robust wind condition
2. Sufficient distance from Navy firing range
3. 150m-deep flat seabed allowing for any types of buoy
4. Former waste dump into green energy park

*Source : FOWF 2019, Ulsan, Korea

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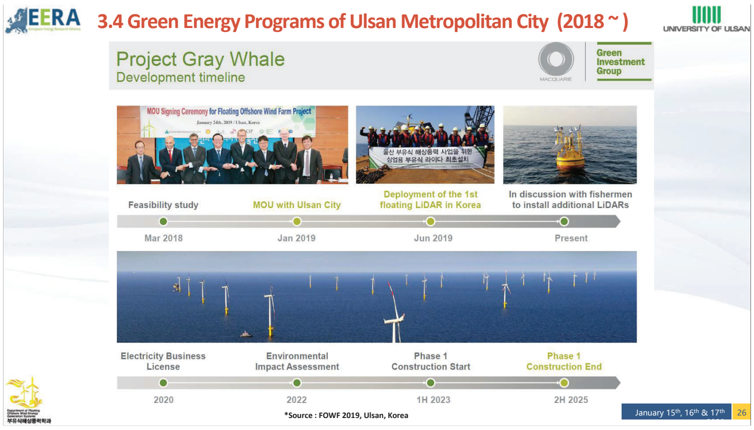

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

Project Gray Whale
Development timeline

Feasibility study	MOU with Ulsan City	Deployment of the 1st floating LiDAR in Korea	In discussion with fishermen to install additional LiDARs
Mar 2018	Jan 2019	Jun 2019	Present

Electricity Business License	Environmental Impact Assessment	Phase 1 Construction Start	Phase 1 Construction End
2020	2022	1H 2023	2H 2025

*Source : FOWF 2019, Ulsan, Korea

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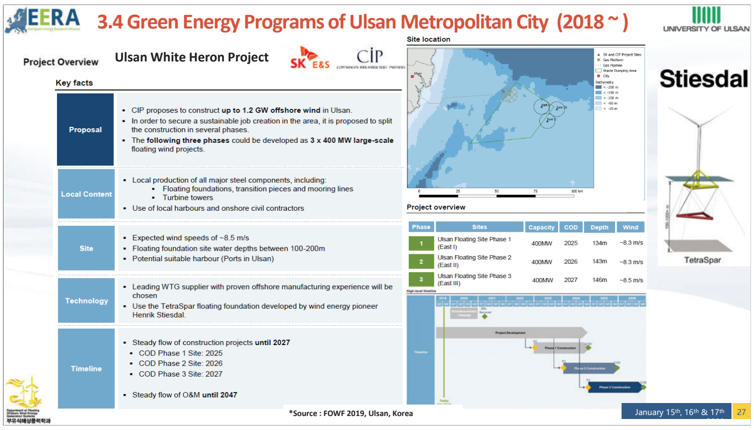

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

Project Overview **Ulsan White Heron Project**

Key facts

Proposal	▪ CIP proposes to construct **up to 1.2 GW offshore wind** in Ulsan. ▪ In order to secure a sustainable job creation in the area, it is proposed to split the construction in several phases. ▪ The **following three phases** could be developed as **3 x 400 MW large-scale** floating wind projects.

Local Content	▪ Local production of all major steel components, including:
	  ▪ Floating foundations, transition pieces and mooring lines
	  ▪ Turbine towers
	▪ Use of local harbours and onshore civil contractors

Site	▪ Expected wind speeds of ~8.5 m/s ▪ Floating foundation site water depths between 100-200m ▪ Potential suitable harbour (Ports in Ulsan)
Technology	▪ Leading WTG supplier with proven offshore manufacturing experience will be chosen ▪ Use the TetraSpar floating foundation developed by wind energy pioneer Henrik Stiesdal.

Timeline	▪ Steady flow of construction projects **until 2027**
	  ▪ COD Phase 1 Site: 2025
	  ▪ COD Phase 2 Site: 2026
	  ▪ COD Phase 3 Site: 2027
	▪ Steady flow of O&M **until 2047**

Site location

Project overview

Phase	Sites	Capacity	COD	Depth	Wind
1	Ulsan Floating Site Phase 1 (East I)	400MW	2025	134m	~8.3 m/s
2	Ulsan Floating Site Phase 2 (East II)	400MW	2026	143m	~8.3 m/s
3	Ulsan Floating Site Phase 3 (East III)	400MW	2027	146m	~8.5 m/s

High-level timeline

*Source : FOWF 2019, Ulsan, Korea

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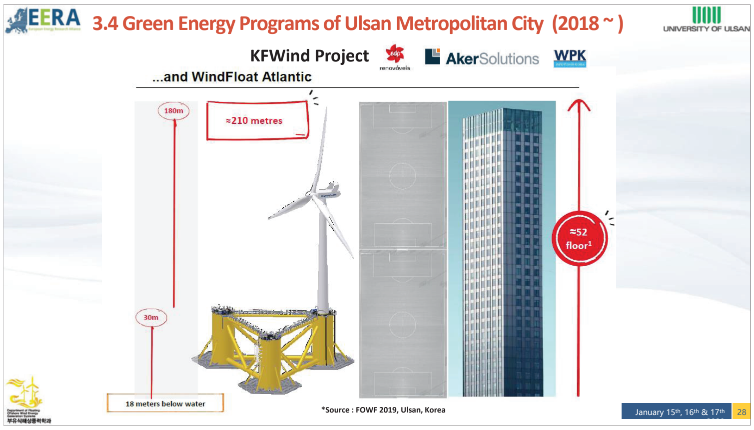

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

KFWind Project

...and WindFloat Atlantic

*Source : FOWF 2019, Ulsan, Korea

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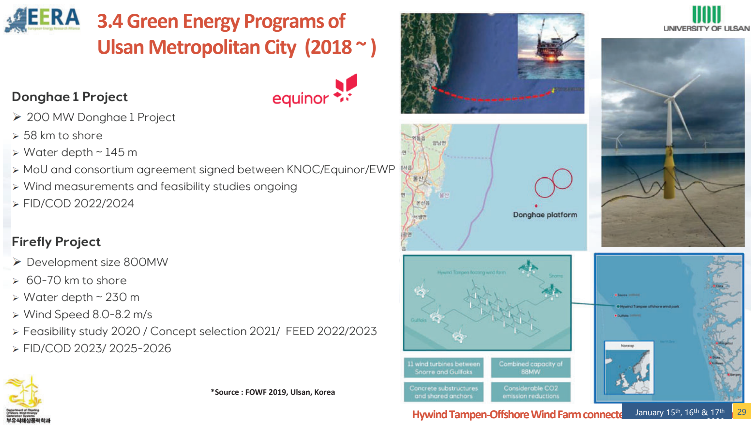

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

Donghae 1 Project

- 200 MW Donghae 1 Project
- 58 km to shore
- Water depth ~ 145 m
- MoU and consortium agreement signed between KNOC/Equinor/EWP
- Wind measurements and feasibility studies ongoing
- FID/COD 2022/2024

Firefly Project

- Development size 800MW
- 60-70 km to shore
- Water depth ~ 230 m
- Wind Speed 8.0-8.2 m/s
- Feasibility study 2020 / Concept selection 2021/ FEED 2022/2023
- FID/COD 2023/ 2025-2026

11 wind turbines between Snorre and Gullfaks

Combined capacity of 88MW

Concrete substructures and shared anchors

Considerable CO2 emission reductions

Hywind Tampen-Offshore Wind Farm connecte

*Source : FOWF 2019, Ulsan, Korea

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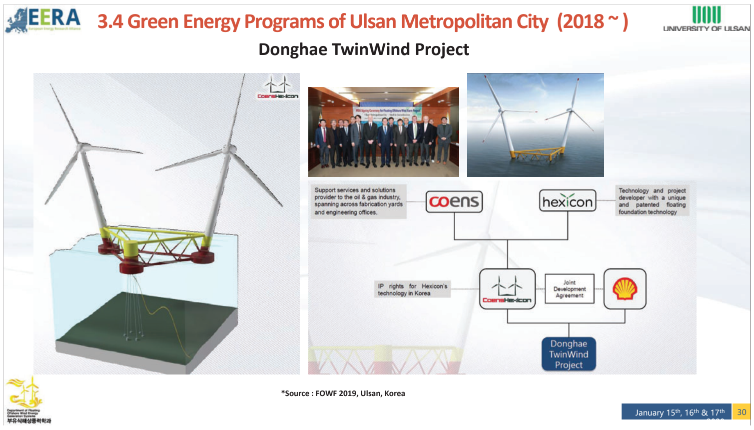

3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

Donghae TwinWind Project

Support services and solutions provider to the oil & gas industry, spanning across fabrication yards and engineering offices.

Technology and project developer with a unique and patented floating foundation technology

IP rights for Hexicon's technology in Korea

*Source : FOWF 2019, Ulsan, Korea

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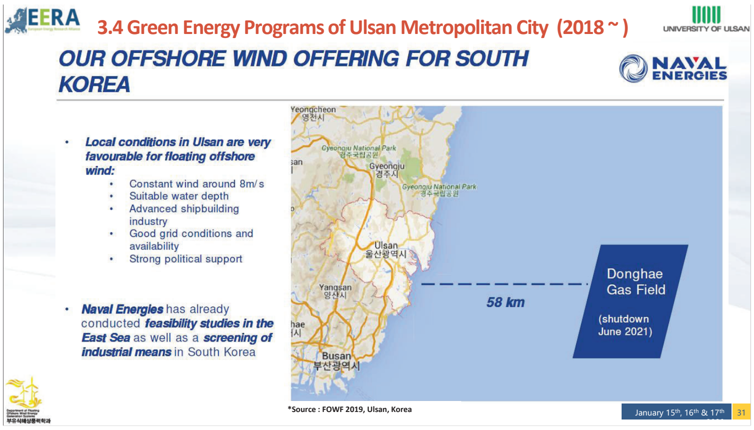
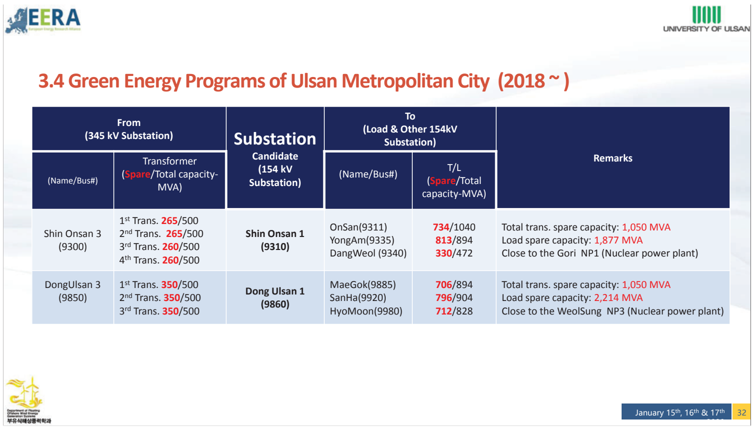


3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

OUR OFFSHORE WIND OFFERING FOR SOUTH KOREA

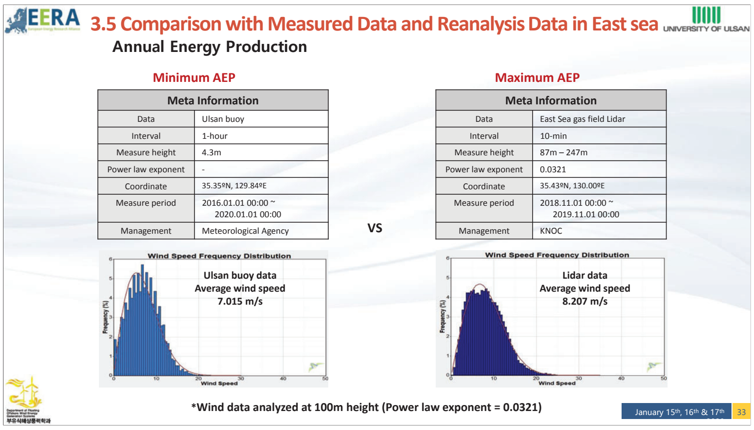
- ***Local conditions in Ulsan are very favourable for floating offshore wind:***
    - Constant wind around 8m/s
    - Suitable water depth
    - Advanced shipbuilding industry
    - Good grid conditions and availability
    - Strong political support
- ***Naval Energies*** has already conducted ***feasibility studies in the East Sea*** as well as a ***screening of industrial means*** in South Korea

*Source : FOWF 2019, Ulsan, Korea



3.4 Green Energy Programs of Ulsan Metropolitan City (2018 ~)

From (345 kV Substation)		Substation	To (Load & Other 154kV Substation)		Remarks
(Name/Bus#)	Transformer (Spare/Total capacity-MVA)	Candidate (154 kV Substation)	(Name/Bus#)	T/L (Spare/Total capacity-MVA)	
Shin Onsan 3 (9300)	1st Trans. **265**/500 2nd Trans. **265**/500 3rd Trans. **260**/500 4th Trans. **260**/500	**Shin Onsan 1 (9310)**	OnSan(9311) YongAm(9335) DangWeol (9340)	**734**/1040 **813**/894 **330**/472	Total trans. spare capacity: 1,050 MVA Load spare capacity: 1,877 MVA Close to the Gori NP1 (Nuclear power plant)
DongUlsan 3 (9850)	1st Trans. **350**/500 2nd Trans. **350**/500 3rd Trans. **350**/500	**Dong Ulsan 1 (9860)**	MaeGok(9885) SanHa(9920) HyoMoon(9980)	**706**/894 **796**/904 **712**/828	Total trans. spare capacity: 1,050 MVA Load spare capacity: 2,214 MVA Close to the WeolSung NP3 (Nuclear power plant)



3.5 Comparison with Measured Data and Reanalysis Data in East sea

Annual Energy Production

Minimum AEP

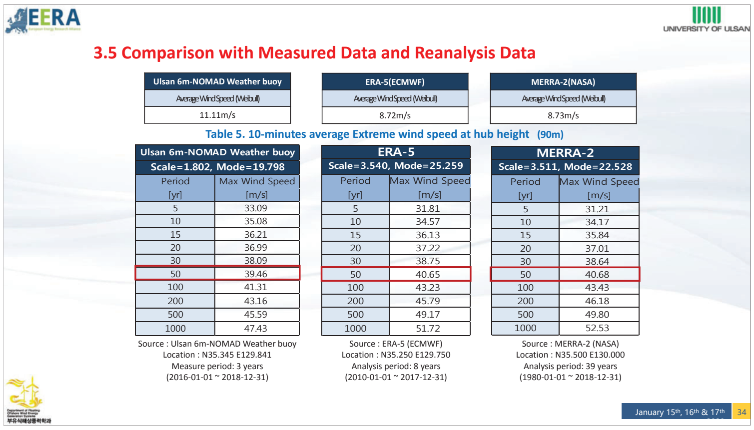
Meta Information	
Data	Ulsan buoy
Interval	1-hour
Measure height	4.3m
Power law exponent	-
Coordinate	35.35ºN, 129.84ºE
Measure period	2016.01.01 00:00 ~ 2020.01.01 00:00
Management	Meteorological Agency

VS

Maximum AEP

Meta Information	
Data	East Sea gas field Lidar
Interval	10-min
Measure height	87m – 247m
Power law exponent	0.0321
Coordinate	35.43ºN, 130.00ºE
Measure period	2018.11.01 00:00 ~ 2019.11.01 00:00
Management	KNOC

*Wind data analyzed at 100m height (Power law exponent = 0.0321)



3.5 Comparison with Measured Data and Reanalysis Data

Ulsan 6m-NOMAD Weather buoy
Average Wind Speed (Weibull)
11.11m/s

ERA-5(ECMWF)
Average Wind Speed (Weibull)
8.72m/s

MERRA-2(NASA)
Average Wind Speed (Weibull)
8.73m/s

Table 5. 10-minutes average Extreme wind speed at hub height (90m)

Ulsan 6m-NOMAD Weather buoy	
Scale=1.802, Mode=19.798	
Period [yr]	Max Wind Speed [m/s]
5	33.09
10	35.08
15	36.21
20	36.99
30	38.09
50	39.46
100	41.31
200	43.16
500	45.59
1000	47.43

Source : Ulsan 6m-NOMAD Weather buoy
Location : N35.345 E129.841
Measure period: 3 years
(2016-01-01 ~ 2018-12-31)

ERA-5	
Scale=3.540, Mode=25.259	
Period [yr]	Max Wind Speed [m/s]
5	31.81
10	34.57
15	36.13
20	37.22
30	38.75
50	40.65
100	43.23
200	45.79
500	49.17
1000	51.72

Source : ERA-5 (ECMWF)
Location : N35.250 E129.750
Analysis period: 8 years
(2010-01-01 ~ 2017-12-31)

MERRA-2	
Scale=3.511, Mode=22.528	
Period [yr]	Max Wind Speed [m/s]
5	31.21
10	34.17
15	35.84
20	37.01
30	38.64
50	40.68
100	43.43
200	46.18
500	49.80
1000	52.53

Source : MERRA-2 (NASA)
Location : N35.500 E130.000
Analysis period: 39 years
(1980-01-01 ~ 2018-12-31)

THANK YOU.

This project is being supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) and by the Ulsan Metropolitan Government, Korea. Also we deliver many thanks to the international developers and wind industries : Shell, CIP, GIG, EDPR, PPI, Aker, Equinor, KNOC, SK enc, Coens, HEXICON, Stiesdal, Ulsan Technopark, etc.

Offshore wind development in China

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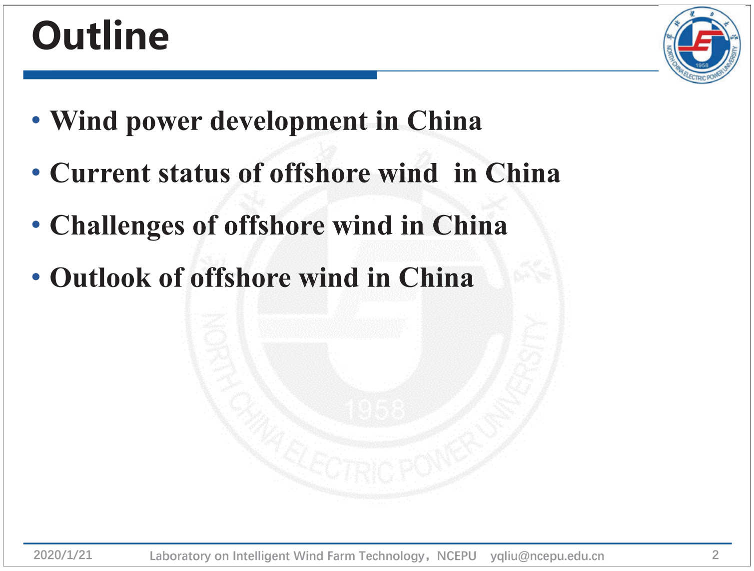
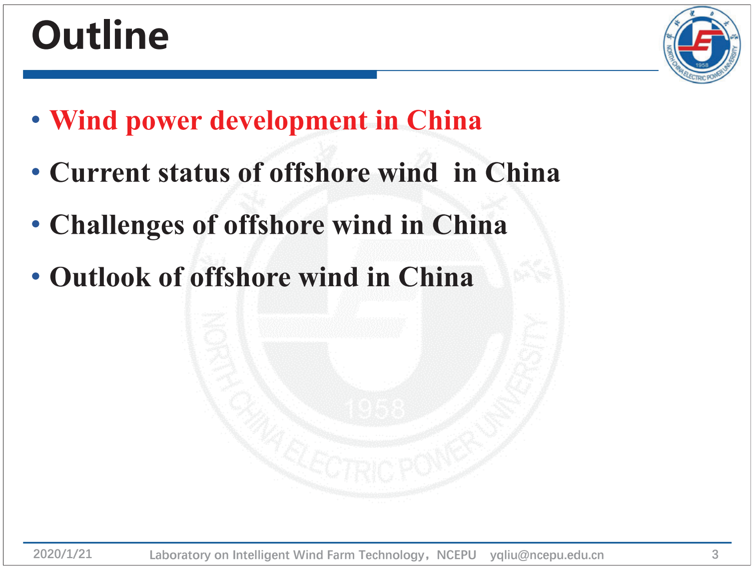


Outline

- Wind power development in China
- Current status of offshore wind in China
- Challenges of offshore wind in China
- Outlook of offshore wind in China



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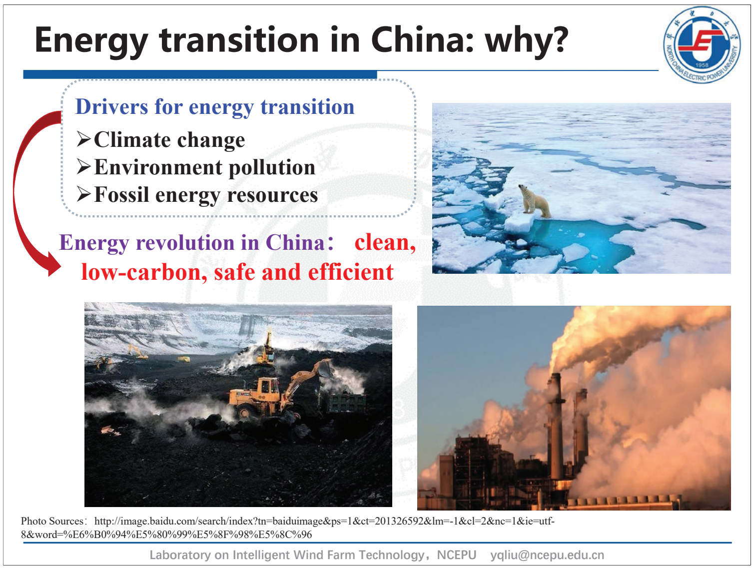
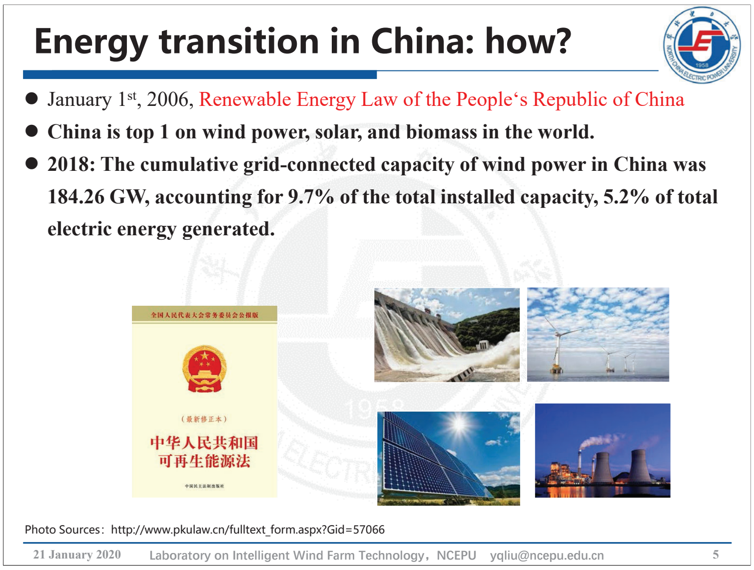


Energy transition in China: why?

Drivers for energy transition
➢Climate change
➢Environment pollution
➢Fossil energy resources

Energy revolution in China： clean, low-carbon, safe and efficient

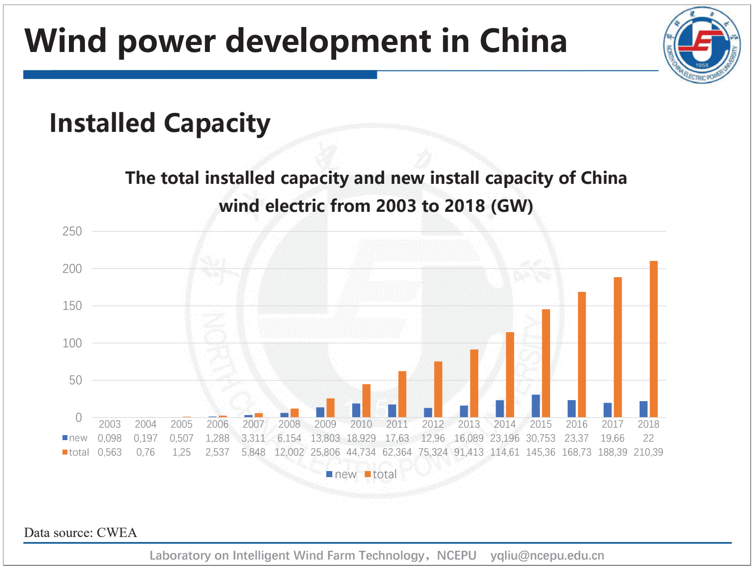
Photo Sources：http://image.baidu.com/search/index?tn=baiduimage&ps=1&ct=201326592&lm=-1&cl=2&nc=1&ie=utf-8&word=%E6%B0%94%E5%80%99%E5%8F%98%E5%8C%96



Energy transition in China: how?

- January 1st, 2006, Renewable Energy Law of the People's Republic of China
- China is top 1 on wind power, solar, and biomass in the world.
- 2018: The cumulative grid-connected capacity of wind power in China was 184.26 GW, accounting for 9.7% of the total installed capacity, 5.2% of total electric energy generated.

Photo Sources：http://www.pkulaw.cn/fulltext_form.aspx?Gid=57066



Wind power development in China

Installed Capacity

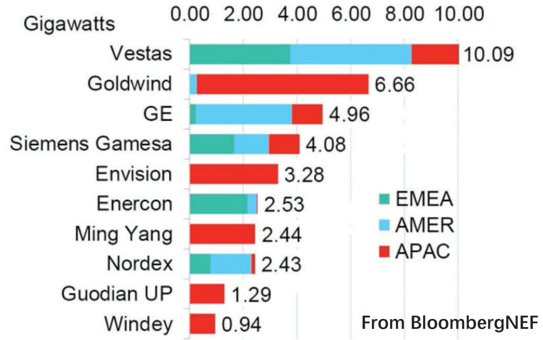
The total installed capacity and new install capacity of China wind electric from 2003 to 2018 (GW)

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
new	0,098	0,197	0,507	1,288	3,311	6,154	13,803	18,929	17,63	12,96	16,089	23,196	30,753	23,37	19,66	22
total	0,563	0,76	1,25	2,537	5,848	12,002	25,806	44,734	62,364	75,324	91,413	114,61	145,36	168,73	188,39	210,39

Data source: CWEA

Wind power development in China

- **2018: Manufacturers,** Newly installed capacity



From BloombergNEF

Outline

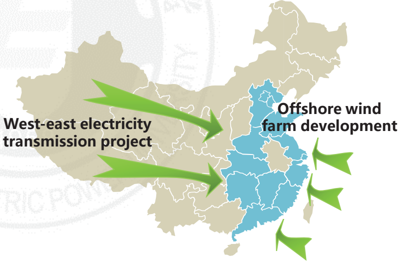
- Renewable energy development in China
- Current status of offshore wind in China
- Challenges of offshore wind in China
- Outlook of offshore wind in China

Why does China need offshore wind?

- **In 2030, the maximum electricity demand of eastern China will reach nearly 1000 GW, which cannot be fully supplied by local energy supply and West-east electricity transmission project.**
- **Offshore wind resources in China is abundant and close to the demand centers. Offshore wind will help China transform from the coal-based to renewable-based energy structure.**

	2018	2030	Incremental rate
Wind	1.8	5.4	3
Solar	1.7	4.2	2.5
Hydro	3.5	5.3	1.5
Nuclear	0.45	1.6	3.5
Thermal	11.4	12	1.05
Other	0.15	0.2	1.3
Total	19	28.7	1.5

Installed capacity (Unit: 100GW)



Data Sources: National Bureau of Statistics of China

Current status of offshore wind in China

◆ **Promote planning and increase the target**

- Planning: 74.72 GW
- Target in 2020: 6.6 GW

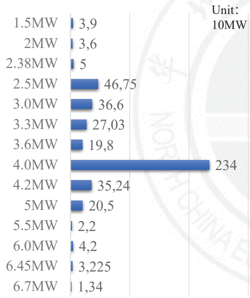
	Planning	Approval time	Grid connected target 2020	Grid connected capacity by Sep 2019
Jiangsu	14.75	2017	3.5	3.87
Fujian	13.30	2017	2.0	0.27
Shandong	12.75	2012	-	0
Guangdong	9.85	2018	0.3	0.10
Zhejiang	6.47	2016	0.3	0.25
Shanghai	6.15	2011	0.3	0.31
Hebei	5.60	2012	-	0
Hainan	3.95	2014	0.1	0
Liaoning	1.90	2013	-	0.15
Tianjin	-	-	0.1	0.09
Guangxi	-	-	-	-
Total	74.72	/	6.6	5.04

Data source: China Renewable Energy Engineering Institute

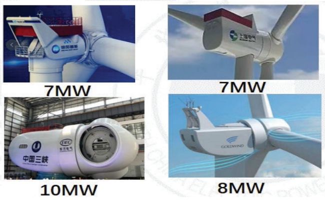
Current status of offshore wind in China

◆ **Manufacturing of large-scale offshore wind turbines**

- In 2018: 52.8% of wind turbines have the capacity of 4MW for offshore in China
- In 2019: 5MW and above units have become mainstream for offshore in China



5~6MW → **Commercial Operation**
7MW → **Prototype Installed**
8MW → **Produced**
10MW → **Under Development**



Current status of offshore wind in China

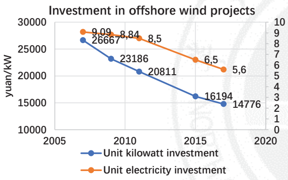
◆ **Advancement of design and construction capacity**

- **Breakthrough 1:** 110kV and 220kV offshore booster stations were successfully installed. At present, there are 18 offshore booster stations in China, and another 6 are under construction, and 2 offshore converter stations are under design.
- **Breakthrough 2:** The basic design capability of wind turbines have been continuously improved, and the anti-icing design and integrated design capabilities have been improved. More than 900 foundations of various types have been completed, of which more than 500 are non-transition single pile foundations. Negative pressure, gravity, and jacket foundations have been applied.

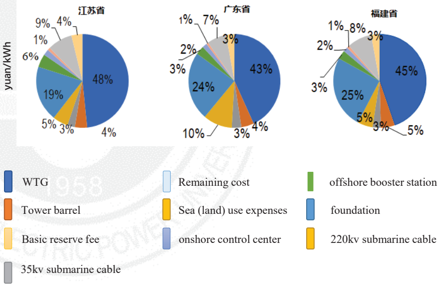
Current status of offshore wind in China

Construction costs are gradually reduced

- Through 10+ years , offshore wind investment per unit has gradually declined.
- The average cost of offshore wind power projects is around 15700 yuan / kW, mainly located in the seas of Jiangsu Province.



Province	Unit kW investment (yuan/kW)
Jiangsu	14,400-16,300
Zhejiang	15,600-16,500
Fujian	17,300-18,500
Guangdong	16,200-17,600



Current status of offshore wind in China

Industry & Acadamy

- 100+ of universities in China dedicates to the research and teaching on wind power, thousands of qualified wind power engineers have been cultivated.

NCEPU	SUT	THU	SJTU	BJTU	HHU	HEBUT
IMAU	IMAU	LUT	XJAU	NPU	NIT	CSUST
CSUST	ZJU	HUST	CQU	CSU	XJTU	NJU

Outline

- Wind power development in China
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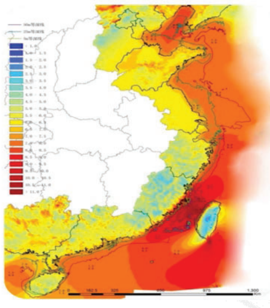
- Outlook of offshore wind in China

Challenges of offshore wind in China

China has 18000 km coastal line, average wind speed is around 7-8.5 m/s (90 m height), lower than in Europe.



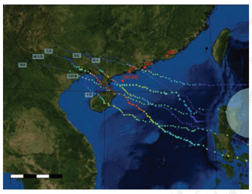
Offshore wind speed distribution for eastern China

Province	Average wind speed（90m m/s)	IEC wind class
Liaoning	6.5～7.3	III
Tianjin	6.9～7.5	III
Hebei	6.9～7.8	III
Shandong	6.7～7.5	III
Jiangsu	7.2～7.8	III～II
Shanghai	7.0～7.6	II～I
zhejiang	7.0～8.0	II～I+
Fujian	7.5～10	I～I+
Guangdong	6.5～8.5	I～I+

Data Sources: IEA report 2011

Challenges of offshore wind in China

Super typhoons are prevalent in east coast of China



Trajectories of Typhoon along east coast of China

Name	Time	Level	Wind speed (m/s)
Rammasun	Jul.	17	60
Kalmaegi	Sep.	13	40
Mujigae	Oct.	15	50
Sarika	Oct.	14	45
Hato	Aug.	15	48
Pakhar	Aug.	12	33
Khanun	Oct.	14	42
Mangkhut	Sep.	15	48

Source：BNEF, 2018

Challenges of offshore wind in China

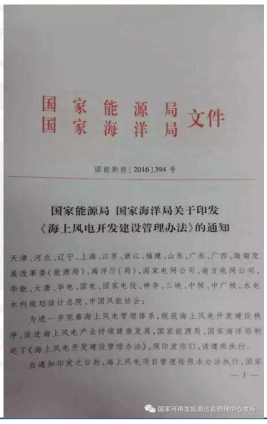
Environmental constraints tightening, near sea is very crowded

Tightening ecological constraints

- 《Coastline protection and utilization management methods》: Strictly restrict construction projects from occupying natural shorelines;
- 《 Measures for the development and construction of offshore wind power 》

Large demand of new sea use

- Fishery use
- Industrial use,
- Transportation use,
- Land use
- Engineering use.



国　家　能　源　局
国　家　海　洋　局　文件

国能新能〔2016〕394 号

国家能源局 国家海洋局关于印发
《海上风电开发建设管理办法》的通知

天津、河北、辽宁、上海、江苏、浙江、福建、山东、广东、广西、海南发展改革委（能源局）、海洋厅（局），国家电网公司、南方电网公司，华能、大唐、华电、国电、国家电投、神华、三峡、中核、中广核，水电水利规划设计总院，中国风能协会：

为进一步完善海上风电管理体系，规范海上风电开发建设秩序，促进海上风电产业持续健康发展，国家能源局、国家海洋局制定了《海上风电开发建设管理办法》，现印发你们，请遵照执行。

自通知印发之日起，海上风电项目管理按照本办法执行，国家

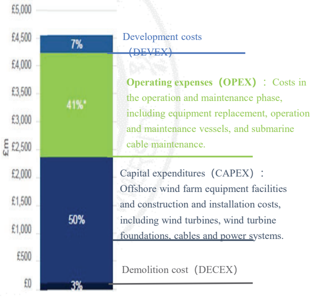
— 1 —

国家可再生能源信息管理中心发布

Challenges of offshore wind in China

Advanced operation and maintenance technologies are needed

- Lack of operation and maintenance experience
- O&M standards needed



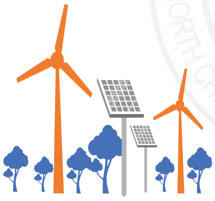
The life cycle cost of a typical 1 GW offshore wind farm

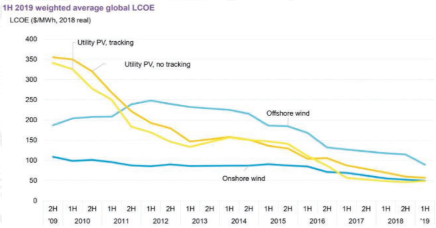
Challenges of offshore wind in China

Decreasing of the Feed-in Tariff

- Competitive pressure, such as UHV transmission channels, local distributed photovoltaics and onshore wind power.
- Reduction and the call off the offshore wind subsidies in China

After 2021: Stop subsidies





Comparison of offshore-wind price with other energy resources

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Outline

- **Wind power development in China**
- **Current status of offshore wind in China**
- **Challenges of offshore wind in China**
- **Outlook of offshore wind in China**

Outlook of offshore wind in China

- **Industry:**
  - Short-term: without subsidies, industrial restructuring;
  - Long-term: high demand, high speed development;
- **Technologies:**
  - Larger wind turbines
  - Smart operation and maintenance
  - deep sea floating wind turbine
- **Industrial policy**
  - Provincial level policies will be issued

Source : GE 2025 White Paper on China's Wind Power Generation Cost

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North China Electric Power University

- Largest energy and electric power university in China: 36,396 students, most of them study energy and electric power related majors
- First undergraduate major of Wind Energy and Power Engineering (from 2006)
- First Renewable Energy school in China (from 2007)
- State key laboratory of alternate electric power system with renewable energy sources

Wind Power Research Center

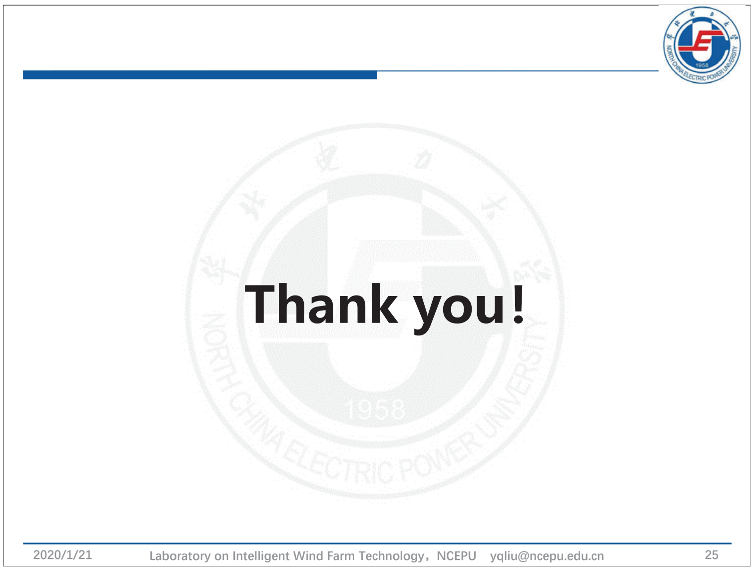
Wind Power Technologies

Efficient wind turbine technologies

- Wind turbine blade design
- Integrated design of wind turbine
- Wind turbine Intelligent control
- Offshore wind turbines

Intelligent wind farm technologies

- Wind Farm Design
- Intelligent control of wind farms
- Intelligent maintenance of wind farms
- Operation of new energy power systems



Thank you!

2020/1/21 Laboratory on Intelligent Wind Farm Technology，NCEPU yqliu@ncepu.edu.cn 25

ETIP Wind
EUROPEAN TECHNOLOGY & INNOVATION
PLATFORM ON WIND ENERGY

Research and Innovation & driving Global offshore

January 2020

etipwind.eu

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Aidan Cronin
Executive Committee chair

This presentation is meant for debate only and does not purport to reflect the precise opinions, plans or strategies of any ETIPWind member.

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Agenda

1. ETIPWind?
2. Where is Offshore Wind heading to in Europe?
3. EU Research & Innovation Offshore Wind
4. Global offshore wind - perspectives

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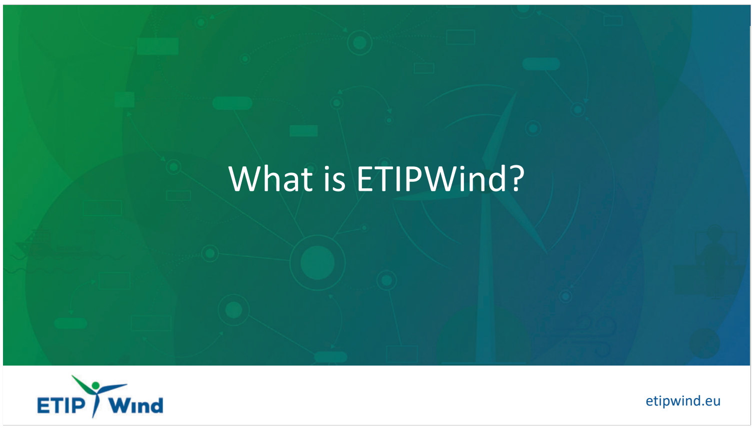

What is ETIPWind?

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OUR OBJECTIVES

Reduce costs

Facilitate system integration

Reinforce European technological leadership

Ensure first-class human resources

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Outlook on Offshore Wind in Europe

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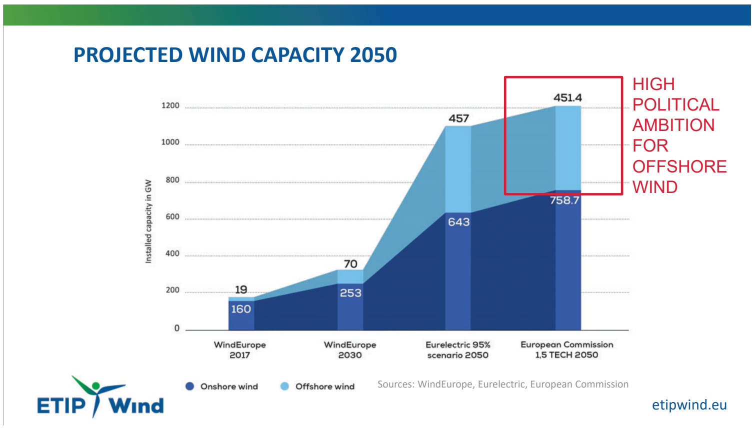

PROJECTED WIND CAPACITY 2050

HIGH POLITICAL AMBITION FOR OFFSHORE WIND

Sources: WindEurope, Eurelectric, European Commission

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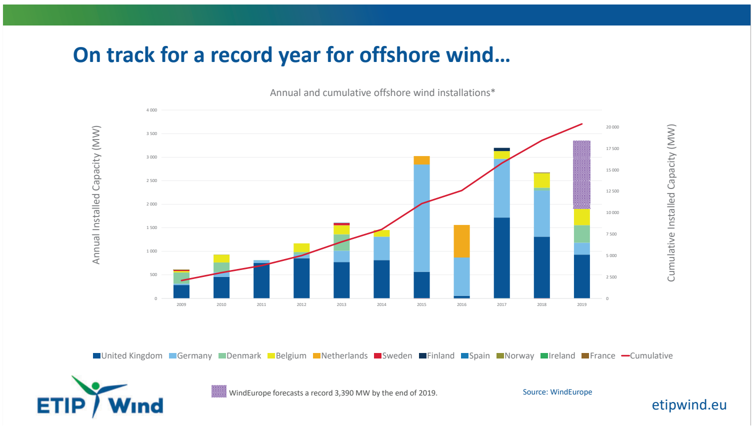

On track for a record year for offshore wind…

Annual and cumulative offshore wind installations*

▨ WindEurope forecasts a record 3,390 MW by the end of 2019.

Source: WindEurope

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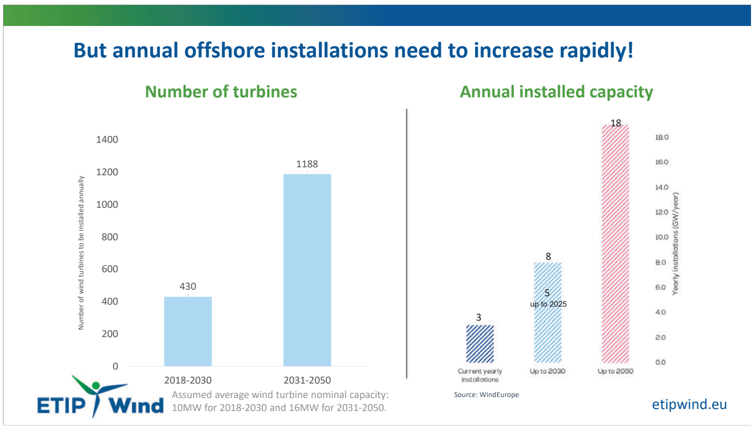

But annual offshore installations need to increase rapidly!

Number of turbines

Assumed average wind turbine nominal capacity: 10MW for 2018-2030 and 16MW for 2031-2050.

Annual installed capacity

Source: WindEurope

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ETIPwind view on Research & Innovation needed to realise Offshore Wind potential

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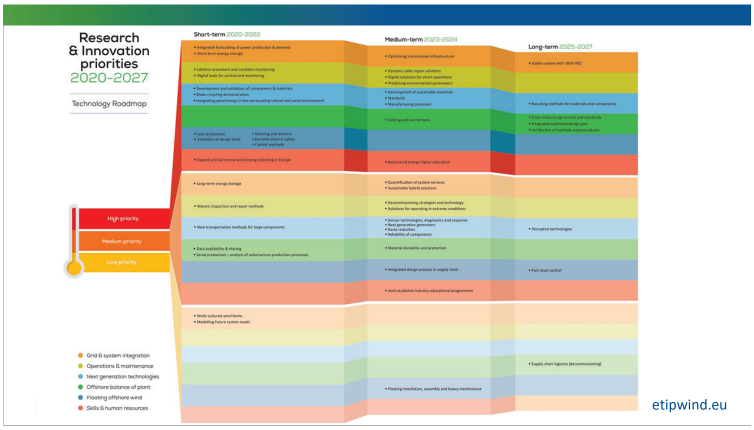

Research & Innovation priorities 2020-2027

Technology Roadmap

Short-term 2020-2022

- Integrated forecasting of power production & demand
- Short-term energy storage
- Lifetime assesment and condition monitoring
- Digital tools for control and monitoring
- Development and validation of components & materials
- Blade recycling demonstration
- Integrating wind energy in the surrounding natural and social environment
- Lean production
- Validation of design tools
- Mooring and anchors
- Dynamic electric cables
- Control methods
- Expand and harmonise wind energy teaching in Europe
- Long-term energy storage
- Robotic inspection and repair methods
- New transportation methods for large components
- Data availability & sharing
- Serial production – analysis of substructure production processes
- Multi-cultured wind farms
- Modelling future system needs

Medium-term 2023-2024

- Optimising transmission infrastructure
- Dynamic cable repair solutions
- Digital solutions for smart operations
- Predicting environmental parameters
- Development of sustainable materials
- Standards
- Manufacturing processes
- Cabling and connections
- Boost wind energy higher education
- Quantification of system services
- Sustainable hybrid solutions
- Decommissioning strategies and technology
- Solutions for operating in extreme conditions
- Sensor technologies, diagnostics and response
- Next generation generators
- Noise reduction
- Reliability of components
- Material durability and protection
- Integrated design process in supply chain
- Joint academia-industry educational programmes
- Floating installation, assembly and heavy maintenance

Long-term 2025-2027

- Stable system with 100% RES
- Recycling methods for materials and components
- Cross-industry agreement and standards
- Integrated optimised design plan
- Verification of methods and procedures
- Disruptive technologies
- Park level control
- Supply chain logistics (decommissioning)

● Grid & system integration
● Operations & maintenance
● Next generation technologies
● Offshore balance of plant
● Floating offshore wind
● Skills & human resources

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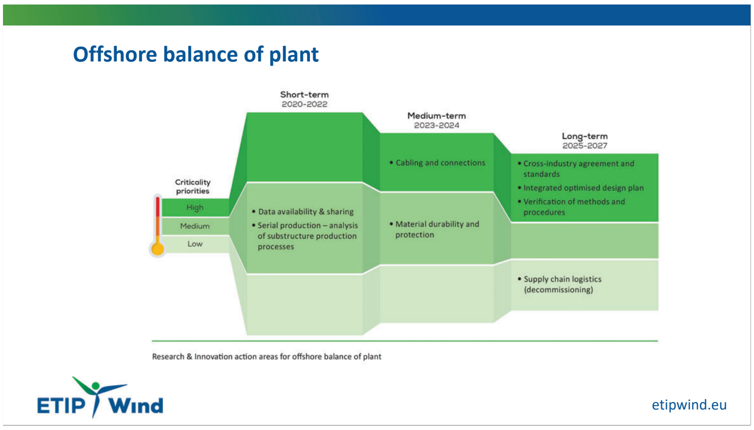

Offshore balance of plant

Short-term 2020-2022

- Data availability & sharing
- Serial production – analysis of substructure production processes

Medium-term 2023-2024

- Cabling and connections
- Material durability and protection

Long-term 2025-2027

- Cross-industry agreement and standards
- Integrated optimised design plan
- Verification of methods and procedures
- Supply chain logistics (decommissioning)

Research & Innovation action areas for offshore balance of plant

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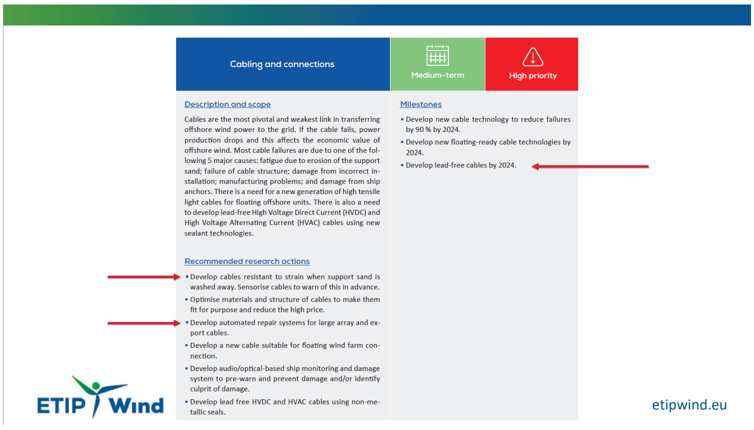

Cabling and connections | Medium-term | High priority

Description and scope

Cables are the most pivotal and weakest link in transferring offshore wind power to the grid. If the cable fails, power production drops and this affects the economic value of offshore wind. Most cable failures are due to one of the following 5 major causes: fatigue due to erosion of the support sand; failure of cable structure; damage from incorrect installation; manufacturing problems; and damage from ship anchors. There is a need for a new generation of high tensile light cables for floating offshore units. There is also a need to develop lead-free High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC) cables using new sealant technologies.

Recommended research actions

- Develop cables resistant to strain when support sand is washed away. Sensorise cables to warn of this in advance.
- Optimise materials and structure of cables to make them fit for purpose and reduce the high price.
- Develop automated repair systems for large array and export cables.
- Develop a new cable suitable for floating wind farm connection.
- Develop audio/optical-based ship monitoring and damage system to pre-warn and prevent damage and/or identify culprit of damage.
- Develop lead free HVDC and HVAC cables using non-metallic seals.

Milestones

- Develop new cable technology to reduce failures by 90 % by 2024.
- Develop new floating-ready cable technologies by 2024.
- Develop lead-free cables by 2024.

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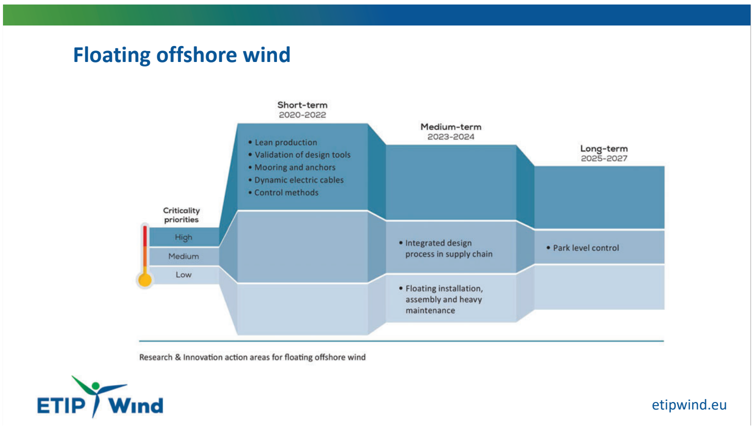

Floating offshore wind

Research & Innovation action areas for floating offshore wind

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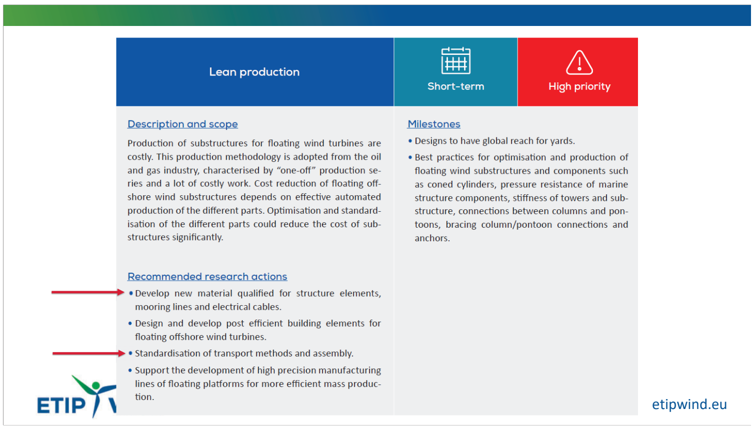

Lean production | Short-term | High priority

Description and scope

Production of substructures for floating wind turbines are costly. This production methodology is adopted from the oil and gas industry, characterised by "one-off" production series and a lot of costly work. Cost reduction of floating offshore wind substructures depends on effective automated production of the different parts. Optimisation and standardisation of the different parts could reduce the cost of substructures significantly.

Recommended research actions

- Develop new material qualified for structure elements, mooring lines and electrical cables.
- Design and develop post efficient building elements for floating offshore wind turbines.
- Standardisation of transport methods and assembly.
- Support the development of high precision manufacturing lines of floating platforms for more efficient mass production.

Milestones

- Designs to have global reach for yards.
- Best practices for optimisation and production of floating wind substructures and components such as coned cylinders, pressure resistance of marine structure components, stiffness of towers and substructure, connections between columns and pontoons, bracing column/pontoon connections and anchors.

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Floating installation, assembly and heavy maintenance | Medium-term | Low priority

Description and scope

Deepwater offshore wind sites exclude use of traditional jack-up vessels for assembly, installation, and heavy maintenance. Floating-to-floating solutions need to be further developed for use in floating offshore wind developments. These solutions will allow for efficient installation and heavy maintenance at site and help to reduce capital expenditure (CAPEX) and operational expenditure (OPEX).

Recommended research actions

- Floating-to-floating motion compensated lifting operation.
- Assess loads on components during crane/lifting operations.
- Adaptable substructures for float over installation or to avoid heavy high-lifts, (e.g. telescopic designs, ... etc.).
- Adapt Rotor-Nacelle-Assembly to allow for large tilting such that blades, nacelle and tower can be assembled horizontally on the ground, towed out, then flipped up vertically offshore for installation.
- Flexible and Rigid Body Dynamic modelling for improved marine operations.

Milestones

- Enable floating-to-floating lifting at 1,5 HS and 10 m/s wind.
- Software tools able to simulate six degrees of freedom motion compensation.

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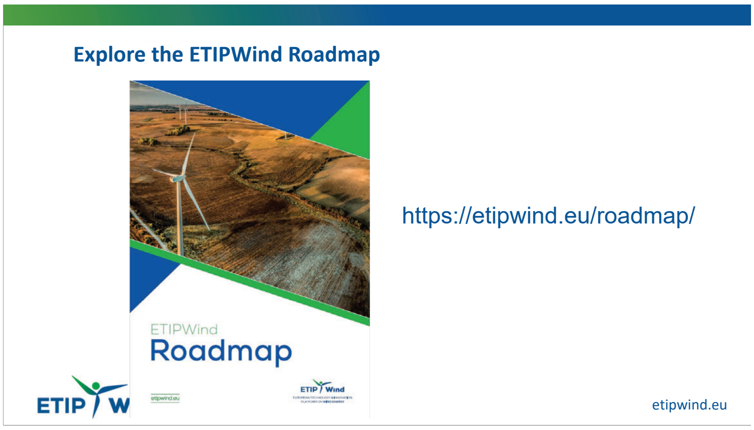

Explore the ETIPWind Roadmap

https://etipwind.eu/roadmap/

ETIP W

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The Global Perspective

ETIP Wind

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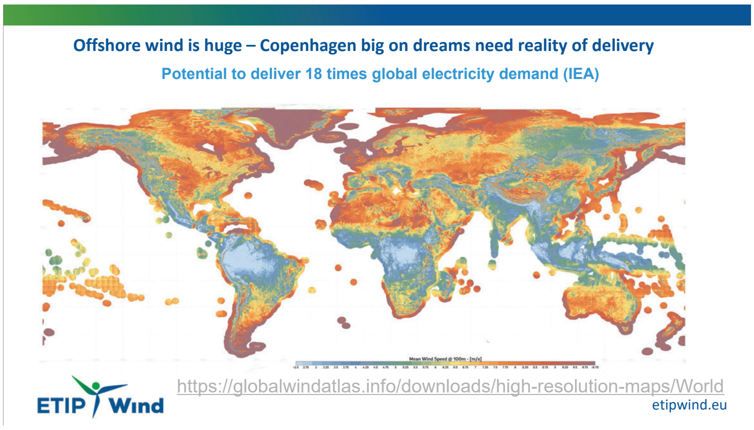

Offshore wind is huge – Copenhagen big on dreams need reality of delivery

Potential to deliver 18 times global electricity demand (IEA)

https://globalwindatlas.info/downloads/high-resolution-maps/World

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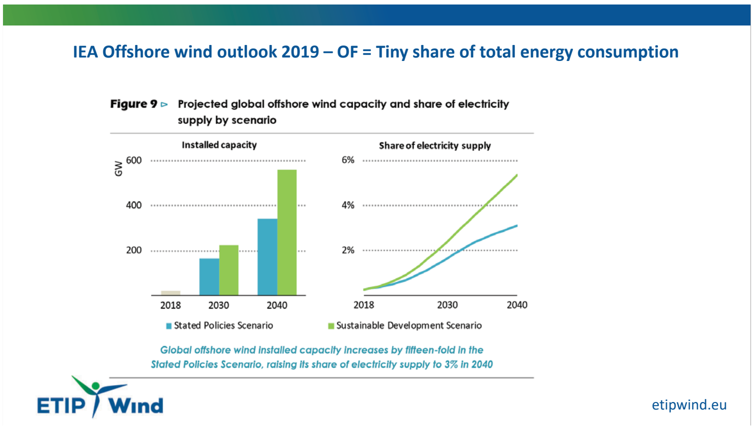

IEA Offshore wind outlook 2019 – OF = Tiny share of total energy consumption

Figure 9 ▹ Projected global offshore wind capacity and share of electricity supply by scenario

Global offshore wind installed capacity increases by fifteen-fold in the Stated Policies Scenario, raising its share of electricity supply to 3% in 2040

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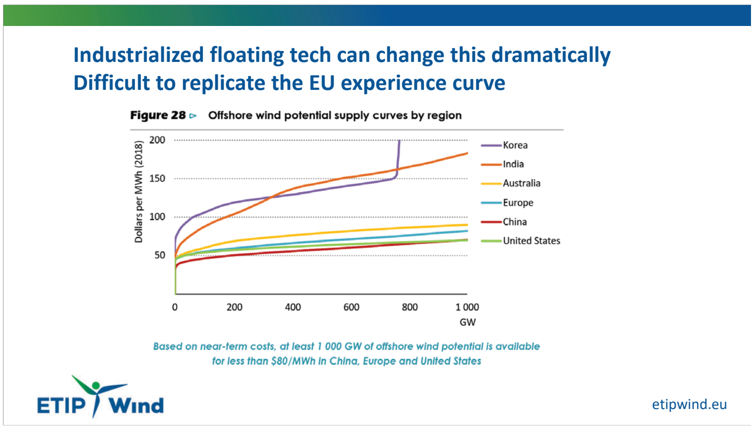

Industrialized floating tech can change this dramatically
Difficult to replicate the EU experience curve

Figure 28 ▹ Offshore wind potential supply curves by region

Based on near-term costs, at least 1 000 GW of offshore wind potential is available for less than $80/MWh in China, Europe and United States

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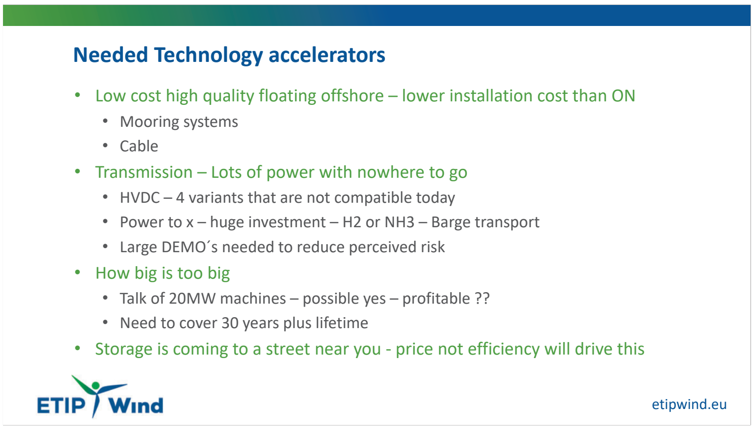

Needed Technology accelerators

- Low cost high quality floating offshore – lower installation cost than ON
  - Mooring systems
  - Cable
- Transmission – Lots of power with nowhere to go
  - HVDC – 4 variants that are not compatible today
  - Power to x – huge investment – H2 or NH3 – Barge transport
  - Large DEMO´s needed to reduce perceived risk
- How big is too big
  - Talk of 20MW machines – possible yes – profitable ??
  - Need to cover 30 years plus lifetime
- Storage is coming to a street near you - price not efficiency will drive this

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The Chinese approach to R&I -
North China Power University

- Well financed University all inclusive. State Grid Corp of China and Government involved– all power technologies represented
- High participation of young women close to 50%
- Risk is relative – ability to test, fail and learn quickly – Open technical reports – City Books
- Patent nesting and national champions
- Open data sharing
- Quality a continuing process – can do attitude
- No lobbyists to muddy the water

GLOBAL Challenges need Global Co-operation

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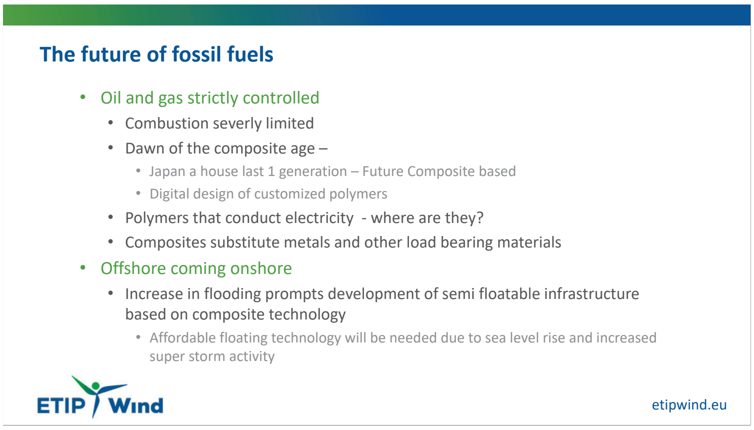

The future of fossil fuels

- Oil and gas strictly controlled
  - Combustion severly limited
  - Dawn of the composite age –
    - Japan a house last 1 generation – Future Composite based
    - Digital design of customized polymers
  - Polymers that conduct electricity - where are they?
  - Composites substitute metals and other load bearing materials
- Offshore coming onshore
  - Increase in flooding prompts development of semi floatable infrastructure based on composite technology
    - Affordable floating technology will be needed due to sea level rise and increased super storm activity

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Some light reading

Offshore wind can deliver huge amounts of needed clean, green particle free power.

Today this is a dream.

You in this room can through your research and innovation make it a reality.

Failure to deliver this potential would be a huge travesty

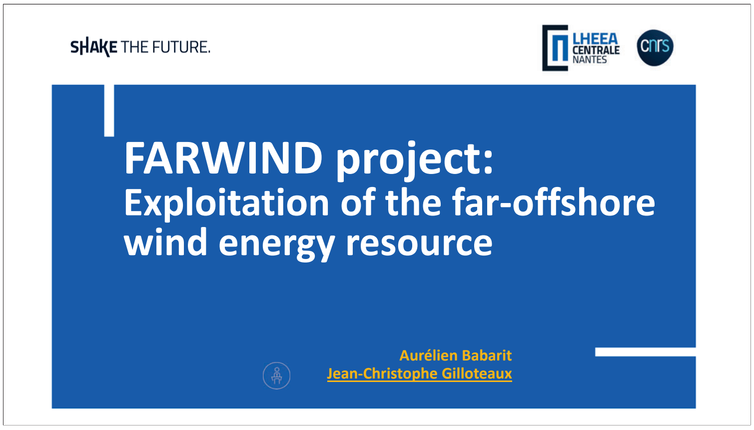
Thank you for your attention

A New turbine and generator technology

Introduction to the FARWIND concept for sustainable fuel production from the far-offshore wind energy resource, C.Gilloteaux, Centrale Nantes - CNRS

Comparison of Electrical Topologies for Multi-rotor System Wind Turbines, P.Pirrie, University of Strathclyde

An Aerospace Solution to Leading Edge Erosion, P.Greaves, ORE Catapult



SHAKE THE FUTURE.

FARWIND project:
Exploitation of the far-offshore wind energy resource

Aurélien Babarit
Jean-Christophe Gilloteaux

Motivation

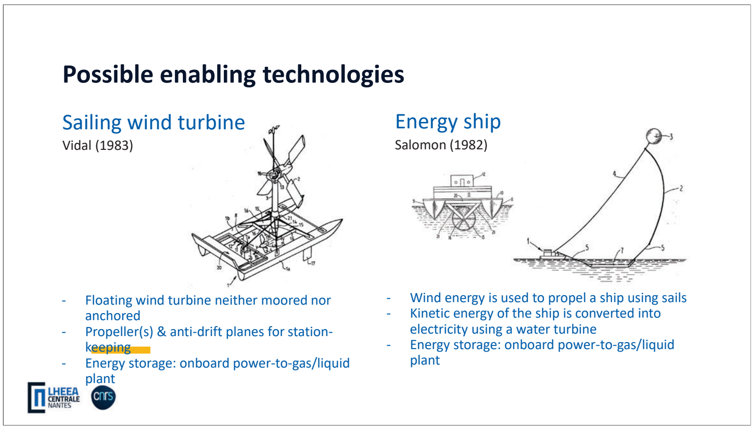
Clean fuels are needed to achieve a carbon-neutral economy

Fuels will still represent at least 45% of the energy demand in the EU in 2050 according to the EC

Far-offshore wind energy resource is a tremendous yet-untapped renewable energy source

Issue: grid-connection, installation and moorings, maintenance costs at long distance & in very deep water

Can we convert far-offshore wind into clean fuels?



Possible enabling technologies

Sailing wind turbine

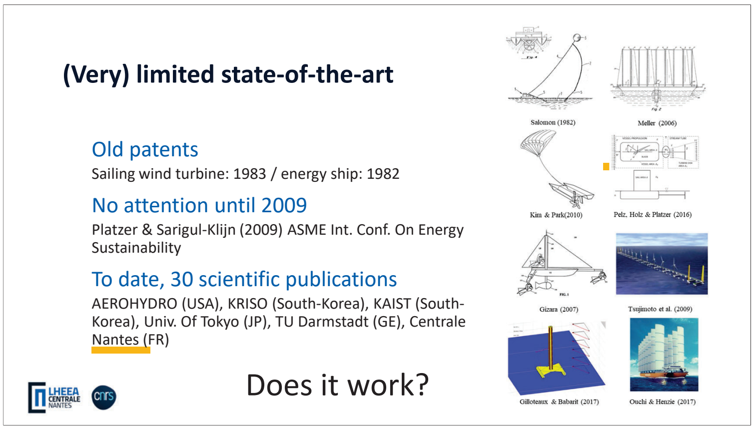
Vidal (1983)

- Floating wind turbine neither moored nor anchored
- Propeller(s) & anti-drift planes for station-keeping
- Energy storage: onboard power-to-gas/liquid plant

Energy ship

Salomon (1982)

- Wind energy is used to propel a ship using sails
- Kinetic energy of the ship is converted into electricity using a water turbine
- Energy storage: onboard power-to-gas/liquid plant



(Very) limited state-of-the-art

Old patents

Sailing wind turbine: 1983 / energy ship: 1982

No attention until 2009

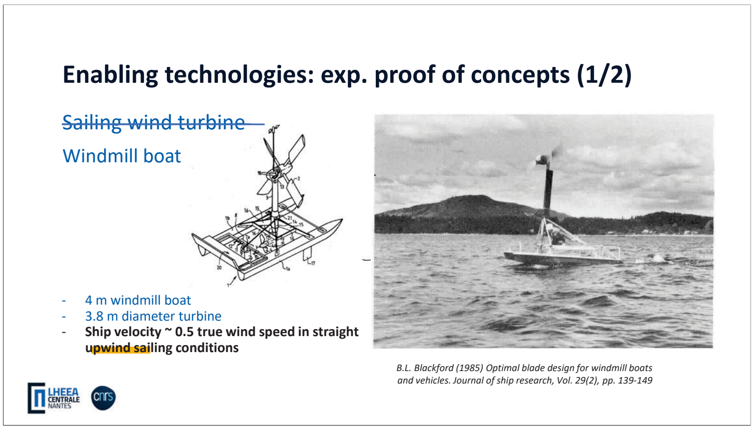
Platzer & Sarigul-Klijn (2009) ASME Int. Conf. On Energy Sustainability

To date, 30 scientific publications

AEROHYDRO (USA), KRISO (South-Korea), KAIST (South-Korea), Univ. Of Tokyo (JP), TU Darmstadt (GE), Centrale Nantes (FR)

Does it work?

Salomon (1982)
Meller (2006)
Kim & Park(2010)
Pelz, Holz & Platzer (2016)
Gizara (2007)
Tsujimoto et al. (2009)
Gilloteaux & Babarit (2017)
Ouchi & Henzie (2017)



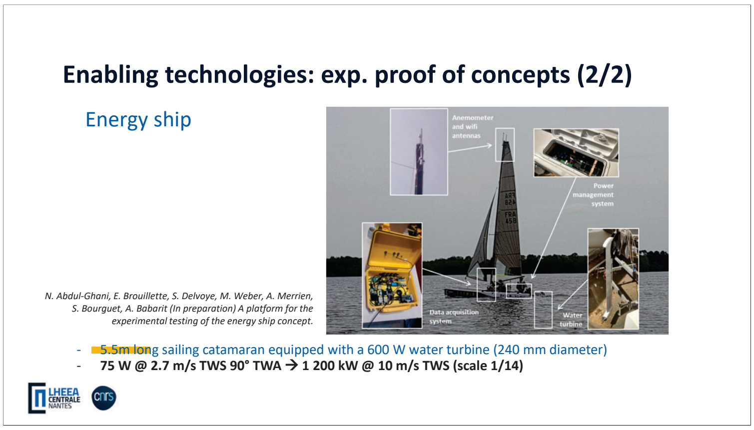
Enabling technologies: exp. proof of concepts (1/2)

~~Sailing wind turbine~~

Windmill boat

- 4 m windmill boat
- 3.8 m diameter turbine
- **Ship velocity ~ 0.5 true wind speed in straight upwind sailing conditions**

B.L. Blackford (1985) Optimal blade design for windmill boats and vehicles. Journal of ship research, Vol. 29(2), pp. 139-149



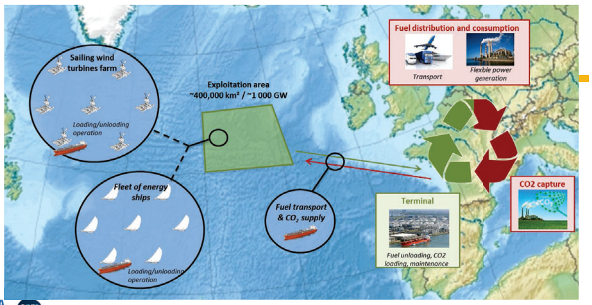
Enabling technologies: exp. proof of concepts (2/2)

Energy ship

N. Abdul-Ghani, E. Brouillette, S. Delvoye, M. Weber, A. Merrien, S. Bourguet, A. Babarit (In preparation) A platform for the experimental testing of the energy ship concept.

- 5.5m long sailing catamaran equipped with a 600 W water turbine (240 mm diameter)
- **75 W @ 2.7 m/s TWS 90° TWA → 1 200 kW @ 10 m/s TWS (scale 1/14)**

Possible concept of operations



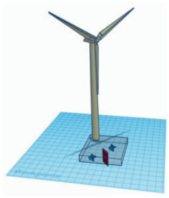
Energy vector: methanol

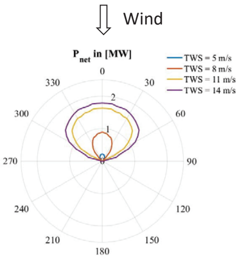
Design examples

Sailing wind turbine

2MW floating wind turbine
40 m x 40 m barge
2 x 6 m diameter propellers
15 m² keel
Propellers control: $V_{mg} = 0$ m/s

P_{net} ~ 1.7 MW @ 11 m/s TWS & 0° TWA





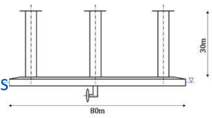
R. Alwan, A. Babarit, T. Choisnet, J-C. Gilloteaux (In preparation) Investigation of the sailing wind turbine concept for the harvesting of the far-offshore wind energy resource.

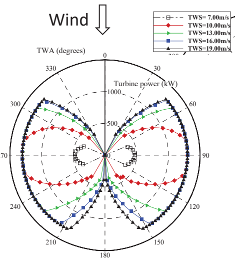
Design examples

Energy ship

80 m long catamaran
3 x 30 m tall Flettner rotors
6 m diameter water turbine

P_{net} = 1.3 MW @ 10 m/s TWS & 90° TWA





A. Babarit, G. Clodic, J-C. Gilloteaux (Submitted) A new energy system for sustainable methanol production from the far-offshore wind energy resource

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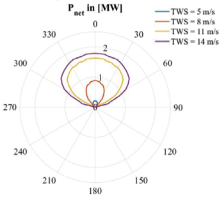
Sailing wind turbine vs energy ship

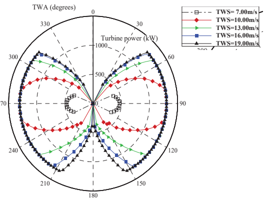
Sailing wind turbine

Best performance when facing the wind
Stationary (V_{mg} ~0 m/s)



Energy ship

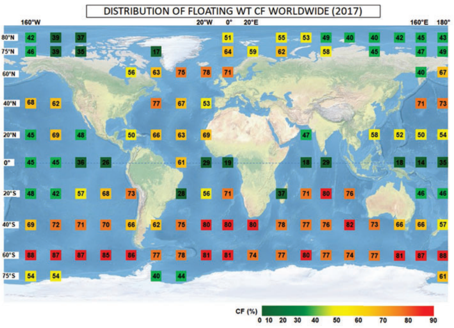
Best performance when sailing beam wind
Sails relatively fast (20 knots)



Capacity factor

Hypothetical stationary floating wind turbines

70 – 80% capacity factor may be achieve



R. Abd-Jamil, J-C. Gilloteaux, P. Lelong, A. Babarit (2019) Comparison of the capacity factor of stationary wind turbines and weather-routed energy ships in the far-offshore. In Proc. Of the EERA DeepWind' conference, Trondheim, Norway

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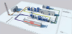
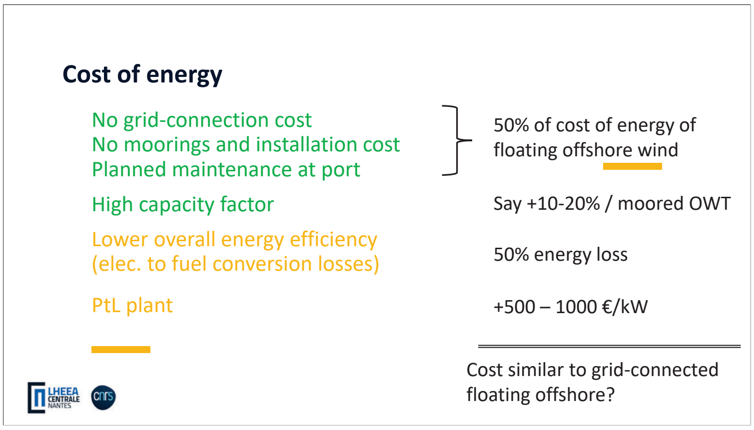
Energy vector

Methanol

Energy vector	H_2	CH_4	CH_3OH	$(\text{-}CH_2\text{-})_n$	NH_3
Process	Electrolysis $2H_2O \rightarrow 2H_2 + O_2$	Electrolysis $2H_2O \rightarrow 2H_2 + O_2$ Methanation $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	Electrolysis $2H_2O \rightarrow 2H_2 + O_2$ CO_2 hydrogenation $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$	Electrolysis $2H_2O \rightarrow 2H_2 + O_2$ Fischer-Tropsch synthesis $nCO_2 + 3nH_2 \rightarrow (-CH_2-)_n + 2nH_2O$	Electrolysis $2H_2O \rightarrow 2H_2 + O_2$ Haber-Bosch process $N_2 + 3H_2 \rightarrow 2NH_3$
TRL	9 	8 	5-8 	5 	4-7 
Energy efficiency	60%	55%	49%	39%	47%
Efficiency inc. transport	36%	50%	47%	37%	43%
State & energy density in STP	Gas ~0.003 kWh/L	Gas 0.01 kWh/L	Liquid ~4 kWh/L	Liquid ~10 kWh/L	Gas ~0.004 kWh/L
Market value (€/MWh_{th})	30 – 150	~20	~20-90	~30-60	~20-90
Market (G€)	~100	~600	~25	~4,000	~25

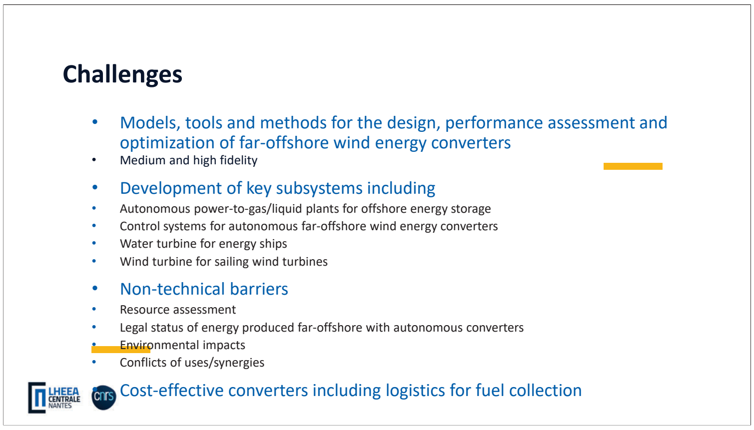
A. Babarit, J-C. Gilloteaux, G. Clodic, M. Duchet, A. Simoneau, M.F. Platzer (2018) Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters. International Journal of Hydrogen Energy.
A. Babarit, J-C. Gilloteaux, E. Body, J-F. Hétet (2019) Energy and economic performance of the FARWIND energy system for sustainable fuel production from the far-offshore wind energy resource. In Proc. Of the 14th EVER conference, Monaco



Cost of energy

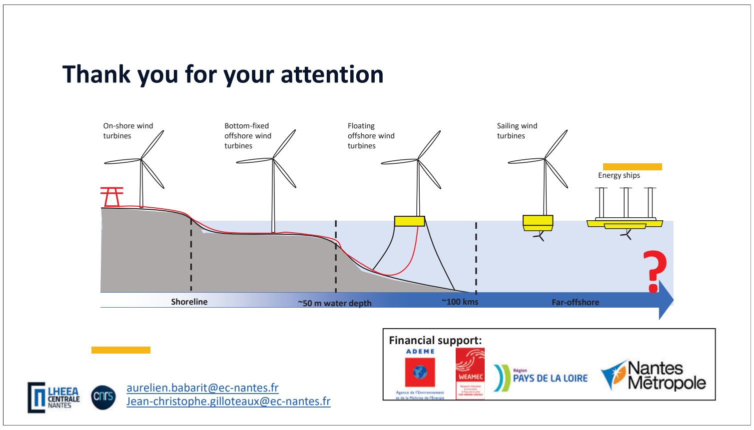
No grid-connection cost No moorings and installation cost Planned maintenance at port	50% of cost of energy of floating offshore wind
High capacity factor	Say +10-20% / moored OWT
Lower overall energy efficiency (elec. to fuel conversion losses)	50% energy loss
PtL plant	+500 – 1000 €/kW

Cost similar to grid-connected floating offshore?



Challenges

- Models, tools and methods for the design, performance assessment and optimization of far-offshore wind energy converters
  - Medium and high fidelity
- Development of key subsystems including
  - Autonomous power-to-gas/liquid plants for offshore energy storage
  - Control systems for autonomous far-offshore wind energy converters
  - Water turbine for energy ships
  - Wind turbine for sailing wind turbines
- Non-technical barriers
  - Resource assessment
  - Legal status of energy produced far-offshore with autonomous converters
  - Environmental impacts
  - Conflicts of uses/synergies
- Cost-effective converters including logistics for fuel collection



Thank you for your attention

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Jean-christophe.gilloteaux@ec-nantes.fr

Financial support:

Comparison of Electrical Topologies for Multi-rotor System Wind Turbines

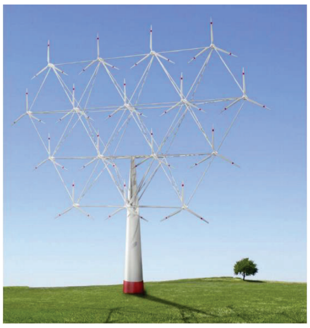
Paul Pirrie[1]

Olimpo Anaya-Lara[1], David Campos-Gaona[1]
[1] – University of Strathclyde

Introduction

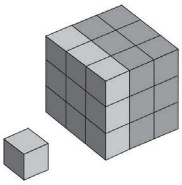
What are Multi-rotor Wind Turbines?

Large number of small wind turbines on one support structure.
Cost effective solution to 15+MW wind turbines



Area $\propto$ Power

Volume $\underset{\sim}{\propto}$ Material cost



Multi-rotor Pros & Cons

Benefits

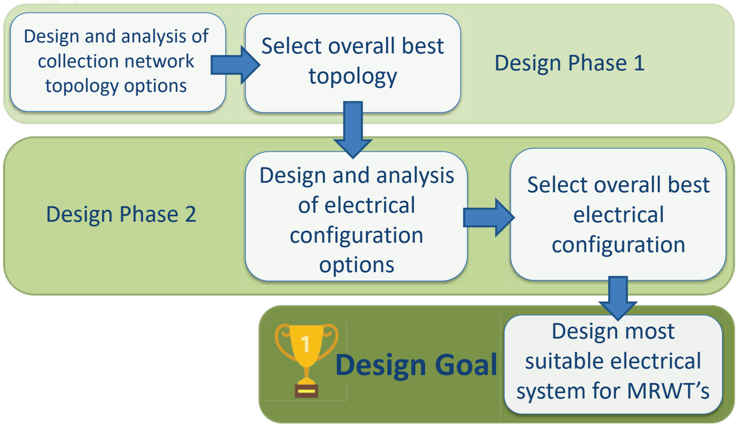
- ✓ Reduced levelised cost of energy (LCOE) due to:
  - ✓ Reduced material costs in blades/drive train
  - ✓ Savings due to standardisation
  - ✓ Significant reduction in installation and transport costs
  - ✓ Significant reduction in O&M costs
- ✓ Reduced loading
- ✓ Load averaging
- ✓ Power gains due to clustering of rotors
- ✓ Increased control possibilities
- ✓ Built in redundancy

Drawbacks

- × Large number of components
- × More complex support structure
- × Possible dynamic effects of associated with multiple rotors

---

Design project outline



Design and analysis of collection network topology options

Select overall best topology

Design Phase 1

Design Phase 2

Design and analysis of electrical configuration options

Select overall best electrical configuration

Design Goal

Design most suitable electrical system for MRWT's

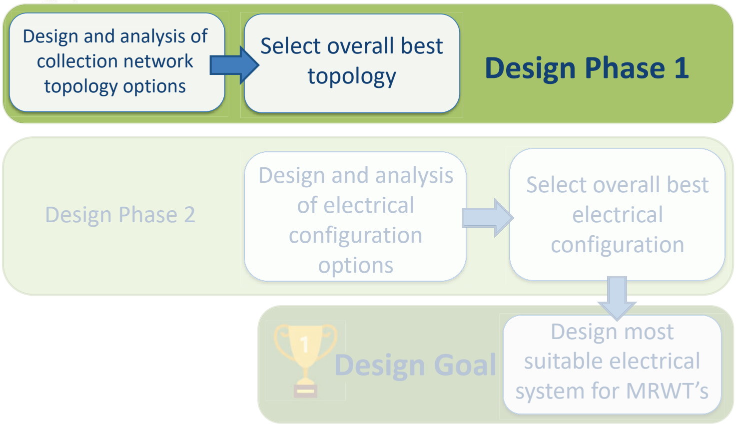
Considerations for electrical system

Minimise mass
- Reduce complexity and cost of support structure
- Nacelle mass more important

Minimise cost
- Don't outweigh other cost savings
- Decrease LCOE

Maximise Efficiency
- Reduce losses
- Decrease LCOE

Maximise Reliability
- Reduce component count
- Improve failure rates
- Take advantage of built in redundancy



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Topology Design

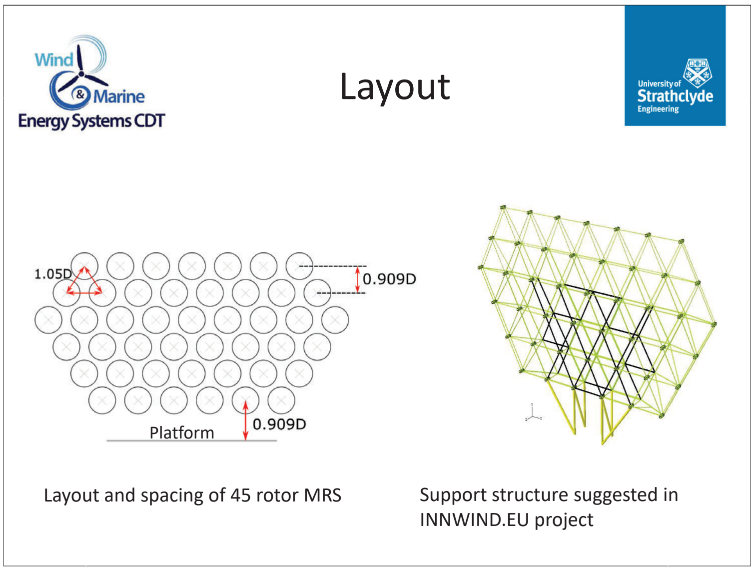
Design Constraints
- 45 rotor MRWT (500kW, 40m diameter)
- Provide AC power to collection network
- Each rotor must have independent speed control

Design Topologies
- Gather power from all turbines
- Based on offshore wind farm collection network designs
- Components kept consistent to focus on type of topology

Cost, mass & loss models
- Models developed to estimate mass, cost and losses of each component in system
- Based on scaling relationships, academic literature and commercial datasheets

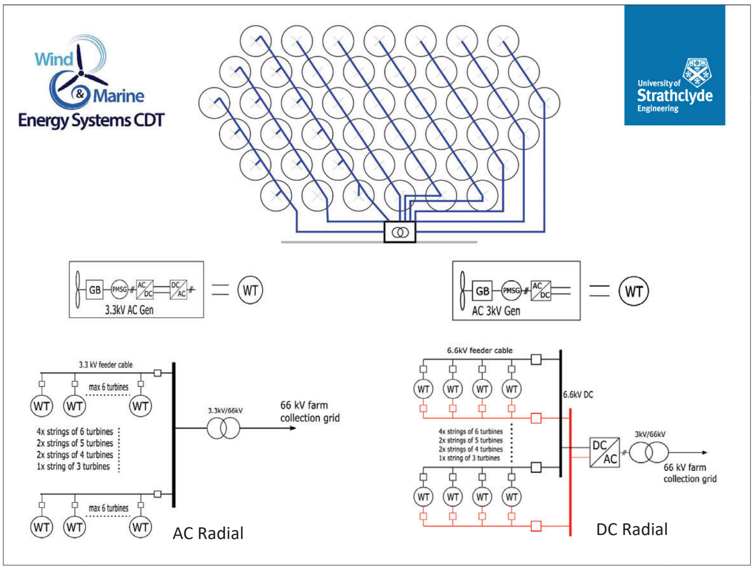
Determine suitability
- Based on the four criteria
- Best performing topologies move onto phase 2.

Layout



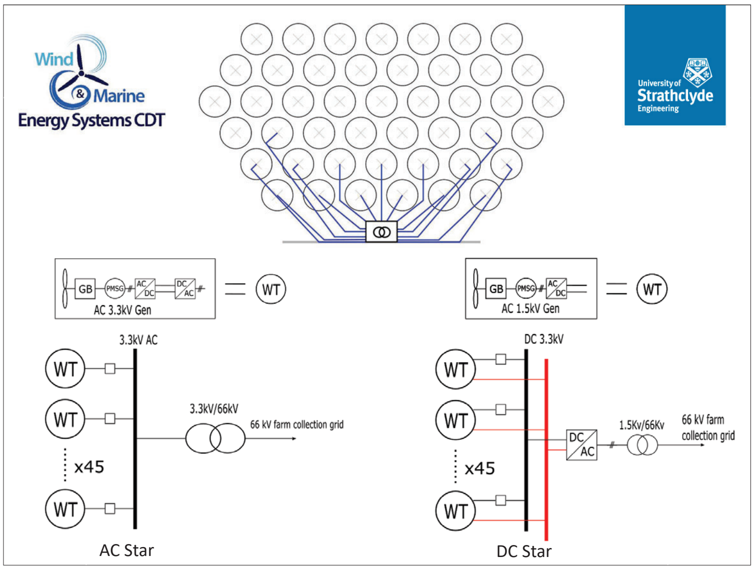
Layout and spacing of 45 rotor MRS

Support structure suggested in INNWIND.EU project



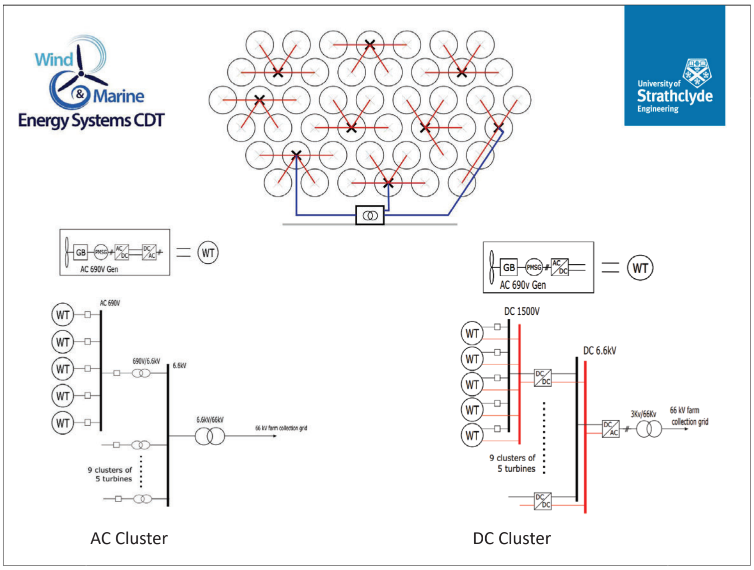
AC Radial

DC Radial



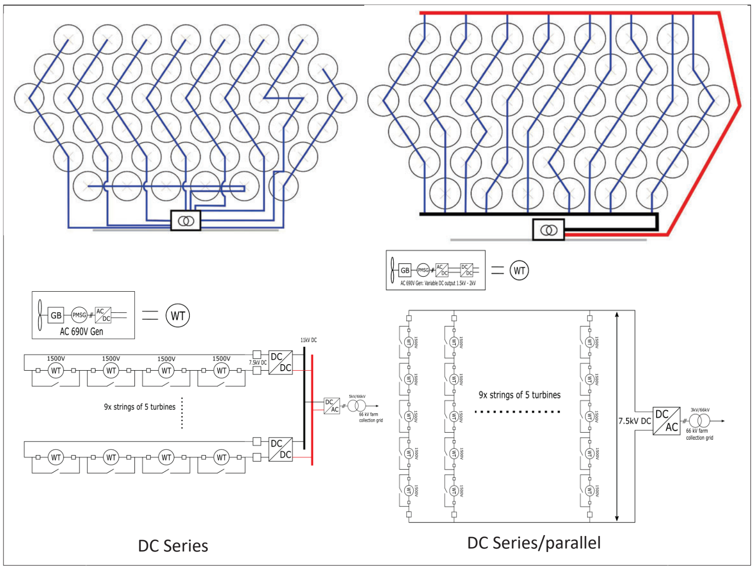
AC Star

DC Star



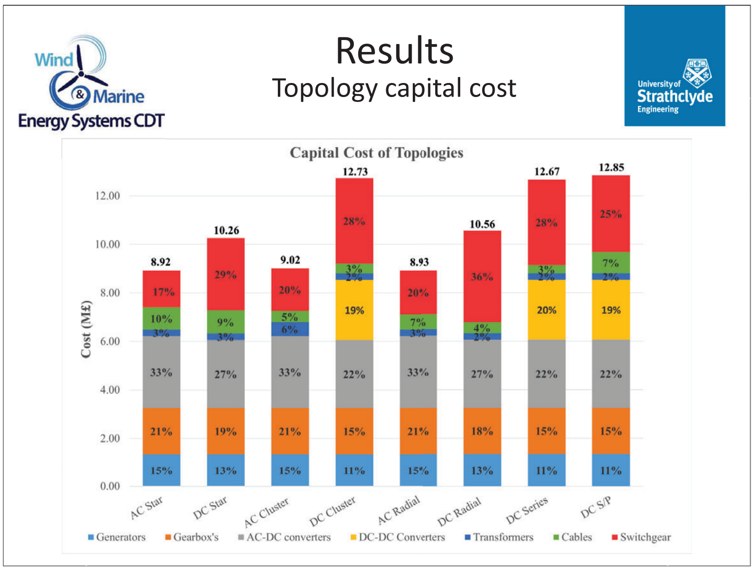
AC Cluster

DC Cluster

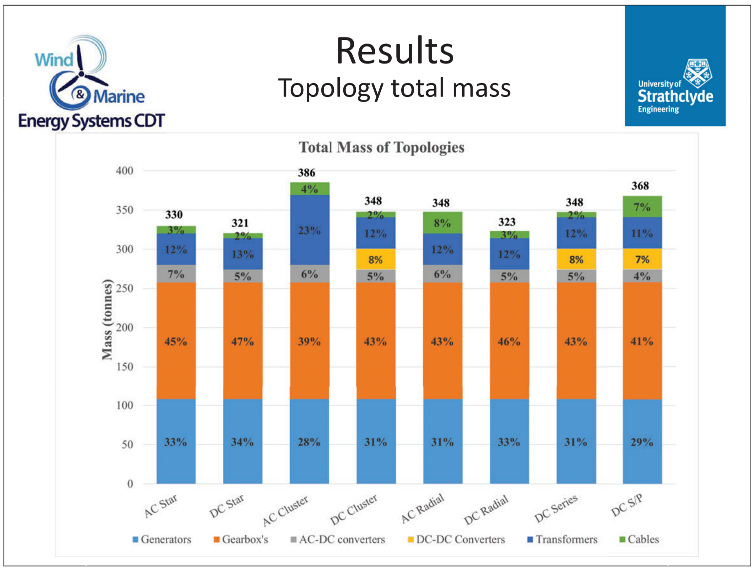


DC Series

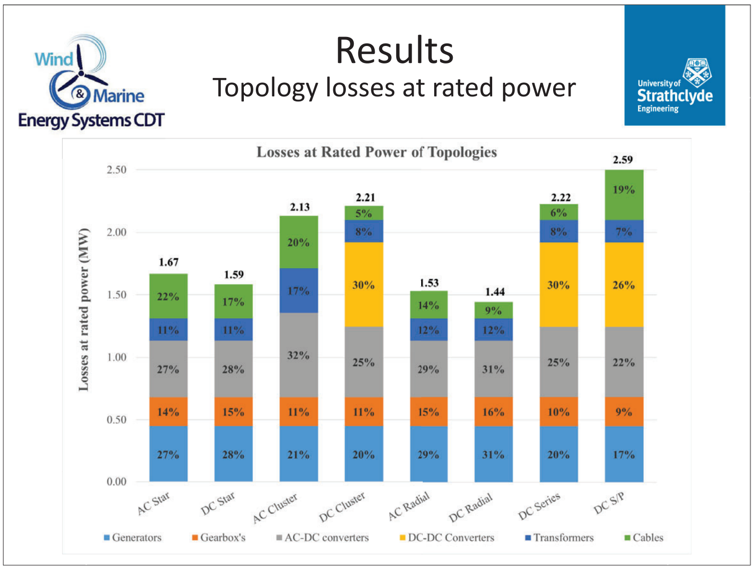
DC Series/parallel



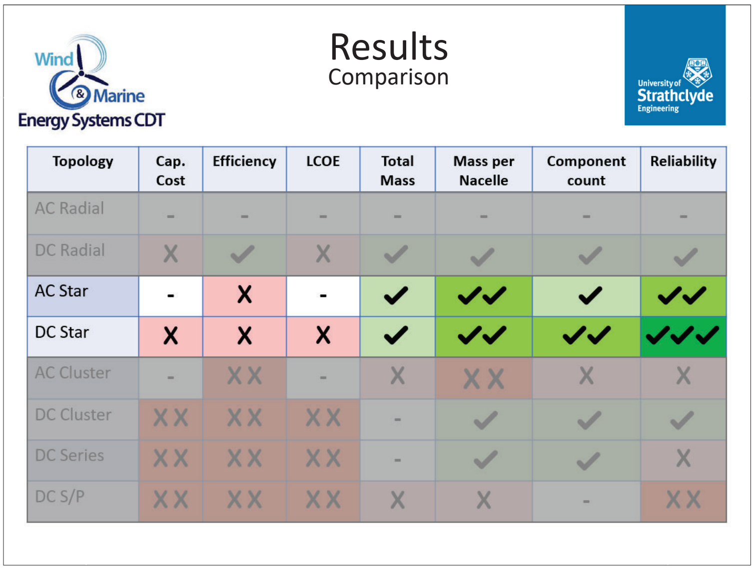
Results
Topology capital cost



Results
Topology total mass

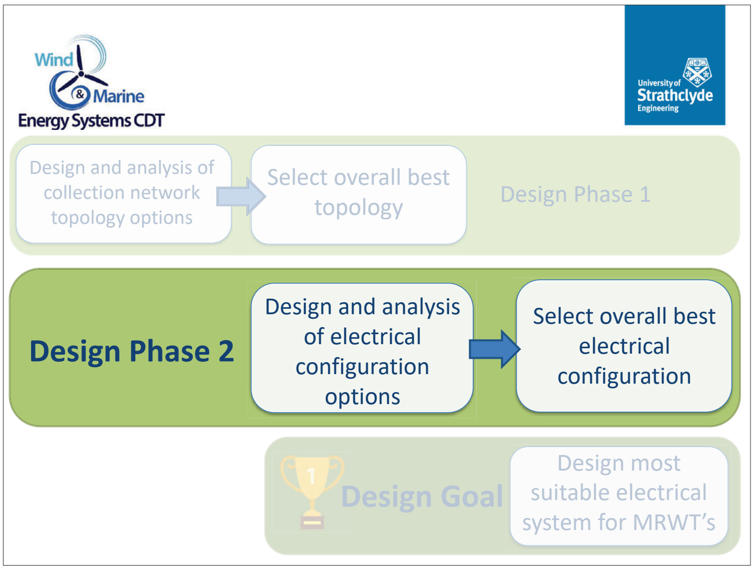


Results
Topology losses at rated power



Results
Comparison

Topology	Cap. Cost	Efficiency	LCOE	Total Mass	Mass per Nacelle	Component count	Reliability
AC Radial	-	-	-	-	-	-	-
DC Radial	X	✓	X	✓	✓	✓	✓
AC Star	-	X	-	✓	✓✓	✓	✓✓
DC Star	X	X	X	✓	✓✓	✓✓	✓✓✓
AC Cluster	-	XX	-	X	XX	X	X
DC Cluster	XX	XX	XX	-	✓	✓	✓
DC Series	XX	XX	XX	-	✓	✓	X
DC S/P	XX	XX	XX	X	X	-	XX



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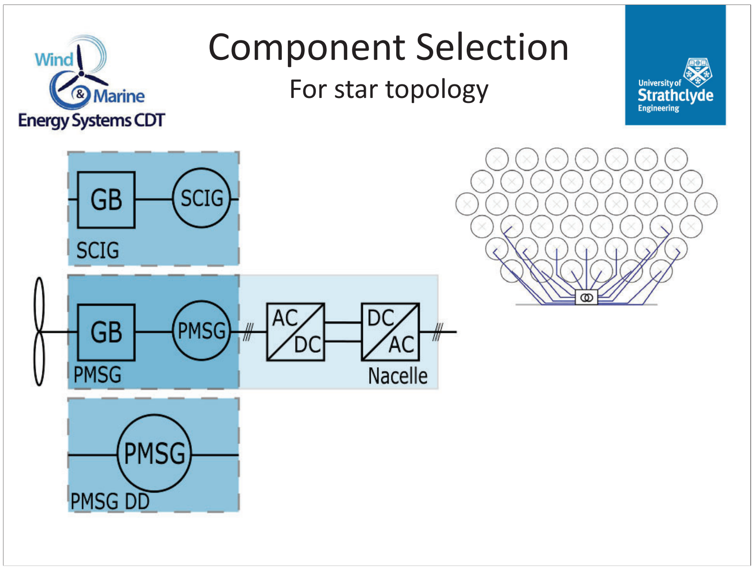
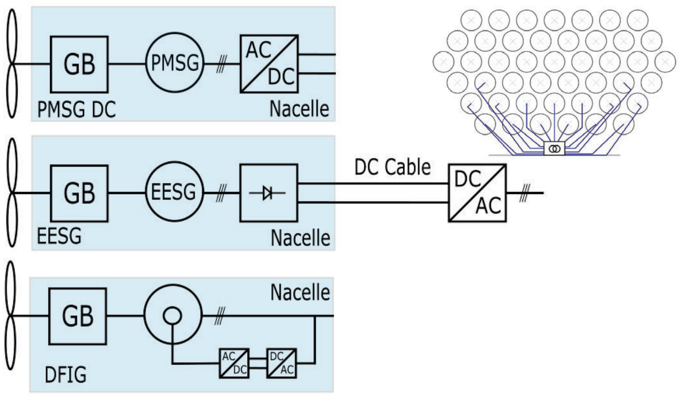


Component Selection
For star topology

Component Selection

For star topology



Quantifying failures

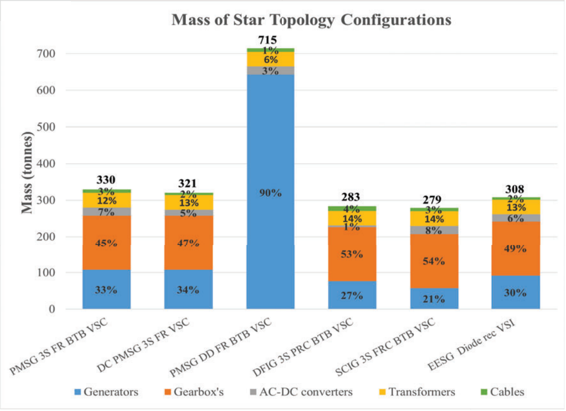
- Assume constant failure rates for each component
- Assume a fixed service period of 6 months
- How many failures will each configuration have in 6 months?
- How much will this cost in lost revenue?

Failure rates of configurations [failures/year/turbine]

Configuration	Generator	Gearbox	Converters	Total failure rate	Failures per 6 months
PMSG	0.076	0.18	0.632	0.888	20
PMSG DC	0.076	0.18	0.316	0.572	13
PMSG DD	0.076		0.632	0.708	16
DFIG	0.123	0.18	0.235	0.538	12
SCIG	0.062	0.18	0.632	0.874	20
EESG	0.123	0.18	0.11	0.413	10

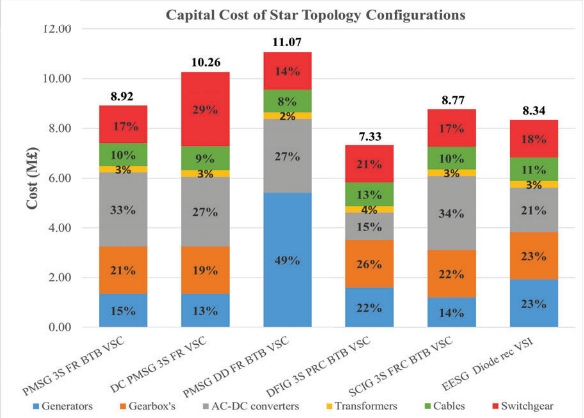
Results

Total mass of star options



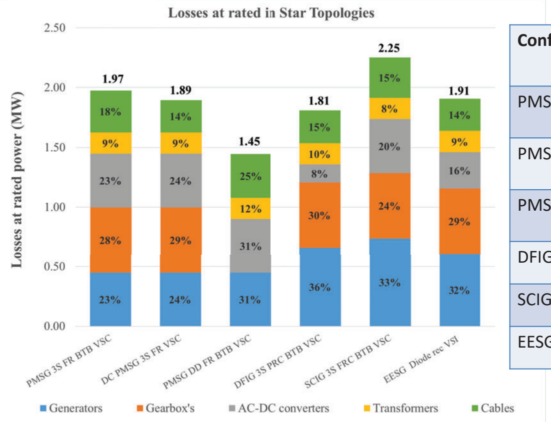
Results

Capital cost of star options



Results

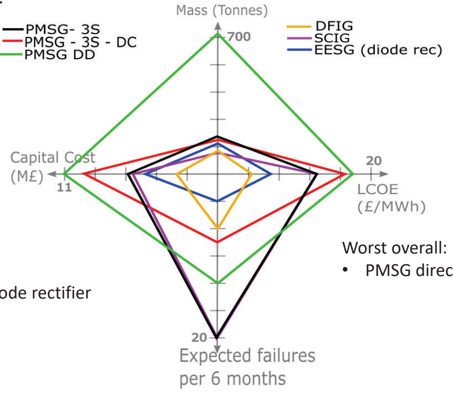
Losses and LCOE of star options



Configuration	LCOE (£/MWh)
PMSG 3S	16.55
PMSG DC	18.31
PMSG DD	18.75
DFIG	12.19
SCIG	16.60
EESG	13.60

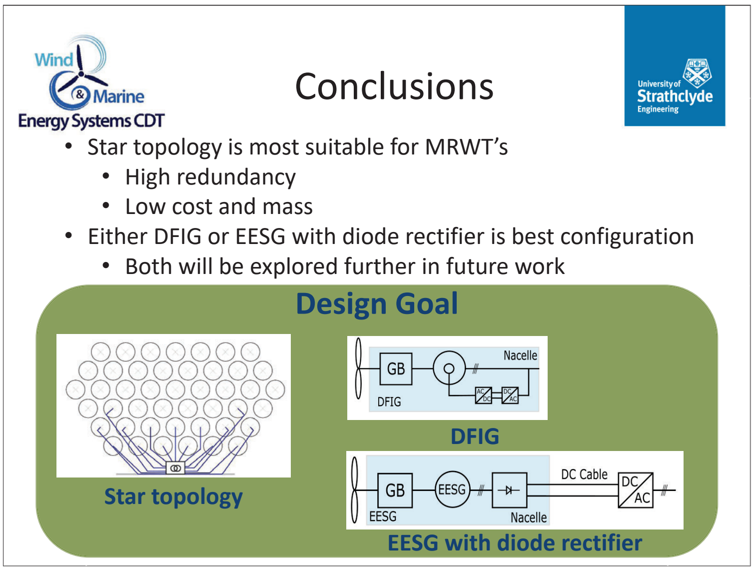
Results

Radar Plot



Best overall:
- DFIG
- EESG with diode rectifier

Worst overall:
- PMSG direct drive



Conclusions

- Star topology is most suitable for MRWT's
  - High redundancy
  - Low cost and mass
- Either DFIG or EESG with diode rectifier is best configuration
  - Both will be explored further in future work

Design Goal

Star topology

DFIG

EESG with diode rectifier

Thanks for listening

Any questions?

Email: paul.pirrie@strath.ac.uk

University of Strathclyde Glasgow

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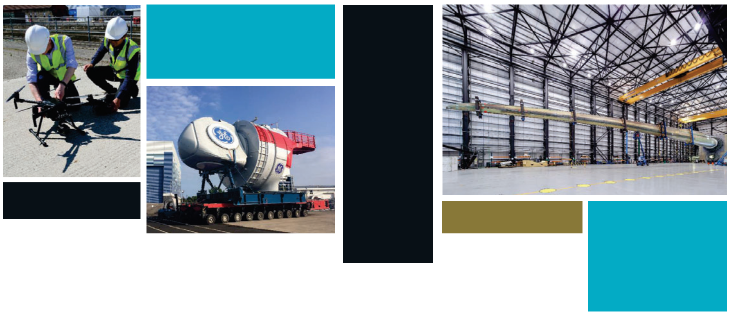


An Aerospace Solution to Leading Edge Erosion

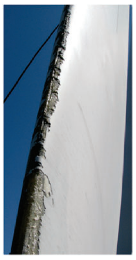
15th January 2019 | Peter Greaves

Agenda

- Leading Edge Erosion
- Introduction to LEFT Project
- Methodology
  - Modelling
  - Experimental
- Results
- Conclusions

Leading Edge Erosion

- Leading edge erosion is caused by raindrops impacting the leading edge near to the tip of the blade, where the local velocity can be close to 100m/s (225mph)
- It is a big problem for the industry (their biggest on blades according to a survey carried out among OEMs and owner operators)
- It costs the industry in two ways:
  - the aerodynamic performance decreases as erosion gets worse
  - Repairs need to be carried out approximately every 5 years
- 108 turbines x 6 days at €100k per day for a jack up rig is €65m in vessel hire, before lost revenue and the cost of repairs has been accounted for!



reNEWS

RENEWABLE ENERGY NEWS ■ ISSUE 377

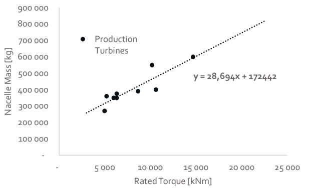
Orsted to repair hundreds of UK offshore blades

is expected to take between three and 10 days to tackle each turbine, depending on

where all 108 turbines need attention.

Benefits of Higher Tip Speeds

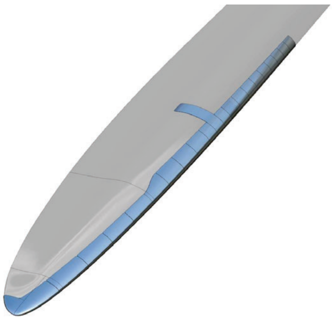
- If the speed limit of leading edge erosion is removed then tip speeds could increase to 120m/s or more
  - A 30% increase on current speeds!
- A nacelle mass trend derived from a survey of current nacelles has shown that the estimated nacelle mass for a 20MW turbine would be:
  - 1025t at 90 m/s
  - 815t at 120 m/s
  - This would lead to a substantial decrease in tower cost as well as nacelle cost
- Jamieson et al [1] demonstrated a turbine CAPEX reduction of 20% for a 5MW turbine when increasing the tip speed and moving to a downwind rotor
- Dykes et al [2] demonstrated a 5.5% reduction in LCOE by moving from 80 m/s to 100m/s flexible blade



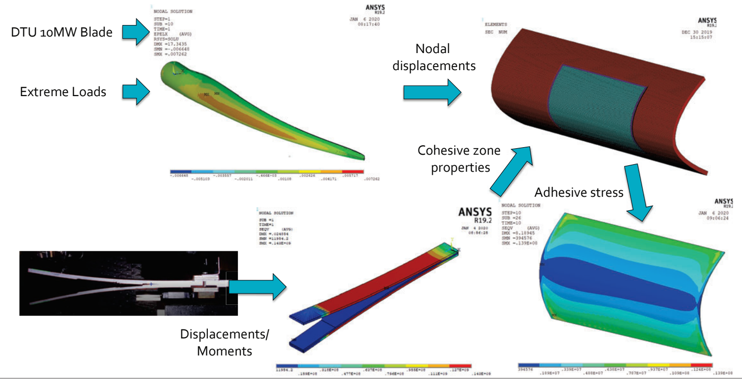
[1] Jamieson P (2009) *Light Weight, High Tip Speed Rotors for Offshore*. EWEC 2009, Stockholm.
[2] Dykes K, Platt A, Guo Y, Ning A, King R, Parsons T, Petch D, Veers P and Resor B (2014) *Effect of Tip Speed Constraints on the Optimised Design of a Wind Turbine*, NREL TP-50000-61726

The LEFT (Leading Edge for Turbines) Project

- The LEFT project is a collaboration between:
  - Radius Aerospace UK
  - Performance Engineered Solutions Ltd
  - The Offshore Renewable Energy Catapult
- It aims to transfer the use of electroformed Ni-Co leading edge protection from the aerospace industry to wind turbines
- The Ni-Co solution has demonstrated extremely good rain erosion performance:
  - It lasts for 85 hours in the ORE Catapult rain erosion rig at 173 m/s
  - Typical solutions last for around 15 hours at 120 m/s
- However, it will be challenging to integrate with wind turbine blades:
  - The alloy has high relative stiffness compared to the blade
  - Lightning protection
- The LEFT project aims to address these issues



Adhesive Validation Methodology



DTU 10MW Blade

Extreme Loads

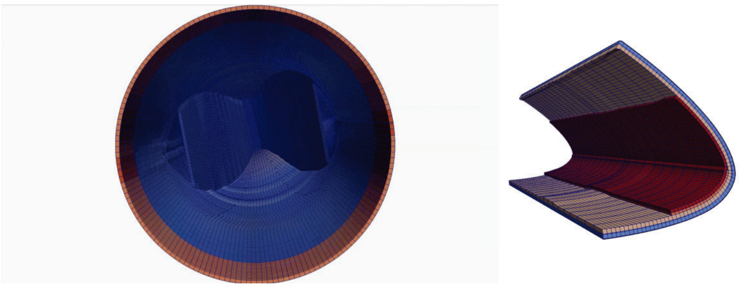
Nodal displacements

Cohesive zone properties

Adhesive stress

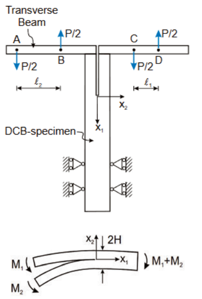
Displacements/ Moments

Global and Sub-Models



Fracture Mechanics Rig

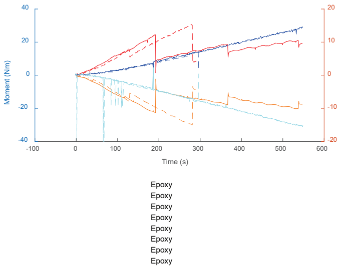
- The test rig was designed and built by PES with rig control using a Raspberry Pi developed by ORE Catapult
- The rig is based on a design by Sorenson et al [3] and applies pure bending moments to the ends of the specimen
  - Enables steady crack growth in mode 1 and mode 2
  - Calculated values are not dependent on the crack length
- The crack length and angle of the arms were determined using a custom image processing algorithm developed in OpenCV

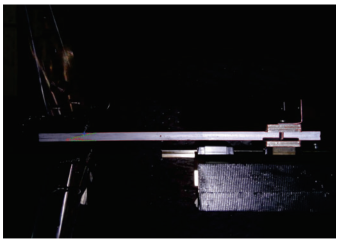


$$J_{ext} = (1 - \upsilon^2)\frac{21(M_1^2 - M_2^2) - 6M_1M_2}{4B^2H^3E}$$

[3] Sorenson B (2004) *A General Mixed Mode Fracture Mechanics Test Specimen*, DTU Report

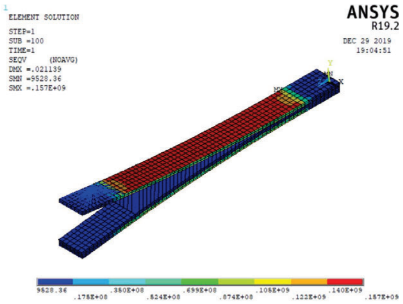
Fracture Mechanics Testing



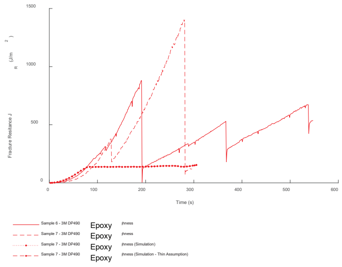


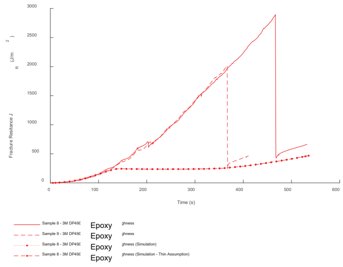
Finite Element Modelling Approach

- The experimental tests have been modelled in ANSYS:
  - SOLID185 elements for adhesive and substrate
  - INTER205 elements with bi-linear cohesive zone model
  - BEAM188 Beam elements connect remote point at which beam angular displacements are applied to the substrate nodes
- The STP Adhesive proved very difficult to model in mode 2 because of its very low modulus

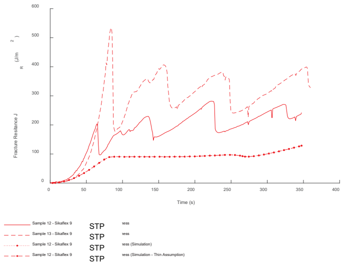


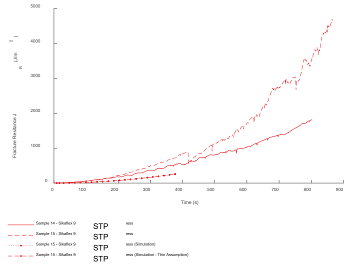
Epoxy Adhesive Results

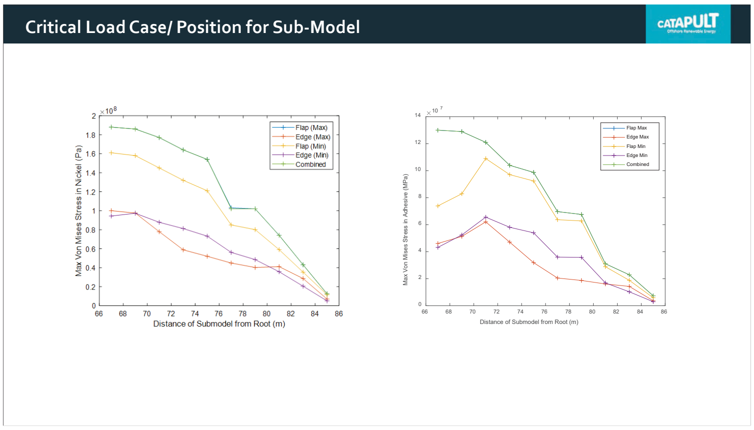




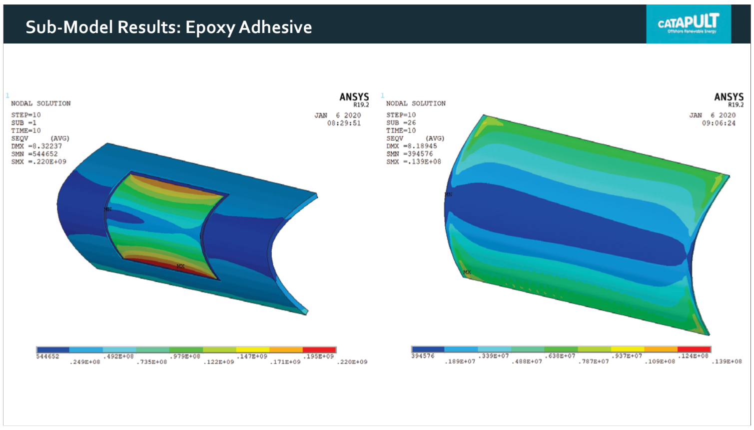
Silane Terminated Polymer Adhesive Results



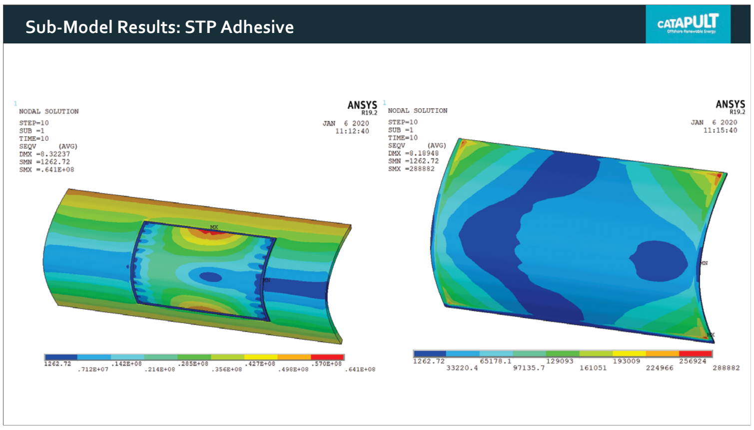




Critical Load Case/ Position for Sub-Model



Sub-Model Results: Epoxy Adhesive



Sub-Model Results: STP Adhesive

Conclusions

- A blade meshing tool has been developed which can generate a global solid mesh of the blade and a detailed solid mesh of the tile system
- A model chain has been developed which can accurately predict the adhesive stresses in the Ni-Co tile system
- It can also be used with more detailed models developed from CAD as long as they occupy the same position in space as the global blade mesh
- The next steps are:
  - Produce a demonstrator of the leading edge system
  - Investigate how the interface between tiles affects the stress
  - Look at certification
  - Integrate the tile into the blade lightning system

Contact us

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B1) Grid connection and power system integration

VIKINGS: Offshore Wind Integration within the Stand-alone Electric Grid at Oil and Gas Offshore Installations, W.He, Equinor – *Presentation not available*

Feasibility assessment of wireless series reactive compensation of long submarine AC cables, G.Lugrin, SINTEF

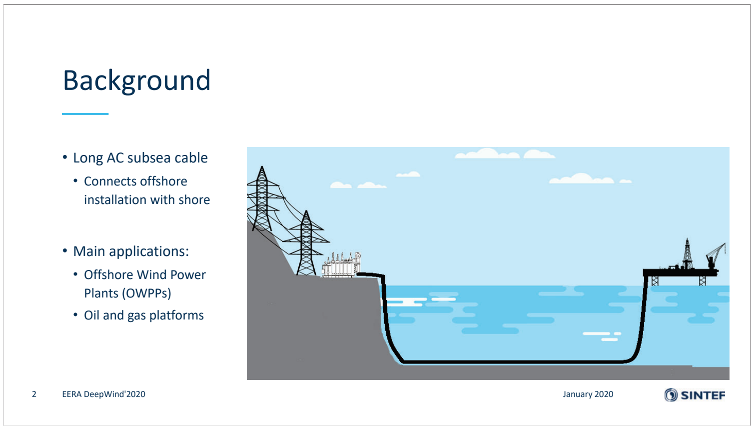
Power Oscillation Damping from Offshore Wind Farms Connected to HVDC via Diode Rectifiers, O.Saborio-Romano, DTU Wind Energy

Dynamic Analysis of Power Cable in Floating Offshore Wind Turbine, M.Sobhaniasl, University of Rome

Feasibility assessment of wireless series reactive compensation of long submarine AC cables

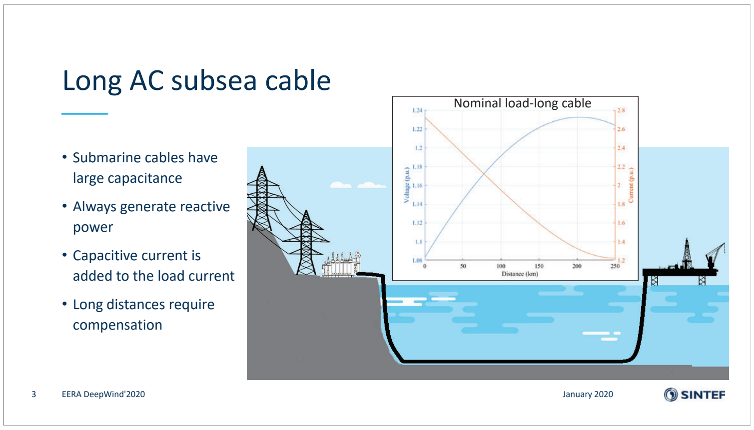
Author: **Gaspard Lugrin**, Research Scientist, SINTEF Energy Research
Presenting: **Andrzej Holdyk**, Research Scientist, SINTEF Energy Research

EERA DeepWind'2020, Trondheim, 16 January 2020



Background

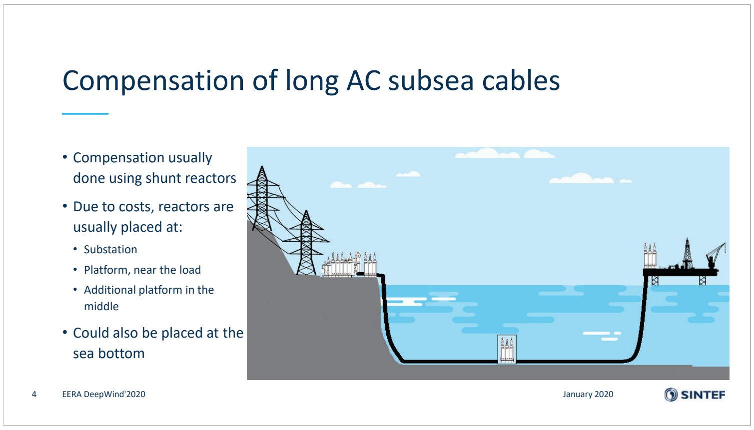
- Long AC subsea cable
  - Connects offshore installation with shore
- Main applications:
  - Offshore Wind Power Plants (OWPPs)
  - Oil and gas platforms



Long AC subsea cable

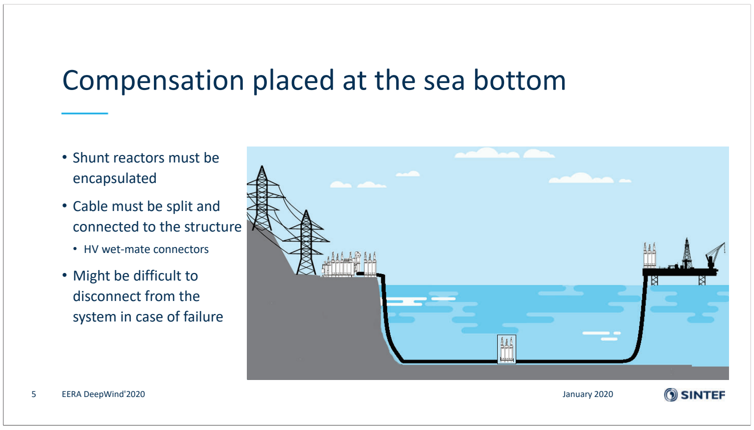
- Submarine cables have large capacitance
- Always generate reactive power
- Capacitive current is added to the load current
- Long distances require compensation

Nominal load-long cable



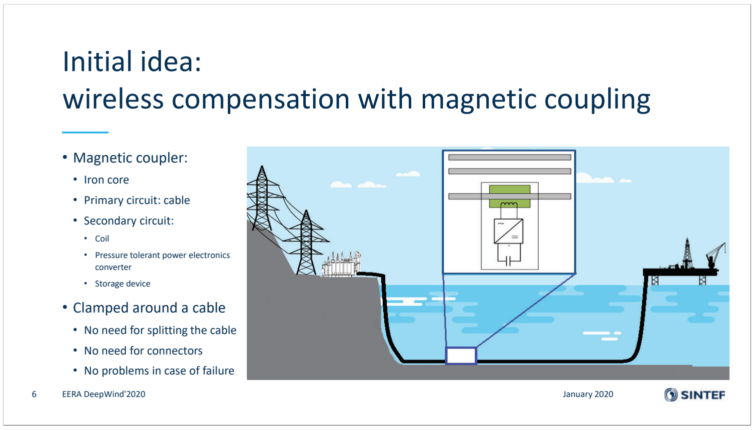
Compensation of long AC subsea cables

- Compensation usually done using shunt reactors
- Due to costs, reactors are usually placed at:
  - Substation
  - Platform, near the load
  - Additional platform in the middle
- Could also be placed at the sea bottom



Compensation placed at the sea bottom

- Shunt reactors must be encapsulated
- Cable must be split and connected to the structure
  - HV wet-mate connectors
- Might be difficult to disconnect from the system in case of failure

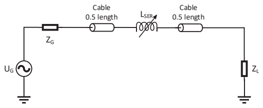


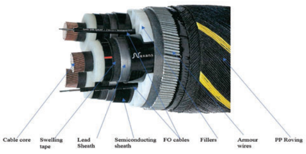
Initial idea: wireless compensation with magnetic coupling

- Magnetic coupler:
  - Iron core
  - Primary circuit: cable
  - Secondary circuit:
    - Coil
    - Pressure tolerant power electronics converter
    - Storage device
- Clamped around a cable
  - No need for splitting the cable
  - No need for connectors
  - No problems in case of failure

Feasibility studies

- Feasibility studies looked into:
  - Load flow
    - Can we dynamically compensate the cable?
    - Is the entire system stable?
    - Do we still need shunt compensation?
  - Cable design and possibilities of connection
  - Coupler
    - Main characteristics and estimation of weight of couplers

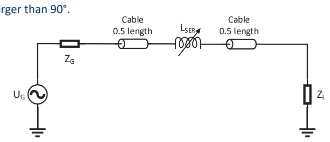




Results: Load flow analysis

✗

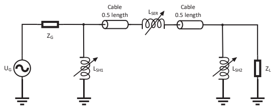
- Initial idea: series inductive compensation only:
  - At low transmitted power, full compensation requires arbitrary high voltage and causes a transmission angle larger than 90°; small partial compensation worsens the voltage at load.
  - For cables longer than a given value (depending on system parameters), full compensation causes transmission angle larger than 90°.



Results: Load flow analysis

!

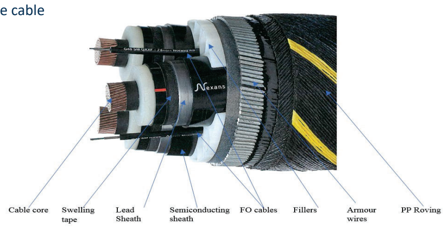
- Proposed method: combination of shunt and series inductive compensation
  - Increase of power transfer capability or operative cable length in comparison with a case where no compensation is present along the cable
  - Requires variable shunt inductances
  - The total installed reactive power for full compensation is larger with the proposed method than with shunt inductive compensation only.
  - Transient behaviour should be checked



Limitations due to cable design

✗

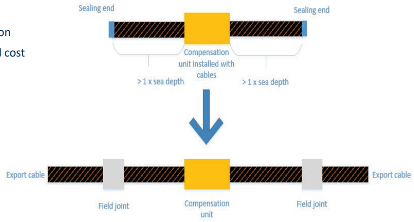
- Initial idea: coupling on a three-core cable
  - Cannot couple to a 3-phase cable directly
  - Armour, semiconductive layers, sheath



Limitations due to cable design

✓

- Proposed method: compensation unit
  - Compensation unit pre-installed on a cable section
  - Subsea system: no need for a platform (potential cost reduction)
  - The method is not "non-intrusive"



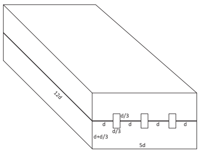
Coupler design

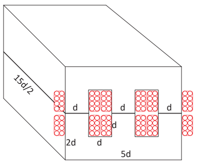
!

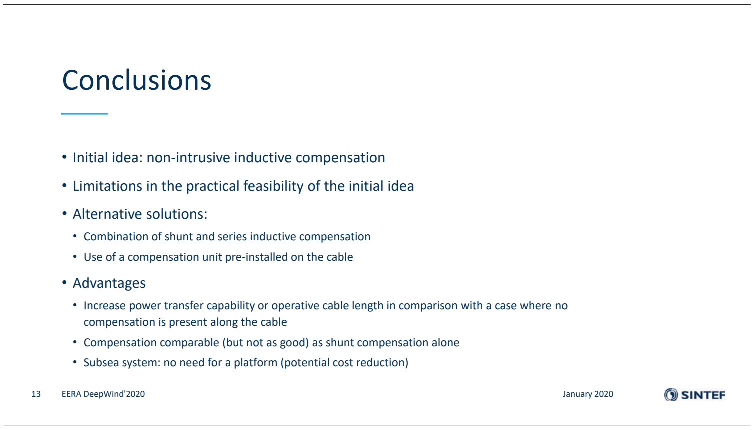
- Initial idea: single-turn secondary winding coupler
  - Very large size and weight

!

- Alternative: multiple-turn secondary winding
  - Weight is reduced in comparison with the single turn secondary winding
  - Would require to coil the cable
  - Not relevant if the compensation is pre-installed on the cable.







Conclusions

- Initial idea: non-intrusive inductive compensation
- Limitations in the practical feasibility of the initial idea
- Alternative solutions:
  - Combination of shunt and series inductive compensation
  - Use of a compensation unit pre-installed on the cable
- Advantages
  - Increase power transfer capability or operative cable length in comparison with a case where no compensation is present along the cable
  - Compensation comparable (but not as good) as shunt compensation alone
  - Subsea system: no need for a platform (potential cost reduction)

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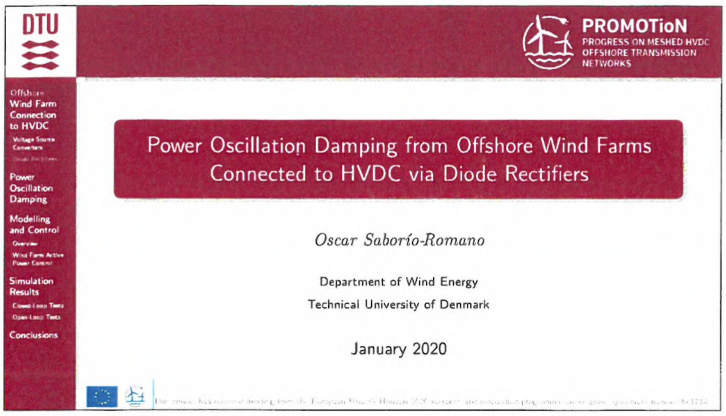
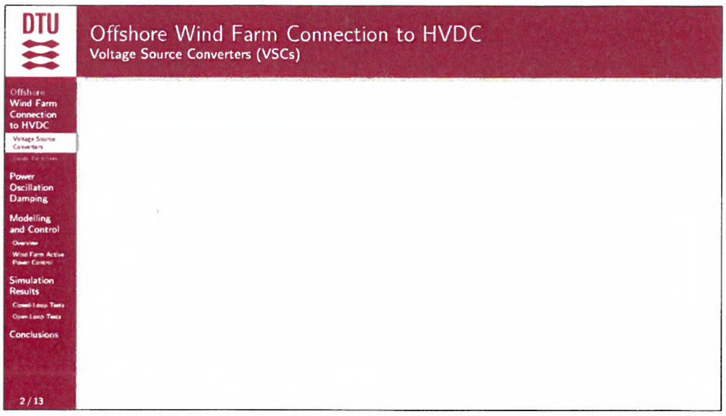


Power Oscillation Damping from Offshore Wind Farms Connected to HVDC via Diode Rectifiers

Oscar Saborío-Romano

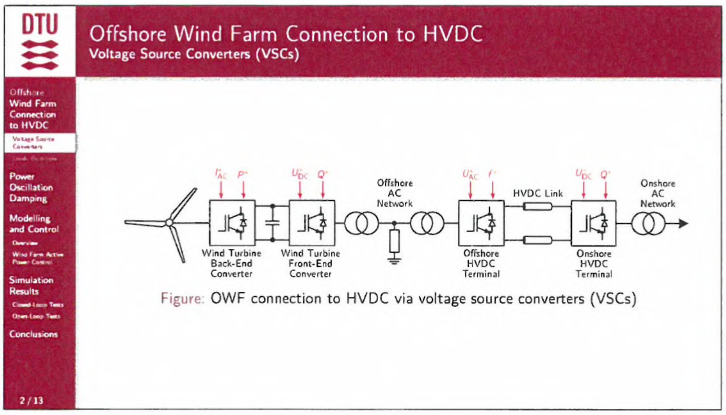
Department of Wind Energy
Technical University of Denmark

January 2020



Offshore Wind Farm Connection to HVDC

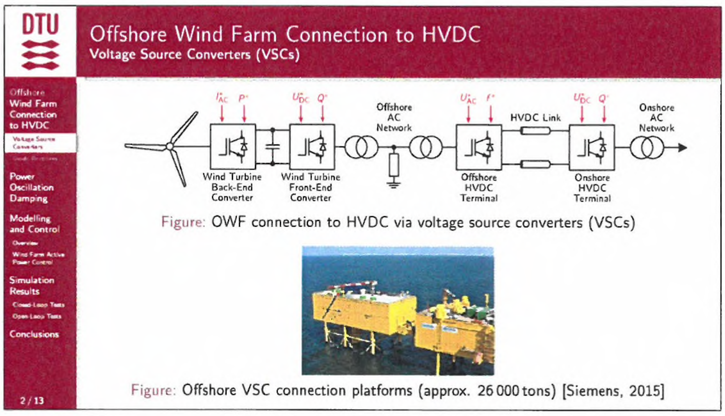
Voltage Source Converters (VSCs)



Offshore Wind Farm Connection to HVDC

Voltage Source Converters (VSCs)

Figure: OWF connection to HVDC via voltage source converters (VSCs)

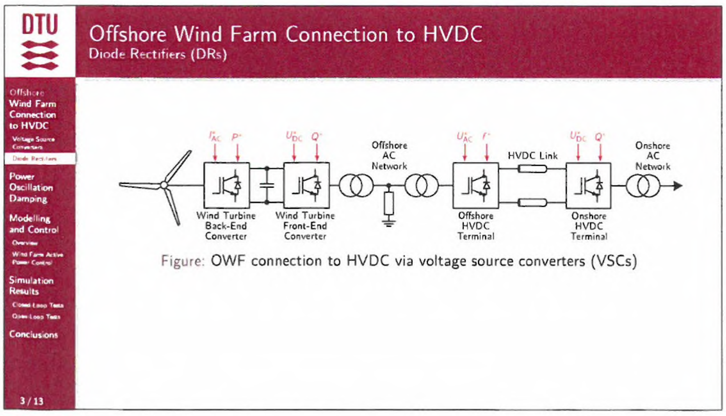


Offshore Wind Farm Connection to HVDC

Voltage Source Converters (VSCs)

Figure: OWF connection to HVDC via voltage source converters (VSCs)

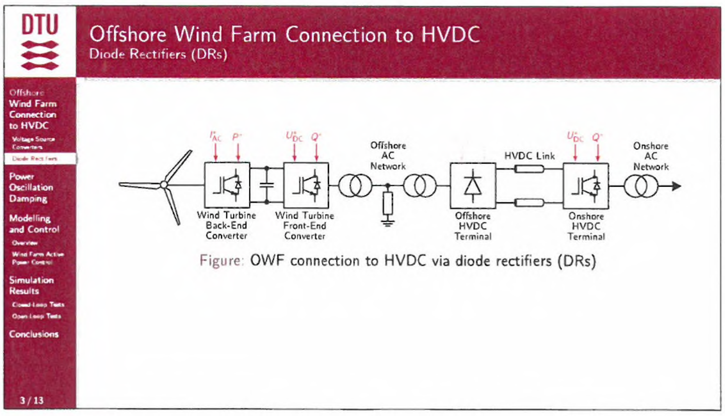
Figure: Offshore VSC connection platforms (approx. 26 000 tons) [Siemens, 2015]



Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

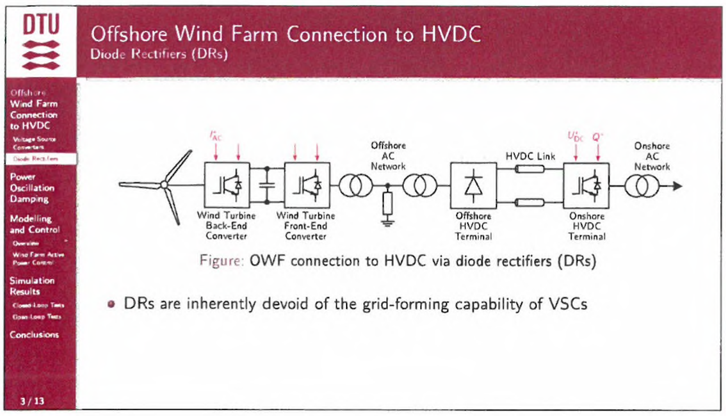
Figure: OWF connection to HVDC via voltage source converters (VSCs)



Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via diode rectifiers (DRs)



Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via diode rectifiers (DRs)

- DRs are inherently devoid of the grid-forming capability of VSCs

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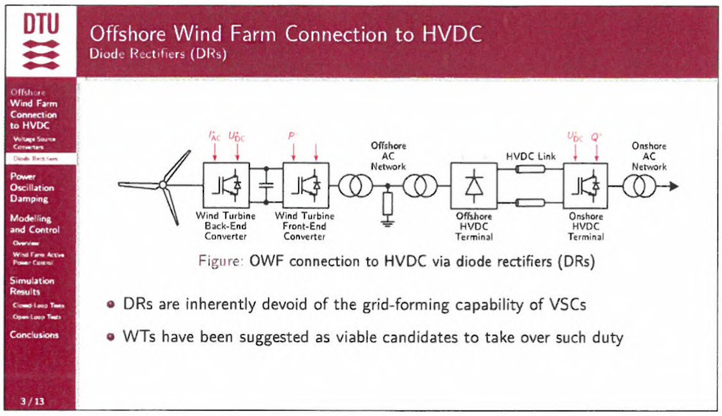


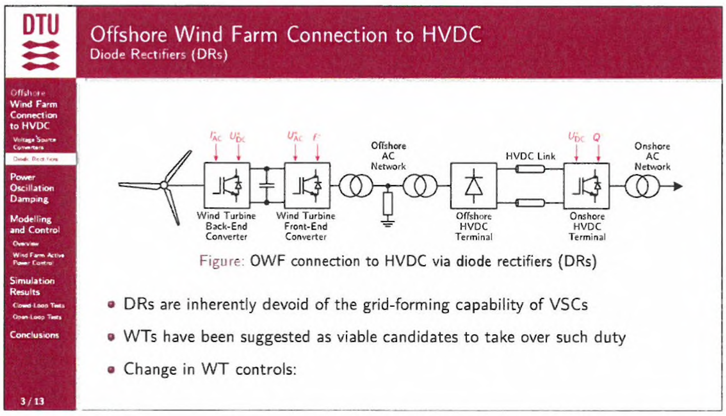
Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via diode rectifiers (DRs)

- DRs are inherently devoid of the grid-forming capability of VSCs
- WTs have been suggested as viable candidates to take over such duty

---

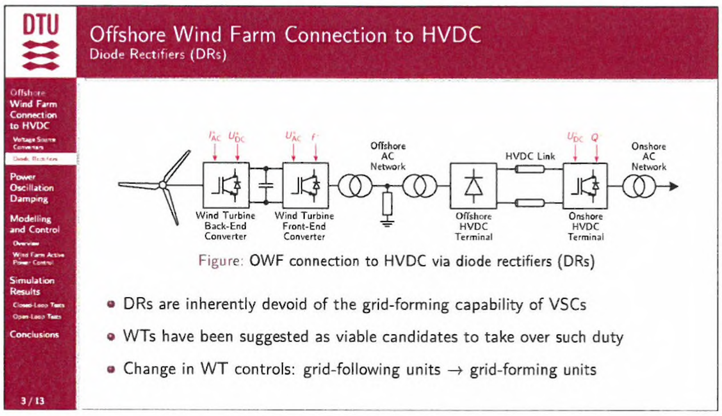


Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via diode rectifiers (DRs)

- DRs are inherently devoid of the grid-forming capability of VSCs
- WTs have been suggested as viable candidates to take over such duty
- Change in WT controls:



Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via diode rectifiers (DRs)

- DRs are inherently devoid of the grid-forming capability of VSCs
- WTs have been suggested as viable candidates to take over such duty
- Change in WT controls: grid-following units → grid-forming units

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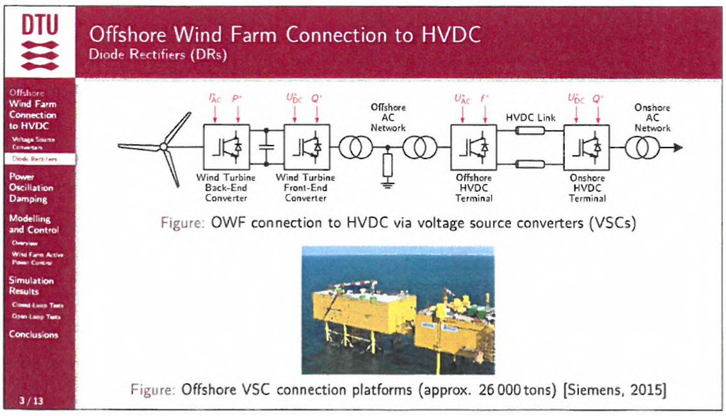
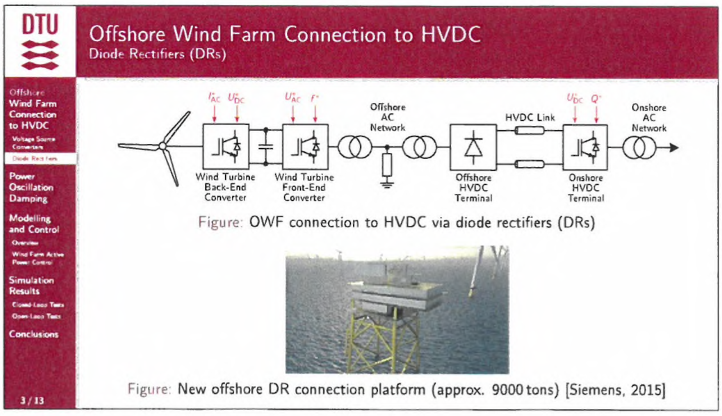


Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via voltage source converters (VSCs)

Figure: Offshore VSC connection platforms (approx. 26 000 tons) [Siemens, 2015]

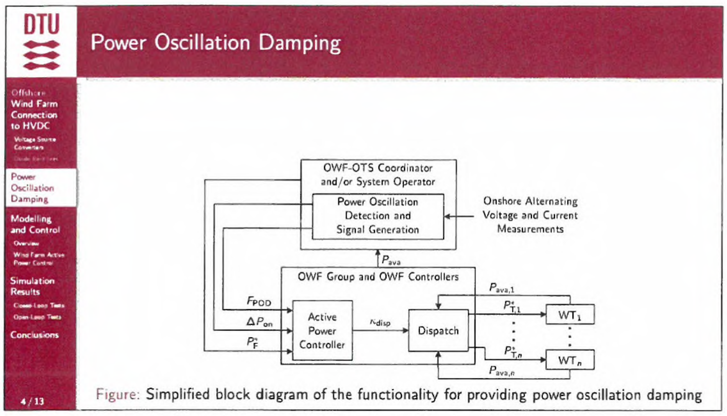


Offshore Wind Farm Connection to HVDC

Diode Rectifiers (DRs)

Figure: OWF connection to HVDC via diode rectifiers (DRs)

Figure: New offshore DR connection platform (approx. 9000 tons) [Siemens, 2015]



Power Oscillation Damping

OWF-OTS Coordinator and/or System Operator

Power Oscillation Detection and Signal Generation

Onshore Alternating Voltage and Current Measurements

P_{ava}

OWF Group and OWF Controllers

F_{POD} ΔP_{on} P_{F}^{*}

Active Power Controller

κ_{disp}

Dispatch

$P_{\text{ava},1}$ $P_{\text{T},1}^{*}$ WT$_1$ $P_{\text{T},n}^{*}$ WT$_n$ $P_{\text{ava},n}$

Figure: Simplified block diagram of the functionality for providing power oscillation damping

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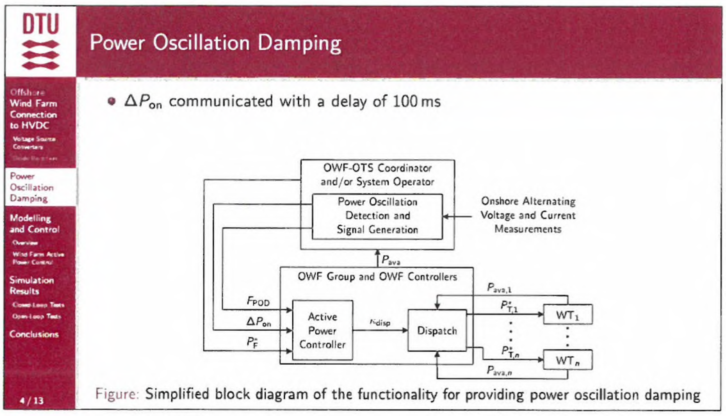

Power Oscillation Damping

- ΔP_{on} communicated with a delay of 100 ms

OWF-OTS Coordinator and/or System Operator

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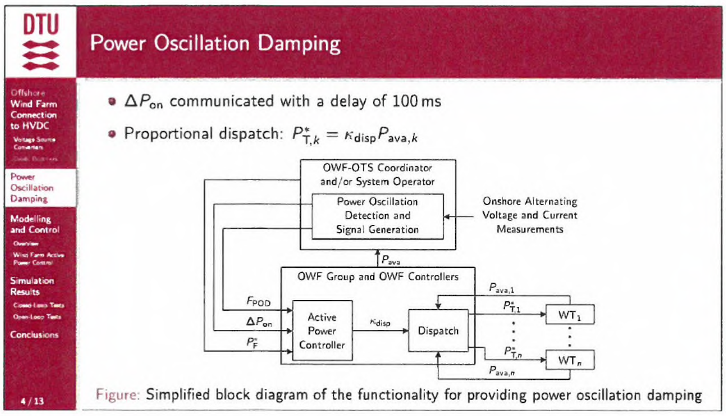
Figure: Simplified block diagram of the functionality for providing power oscillation damping

4 / 13



Power Oscillation Damping

- ΔP_{on} communicated with a delay of 100 ms
- Proportional dispatch: $P_{\text{T},k}^{*} = \kappa_{\text{disp}} P_{\text{ava},k}$

OWF-OTS Coordinator and/or System Operator

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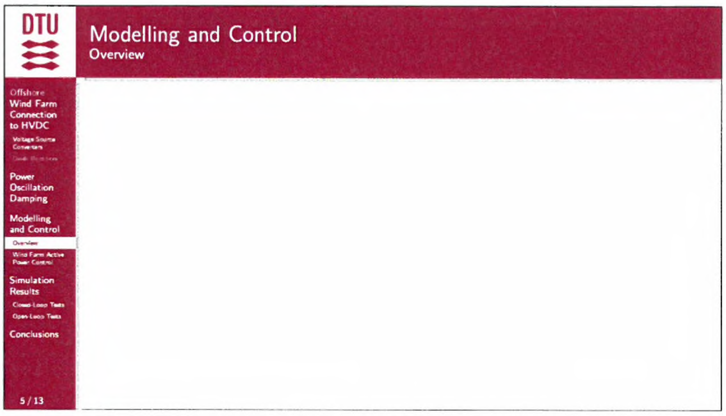
Figure: Simplified block diagram of the functionality for providing power oscillation damping

4 / 13



Modelling and Control

Overview

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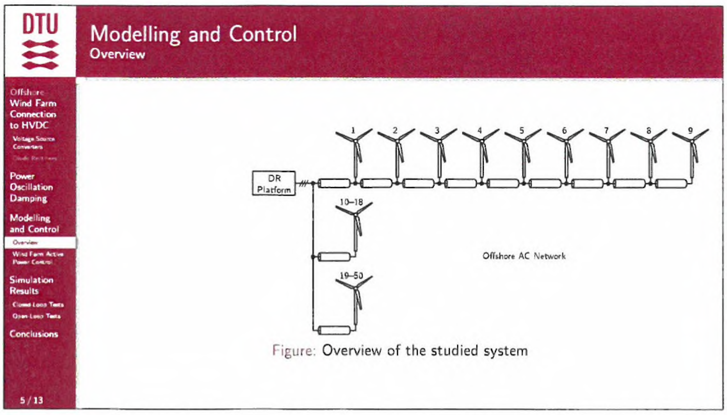
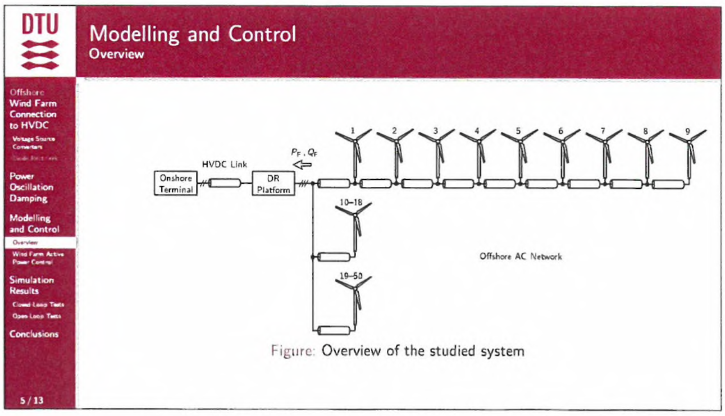


Modelling and Control

Overview

Figure: Overview of the studied system

5 / 13

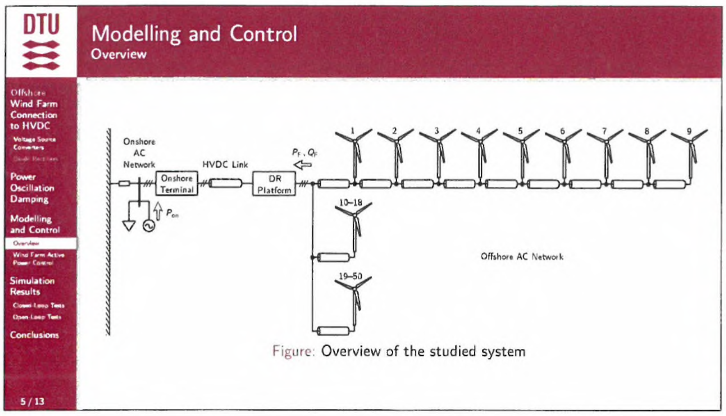


Modelling and Control

Overview

Figure: Overview of the studied system

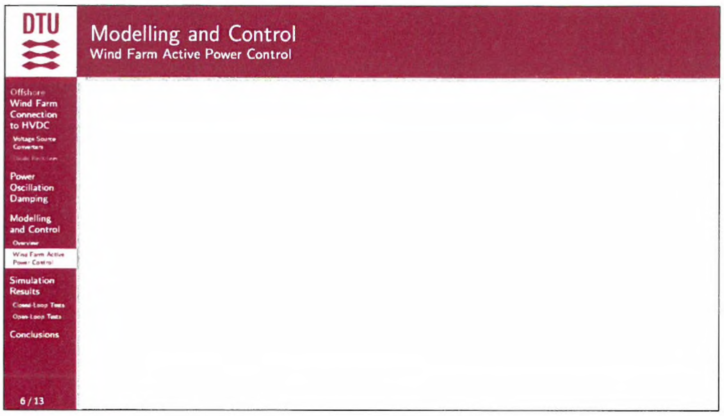
5 / 13



Modelling and Control

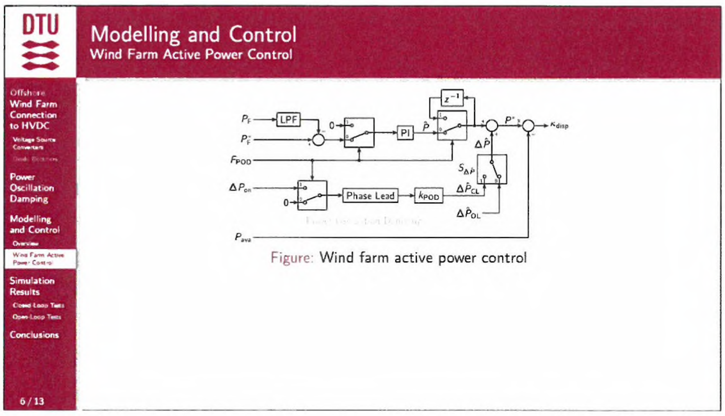
Overview

Figure: Overview of the studied system



Modelling and Control

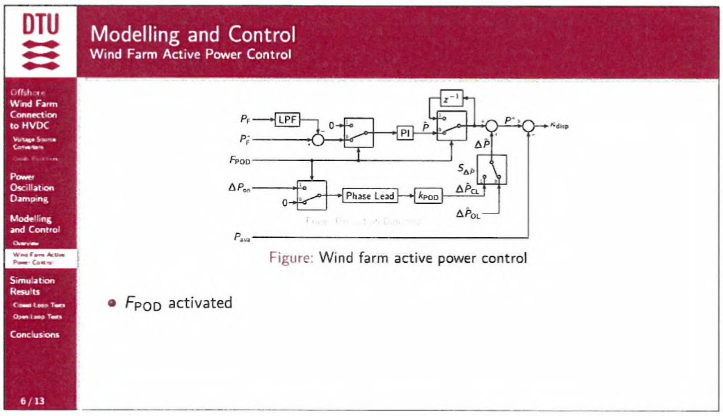
Wind Farm Active Power Control



Modelling and Control

Wind Farm Active Power Control

Figure: Wind farm active power control

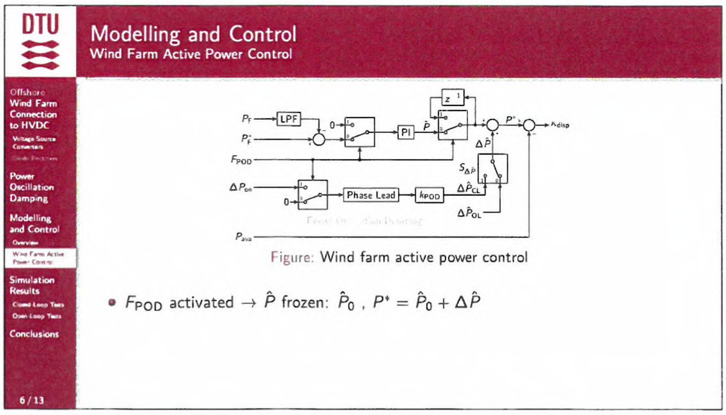


Modelling and Control

Wind Farm Active Power Control

Figure: Wind farm active power control

- F_{POD} activated

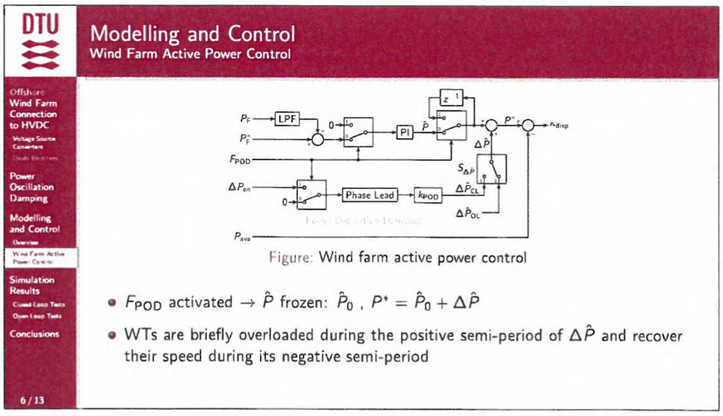


Modelling and Control

Wind Farm Active Power Control

Figure: Wind farm active power control

- F_{POD} activated $\rightarrow$ $\hat{P}$ frozen: $\hat{P}_0$, $P^* = \hat{P}_0 + \Delta\hat{P}$

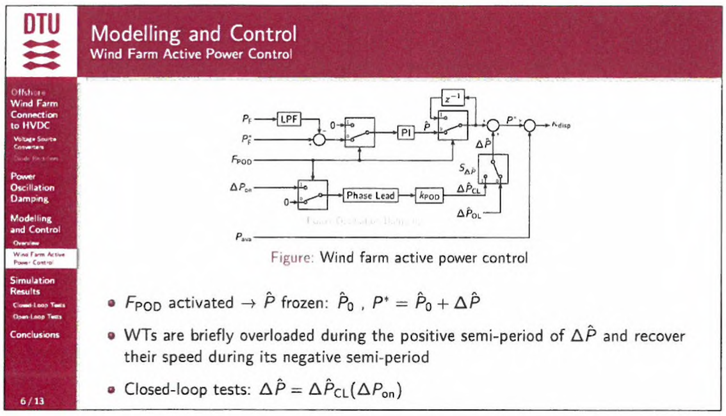


Modelling and Control

Wind Farm Active Power Control

Figure: Wind farm active power control

- F_{POD} activated $\rightarrow$ $\hat{P}$ frozen: $\hat{P}_0$, $P^* = \hat{P}_0 + \Delta\hat{P}$
- WTs are briefly overloaded during the positive semi-period of $\Delta\hat{P}$ and recover their speed during its negative semi-period

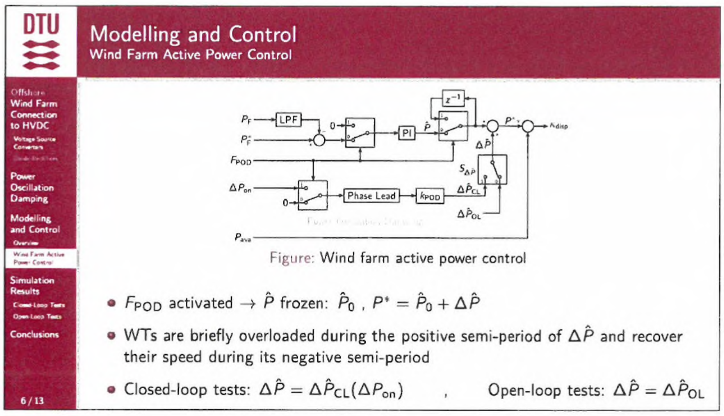


Modelling and Control

Wind Farm Active Power Control

Figure: Wind farm active power control

- F_{POD} activated → $\hat{P}$ frozen: $\hat{P}_0$, $P^* = \hat{P}_0 + \Delta\hat{P}$
- WTs are briefly overloaded during the positive semi-period of $\Delta\hat{P}$ and recover their speed during its negative semi-period
- Closed-loop tests: $\Delta\hat{P} = \Delta\hat{P}_{CL}(\Delta P_{on})$

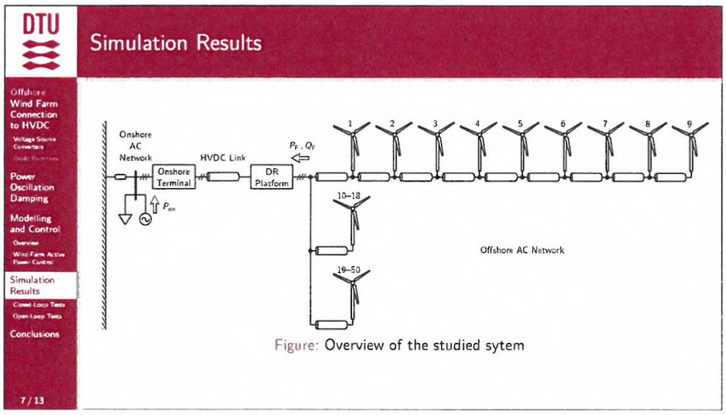


Modelling and Control

Wind Farm Active Power Control

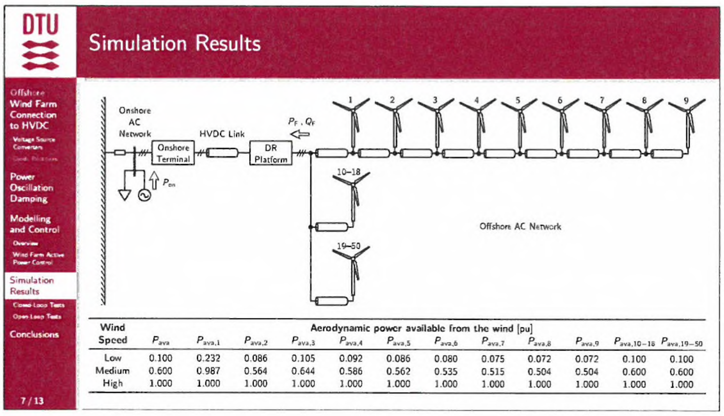
Figure: Wind farm active power control

- F_{POD} activated → $\hat{P}$ frozen: $\hat{P}_0$, $P^* = \hat{P}_0 + \Delta\hat{P}$
- WTs are briefly overloaded during the positive semi-period of $\Delta\hat{P}$ and recover their speed during its negative semi-period
- Closed-loop tests: $\Delta\hat{P} = \Delta\hat{P}_{CL}(\Delta P_{on})$, Open-loop tests: $\Delta\hat{P} = \Delta\hat{P}_{OL}$



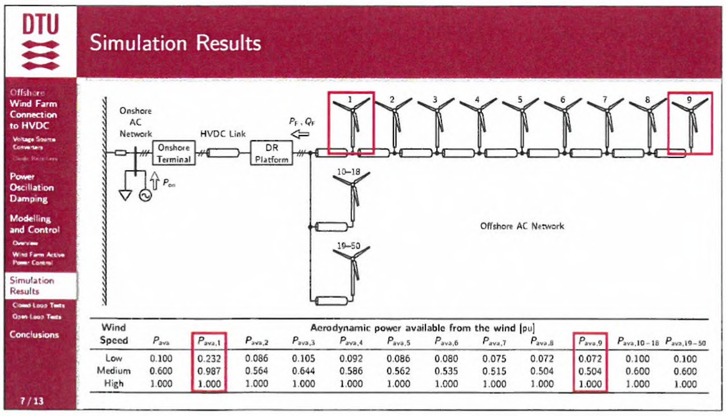
Simulation Results

Figure: Overview of the studied sytem



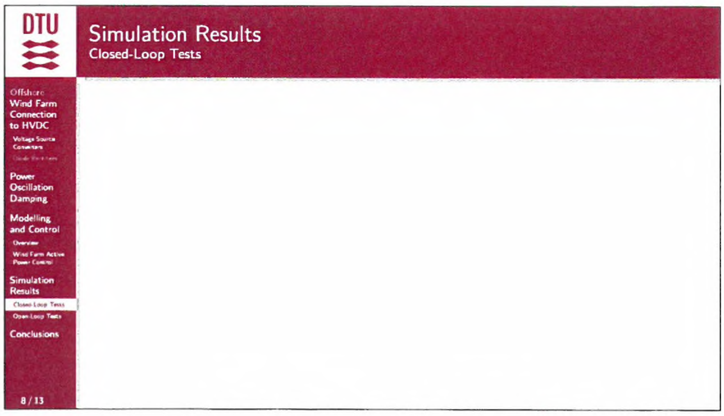
Simulation Results

Wind Speed	Aerodynamic power available from the wind [pu] P_{ava}	$P_{ava,1}$	$P_{ava,2}$	$P_{ava,3}$	$P_{ava,4}$	$P_{ava,5}$	$P_{ava,6}$	$P_{ava,7}$	$P_{ava,8}$	$P_{ava,9}$	$P_{ava,10-18}$	$P_{ava,19-50}$
Low	0.100	0.232	0.086	0.105	0.092	0.086	0.080	0.075	0.072	0.072	0.100	0.100
Medium	0.600	0.987	0.564	0.644	0.586	0.562	0.535	0.515	0.504	0.504	0.600	0.600
High	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000



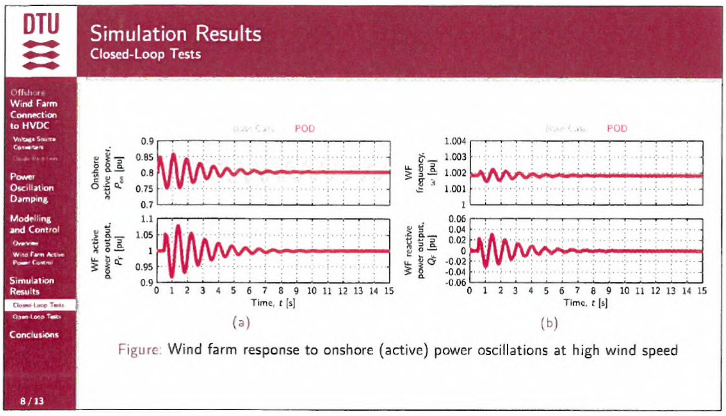
Simulation Results

Wind Speed	Aerodynamic power available from the wind [pu] P_{ava}	$P_{ava,1}$	$P_{ava,2}$	$P_{ava,3}$	$P_{ava,4}$	$P_{ava,5}$	$P_{ava,6}$	$P_{ava,7}$	$P_{ava,8}$	$P_{ava,9}$	$P_{ava,10-18}$	$P_{ava,19-50}$
Low	0.100	0.232	0.086	0.105	0.092	0.086	0.080	0.075	0.072	0.072	0.100	0.100
Medium	0.600	0.987	0.564	0.644	0.586	0.562	0.535	0.515	0.504	0.504	0.600	0.600
High	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000



Simulation Results

Closed-Loop Tests



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(a) (b)

Figure: Wind farm response to onshore (active) power oscillations at high wind speed

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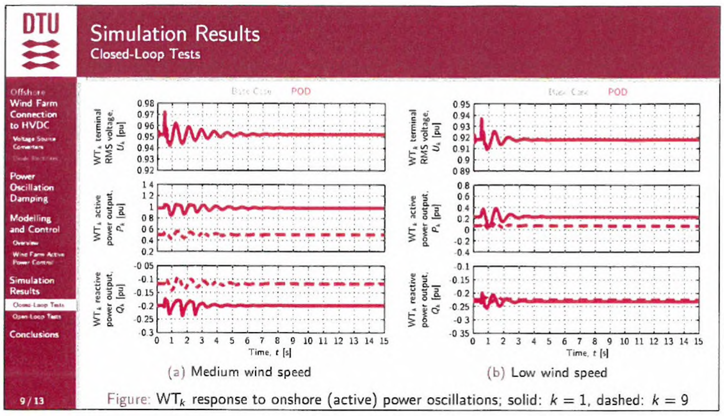

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(a) Medium wind speed (b) Low wind speed

Figure: WT$_k$ response to onshore (active) power oscillations; solid: $k = 1$, dashed: $k = 9$

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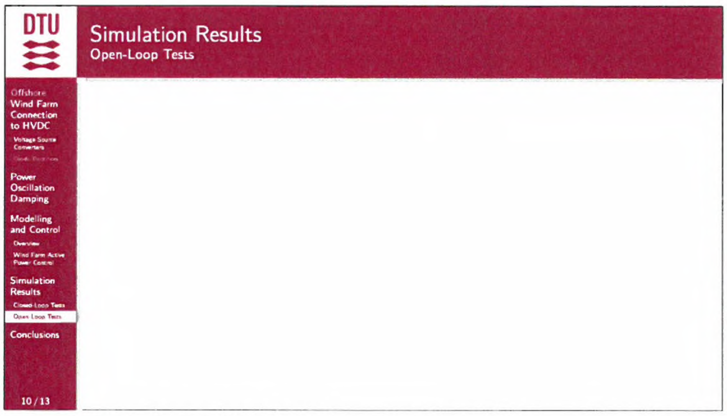

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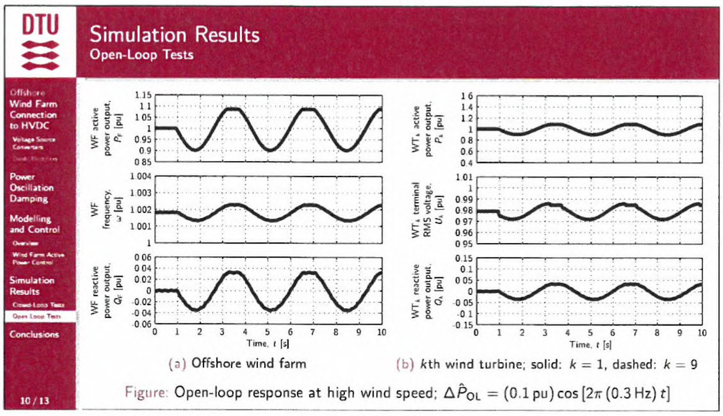

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(a) Offshore wind farm (b) kth wind turbine; solid: $k = 1$, dashed: $k = 9$

Figure: Open-loop response at high wind speed; $\Delta\hat{P}_{\mathrm{OL}} = (0.1\,\mathrm{pu})\cos\left[2\pi\,(0.3\,\mathrm{Hz})\,t\right]$

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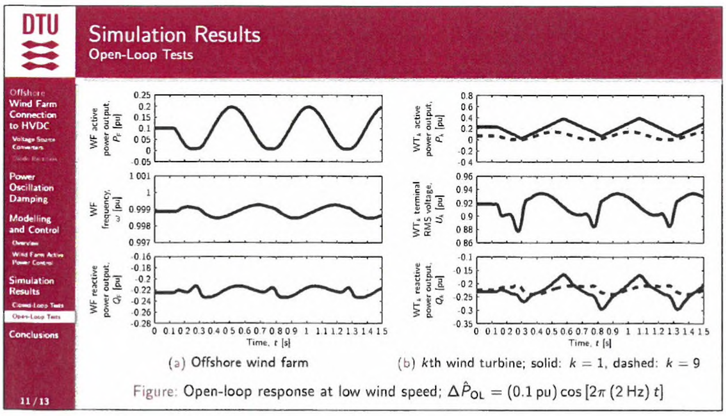

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(a) Offshore wind farm (b) kth wind turbine; solid: $k = 1$, dashed: $k = 9$

Figure: Open-loop response at low wind speed; $\Delta\hat{P}_{\mathrm{OL}} = (0.1\,\mathrm{pu})\cos\left[2\pi\,(2\,\mathrm{Hz})\,t\right]$

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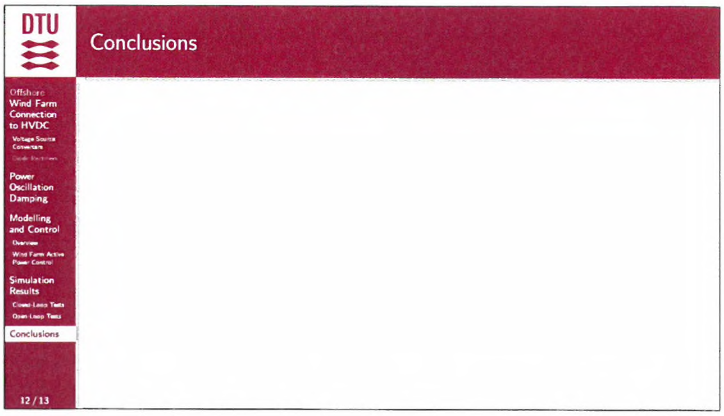

Conclusions

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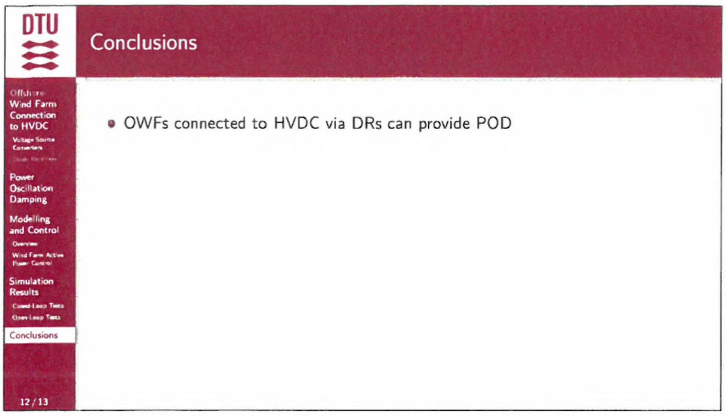

Conclusions

- OWFs connected to HVDC via DRs can provide POD

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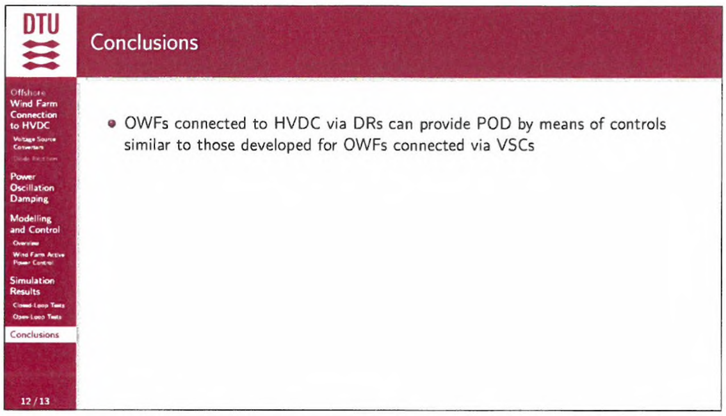

Conclusions

- OWFs connected to HVDC via DRs can provide POD by means of controls similar to those developed for OWFs connected via VSCs

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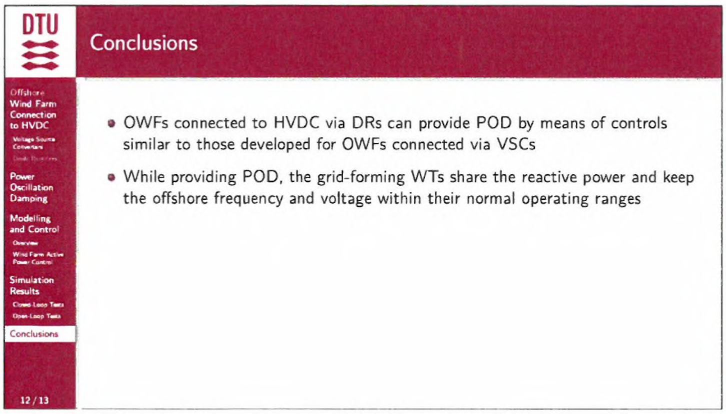

Conclusions

- OWFs connected to HVDC via DRs can provide POD by means of controls similar to those developed for OWFs connected via VSCs
- While providing POD, the grid-forming WTs share the reactive power and keep the offshore frequency and voltage within their normal operating ranges

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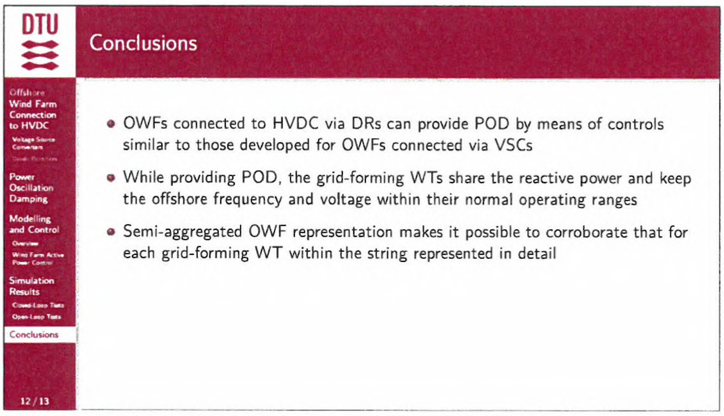

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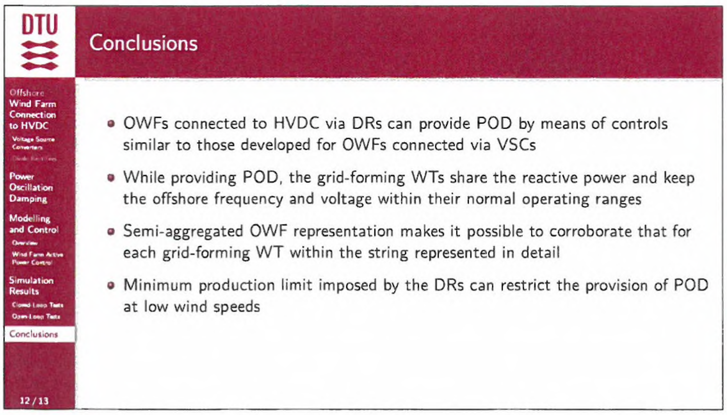

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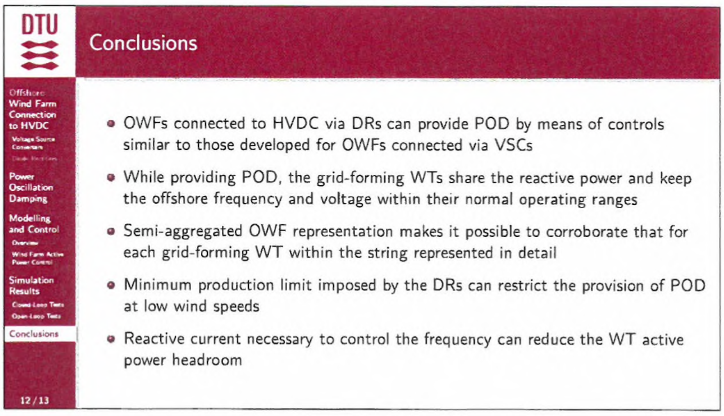

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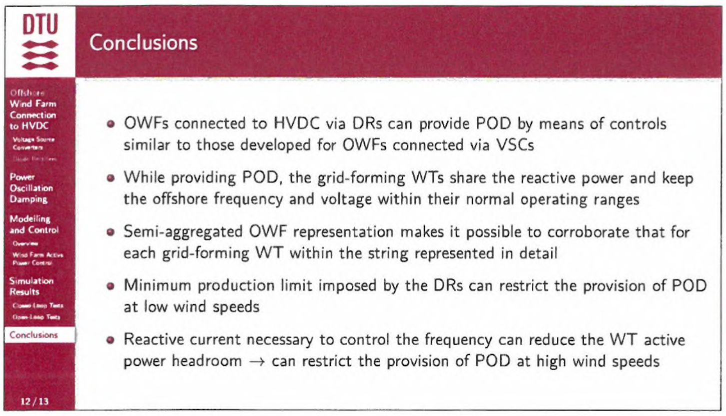

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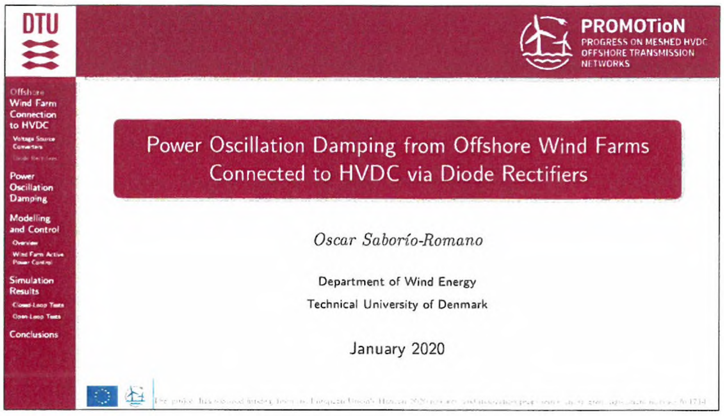


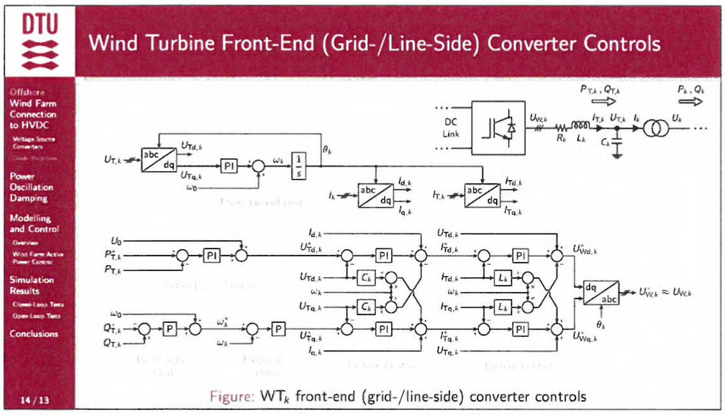
PROMOTioN
PROGRESS ON MESHED HVDC
OFFSHORE TRANSMISSION
NETWORKS

Power Oscillation Damping from Offshore Wind Farms Connected to HVDC via Diode Rectifiers

Oscar Saborío-Romano

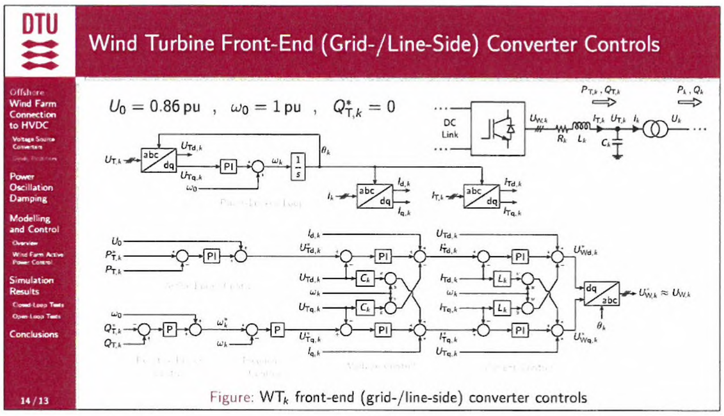
Department of Wind Energy
Technical University of Denmark

January 2020



Wind Turbine Front-End (Grid-/Line-Side) Converter Controls

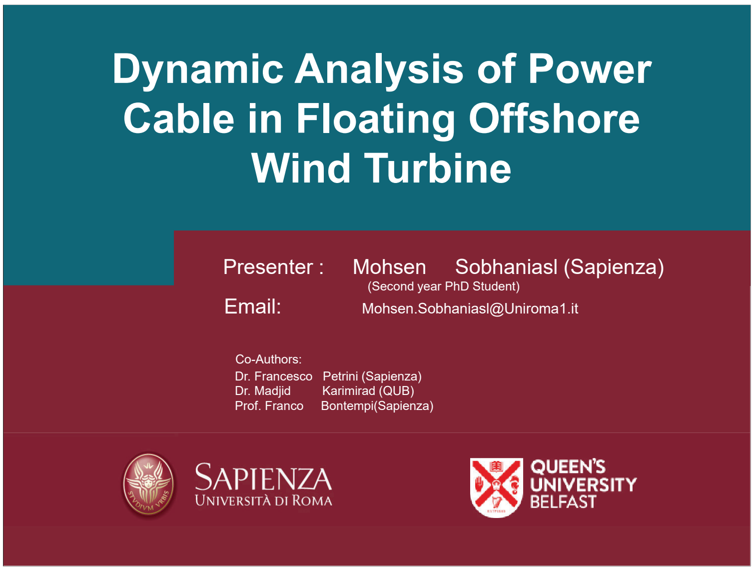
Figure: WT_k front-end (grid-/line-side) converter controls



Wind Turbine Front-End (Grid-/Line-Side) Converter Controls

$U_0 = 0.86\,\text{pu}$, $\omega_0 = 1\,\text{pu}$, $Q^*_{T,k} = 0$

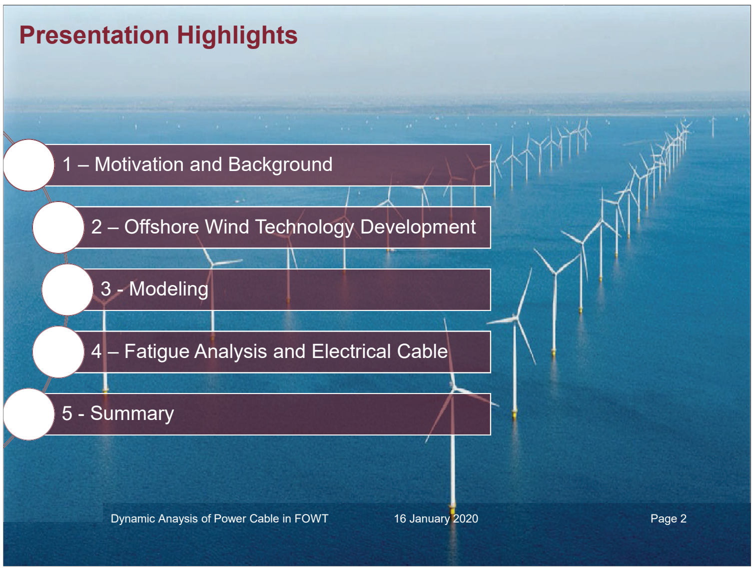
Figure: WT_k front-end (grid-/line-side) converter controls



Dynamic Analysis of Power Cable in Floating Offshore Wind Turbine

Presenter : Mohsen Sobhaniasl (Sapienza)
(Second year PhD Student)
Email: Mohsen.Sobhaniasl@Uniroma1.it

Co-Authors:
Dr. Francesco Petrini (Sapienza)
Dr. Madjid Karimirad (QUB)
Prof. Franco Bontempi(Sapienza)



Presentation Highlights

- 1 – Motivation and Background
- 2 – Offshore Wind Technology Development
- 3 - Modeling
- 4 – Fatigue Analysis and Electrical Cable
- 5 - Summary

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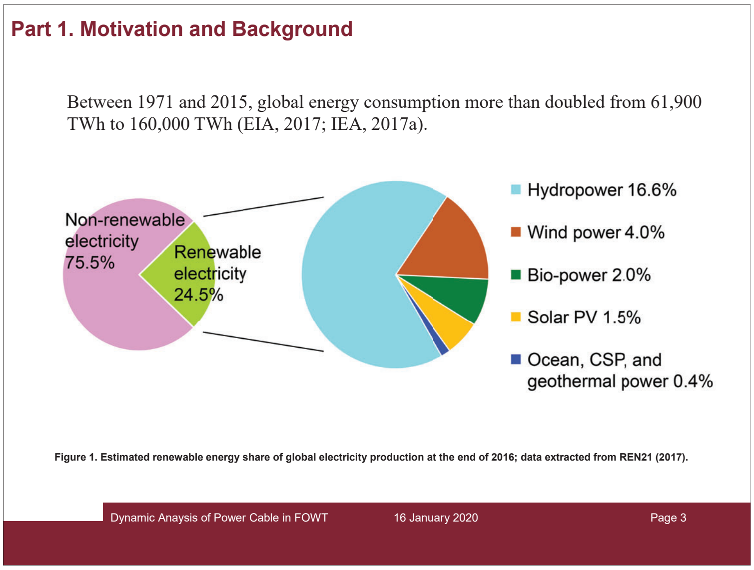

Part 1. Motivation and Background

Between 1971 and 2015, global energy consumption more than doubled from 61,900 TWh to 160,000 TWh (EIA, 2017; IEA, 2017a).

Figure 1. Estimated renewable energy share of global electricity production at the end of 2016; data extracted from REN21 (2017).

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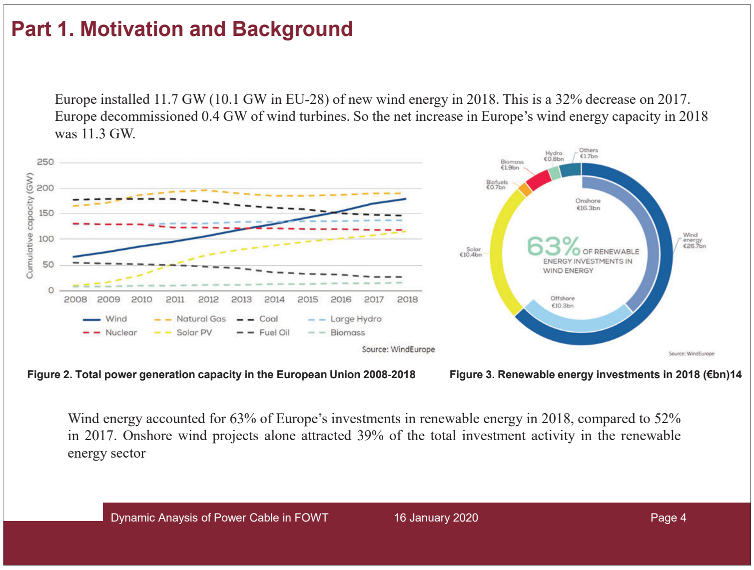

Part 1. Motivation and Background

Europe installed 11.7 GW (10.1 GW in EU-28) of new wind energy in 2018. This is a 32% decrease on 2017. Europe decommissioned 0.4 GW of wind turbines. So the net increase in Europe's wind energy capacity in 2018 was 11.3 GW.

Source: WindEurope

Source: WindEurope

Figure 2. Total power generation capacity in the European Union 2008-2018

Figure 3. Renewable energy investments in 2018 (€bn)14

Wind energy accounted for 63% of Europe's investments in renewable energy in 2018, compared to 52% in 2017. Onshore wind projects alone attracted 39% of the total investment activity in the renewable energy sector

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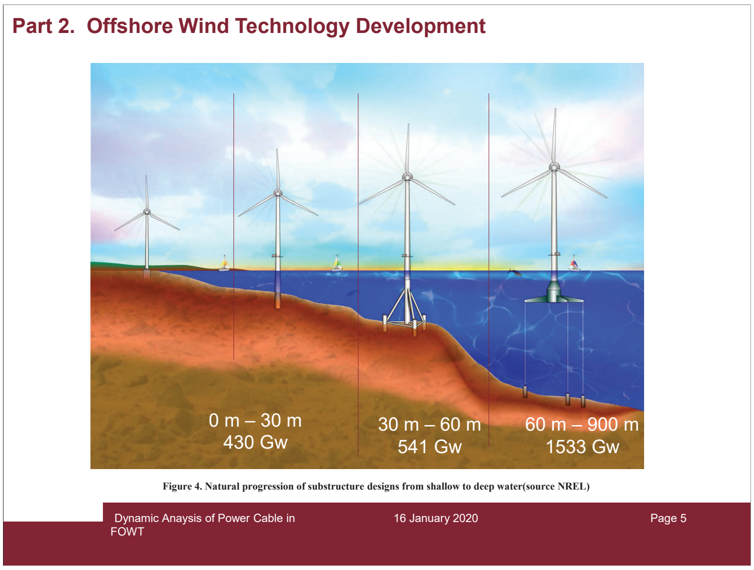

Part 2. Offshore Wind Technology Development

Figure 4. Natural progression of substructure designs from shallow to deep water(source NREL)

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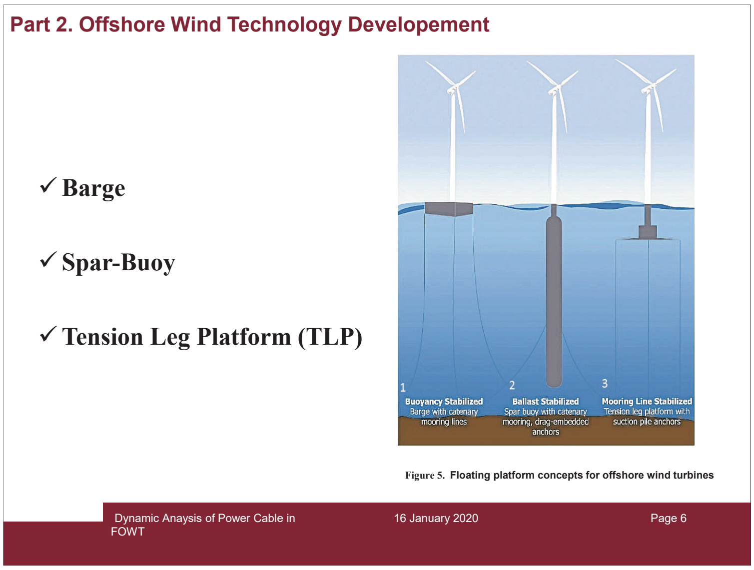

Part 2. Offshore Wind Technology Developement

- ✓ **Barge**
- ✓ **Spar-Buoy**
- ✓ **Tension Leg Platform (TLP)**

Figure 5. Floating platform concepts for offshore wind turbines

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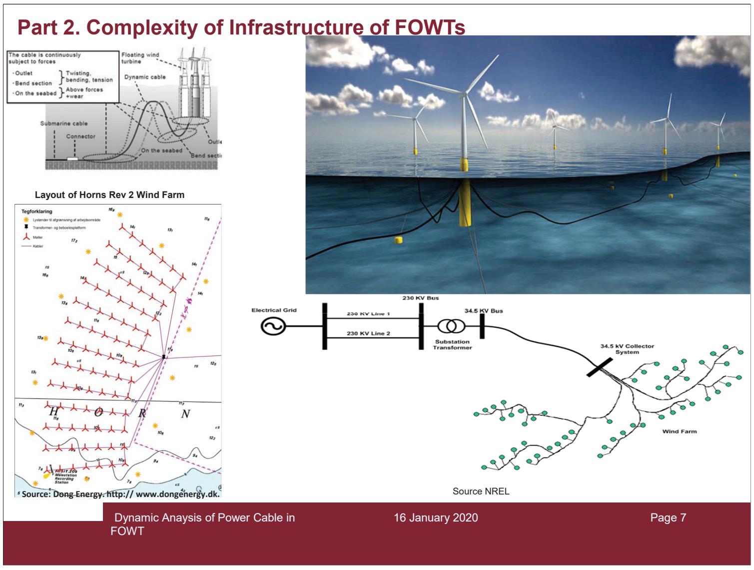
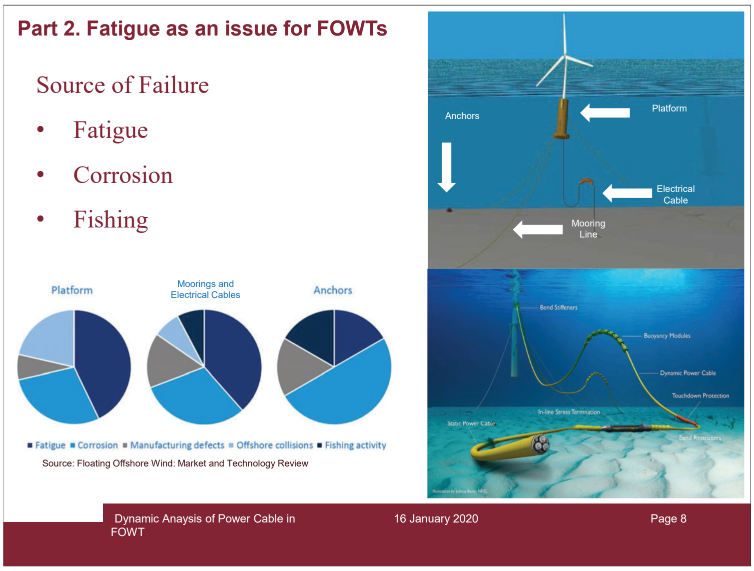


Part 2. Complexity of Infrastructure of FOWTs

Layout of Horns Rev 2 Wind Farm

Source: Dong Energy. http:// www.dongenergy.dk.

Source NREL



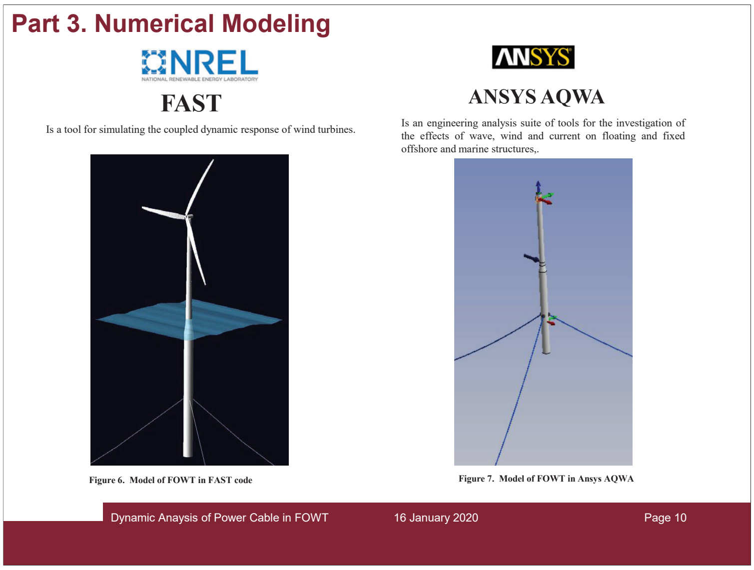
Part 2. Fatigue as an issue for FOWTs

Source of Failure

- Fatigue
- Corrosion
- Fishing

Source: Floating Offshore Wind: Market and Technology Review

Modeling



Part 3. Numerical Modeling

FAST

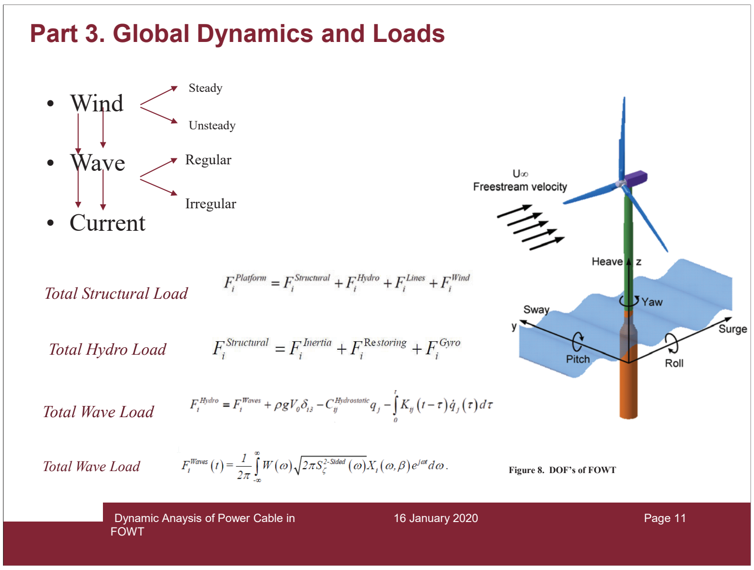
Is a tool for simulating the coupled dynamic response of wind turbines.

Figure 6. Model of FOWT in FAST code

ANSYS AQWA

Is an engineering analysis suite of tools for the investigation of the effects of wave, wind and current on floating and fixed offshore and marine structures,.

Figure 7. Model of FOWT in Ansys AQWA



Part 3. Global Dynamics and Loads

- Wind
  - Steady
  - Unsteady
- Wave
  - Regular
  - Irregular
- Current

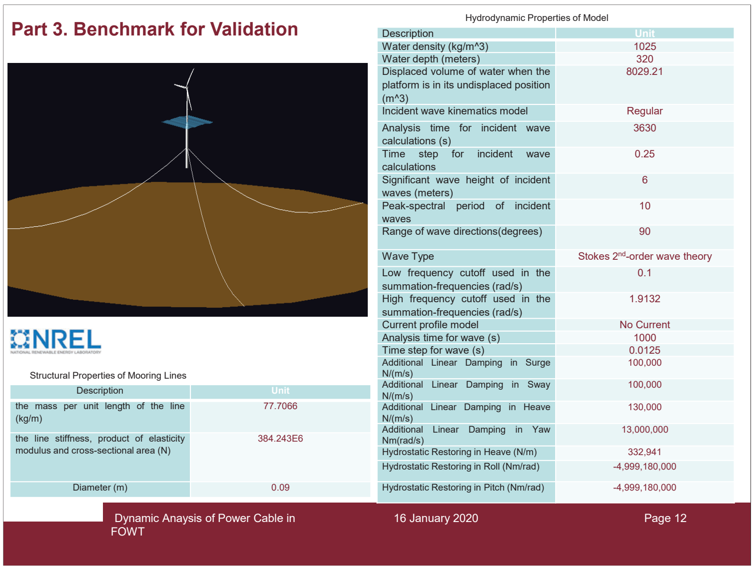
Figure 8. DOF's of FOWT

Total Structural Load $F_i^{Platform} = F_i^{Structural} + F_i^{Hydro} + F_i^{Lines} + F_i^{Wind}$

Total Hydro Load $F_i^{Structural} = F_i^{Inertia} + F_i^{Restoring} + F_i^{Gyro}$

Total Wave Load $F_i^{Hydro} = F_i^{Waves} + \rho g V_0 \delta_{i3} - C_{ij}^{Hydrostatic} q_j - \int_0^t K_{ij}(t-\tau)\dot{q}_j(\tau)d\tau$

Total Wave Load $F_i^{Waves}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} W(\omega)\sqrt{2\pi S_{\zeta}^{2\text{-}Sided}(\omega)}X_i(\omega,\beta)e^{j\omega t}d\omega.$



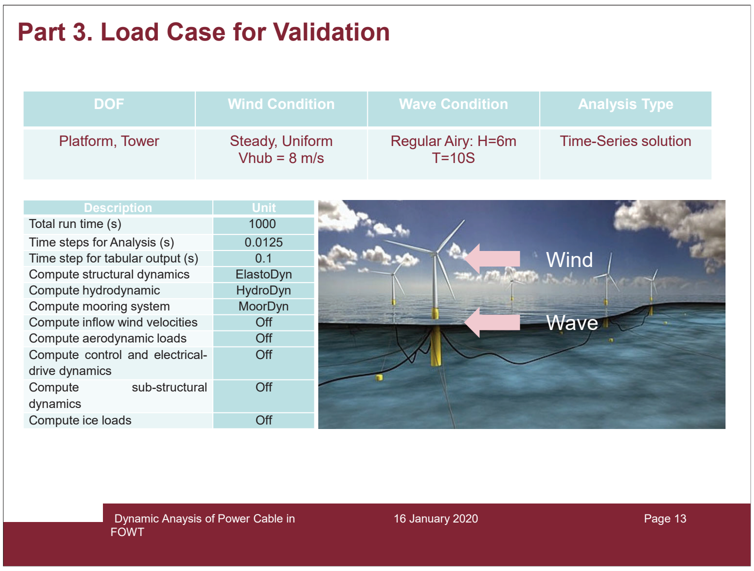
Part 3. Benchmark for Validation

Structural Properties of Mooring Lines

Description	Unit
the mass per unit length of the line (kg/m)	77.7066
the line stiffness, product of elasticity modulus and cross-sectional area (N)	384.243E6
Diameter (m)	0.09

Hydrodynamic Properties of Model

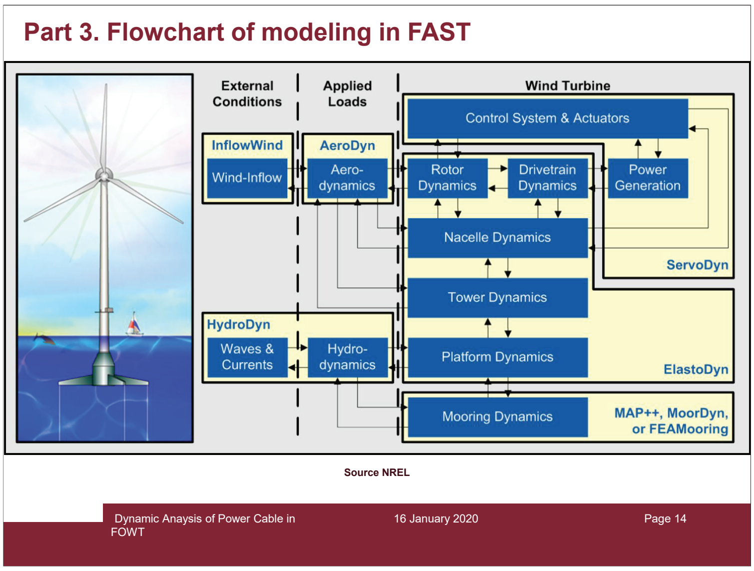
Description	Unit
Water density (kg/m^3)	1025
Water depth (meters)	320
Displaced volume of water when the platform is in its undisplaced position (m^3)	8029.21
Incident wave kinematics model	Regular
Analysis time for incident wave calculations (s)	3630
Time step for incident wave calculations	0.25
Significant wave height of incident waves (meters)	6
Peak-spectral period of incident waves	10
Range of wave directions(degrees)	90
Wave Type	Stokes 2nd-order wave theory
Low frequency cutoff used in the summation-frequencies (rad/s)	0.1
High frequency cutoff used in the summation-frequencies (rad/s)	1.9132
Current profile model	No Current
Analysis time for wave (s)	1000
Time step for wave (s)	0.0125
Additional Linear Damping in Surge N/(m/s)	100,000
Additional Linear Damping in Sway N/(m/s)	100,000
Additional Linear Damping in Heave N/(m/s)	130,000
Additional Linear Damping in Yaw Nm(rad/s)	13,000,000
Hydrostatic Restoring in Heave (N/m)	332,941
Hydrostatic Restoring in Roll (Nm/rad)	-4,999,180,000
Hydrostatic Restoring in Pitch (Nm/rad)	-4,999,180,000



Part 3. Load Case for Validation

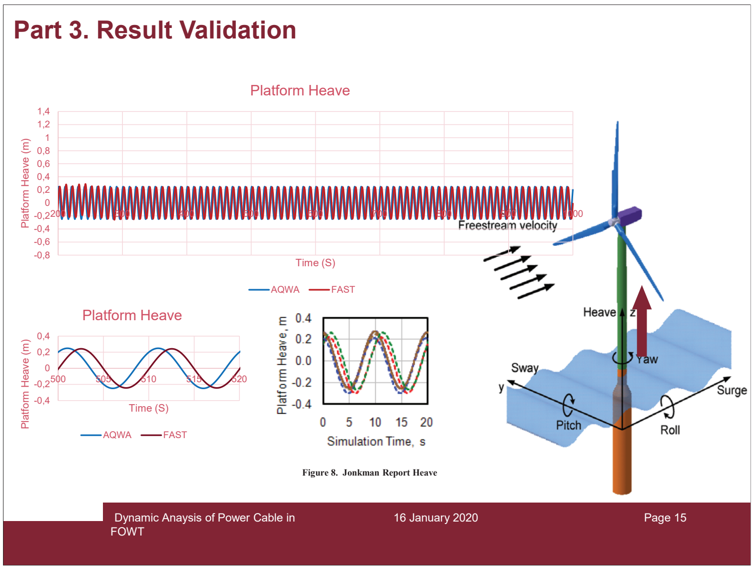
DOF	Wind Condition	Wave Condition	Analysis Type
Platform, Tower	Steady, Uniform Vhub = 8 m/s	Regular Airy: H=6m T=10S	Time-Series solution

Description	Unit
Total run time (s)	1000
Time steps for Analysis (s)	0.0125
Time step for tabular output (s)	0.1
Compute structural dynamics	ElastoDyn
Compute hydrodynamic	HydroDyn
Compute mooring system	MoorDyn
Compute inflow wind velocities	Off
Compute aerodynamic loads	Off
Compute control and electrical-drive dynamics	Off
Compute sub-structural dynamics	Off
Compute ice loads	Off



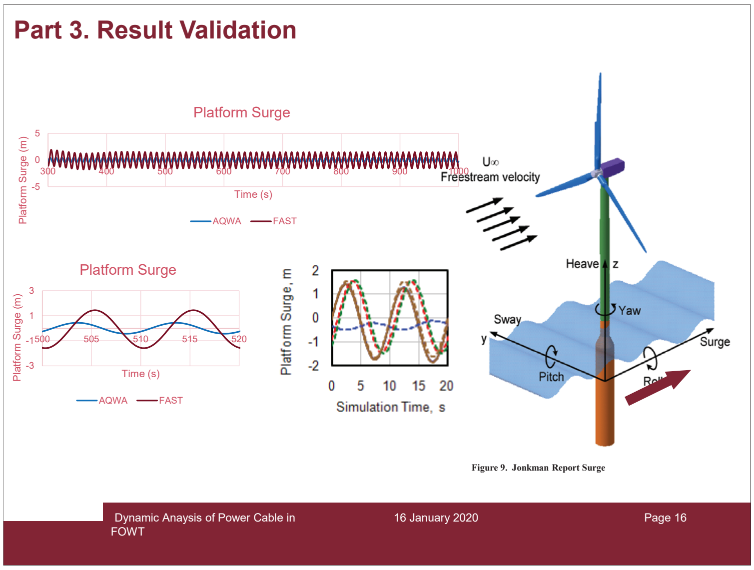
Part 3. Flowchart of modeling in FAST

Source NREL



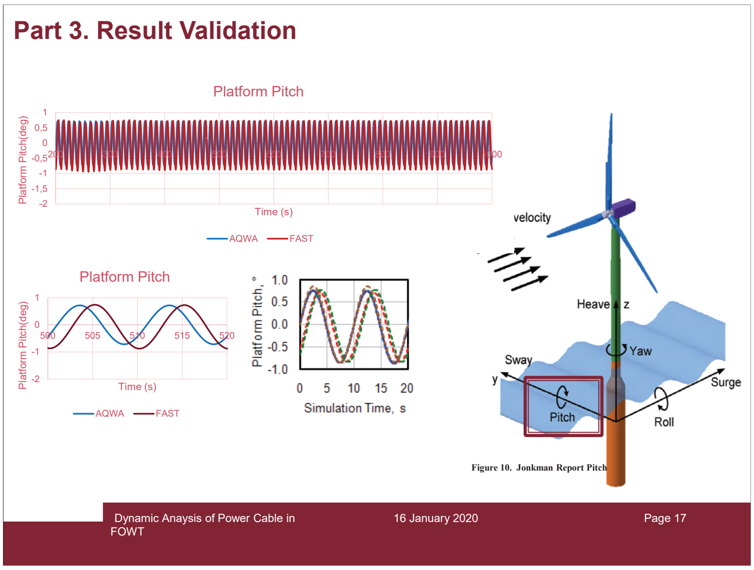
Part 3. Result Validation

Figure 8. Jonkman Report Heave



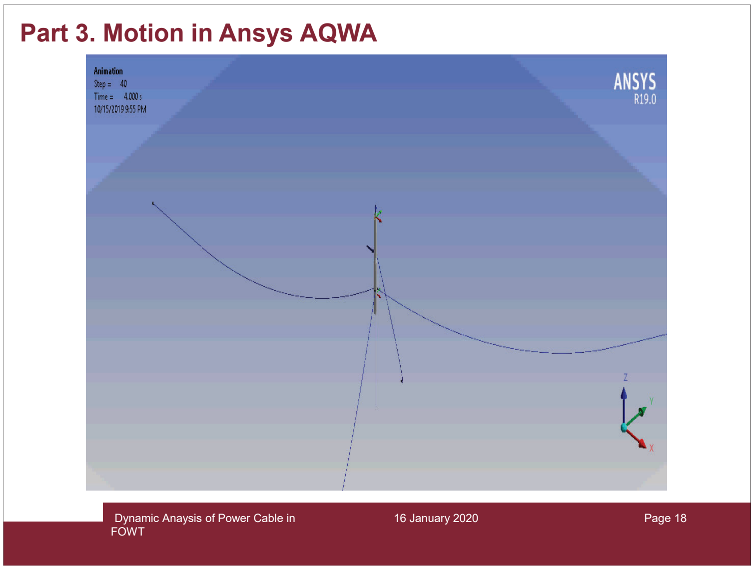
Part 3. Result Validation

Figure 9. Jonkman Report Surge

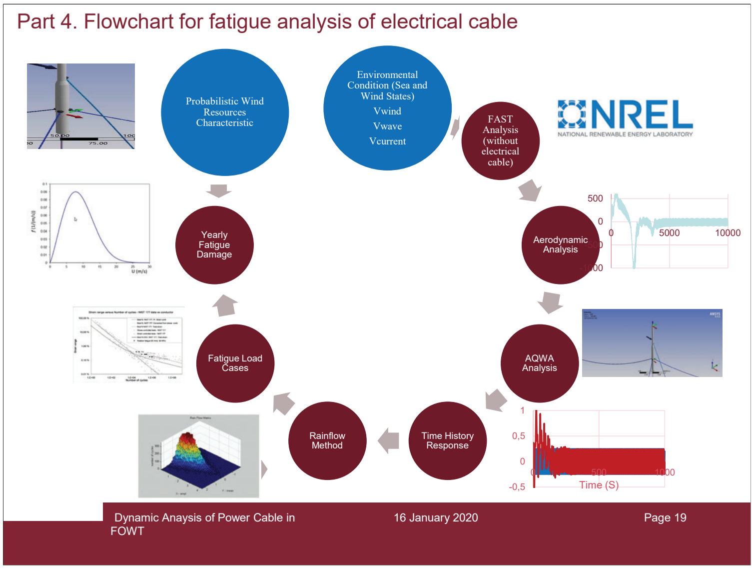


Part 3. Result Validation

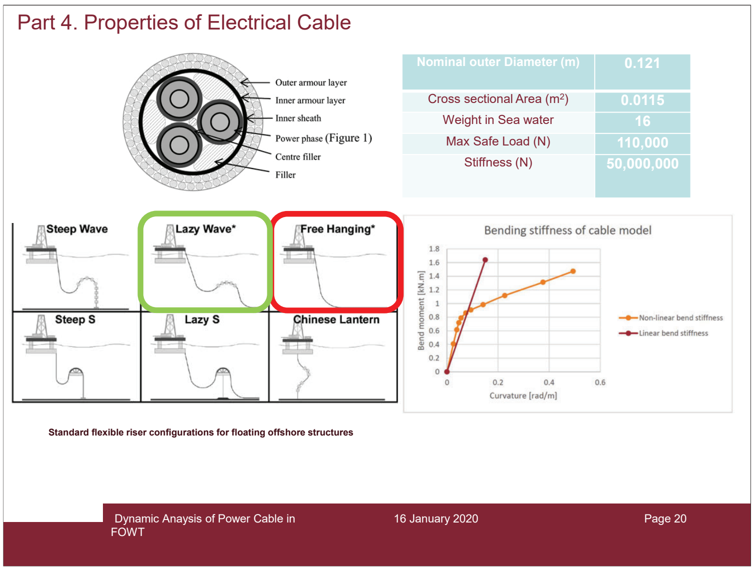
Figure 10. Jonkman Report Pitch



Part 3. Motion in Ansys AQWA



Part 4. Flowchart for fatigue analysis of electrical cable

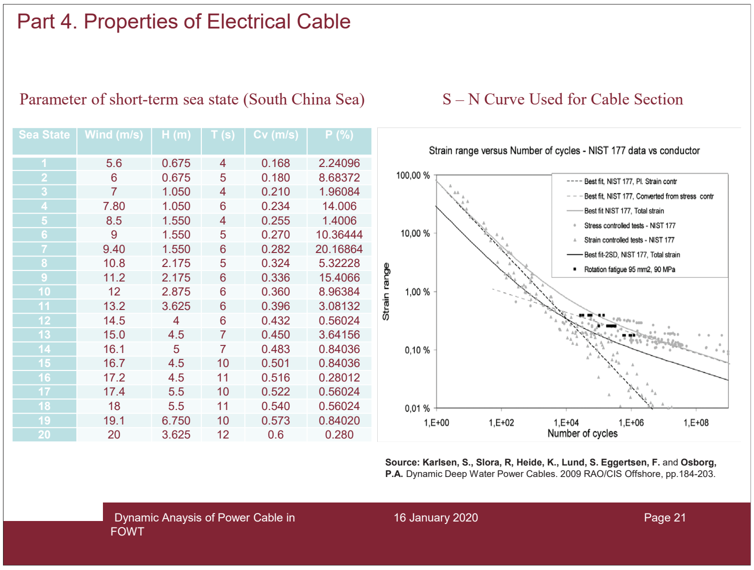


Part 4. Properties of Electrical Cable

Nominal outer Diameter (m)	0.121
Cross sectional Area (m^2)	0.0115
Weight in Sea water	16
Max Safe Load (N)	110,000
Stiffness (N)	50,000,000

Standard flexible riser configurations for floating offshore structures

Bending stiffness of cable model



Part 4. Properties of Electrical Cable

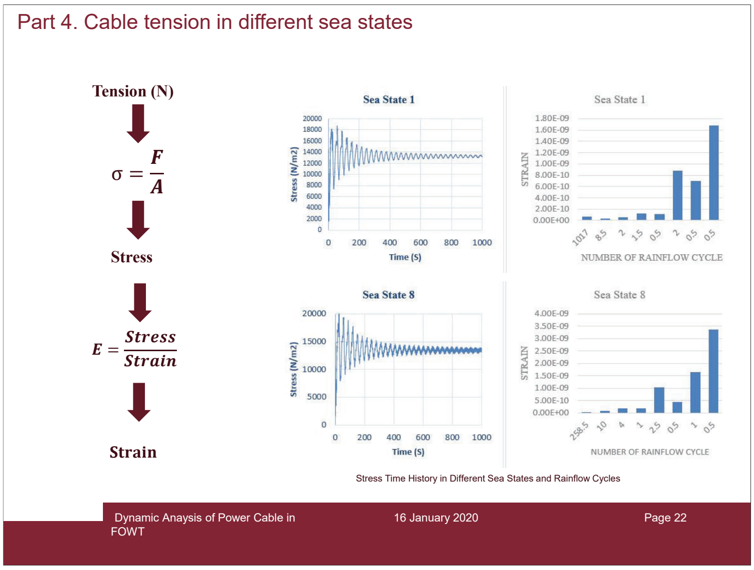
Parameter of short-term sea state (South China Sea)

Sea State	Wind (m/s)	H (m)	T (s)	Cv (m/s)	P (%)
1	5.6	0.675	4	0.168	2.24096
2	6	0.675	5	0.180	8.68372
3	7	1.050	4	0.210	1.96084
4	7.80	1.050	6	0.234	14.006
5	8.5	1.550	4	0.255	1.4006
6	9	1.550	5	0.270	10.36444
7	9.40	1.550	6	0.282	20.16864
8	10.8	2.175	5	0.324	5.32228
9	11.2	2.175	6	0.336	15.4066
10	12	2.875	6	0.360	8.96384
11	13.2	3.625	6	0.396	3.08132
12	14.5	4	6	0.432	0.56024
13	15.0	4.5	7	0.450	3.64156
14	16.1	5	7	0.483	0.84036
15	16.7	4.5	10	0.501	0.84036
16	17.2	4.5	11	0.516	0.28012
17	17.4	5.5	10	0.522	0.56024
18	18	5.5	11	0.540	0.56024
19	19.1	6.750	10	0.573	0.84020
20	20	3.625	12	0.6	0.280

S – N Curve Used for Cable Section

Strain range versus Number of cycles - NIST 177 data vs conductor

Source: Karlsen, S., Slora, R, Heide, K., Lund, S. Eggertsen, F. and **Osborg, P.A.** Dynamic Deep Water Power Cables. 2009 RAO/CIS Offshore, pp.184-203.



Part 4. Cable tension in different sea states

Tension (N)

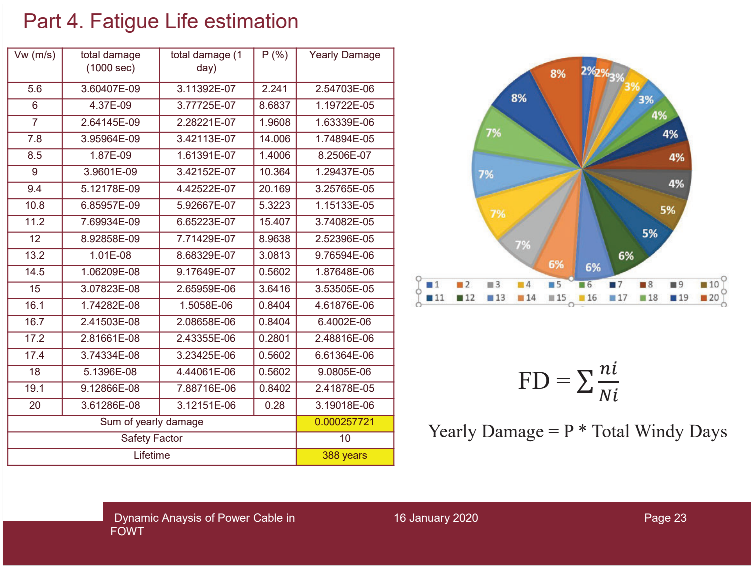
$$\sigma = \frac{F}{A}$$

Stress

$$E = \frac{Stress}{Strain}$$

Strain

Stress Time History in Different Sea States and Rainflow Cycles



Part 4. Fatigue Life estimation

Vw (m/s)	total damage (1000 sec)	total damage (1 day)	P (%)	Yearly Damage
5.6	3.60407E-09	3.11392E-07	2.241	2.54703E-06
6	4.37E-09	3.77725E-07	8.6837	1.19722E-05
7	2.64145E-09	2.28221E-07	1.9608	1.63339E-06
7.8	3.95964E-09	3.42113E-07	14.006	1.74894E-05
8.5	1.87E-09	1.61391E-07	1.4006	8.2506E-07
9	3.9601E-09	3.42152E-07	10.364	1.29437E-05
9.4	5.12178E-09	4.42522E-07	20.169	3.25765E-05
10.8	6.85957E-09	5.92667E-07	5.3223	1.15133E-05
11.2	7.69934E-09	6.65223E-07	15.407	3.74082E-05
12	8.92858E-09	7.71429E-07	8.9638	2.52396E-05
13.2	1.01E-08	8.68329E-07	3.0813	9.76594E-06
14.5	1.06209E-08	9.17649E-07	0.5602	1.87648E-06
15	3.07823E-08	2.65959E-06	3.6416	3.53505E-05
16.1	1.74282E-08	1.5058E-06	0.8404	4.61876E-06
16.7	2.41503E-08	2.08658E-06	0.8404	6.4002E-06
17.2	2.81661E-08	2.43355E-06	0.2801	2.48816E-06
17.4	3.74334E-08	3.23425E-06	0.5602	6.61364E-06
18	5.1396E-08	4.44061E-06	0.5602	9.0805E-06
19.1	9.12866E-08	7.88716E-06	0.8402	2.41878E-05
20	3.61286E-08	3.12151E-06	0.28	3.19018E-06
Sum of yearly damage				0.000257721
Safety Factor				10
Lifetime				388 years

$$FD = \sum \frac{ni}{Ni}$$

Yearly Damage = P * Total Windy Days

In Process

- More Sea States and Different Seed Numbers
- Considering Bending Stiffness
- Modeling Lazy Wave Configuration for the cable

Future

- Using Irregular sea states

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Thanks for Your Attention

B2) Grid connection and power system integration

Can levelised revenues from auctions be used to deduct levelised cost of offshore wind farms? The case of Kriegers Flak, L.Kitzing, DTU

Measuring cost reductions of offshore wind using European offshore auctions, L.Kitzing, DTU
Presentation not available

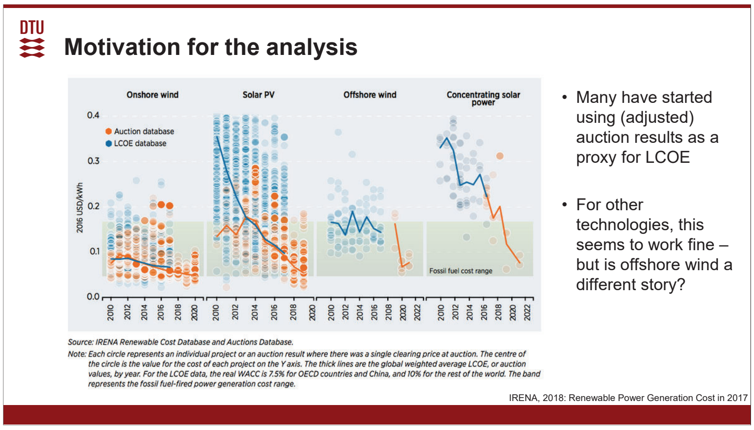
Forecasting Wind Power as a Dispatchable Generation Source for Grid Frequency Control, L.May, Strathclyde University

Surrogate model of offshore farm to farm wake effects for large scale energy system applications, J.P.Murcia, DTU

Can levelised revenues from auctions be used to deduct levelised cost of offshore wind farms? The case of Kriegers Flak

DeepWind 2020

Lena Kitzing
Energy Economics and Regulation Group
Department of Technology, Management and Economics



Motivation for the analysis

Source: IRENA Renewable Cost Database and Auctions Database.
Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

IRENA, 2018: Renewable Power Generation Cost in 2017

- Many have started using (adjusted) auction results as a proxy for LCOE
- For other technologies, this seems to work fine – but is offshore wind a different story?

Levelised Cost of Energy (LCOE) and Levelised Revenue of Energy (LROE)

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n} \frac{\mathrm{TC}_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{q_t}{(1+r)^t}}$$

Average, per production unit, discounted costs over the project's lifetime

$$\mathrm{LROE} = \frac{\sum_{t=0}^{n} \frac{\mathrm{TR}_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{q_t}{(1+r)^t}}$$

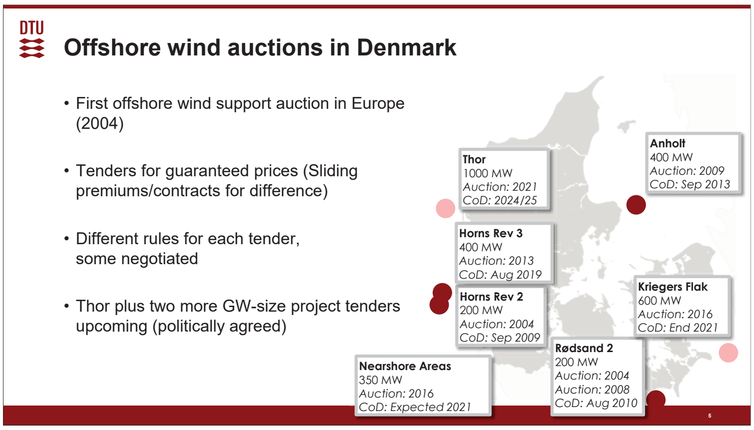
Average, per production unit, discounted revenues over the project's lifetime

Note: both can be derived pre-tax or post-tax and real or nominal

Levelised Cost of Energy (LCOE) and Levelised Revenue of Energy (LROE)

Argumentation:

- In a competitive market environment, LCOE should be directly reflected in LROE (as long as all revenue and all cost items are adequately considered).
- In competitive auction environments, investors are incentivised to reveal their 'true cost' in bids for required support levels (no expected losses or excessive profits).
- LROE can then be derived from auction results and used as a central element for estimating cost as well as calibrating input assumptions for bottom-up cost modeling.
- Offshore wind should be especially suited for this approach, because auctions are specific for projects, and much information is available.



Offshore wind auctions in Denmark

- First offshore wind support auction in Europe (2004)
- Tenders for guaranteed prices (Sliding premiums/contracts for difference)
- Different rules for each tender, some negotiated
- Thor plus two more GW-size project tenders upcoming (politically agreed)

Thor
1000 MW
Auction: 2021
CoD: 2024/25

Anholt
400 MW
Auction: 2009
CoD: Sep 2013

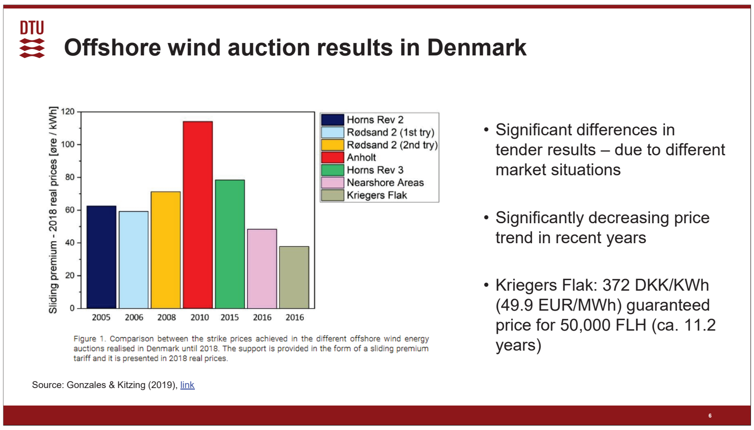
Horns Rev 3
400 MW
Auction: 2013
CoD: Aug 2019

Horns Rev 2
200 MW
Auction: 2004
CoD: Sep 2009

Kriegers Flak
600 MW
Auction: 2016
CoD: End 2021

Nearshore Areas
350 MW
Auction: 2016
CoD: Expected 2021

Rødsand 2
200 MW
Auction: 2004
Auction: 2008
CoD: Aug 2010



Offshore wind auction results in Denmark

Figure 1. Comparison between the strike prices achieved in the different offshore wind energy auctions realised in Denmark until 2018. The support is provided in the form of a sliding premium tariff and it is presented in 2018 real prices.

Source: Gonzales & Kitzing (2019), link

- Significant differences in tender results – due to different market situations
- Significantly decreasing price trend in recent years
- Kriegers Flak: 372 DKK/KWh (49.9 EUR/MWh) guaranteed price for 50,000 FLH (ca. 11.2 years)

Kriegers Flak specifications

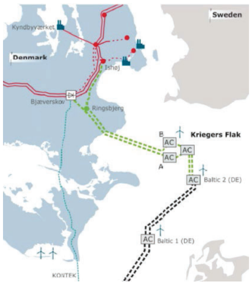
- Auction won: 2016; Turbines ordered: Nov 2017; FID: Q4 2018; CoD: end 2021
- Expected wind turbine size at auctioning: 8-10 MW

Actual specifications:

- 605 MW, 72 turbines, SG 8.0-167 DD turbines, B82 blades, monopiles
- Distance from shore: 15-40 km
- Water depth 15-30 m

- Installation of foundations from May 2019; installation of turbines scheduled for February 2021; Commercial operation end of 2021

- Financing completed in Dec 2018 (as announced by Vattenfall); incl. two Power Purchase Agreements with Novo Nordic and Novozymes for approx. 20% of output
- The project is also supported by the European Union, as a PCI (project of common interest)



Methodology of analysis

- Full cash flow analysis of the project (in Excel), then scenario analysis and deriving thresholds

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n} \frac{TC_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{q_t}{(1+r)^t}}$$

Considered elements:
- OPEX,
- CAPEX,
- Inflation
- Tax payments

$$\mathrm{LROE} = \frac{\sum_{t=0}^{n} \frac{TR_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{q_t}{(1+r)^t}}$$

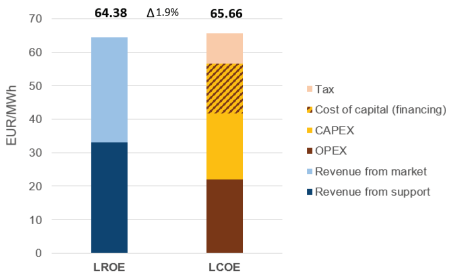
Considered elements:
- Revenues from support (guaranteed price at 49.9 EUR/MWh, nominal)
- Inflation
- Revenues from power market sales (DK2 spot, wind weighted achieved prices), DEA forecasts from 2016 and 2018

Commission Year	2021
Lifetime	25 years
Support Grant Period	11.2 years (50,000 FLH)
Capacity	600 MW
Annual Power Production	2,400 GWh/year
CAPEX	1,970 €/kW
OPEX	$62_{\mathrm{real,2016}}$ €/kW/year
WACC, nominal	6.42%
Tax Rate	22%
Depreciation	15% declining balance

Sources: Danish Energy Agency, "Basisfremskrivning 2016", "Basisfremskrivning 2018", Technology catalogue 2019; IEA TCP Wind Task 26 offshore wind report 2018

Results: LCOE / LROE comparison for Kriegers Flak

At time of auction (price assumptions from 2016)



- Slight differences could be mitigated by:
  - 8.4% lower assumed OPEX OR
  - 3.8% lower assumed CAPEX OR
  - 6.6% lower cost of capital (financing): WACC 5.99% OR
  - 4.1% higher market price expectations

- Overall, the auction bid seems to be very well in line with the (public) cost and price expectations at the time of bid

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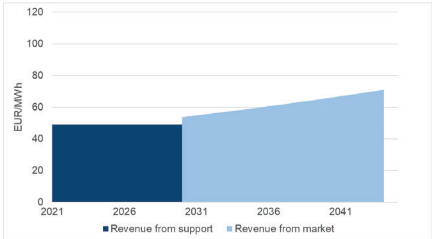
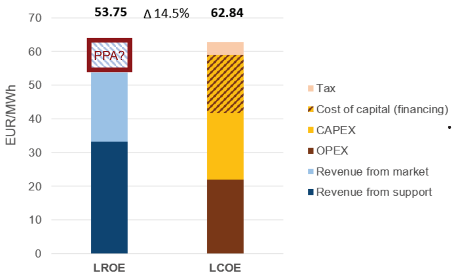
Development of power price forecasts between 2016 and 2018

At Final Investment Decision (price assumptions from 2018)



Results: LCOE / LROE comparison for Kriegers Flak

At Final Investment Decision (price assumptions from 2018)



- Much increased gap mostly due to drop in power market price forecasts. A matching of values would now require
  - 63.3% lower assumed OPEX OR
  - 28.1% lower assumed CAPEX OR
  - 46.3% lower cost of capital OR
  - 23.3% higher production OR
  - 44.1% higher market price expectations

- Even in a combination of factors, a matching of values seems unrealistic
  -> so what was behind FID?
  1) PPA for 20% of volume must have been attractive (above 65 EUR/MWh (nominal) with our simple base assumptions)
  2) hedging or insurance against power price development since 2016?
  3) major differences in assumptions? (e.g. longer lifetime, other income,…)

Conclusions

- Auction results can easily be technically translated into levelised revenues of electricity (LROE), using an approach similar to LCOE, albeit with many assumptions to be made (esp. on future power prices)

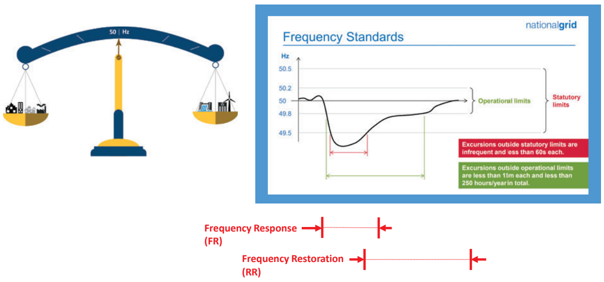
- Anyways, they are not easily used as proxy for cost (LCOE):
  - Significant simplifications
  - Timing issue related to forecasts
  - Alternative income streams often unknown

- The comparison between LROE and LCOE for Kriegers Flak (based on publicly available data / official estimations) suggests a reasonable match at time of auction, but not anymore at FID.

Forecasting Wind Power As A Dispatchable
Generation Source for Grid Frequency Control

Leo May – University of Strathclyde

Grid Frequency Control



Sources:
https://www.nationalgrideso.com/sites/eso/files/documents/Faster%20Acting%20Response%20Workshop%20%282018-07%29.pdf
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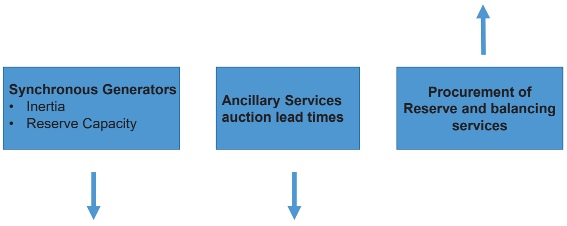
Decarbonisation



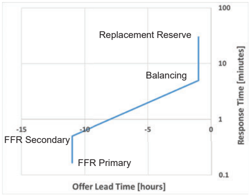
Synchronous Generators
- Inertia
- Reserve Capacity

Ancillary Services auction lead times

Procurement of Reserve and balancing services

Time Horizon Value

- Assuming electricity markets are discovering value; fast response times are more valuable at longer lead times, especially in weaker grids.
- Due to ramping speeds, the auction for products with slow response times is more saturated.



Future of Offshore Wind

Strengths:
- High capacity share
- Operational Flexibility
- Low LCOE (right now)

Weaknesses:
- 'Infirm' capacity
- Subsidy based operation

Opportunities:
- Ancillary services
- Floating wind geographical flexibility
- Interconnector integration

Threats:
- Low wholesale energy price on windy days
- Slow policy reforms denying market access.

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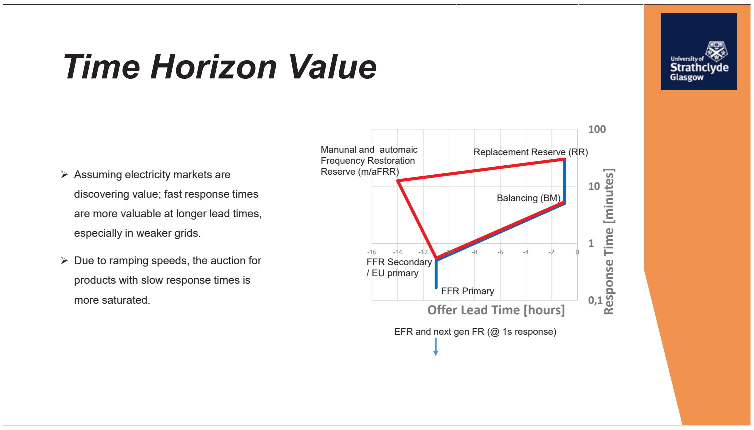

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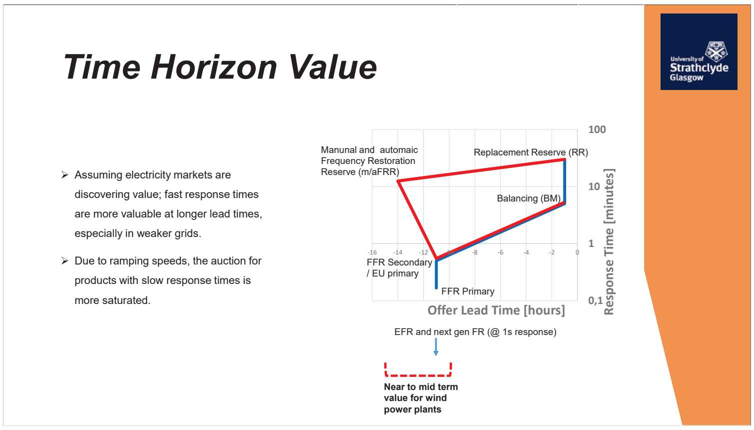

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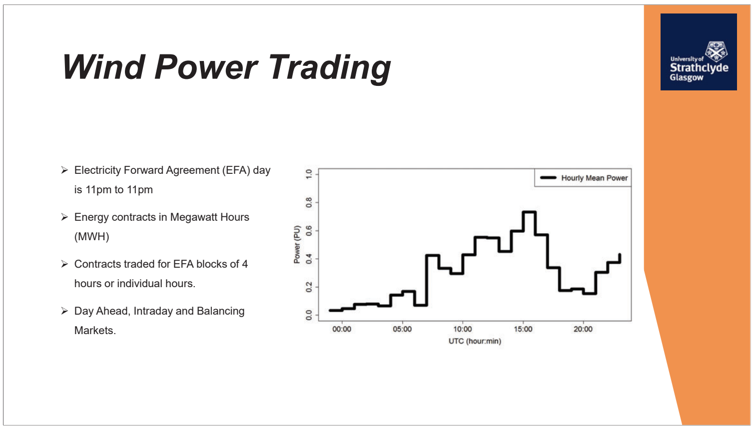
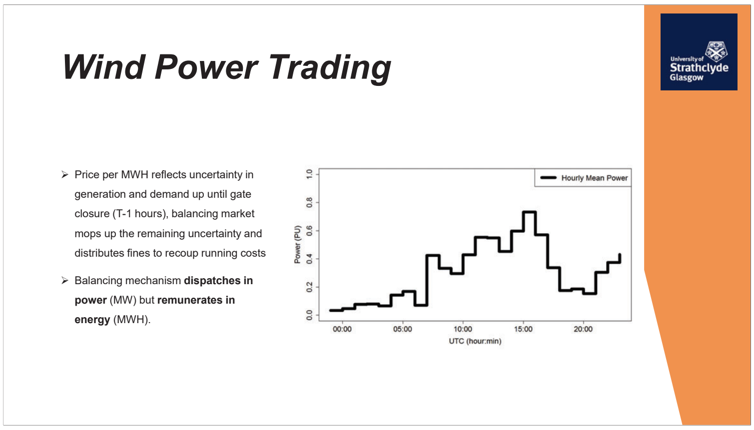


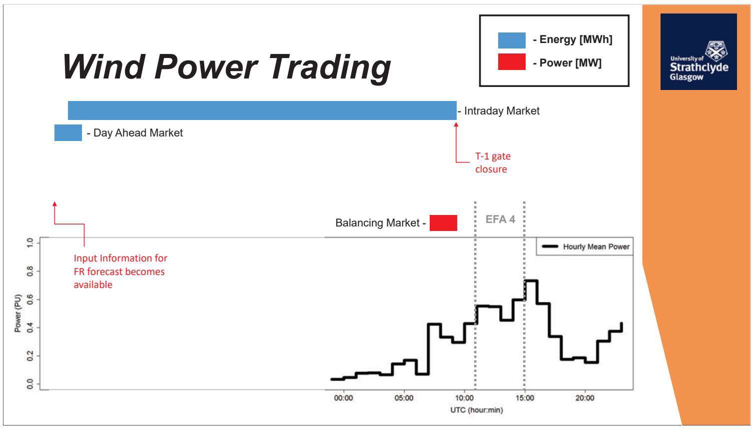
Wind Power Trading

- Electricity Forward Agreement (EFA) day is 11pm to 11pm
- Energy contracts in Megawatt Hours (MWH)
- Contracts traded for EFA blocks of 4 hours or individual hours.
- Day Ahead, Intraday and Balancing Markets.



Wind Power Trading

- Price per MWH reflects uncertainty in generation and demand up until gate closure (T-1 hours), balancing market mops up the remaining uncertainty and distributes fines to recoup running costs
- Balancing mechanism **dispatches** in **power** (MW) but **remunerates in energy** (MWH).



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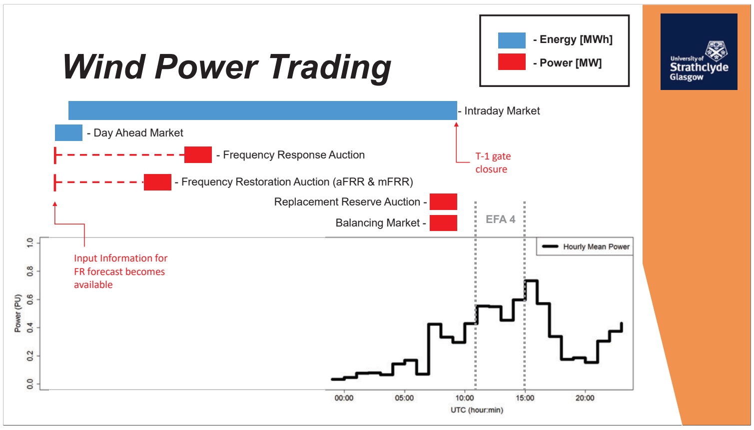

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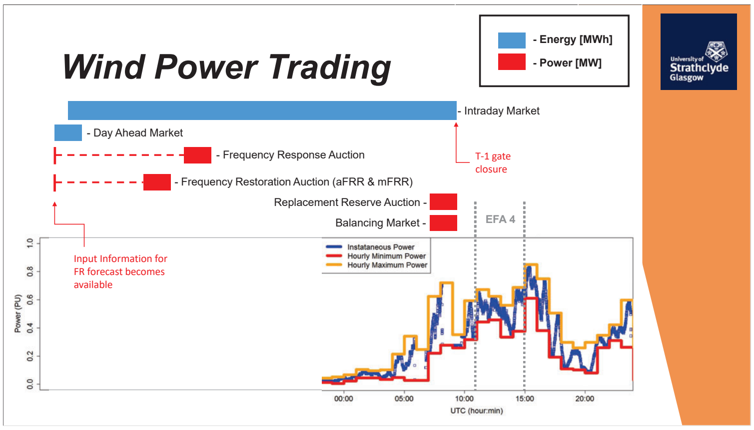


Wind Power Trading

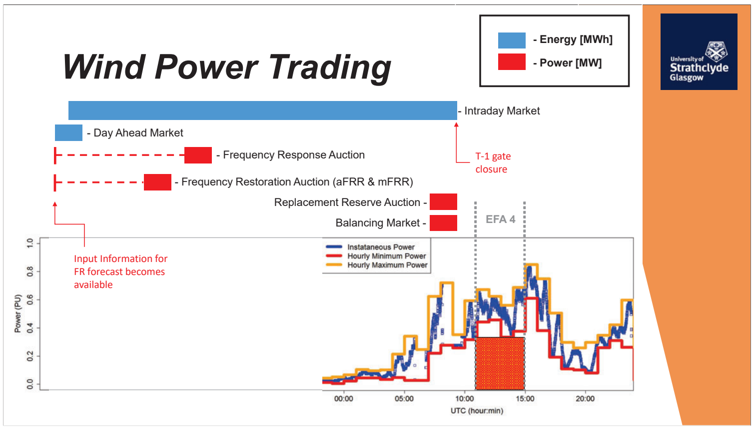
🟦 - Energy [MWh]
🟥 - Power [MW]

- Intraday Market
- Day Ahead Market
- Frequency Response Auction
- Frequency Restoration Auction (aFRR & mFRR)
Replacement Reserve Auction -
Balancing Market -

T-1 gate closure

EFA 4

Input Information for FR forecast becomes available



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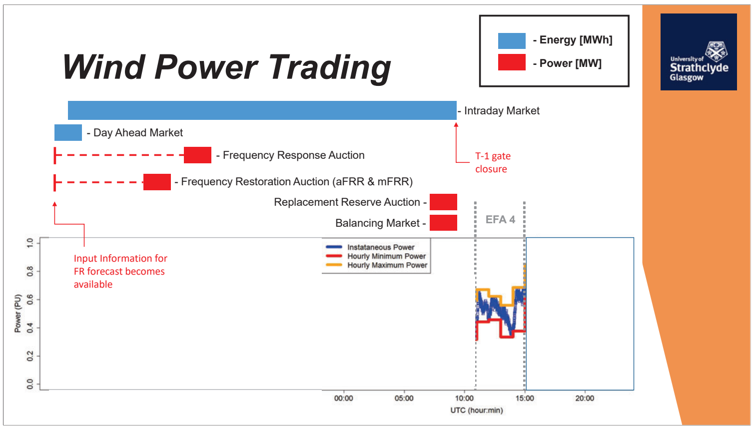

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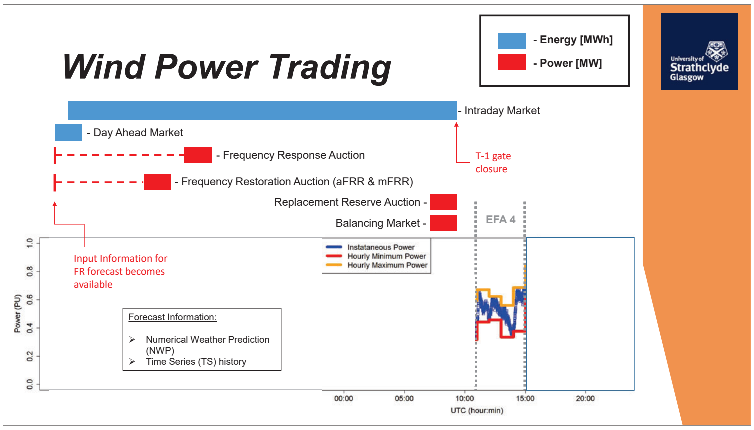

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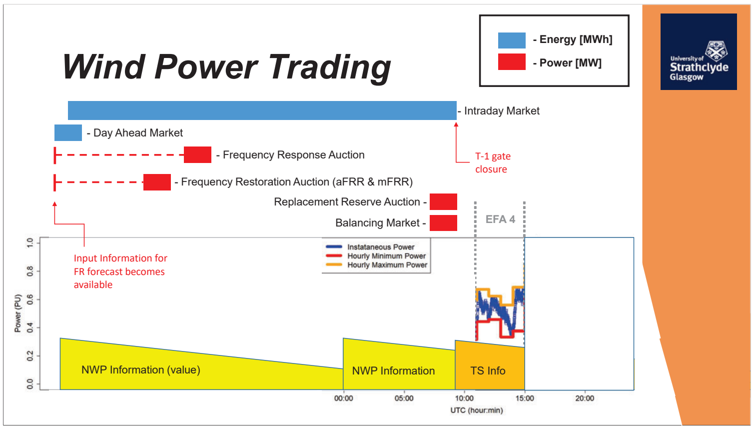
T-1 gate closure

EFA 4

Input Information for FR forecast becomes available

Forecast Information:

- ➢ Numerical Weather Prediction (NWP)
- ➢ Time Series (TS) history



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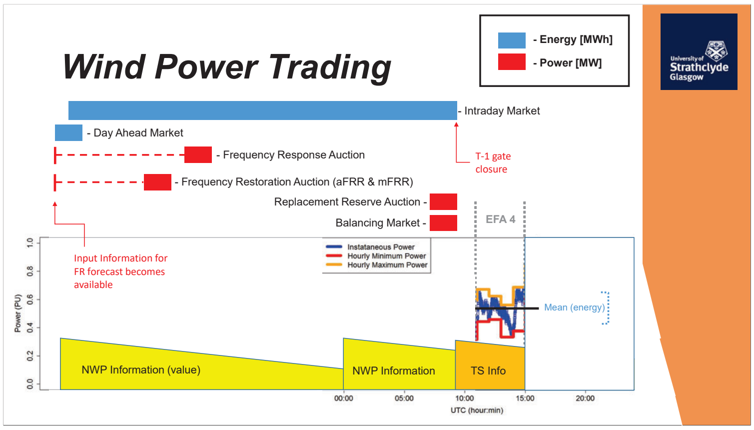

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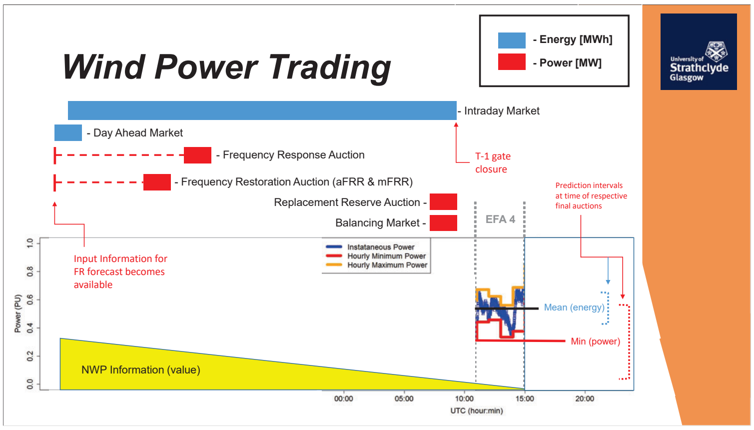

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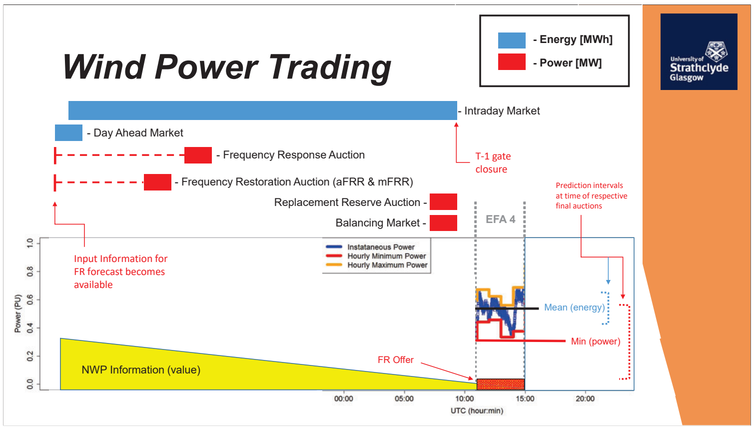

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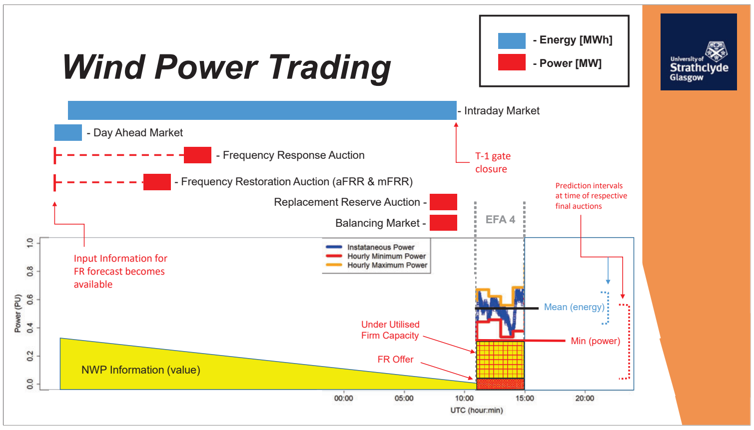
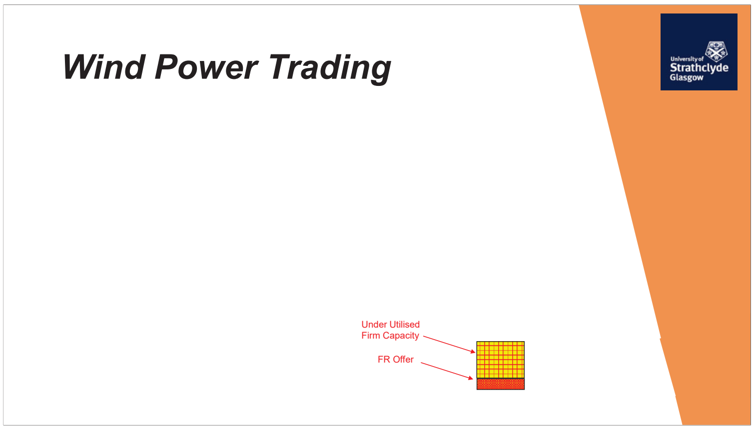
- 🟦 - Energy [MWh]
- 🟥 - Power [MW]

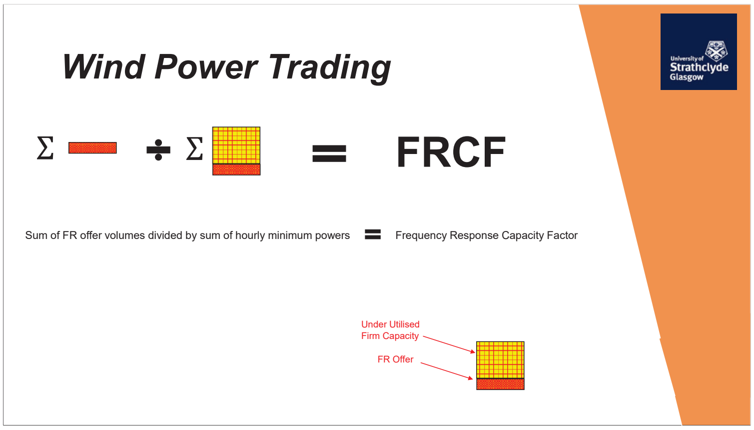


Wind Power Trading

- 🟦 - Energy [MWh]
- 🟥 - Power [MW]



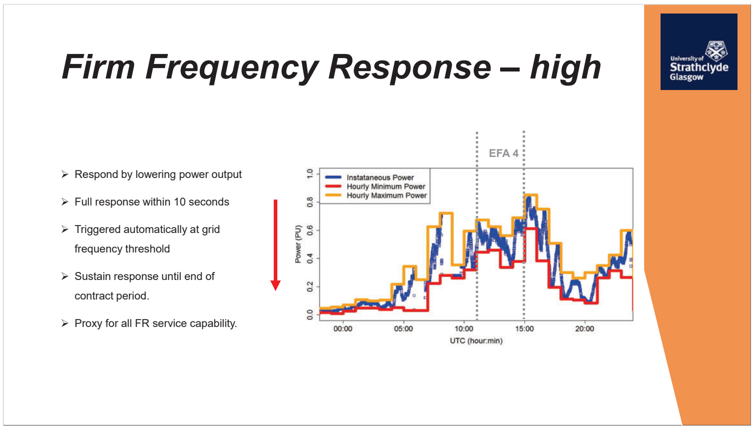
Wind Power Trading



Wind Power Trading

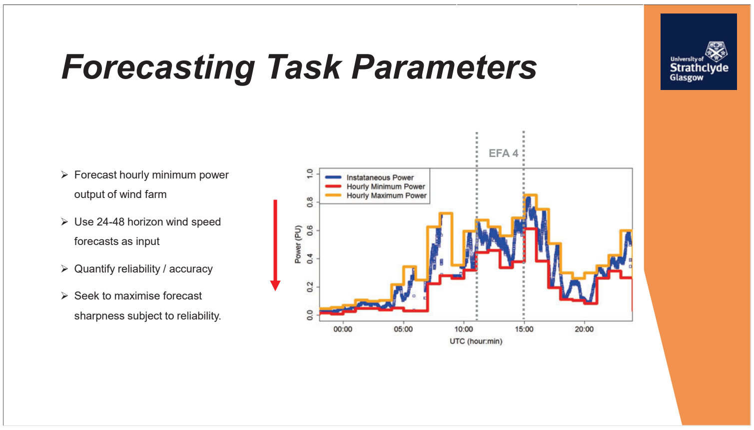
Σ ▨ ÷ Σ ▦ = FRCF

Sum of FR offer volumes divided by sum of hourly minimum powers = Frequency Response Capacity Factor



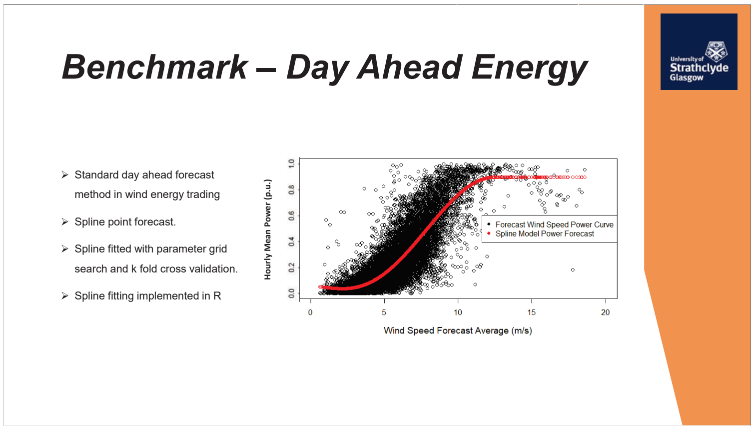
Firm Frequency Response – high

- Respond by lowering power output
- Full response within 10 seconds
- Triggered automatically at grid frequency threshold
- Sustain response until end of contract period.
- Proxy for all FR service capability.



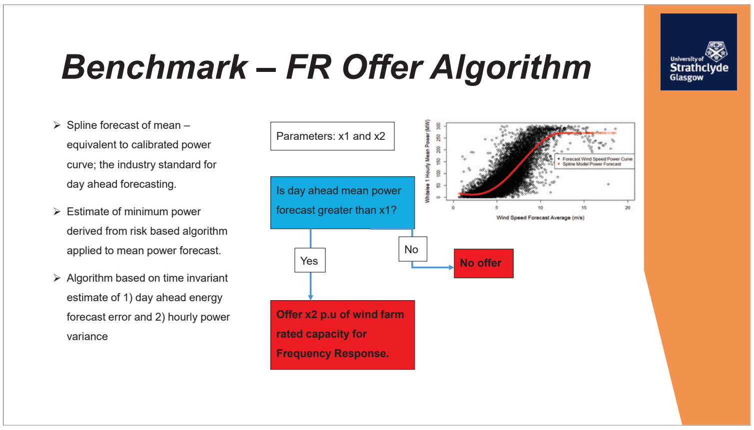
Forecasting Task Parameters

- Forecast hourly minimum power output of wind farm
- Use 24-48 horizon wind speed forecasts as input
- Quantify reliability / accuracy
- Seek to maximise forecast sharpness subject to reliability.



Benchmark – Day Ahead Energy

- Standard day ahead forecast method in wind energy trading
- Spline point forecast.
- Spline fitted with parameter grid search and k fold cross validation.
- Spline fitting implemented in R



Benchmark – FR Offer Algorithm

- Spline forecast of mean – equivalent to calibrated power curve; the industry standard for day ahead forecasting.
- Estimate of minimum power derived from risk based algorithm applied to mean power forecast.
- Algorithm based on time invariant estimate of 1) day ahead energy forecast error and 2) hourly power variance

Parameters: x1 and x2

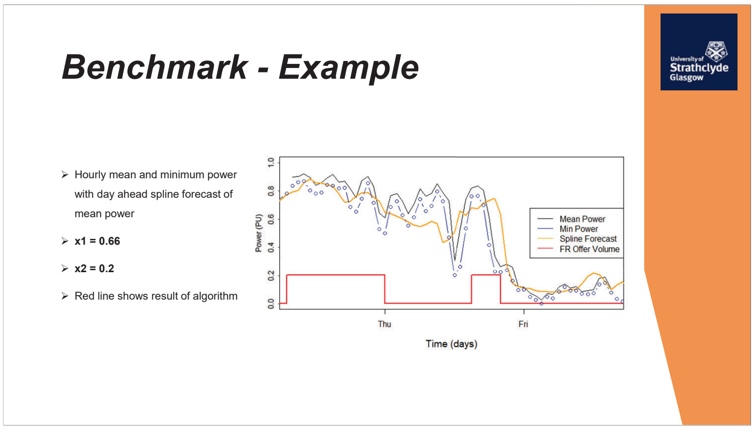
Is day ahead mean power forecast greater than x1?

Yes

No

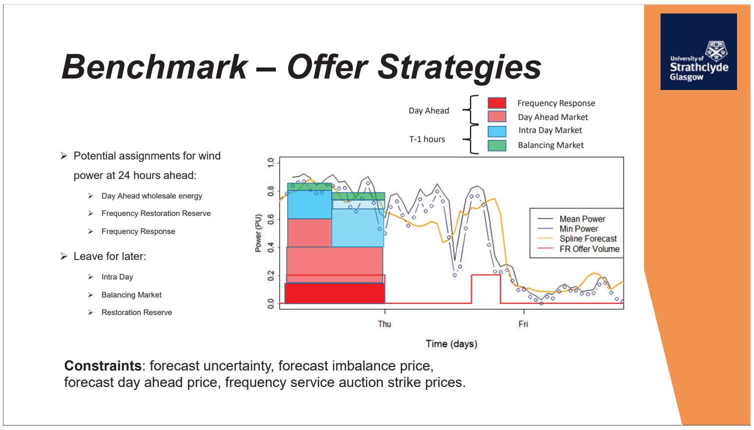
No offer

Offer x2 p.u of wind farm rated capacity for Frequency Response.



Benchmark - Example

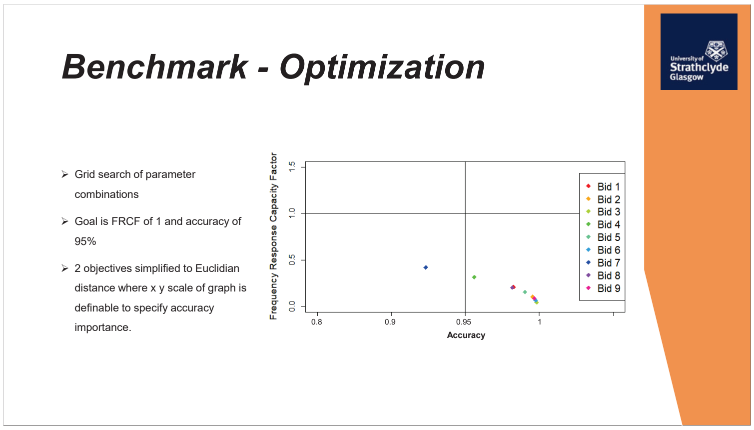
- Hourly mean and minimum power with day ahead spline forecast of mean power
- **x1 = 0.66**
- **x2 = 0.2**
- Red line shows result of algorithm



Benchmark – Offer Strategies

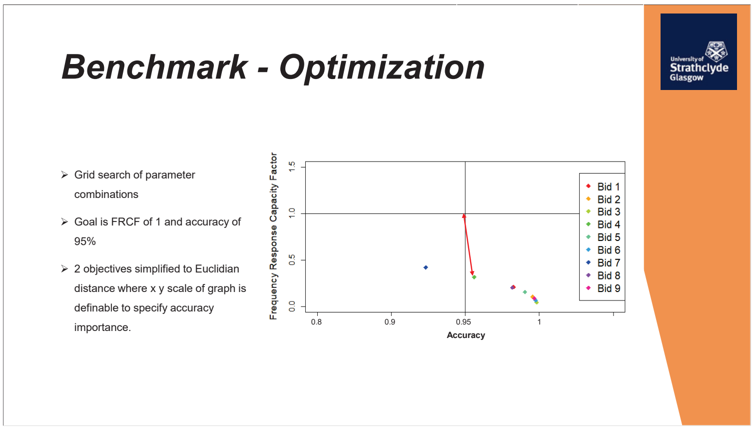
- Potential assignments for wind power at 24 hours ahead:
  - Day Ahead wholesale energy
  - Frequency Restoration Reserve
  - Frequency Response
- Leave for later:
  - Intra Day
  - Balancing Market
  - Restoration Reserve

Constraints: forecast uncertainty, forecast imbalance price, forecast day ahead price, frequency service auction strike prices.



Benchmark - Optimization

- Grid search of parameter combinations
- Goal is FRCF of 1 and accuracy of 95%
- 2 objectives simplified to Euclidian distance where x y scale of graph is definable to specify accuracy importance.



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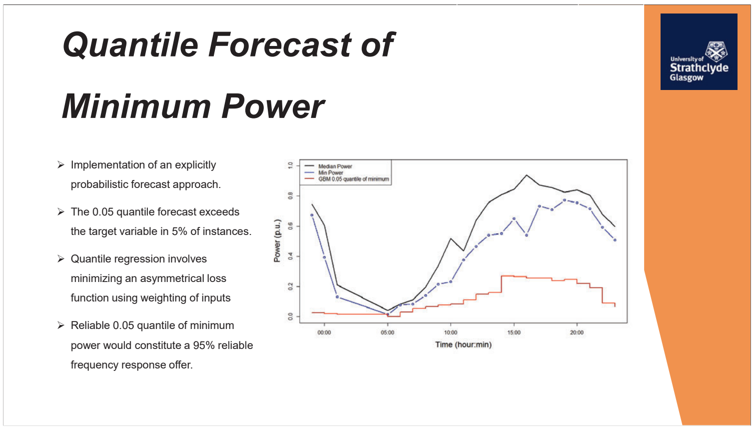
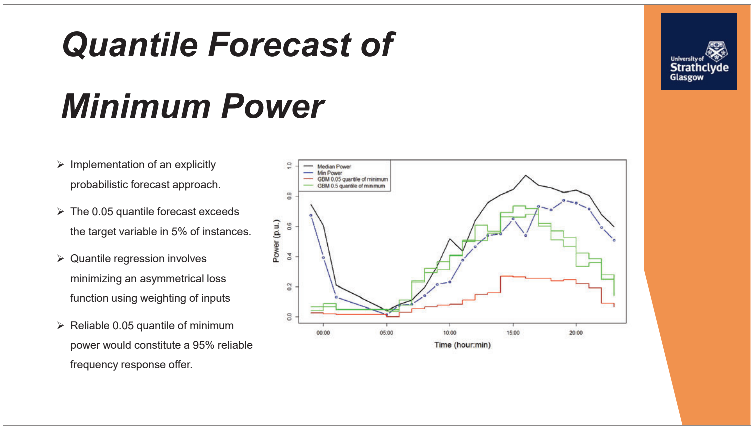


Quantile Forecast of Minimum Power

- Implementation of an explicitly probabilistic forecast approach.
- The 0.05 quantile forecast exceeds the target variable in 5% of instances.
- Quantile regression involves minimizing an asymmetrical loss function using weighting of inputs
- Reliable 0.05 quantile of minimum power would constitute a 95% reliable frequency response offer.



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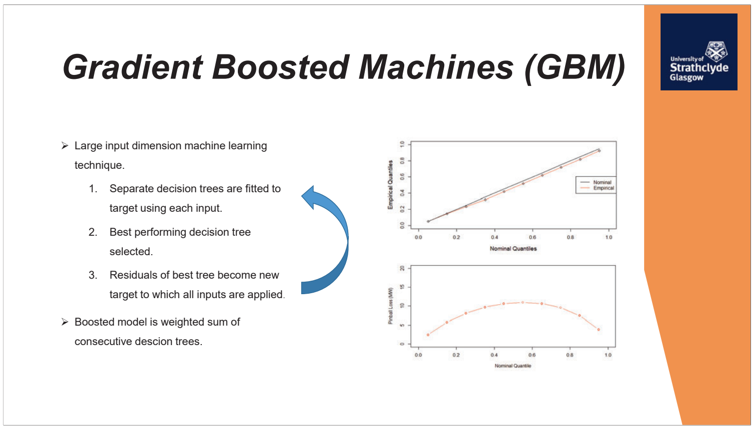
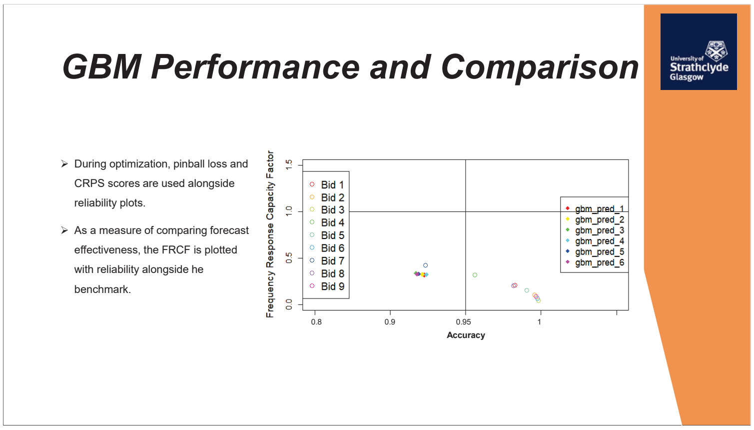


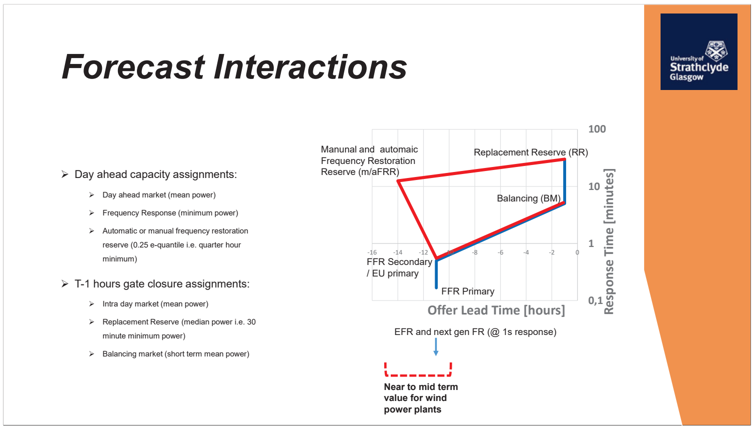
Gradient Boosted Machines (GBM)

- Large input dimension machine learning technique.
  1. Separate decision trees are fitted to target using each input.
  2. Best performing decision tree selected.
  3. Residuals of best tree become new target to which all inputs are applied.
- Boosted model is weighted sum of consecutive descion trees.



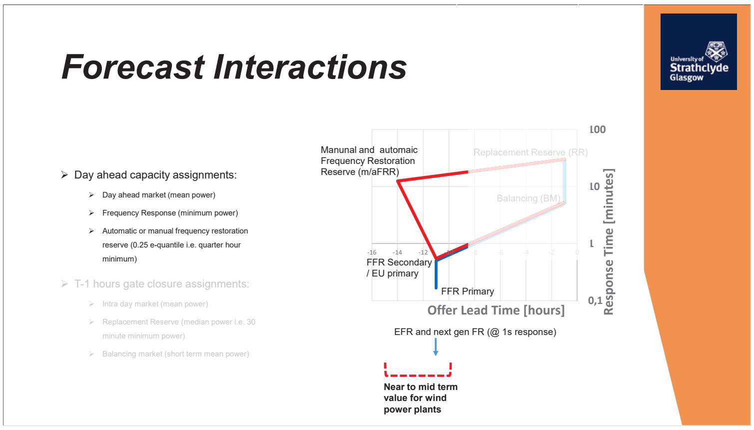
GBM Performance and Comparison

- During optimization, pinball loss and CRPS scores are used alongside reliability plots.
- As a measure of comparing forecast effectiveness, the FRCF is plotted with reliability alongside he benchmark.



Forecast Interactions

- Day ahead capacity assignments:
  - Day ahead market (mean power)
  - Frequency Response (minimum power)
  - Automatic or manual frequency restoration reserve (0.25 e-quantile i.e. quarter hour minimum)
- T-1 hours gate closure assignments:
  - Intra day market (mean power)
  - Replacement Reserve (median power i.e. 30 minute minimum power)
  - Balancing market (short term mean power)



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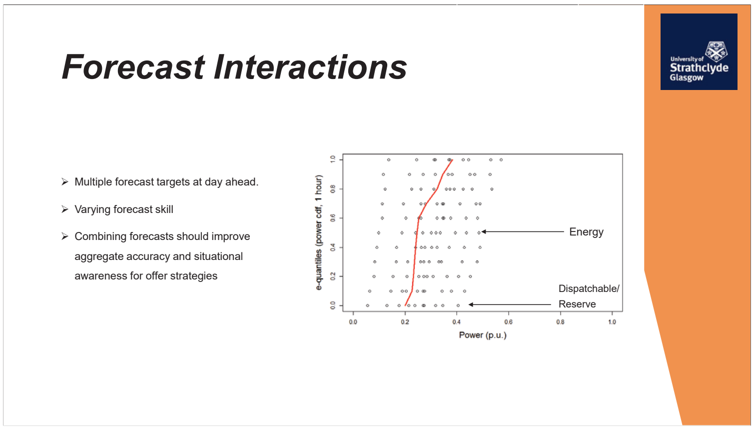

Forecast Interactions

- Multiple forecast targets at day ahead.
- Varying forecast skill
- Combining forecasts should improve aggregate accuracy and situational awareness for offer strategies

Leo May

PhD Student

Wind Power Forecasting for Grid Frequency Control

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C1) Met-ocean conditions

Evaluation of different methods for reducing offshore wind measurements at oil platforms to 10 m reference height, E.Berge, Norwegian Meteorological Institute

Ship-based multi-sensor remote sensing and its potential for offshore wind research, C.A.Duscha, UiB

Taking the motion out of floating lidar: A method for correcting estimates of turbulence intensity, F.Kelberlau, NTNU

Framework for optimal met-ocean sensor placement in offshore wind farms, E.Salo, University of Strathclyde


Photo: Kristine Gjesdal, MET Norway

Evaluation of different methods for reducing wind at oil platforms to 10 m reference height

Olsen, A.M., Berge. E., Øiestad, M.H., Køltzow, M.Ø. and Valkonen, T. The Norwegian Meteoreological Institute

21.01.2020

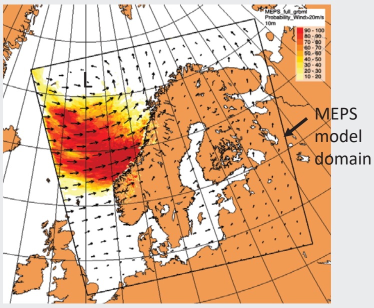
Background for this study:

- Assimilation of measurements is a key part of modern Numerical Weather Prediction (NWP).
- Wind measurements at oil platforms are presently reduced to 10 m above sea level (a.s.l) before assimilated in MET's NWP-model.
- In this study we want to assess and improve current methods for wind speed reduction to 10 m a.s.l. and thereby increase the accuracy of the weather predictions.
- The results are applicable both to offshore wind resource assessment and short term wind energy forecasting.

MEPS NWP-model at MET:

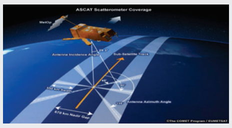
- MEPS
  - M-MetCoOp operational cooperation with Sweden and Finland
  - EPS-Ensemble Prediction System
- 10 ensemble members are run every 6-hour. From 4 Feb. 2020 a continuous production will provide 30 new ensemble members within a 6-hour window
- MEPS gives probability forecasts of for example wind speed (see figure)
- Data available at https://thredds.met.no

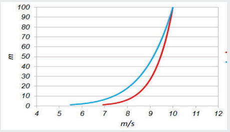
Probability of exceeding 20 m/s at 10 m a.s.l., 18 UTC 08.01.2020 given by MEPS



Data and methodology:

- Hourly platform observations of wind
- Screening of the quality of the wind observations and selection of the dataseries.
- Advanced Scatterometer (ASCAT) satellite data at 10 m a.s.l. for validation
- Evaluating six different wind profiles to calculate 10 m a.s.l. wind speed.

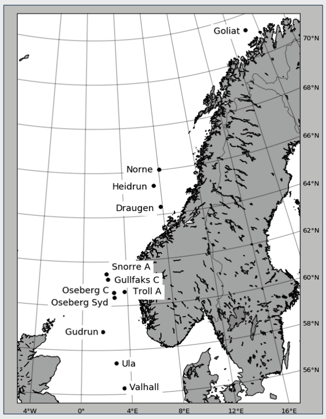




Selected platform observations:

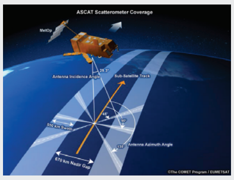
- 12 out of 26 observations selected for this study
- Cover North Sea, Norwegian Sea, Barents Sea
- Sensor heights: 47-140 m a.s.l.

Platform	Height above sea level [m]
Draugen	78
Goliat	71
Gudrun	84
Gullfaks C	140
Heidrun	131
Norne	47
Oseberg C	120
Oseberg Syd	126
Snorre A	115
Troll A	94
Ula	111
Valhall	120



Advanced Scatterometer (ASCAT):

- Microwave radar onboard polar-orbiting satellites
- Wind speed and direction can be retrieved from the backscattered signal
- The Ocean and Sea Ice Satellite Application Facility (OSI SAF) of EUMETSAT processes the wind products from the calibrated backscatter



< 1 m/s

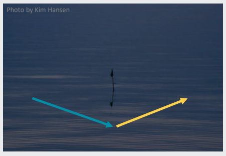


Photo by Kim Hansen

15 m/s

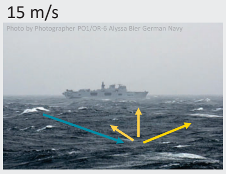


Photo by Photographer PO1/OR-6 Alyssa Bier German Navy

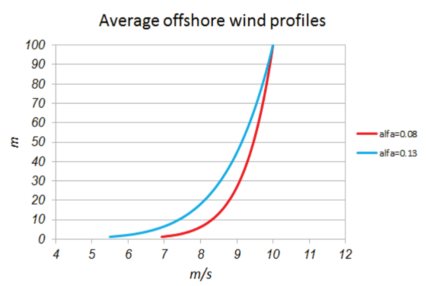
Fan beam scatterometer METOP-ASCAT

Frequency:	5.3 GHz (C-band)
Wavelength:	5 cm
Limitations:	higher wind range >30 m/s
Sampling:	12.5 - 25 km
Geometry:	static
Swath :	double (about 550 km each)

Wind profiles:

- **Power Law:**

$$U_s = U_{10}\left(\frac{h}{10}\right)^{p}$$



U_s - wind speed at sensor level h
U_{10} - wind speed at 10 meter height

4 different profile methods are tested:
- p = 0.13 (present method)
- p = 0.08 (typical value for neutral stability and wind speeds of 8-10 m/s).
- p dependent on stability
- p dependent on stability and wind speed

Norwegian Meteorological Institute

Wind profiles continued:

- **NORSOK wind profile (Standards Norway, 2007)**. Based on the near offshore measurements at the island of Frøya.

$$U_s = U_{10}\left[1 + C\ ln\left(\frac{h}{10}\right)\right]$$
$$\text{where } C = 5.73 \times 10^{-2}\left[1 + 0.15 \times U_{10}\right]^{1/2}$$

- **Gryning et al. (2007) wind profile.** Vertical wind profile method for which three length scales L_{SL}(surface), L_{MBL} (middle boundary layer) and L_{UBL} (upper boundary layer) are calculated for neutral, stable and unstable conditions.
- In addition to atmospheric stability, friction velocity, sensible heat flux and boundary layer heights are important input parameters to the scheme.
- All parameters for the Gryning method are obtained from the MEPS NWP-model.

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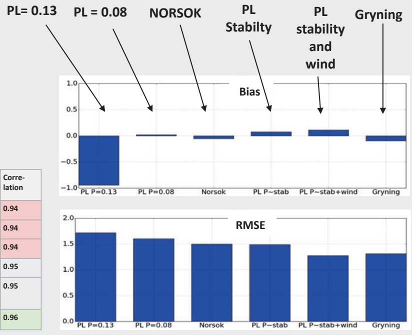
Summary of results from all 12 platforms:

PL - Power Law

Bias - Mean Error
RMSE - Root Mean Square Error

	Bias	RMSE	MAE	Corre-lation
Power law P=0.13	-0.94	1.72	1.4	0.94
Power law P=0.08	0.02	1.60	1.22	0.94
Norsok	-0.05	1.50	1.22	0.94
Power law (P varies with stability)	0.08	1.49	1.12	0.95
Power law (P varies with stability and wind speed)	0.11	1.28	0.95	0.95
Gryning	-0.10	1.31	0.98	0.96



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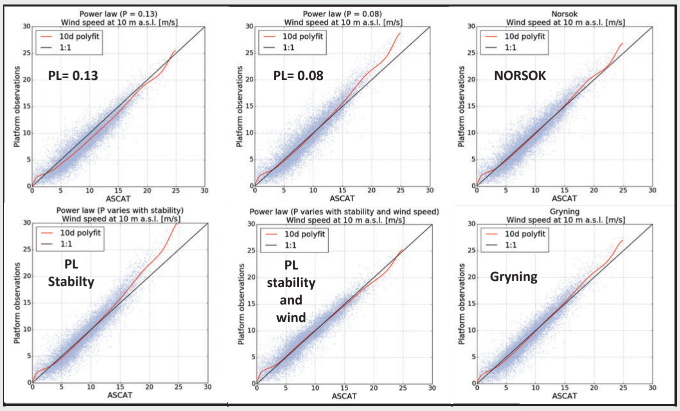
Scatter plots – all platforms:



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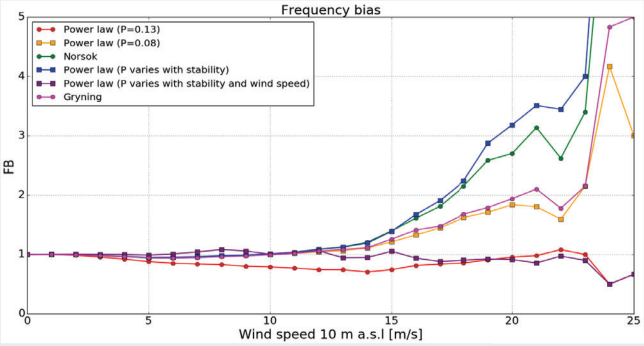
Frequency bias (FB) all platforms:

- FB > 1 occurrence overpredicted, FB < 1 occurrence underpredicted



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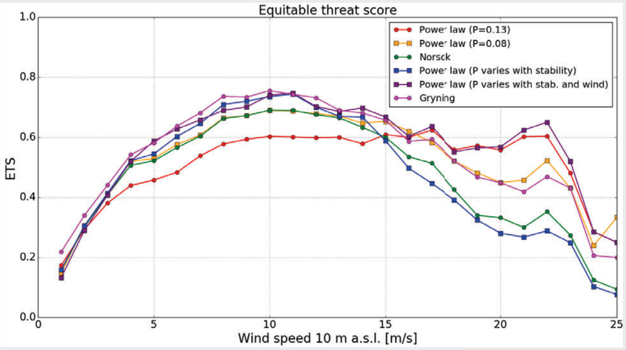
Equitable threat score (ETS) – all platforms:

- ETS = 1 perfect prediction, ETS=0 no prediction skill

Improved agreement



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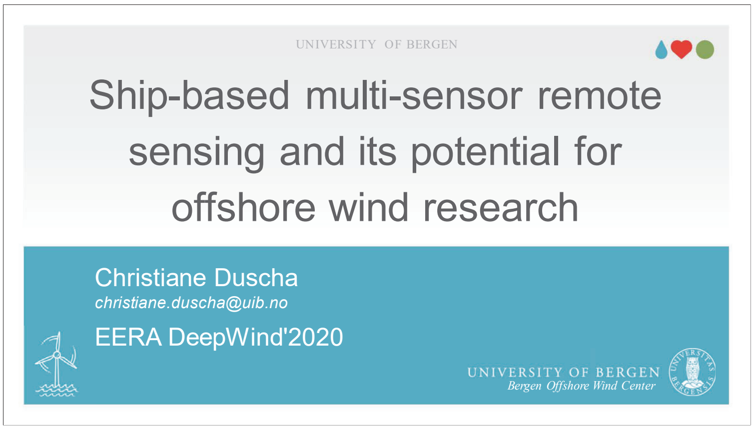
Summary:

- Present wind speed reductions at Norwegian oil platforms underestimate wind speed at 10 m height. An exception is during very high wind speeds.
- An empirical derived method applying the power law with a dependence on stability and wind speed (PL-stability and wind) yields the best wind speed reduction among the 6 methods compared in this study.
- The Gryning et al. (2007) method also gives good agreement, but PL-stability and wind shows better results for wind speeds above ca. 15 m/s
- Inaccuracies in the platform observations and uncertainties in the ASCAT data may have influenced the results

Summary :

- For offshore wind energy analysis: It is recommended to test the PL-stability and wind method further with offshore wind profile measurements from Lidars and/or offshore masts.
- For assimilation in NWP-models: It is recommended (1) to test assimilations of the 10 m level data after applying the PL-stability and wind method, and (2) to test assimilation of the measurements at the observations level.



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Ship-based multi-sensor remote sensing and its potential for offshore wind research

Christiane Duscha
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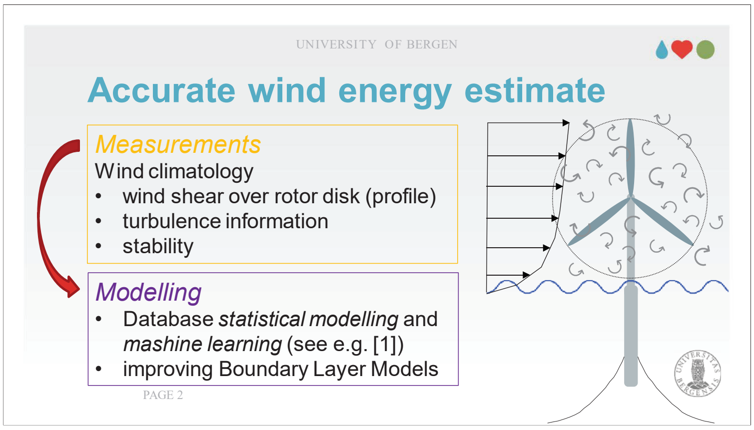
EERA DeepWind'2020

UNIVERSITY OF BERGEN
Bergen Offshore Wind Center



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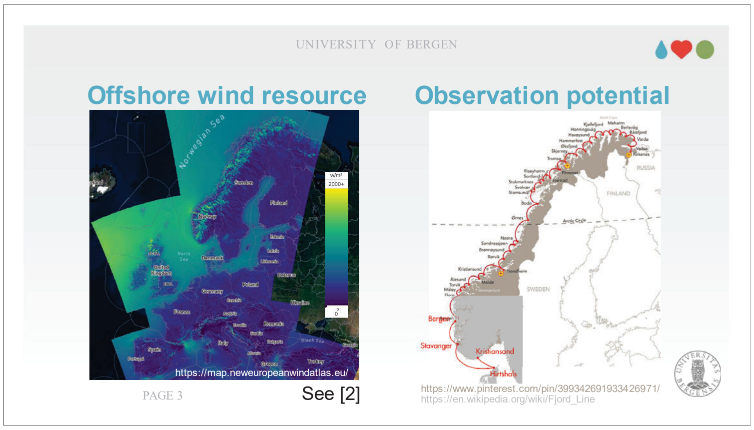
Accurate wind energy estimate

Measurements
Wind climatology
- wind shear over rotor disk (profile)
- turbulence information
- stability

Modelling
- Database *statistical modelling* and *mashine learning* (see e.g. [1])
- improving Boundary Layer Models



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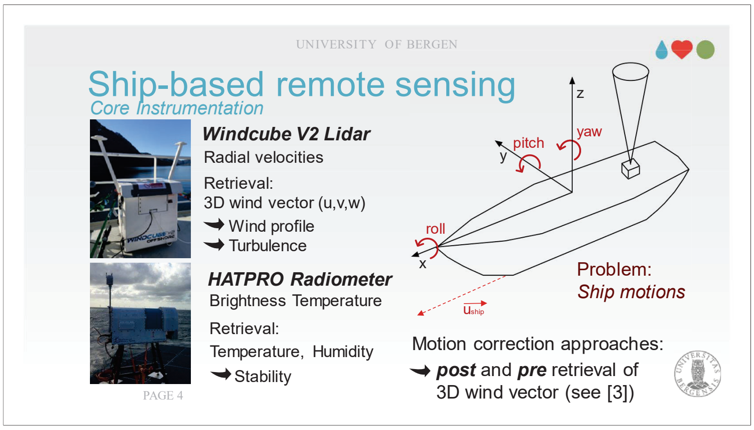
Offshore wind resource

https://map.neweuropeanwindatlas.eu/

See [2]

Observation potential

https://www.pinterest.com/pin/399342691933426971/
https://en.wikipedia.org/wiki/Fjord_Line



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Ship-based remote sensing

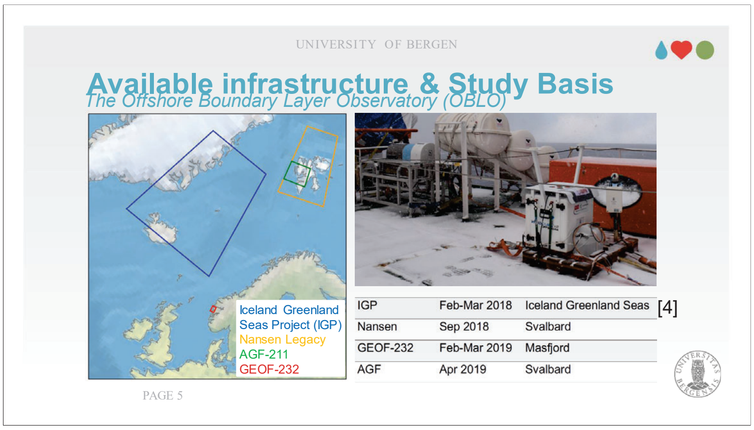
Core Instrumentation

Windcube V2 Lidar
Radial velocities
Retrieval:
3D wind vector (u,v,w)
➜ Wind profile
➜ Turbulence

HATPRO Radiometer
Brightness Temperature
Retrieval:
Temperature, Humidity
➜ Stability

Problem:
Ship motions

Motion correction approaches:
➜ ***post*** and ***pre*** retrieval of 3D wind vector (see [3])



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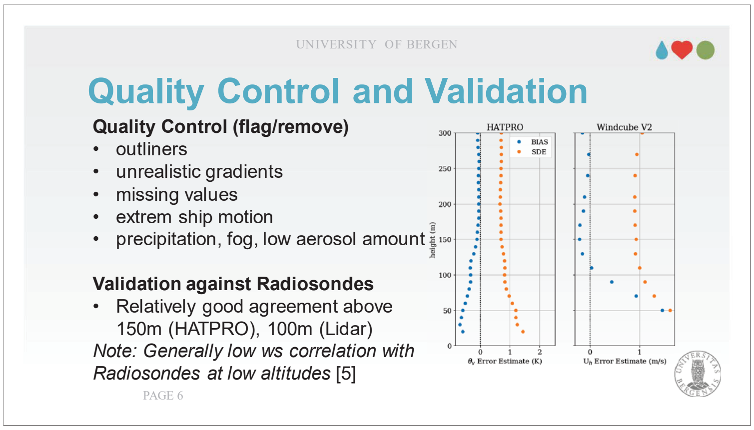
Available infrastructure & Study Basis

The Offshore Boundary Layer Observatory (OBLO)

Iceland Greenland Seas Project (IGP)
Nansen Legacy
AGF-211
GEOF-232

IGP	Feb-Mar 2018	Iceland Greenland Seas [4]
Nansen	Sep 2018	Svalbard
GEOF-232	Feb-Mar 2019	Masfjord
AGF	Apr 2019	Svalbard



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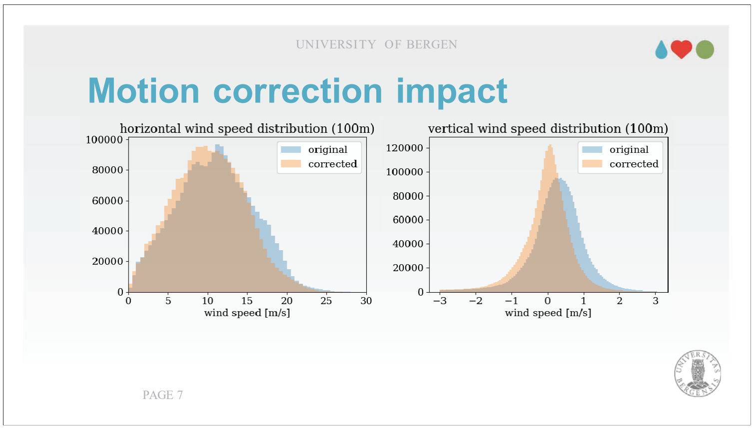
Quality Control and Validation

Quality Control (flag/remove)
- outliners
- unrealistic gradients
- missing values
- extrem ship motion
- precipitation, fog, low aerosol amount

Validation against Radiosondes
- Relatively good agreement above 150m (HATPRO), 100m (Lidar)

Note: Generally low ws correlation with Radiosondes at low altitudes [5]



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Motion correction impact

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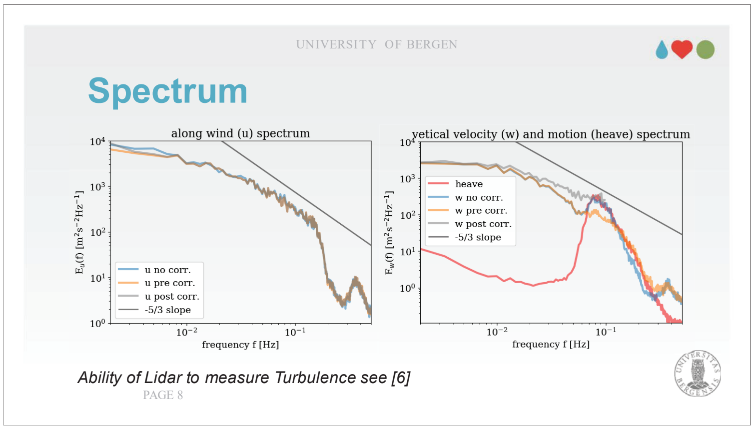

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Spectrum

Ability of Lidar to measure Turbulence see [6]

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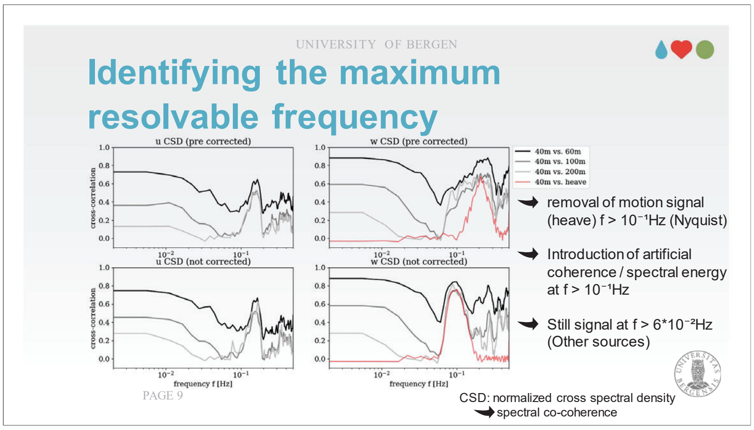

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Identifying the maximum resolvable frequency

➜ removal of motion signal (heave) f > 10⁻¹Hz (Nyquist)

➜ Introduction of artificial coherence / spectral energy at f > 10⁻¹Hz

➜ Still signal at f > 6*10⁻²Hz (Other sources)

CSD: normalized cross spectral density
➜ spectral co-coherence

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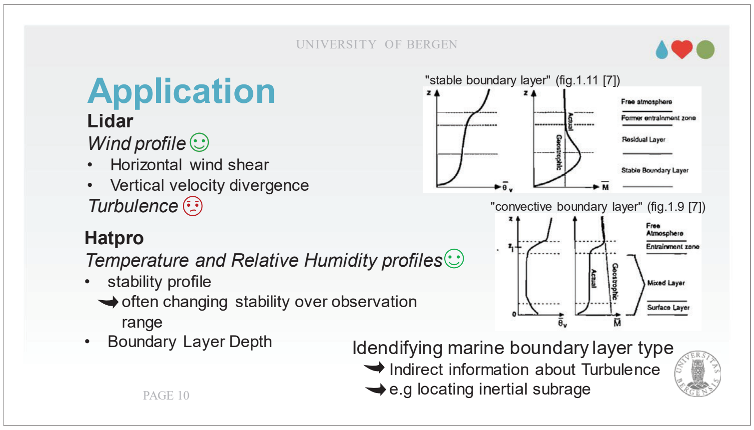

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Application

Lidar

Wind profile ☺
- Horizontal wind shear
- Vertical velocity divergence

Turbulence ☹

Hatpro

Temperature and Relative Humidity profiles ☺
- stability profile
  ➜ often changing stability over observation range
- Boundary Layer Depth

"stable boundary layer" (fig.1.11 [7])

"convective boundary layer" (fig.1.9 [7])

Idendifying marine boundary layer type
➜ Indirect information about Turbulence
➜ e.g locating inertial subrage

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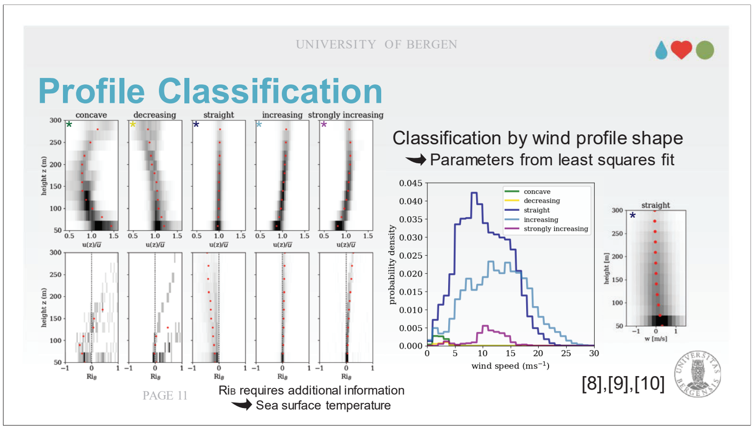

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Profile Classification

Classification by wind profile shape
➜ Parameters from least squares fit

Ri_B requires additional information
➜ Sea surface temperature

[8],[9],[10]

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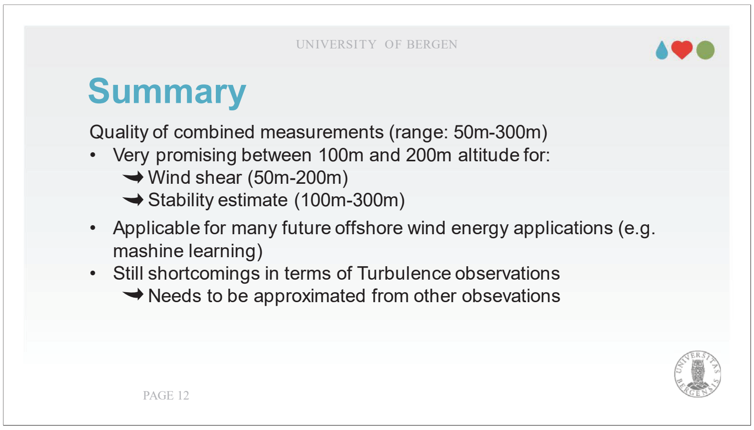

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Summary

Quality of combined measurements (range: 50m-300m)
- Very promising between 100m and 200m altitude for:
  ➜ Wind shear (50m-200m)
  ➜ Stability estimate (100m-300m)
- Applicable for many future offshore wind energy applications (e.g. mashine learning)
- Still shortcomings in terms of Turbulence observations
  ➜ Needs to be approximated from other observations

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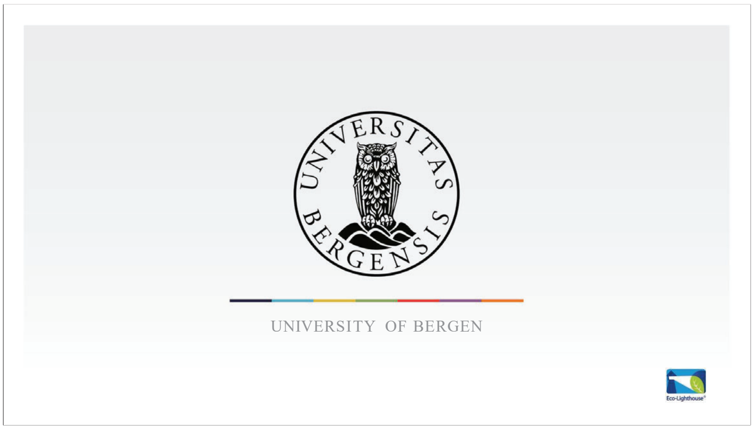

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NTNU
Kunnskap for en bedre verden

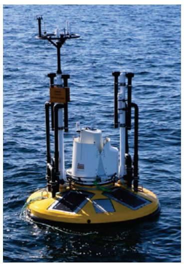
Taking the motion out of floating lidar: A method for correcting estimates of turbulence intensity

Felix Kelberlau (NTNU)
Vegar Neshaug (Fugro)
Lasse Lønseth (Fugro)
Tania Bracchi (NTNU)
Jakob Mann (DTU)

EERA DeepWind'2020, Trondheim, Norway 15 - 17 January 2020

Norwegian University of Science and Technology

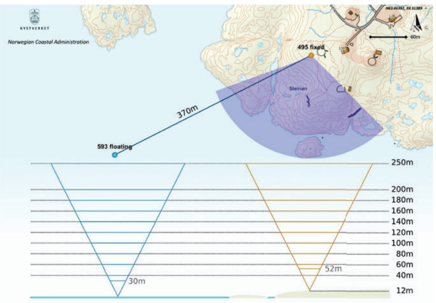
Setup (1/2): SEAWATCH wind lidar buoy



- ZX300M wind lidar (ZX Lidars)
  - Doppler spectra, 49Hz
- MRU 6000 IMU (Norwegian Subsea)
  - 6 DOF motion, 50Hz
- Embedded PC
- GPS time server

Setup (2/2): Land based reference lidar

- Onshore reference lidar (ZX300)
- Frøya, Norway
- One month of data: April/May 2019
- 11 heights
  - 10 comparable: 30-250m a.s.l.
- Offshore sector



Objective: Removing motion induced turbulence

Buoy motion increases estimates of turbulence intensity (TI)

- Compensate for the motion induced TI

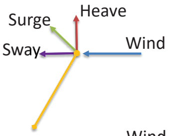
$$TI_{lidar,floating} = TI_{lidar,fixed}$$

- ~~Improve lidar estimated TI values~~

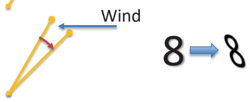
Approach

Compensation for **every single line-of-sight** measurement

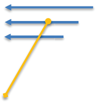
1. Translatory motion
   (Changed radial velocities)



2. Changing scanning geometry
   (Figure-of-eight fitting)

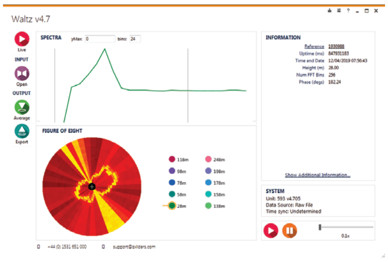


3. Wind shear and veer
   (Changing measurement height)



Challenge 1: Access to line-of-sight data

- Embedded PC onboard
- Remote connection
- Waltz stream to file
- Files contain Doppler spectra but no radial velocities
- Determine radial velocities from Doppler spectra



yMax: 0
bins: 24

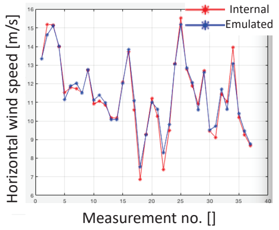
Reference 1930988
Uptime (ms) 847931183
Time and Date 12/04/2019 07:56:43
Height (m) 28.00
Num FFT Bins 256
Phase (degs) 182.24

Unit: 593 v4.705
Data Source: Raw File
Time sync: Undetermined

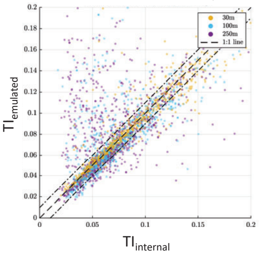
+44 (0) 1531 651 000
support@zxlidars.com

Challenge 2: Emulate data processing (1/2)

- Wind vectors reconstructed by the unit's internal and my emulated processing are similar but **not identical**:



TI: emulated vs. internal processing



Height	$\lvert TI_{emu} - TI_{int}\rvert > 0.01$
30 m	18.8%
100 m	33.4%
250 m	49.5%

- The effect is stronger for **higher elevations**
- Potential reasons:
  - Advanced **radial velocity determination** from Doppler spectra (Cloud detection)
  - Filtering of certain "bad" radial velocities

➢ We **cannot imitate the ZX300** processing exactly

Challenge 2: Emulate data processing (2/2)

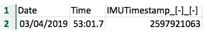
- As a consequence we will use three different datasets:

1. **Land reference**: Data as it comes out of fixed unit 495
2. **Floating uncompensated**: Data as it comes out of floating unit 593
   I. **Emulated uncompensated**: Data of unit 593 processed in a conventional way by my *own code*
   II. **Emulated compensated**: Data of unit 593 processed in a conventional way by my *own code with motion compensation*
3. **Floating compensated**:

$$\text{Floating uncompensated} - \underbrace{(\text{Emulated uncompensated} - \text{Emulated compensated})}_{\text{Motion compensation}}$$

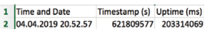
➢ The aim is to see the **same results** between 1. & 3.

Challenge 3: Time synchronization (1/2)



1	Date	Time	IMUTimestamp_[-]_[-]
2	03/04/2019	53:01.7	2597921063

- **MRU** timestamp can be used directly (hh:mm:ss.xxxx)

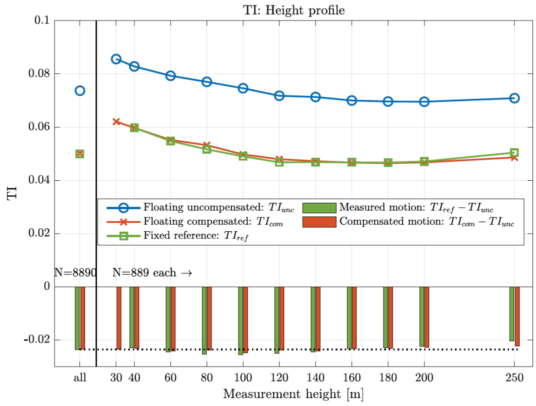


1	Time and Date	Timestamp (s)	Uptime (ms)
2	04.04.2019 20.52.57	621809577	203314069

- **Lidar** Timestamp (hh:mm:ss) and Uptime value (ms) are independent
  - Uptime values are slower than Timestamp. Approx. 1.2s shift per day -> Reset once per day

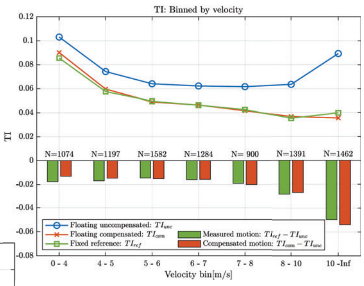
➢ Motion and wind data must be synchronized

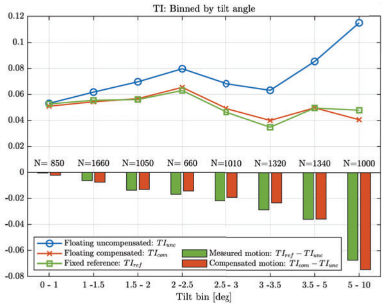
Results (1/4): TI vertical profile



Results (2/4)

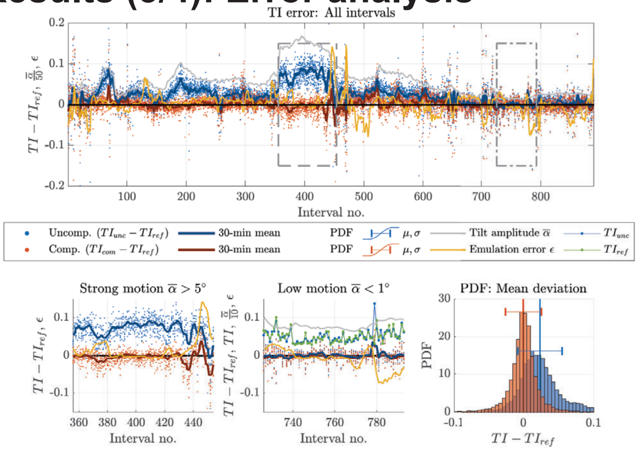
TI binned by wind velocities

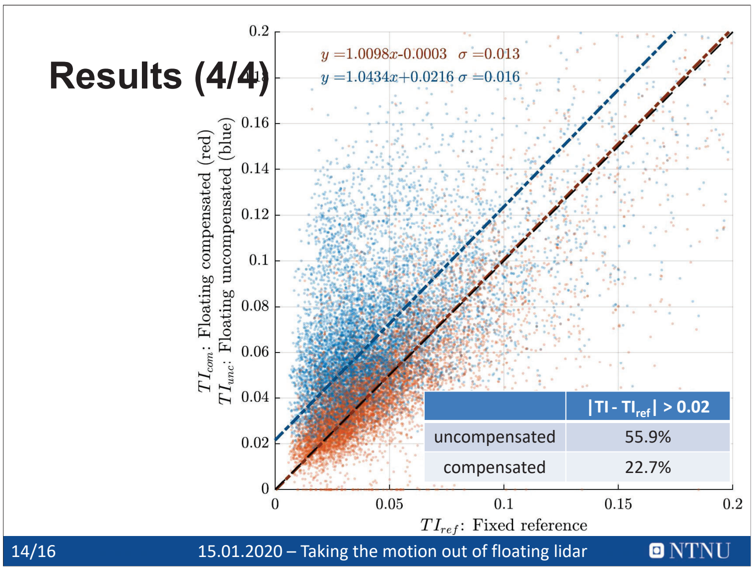




TI binned by buoy tilt angle

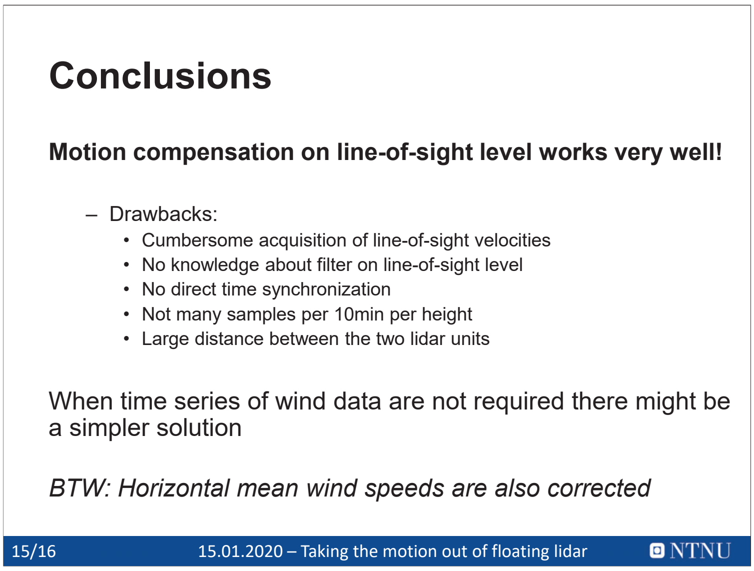
Results (3/4): Error analysis





Results (4/4)

	$\lvert TI - TI_{ref}\rvert > 0.02$
uncompensated	55.9%
compensated	22.7%



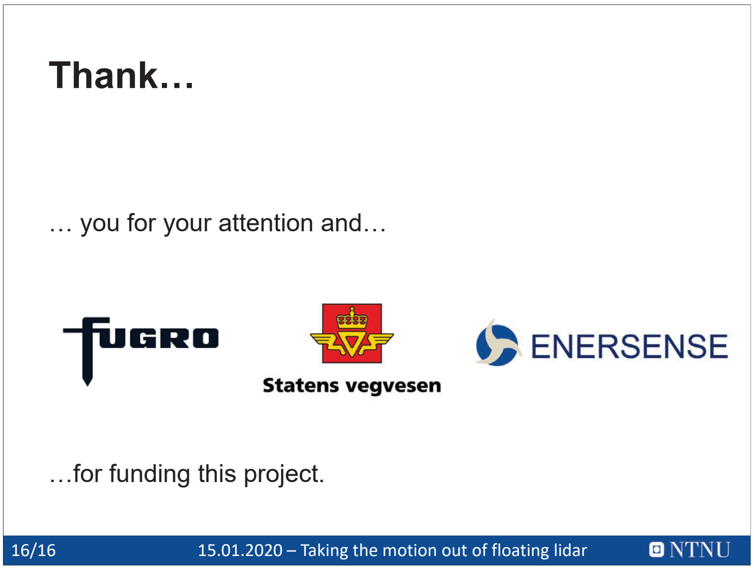
Conclusions

Motion compensation on line-of-sight level works very well!

- Drawbacks:
  - Cumbersome acquisition of line-of-sight velocities
  - No knowledge about filter on line-of-sight level
  - No direct time synchronization
  - Not many samples per 10min per height
  - Large distance between the two lidar units

When time series of wind data are not required there might be a simpler solution

BTW: Horizontal mean wind speeds are also corrected

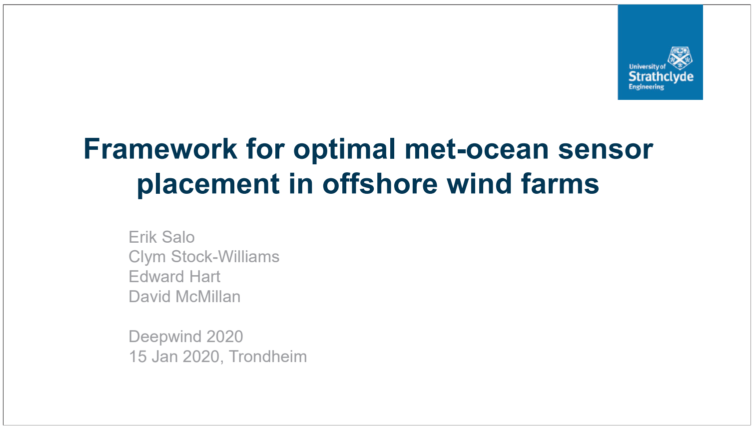


Thank…

… you for your attention and…

FUGRO Statens vegvesen ENERSENSE

…for funding this project.



Framework for optimal met-ocean sensor placement in offshore wind farms

Erik Salo
Clym Stock-Williams
Edward Hart
David McMillan

Deepwind 2020
15 Jan 2020, Trondheim

Project partners

MIROS

University of Strathclyde Glasgow

Innovate UK

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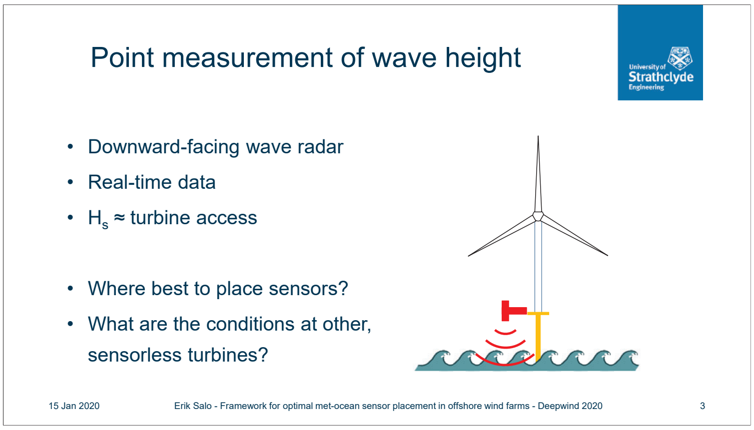

Point measurement of wave height

- Downward-facing wave radar
- Real-time data
- $H_s \approx$ turbine access

- Where best to place sensors?
- What are the conditions at other, sensorless turbines?

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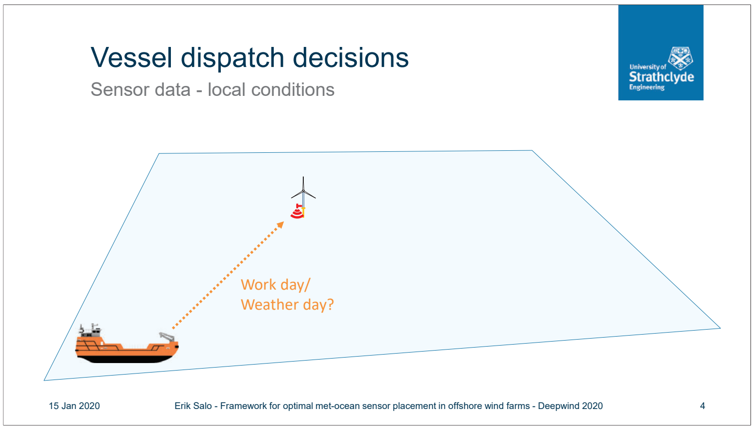

Vessel dispatch decisions

Sensor data - local conditions

Work day/
Weather day?

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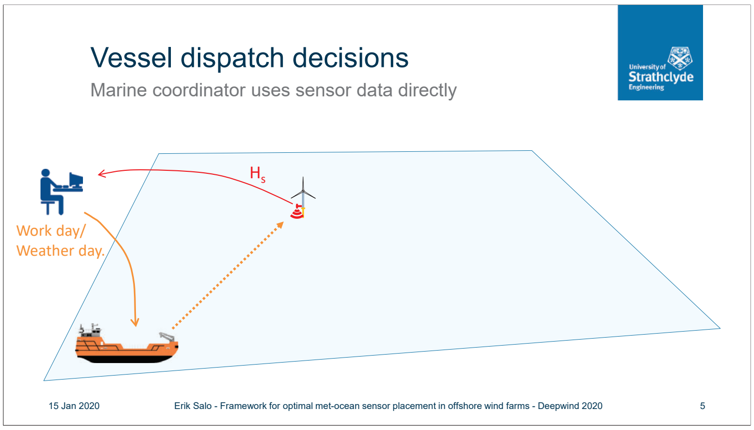

Vessel dispatch decisions

Marine coordinator uses sensor data directly

H_s

Work day/
Weather day.

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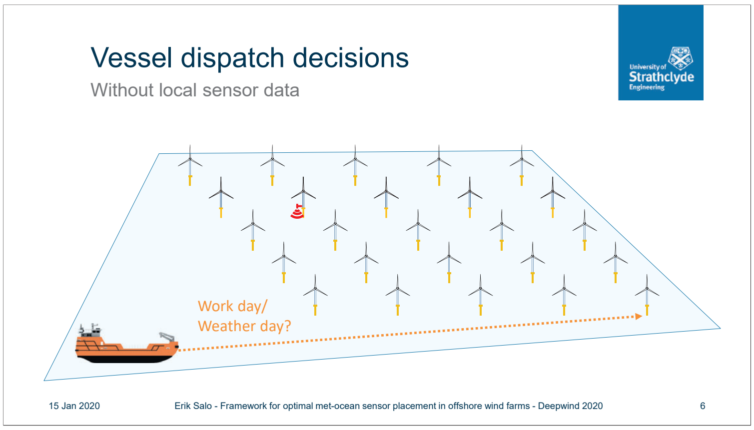

Vessel dispatch decisions

Without local sensor data

Work day/
Weather day?

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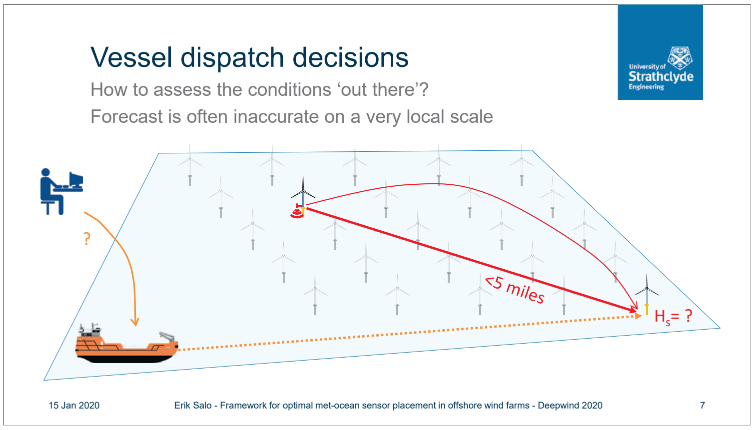
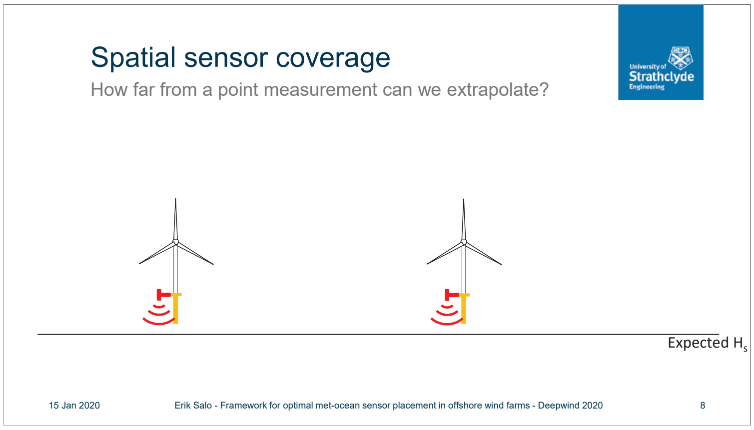


Vessel dispatch decisions

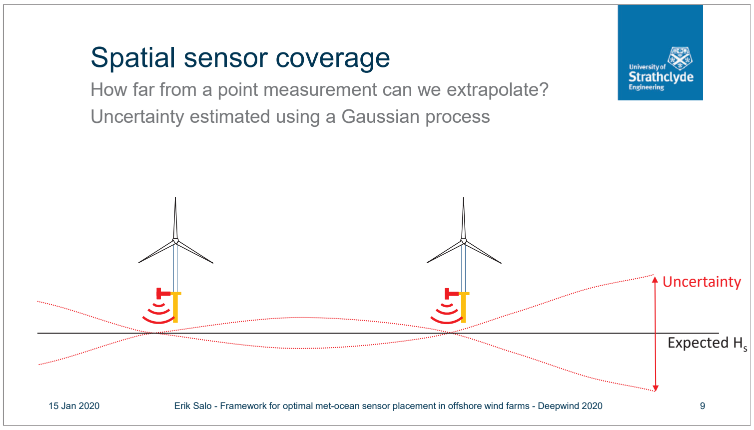
How to assess the conditions 'out there'?

Forecast is often inaccurate on a very local scale



Spatial sensor coverage

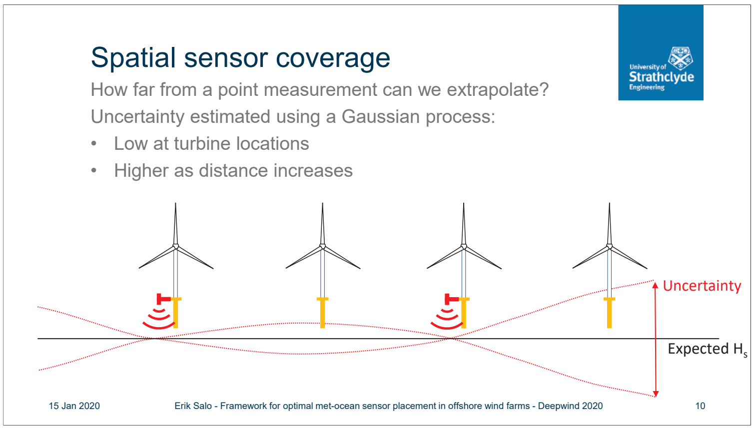
How far from a point measurement can we extrapolate?



Spatial sensor coverage

How far from a point measurement can we extrapolate?

Uncertainty estimated using a Gaussian process

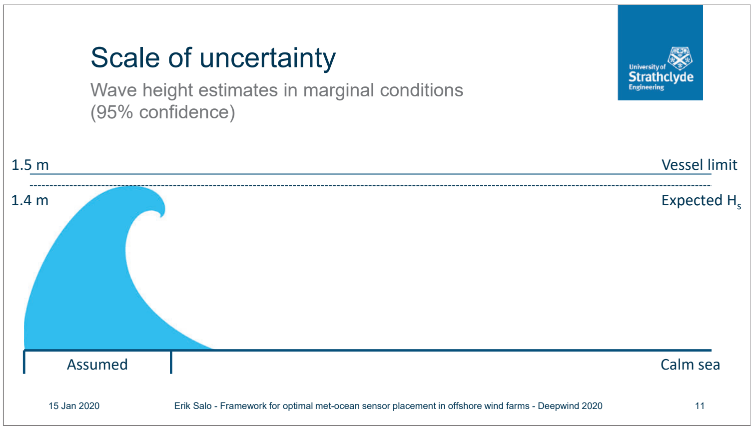


Spatial sensor coverage

How far from a point measurement can we extrapolate?

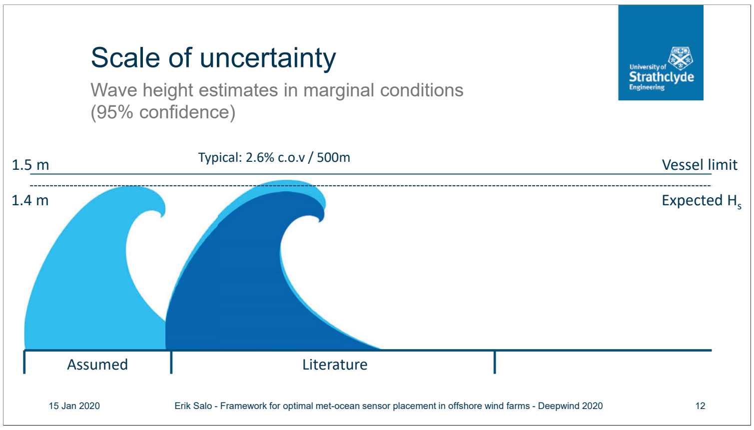
Uncertainty estimated using a Gaussian process:

- Low at turbine locations
- Higher as distance increases



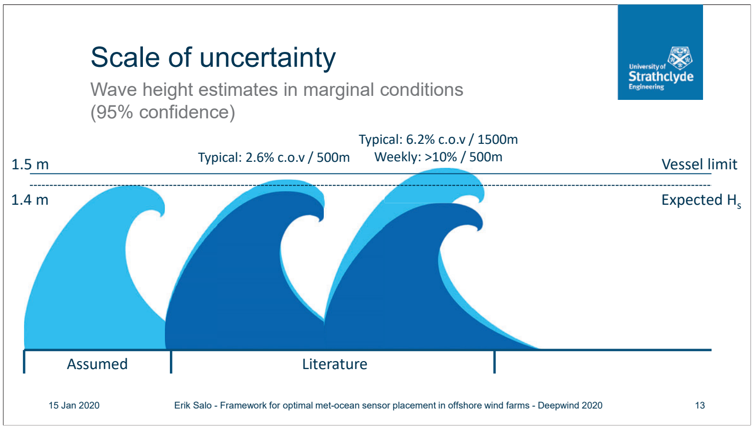
Scale of uncertainty

Wave height estimates in marginal conditions
(95% confidence)



Scale of uncertainty

Wave height estimates in marginal conditions
(95% confidence)



Scale of uncertainty

Wave height estimates in marginal conditions (95% confidence)

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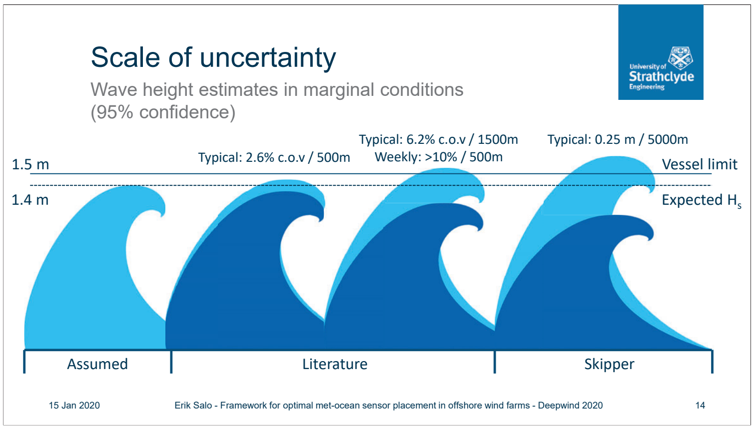

Scale of uncertainty

Wave height estimates in marginal conditions (95% confidence)

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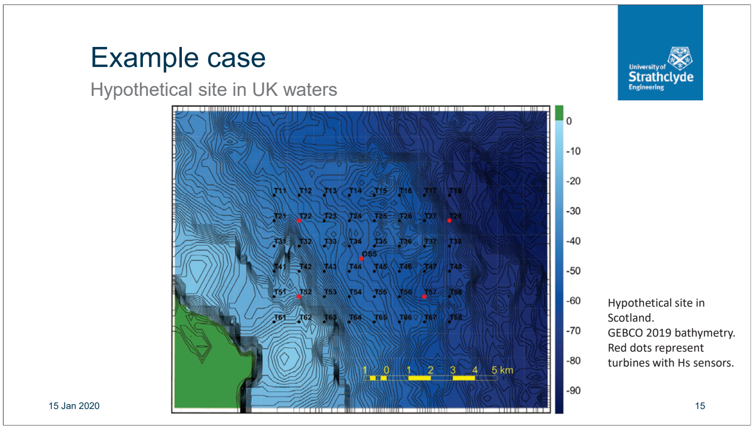

Example case

Hypothetical site in UK waters

Hypothetical site in Scotland.
GEBCO 2019 bathymetry.
Red dots represent turbines with Hs sensors.

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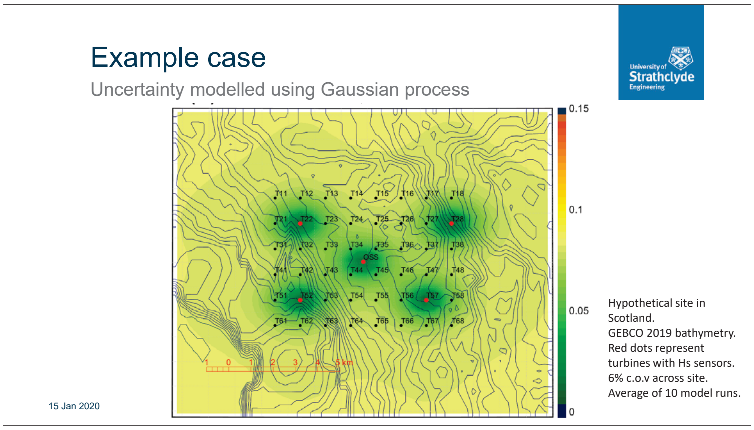

Example case

Uncertainty modelled using Gaussian process

Hypothetical site in Scotland.
GEBCO 2019 bathymetry.
Red dots represent turbines with Hs sensors.
6% c.o.v across site.
Average of 10 model runs.

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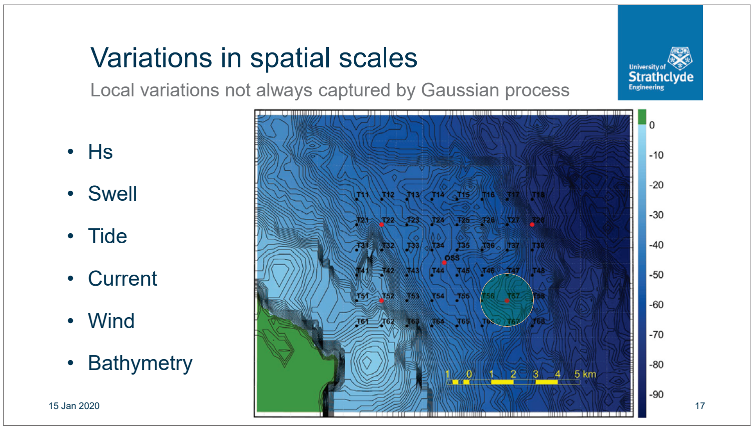

Variations in spatial scales

Local variations not always captured by Gaussian process

- Hs
- Swell
- Tide
- Current
- Wind
- Bathymetry

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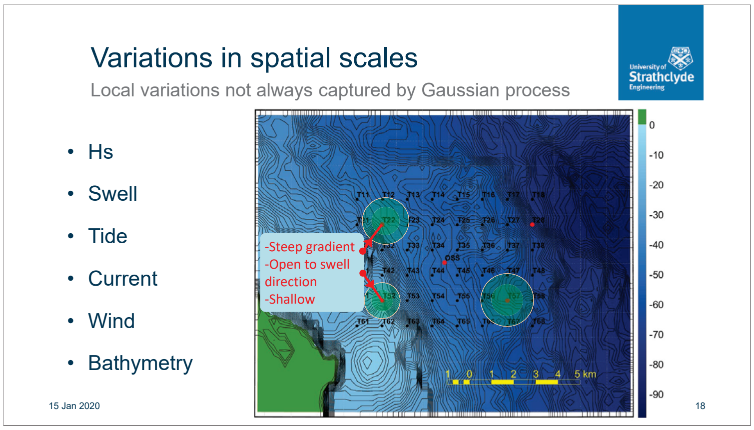

Variations in spatial scales

Local variations not always captured by Gaussian process

- Hs
- Swell
- Tide
- Current
- Wind
- Bathymetry

-Steep gradient
-Open to swell direction
-Shallow

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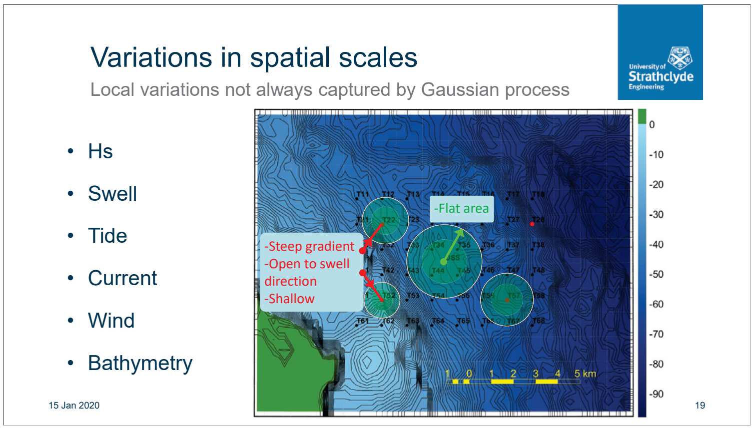
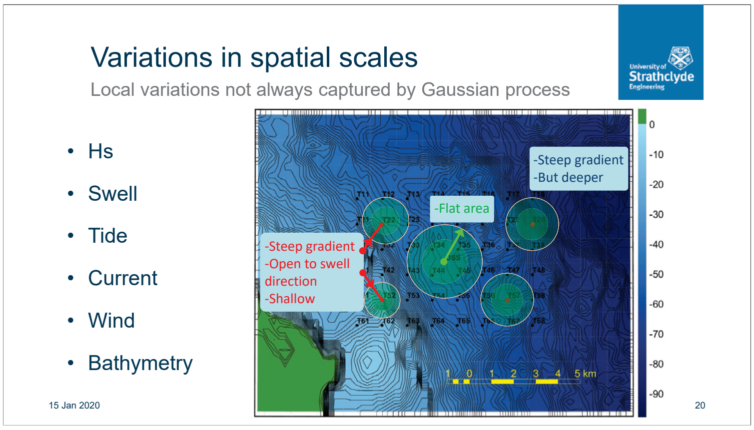


Variations in spatial scales

Local variations not always captured by Gaussian process

- Hs
- Swell
- Tide
- Current
- Wind
- Bathymetry



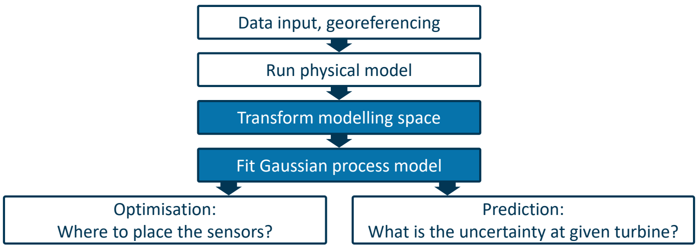
Variations in spatial scales

Local variations not always captured by Gaussian process

- Hs
- Swell
- Tide
- Current
- Wind
- Bathymetry

Proposed framework

To include spatial uncertainty in decision-making



Data input, georeferencing

Run physical model

Transform modelling space

Fit Gaussian process model

Optimisation:
Where to place the sensors?

Prediction:
What is the uncertainty at given turbine?

Conclusions

- We propose a framework to maximise the decision value of Hs point measurements
- 3-5 point measurements seen as optimum
  - Bathymetry mainly determines placement
- Value of uncertainty quantification in O&M decisions:
  - <£1 M per year per site
- Ongoing work:
  - Trials at two UK sites
  - Transformations
  - Validation

Thank you for your attention!

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C2) Met-ocean conditions

Dynamic response of bottom fixed and floating wind turbines. Sensitivity to wind field models, F.G.Nielsen, UiB

Relevance of sea waves and farm-farm wakes for offshore wind resource assessment, J.Fischereit, DTU Wind Energy

Dependence of Floating Lidar Performance on External Parameters – Results of a System Classification Focussing on Sea States, G.Wolken-Möhlmann, Fraunhofer IWES

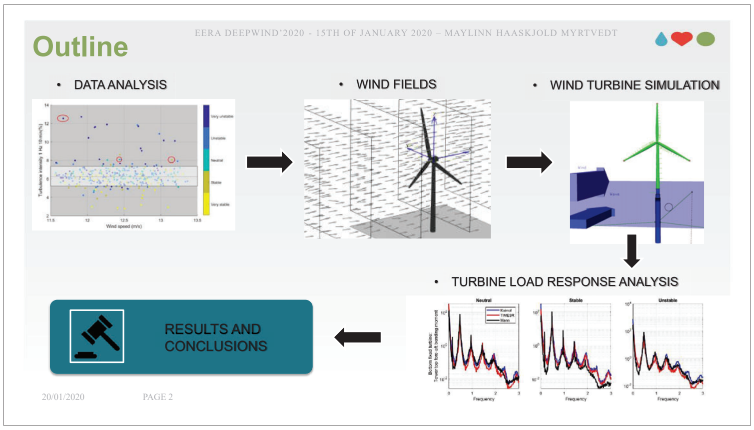
EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

The dynamic response of offshore wind turbines and their sensitivity to wind field models

Maylinn Haaskjold Myrtvedt
Astrid Nybø & Finn Gunnar Nielsen

Geophysical Institute & Bergen Offshore Wind Centre

UNIVERSITY OF BERGEN



Outline

EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

- DATA ANALYSIS
- WIND FIELDS
- WIND TURBINE SIMULATION
- TURBINE LOAD RESPONSE ANALYSIS

RESULTS AND CONCLUSIONS

20/01/2020 PAGE 2

Motivation

EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Generate turbulence wind fields based on: IEC standard and measurements

Find the impact on turbine response due to coherence and atmospheric stability

Investigate global and local responses of offshore wind turbines

Bottom fixed and spar floater simulations

Simulation program: SIMA
Input: pre-generated wind fields

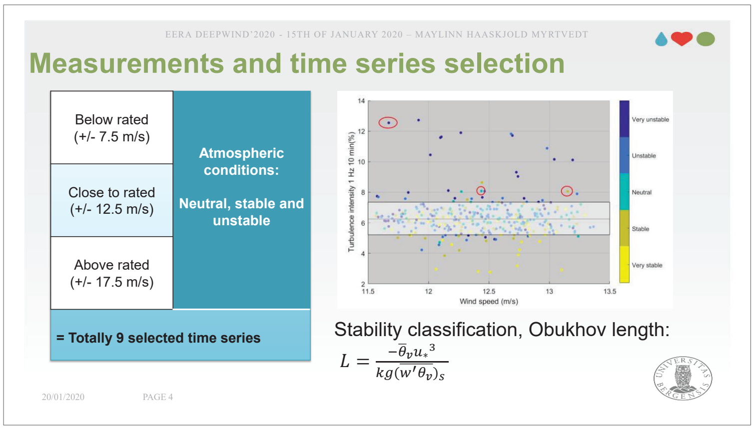
Global response:

- Tower bottom fore-aft bending moment (TBBM)
- Tower top fore-aft bending moment (TTBM)
- Tower top yaw moments (TTYM)

Local response:

- Flapwise bending moment in the blade root (one blade) (FBM)

20/01/2020 PAGE 3



Measurements and time series selection

EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Below rated (+/- 7.5 m/s)	**Atmospheric conditions:** **Neutral, stable and unstable**
Close to rated (+/- 12.5 m/s)	
Above rated (+/- 17.5 m/s)	

= Totally 9 selected time series

Stability classification, Obukhov length:

$$L = \frac{-\bar{\theta}_v u_*^3}{kg(w'\theta_v)_s}$$

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The wind fields

EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Kaimal spectral model: *TurbSim turbulence simulator*

- Reproduce turbulence time series using Kaimal spectrum and IEC exponential coherence function

Mann uniform shear model: *DTU Mann generator*

- Three-dimensional wind boxes with turbulence from spectral tensor. Coherence implicit.

TIMESR: *A TurbSim option*

- Spectral amplitudes and phase angles measured time series. (40, 60 and 80 m height). Davenport coherence function.

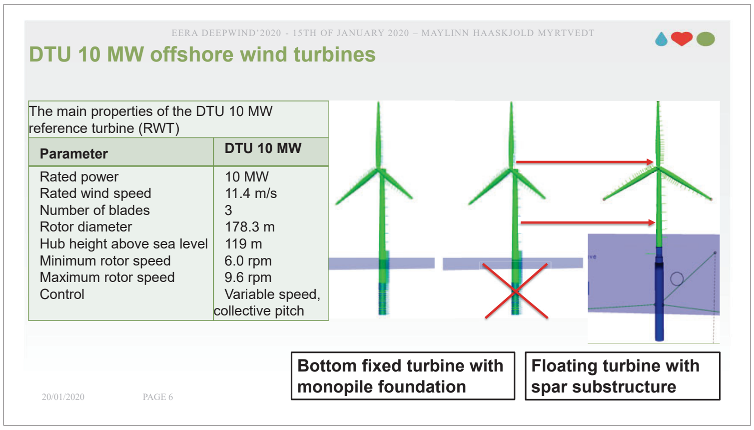
Mean wind speed	Atmospheric stability:
+/-7.5 m/s	Neutral
	Stable
	Unstable
+/-12.5 m/s	Neutral
	Stable
	Unstable
+/-17.5 m/s	Neutral
	Stable
	Unstable

Each wind speed case and atmospheric condition:

Same ***turbulence intensity***

Same ***wind shear profile***

20/01/2020 PAGE 5



DTU 10 MW offshore wind turbines

EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

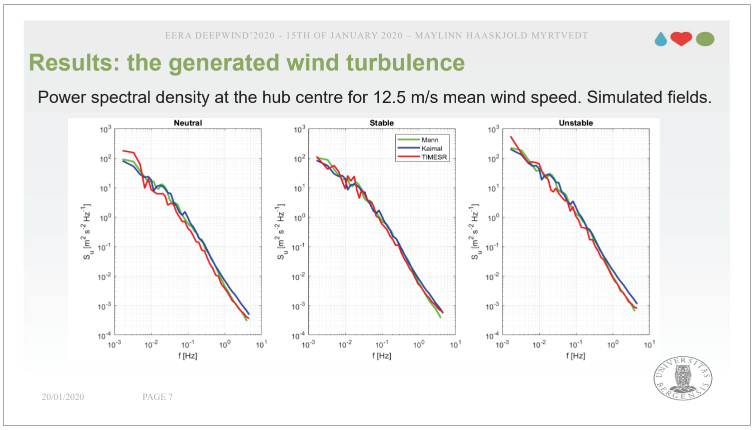
The main properties of the DTU 10 MW reference turbine (RWT)

Parameter	DTU 10 MW
Rated power	10 MW
Rated wind speed	11.4 m/s
Number of blades	3
Rotor diameter	178.3 m
Hub height above sea level	119 m
Minimum rotor speed	6.0 rpm
Maximum rotor speed	9.6 rpm
Control	Variable speed, collective pitch

Bottom fixed turbine with monopile foundation

Floating turbine with spar substructure

20/01/2020 PAGE 6

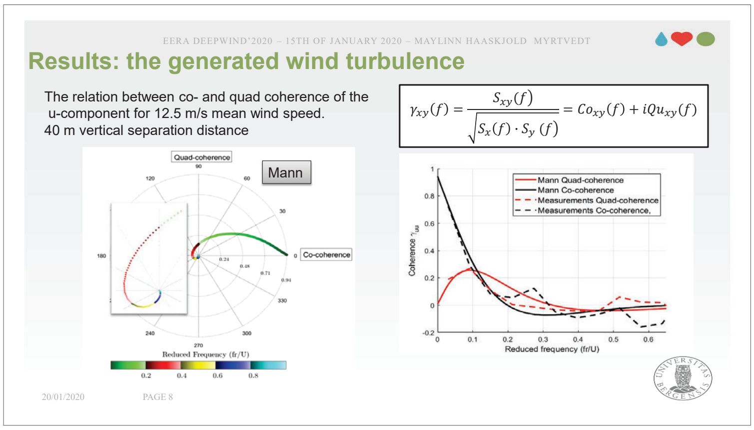


EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Results: the generated wind turbulence

Power spectral density at the hub centre for 12.5 m/s mean wind speed. Simulated fields.

20/01/2020 PAGE 7



EERA DEEPWIND'2020 – 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Results: the generated wind turbulence

The relation between co- and quad coherence of the u-component for 12.5 m/s mean wind speed.
40 m vertical separation distance

$$\gamma_{xy}(f) = \frac{S_{xy}(f)}{\sqrt{S_x(f) \cdot S_y(f)}} = Co_{xy}(f) + iQu_{xy}(f)$$

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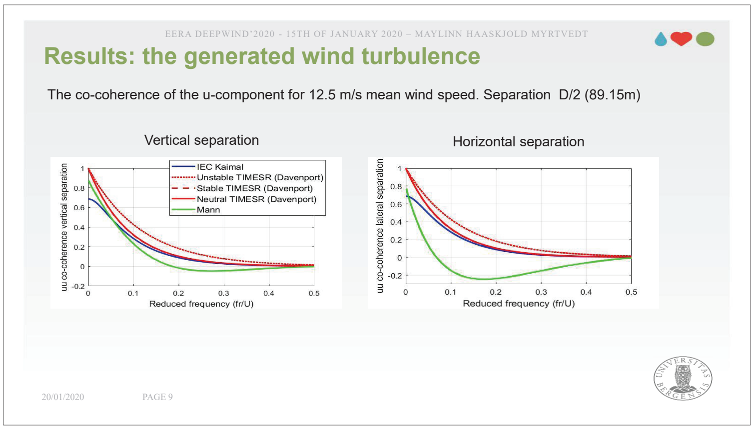


EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

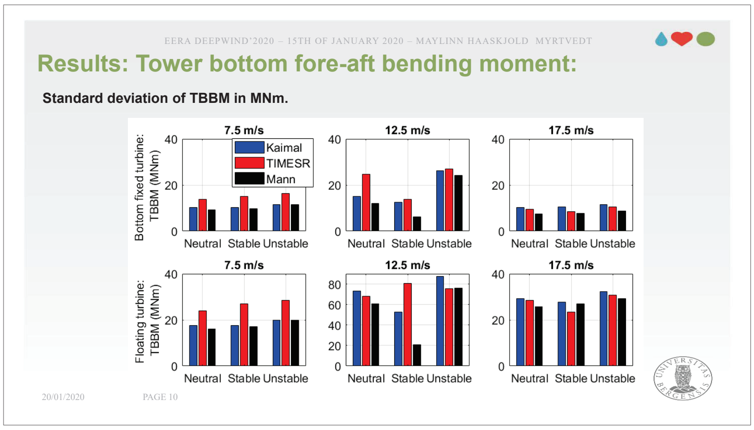
Results: the generated wind turbulence

The co-coherence of the u-component for 12.5 m/s mean wind speed. Separation D/2 (89.15m)

Vertical separation

Horizontal separation

20/01/2020 PAGE 9



EERA DEEPWIND'2020 – 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Results: Tower bottom fore-aft bending moment:

Standard deviation of TBBM in MNm.

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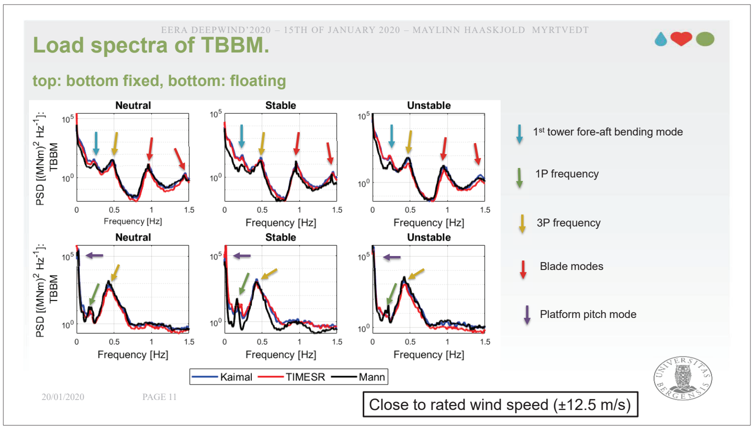

EERA DEEPWIND'2020 – 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Load spectra of TBBM.

top: bottom fixed, bottom: floating

1st tower fore-aft bending mode

1P frequency

3P frequency

Blade modes

Platform pitch mode

Close to rated wind speed (±12.5 m/s)

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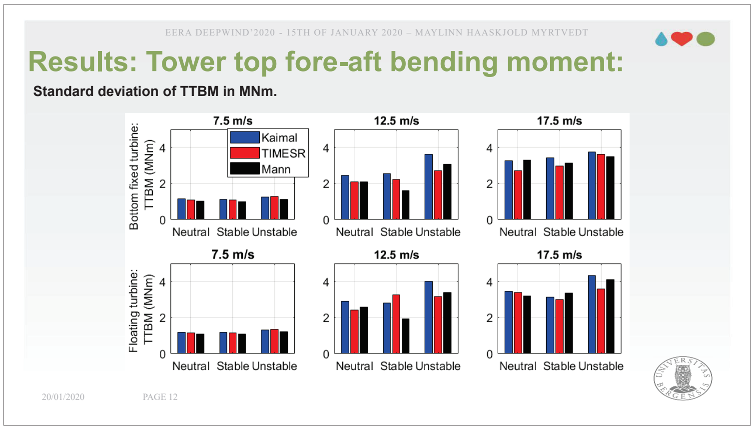
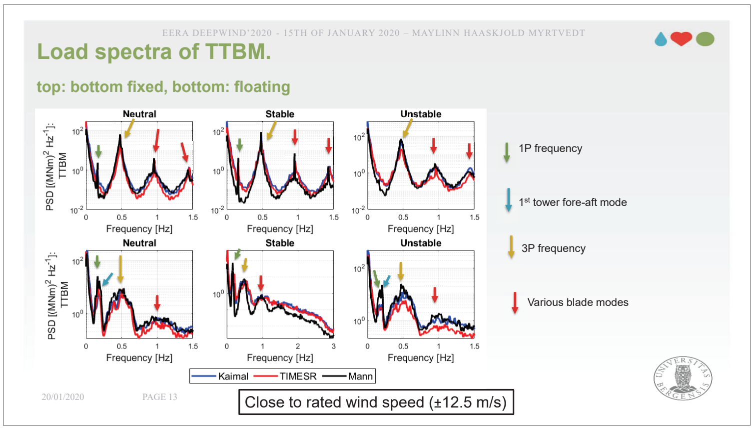


EERA DEEPWIND'2020 – 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Results: Tower top fore-aft bending moment:

Standard deviation of TTBM in MNm.

20/01/2020 PAGE 12



EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Load spectra of TTBM.

top: bottom fixed, bottom: floating

1P frequency

1st tower fore-aft mode

3P frequency

Various blade modes

Close to rated wind speed (±12.5 m/s)

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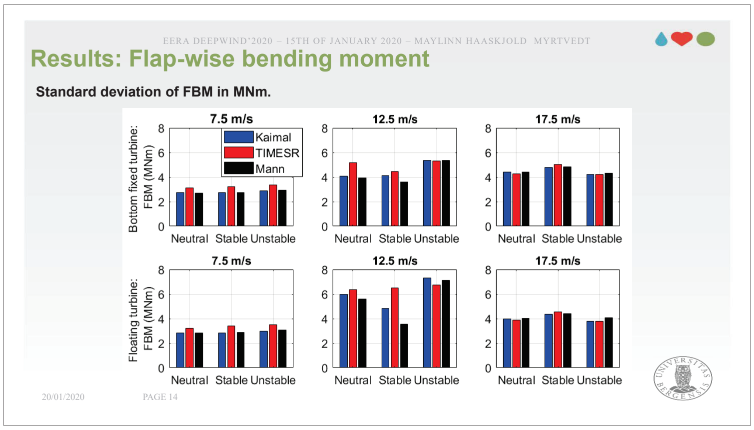

EERA DEEPWIND'2020 – 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Results: Flap-wise bending moment

Standard deviation of FBM in MNm.

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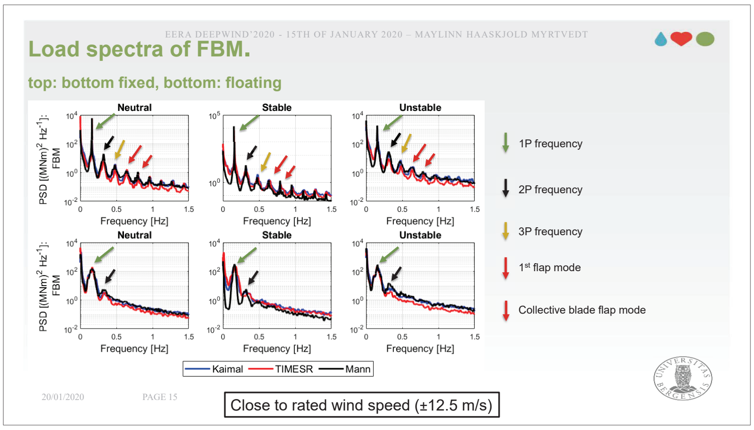


EERA DEEPWIND'2020 - 15TH OF JANUARY 2020 – MAYLINN HAASKJOLD MYRTVEDT

Load spectra of FBM.

top: bottom fixed, bottom: floating

1P frequency

2P frequency

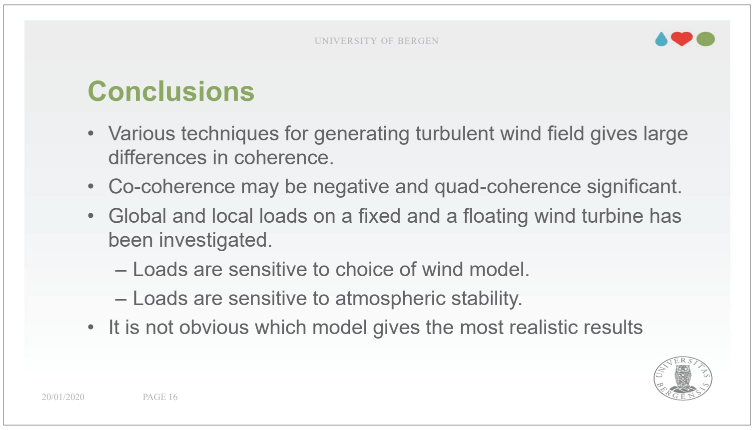
3P frequency

1st flap mode

Collective blade flap mode

Close to rated wind speed (±12.5 m/s)

20/01/2020 PAGE 15



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Conclusions

- Various techniques for generating turbulent wind field gives large differences in coherence.
- Co-coherence may be negative and quad-coherence significant.
- Global and local loads on a fixed and a floating wind turbine has been investigated.
  - Loads are sensitive to choice of wind model.
  - Loads are sensitive to atmospheric stability.
- It is not obvious which model gives the most realistic results

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Thank you for the attention!

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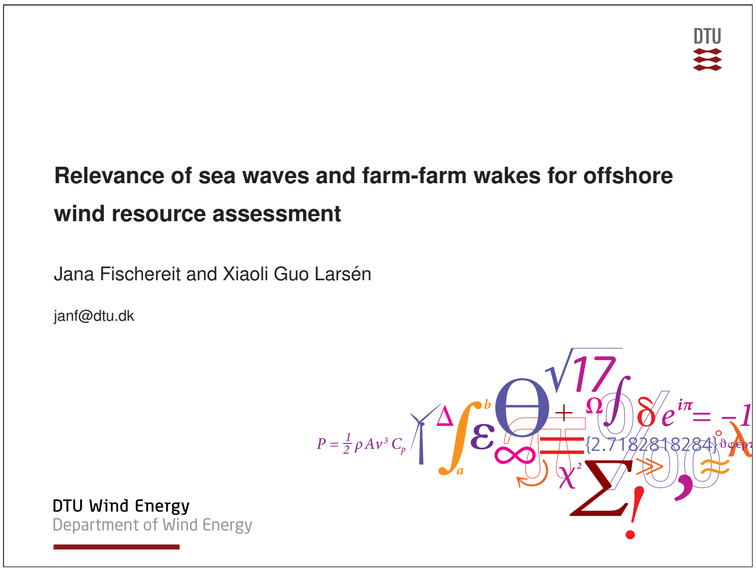
Bergen Offshore Wind Centre



Relevance of sea waves and farm-farm wakes for offshore wind resource assessment

Jana Fischereit and Xiaoli Guo Larsén

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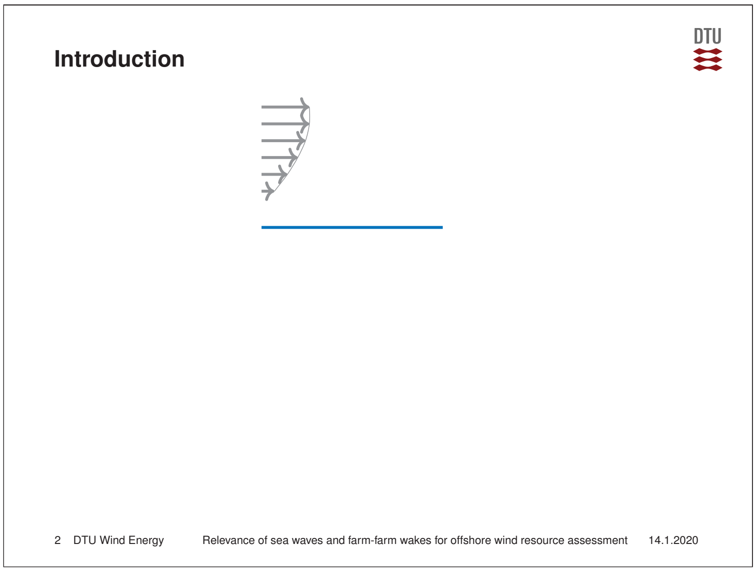
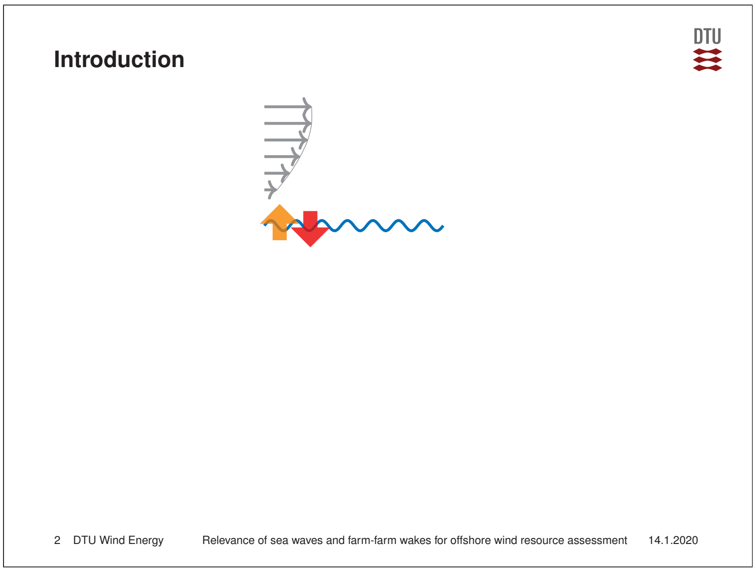
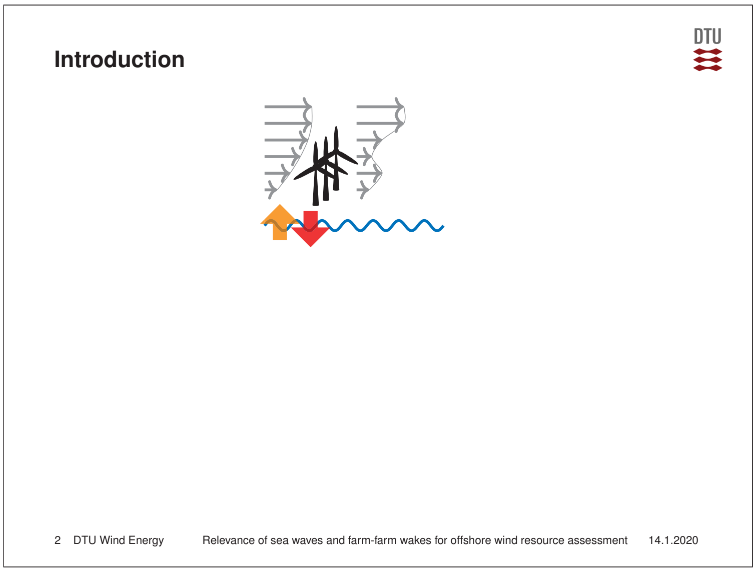
DTU Wind Energy
Department of Wind Energy



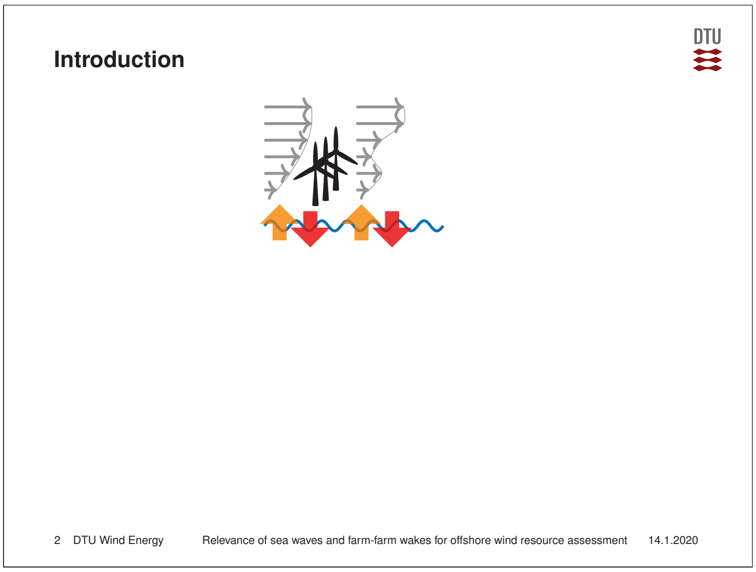
Introduction



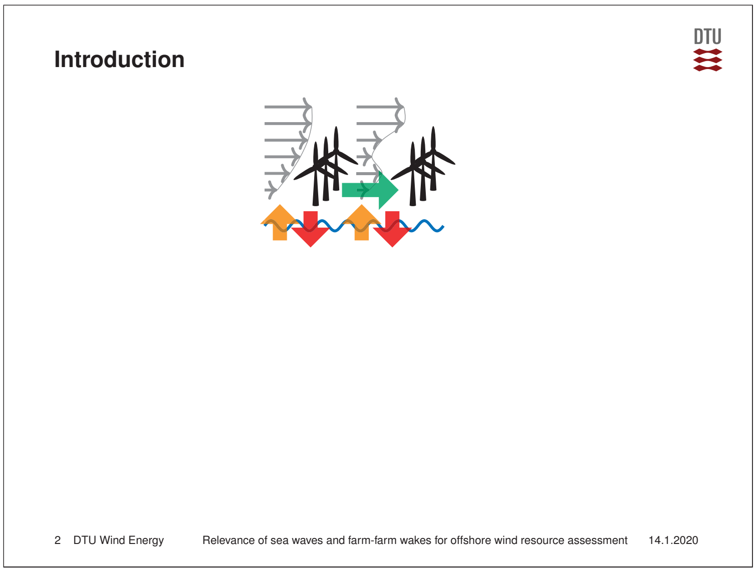
Introduction



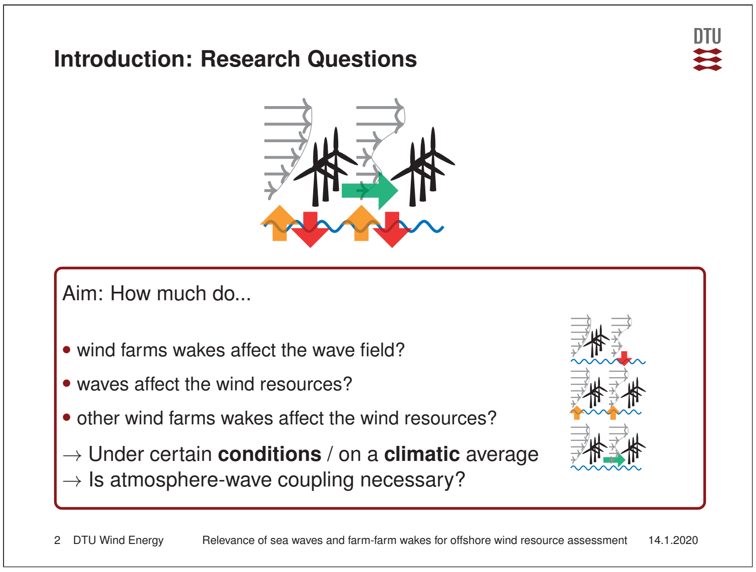
Introduction



Introduction



Introduction

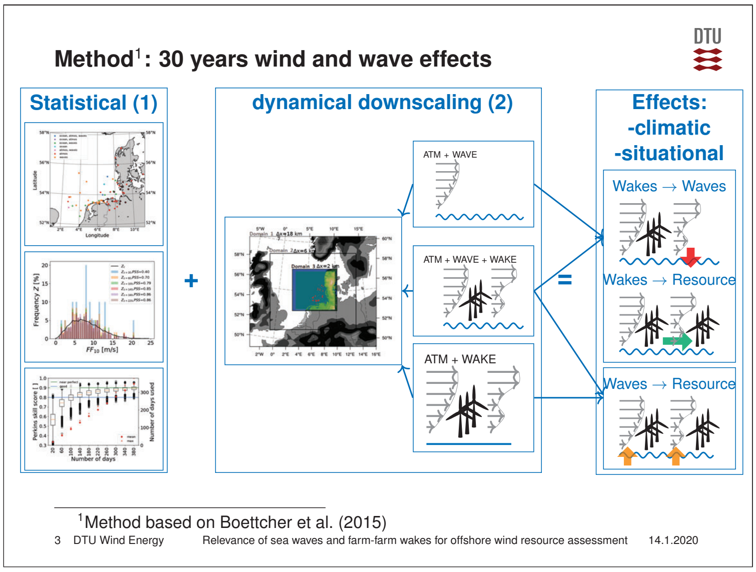


Introduction: Research Questions

Aim: How much do...

- wind farms wakes affect the wave field?
- waves affect the wind resources?
- other wind farms wakes affect the wind resources?

→ Under certain **conditions** / on a **climatic** average
→ Is atmosphere-wave coupling necessary?



Method[1]: 30 years wind and wave effects

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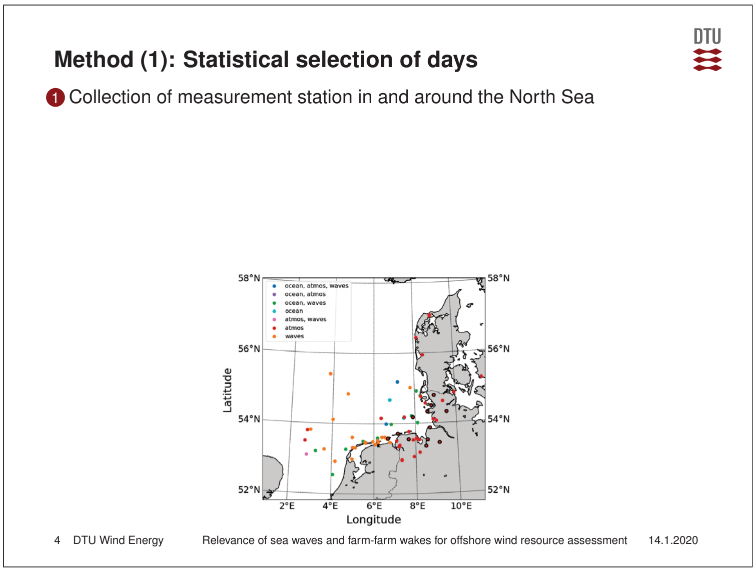
[1] Method based on Boettcher et al. (2015)



Method (1): Statistical selection of days

① Collection of measurement station in and around the North Sea

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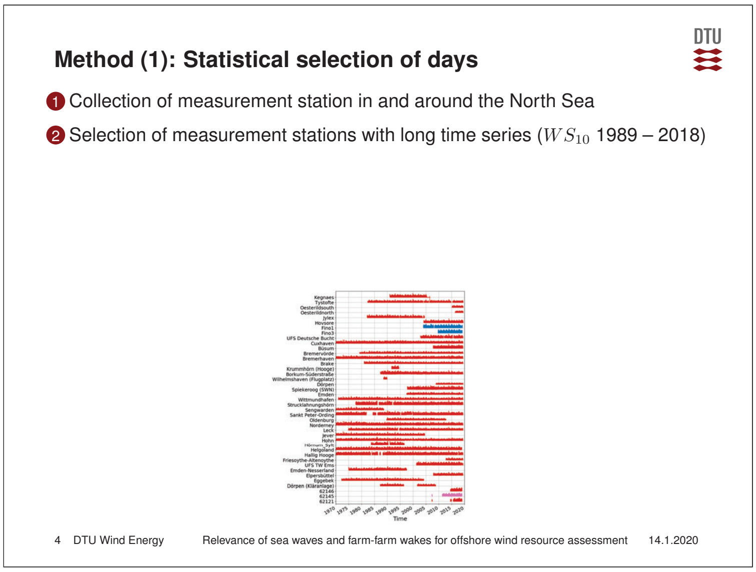
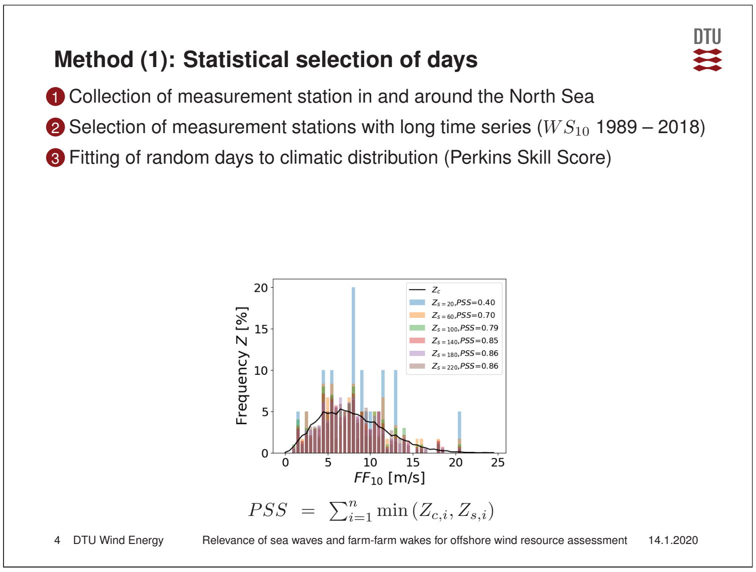


Method (1): Statistical selection of days

① Collection of measurement station in and around the North Sea

② Selection of measurement stations with long time series (WS_{10} 1989 – 2018)



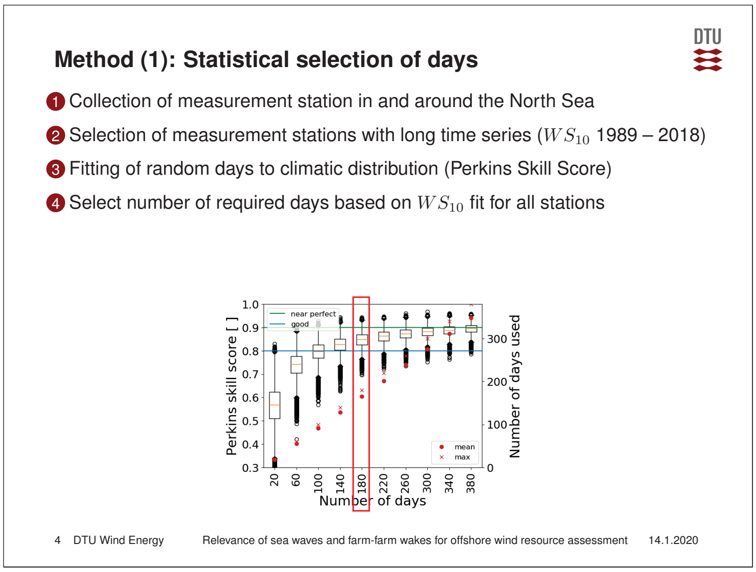
Method (1): Statistical selection of days

① Collection of measurement station in and around the North Sea

② Selection of measurement stations with long time series (WS_{10} 1989 – 2018)

③ Fitting of random days to climatic distribution (Perkins Skill Score)

$$PSS = \sum_{i=1}^{n} \min\left(Z_{c,i}, Z_{s,i}\right)$$



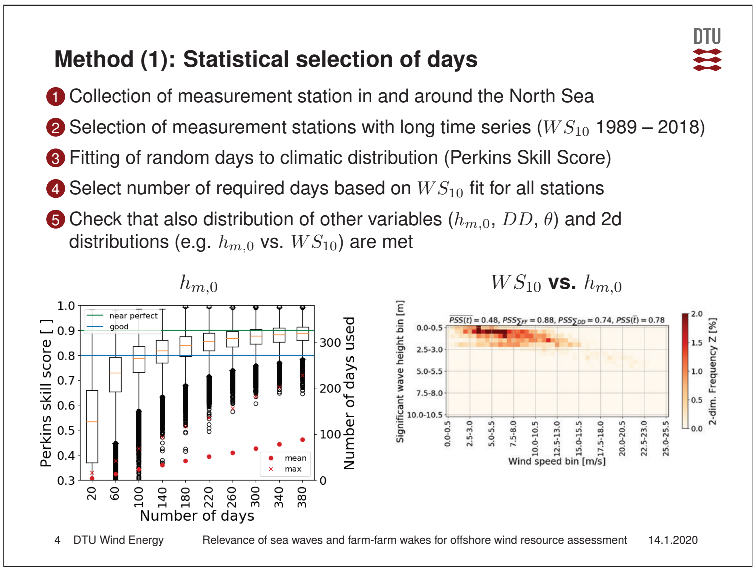
Method (1): Statistical selection of days

① Collection of measurement station in and around the North Sea

② Selection of measurement stations with long time series (WS_{10} 1989 – 2018)

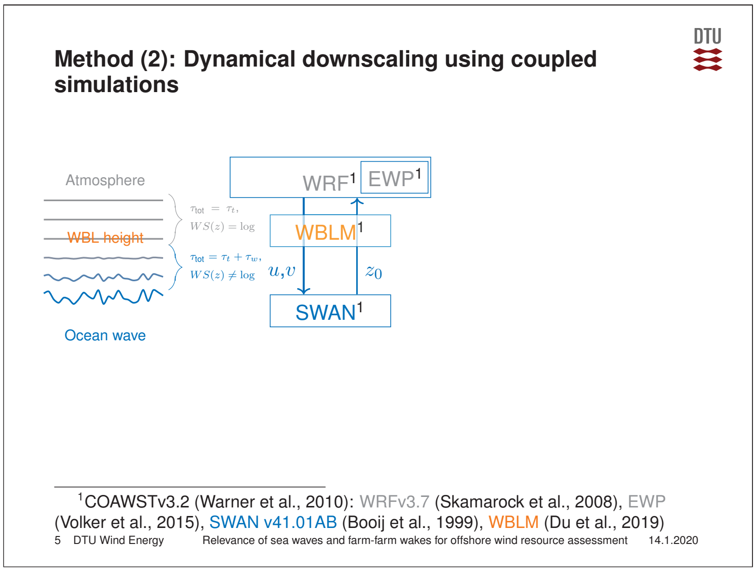
③ Fitting of random days to climatic distribution (Perkins Skill Score)

④ Select number of required days based on WS_{10} fit for all stations



Method (1): Statistical selection of days

① Collection of measurement station in and around the North Sea
② Selection of measurement stations with long time series (WS_{10} 1989 – 2018)
③ Fitting of random days to climatic distribution (Perkins Skill Score)
④ Select number of required days based on WS_{10} fit for all stations
⑤ Check that also distribution of other variables ($h_{m,0}$, DD, θ) and 2d distributions (e.g. $h_{m,0}$ vs. WS_{10}) are met



Method (2): Dynamical downscaling using coupled simulations

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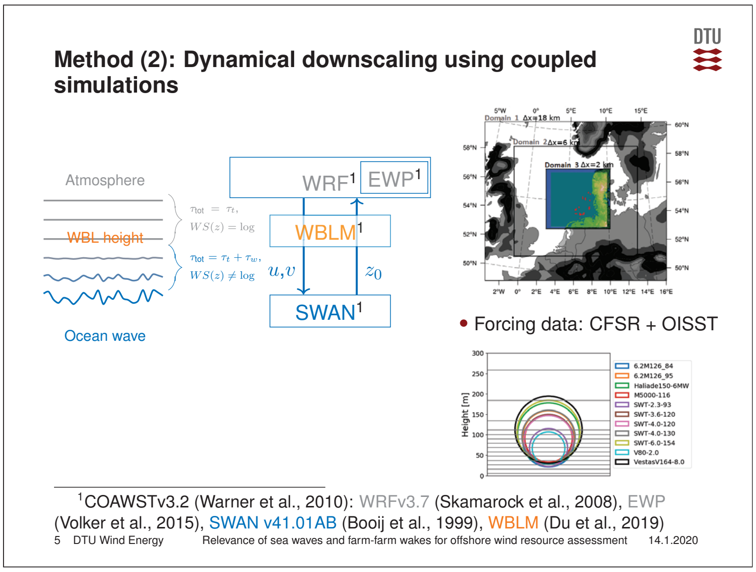
[1] COAWSTv3.2 (Warner et al., 2010): WRFv3.7 (Skamarock et al., 2008), EWP (Volker et al., 2015), SWAN v41.01AB (Booij et al., 1999), WBLM (Du et al., 2019)



Method (2): Dynamical downscaling using coupled simulations

- Forcing data: CFSR + OISST

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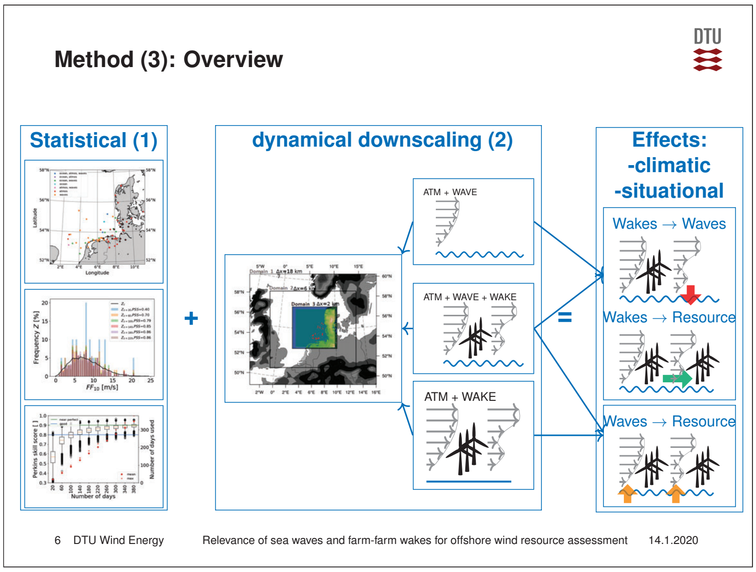
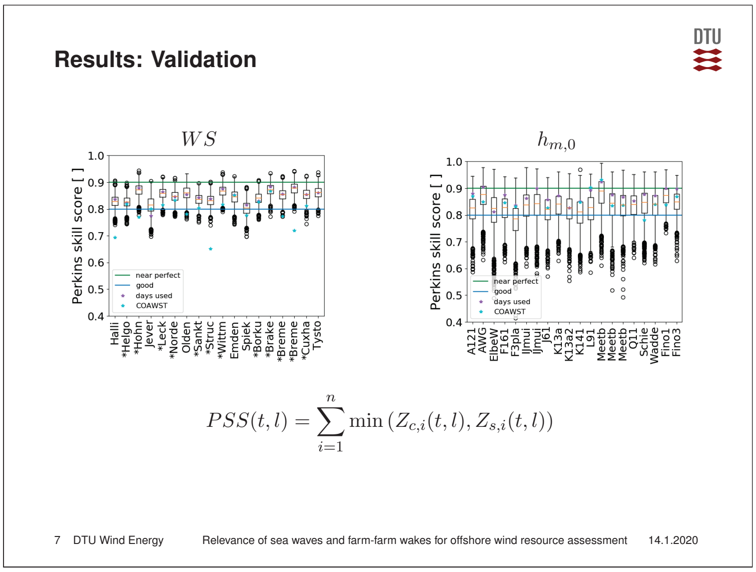
[1] COAWSTv3.2 (Warner et al., 2010): WRFv3.7 (Skamarock et al., 2008), EWP (Volker et al., 2015), SWAN v41.01AB (Booij et al., 1999), WBLM (Du et al., 2019)

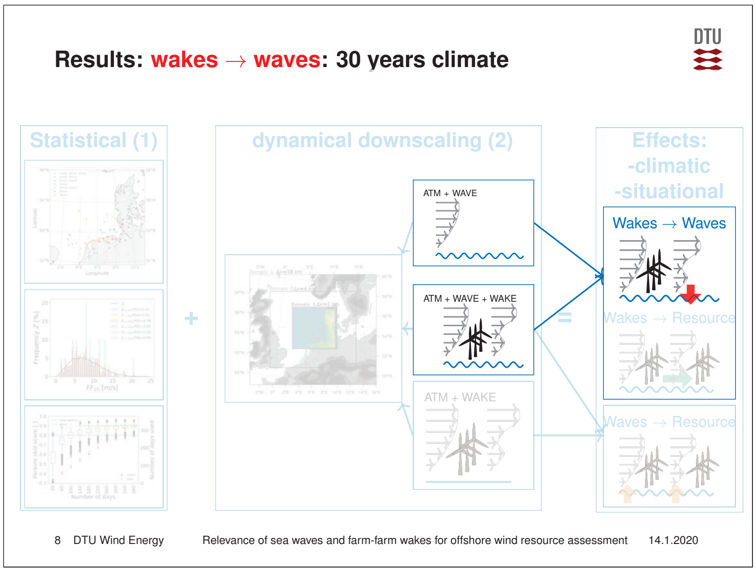


Method (3): Overview



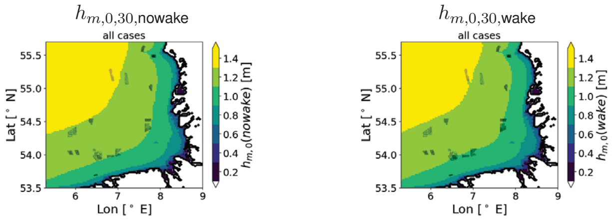
Results: Validation

$$PSS(t,l) = \sum_{i=1}^{n} \min\left(Z_{c,i}(t,l), Z_{s,i}(t,l)\right)$$

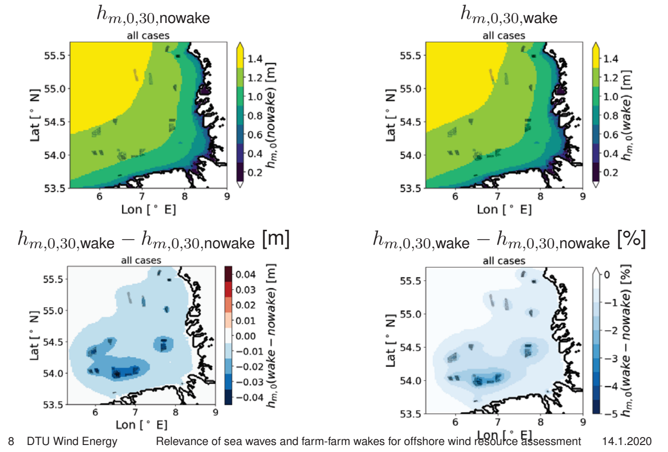


Results: wakes → waves: 30 years climate

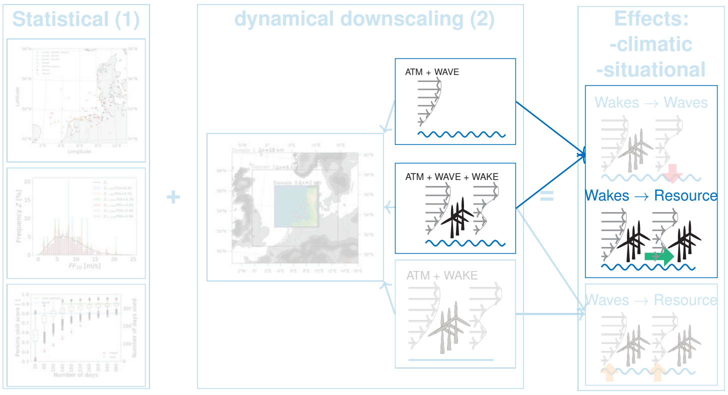
Results: wakes → waves: 30 years climate



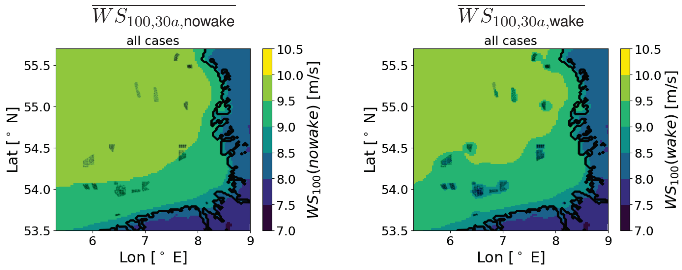
Results: wakes → waves: 30 years climate



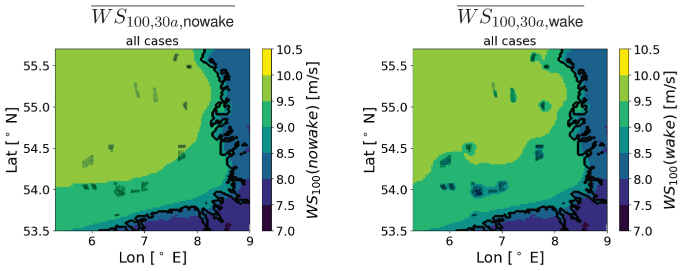
Results: wakes → resources: 30 years climate



Results: wakes → resources: 30 years climate



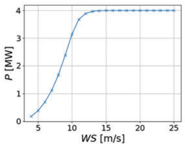
Results: wakes → resources: 30 years climate



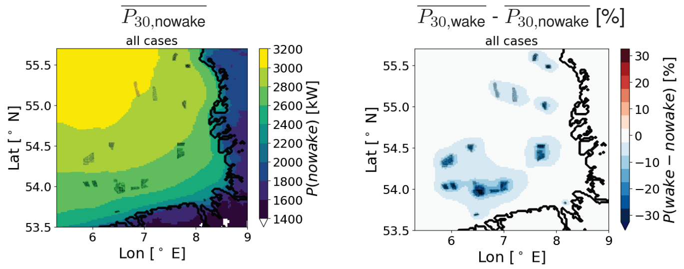
Implication for power:

① Use a SWT-4.0-120 turbine power curve

② Derive $\overline{P_{100,30a,\text{wake}}}$ and $\overline{P_{100,30a,\text{nowake}}}$ from $\overline{WS_{100,30a,\text{wake}}}$ and $\overline{WS_{100,30a,\text{nowake}}}$



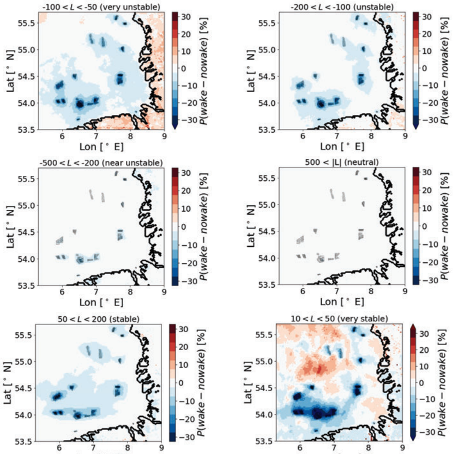
Results: wakes → resources: 30 years climate



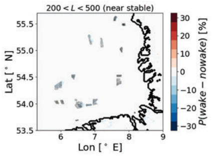
Results: wakes → resources: Stability dependence

$$\overline{P_{\text{wake}}(x,y,t)|_{L_{\text{nowake}}}}$$
$$-$$
$$\overline{P_{\text{nowake}}(x,y,t)|_{L_{\text{nowake}}}}$$

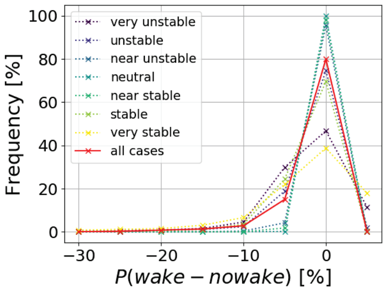
Results: wakes → resources: Stability dependence



$$\overline{P_{\text{wake}}(x,y,t)|_{L_{\text{nowake}}}}$$
$$-$$
$$\overline{P_{\text{nowake}}(x,y,t)|_{L_{\text{nowake}}}}$$

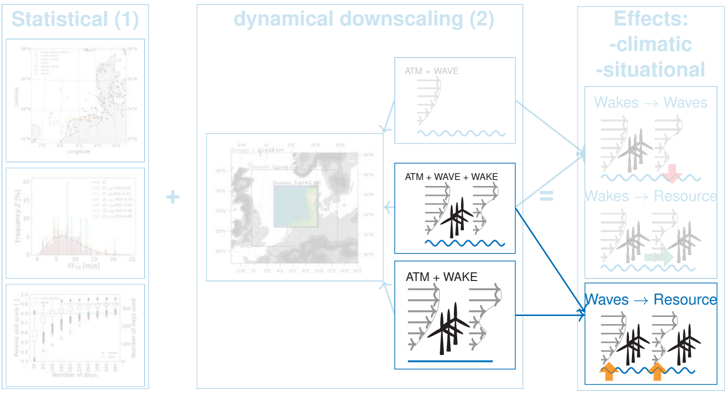


Results: wakes → resources: Stability dependence

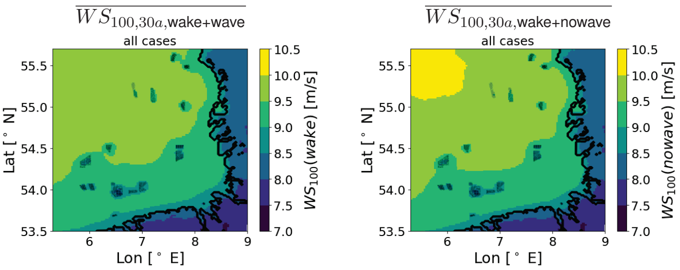


Note: both on- and offshore areas included

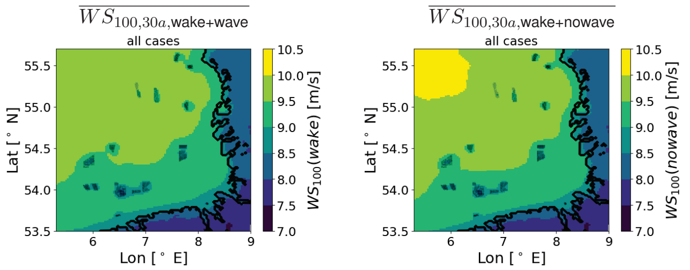
Results: waves → resources: 30 years climate



Results: waves → resources: 30 years climate



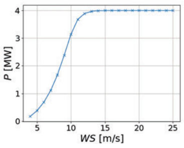
Results: waves → resources: 30 years climate



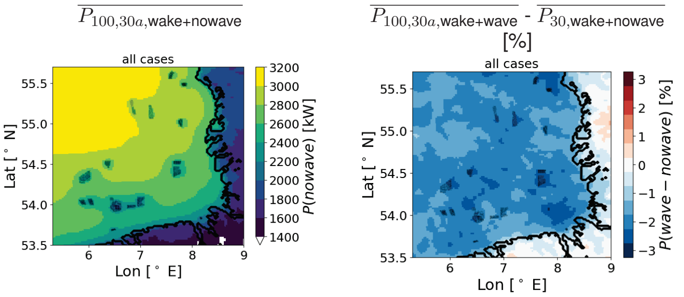
Implication for power:

① Use a SWT-4.0-120 turbine power curve

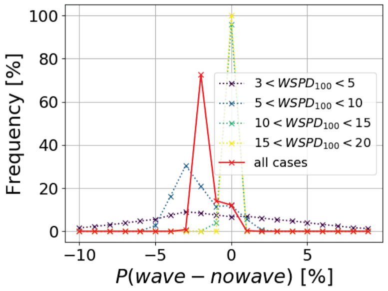
② Derive $\overline{P_{30,\text{wake+wave}}}$ and $\overline{P_{30,\text{wake+nowave}}}$ from $\overline{WS_{30,\text{wake+wave}}}$ and $\overline{WS_{30,\text{wake+nowave}}}$



Results: waves → resources: 30 years climate



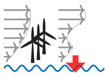
Results: waves → resources: 30 years climate



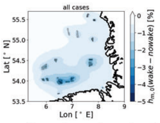
Note: both on- and offshore areas included

Conclusion

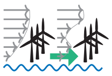
Wakes→Waves



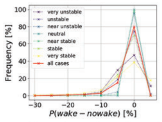
- wave height reduces by 3-5 % on average



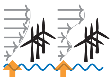
Wakes→Resources



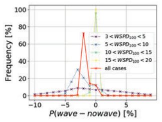
- Zone of reduced wind resources extends to other wind farms
- Depends on stability



Waves→Resources



- Wave effect one $\mathcal{O}$ smaller
- non-linear effect within the wake region



→ Coupled atmosphere-wave simulation for offshore resource predictions?

Conclusion

Wakes→Waves

- wave height reduces by 3-5 % on average

Wakes→Resources

Thank you!
Contact: Jana Fischereit `janf@dtu.dk`

Waves→Resources

- Wave effect one $\mathcal{O}$ smaller
- non-linear effect within the wake region

→ Coupled atmosphere-wave simulation for offshore resource predictions?

References and Acknowledgments

This study is mainly supported by the Danish EUDP/ForskEL project OffshoreWake (64017-0017/12521).

Data sources:

- **Deutscher Wetterdienst (German Weather Service), Climate Data Center (CDC)**
- **FINO Datenbank (Bundesamt für Seeschifffahrt und Hydrographie)**
- **EMODnet Physics system** `http://www.emodnet-physics.eu/Map/`
- **CFSR data from http://rda.ucar.edu/datasets (National Center for Atmospheric Research Staff (Eds), 2017)**
- **DTU Wind Energy mast measurements** `http://rodeo.dtu.dk/rodeo/ProjectListMap.aspx?&Rnd=441824`

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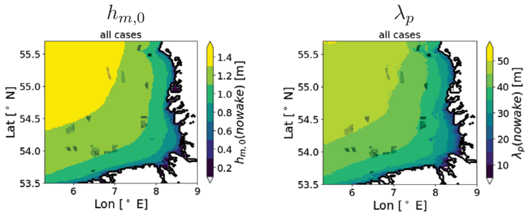
Results: wakes → waves: 30 years climate

$\overline{x_{30,\text{nowake}}}$



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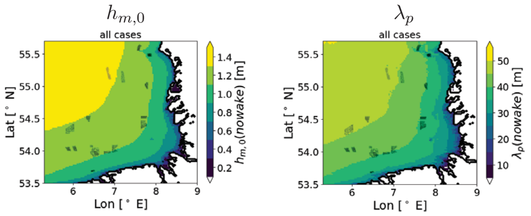
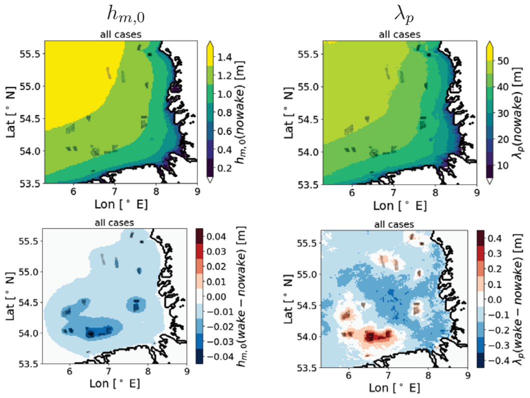


Results: wakes → waves: 30 years climate

$\overline{x_{30,\text{nowake}}}$

$\overline{x_{30,\text{wake}}}-\overline{x_{30,\text{nowake}}}$

[m]



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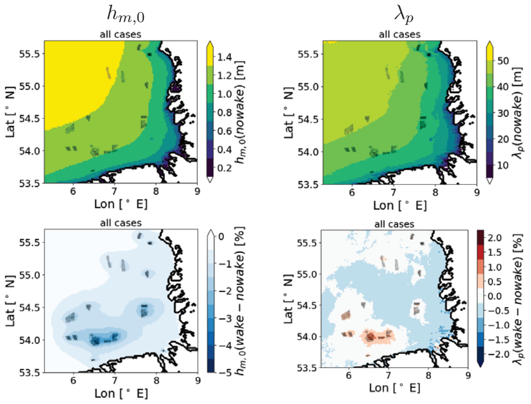
$\overline{x_{30,\text{nowake}}}$

$\overline{x_{30,\text{wake}}}-\overline{x_{30,\text{nowake}}}$

[%]



Dependence of Floating LiDAR Performance on External Parameters – Are existing onshore classification methods Applicable?

G. Wolken-Möhlmann, J. Gottschall

EERA Deepwind 2020, Trondheim, 15-17 Jan 2020

Outline

- Introduction
- FLS verification vs classification
- Case Study: Fraunhofer IWES LiDAR Buoy
- Resume

Introduction

Floating LiDAR Systems (FLS)

- Commercially available since 2010
- **Several providers** for systems or measurements, number growing
- FLS can **replace offshore meteorological masts** for site assessment, power curve measurements etc…

From: Gottschall et al: Floating lidar as an advanced offshore wind speed measurement technique, WIREs Energy and Environment, 2017 [1]

Introduction

Technology

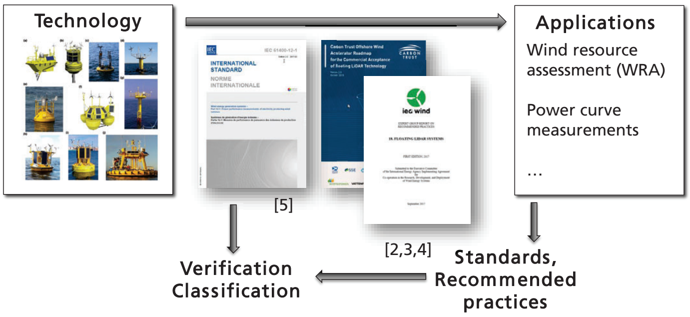
Applications

Wind resource assessment (WRA)

Power curve measurements

…

Introduction



Technology

Applications

Wind resource assessment (WRA)

Power curve measurements

…

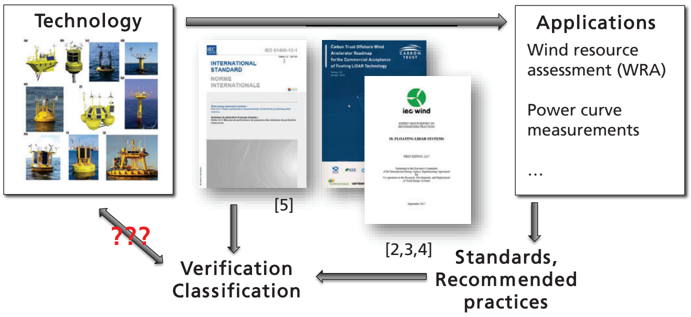
[5]

[2,3,4]

Verification Classification

Standards, Recommended practices

Introduction



Technology

Applications

Wind resource assessment (WRA)

Power curve measurements

…

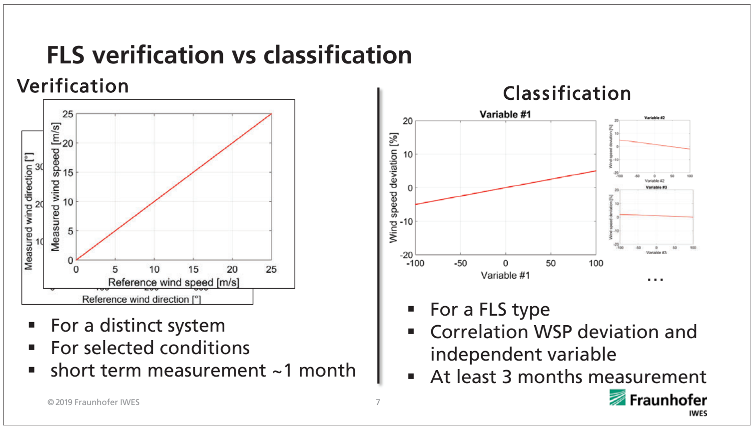
???

[5]

[2,3,4]

Verification Classification

Standards, Recommended practices



FLS verification vs classification

Verification

- For a distinct system
- For selected conditions
- short term measurement ~1 month

Classification

- For a FLS type
- Correlation WSP deviation and independent variable
- At least 3 months measurement

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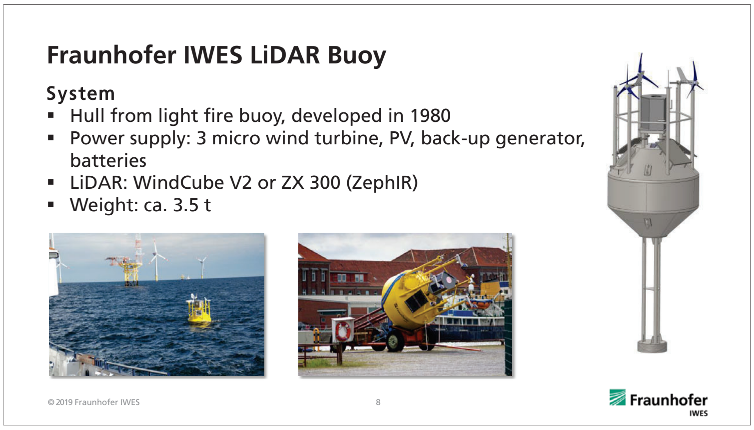

Fraunhofer IWES LiDAR Buoy

System

- Hull from light fire buoy, developed in 1980
- Power supply: 3 micro wind turbine, PV, back-up generator, batteries
- LiDAR: WindCube V2 or ZX 300 (ZephIR)
- Weight: ca. 3.5 t

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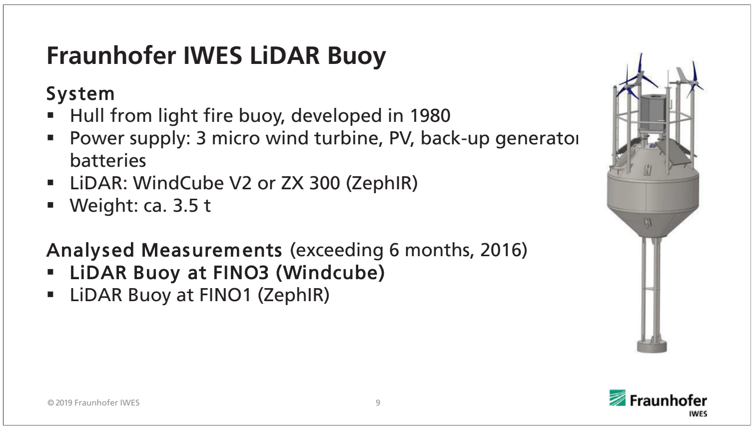

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- LiDAR: WindCube V2 or ZX 300 (ZephIR)
- Weight: ca. 3.5 t

Analysed Measurements (exceeding 6 months, 2016)

- **LiDAR Buoy at FINO3 (Windcube)**
- LiDAR Buoy at FINO1 (ZephIR)

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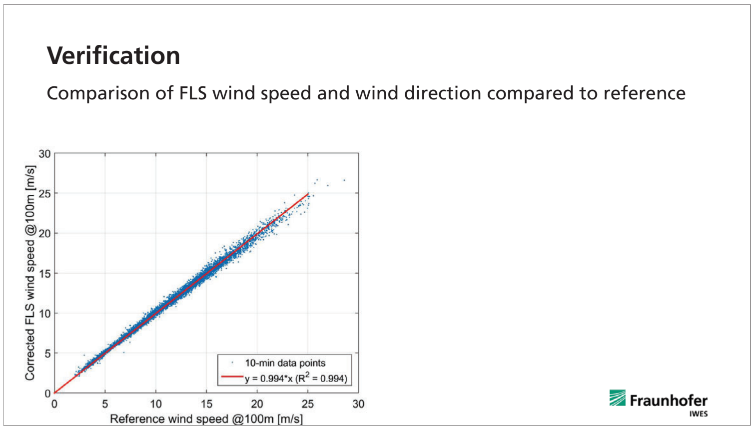
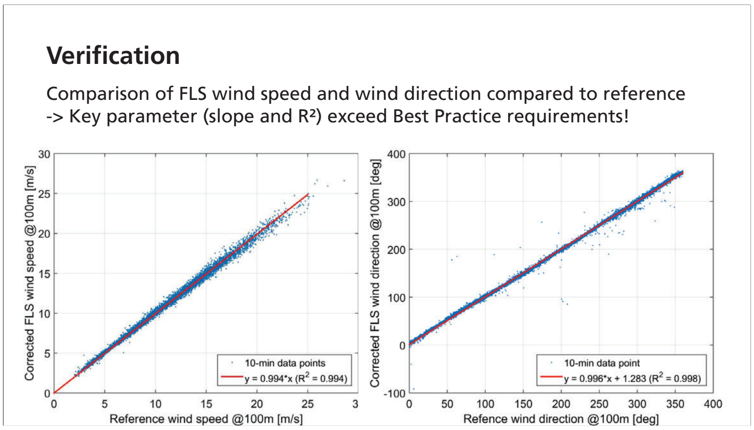


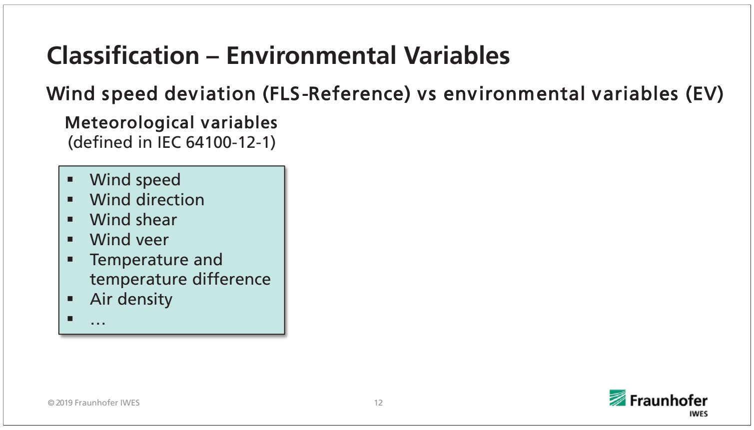
Verification

Comparison of FLS wind speed and wind direction compared to reference



Verification

Comparison of FLS wind speed and wind direction compared to reference
-> Key parameter (slope and R²) exceed Best Practice requirements!



Classification – Environmental Variables

Wind speed deviation (FLS-Reference) vs environmental variables (EV)

Meteorological variables
(defined in IEC 64100-12-1)

- Wind speed
- Wind direction
- Wind shear
- Wind veer
- Temperature and temperature difference
- Air density
- …

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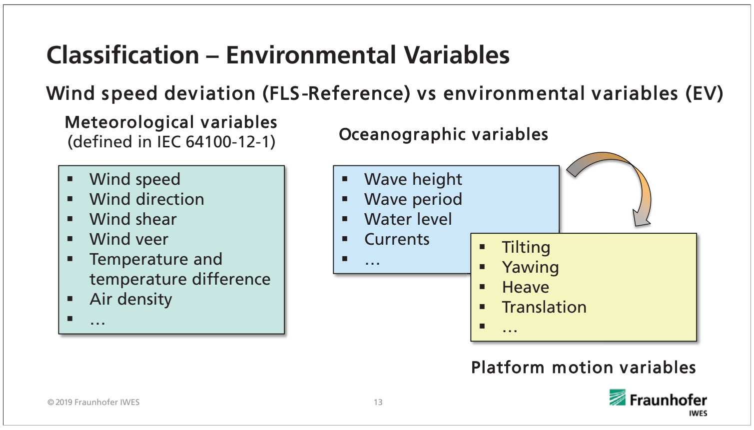


Classification – Environmental Variables

Wind speed deviation (FLS-Reference) vs environmental variables (EV)

Meteorological variables
(defined in IEC 64100-12-1)

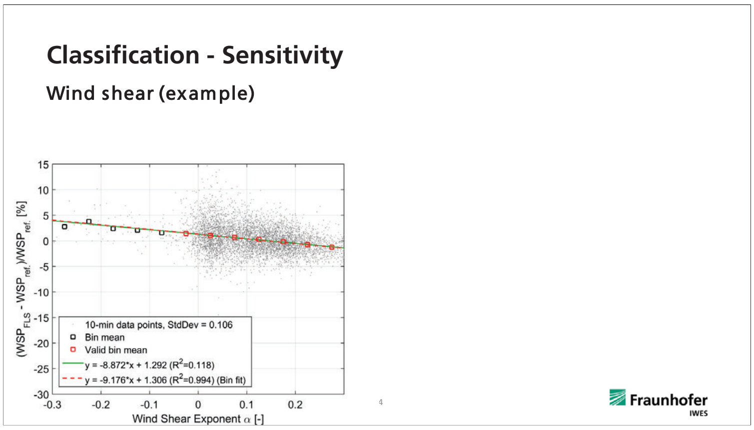
- Wind speed
- Wind direction
- Wind shear
- Wind veer
- Temperature and temperature difference
- Air density
- …

Oceanographic variables

- Wave height
- Wave period
- Water level
- Currents
- …

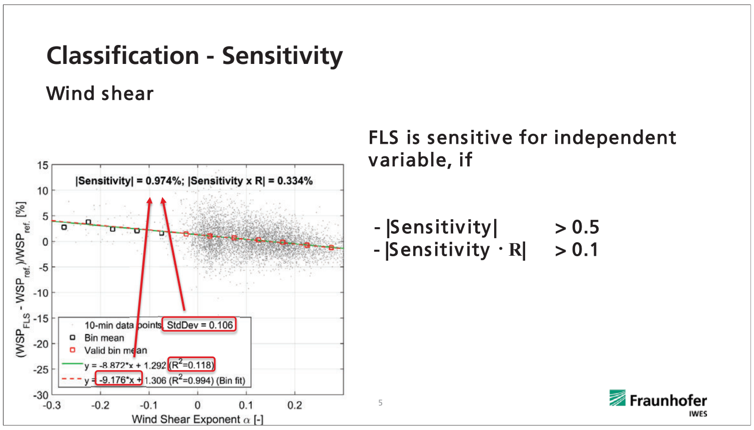
- Tilting
- Yawing
- Heave
- Translation
- …

Platform motion variables



Classification - Sensitivity

Wind shear (example)

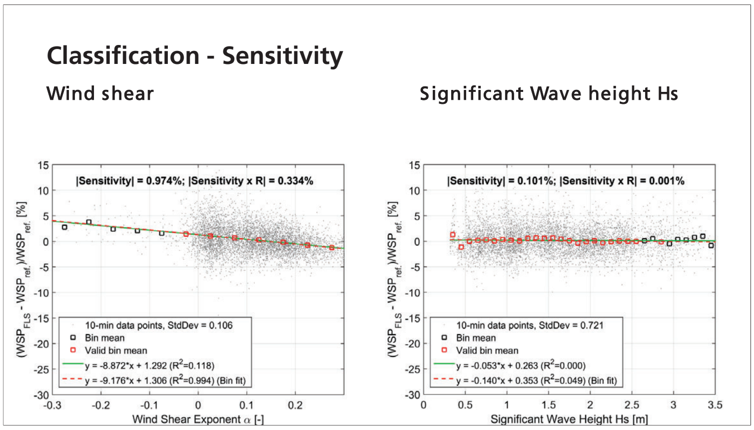


Classification - Sensitivity

Wind shear

FLS is sensitive for independent variable, if

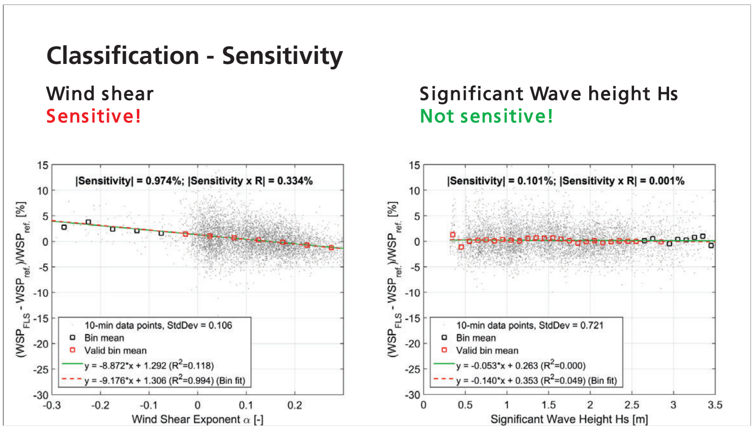
- |Sensitivity| > 0.5
- |Sensitivity · R| > 0.1



Classification - Sensitivity

Wind shear

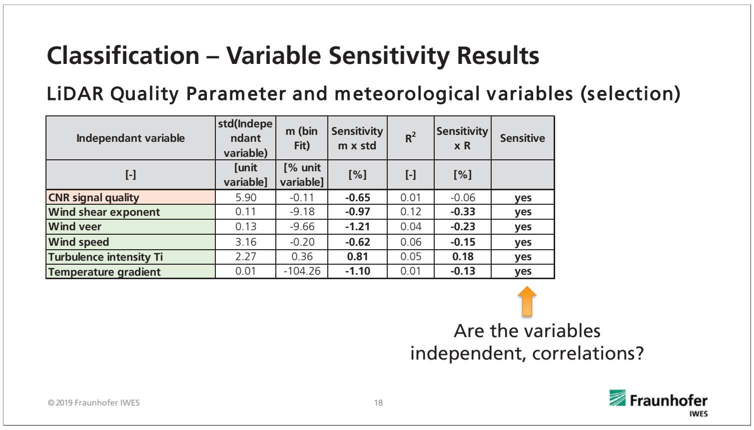
Significant Wave height Hs



Classification - Sensitivity

Wind shear
Sensitive!

Significant Wave height Hs
Not sensitive!

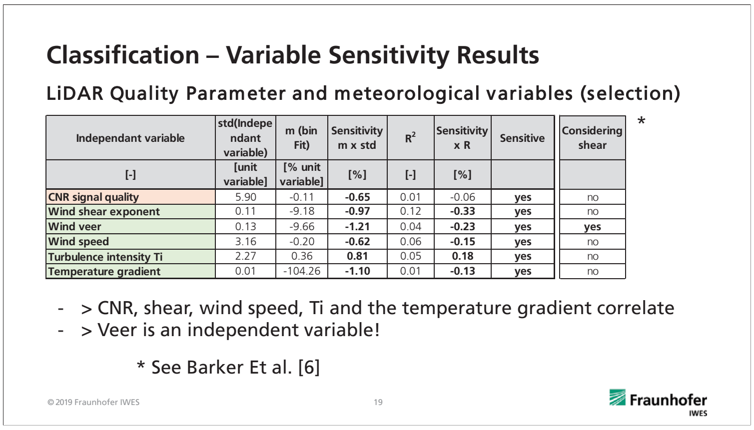


Classification – Variable Sensitivity Results

LiDAR Quality Parameter and meteorological variables (selection)

Independant variable	std(Independant variable)	m (bin Fit)	Sensitivity m x std	R^2	Sensitivity x R	Sensitive
[-]	[unit variable]	[% unit variable]	[%]	[-]	[%]	
CNR signal quality	5.90	-0.11	**-0.65**	0.01	-0.06	**yes**
Wind shear exponent	0.11	-9.18	**-0.97**	0.12	**-0.33**	**yes**
Wind veer	0.13	-9.66	**-1.21**	0.04	**-0.23**	**yes**
Wind speed	3.16	-0.20	**-0.62**	0.06	**-0.15**	**yes**
Turbulence intensity Ti	2.27	0.36	**0.81**	0.05	**0.18**	**yes**
Temperature gradient	0.01	-104.26	**-1.10**	0.01	**-0.13**	**yes**

Are the variables independent, correlations?



Classification – Variable Sensitivity Results

LiDAR Quality Parameter and meteorological variables (selection)

Independant variable	std(Independant variable)	m (bin Fit)	Sensitivity m x std	R^2	Sensitivity x R	Sensitive	Considering shear *
[-]	[unit variable]	[% unit variable]	[%]	[-]	[%]		
CNR signal quality	5.90	-0.11	**-0.65**	0.01	-0.06	**yes**	no
Wind shear exponent	0.11	-9.18	**-0.97**	0.12	**-0.33**	**yes**	no
Wind veer	0.13	-9.66	**-1.21**	0.04	**-0.23**	**yes**	**yes**
Wind speed	3.16	-0.20	**-0.62**	0.06	**-0.15**	**yes**	no
Turbulence intensity Ti	2.27	0.36	**0.81**	0.05	**0.18**	**yes**	no
Temperature gradient	0.01	-104.26	**-1.10**	0.01	**-0.13**	**yes**	no

- \> CNR, shear, wind speed, Ti and the temperature gradient correlate
- \> Veer is an independent variable!

* See Barker Et al. [6]

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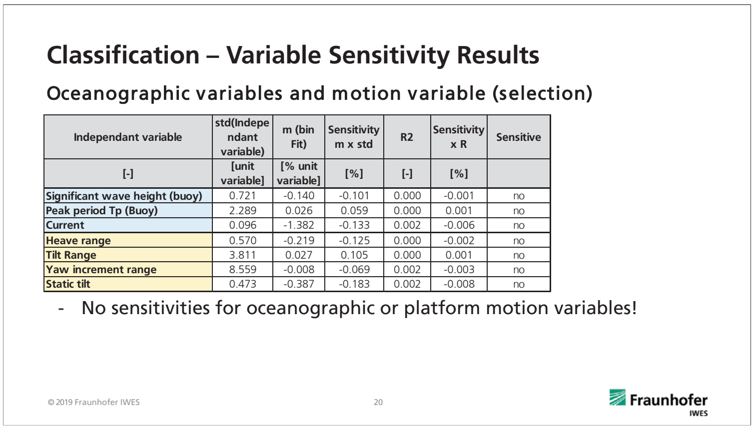

Classification – Variable Sensitivity Results

Oceanographic variables and motion variable (selection)

Independant variable	std(Independant variable)	m (bin Fit)	Sensitivity m x std	R2	Sensitivity x R	Sensitive
[-]	[unit variable]	[% unit variable]	[%]	[-]	[%]	
Significant wave height (buoy)	0.721	-0.140	-0.101	0.000	-0.001	no
Peak period Tp (Buoy)	2.289	0.026	0.059	0.000	0.001	no
Current	0.096	-1.382	-0.133	0.002	-0.006	no
Heave range	0.570	-0.219	-0.125	0.000	-0.002	no
Tilt Range	3.811	0.027	0.105	0.000	0.001	no
Yaw increment range	8.559	-0.008	-0.069	0.002	-0.003	no
Static tilt	0.473	-0.387	-0.183	0.002	-0.008	no

- No sensitivities for oceanographic or platform motion variables!

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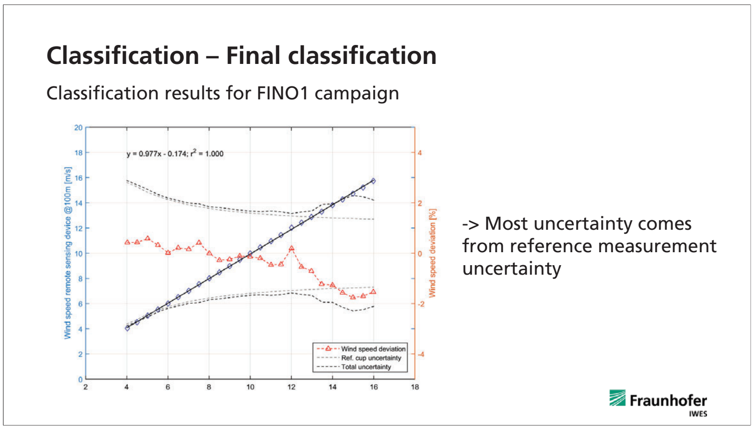
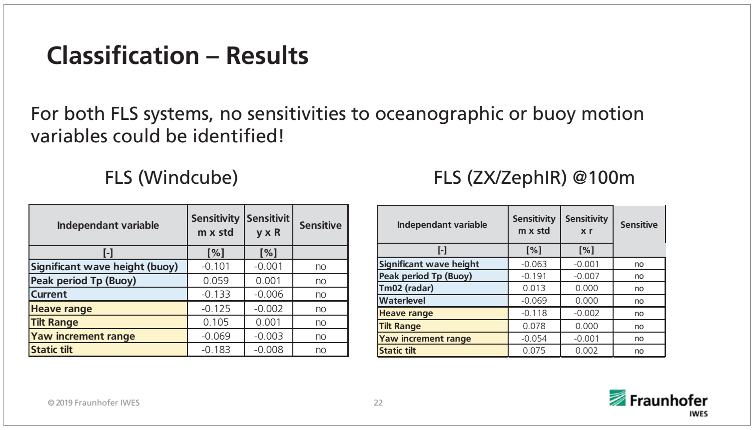


Classification – Final classification

Classification results for FINO1 campaign

-> Most uncertainty comes from reference measurement uncertainty



Classification – Results

For both FLS systems, no sensitivities to oceanographic or buoy motion variables could be identified!

FLS (Windcube)

Independant variable	Sensitivity m x std	Sensitivity x R	Sensitive
[-]	[%]	[%]	
Significant wave height (buoy)	-0.101	-0.001	no
Peak period Tp (Buoy)	0.059	0.001	no
Current	-0.133	-0.006	no
Heave range	-0.125	-0.002	no
Tilt Range	0.105	0.001	no
Yaw increment range	-0.069	-0.003	no
Static tilt	-0.183	-0.008	no

FLS (ZX/ZephIR) @100m

Independant variable	Sensitivity m x std	Sensitivity x r	Sensitive
[-]	[%]	[%]	
Significant wave height	-0.063	-0.001	no
Peak period Tp (Buoy)	-0.191	-0.007	no
Tm02 (radar)	0.013	0.000	no
Waterlevel	-0.069	0.000	no
Heave range	-0.118	-0.002	no
Tilt Range	0.078	0.000	no
Yaw increment range	-0.054	-0.001	no
Static tilt	0.075	0.002	no

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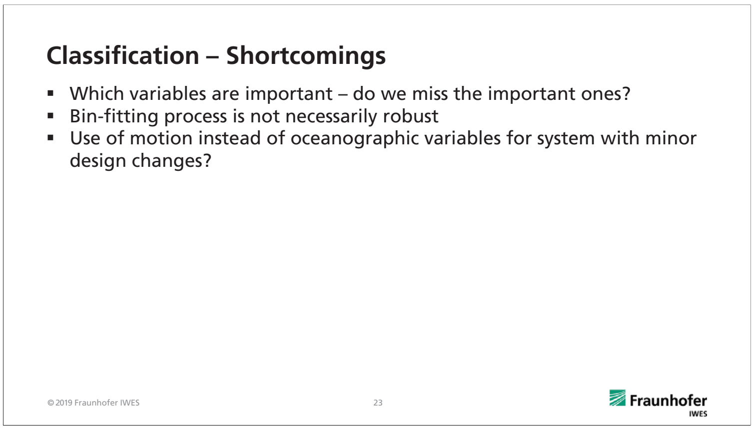

Classification – Shortcomings

- Which variables are important – do we miss the important ones?
- Bin-fitting process is not necessarily robust
- Use of motion instead of oceanographic variables for system with minor design changes?

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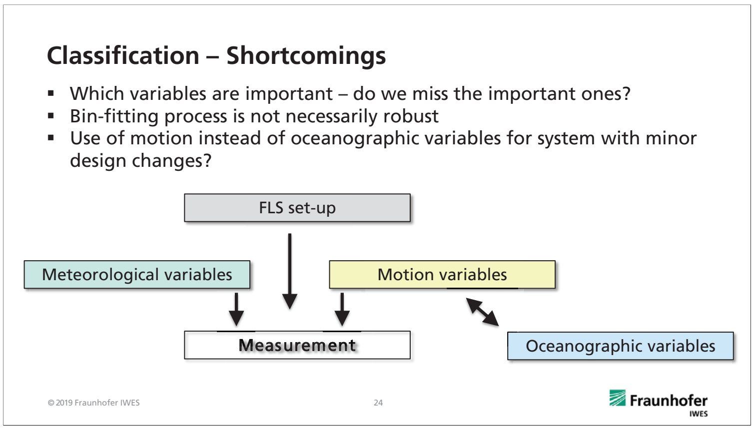

Classification – Shortcomings

- Which variables are important – do we miss the important ones?
- Bin-fitting process is not necessarily robust
- Use of motion instead of oceanographic variables for system with minor design changes?

FLS set-up

Meteorological variables

Motion variables

Measurement

Oceanographic variables

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Resume

- Verification and classification are important for the commercial acceptance of FLS
- Both IWES FLS using Windcube or ZX/ZephIR show no sensitivities to motions or oceanographic variables
- Method of classification (according to IEC) must be adapted for offshore, due to more variables… which variables are important for a measurement sensitivity forecast?

Acknowledgements

The presented work was done in cooperation with Stiftungslehrstuhl Windenergie SWE Stuttgart within the research project MALIBU, funded by the German Federal Ministry For **Economics Affairs and Energy (BMWi)** under Grant number 0324197B, as well as the support of **Project Management Jülich (PTJ)**

Fraunhofer IWES is funded by:

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Federal Ministry of Education and Research

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Federal State of Bremen

- Senator of Civil Engineering, Environment and Transportation
- Senator of Economy, Labor and Ports
- Senator of Science, Health and Consumer Protection
- Bremerhavener Gesellschaft für Investitionsförderung und Stadtentwicklung mbH

Federal State of Lower Saxony

Free and Hanseatic City of Hamburg

Thanks a lot for your attention!

gerrit.wolken-moehlmann@iwes.fraunhofer.de

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[1] Gottschall Et al.: Floating lidar as an advanced offshore wind speed measurement technique: current technology status and gap analysis in regard to full maturity, WIREs Energy Environment 2017, e250. doi: 10.1002/wene.250
[2] Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology, Version 1.0, November 2013.
[3] Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology, Version 2.0, October 2018.
[4] IEA Wind, Expert Group Report on Recommended Practices, 18.Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef
[5] IEC 61400-12-1:2017 Wind energy generation systems -Part 12-1: Power performance measurements of electricity producing wind turbines, Annex L: The application of remote sensing technology
[6] Barker et. Al. Correlation effects in the field classification of ground based remote sensors, Conference paper, EWEA 2014, Barcelona, Spain

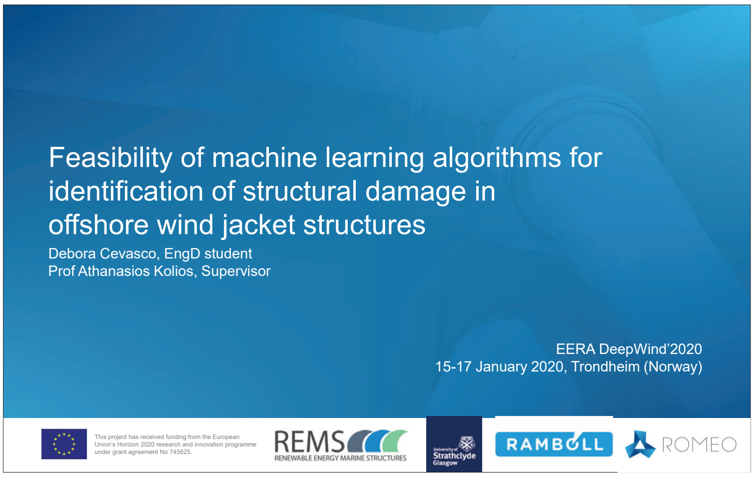
D1) Operations & maintenance

Potential of machine learning algorithms for the identification of structural damages in offshore jacket structures, D.Cevasco, University of Strathclyde

Automated inspection of offshore wind turbine foundation using complementary NDT and defect detection techniques, S.Subramaniam, Brunel Innovation Centre

Load Estimation for Condition Monitoring in Wind Turbines Based on Physical Modeling, M.Pagitsch, RWTH Aachen Univ.

Digital Assistance in the Maintenance of Offshore Wind Parks, M.Stepputat, Fraunhofer

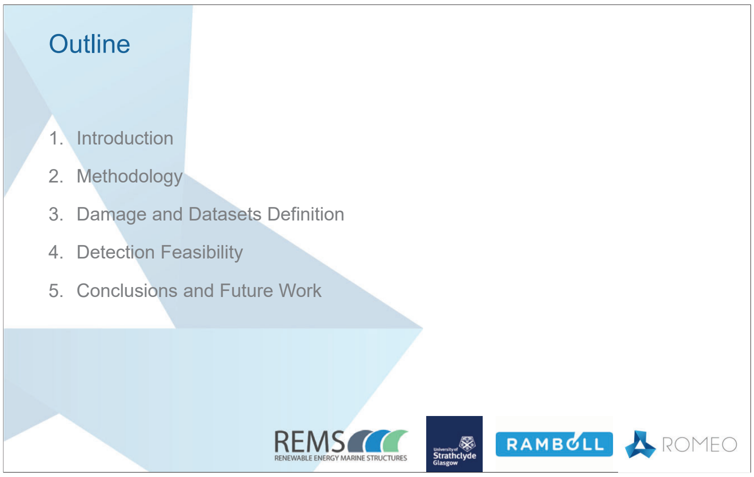


Feasibility of machine learning algorithms for identification of structural damage in offshore wind jacket structures

Debora Cevasco, EngD student
Prof Athanasios Kolios, Supervisor

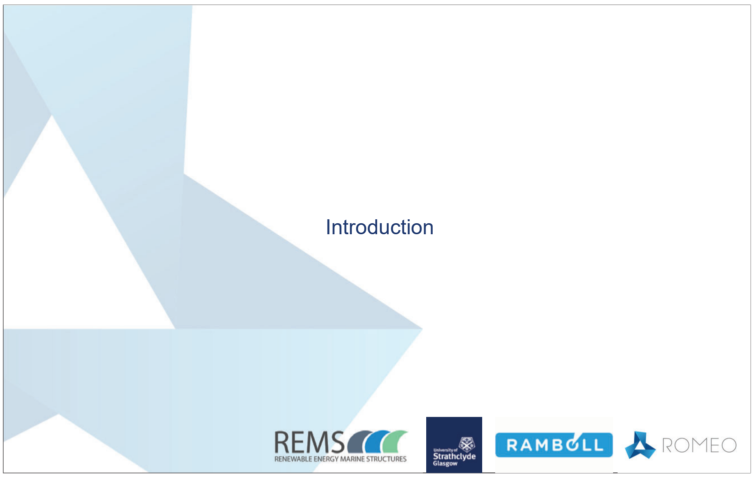
EERA DeepWind'2020
15-17 January 2020, Trondheim (Norway)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 745625.

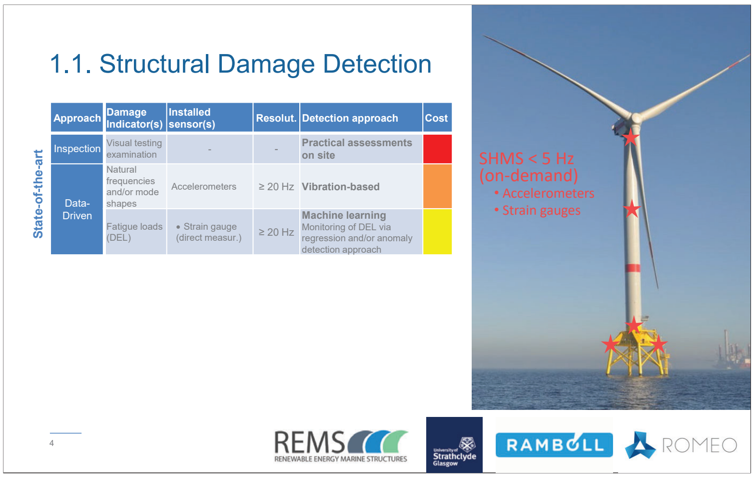


Outline

1. Introduction
2. Methodology
3. Damage and Datasets Definition
4. Detection Feasibility
5. Conclusions and Future Work



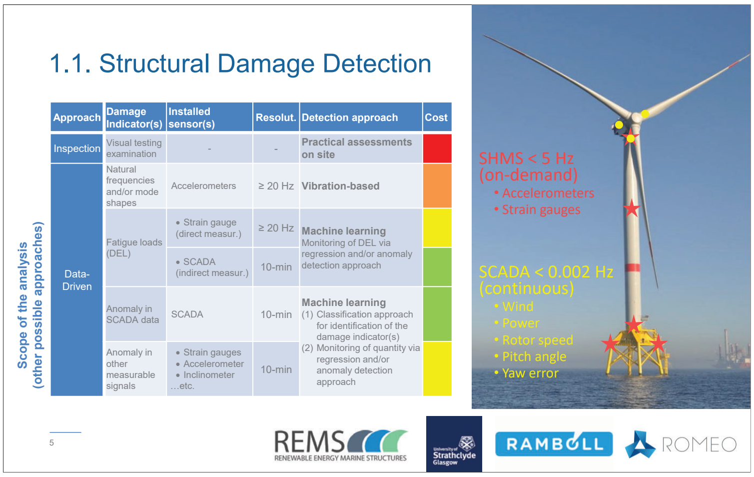
Introduction



1.1. Structural Damage Detection

State-of-the-art

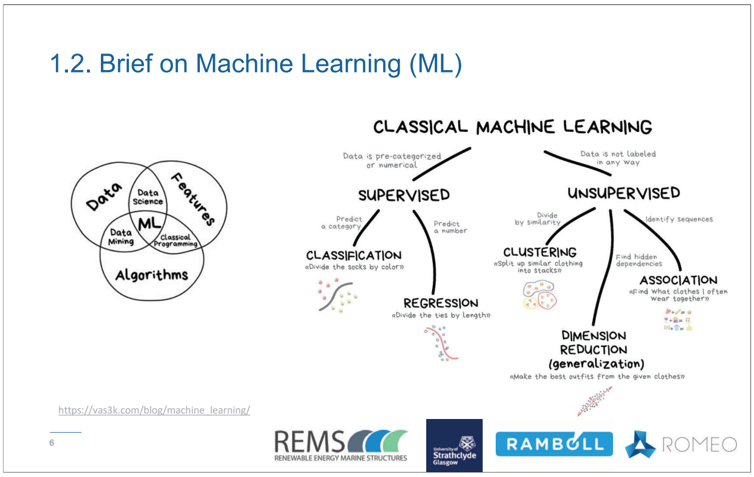
Approach	Damage Indicator(s)	Installed sensor(s)	Resolut.	Detection approach	Cost
Inspection	Visual testing examination	-	-	**Practical assessments on site**	🟥
Data-Driven	Natural frequencies and/or mode shapes	Accelerometers	≥ 20 Hz	**Vibration-based**	🟧
	Fatigue loads (DEL)	• Strain gauge (direct measur.)	≥ 20 Hz	**Machine learning** Monitoring of DEL via regression and/or anomaly detection approach	🟨



1.1. Structural Damage Detection

Scope of the analysis
(other possible approaches)

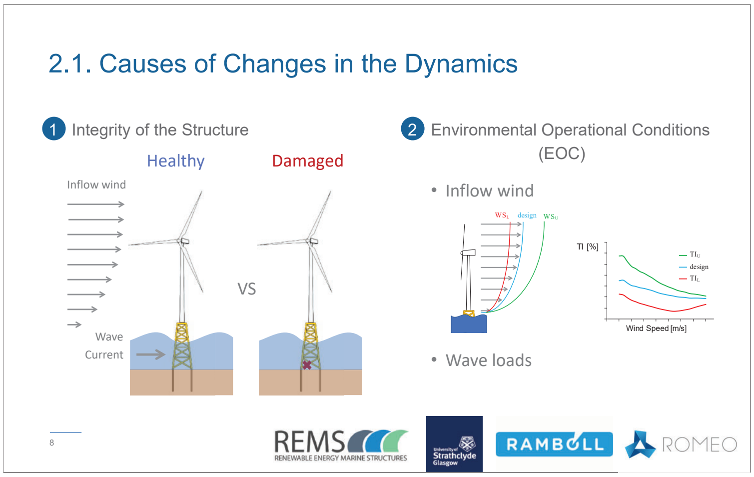
Approach	Damage Indicator(s)	Installed sensor(s)	Resolut.	Detection approach	Cost
Inspection	Visual testing examination	-	-	**Practical assessments on site**	🟥
Data-Driven	Natural frequencies and/or mode shapes	Accelerometers	≥ 20 Hz	**Vibration-based**	🟧
	Fatigue loads (DEL)	• Strain gauge (direct measur.)	≥ 20 Hz	**Machine learning** Monitoring of DEL via regression and/or anomaly detection approach	🟨
		• SCADA (indirect measur.)	10-min		🟩
	Anomaly in SCADA data	SCADA	10-min	**Machine learning** (1) Classification approach for identification of the damage indicator(s) (2) Monitoring of quantity via regression and/or anomaly detection approach	🟩
	Anomaly in other measurable signals	• Strain gauges • Accelerometer • Inclinometer …etc.	10-min		🟨



1.2. Brief on Machine Learning (ML)

https://vas3k.com/blog/machine_learning/

Methodology



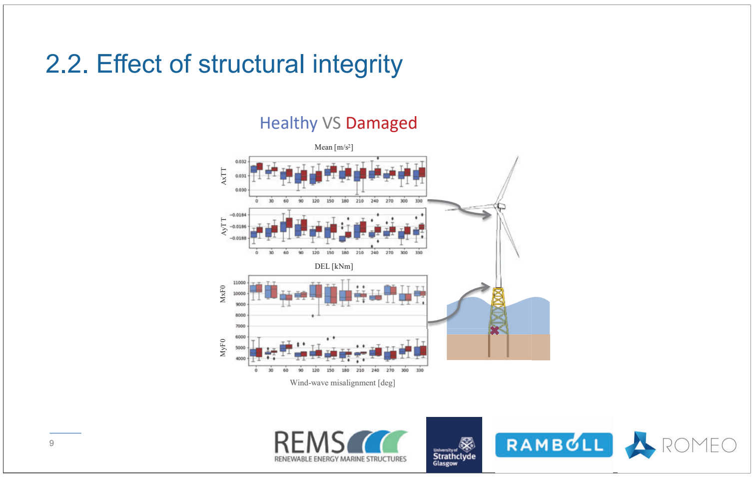
2.1. Causes of Changes in the Dynamics

① Integrity of the Structure

② Environmental Operational Conditions (EOC)

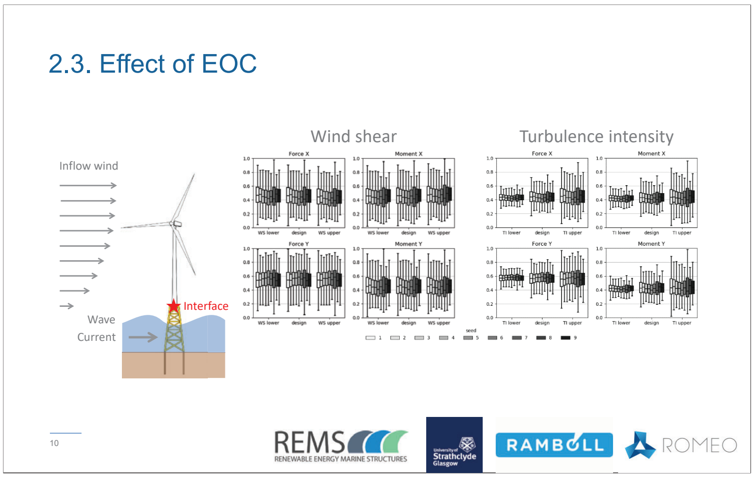
- Inflow wind

- Wave loads

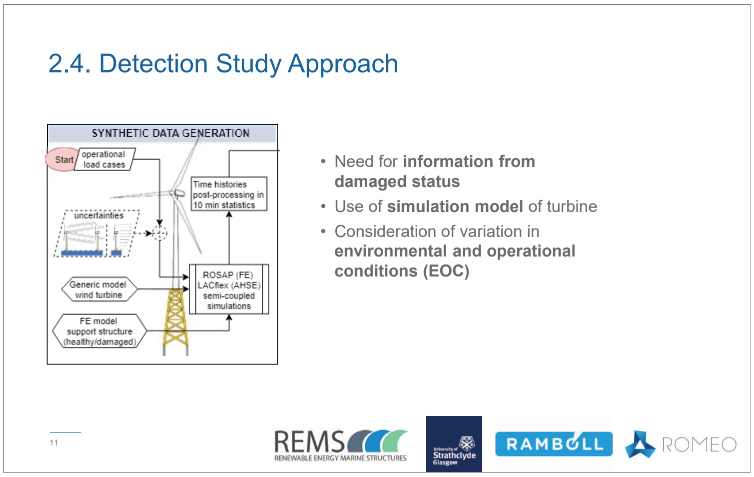


2.2. Effect of structural integrity

Healthy VS Damaged

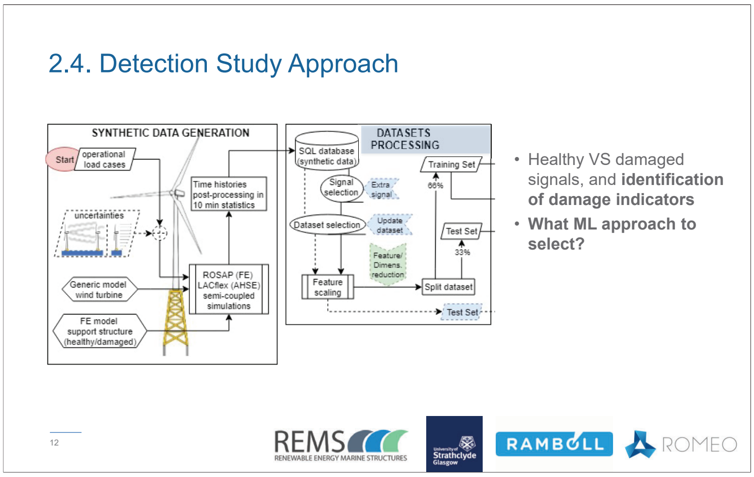


2.3. Effect of EOC



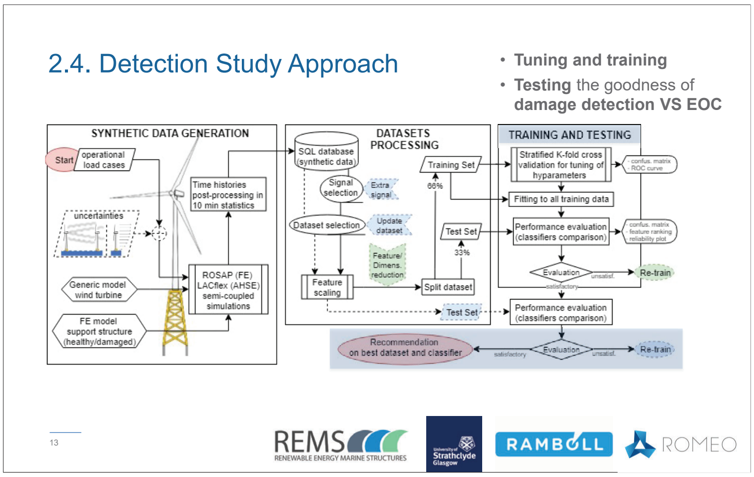
2.4. Detection Study Approach

- Need for **information from damaged status**
- Use of **simulation model** of turbine
- Consideration of variation in **environmental and operational conditions (EOC)**



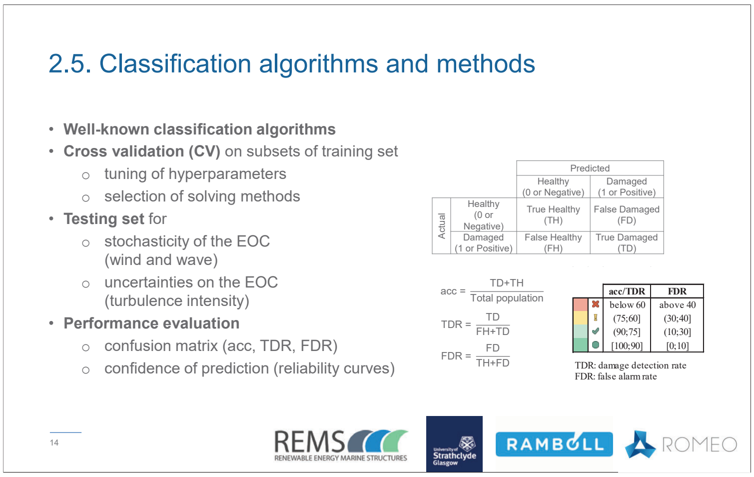
2.4. Detection Study Approach

- Healthy VS damaged signals, and **identification of damage indicators**
- **What ML approach to select?**



2.4. Detection Study Approach

- **Tuning and training**
- **Testing** the goodness of **damage detection VS EOC**



2.5. Classification algorithms and methods

- **Well-known classification algorithms**
- **Cross validation (CV)** on subsets of training set
    - tuning of hyperparameters
    - selection of solving methods
- **Testing set** for
    - stochasticity of the EOC (wind and wave)
    - uncertainties on the EOC (turbulence intensity)
- **Performance evaluation**
    - confusion matrix (acc, TDR, FDR)
    - confidence of prediction (reliability curves)

		Predicted	
		Healthy (0 or Negative)	Damaged (1 or Positive)
Actual	Healthy (0 or Negative)	True Healthy (TH)	False Damaged (FD)
	Damaged (1 or Positive)	False Healthy (FH)	True Damaged (TD)

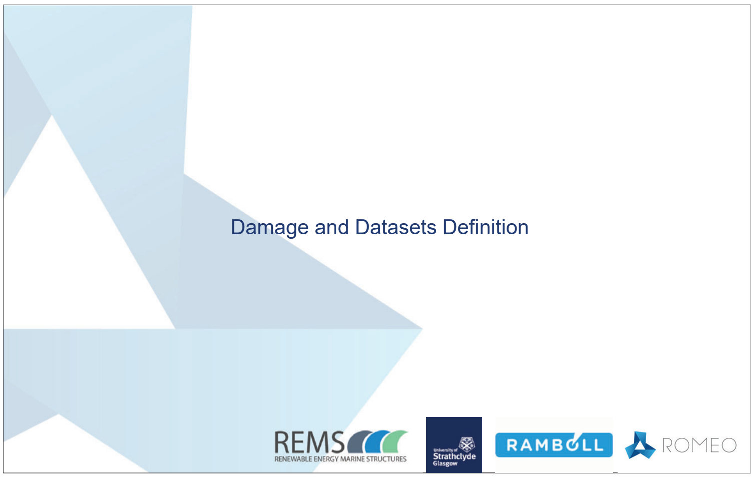
$$acc = \frac{TD+TH}{\text{Total population}}$$

$$TDR = \frac{TD}{FH+TD}$$

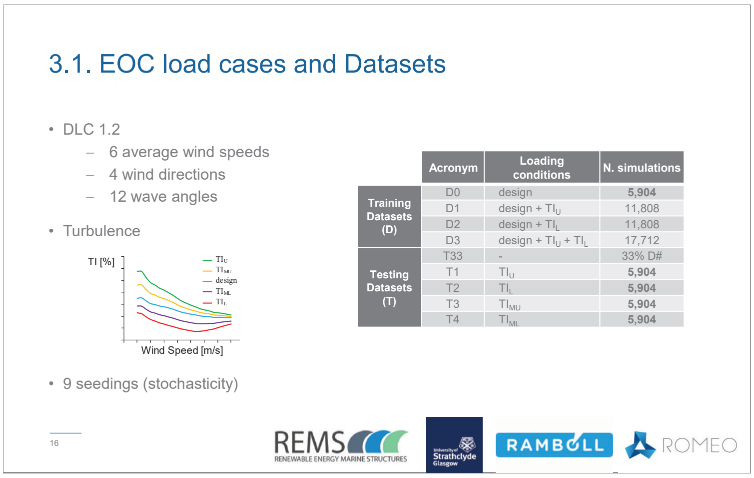
$$FDR = \frac{FD}{TH+FD}$$

		acc/TDR	FDR
🟥	✗	below 60	above 40
🟨	!	(75;60]	(30;40]
🟩	✓	(90;75]	(10;30]
🟩	●	[100;90]	[0;10]

TDR: damage detection rate
FDR: false alarm rate



Damage and Datasets Definition

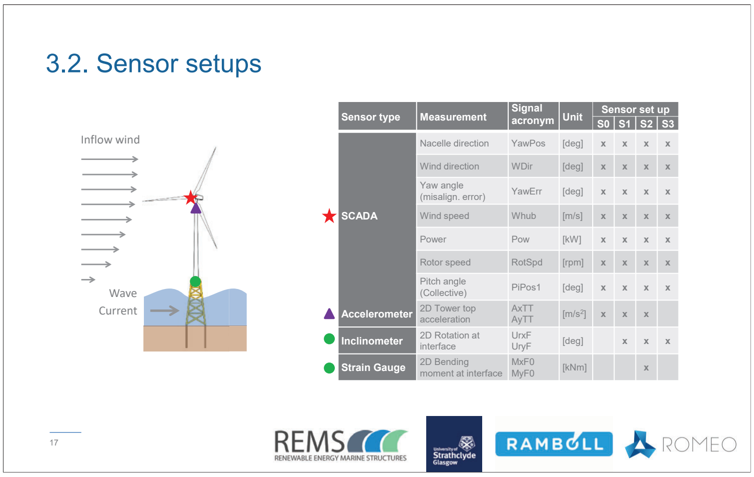


3.1. EOC load cases and Datasets

- DLC 1.2
    - – 6 average wind speeds
    - – 4 wind directions
    - – 12 wave angles
- Turbulence

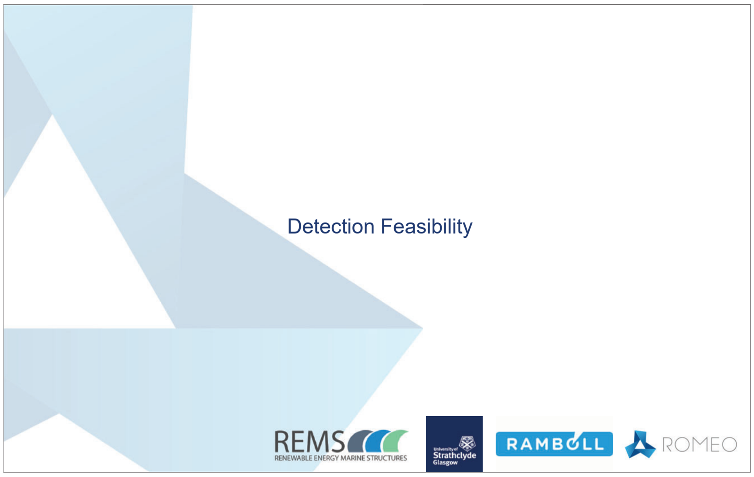
- 9 seedings (stochasticity)

	Acronym	Loading conditions	N. simulations
Training Datasets (D)	D0	design	**5,904**
	D1	design + TI_U	11,808
	D2	design + TI_L	11,808
	D3	design + TI_U + TI_L	17,712
Testing Datasets (T)	T33	-	33% D#
	T1	TI_U	**5,904**
	T2	TI_L	**5,904**
	T3	TI_{MU}	**5,904**
	T4	TI_{ML}	**5,904**

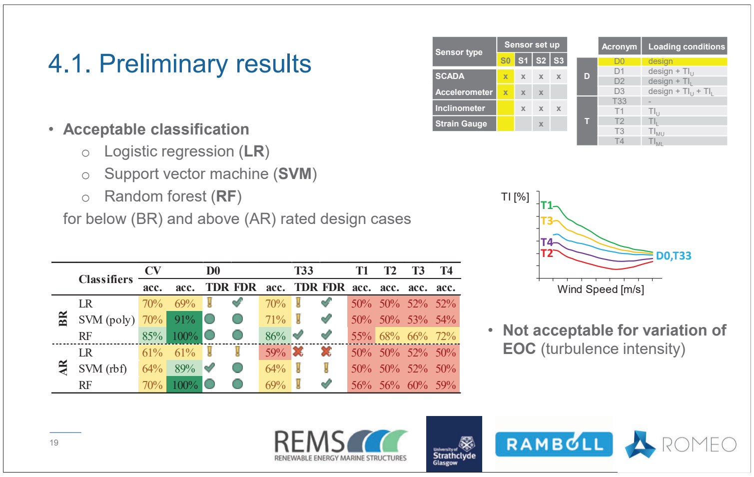


3.2. Sensor setups

Sensor type	Measurement	Signal acronym	Unit	Sensor set up			
				S0	S1	S2	S3
★ **SCADA**	Nacelle direction	YawPos	[deg]	x	x	x	x
	Wind direction	WDir	[deg]	x	x	x	x
	Yaw angle (misalign. error)	YawErr	[deg]	x	x	x	x
	Wind speed	Whub	[m/s]	x	x	x	x
	Power	Pow	[kW]	x	x	x	x
	Rotor speed	RotSpd	[rpm]	x	x	x	x
	Pitch angle (Collective)	PiPos1	[deg]	x	x	x	x
▲ **Accelerometer**	2D Tower top acceleration	AxTT AyTT	[m/s²]	x	x	x	
● **Inclinometer**	2D Rotation at interface	UrxF UryF	[deg]		x	x	x
● **Strain Gauge**	2D Bending moment at interface	MxF0 MyF0	[kNm]			x	



Detection Feasibility



4.1. Preliminary results

Sensor type	Sensor set up			
	S0	S1	S2	S3
SCADA	x	x	x	x
Accelerometer	x	x	x	
Inclinometer		x	x	x
Strain Gauge			x	

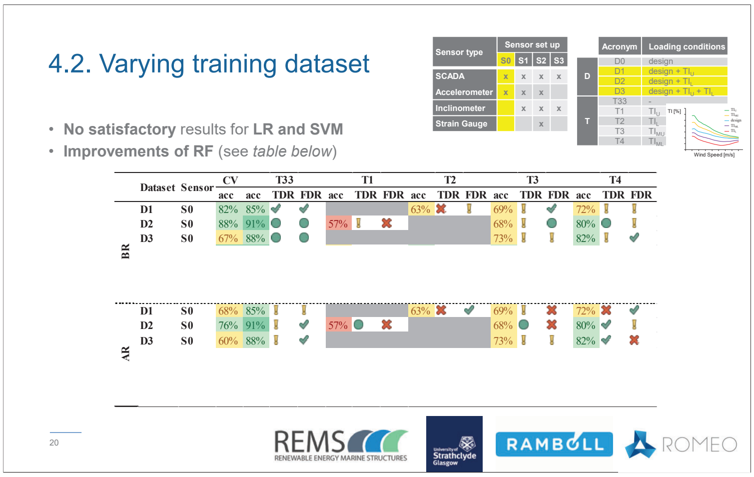
	Acronym	Loading conditions
D	D0	design
	D1	design + TI_U
	D2	design + TI_L
	D3	design + TI_U + TI_L
T	T33	-
	T1	TI_U
	T2	TI_L
	T3	TI_{MU}
	T4	TI_{ML}

- **Acceptable classification**
  - Logistic regression (**LR**)
  - Support vector machine (**SVM**)
  - Random forest (**RF**)

  for below (BR) and above (AR) rated design cases

- **Not acceptable for variation of EOC** (turbulence intensity)

	Classifiers	CV	D0			T33			T1	T2	T3	T4
		acc.	acc.	TDR	FDR	acc.	TDR	FDR	acc.	acc.	acc.	acc.
BR	LR	70%	69%	!	✓	70%	!	✓	50%	50%	52%	52%
	SVM (poly)	70%	91%	●	●	71%	!	✓	50%	50%	53%	54%
	RF	85%	100%	●	●	86%	✓	✓	55%	68%	66%	72%
AR	LR	61%	61%	!	!	59%	✗	✗	50%	50%	52%	50%
	SVM (rbf)	64%	89%	✓	●	64%	!	!	50%	50%	52%	50%
	RF	70%	100%	●	●	69%	!	✓	56%	56%	60%	59%



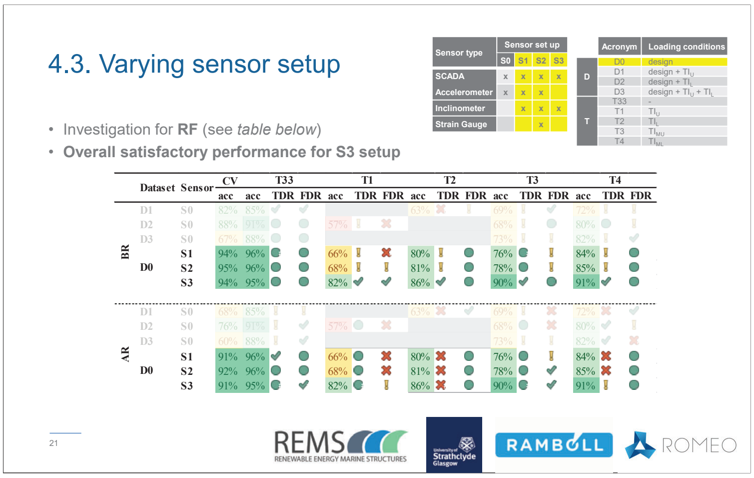
4.2. Varying training dataset

Sensor type	Sensor set up			
	S0	S1	S2	S3
SCADA	x	x	x	x
Accelerometer	x	x	x	
Inclinometer		x	x	x
Strain Gauge			x	

	Acronym	Loading conditions
D	D0	design
	D1	design + TI_U
	D2	design + TI_L
	D3	design + TI_U + TI_L
T	T33	-
	T1	TI_U
	T2	TI_L
	T3	TI_{MU}
	T4	TI_{ML}

- **No satisfactory** results for **LR and SVM**
- **Improvements of RF** (see *table below*)

	Dataset	Sensor	CV	T33			T1			T2			T3			T4		
			acc	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR
BR	D1	S0	82%	85%	✓	✓				63%	✗	!	69%	!	✓	72%	!	!
	D2	S0	88%	91%	●	●	57%	!	✗				68%	!	●	80%	●	!
	D3	S0	67%	88%	●	●							73%	!	!	82%	!	✓
AR	D1	S0	68%	85%	!	!				63%	✗	✓	69%	!	✗	72%	✗	✓
	D2	S0	76%	91%	!	✓	57%	●	✗				68%	●	✗	80%	✓	!
	D3	S0	60%	88%	!	✓							73%	!	!	82%	✓	✗



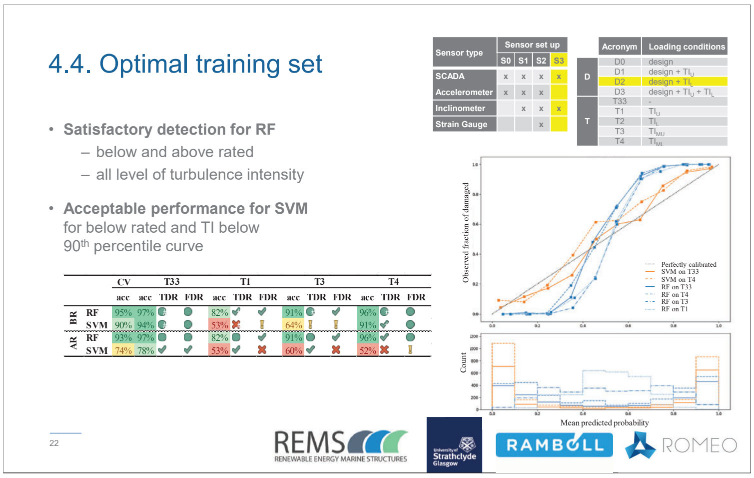
4.3. Varying sensor setup

Sensor type	Sensor set up			
	S0	S1	S2	S3
SCADA	x	x	x	x
Accelerometer	x	x	x	
Inclinometer		x	x	x
Strain Gauge			x	

	Acronym	Loading conditions
D	D0	design
	D1	design + TI_U
	D2	design + TI_L
	D3	design + TI_U + TI_L
T	T33	-
	T1	TI_U
	T2	TI_L
	T3	TI_{MU}
	T4	TI_{ML}

- Investigation for **RF** (see *table below*)
- **Overall satisfactory performance for S3 setup**

	Dataset	Sensor	CV	T33			T1			T2			T3			T4		
			acc	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR
BR	D1	S0	82%	85%	✓	✓				63%	✗	!	69%	!	✓	72%	!	!
	D2	S0	88%	91%	●	●	57%	!	✗				68%	!	●	80%	●	!
	D3	S0	67%	88%	●	●							73%	!	!	82%	!	✓
	D0	S1	94%	96%	●	●	66%	!	✗	80%	!	●	76%	●	!	84%	!	●
		S2	95%	96%	●	●	68%	!	!	81%	!	●	78%	●	!	85%	!	●
		S3	94%	95%	●	●	82%	✓	✓	86%	✓	●	90%	✓	●	91%	✓	●
AR	D1	S0	68%	85%	!	!				63%	✗	✓	69%	!	✗	72%	✗	✓
	D2	S0	76%	91%	!	✓	57%	●	✗				68%	●	✗	80%	✓	!
	D3	S0	60%	88%	!	✓							73%	!	!	82%	✓	✗
	D0	S1	91%	96%	✓	●	66%	●	✗	80%	✗	●	76%	●	!	84%	✗	●
		S2	92%	96%	●	●	68%	●	✗	81%	✗	●	78%	●	✓	85%	✗	●
		S3	91%	95%	●	✓	82%	●	!	86%	✗	●	90%	●	✓	91%	!	●



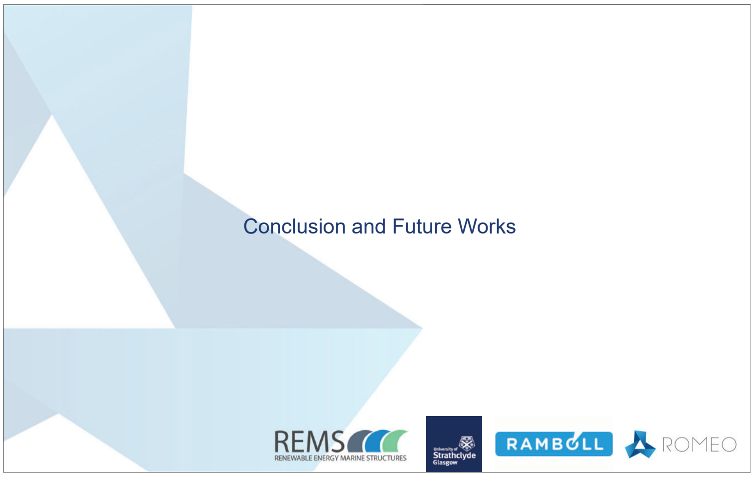
4.4. Optimal training set

Sensor type	Sensor set up			
	S0	S1	S2	S3
SCADA	x	x	x	x
Accelerometer	x	x	x	
Inclinometer		x	x	x
Strain Gauge			x	

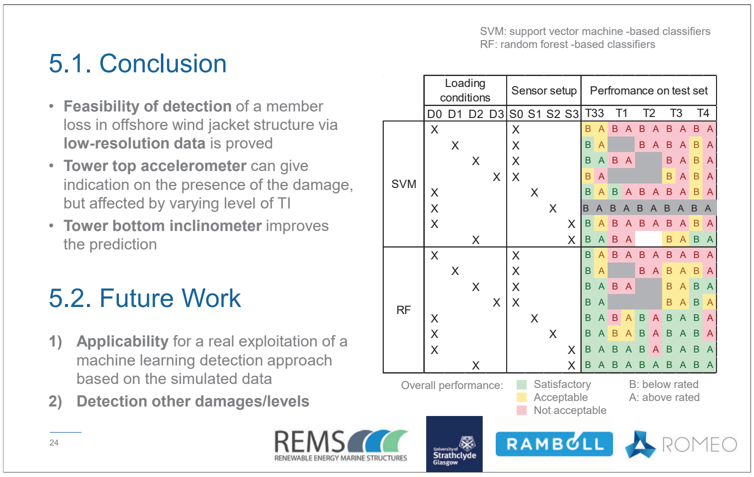
	Acronym	Loading conditions
D	D0	design
	D1	design + TI_U
	D2	design + TI_L
	D3	design + TI_U + TI_L
T	T33	-
	T1	TI_U
	T2	TI_L
	T3	TI_{MU}
	T4	TI_{ML}

- **Satisfactory detection for RF**
  - below and above rated
  - all level of turbulence intensity
- **Acceptable performance for SVM** for below rated and TI below 90th percentile curve

		CV	T33			T1			T3			T4		
		acc	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR
BR	RF	95%	97%	●	●	82%	✓	✓	91%	●	✓	96%	●	●
	SVM	90%	94%	●	●	53%	✗	!	64%	!	!	91%	✓	●
AR	RF	93%	97%	●	●	82%	●	✓	91%	●	✓	96%	✓	●
	SVM	74%	78%	✓	✓	53%	✓	✗	60%	✓	✗	52%	✗	!



Conclusion and Future Works



SVM: support vector machine -based classifiers
RF: random forest -based classifiers

5.1. Conclusion

- **Feasibility of detection** of a member loss in offshore wind jacket structure via **low-resolution data** is proved
- **Tower top accelerometer** can give indication on the presence of the damage, but affected by varying level of TI
- **Tower bottom inclinometer** improves the prediction

5.2. Future Work

1) **Applicability** for a real exploitation of a machine learning detection approach based on the simulated data
2) **Detection other damages/levels**

	Loading conditions				Sensor setup				Perfromance on test set									
	D0	D1	D2	D3	S0	S1	S2	S3	T33		T1		T2		T3		T4	
SVM	X				X				B	A	B	A	B	A	B	A	B	A
		X			X				B	A			B	A	B	A	B	A
			X		X				B	A	B	A			B	A	B	A
				X	X				B	A					B	A	B	A
	X					X			B	A	B	A	B	A	B	A	B	A
	X						X		B	A	B	A	B	A	B	A	B	A
	X							X	B	A	B	A	B	A	B	A	B	A
			X					X	B	A	B	A			B	A	B	A
RF	X				X				B	A	B	A	B	A	B	A	B	A
		X			X				B	A			B	A	B	A	B	A
			X		X				B	A	B	A			B	A	B	A
				X	X				B	A					B	A	B	A
	X					X			B	A	B	A	B	A	B	A	B	A
	X						X		B	A	B	A	B	A	B	A	B	A
	X							X	B	A	B	A	B	A	B	A	B	A
			X					X	B	A	B	A	B	A	B	A	B	A

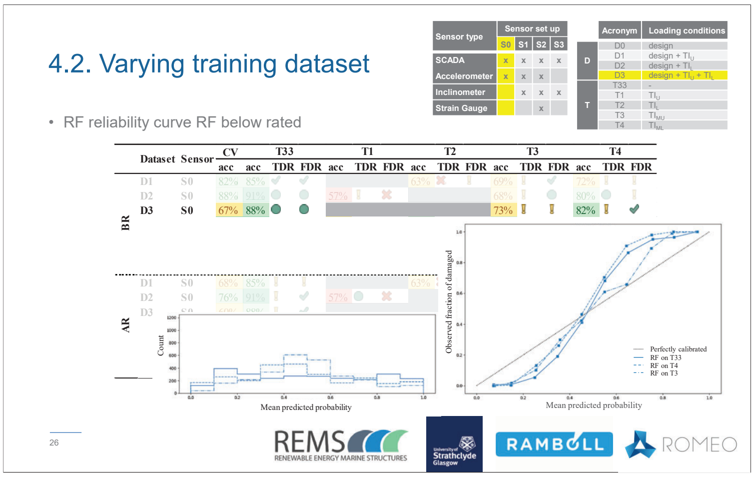
Overall performance: 🟩 Satisfactory 🟨 Acceptable 🟥 Not acceptable

B: below rated
A: above rated

Questions?

Thanks for your attention!

This project has received funding from the European Union's Horizon 2020 research and innovation programme
under grant agreement No 745625.



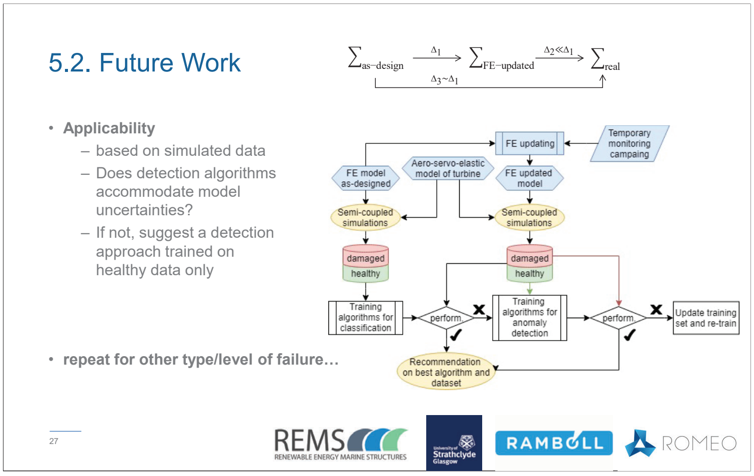
4.2. Varying training dataset

- RF reliability curve RF below rated

Sensor type	Sensor set up S0	S1	S2	S3
SCADA	x	x	x	x
Accelerometer	x	x	x	
Inclinometer		x	x	x
Strain Gauge			x	

	Acronym	Loading conditions
D	D0	design
	D1	design + TI_U
	D2	design + TI_L
	D3	design + TI_U + TI_L
T	T33	-
	T1	TI_U
	T2	TI_L
	T3	TI_{MU}
	T4	TI_{ML}

	Dataset	Sensor	CV	T33			T1			T2			T3			T4		
			acc	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR	acc	TDR	FDR
BR	D1	S0	82%	85%	✓	✓				63%	✗	!	69%	!	✓	72%	!	!
	D2	S0	88%	91%	●	●	57%	!	✗				68%	!	●	80%	●	!
	D3	S0	67%	88%	●	●							73%	!	!	82%	!	✓
AR	D1	S0	68%	85%	!	!				63%								
	D2	S0	76%	91%	!	✓	57%	●	✗									
	D3																	



5.2. Future Work

$$\begin{tikzcd}
\sum_{\text{as-design}} \arrow[r, "\Delta_1"] \arrow[rr, bend right, "\Delta_3 \sim \Delta_1"'] & \sum_{\text{FE-updated}} \arrow[r, "\Delta_2 \ll \Delta_1"] & \sum_{\text{real}}
\end{tikzcd}$$

- **Applicability**
  - based on simulated data
  - Does detection algorithms accommodate model uncertainties?
  - If not, suggest a detection approach trained on healthy data only
- **repeat for other type/level of failure…**

EERA DeepWind'2020

Automated inspection of offshore wind turbine foundation using complementary NDT and defect detection techniques

Authors

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15.01.2020

Amphibious robot for inspection and predictive maintenance
of offshore wind assets

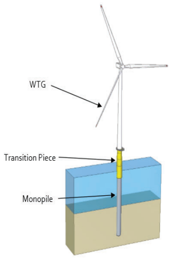
iFROG

The project iFROG combines enabling capabilities in electronics/sensors/photonics and robotics to deliver innovative marinised autonomous robot for inspection and predictive maintenance of offshore wind turbine foundations both above and below the water line.

Overview of the Presentation

- Introduction
- Inspection scheme of the Monopile
- Hybrid NDT techniques
- NDT signal and image processing
- Interactive GUI for defect detection
- Conclusion and future scope

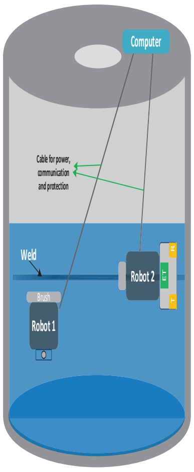
Introduction



- The wind turbine generator interfaces with the monopile through a transition piece.
  - Grouted connection
  - Bolted connection
- The main platforms of the Monopile,
  - ***The bottom portion close to the connection between the transition piece and Monopile.***
  - ***The above portion airtight platform for sealing the foundation.***
- Designers have assumed that by sealing the Monopile internal from seawater and air, oxygen will be consumed, and corrosion will be suppressed.
  - It is very difficult to completely seal the platforms.
  - The result is corrosion - seawater ingress.
- Human inspection is no longer possible for inside of older Monopile foundations due to presence of partially filled water.

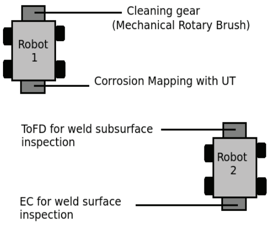
Need for This Project

- **Remote inspection and monitoring**
- Diver or ROV (remotely operated vehicle)
  - Visually inspect for cracks
  - Challenging due to potential issues with visibility and marine growth.
- Sonar or acoustic emission non-destructive testing
  - Indication of defect existence
  - Lack the ability to size the defects.
- A scheme for the automated inspection of wind turbine monopiles has been developed by combining,
  - I. **Two autonomous robots**
  - II. **Three complementary non-destructive testing (NDT) techniques**
  - III. **NDT software for automatic defect detection**



Inspection Scheme of the Monopile

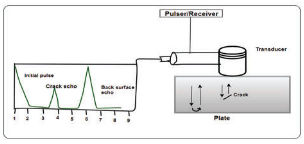
- Welds occur as circumferential lines at approximately 2-meter intervals along the length of the Monopile as well as vertical welds on each section.
- Amphibious robotic platform capable of climbing and navigating on the wind turbine foundations in air and underwater.
- The two robots are physically connected with tether distributed around the Monopile foundation to prevent falling and moving.
- Cleaning (Robot 1)
- NDT inspection (Robot 2).



NDT techniques

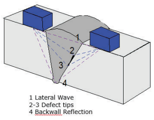
❖ Ultrasonic technique(UT)

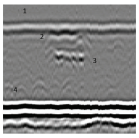
❑ Corrosion mapping



❖ Time of flight diffraction technique(TOFD)

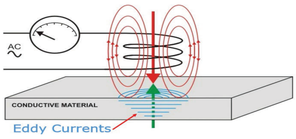
❑ Sub-surface mapping





❖ Eddy current testing(ECT)

❑ Surface mapping



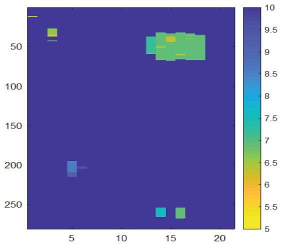
UT Data Analysis

❖ Find the distance from starting to first peak of the A-Scan signal and multiply by ultrasound resolution to calculate thickness in each point.

❖ Using the thickness measurement, the corrosion map is plotted.

❖ The defects or corrosion in the reference plate is simulated by the human operator.

❖ The plotted corrosion map indicates the correct identification of corrosion thickness and the same verified with the actual corrosion map.



TOFD Data Analysis

❖ The wavelet based denoising is used to enhance the signal to noise ratio of the signal.

❖ Scan alignment is carried out by subsampling each scan and cross correlating each scan with reference scan.

❖ First positive maximum of the signal is identified using some threshold and marked as a lateral wave.

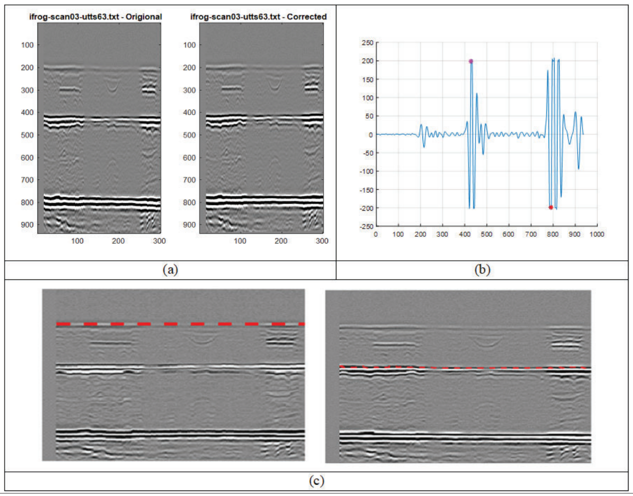
❖ Then autocorrelation function used to find the backwall eco and the region between lateral and backwall eco marked as an area of interest(ROI).

❖ ROI is segmented using thresholds (T) can be represented by the following expression $T = \mu + z.\sigma$

❖ where $\mu -$ mean gray level of the entire image pixels. $\sigma -$standard deviation of the mean gray levels in the defective image (original). z– could be selected by trial and error to determine strictness of the defect-detection test.

❖ Automated sizing has been done using some predetermined calibration parameters and signal processing algorithms.

TOFD Data Analysis

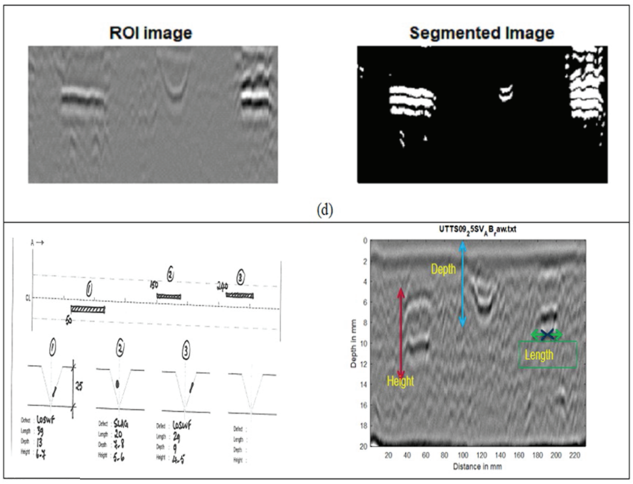


(a)

(b)

(c)

TOFD Data Analysis

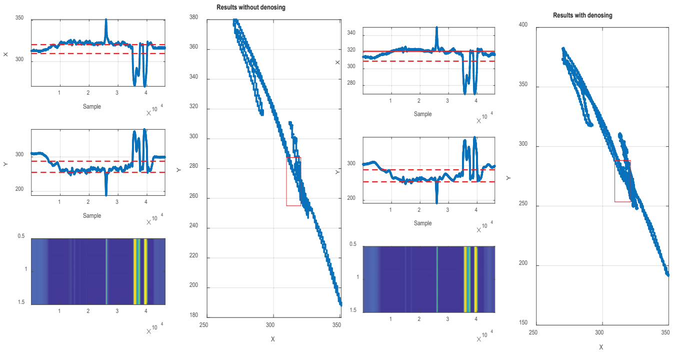


(d)

Eddy Current Data Analysis

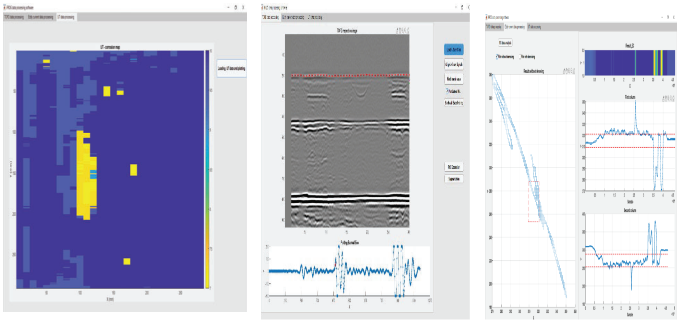
❖ The signal is denoised with Wavelet transform+ Donoho and Johnstone's universal threshold denoising

❖ Rectangle is plotted over the reference signal and based on this rectangle the points lies outside the rectangle of the other signals are marked as a defect.

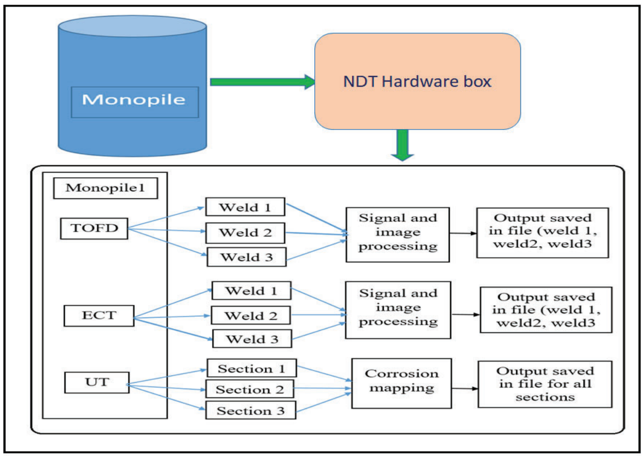


NDT Software

- ❖ The developed TOFD, ECT and UT signal processing algorithms are incorporated into one GUI,
- ❖ GUI provides an interface to end user, allowing them to view the acquired signals, apply developed signal and image processing algorithms to process signals and view the detected defects.



Output Structure



Conclusion and Future Scope

- ❖ The NDT equipped robots can move across the monopile efficiently and reliably.
- ❖ The addressed signal and image processing approaches for all three NDT techniques have been extremely promising in the context of automatic defect detection.
- ❖ The outcome of this project reduces the overall maintenance costs and provide a safe strategy; rather than human assisted methods.
- ❖ This is a unique intelligent procedure for inspecting offshore windfarm monopiles especially in the underwater and deep-sea environments.
- ❖ Overall, the automatic defect detection lead to several actionable insights over the next coming years.
- ❖ There will be a potential to use artificial intelligence techniques in automatic defect detection.

Acknowledgement

- ❖ The research leading to these results has received funding from the UK's innovation agency, Innovate UK under grant agreement No 103991.The research has been undertaken as a part of the project **'Amphibious robot for inspection and predictive maintenance of offshore wind assets (iFROG)'**.

- ❖ The iFROG project is a collaboration between the following organisations:
  - Innovative Technology & science limited (InnoTecUK)
  - Brunel Innovation Centre, Brunel University London
  - TWI Limited**,**
  - ORE Catapult Development Services Limited.

21 January 2020

Automated inspection of offshore wind turbine foundation using complementary NDT and defect detection techniques

Load Estimation for Condition Monitoring in Wind Turbines Based on Physical Modeling

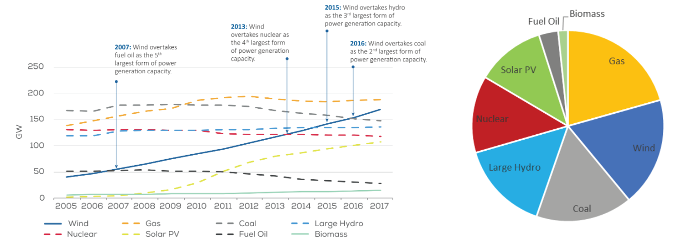
EERA DeepWind‘2020, Trondheim, 16 January 2020

Michael Pagitsch, Georg Jacobs, Dennis Bosse, Tobias Duda

Contents

Motivation

Total power generation capacity in the EU



WindEurope: Wind in power 2017. Annual combined onshore and offshore wind energy statistics, 2018

Motivation

Availability

*“ability of an item **to be in a state to perform as and when required**, under given conditions, assuming that the necessary external resources are provided”*

- Condition monitoring
  - Avoid long downtimes
  - Enable immediate reaction to failures

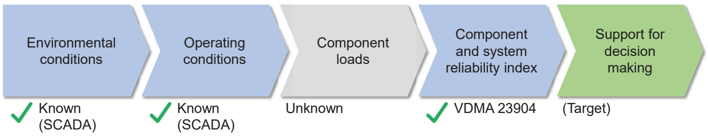
Reliability

*“ability of an item **to perform a required function** under given conditions **for a given time interval**”*

- Adjustment of operational management
  - Demand- and degradation-oriented
  - Prevent under- or overloading of individual WTs proactively
  - Adapt load situation to assumptions made in the design process

DIN EN 13306:2017: Maintenance – Maintenance Terminology

Motivation



Environmental conditions	Operating conditions	Component loads	Component and system reliability index	Support for decision making
✓ Known (SCADA)	✓ Known (SCADA)	Unknown	✓ VDMA 23904	(Target)

- Target: **Model-based load monitoring**
- Continuous calculation of a system reliability index for support in decision making
  - Degradation-oriented adaption of operational management
  - Spare parts stockkeeping
  - Appropriate maintenance strategies for old WTs
  - Wind farm life extension

VDMA 23904:2019: Reliability Assessment for Wind Energy Gearboxes

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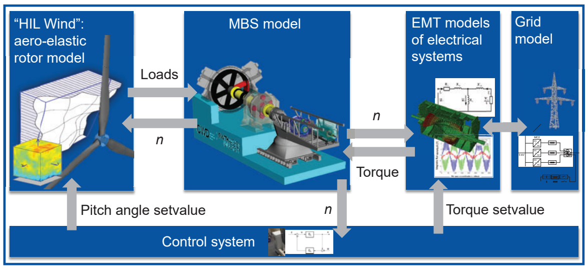
Motivation

Reference model: Validated multi-physical model of a full size research turbine



Matzke D et al. 2018 *J. Phys.: Conf. Series* **1037** 062025

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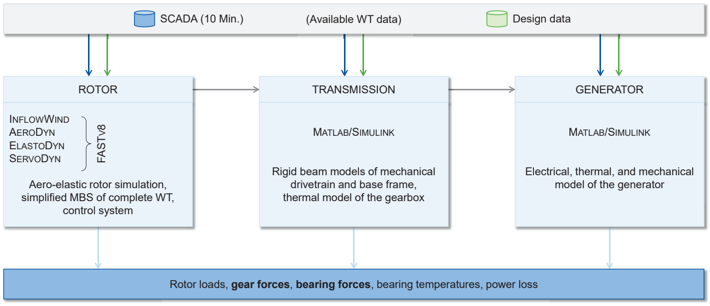
1 Motivation: SCADA-based condition monitoring

2 Model-based load calculation

3 Model validation and sensitivity analysis

4 Conclusion and outlook

Model-based load monitoring



SCADA (10 Min.) (Available WT data) Design data

ROTOR

INFLOWWIND
AERODYN
ELASTODYN
SERVODYN
FASTv8

Aero-elastic rotor simulation, simplified MBS of complete WT, control system

TRANSMISSION

MATLAB/SIMULINK

Rigid beam models of mechanical drivetrain and base frame, thermal model of the gearbox

GENERATOR

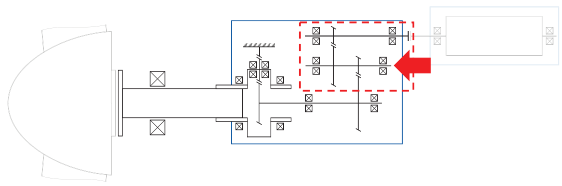
MATLAB/SIMULINK

Electrical, thermal, and mechanical model of the generator

Rotor loads, **gear forces**, **bearing forces**, bearing temperatures, power loss

---

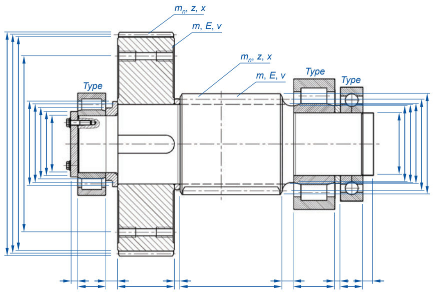
Model-based load monitoring



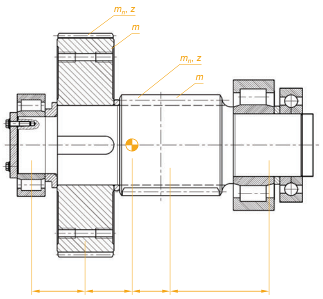
ROTOR	TRANSMISSION		GENERATOR
Geometry; masses and moments of inertia of major WT components; bending characteristics (tower, blades); control system	Drive train configuration Overall dimension Inner dimensions Masses of rotating parts	**24 parameters for considered sub-system**	Generator type Overall dimension Rotor mass

---

MBS-model: Parameter requirements



Analytical model: Parameter requirements



Contents

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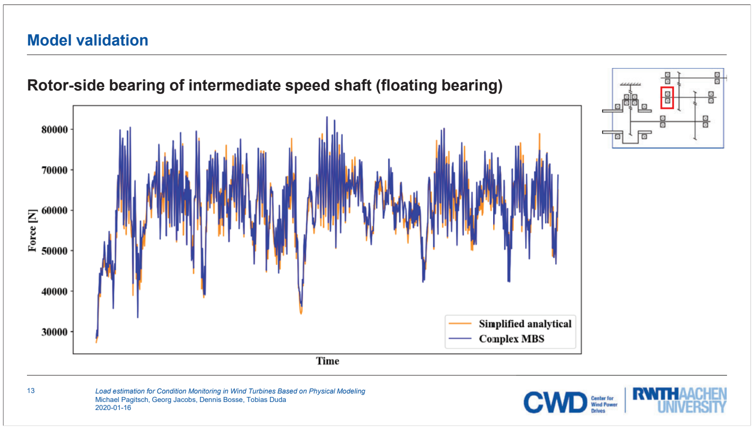
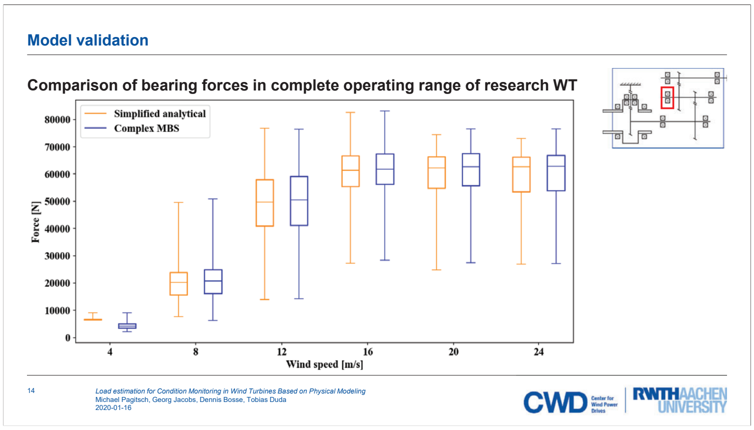


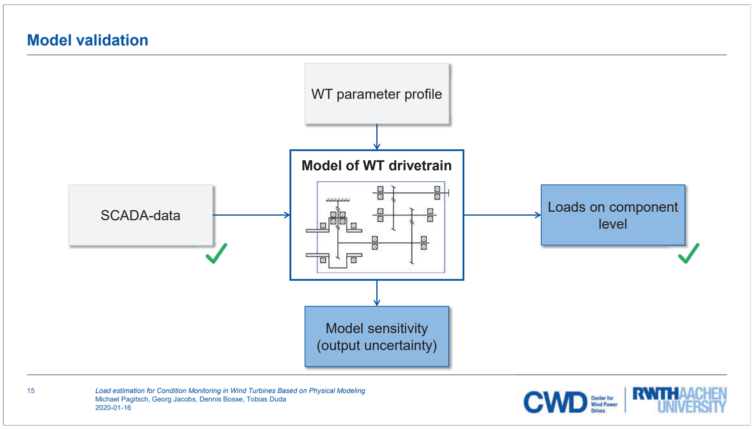
Model validation

Rotor-side bearing of intermediate speed shaft (floating bearing)



Model validation

Comparison of bearing forces in complete operating range of research WT



Model validation

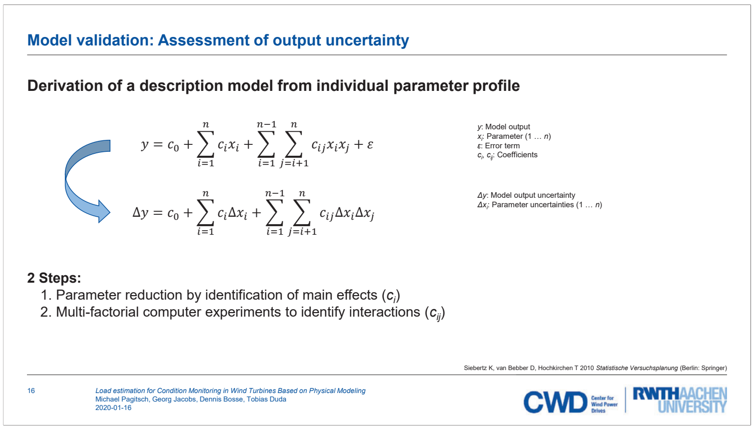
WT parameter profile

Model of WT drivetrain

SCADA-data ✓

Loads on component level ✓

Model sensitivity (output uncertainty)



Model validation: Assessment of output uncertainty

Derivation of a description model from individual parameter profile

$$y = c_0 + \sum_{i=1}^{n} c_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} c_{ij} x_i x_j + \varepsilon$$

$$\Delta y = c_0 + \sum_{i=1}^{n} c_i \Delta x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} c_{ij} \Delta x_i \Delta x_j$$

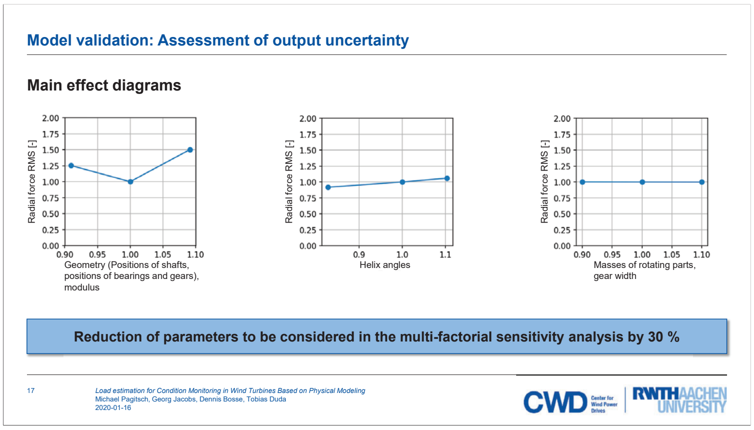
y: Model output
x_i: Parameter (1 … *n*)
ε: Error term
c_i, c_{ij}: Coefficients

Δy: Model output uncertainty
Δx_i: Parameter uncertainties (1 … *n*)

2 Steps:

1. Parameter reduction by identification of main effects (c_i)
2. Multi-factorial computer experiments to identify interactions (c_{ij})

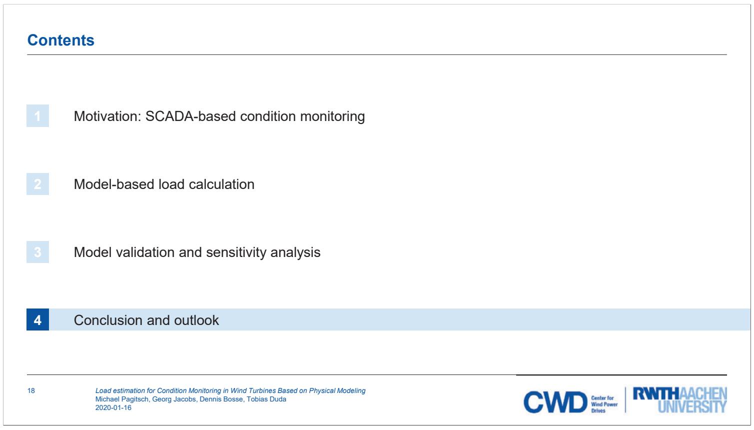
Siebertz K, van Bebber D, Hochkirchen T 2010 *Statistische Versuchsplanung* (Berlin: Springer)



Model validation: Assessment of output uncertainty

Main effect diagrams

Reduction of parameters to be considered in the multi-factorial sensitivity analysis by 30 %



Contents

Conclusion and outlook

Accomplishments

- Developed a generic WT model for calculating inner loads from SCADA records
  - Real-time capable
  - Minimal parameter requirements
- Outputs used for continuous calculation of a reliability index
  - Continuous decision support throughout the WT's service life
- Introduced a method for accuracy assessment of model outputs

Next steps

- Multi-factorial parameter variation (computer experiment) for identifying parameter interactions
- Application of a prototype to field data
  - Prove practical applicability

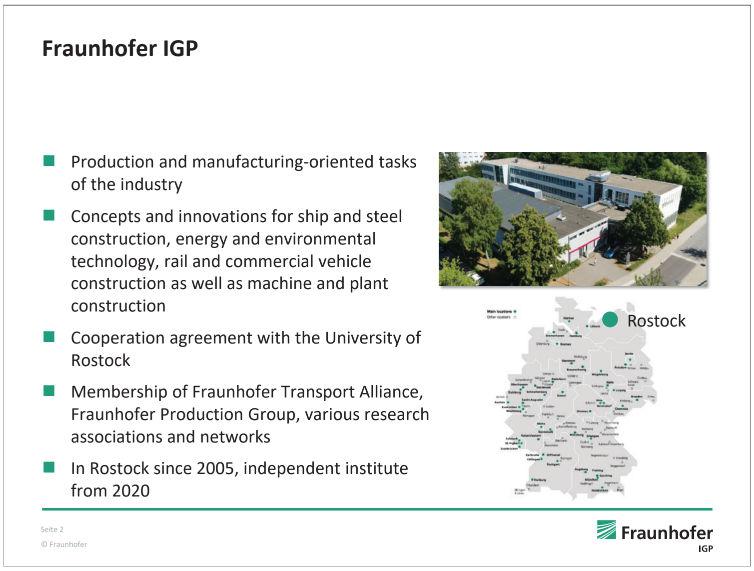
Thank you!

Funded by
EUROPÄISCHE UNION
Investition in unsere Zukunft
Europäischer Fonds
für regionale Entwicklung
EFRE.NRW
Investitionen in Wachstum
und Beschäftigung

DIGITAL ASSISTANCE IN THE MAINTENANCE OF OFFSHORE WIND PARKS

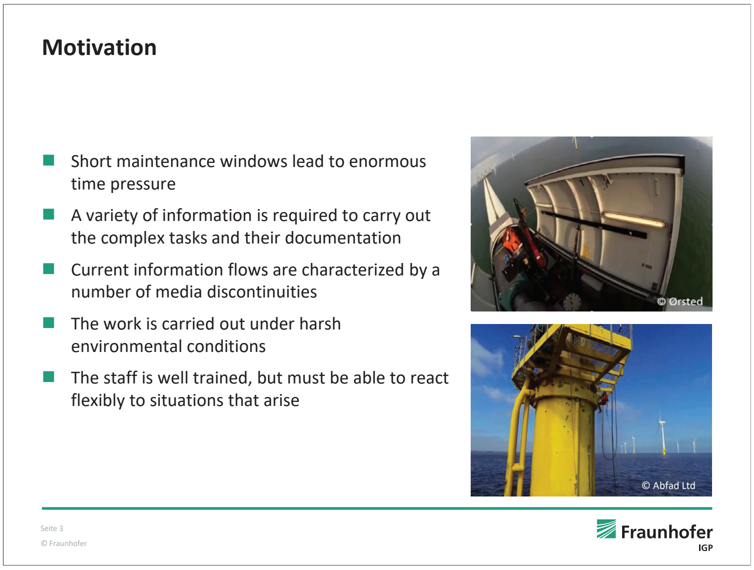
Martin Eggert, **Marten Stepputat**, Florian Beuß, Wilko Flügge

Fraunhofer
IGP



Fraunhofer IGP

- Production and manufacturing-oriented tasks of the industry
- Concepts and innovations for ship and steel construction, energy and environmental technology, rail and commercial vehicle construction as well as machine and plant construction
- Cooperation agreement with the University of Rostock
- Membership of Fraunhofer Transport Alliance, Fraunhofer Production Group, various research associations and networks
- In Rostock since 2005, independent institute from 2020

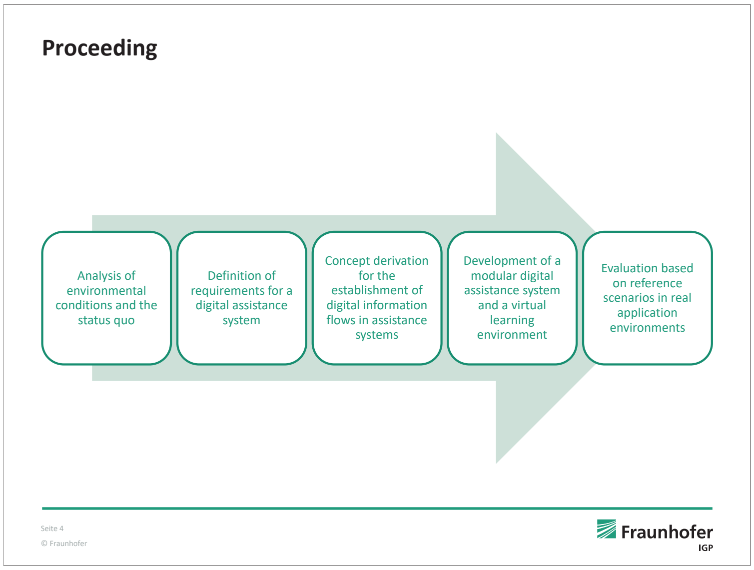


Motivation

- Short maintenance windows lead to enormous time pressure
- A variety of information is required to carry out the complex tasks and their documentation
- Current information flows are characterized by a number of media discontinuities
- The work is carried out under harsh environmental conditions
- The staff is well trained, but must be able to react flexibly to situations that arise

© Ørsted

© Abfad Ltd



Proceeding

Analysis of environmental conditions and the status quo

Definition of requirements for a digital assistance system

Concept derivation for the establishment of digital information flows in assistance systems

Development of a modular digital assistance system and a virtual learning environment

Evaluation based on reference scenarios in real application environments

Analysis of environmental factors for a digital assistance system

Krebs Korrosionsschutz GmbH

Analysis of environmental factors for a digital assistance system

Wireless-mag.com

maintworld.com

automotiveit.eu

telekom-presse.at

Interaction possibilities with digital terminal devices

vs

Interaction restrictions due to the work task

Muehlhan AG

eu.fotolia.com

https://www.youtube.com/watch?v=Rb6a6yfLrxE

eu.fotolia.com

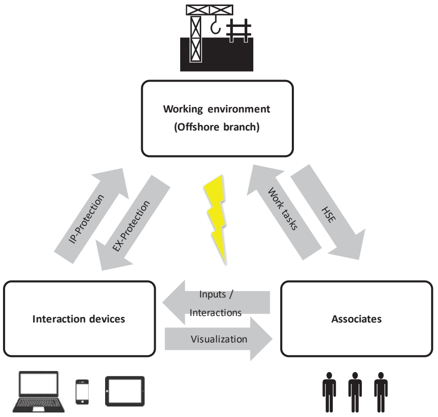
Analysis of environmental factors for a digital assistance system

Identification of information demands

Estimation of the data volume

Possibilities of data transmission

Analysis of environmental factors for a digital assistance system



Working environment (Offshore branch)

IP-Protection

EX-Protection

Work tasks

HSE

Interaction devices

Inputs / Interactions

Visualization

Associates

Definition of requirements for a mobile assistance system for the maintenance of offshore wind farms

Offshore Wind Solutions Mecklenburg Vorpommern

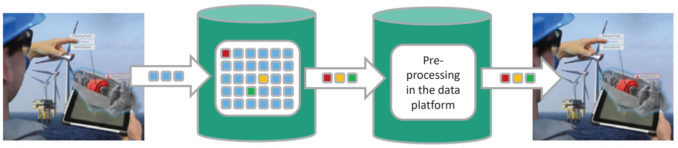
Requirements for a mobile assistance system for use in the operation and maintenance of offshore wind farms in the German Baltic Sea region

Fraunhofer

Definition of requirements for a mobile assistance system for the maintenance of offshore wind farms

- Performance
- Communication
- Information flow
- Protection against the environment
- Interaction
- User Interface
- Integration to equipment
- HSE

Concept and design of the demand-oriented digital information flows and system configuration



Information request of the assistance system

Selection of information from the data platform

Preprocessing of the information

Presentation of information with the assistance system

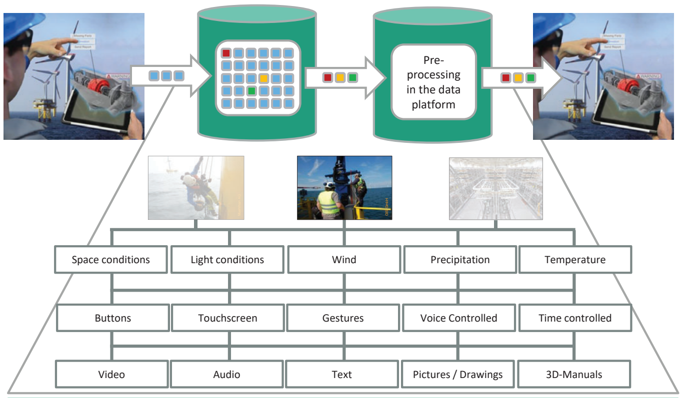
- Device type
- Use case
- Requested information bundle
- Requested information processing

- Evaluation of device type and use case
- Information selection
- Provision of information

- Szenario-specific pre-processing of information
- Compression of the data packages

- Unpacking of the information bundles
- Szenario-specific processing of the information
- Presentation and output of the information

Concept and design of the demand-oriented digital information flows and system configuration



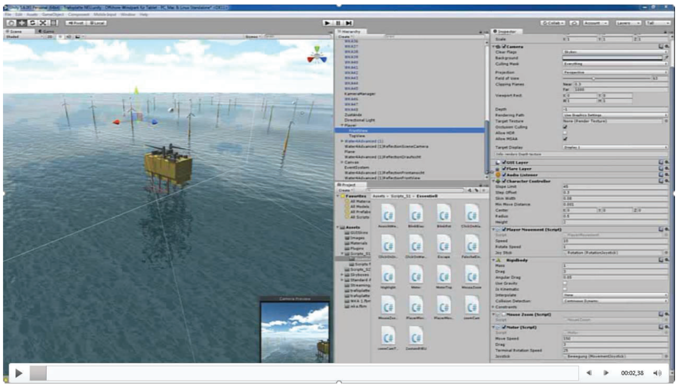
Pre-processing in the data platform

Space conditions | Light conditions | Wind | Precipitation | Temperature

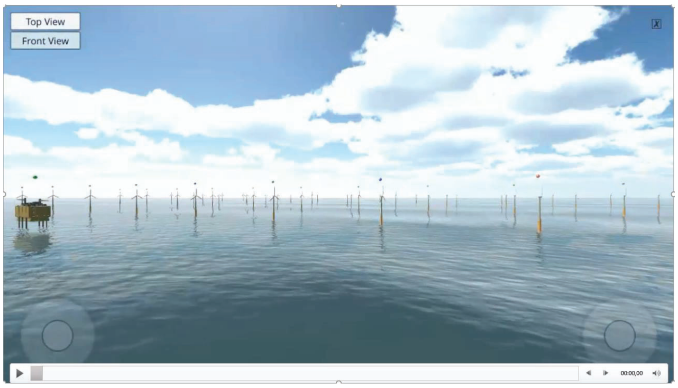
Buttons | Touchscreen | Gestures | Voice Controlled | Time controlled

Video | Audio | Text | Pictures / Drawings | 3D-Manuals

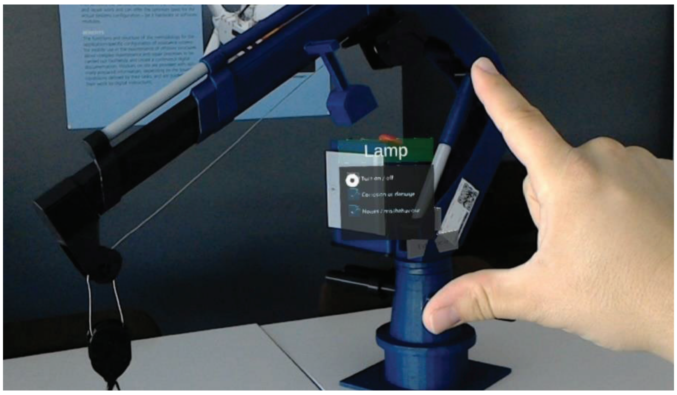
Development of a digital, mobile assistance system for the maintenance of offshore wind farms



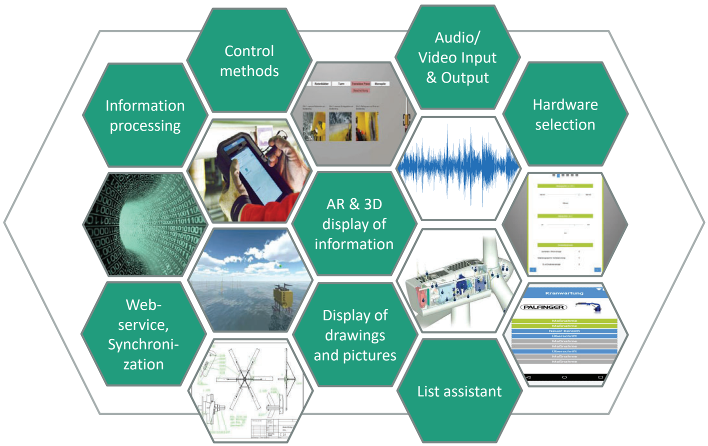
Development of a digital, mobile assistance system for the maintenance of offshore wind farms



Augmented Reality as training und assistance technology for the maintenance of offshore wind farms



Configuration of the digital assistance system



Control methods

Audio/ Video Input & Output

Information processing

Hardware selection

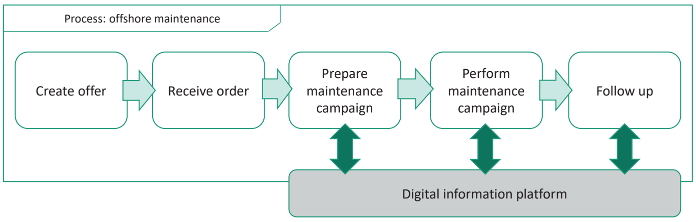
AR & 3D display of information

Web-service, Synchronization

Display of drawings and pictures

List assistant

Benefits of the digital assistance system for the maintenance of offshore wind farms



Process: offshore maintenance

Create offer → Receive order → Prepare maintenance campaign → Perform maintenance campaign → Follow up

Digital information platform

- Access to maintenance and repair history of equipment and systems
- Consideration of and coordination with other activities
- Digital support before, during and after maintenance with demand-specific 3D data and models
- Elimination of media discontinuities through digitization and networking

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THANK YOU! TUSEN TAKK! VIELEN DANK!

Fraunhofer Research Institution for Large
Structures in Production Engineering IGP
www.igp.fraunhofer.de

Contact:
M.Sc. Marten Stepputat
marten.stepputat@igp.fraunhofer.de

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D2) Operations & maintenance

Life Extension of Offshore Wind Farms: A Decision Support Tool, M.Shafiee, Cranfield University – *Presentation not available*

A versatile and highly accurate sensor technology for load measurements, T.Veltkamp, TNO Energy Transition

Are seakeeping simulations useful for the planning of offshore wind O&M? S.Gueydon, MARIN

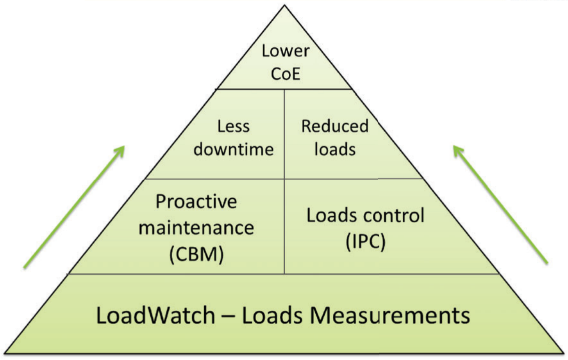
A NEW SENSOR TECHNOLOGY FOR LOAD MONITORING "LOADWATCH"

Peter Eecen[1], Ton Veltkamp[1], ton.veltkamp@tno.nl, Mar van der Hoek[2], Frank Kaandorp[1], Jan Willem Wagenaar[1], Maarten van Balveren[3]

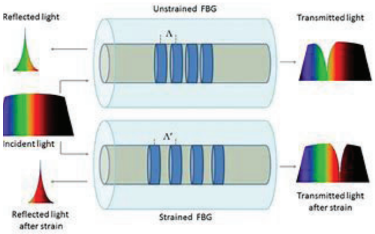
[1]TNO Energy Transition, Westerduinweg 3, 1755 LE Petten, The Netherlands,
[2]vanderHoekPhotonics, Cederdreef 7, 3137 PA Vlaardingen, The Netherlands,
[3]Voestalpine SIGNALING Siershahn GmbH, Coenocoop 84, 2741 PD Waddinxveen, The Netherlands

CONTENT

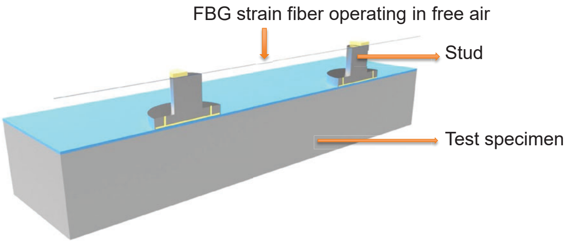
- Load sensing by optical fiber technology
- Introduction of LoadWatch sensor
- Measurement campaign in 2.5 MW research turbine
- Adverse effect of glue/encapsulants on strain measurements
- Concluding remarks



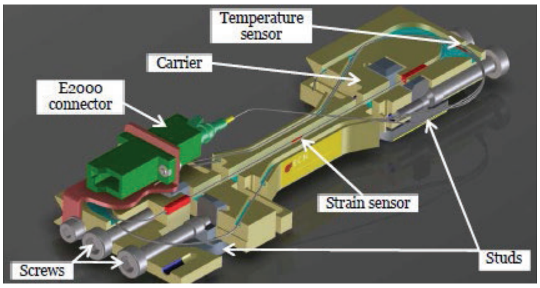
OPTICAL FIBER BRAGG GRATING

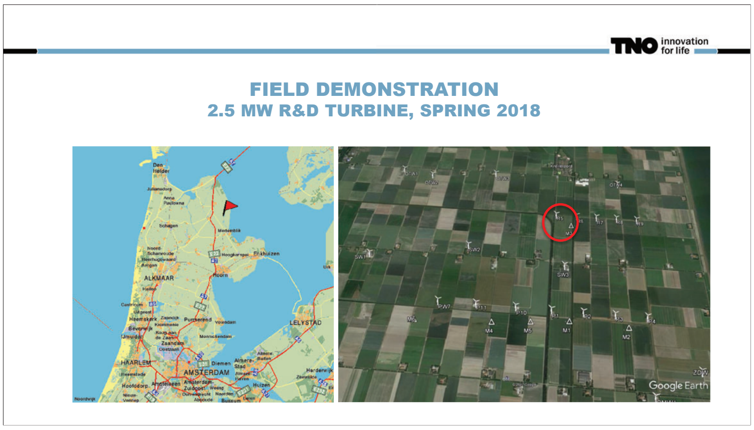


LOADWATCH PRINCIPLE

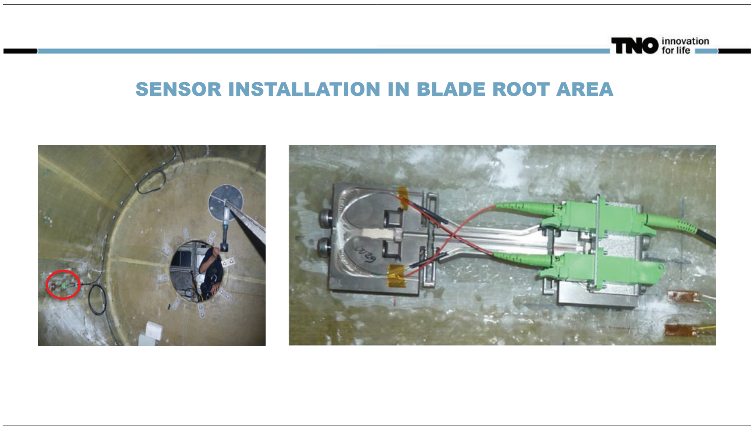


LOADWATCH DESIGN (PATENT)

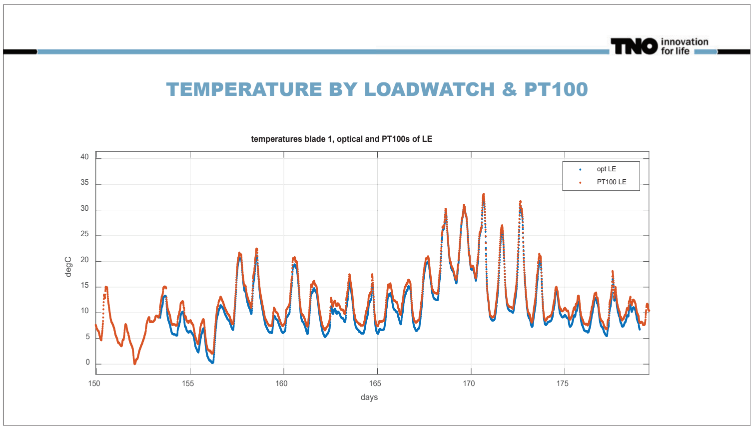




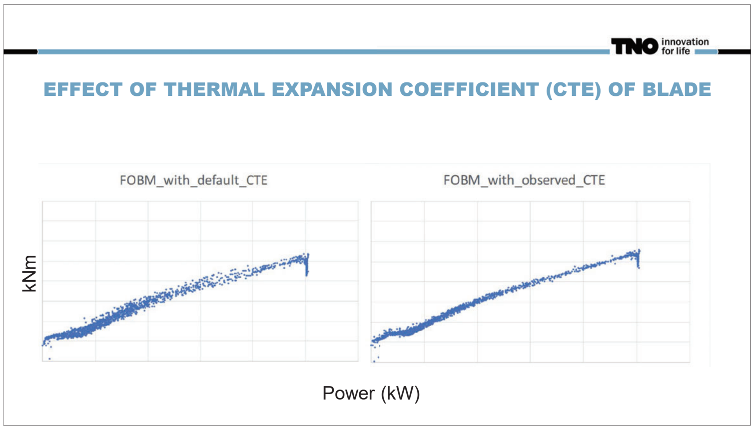
FIELD DEMONSTRATION
2.5 MW R&D TURBINE, SPRING 2018



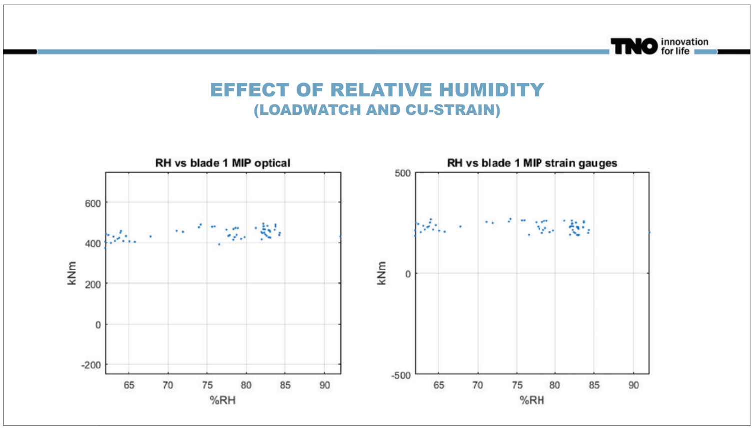
SENSOR INSTALLATION IN BLADE ROOT AREA



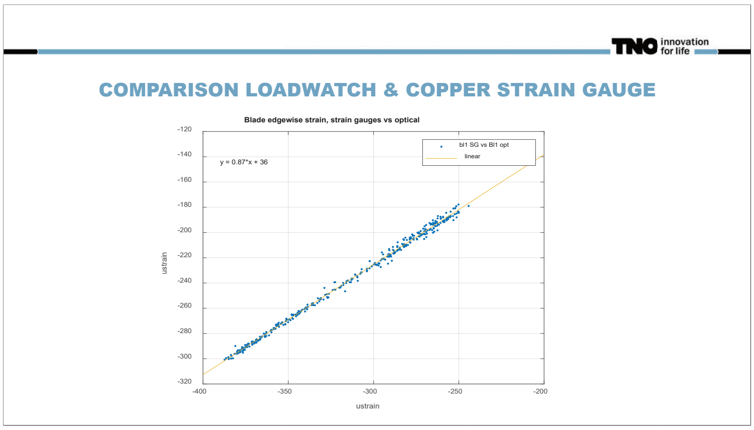
TEMPERATURE BY LOADWATCH & PT100



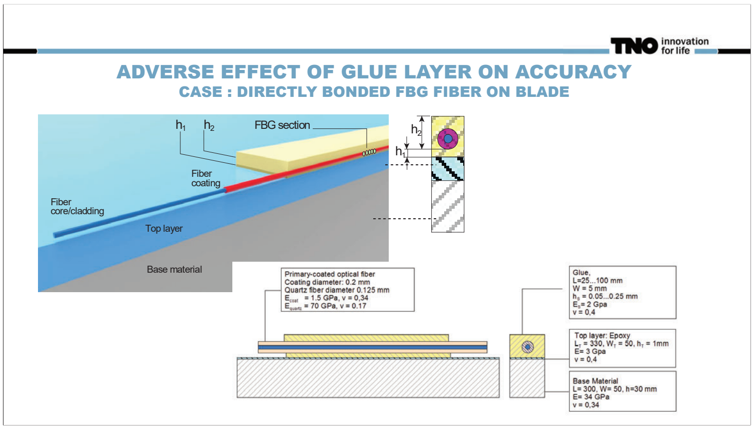
EFFECT OF THERMAL EXPANSION COEFFICIENT (CTE) OF BLADE



EFFECT OF RELATIVE HUMIDITY
(LOADWATCH AND CU-STRAIN)



COMPARISON LOADWATCH & COPPER STRAIN GAUGE



ADVERSE EFFECT OF GLUE LAYER ON ACCURACY

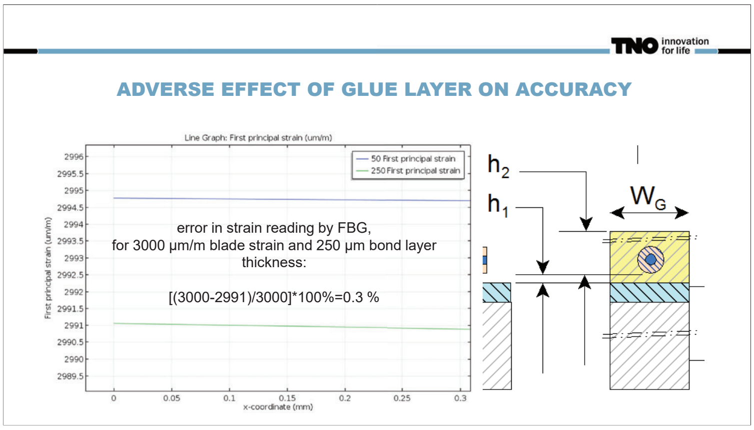
CASE : DIRECTLY BONDED FBG FIBER ON BLADE

Primary-coated optical fiber
Coating diameter: 0.2 mm
Quartz fiber diameter 0.125 mm
E_{coat} = 1.5 GPa, v = 0,34
E_{quartz} = 70 GPa, v = 0.17

Glue,
L=25...100 mm
W = 5 mm
h_S = 0.05...0.25 mm
E_S= 2 Gpa
v = 0,4

Top layer: Epoxy
L_T = 330, W_T = 50, h_T = 1mm
E= 3 Gpa
v = 0,4

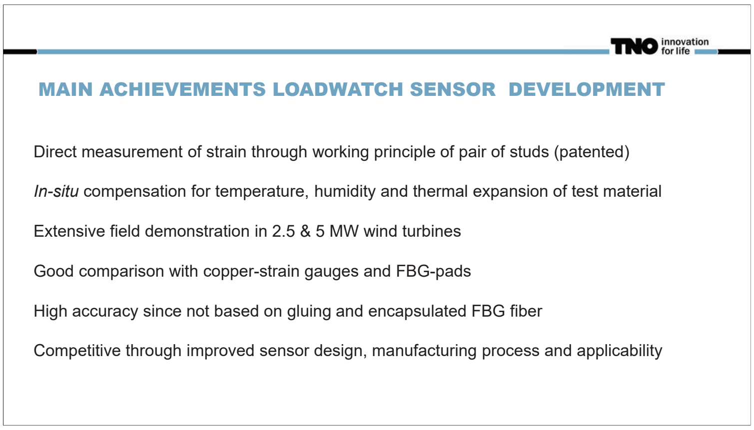
Base Material
L= 300, W= 50, h=30 mm
E= 34 GPa
v = 0,34



ADVERSE EFFECT OF GLUE LAYER ON ACCURACY

error in strain reading by FBG,
for 3000 µm/m blade strain and 250 µm bond layer thickness:

[(3000-2991)/3000]*100%=0.3 %



MAIN ACHIEVEMENTS LOADWATCH SENSOR DEVELOPMENT

Direct measurement of strain through working principle of pair of studs (patented)

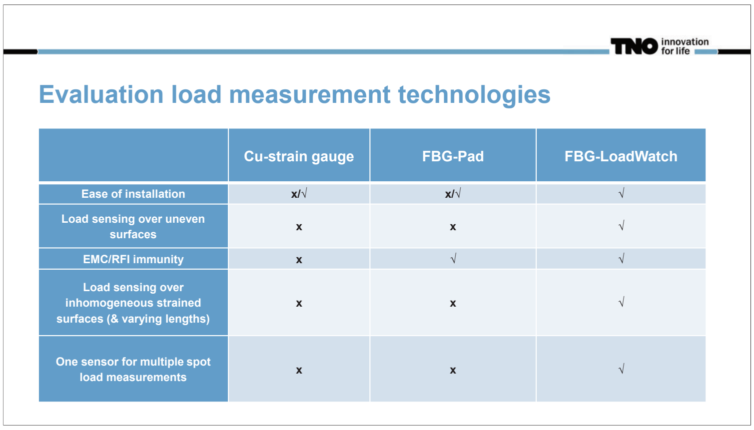
In-situ compensation for temperature, humidity and thermal expansion of test material

Extensive field demonstration in 2.5 & 5 MW wind turbines

Good comparison with copper-strain gauges and FBG-pads

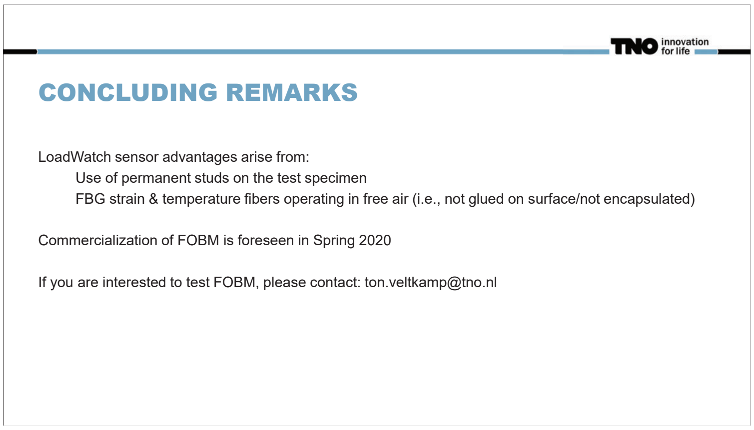
High accuracy since not based on gluing and encapsulated FBG fiber

Competitive through improved sensor design, manufacturing process and applicability



Evaluation load measurement technologies

	Cu-strain gauge	FBG-Pad	FBG-LoadWatch
Ease of installation	x/√	x/√	√
Load sensing over uneven surfaces	x	x	√
EMC/RFI immunity	x	√	√
Load sensing over inhomogeneous strained surfaces (& varying lengths)	x	x	√
One sensor for multiple spot load measurements	x	x	√

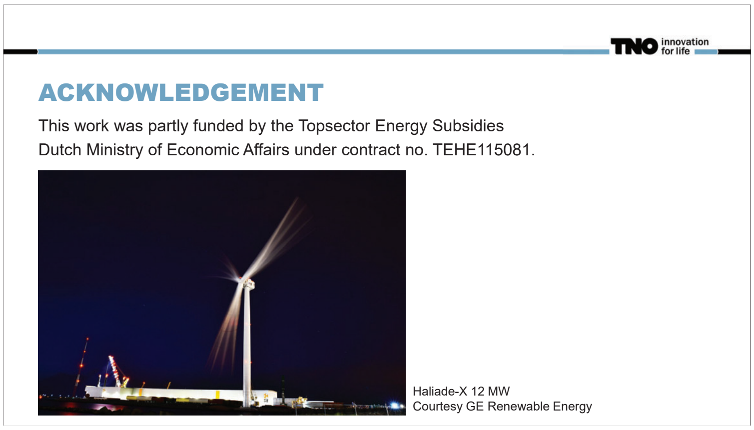


CONCLUDING REMARKS

LoadWatch sensor advantages arise from:
- Use of permanent studs on the test specimen
- FBG strain & temperature fibers operating in free air (i.e., not glued on surface/not encapsulated)

Commercialization of FOBM is foreseen in Spring 2020

If you are interested to test FOBM, please contact: ton.veltkamp@tno.nl

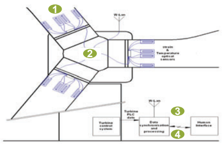


ACKNOWLEDGEMENT

This work was partly funded by the Topsector Energy Subsidies Dutch Ministry of Economic Affairs under contract no. TEHE115081.

Haliade-X 12 MW
Courtesy GE Renewable Energy

ONE POSSIBLE SET-UP OF FOBM



This typical measurement system consists of:

- -12 FOBM sensors
- -Interrogator
- -PC with Wi-Fi
- -Proprietary software

FOBM sensor

- Patented sensor assembly: 4 strain and 4 temperature sensors per blade

Interrogator

- The interrogator reads out the 12 fibre optic sensors and generates measurement data. These are commercially available. ECN has successfully used interrogators from different suppliers.

PC with Wi-Fi

- This computer gathers the strain data from the interrogator and PLC data from the wind turbine and translates this into load data.

ECN's proprietary software

- Sophisticated software developed by ECN for data processing, integration with turbine's SCADA data to generate load statistics for other components than the blades and to provide dashboard and statistics to operator for O&M optimization.

BETTER SHIPS, BLUE OCEANS

SPOWTT
Improving Safety and Productivity of Offshore Wind Technician Transit

EERA DEEPWIND 2020
“Are seakeeping simulations useful for the planning of offshore wind O&M?”

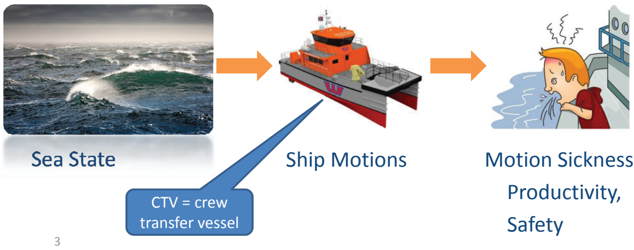
Sebastien GUEYDON, 16 January 2020

Outline

- Intro: SPOWTT
- Objective & methodology
- Ship motion numerical assessment
- Onboard measurements
- Summary

About SPOWTT

improving **S**afety and **P**roductivity of **O**ffshore **W**ind **T**echnician **T**ransits

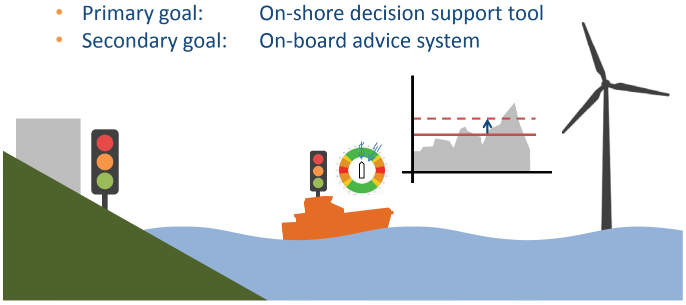


SPOWTT: Project consortium

SIEMENS Gamesa RENEWABLE ENERGY
MARIN
CATAPULT Offshore Renewable Energy
ECN › TNO innovation for life
UNIVERSITY OF HULL
BMO OFFSHORE
SMC

Project goals

- Primary goal: On-shore decision support tool
- Secondary goal: On-board advice system



Examples CTV

Types:
Monohull
Catamaran
Swath

CATAMARANS POPULAR AMONG CTVs

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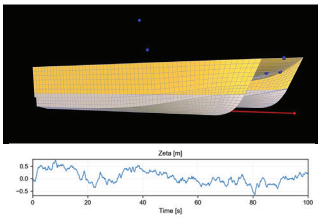
Are seakeeping simulations useful for the planning of O&M?

- Objective: “Validation” of calculated vessel motion data against full scale motion measurement data.

Ship motion simulation code

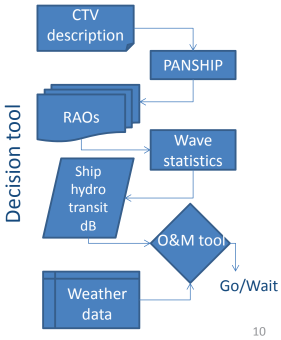


Real measurement on CTVs

How can seakeeping simulations be used for the planning of O&M?

- **Operability of transit journeys is determined using a dB of motion SDAs**

  SDA = Significant Double Amplitude
- SDA are calculated from motion RAOs
- RAOs are determined thanks to a ship motion simulation code: PANSHIP
- PANSHIP implements a semi-non-linear panel methods to predict hydrodynamic loads on fast ships
  - Accounting for lifting devices (foil/trim flap)



Decision tool

CTV description

PANSHIP

RAOs

Wave statistics

Ship hydro transit dB

O&M tool

Go/Wait

Weather data

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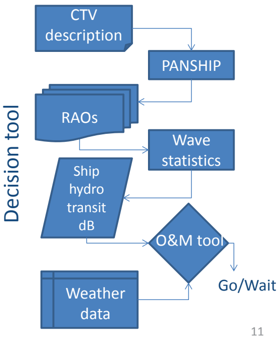

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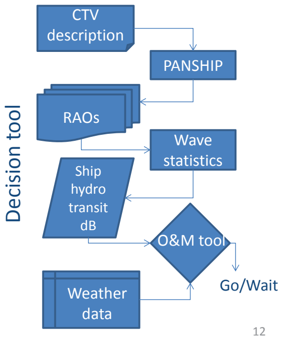

Decision tool

CTV description

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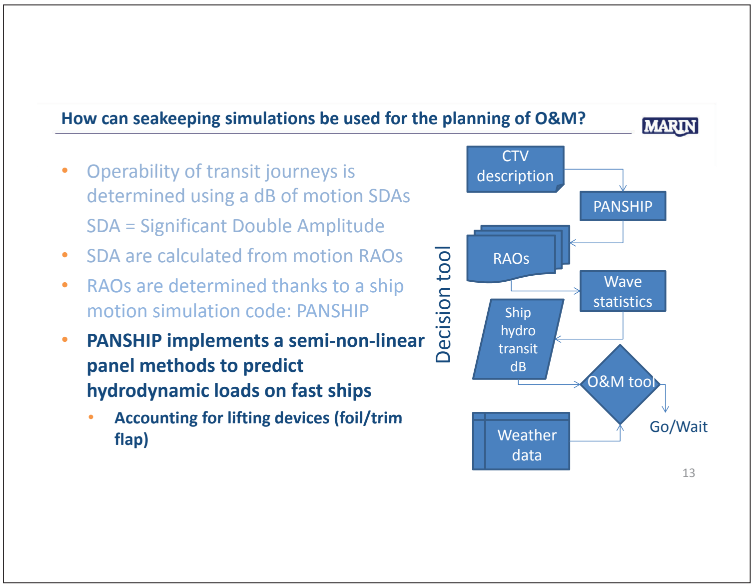

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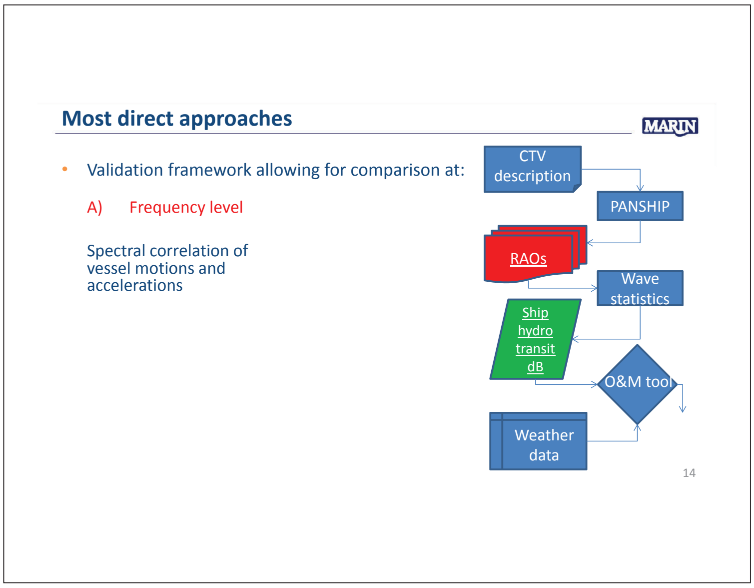
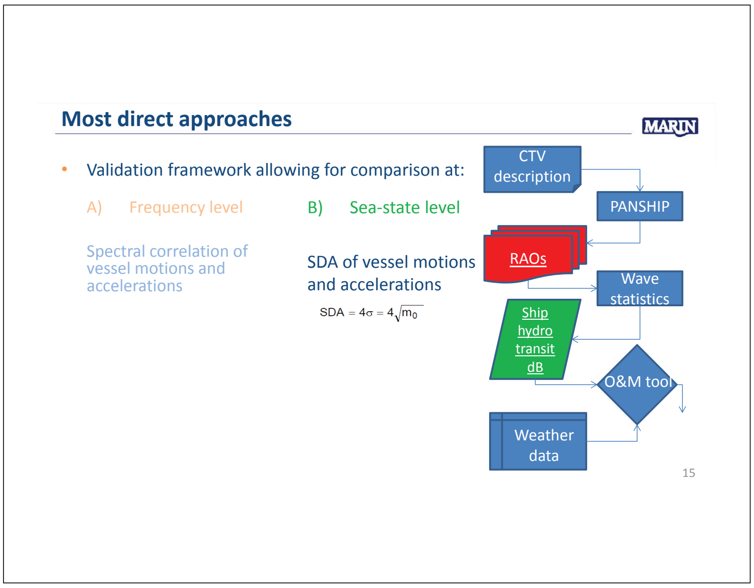


Most direct approaches

- Validation framework allowing for comparison at:

  A) Frequency level

  Spectral correlation of vessel motions and accelerations



Most direct approaches

- Validation framework allowing for comparison at:

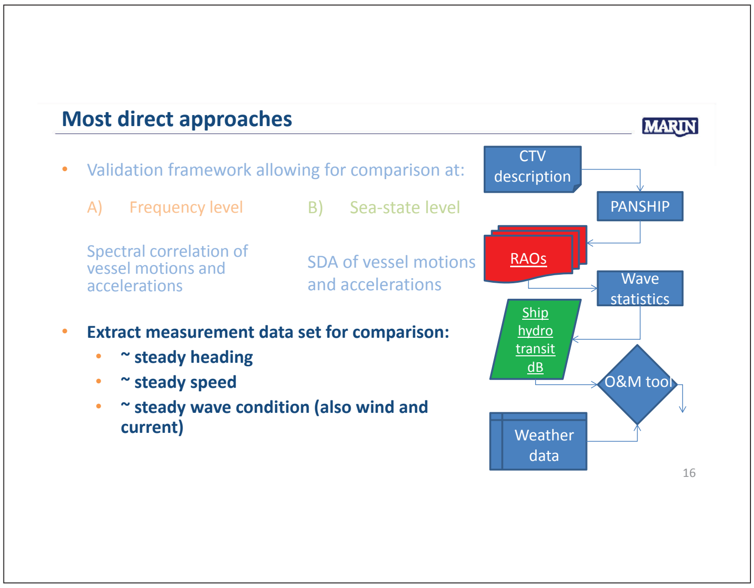
  A) Frequency level

  Spectral correlation of vessel motions and accelerations

  B) Sea-state level

  SDA of vessel motions and accelerations

  $SDA = 4\sigma = 4\sqrt{m_0}$



Most direct approaches

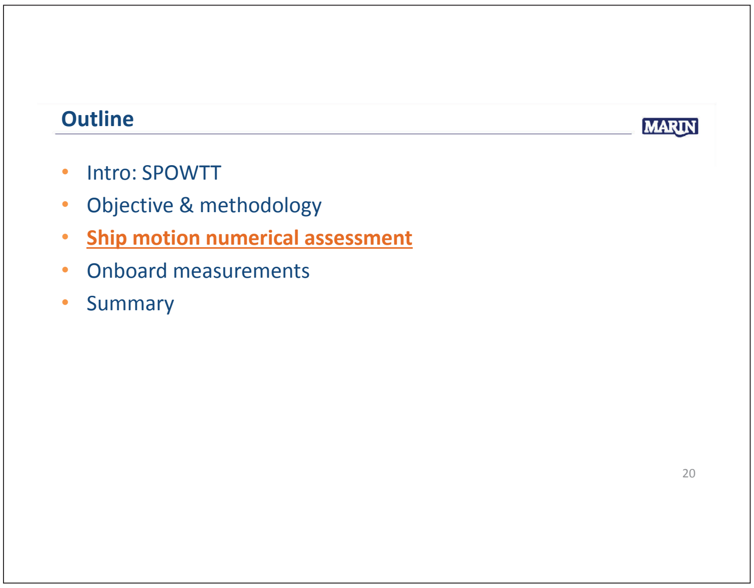
- Validation framework allowing for comparison at:

  A) Frequency level

  Spectral correlation of vessel motions and accelerations

  B) Sea-state level

  SDA of vessel motions and accelerations
- **Extract measurement data set for comparison:**
  - **~ steady heading**
  - **~ steady speed**
  - **~ steady wave condition (also wind and current)**



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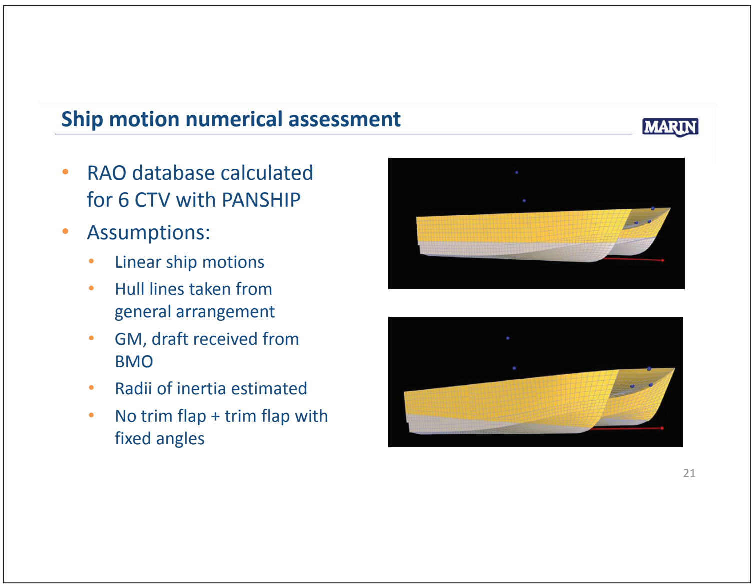
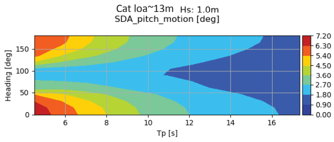
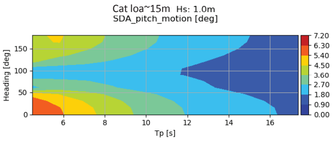


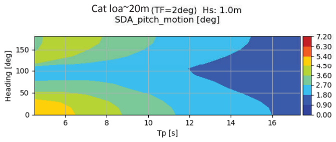
Ship motion numerical assessment

- RAO database calculated for 6 CTV with PANSHIP
- Assumptions:
  - Linear ship motions
  - Hull lines taken from general arrangement
  - GM, draft received from BMO
  - Radii of inertia estimated
  - No trim flap + trim flap with fixed angles

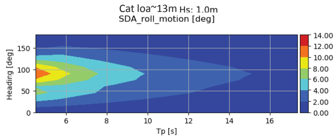
SDA pitch in Hs=1m @ Vs=25kn

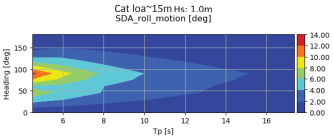

Cat loa~13m Hs: 1.0m
SDA_pitch_motion [deg]

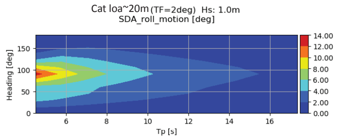

Cat loa~15m Hs: 1.0m
SDA_pitch_motion [deg]


Cat loa~20m (TF=2deg) Hs: 1.0m
SDA_pitch_motion [deg]

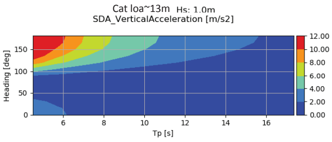
SDA roll in Hs=1m @ Vs=25kn

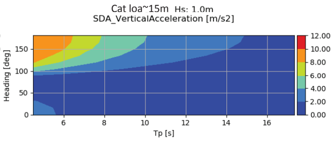

Cat loa~13m Hs: 1.0m
SDA_roll_motion [deg]

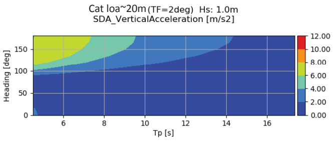

Cat loa~15m Hs: 1.0m
SDA_roll_motion [deg]


Cat loa~20m (TF=2deg) Hs: 1.0m
SDA_roll_motion [deg]

SDA vertical acceleration in Hs=1m @ Vs=25kn

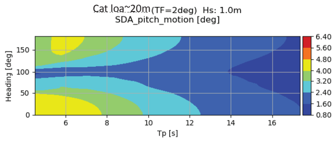

Cat loa~13m Hs: 1.0m
SDA_VerticalAcceleration [m/s2]

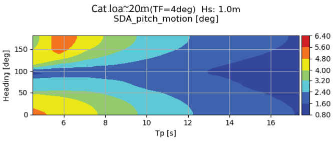

Cat loa~15m Hs: 1.0m
SDA_VerticalAcceleration [m/s2]

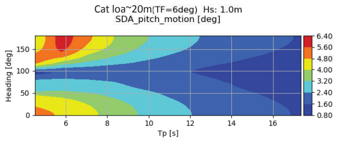

Cat loa~20m (TF=2deg) Hs: 1.0m
SDA_VerticalAcceleration [m/s2]

@Crew seats
Nordforsk: 11 m/s²

Effect of trim flap angle on pitch


Cat loa~20m (TF=2deg) Hs: 1.0m
SDA_pitch_motion [deg]


Cat loa~20m (TF=4deg) Hs: 1.0m
SDA_pitch_motion [deg]


Cat loa~20m (TF=6deg) Hs: 1.0m
SDA_pitch_motion [deg]

Outline

- Intro: SPOWTT
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- **Onboard measurements**
- Summary

Explore and analyze measurements prior to validation

- Wave data
  - Wave buoy (not everywhere)
  - Satellite (+model(s)): Copernicus
- Vessel motion data
  - BMO data

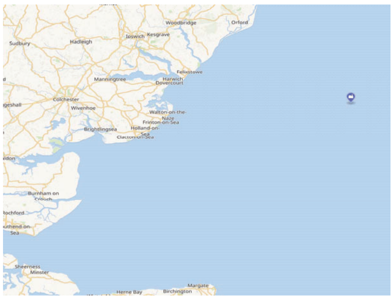
Greater Gabbard

Location of Greater Gabbard wind farm in the North Sea

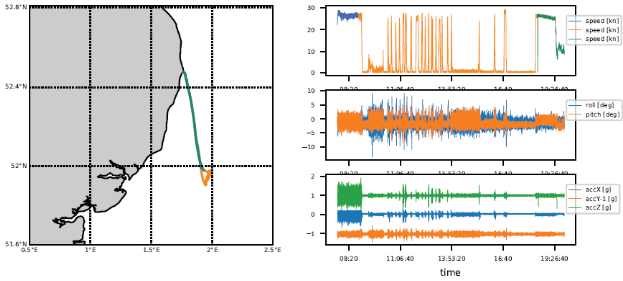
Country	England
Location	Inner Gabbard and The Galloper banks North Sea Suffolk Coast
Coordinates	51°52′48″N 1°56′24″E
Status	Operational
Commission date	2012
Owner(s)	Scottish and Southern RWE Npower Renewables
Wind farm	
Type	Offshore
Distance from shore	23 km (14 mi)
Power generation	
Units operational	140
Make and model	Siemens Wind Power: SWT3.6–107
Nameplate capacity	504 MW
Annual net output	1,800 GW·h (2013)[1]
External links	
Commons	Related media on Commons

[edit on Wikidata]

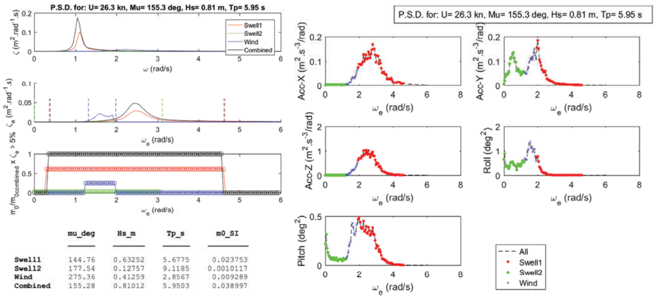
Greater Gabbard



Example of vessel measurement data



Example of PSDs during transit

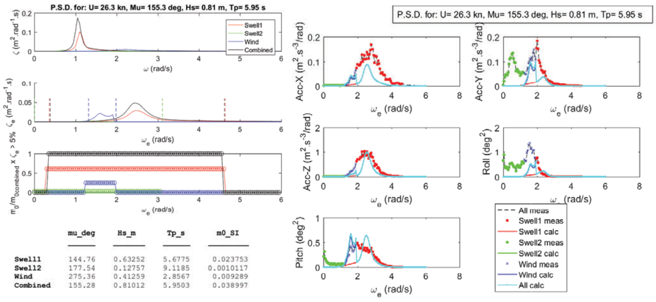


```
            mu_deg     Hs_m       Tp_s       m0_SI
            ______    _______    ______    _________

Swell1      144.76    0.63252    5.6775     0.023753
Swell2      177.54    0.12757    9.1185    0.0010117
Wind        275.36    0.41259    2.8567     0.009289
Combined    155.28    0.81012    5.9503     0.038997
```

WAFO: http://www.maths.lth.se/matstat/wafo

Example of PSDs during transit with simulation results



```
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```
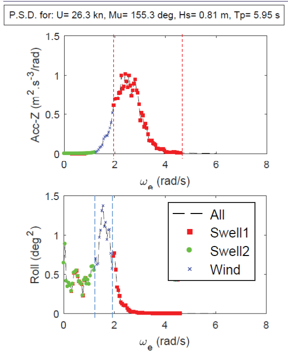

WAFO: http://www.maths.lth.se/matstat/wafo

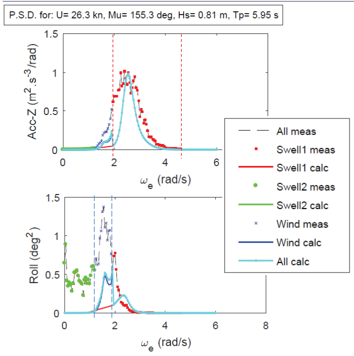
PSD of vertical acceleration and PSD of roll



Observations:

- Importance of distinct wave components
- Peaks are generally linked to a main WF component
- Lot's happening outside the main wave component:
  - LF response (roll)

PSD of vertical acceleration and PSD of roll



+:

- Distinct wave components
- Peaks are represented (global trend is there)

- :

- Amplitude are different (wind wave)
- Different m_0 (SDA)
- What's happening outside the main wave components is disregarded
  - No LF response (or swell 2)

First lessons, some hypotheses are questionable:

- JONSWAP for small waves
- Linear assumption
- Fidelity of CTV input data

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Conclusions

- **A lot to learn from onboard measurements**
  - Most precise definition as possible is recommended
    - Copernicus is a good start (more wave components in distinct directions)
    - Quantification of directional spreading is currently missing
- PANSHIP validation based on onboard measurements not easy
  - Hull lines, loading condition and trim flap angle not known and all have large effect on linear ship motions
  - Local weather conditions not fully known (directional spreading, current, wind)
  - Uncertainty over heading, trim flap
- Driving factor for operability not precisely known but **seakeeping tools can help** with:
  - Seasickness/fatigue of maintenance crew
    - MSI within tool boundaries

Conclusions

- A lot to learn from onboard measurements
  - Most precise definition as possible is recommended
    - Copernicus is a good start (more wave components in distinct directions)
    - Quantification of directional spreading is currently missing
- **PANSHIP validation based on onboard measurements not easy**
  - Hull lines, loading condition and trim flap angle not known and all have large effect on linear ship motions
  - Local weather conditions not fully known (directional spreading, current, wind)
  - Uncertainty over heading, trim flap
- Driving factor for operability not precisely known but **seakeeping tools can help** with:
  - Seasickness/fatigue of maintenance crew
    - MSI within tool boundaries

Conclusions

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Conclusions

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THANK YOU!

Contributors:

- BMO team
- Gerben Spaans
- Rob Grin
- Christian Lena
- Ka Wing Lam
- Erik-Jan de Ridder
- Jorrit-Jan Serraris

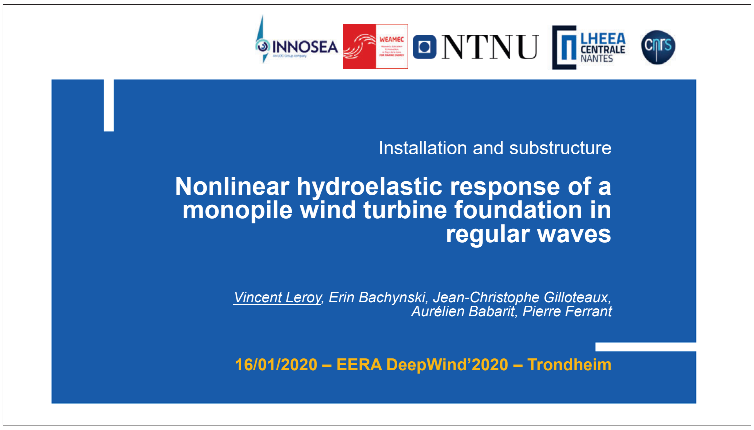
- EU with Copernicus
- Lund University with WAFO

E1) Installation and sub-structures

Nonlinear hydroelastic responses of monopile and spar wind turbines in regular waves, V.Leroy, LHEEA Lab, Centrale Nantes

From pre-design to operation: Outlook and first results of the FloatStep project, H.Bredmose, DTU Wind Energy

Mooring line dynamics of a semi-submersible wind energy platform. Cross validation of two commercial numerical codes with experimental data, R.Chester, University College Cork

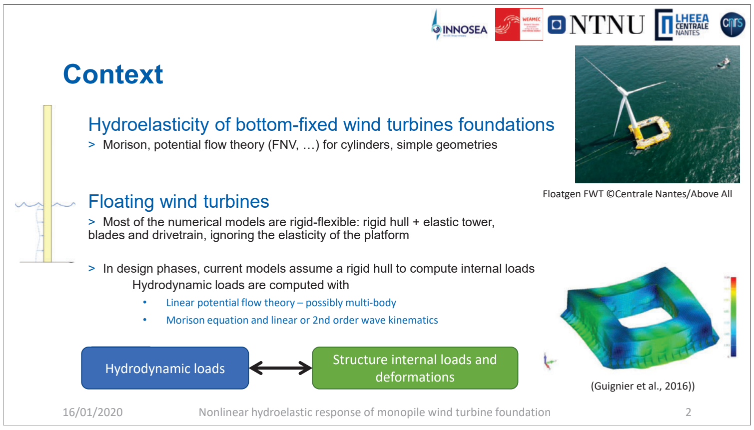


Installation and substructure

Nonlinear hydroelastic response of a monopile wind turbine foundation in regular waves

Vincent Leroy, *Erin Bachynski, Jean-Christophe Gilloteaux,*
Aurélien Babarit, Pierre Ferrant

16/01/2020 – EERA DeepWind'2020 – Trondheim



Context

Hydroelasticity of bottom-fixed wind turbines foundations

- Morison, potential flow theory (FNV, …) for cylinders, simple geometries

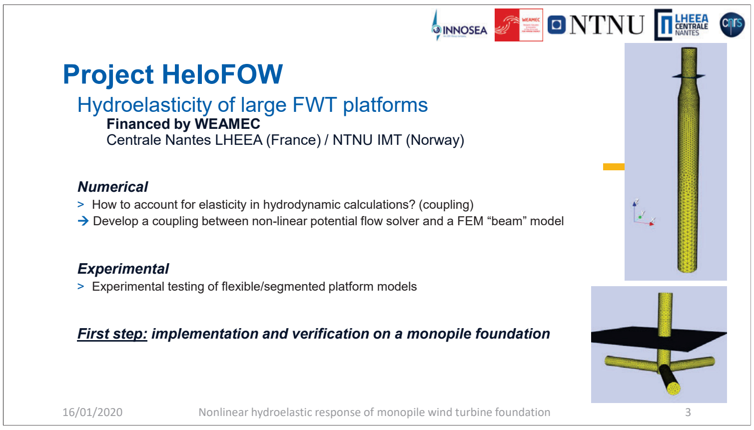
Floatgen FWT ©Centrale Nantes/Above All

Floating wind turbines

- Most of the numerical models are rigid-flexible: rigid hull + elastic tower, blades and drivetrain, ignoring the elasticity of the platform
- In design phases, current models assume a rigid hull to compute internal loads
  Hydrodynamic loads are computed with
  - Linear potential flow theory – possibly multi-body
  - Morison equation and linear or 2nd order wave kinematics

Hydrodynamic loads ⟷ Structure internal loads and deformations

(Guignier et al., 2016))



Project HeloFOW

Hydroelasticity of large FWT platforms

Financed by WEAMEC
Centrale Nantes LHEEA (France) / NTNU IMT (Norway)

Numerical

- How to account for elasticity in hydrodynamic calculations? (coupling)

→ Develop a coupling between non-linear potential flow solver and a FEM "beam" model

Experimental

- Experimental testing of flexible/segmented platform models

<u>First step:</u> implementation and verification on a monopile foundation

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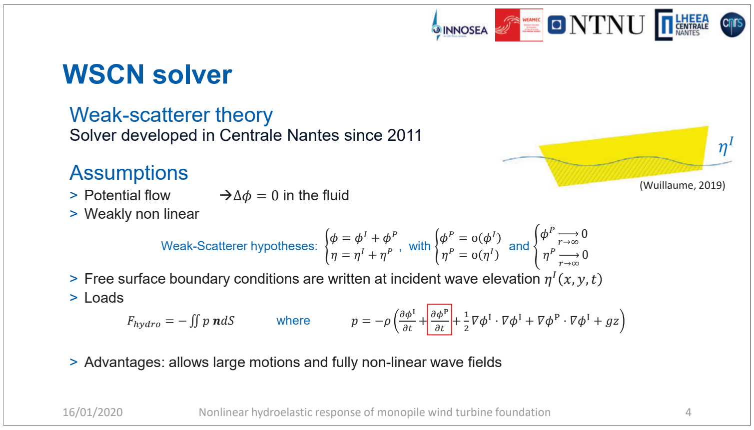

WSCN solver

Weak-scatterer theory

Solver developed in Centrale Nantes since 2011

(Wuillaume, 2019)

Assumptions

- Potential flow →$\Delta\phi = 0$ in the fluid
- Weakly non linear

Weak-Scatterer hypotheses: $\begin{cases}\phi = \phi^I + \phi^P \\ \eta = \eta^I + \eta^P\end{cases}$, with $\begin{cases}\phi^P = o(\phi^I) \\ \eta^P = o(\eta^I)\end{cases}$ and $\begin{cases}\phi^P \xrightarrow[r\to\infty]{} 0 \\ \eta^P \xrightarrow[r\to\infty]{} 0\end{cases}$

- Free surface boundary conditions are written at incident wave elevation $\eta^I(x,y,t)$
- Loads

$F_{hydro} = -\iint p\,\boldsymbol{n}dS$ where $p = -\rho\left(\frac{\partial\phi^I}{\partial t} + \boxed{\frac{\partial\phi^P}{\partial t}} + \frac{1}{2}\nabla\phi^I\cdot\nabla\phi^I + \nabla\phi^P\cdot\nabla\phi^I + gz\right)$

- Advantages: allows large motions and fully non-linear wave fields

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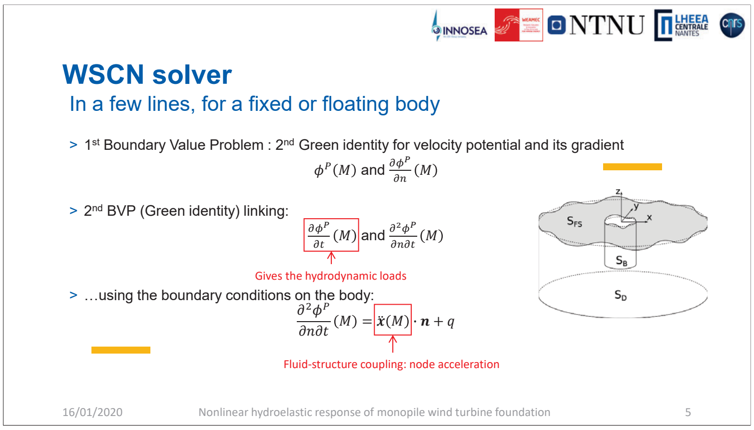


WSCN solver

In a few lines, for a fixed or floating body

- 1st Boundary Value Problem : 2nd Green identity for velocity potential and its gradient

$$\phi^P(M) \text{ and } \frac{\partial\phi^P}{\partial n}(M)$$

- 2nd BVP (Green identity) linking:

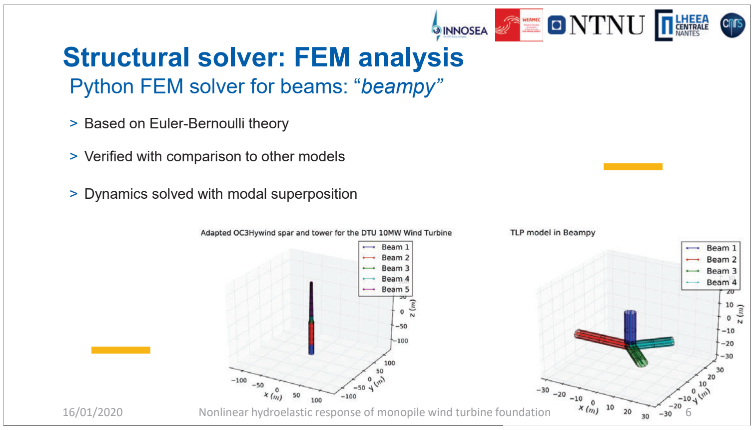
$$\boxed{\frac{\partial\phi^P}{\partial t}(M)} \text{ and } \frac{\partial^2\phi^P}{\partial n\partial t}(M)$$

Gives the hydrodynamic loads

- …using the boundary conditions on the body:

$$\frac{\partial^2\phi^P}{\partial n\partial t}(M) = \boxed{\ddot{\boldsymbol{x}}(M)}\cdot\boldsymbol{n} + q$$

Fluid-structure coupling: node acceleration



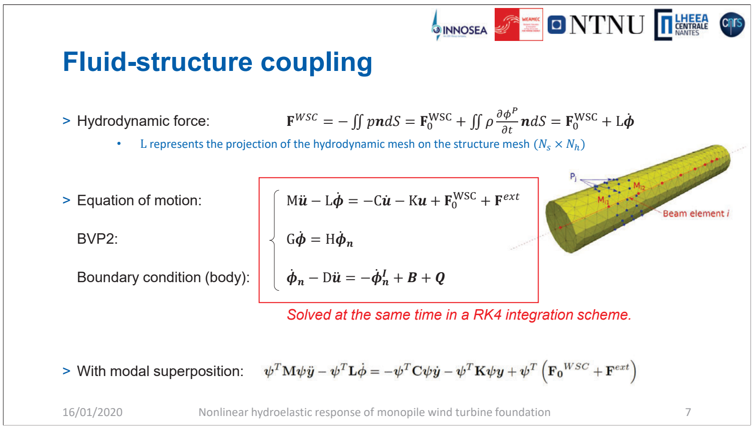
Structural solver: FEM analysis

Python FEM solver for beams: "*beampy*"

- Based on Euler-Bernoulli theory
- Verified with comparison to other models
- Dynamics solved with modal superposition

Adapted OC3Hywind spar and tower for the DTU 10MW Wind Turbine

TLP model in Beampy



Fluid-structure coupling

- Hydrodynamic force: $\mathbf{F}^{WSC} = -\iint p\boldsymbol{n}dS = \mathbf{F}_0^{\mathrm{WSC}} + \iint \rho\frac{\partial\phi^P}{\partial t}\boldsymbol{n}dS = \mathbf{F}_0^{\mathrm{WSC}} + \mathrm{L}\dot{\boldsymbol{\phi}}$
  - L represents the projection of the hydrodynamic mesh on the structure mesh $(N_s \times N_h)$

- Equation of motion: $\mathrm{M}\ddot{\boldsymbol{u}} - \mathrm{L}\dot{\boldsymbol{\phi}} = -\mathrm{C}\dot{\boldsymbol{u}} - \mathrm{K}\boldsymbol{u} + \mathbf{F}_0^{\mathrm{WSC}} + \mathbf{F}^{ext}$

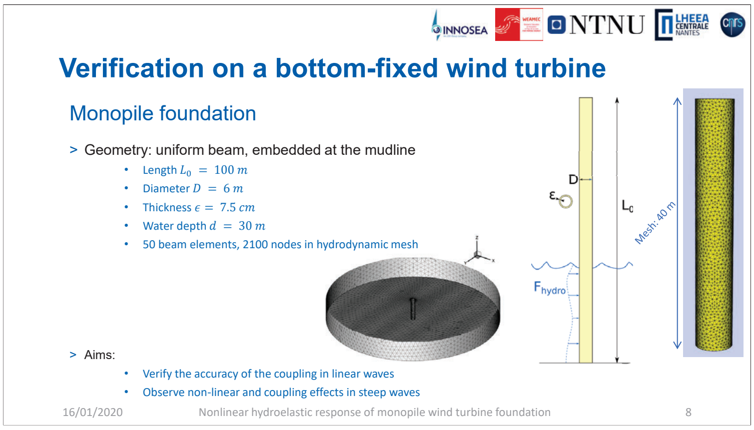
  BVP2: $\mathrm{G}\dot{\boldsymbol{\phi}} = \mathrm{H}\dot{\boldsymbol{\phi}}_{\boldsymbol{n}}$

  Boundary condition (body): $\dot{\boldsymbol{\phi}}_{\boldsymbol{n}} - \mathrm{D}\ddot{\boldsymbol{u}} = -\dot{\boldsymbol{\phi}}_{\boldsymbol{n}}^{I} + \boldsymbol{B} + \boldsymbol{Q}$

Solved at the same time in a RK4 integration scheme.

- With modal superposition: $\psi^T\mathbf{M}\psi\ddot{y} - \psi^T\mathbf{L}\dot{\phi} = -\psi^T\mathbf{C}\psi\dot{y} - \psi^T\mathbf{K}\psi y + \psi^T\left(\mathbf{F_0}^{WSC} + \mathbf{F}^{ext}\right)$

16/01/2020 Nonlinear hydroelastic response of monopile wind turbine foundation 7



Verification on a bottom-fixed wind turbine

Monopile foundation

- Geometry: uniform beam, embedded at the mudline
  - Length $L_0 = 100\ m$
  - Diameter $D = 6\ m$
  - Thickness $\epsilon = 7.5\ cm$
  - Water depth $d = 30\ m$
  - 50 beam elements, 2100 nodes in hydrodynamic mesh

- Aims:
  - Verify the accuracy of the coupling in linear waves
  - Observe non-linear and coupling effects in steep waves

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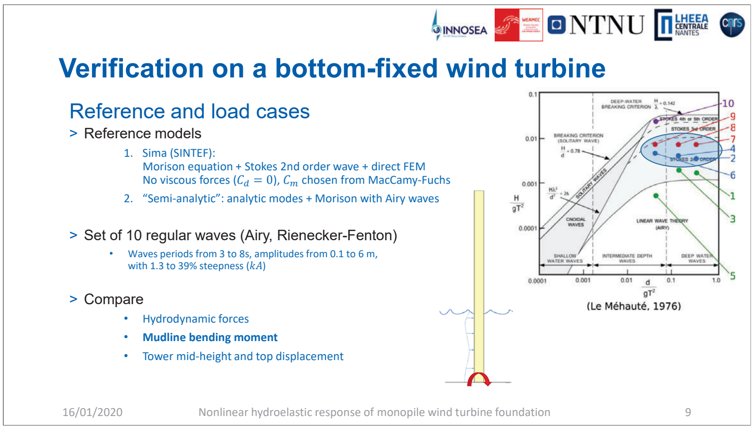


Verification on a bottom-fixed wind turbine

Reference and load cases

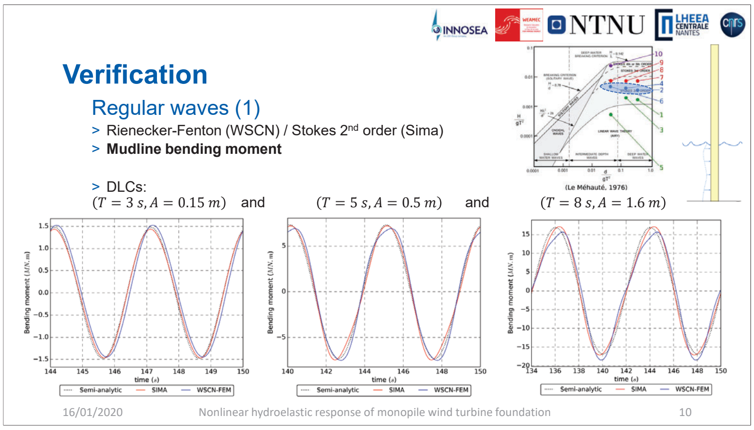
- Reference models
  1. Sima (SINTEF):
     Morison equation + Stokes 2nd order wave + direct FEM
     No viscous forces ($C_d = 0$), C_m chosen from MacCamy-Fuchs
  2. "Semi-analytic": analytic modes + Morison with Airy waves

- Set of 10 regular waves (Airy, Rienecker-Fenton)
  - Waves periods from 3 to 8s, amplitudes from 0.1 to 6 m, with 1.3 to 39% steepness (kA)

- Compare
  - Hydrodynamic forces
  - **Mudline bending moment**
  - Tower mid-height and top displacement

(Le Méhauté, 1976)

16/01/2020 Nonlinear hydroelastic response of monopile wind turbine foundation 9



Verification

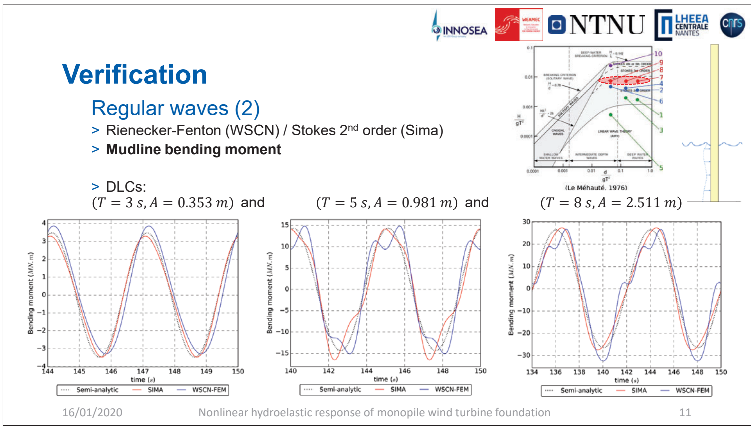
Regular waves (1)

- Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)
- **Mudline bending moment**

(Le Méhauté, 1976)

- DLCs:
  $(T = 3\ s, A = 0.15\ m)$ and $(T = 5\ s, A = 0.5\ m)$ and $(T = 8\ s, A = 1.6\ m)$

16/01/2020 Nonlinear hydroelastic response of monopile wind turbine foundation 10



Verification

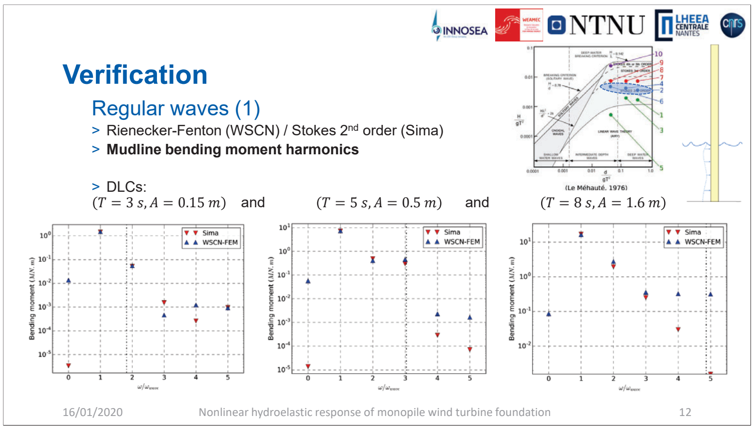
Regular waves (2)

- Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)
- **Mudline bending moment**

(Le Méhauté, 1976)

- DLCs:
  $(T = 3\ s, A = 0.353\ m)$ and $(T = 5\ s, A = 0.981\ m)$ and $(T = 8\ s, A = 2.511\ m)$

16/01/2020 Nonlinear hydroelastic response of monopile wind turbine foundation 11



Verification

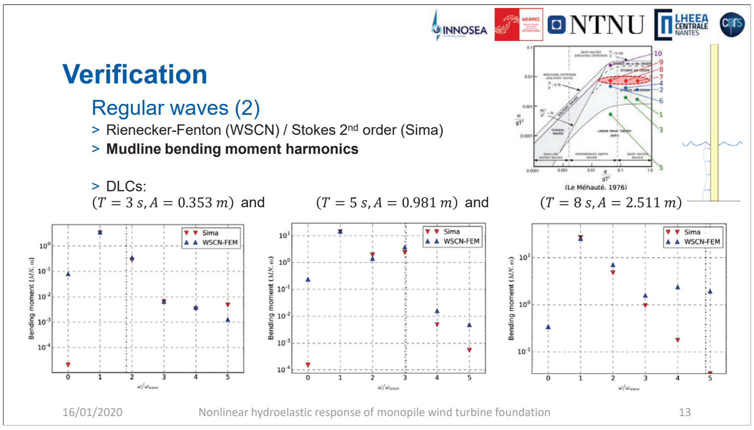
Regular waves (1)

- Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)
- **Mudline bending moment harmonics**

(Le Méhauté, 1976)

- DLCs:
  $(T = 3\ s, A = 0.15\ m)$ and $(T = 5\ s, A = 0.5\ m)$ and $(T = 8\ s, A = 1.6\ m)$

16/01/2020 Nonlinear hydroelastic response of monopile wind turbine foundation 12



Verification

Regular waves (2)

- > Rienecker-Fenton (WSCN) / Stokes 2nd order (Sima)
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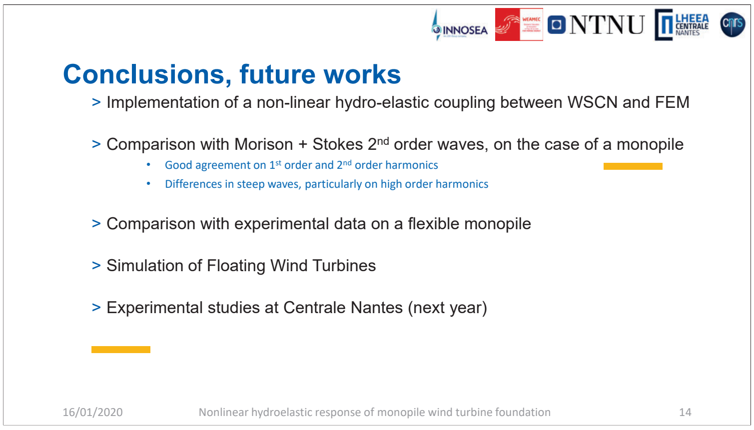
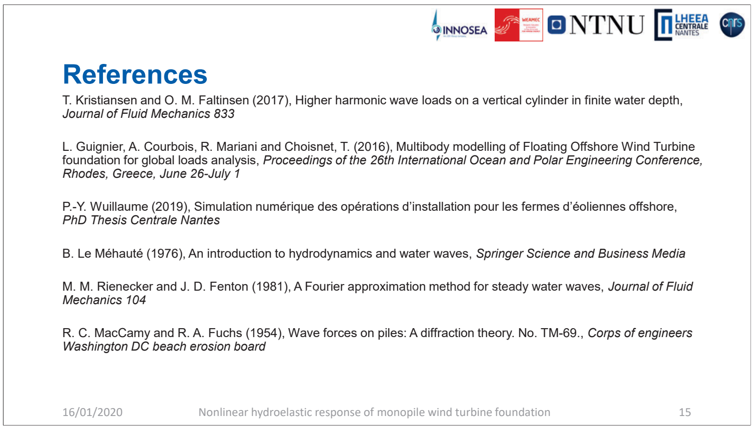


Conclusions, future works

- > Implementation of a non-linear hydro-elastic coupling between WSCN and FEM
- > Comparison with Morison + Stokes 2nd order waves, on the case of a monopile
  - Good agreement on 1st order and 2nd order harmonics
  - Differences in steep waves, particularly on high order harmonics
- > Comparison with experimental data on a flexible monopile
- > Simulation of Floating Wind Turbines
- > Experimental studies at Centrale Nantes (next year)



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L. Guignier, A. Courbois, R. Mariani and Choisnet, T. (2016), Multibody modelling of Floating Offshore Wind Turbine foundation for global loads analysis, *Proceedings of the 26th International Ocean and Polar Engineering Conference, Rhodes, Greece, June 26-July 1*

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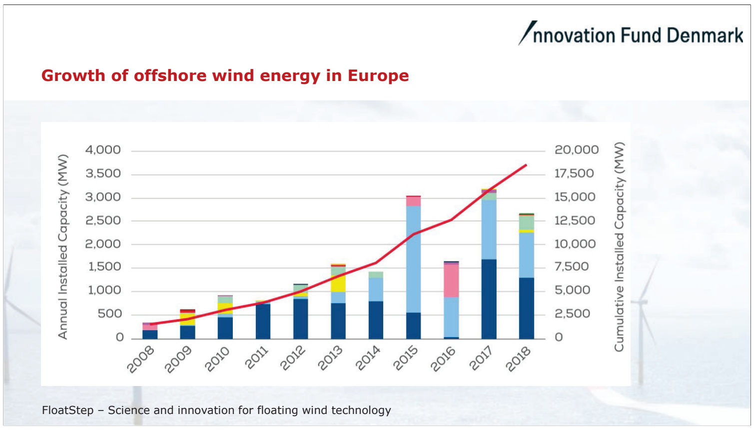
Thank you for your attention

From pre-design to operation:
Outlook and first results of the FloatStep project

Henrik Bredmose[1], Mathias Stolpe[1], Antonio Pegalajar-Jurado[1], Kasper Laugesen[2], Bjarne Jensen[3], Michael Borg[4], Johan Rønby[5], Jana Orszaghova[6]

DTU 1
SIEMENS Gamesa RENEWABLE ENERGY 2
DHI 3
Stiesdal Offshore Technologies 4
STROMNING 5
THE UNIVERSITY OF WESTERN AUSTRALIA 6



Growth of offshore wind energy in Europe

FloatStep – Science and innovation for floating wind technology

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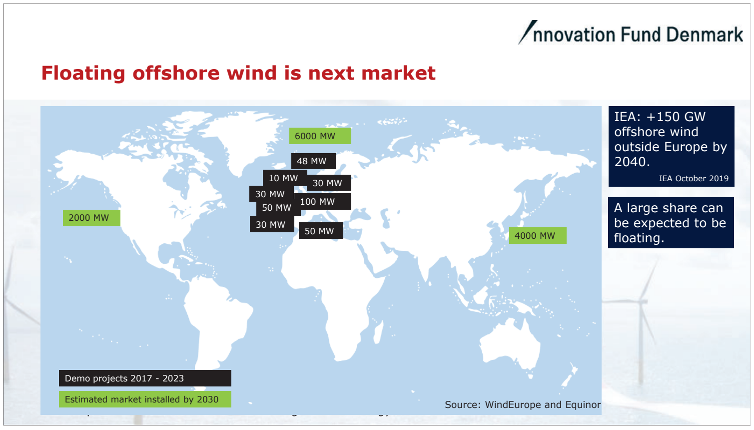


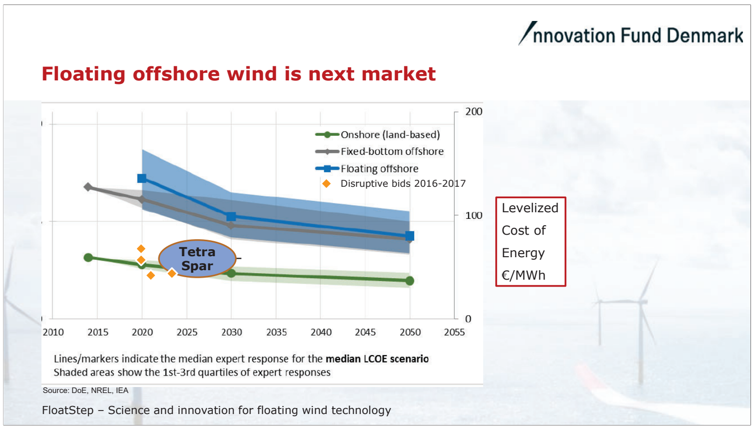
Floating offshore wind is next market

Source: WindEurope and Equinor

IEA: +150 GW offshore wind outside Europe by 2040.

IEA October 2019

A large share can be expected to be floating.



Floating offshore wind is next market

Lines/markers indicate the median expert response for the **median LCOE scenario**
Shaded areas show the 1st-3rd quartiles of expert responses

Source: DoE, NREL, IEA

Levelized Cost of Energy €/MWh

FloatStep – Science and innovation for floating wind technology

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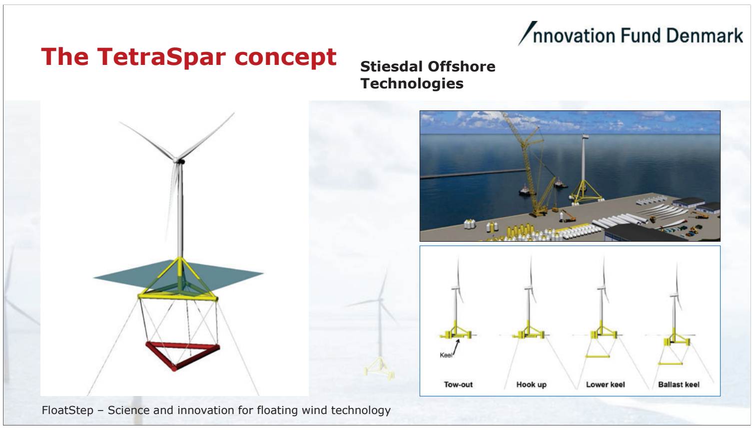

The TetraSpar concept

Stiesdal Offshore Technologies

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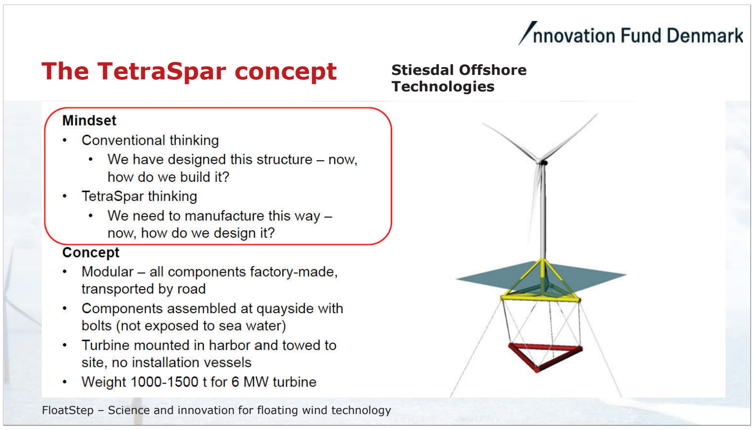

The TetraSpar concept

Stiesdal Offshore Technologies

Mindset
- Conventional thinking
  - We have designed this structure – now, how do we build it?
- TetraSpar thinking
  - We need to manufacture this way – now, how do we design it?

Concept
- Modular – all components factory-made, transported by road
- Components assembled at quayside with bolts (not exposed to sea water)
- Turbine mounted in harbor and towed to site, no installation vessels
- Weight 1000-1500 t for 6 MW turbine

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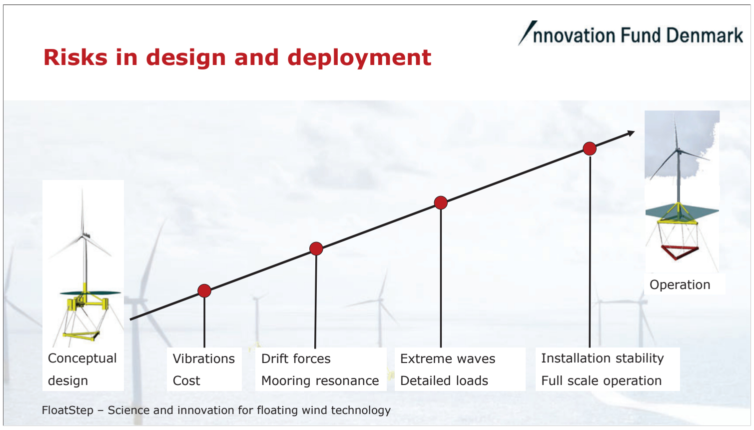


Risks in design and deployment

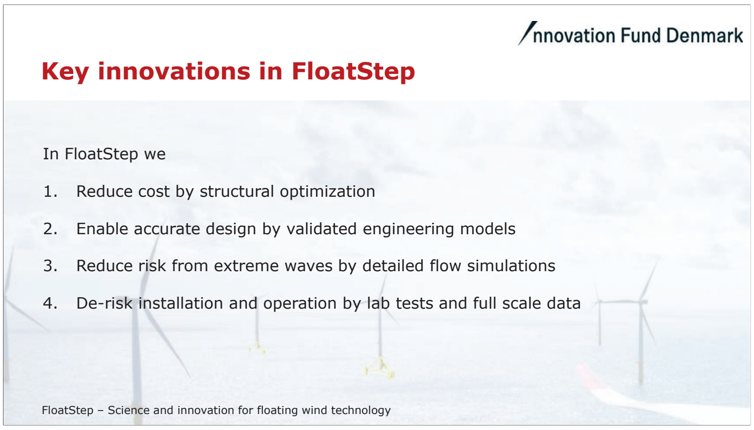
FloatStep – Science and innovation for floating wind technology

The FloatStep project

2018-2022

Stiesdal Offshore Technologies

Image: Bourbon Offshore



Key innovations in FloatStep

In FloatStep we

1. Reduce cost by structural optimization
2. Enable accurate design by validated engineering models
3. Reduce risk from extreme waves by detailed flow simulations
4. De-risk installation and operation by lab tests and full scale data

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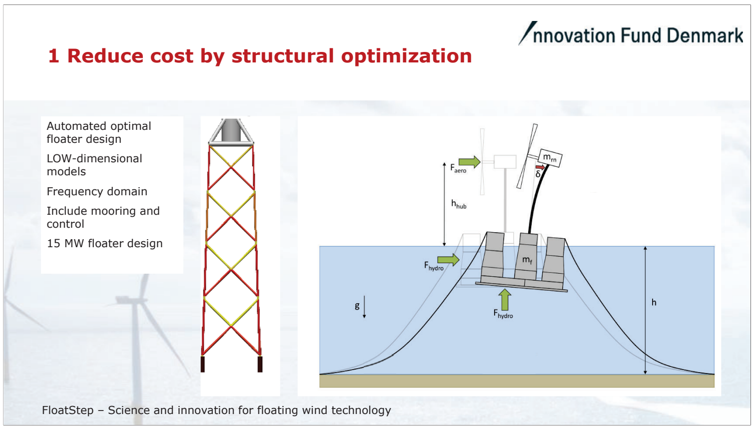

1 Reduce cost by structural optimization

Automated optimal floater design

LOW-dimensional models

Frequency domain

Include mooring and control

15 MW floater design

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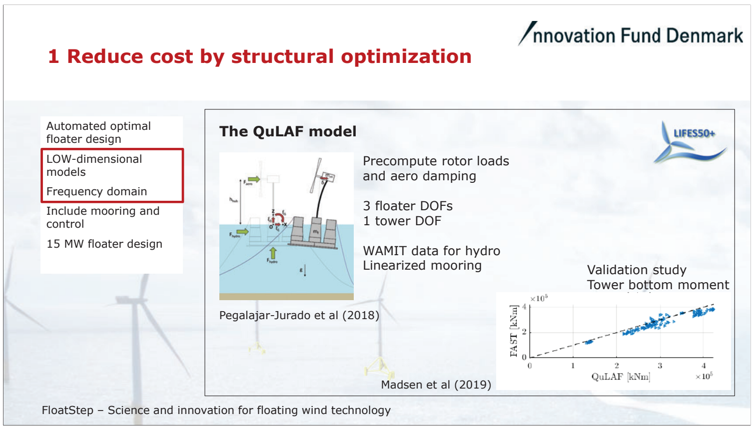


1 Reduce cost by structural optimization

Automated optimal floater design

LOW-dimensional models

Frequency domain

Include mooring and control

15 MW floater design

The QuLAF model

Precompute rotor loads
and aero damping

3 floater DOFs
1 tower DOF

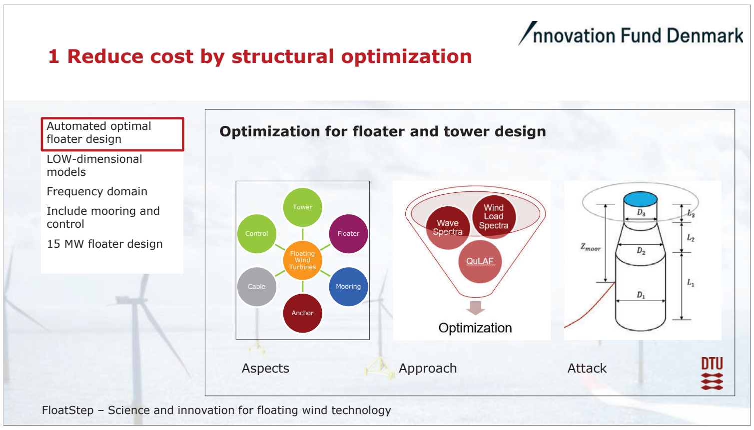
WAMIT data for hydro
Linearized mooring

Pegalajar-Jurado et al (2018)

Validation study
Tower bottom moment

Madsen et al (2019)

FloatStep – Science and innovation for floating wind technology



1 Reduce cost by structural optimization

Automated optimal floater design

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Frequency domain

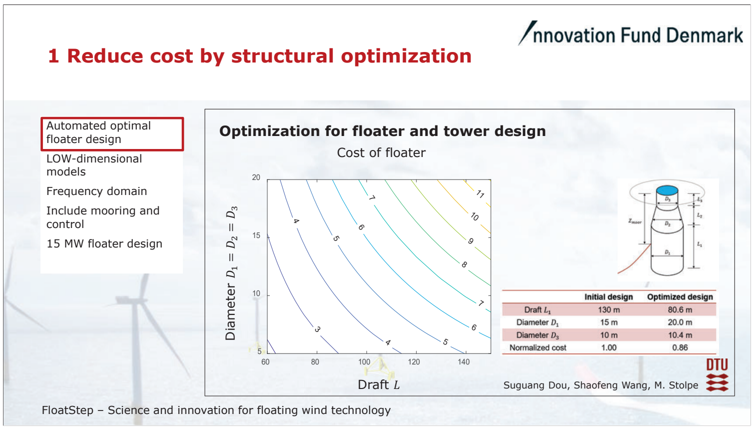
Include mooring and control

15 MW floater design

Optimization for floater and tower design

Aspects Approach Attack

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

1 Reduce cost by structural optimization

- Automated optimal floater design
- LOW-dimensional models
- Frequency domain
- Include mooring and control
- 15 MW floater design

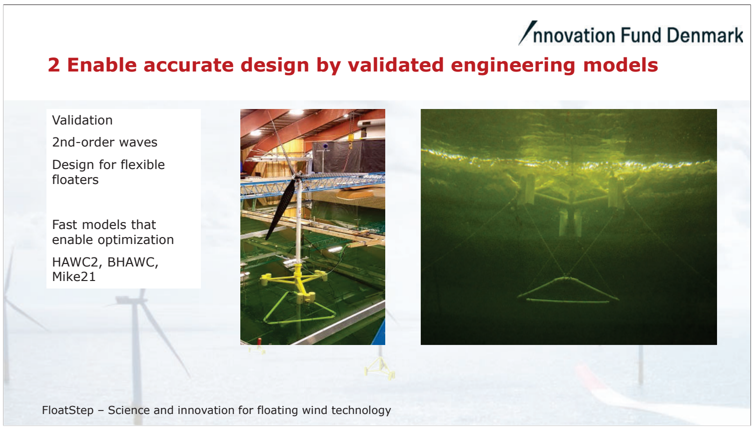
Optimization for floater and tower design

Cost of floater

	Initial design	Optimized design
Draft L_1	130 m	80.6 m
Diameter D_1	15 m	20.0 m
Diameter D_3	10 m	10.4 m
Normalized cost	1.00	0.86

Suguang Dou, Shaofeng Wang, M. Stolpe

FloatStep – Science and innovation for floating wind technology

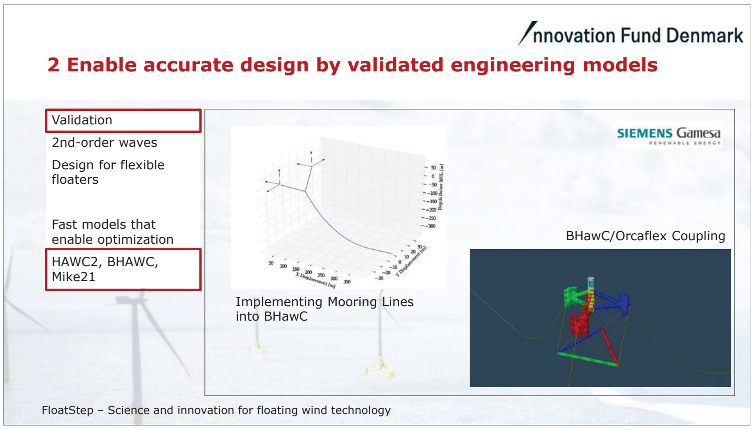


Innovation Fund Denmark

2 Enable accurate design by validated engineering models

- Validation
- 2nd-order waves
- Design for flexible floaters
- Fast models that enable optimization
- HAWC2, BHAWC, Mike21

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

2 Enable accurate design by validated engineering models

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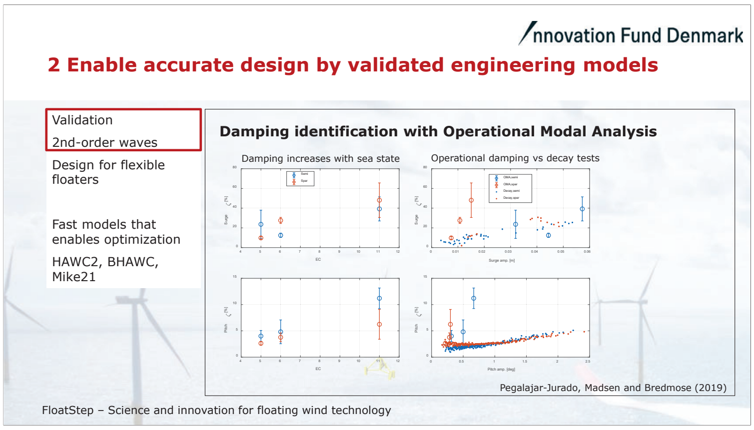
SIEMENS Gamesa

Implementing Mooring Lines into BHawC

BHawC/Orcaflex Coupling

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

2 Enable accurate design by validated engineering models

- Validation
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Damping identification with Operational Modal Analysis

Damping increases with sea state

Operational damping vs decay tests

Pegalajar-Jurado, Madsen and Bredmose (2019)

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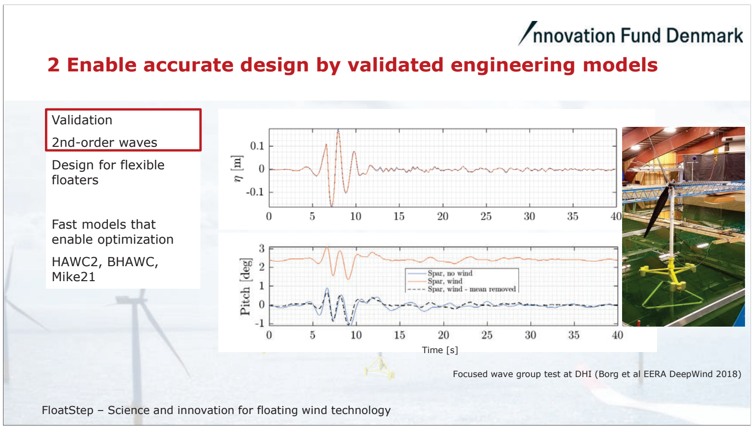

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2 Enable accurate design by validated engineering models

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Focused wave group test at DHI (Borg et al EERA DeepWind 2018)

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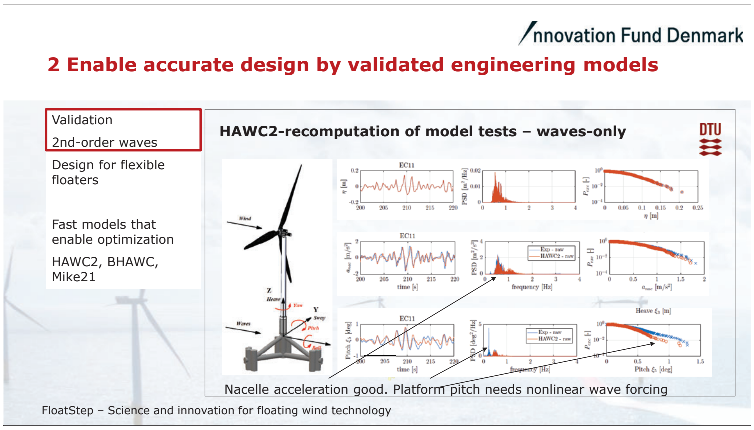


Innovation Fund Denmark

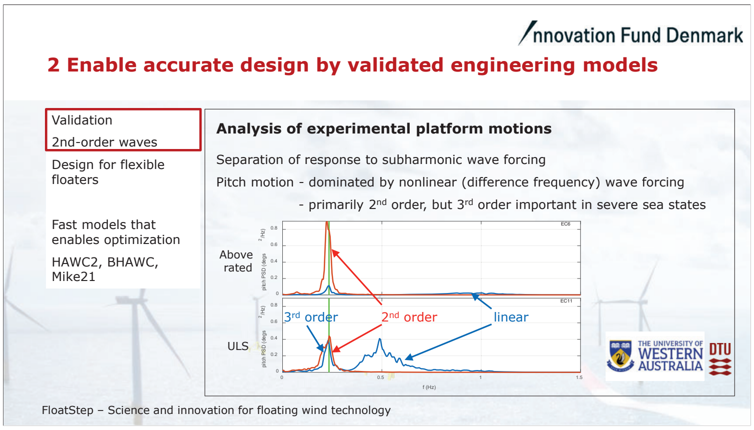
2 Enable accurate design by validated engineering models

- Validation
- 2nd-order waves
- Design for flexible floaters
- Fast models that enable optimization
- HAWC2, BHAWC, Mike21

HAWC2-recomputation of model tests – waves-only

Nacelle acceleration good. Platform pitch needs nonlinear wave forcing

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

2 Enable accurate design by validated engineering models

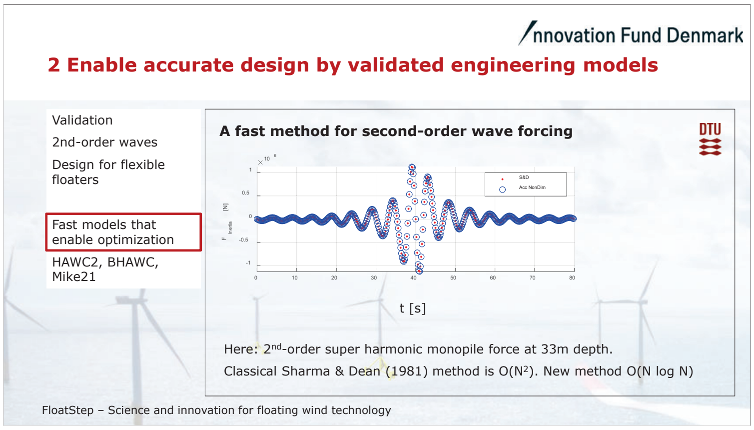
Validation
2nd-order waves
Design for flexible floaters
Fast models that enables optimization
HAWC2, BHAWC, Mike21

Analysis of experimental platform motions

Separation of response to subharmonic wave forcing

Pitch motion - dominated by nonlinear (difference frequency) wave forcing
- primarily 2nd order, but 3rd order important in severe sea states

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

2 Enable accurate design by validated engineering models

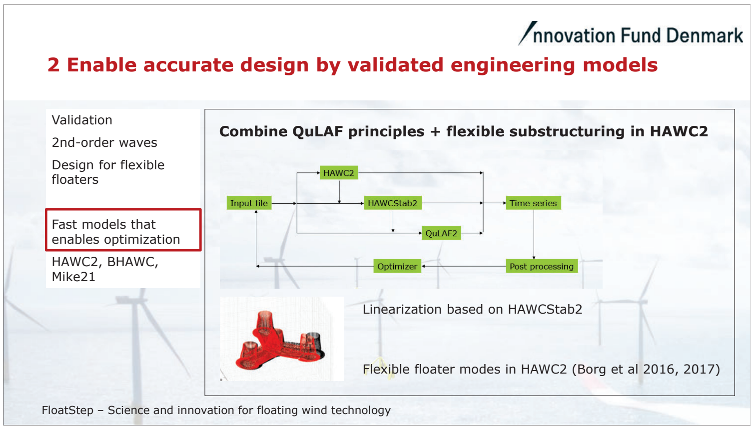
Validation
2nd-order waves
Design for flexible floaters
Fast models that enable optimization
HAWC2, BHAWC, Mike21

A fast method for second-order wave forcing

Here: 2nd-order super harmonic monopile force at 33m depth.

Classical Sharma & Dean (1981) method is $O(N^2)$. New method $O(N \log N)$

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

2 Enable accurate design by validated engineering models

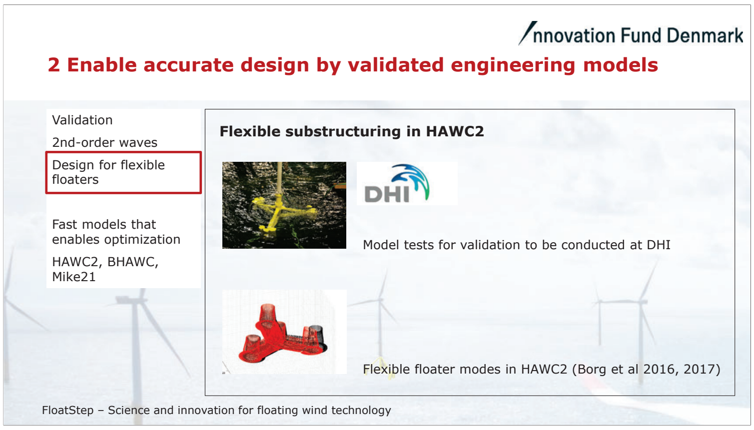
Validation
2nd-order waves
Design for flexible floaters
Fast models that enables optimization
HAWC2, BHAWC, Mike21

Combine QuLAF principles + flexible substructuring in HAWC2

Linearization based on HAWCStab2

Flexible floater modes in HAWC2 (Borg et al 2016, 2017)

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

2 Enable accurate design by validated engineering models

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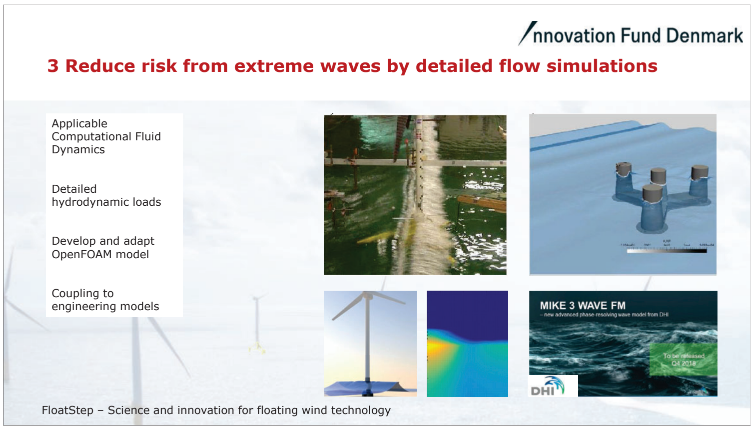
Flexible substructuring in HAWC2

Model tests for validation to be conducted at DHI

Flexible floater modes in HAWC2 (Borg et al 2016, 2017)

FloatStep – Science and innovation for floating wind technology

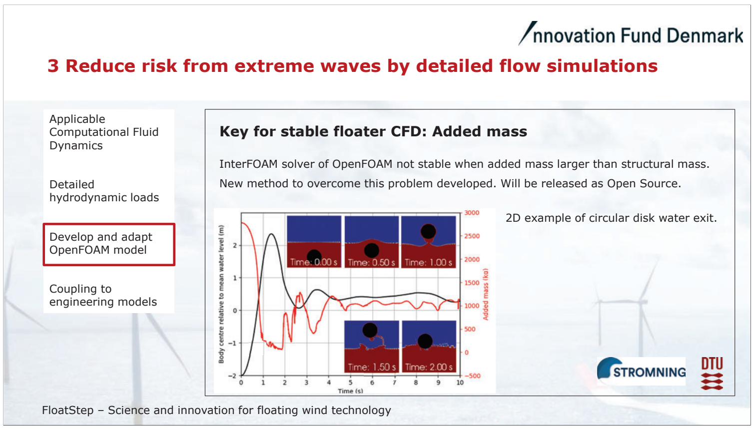


Innovation Fund Denmark

3 Reduce risk from extreme waves by detailed flow simulations

Applicable Computational Fluid Dynamics
Detailed hydrodynamic loads
Develop and adapt OpenFOAM model
Coupling to engineering models

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

3 Reduce risk from extreme waves by detailed flow simulations

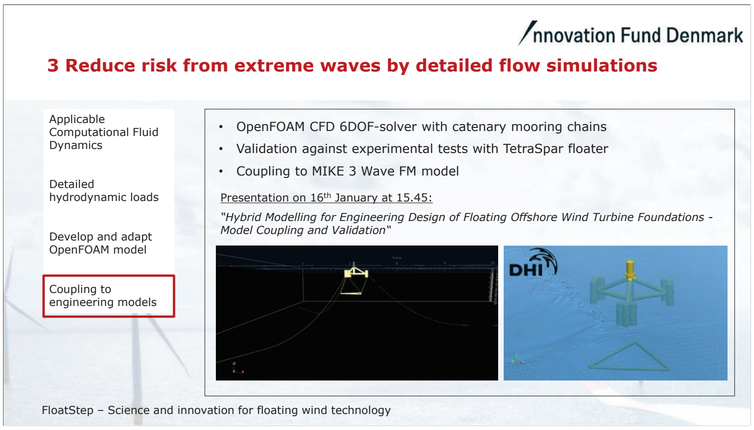
Applicable Computational Fluid Dynamics
Detailed hydrodynamic loads
Develop and adapt OpenFOAM model
Coupling to engineering models

Key for stable floater CFD: Added mass

InterFOAM solver of OpenFOAM not stable when added mass larger than structural mass.
New method to overcome this problem developed. Will be released as Open Source.

2D example of circular disk water exit.

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

3 Reduce risk from extreme waves by detailed flow simulations

Applicable Computational Fluid Dynamics

Detailed hydrodynamic loads

Develop and adapt OpenFOAM model

Coupling to engineering models

- OpenFOAM CFD 6DOF-solver with catenary mooring chains
- Validation against experimental tests with TetraSpar floater
- Coupling to MIKE 3 Wave FM model

Presentation on 16th January at 15.45:

"Hybrid Modelling for Engineering Design of Floating Offshore Wind Turbine Foundations - Model Coupling and Validation"

FloatStep – Science and innovation for floating wind technology

Innovation Fund Denmark

4 De-risk installation and operation by lab tests and full scale data

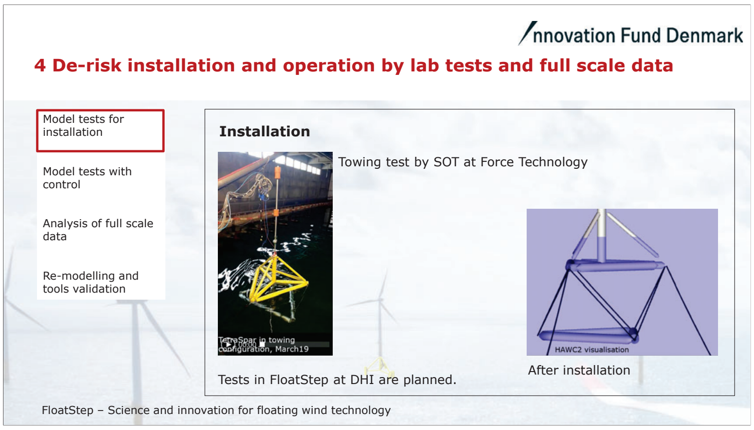
Model tests for installation

Model tests with control

Analysis of full scale data

Re-modelling and tools validation

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

4 De-risk installation and operation by lab tests and full scale data

Model tests for installation

Model tests with control

Analysis of full scale data

Re-modelling and tools validation

Installation

Towing test by SOT at Force Technology

After installation

Tests in FloatStep at DHI are planned.

FloatStep – Science and innovation for floating wind technology

Innovation Fund Denmark

4 De-risk installation and operation by lab tests and full scale data

Model tests for installation

Model tests with control

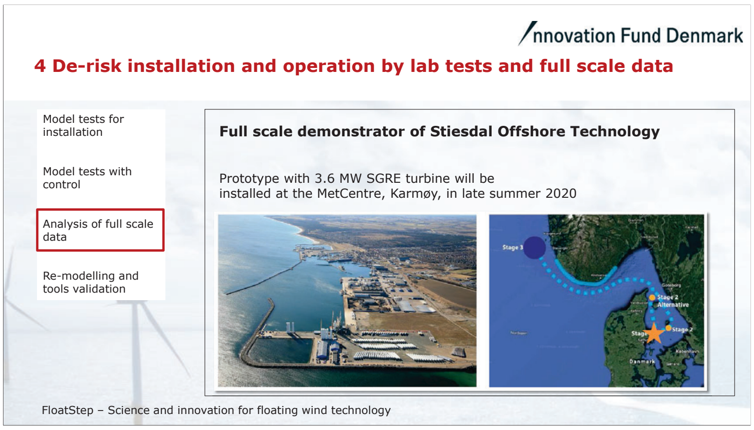
Analysis of full scale data

Re-modelling and tools validation

Active blade pitching

Tests of DTU and SOT at DHI 2017

FloatStep – Science and innovation for floating wind technology



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4 De-risk installation and operation by lab tests and full scale data

Model tests for installation

Model tests with control

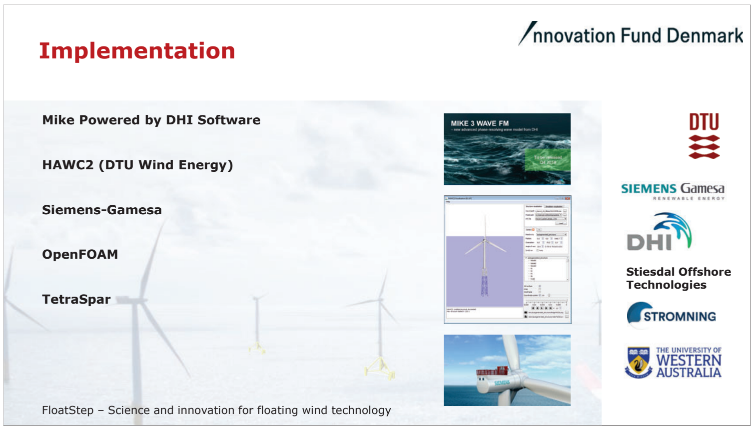
Analysis of full scale data

Re-modelling and tools validation

Full scale demonstrator of Stiesdal Offshore Technology

Prototype with 3.6 MW SGRE turbine will be installed at the MetCentre, Karmøy, in late summer 2020

FloatStep – Science and innovation for floating wind technology



Innovation Fund Denmark

Implementation

Mike Powered by DHI Software

HAWC2 (DTU Wind Energy)

Siemens-Gamesa

OpenFOAM

TetraSpar

DTU

SIEMENS Gamesa RENEWABLE ENERGY

DHI

Stiesdal Offshore Technologies

STROMNING

THE UNIVERSITY OF WESTERN AUSTRALIA

FloatStep – Science and innovation for floating wind technology

DTU

First publications of FloatStep

Pegalajar-Jurado, Madsen and Bredmose (2019) ‘Damping identification of the TetraSpar floater in two configurations with Operational Modal Analysis’. 2nd Int Offshore Wind Technical Conference, Malta, November 2019. ASME.

Madsen, Pegalajar-Jurado and Bredmose (2019) ‘Performance study of the QuLAF pre-design model for a 10MW floating wind turbine’, Wind Energy Science (2019). Available online.

Pegalajar-Jurado, Pisi, Fandino, Madsen and Bredmose (2019) ‘Study on aerodynamic damping for application in frequency-domain models for floating wind turbines’. Poster at WindEurope Offshore, Copenhagen, November 2019

Pirrung et al (2019) ‘Modal reduction in HAWCSTAB2 applied to floating wind turbines.’ Poster at WindEurope Offshore, Copenhagen, November 2019

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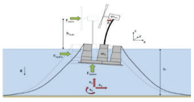
Papers are planned for Torque 2020, IWWWFB 2020, ICTAM 2020 and OMAE 2020

From pre-design to operation:
Outlook and first results of the FloatStep project



Henrik Bredmose[1], Mathias Stolpe[1], Antonio Pegalajar-Jurado[1], Kasper Laugesen[2], Bjarne Jensen[3], Michael Borg[4], Johan Rønby[5], Jana Orszaghova[6]

DTU 1
SIEMENS Gamesa RENEWABLE ENERGY 2
DHI 3
Stiesdal Offshore Technologies 4
STROMNING 5
THE UNIVERSITY OF WESTERN AUSTRALIA 6

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Mooring Line Dynamics of a Semi-submersible Wind Energy Platform: Cross Validation of Two Commercial Numerical Codes with Experimental Data

Presenter : Rachel Chester
Role : Researcher
Institution : University College Cork

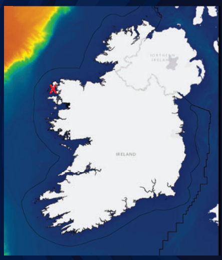
INTRODUCTION

Mooring Line Dynamics of a Semi-submersible Wind Energy Platform: Cross Validation of Two Commercial Numerical Codes with Experimental Data

Content

- **Methodology**
- **Numerical Software**
- **Experimental Data & Tank Testing**
- **Validation Results**
- **Conclusions and Future Work**

METHODOLOGY



Location of the Atlantic Marine Energy Test Site in Belmullet, Ireland

Environment

- Dataset taken from Atlantic Marine Energy Test Site (AMETS) in Belmullet, Ireland
- Testing regular and irregular wave loads
- With and without a constant wind load

METHODOLOGY

Example semi-submersible platform [Source: DNV-GL]

Technology

- INNWIND Semi-submersible floating platform
- 5 MW Reference Turbine
- 3 Leg Catenary Mooring System

METHODOLOGY

Example semi-submersible platform [Source: DNV-GL]

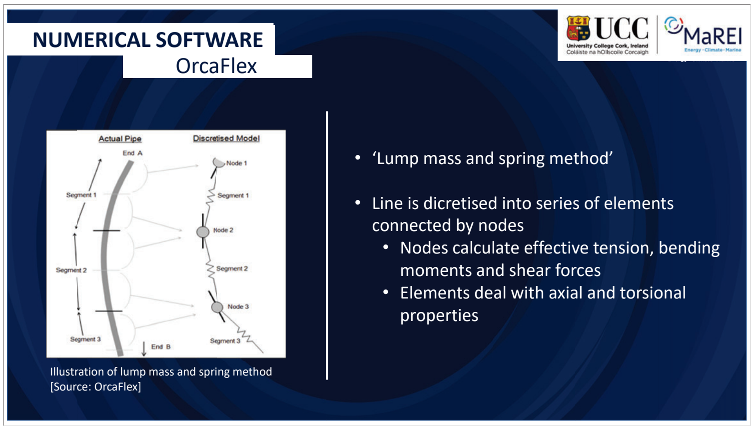
Focus Points

- Response Amplitude Operators (RAOs)
- Fairlead Loads
- Acceleration at Hub Height

NUMERICAL SOFTWARE

orcina Flexcom

ORCAFLEX & FLEXCOM

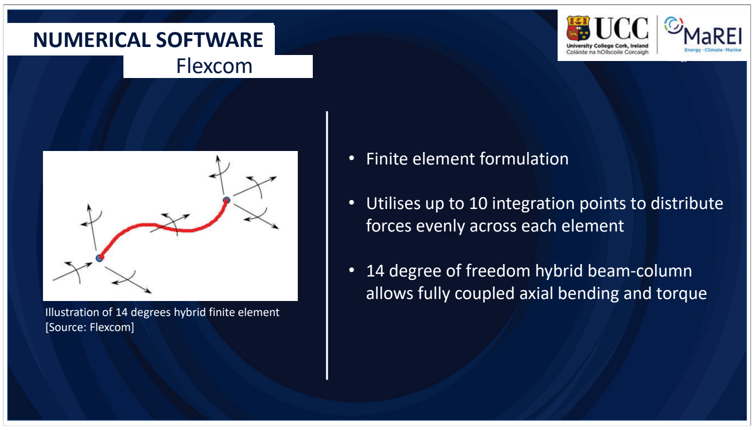


NUMERICAL SOFTWARE

OrcaFlex

Illustration of lump mass and spring method
[Source: OrcaFlex]

- ‘Lump mass and spring method’
- Line is dicretised into series of elements connected by nodes
  - Nodes calculate effective tension, bending moments and shear forces
  - Elements deal with axial and torsional properties

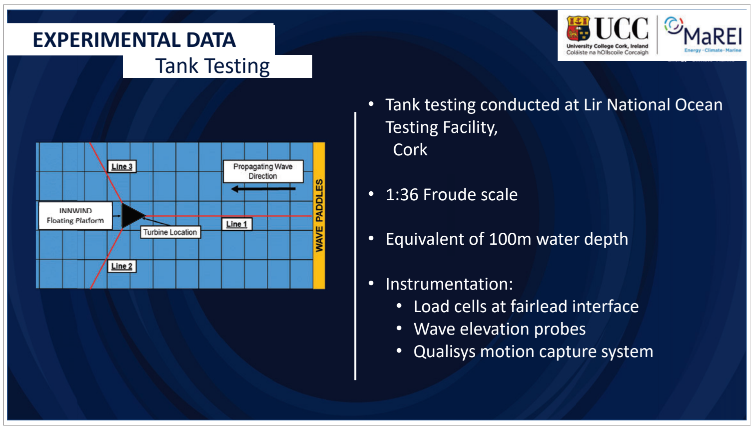


NUMERICAL SOFTWARE

Flexcom

Illustration of 14 degrees hybrid finite element
[Source: Flexcom]

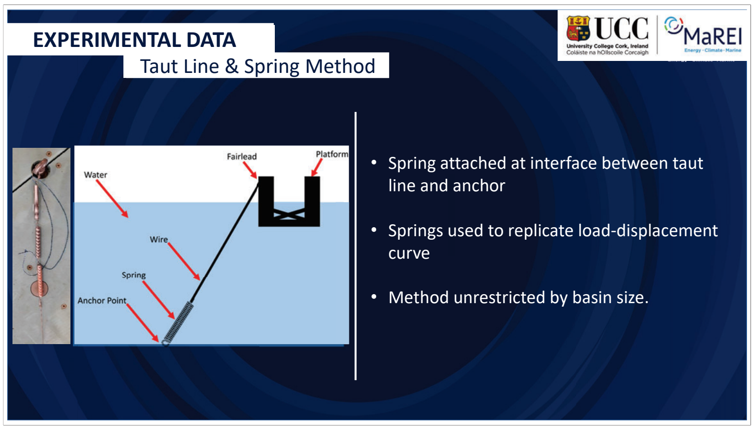
- Finite element formulation
- Utilises up to 10 integration points to distribute forces evenly across each element
- 14 degree of freedom hybrid beam-column allows fully coupled axial bending and torque



EXPERIMENTAL DATA

Tank Testing

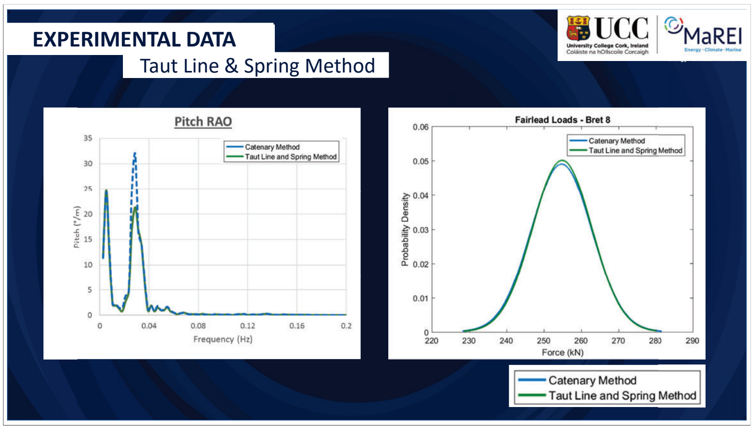
- Tank testing conducted at Lir National Ocean Testing Facility, Cork
- 1:36 Froude scale
- Equivalent of 100m water depth
- Instrumentation:
  - Load cells at fairlead interface
  - Wave elevation probes
  - Qualisys motion capture system



EXPERIMENTAL DATA

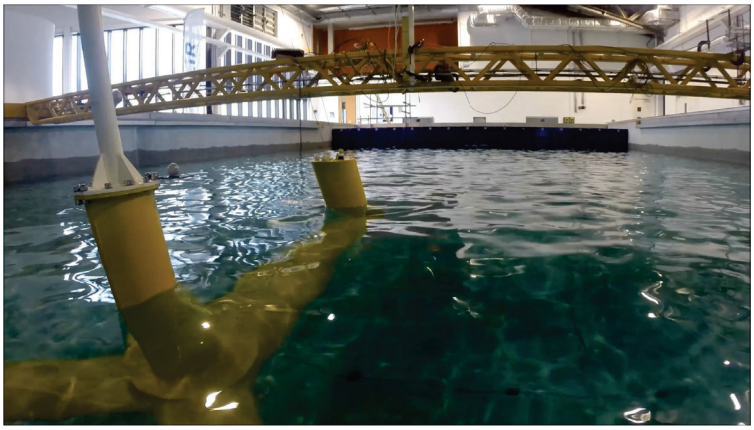
Taut Line & Spring Method

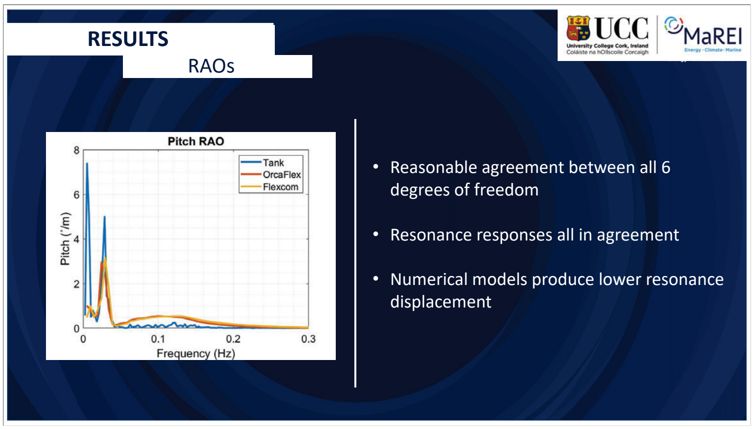
- Spring attached at interface between taut line and anchor
- Springs used to replicate load-displacement curve
- Method unrestricted by basin size.



EXPERIMENTAL DATA

Taut Line & Spring Method

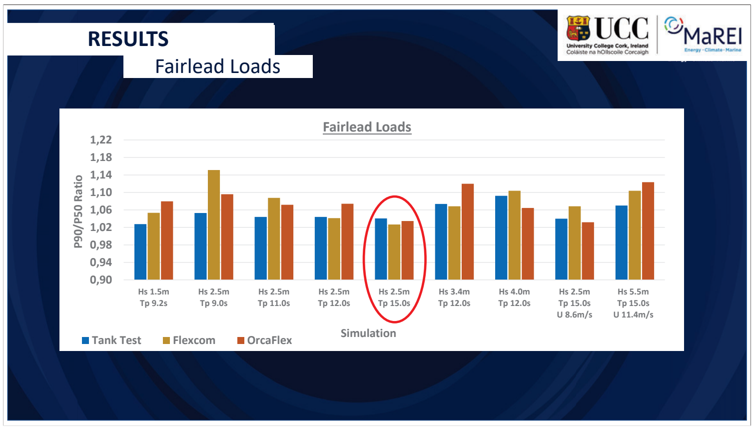




RESULTS

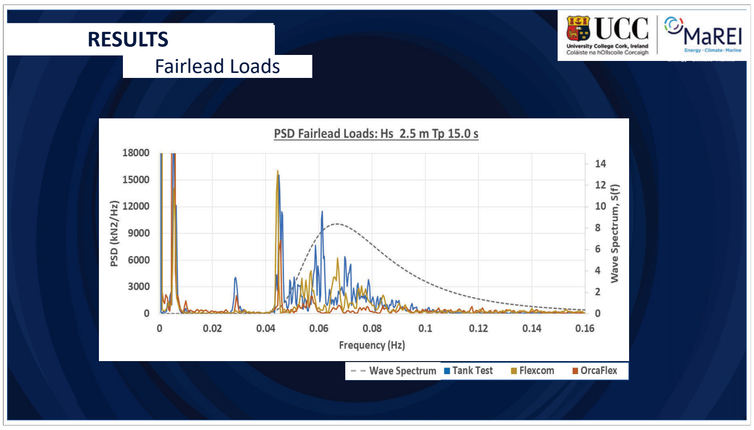
RAOs

- Reasonable agreement between all 6 degrees of freedom
- Resonance responses all in agreement
- Numerical models produce lower resonance displacement



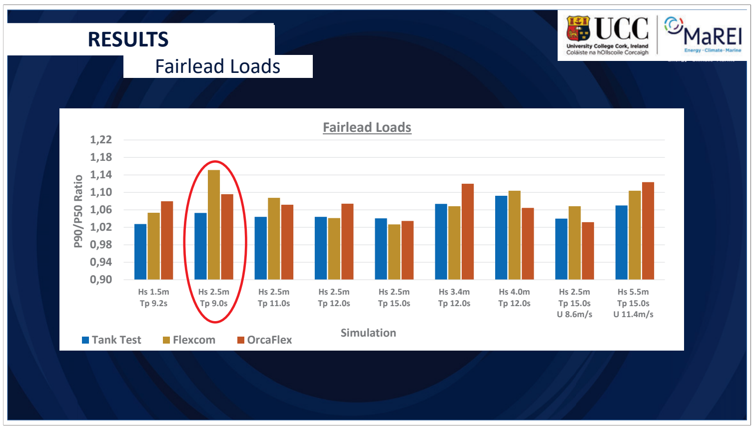
RESULTS

Fairlead Loads



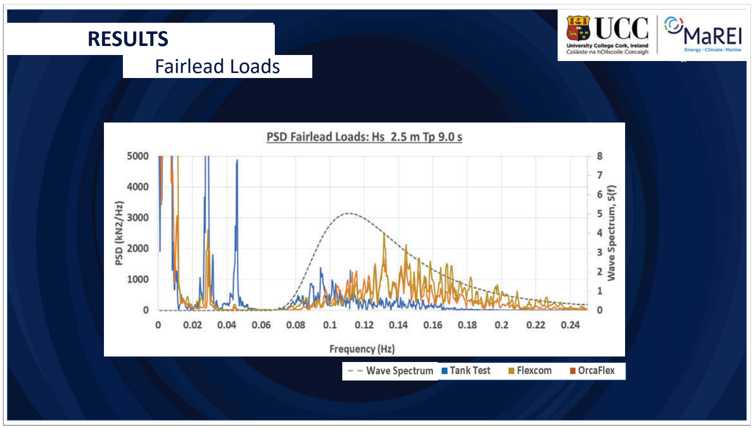
RESULTS

Fairlead Loads



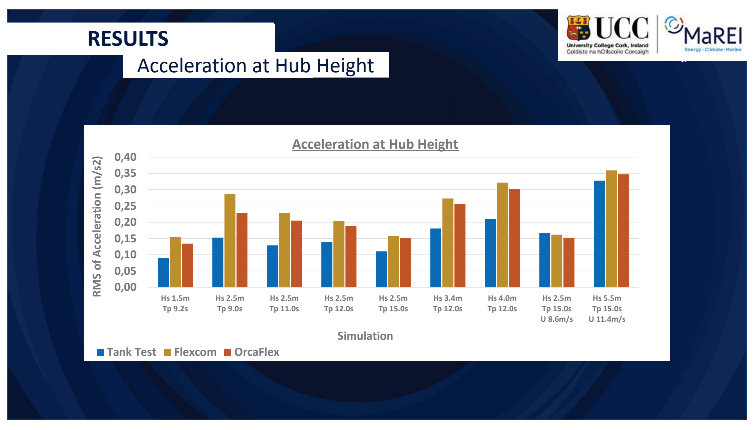
RESULTS

Fairlead Loads



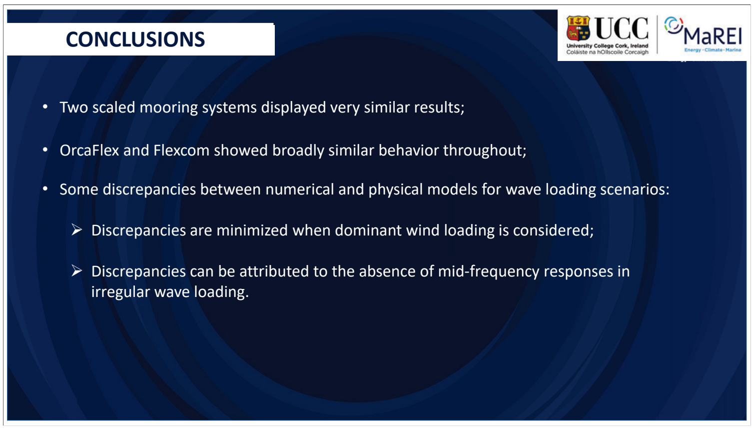
RESULTS

Fairlead Loads



RESULTS

Acceleration at Hub Height



CONCLUSIONS

- Two scaled mooring systems displayed very similar results;
- OrcaFlex and Flexcom showed broadly similar behavior throughout;
- Some discrepancies between numerical and physical models for wave loading scenarios:
  - Discrepancies are minimized when dominant wind loading is considered;
  - Discrepancies can be attributed to the absence of mid-frequency responses in irregular wave loading.

FUTURE WORK

Tank testing with SIL fan
[Source: INNWind]

Incorporation of variable wind loading:

- SIL fan in tank testing
- Incorporation of FAST
- Using wind turbine updates in numerical software

THANK YOU FOR LISTENING

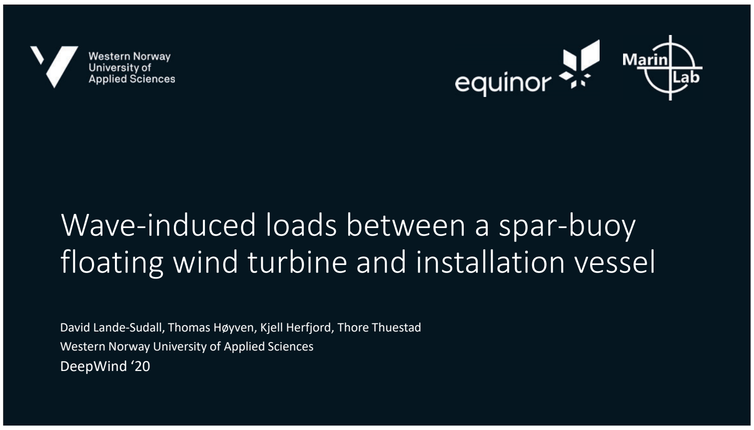
QUESTIONS?

E2) Installation and sub-structures

Wave-induced collision loads and moments between a spar-buoy floating wind turbine and an installation vessel, D.Lande-Sudall, Western Norway University of Applied Sciences

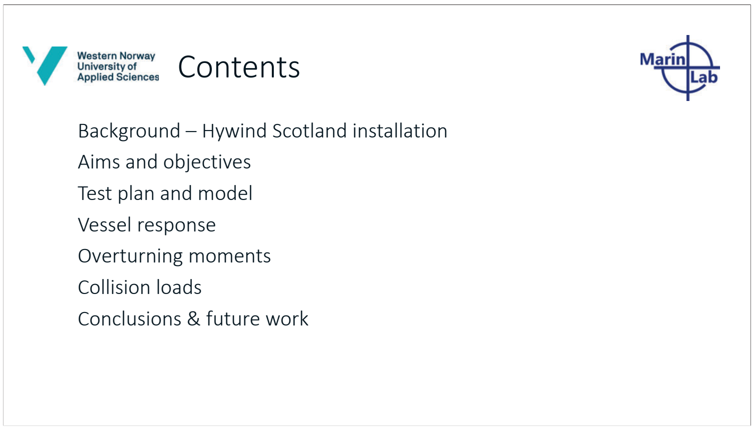
Implementation of Substructure Flexibility and Member-Level Load Capabilities for Floating Offshore Wind Turbines in OpenFAST, J.Jonkman, NREL

Levelized Cost of Energy and Life Cycle Assessment of IDL Tower, N.Saraswati, TNO –



Wave-induced loads between a spar-buoy floating wind turbine and installation vessel

David Lande-Sudall, Thomas Høyven, Kjell Herfjord, Thore Thuestad
Western Norway University of Applied Sciences
DeepWind '20



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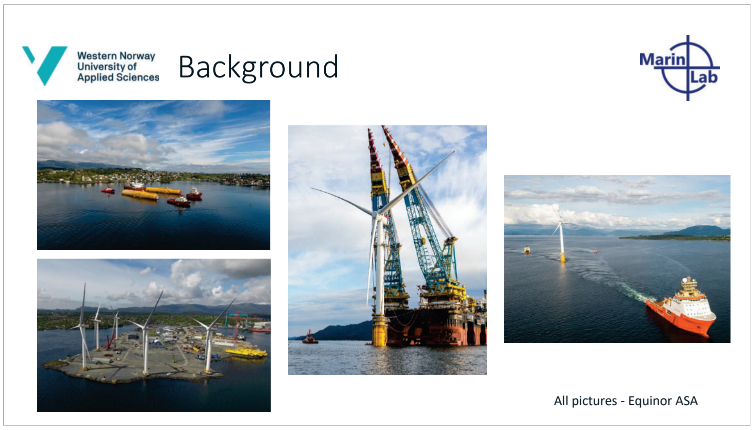
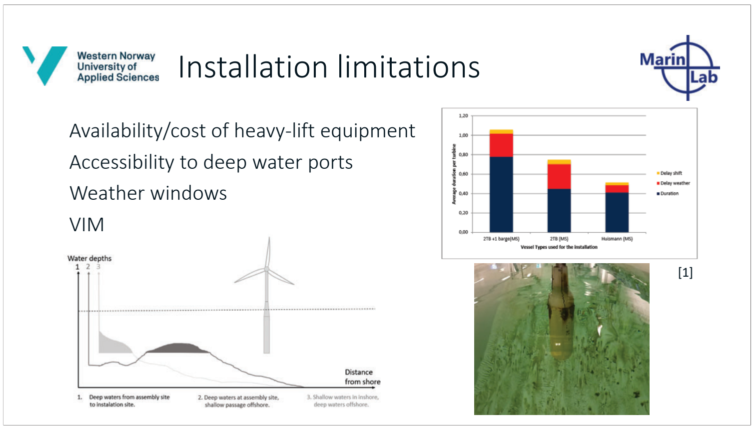


Background

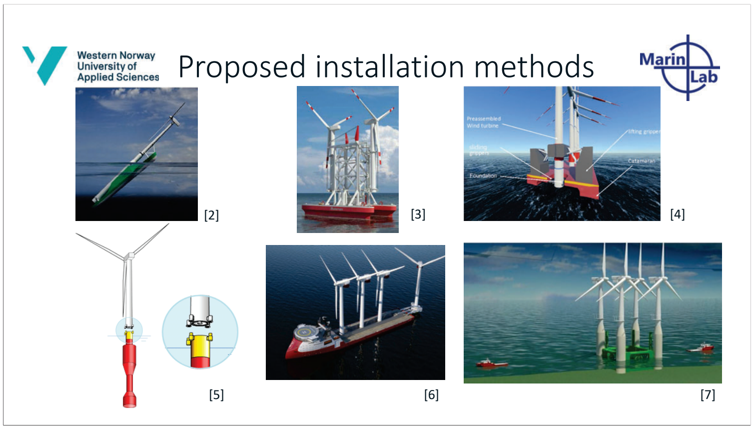
All pictures - Equinor ASA



Installation limitations

Availability/cost of heavy-lift equipment
Accessibility to deep water ports
Weather windows
VIM

[1]



Proposed installation methods

[2]
[3]
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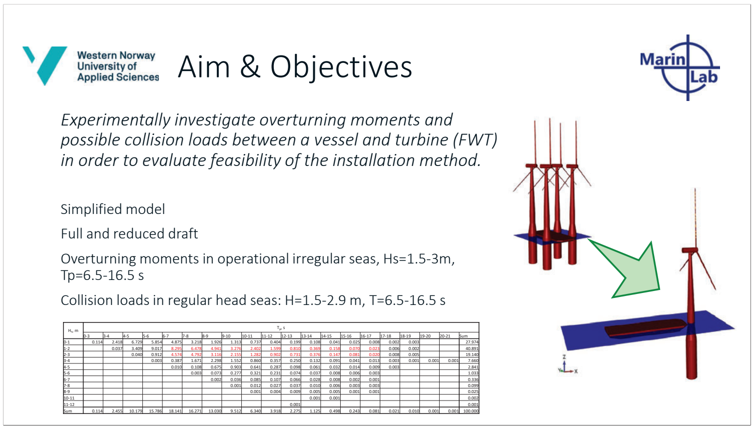

Aim & Objectives

Experimentally investigate overturning moments and possible collision loads between a vessel and turbine (FWT) in order to evaluate feasibility of the installation method.

Simplified model

Full and reduced draft

Overturning moments in operational irregular seas, Hs=1.5-3m, Tp=6.5-16.5 s

Collision loads in regular head seas: H=1.5-2.9 m, T=6.5-16.5 s

H_s, m	T_p, s																			
	0-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	Sum
0-1	0.114	2.418	6.729	5.854	4.875	3.218	1.926	1.313	0.737	0.404	0.199	0.108	0.041	0.025	0.008	0.002	0.003			27.974
1-2		0.037	3.409	9.017	8.295	6.478	4.941	3.276	2.402	1.599	0.810	0.369	0.158	0.070	0.023	0.006	0.002			40.891
2-3			0.040	0.912	4.574	4.792	3.116	2.155	1.282	0.902	0.731	0.376	0.147	0.081	0.020	0.008	0.005			19.140
3-4				0.003	0.387	1.671	2.298	1.552	0.860	0.357	0.250	0.132	0.091	0.041	0.013	0.003	0.001	0.001	0.001	7.660
4-5					0.010	0.108	0.675	0.903	0.641	0.287	0.098	0.061	0.032	0.014	0.009	0.003				2.841
5-6						0.003	0.073	0.277	0.321	0.231	0.074	0.037	0.008	0.006	0.003					1.033
6-7							0.002	0.036	0.085	0.107	0.066	0.028	0.008	0.002	0.001					0.336
7-8								0.001	0.012	0.027	0.037	0.010	0.006	0.003	0.003					0.099
8-9									0.001	0.004	0.009	0.005	0.005	0.001	0.001					0.025
10-11												0.001	0.001							0.002
11-12											0.001									0.001
Sum	0.114	2.455	10.179	15.786	18.141	16.271	13.030	9.512	6.340	3.918	2.275	1.125	0.498	0.243	0.081	0.021	0.010	0.001	0.001	100.000

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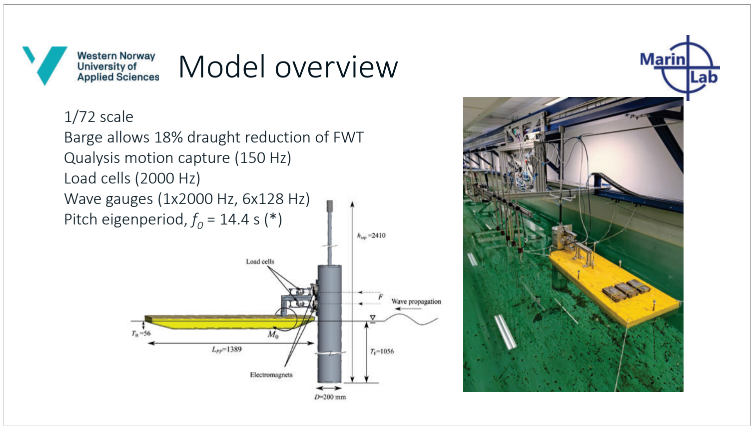
MarinLab towing tank

50m x 3m x 2.2m
EDesigns 6 flap-type wavemaker
H_{max}=0.5 m, T=0.5-3 s
Carriage – U=5m/s, $\dot{U}$=1.2m/s^2



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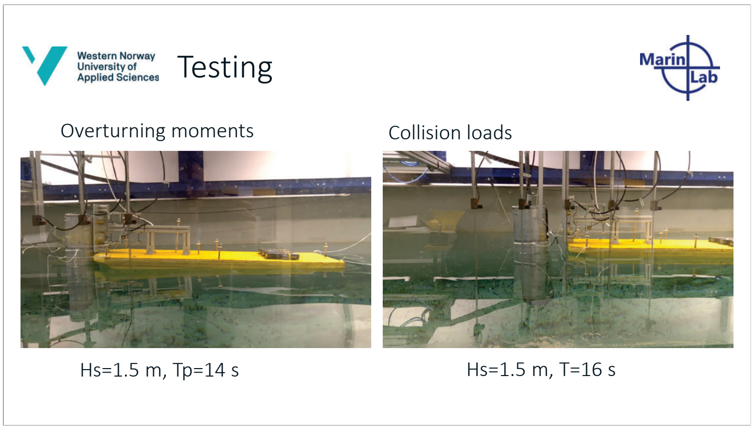
Model overview

1/72 scale
Barge allows 18% draught reduction of FWT
Qualysis motion capture (150 Hz)
Load cells (2000 Hz)
Wave gauges (1x2000 Hz, 6x128 Hz)
Pitch eigenperiod, f_0 = 14.4 s (*)



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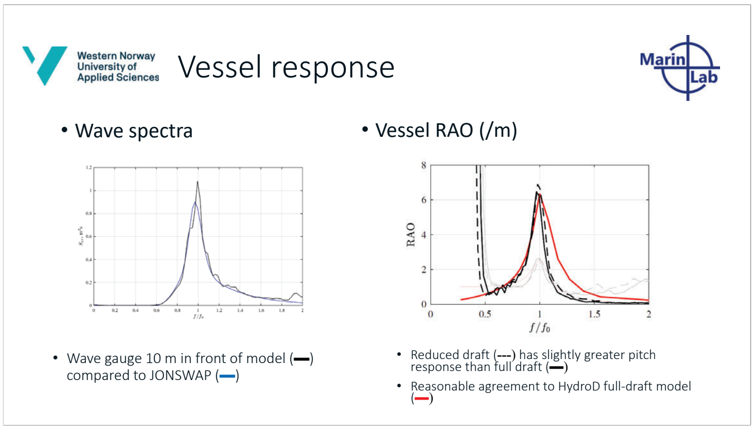
Testing

Overturning moments

Collision loads

Hs=1.5 m, Tp=14 s

Hs=1.5 m, T=16 s



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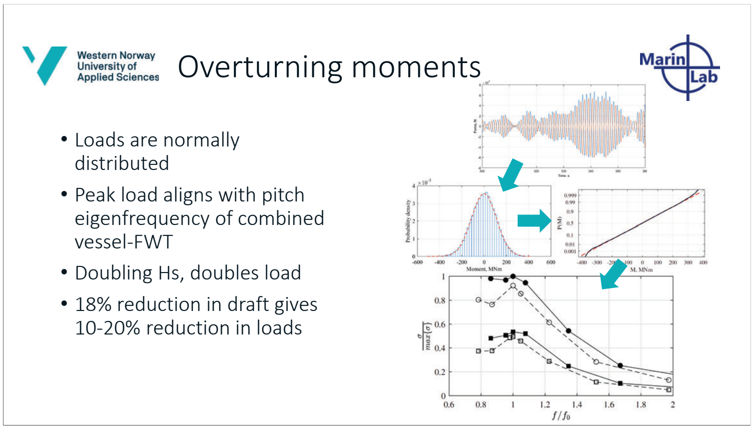
Vessel response

- Wave spectra
- Vessel RAO (/m)

- Wave gauge 10 m in front of model (▬) compared to JONSWAP (▬)

- Reduced draft (---) has slightly greater pitch response than full draft (▬)
- Reasonable agreement to HydroD full-draft model (▬)



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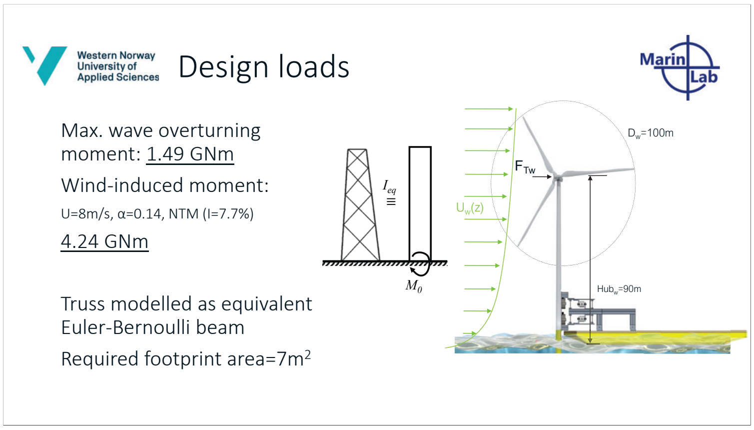
Overturning moments

- Loads are normally distributed
- Peak load aligns with pitch eigenfrequency of combined vessel-FWT
- Doubling Hs, doubles load
- 18% reduction in draft gives 10-20% reduction in loads



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Design loads

Max. wave overturning moment: 1.49 GNm

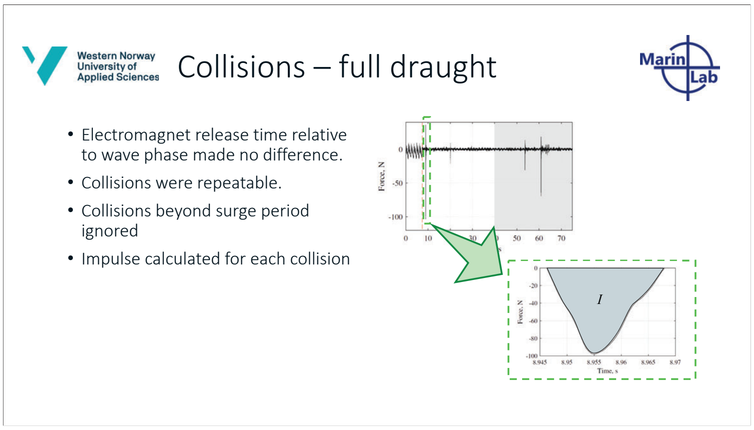
Wind-induced moment:

U=8m/s, α=0.14, NTM (I=7.7%)

4.24 GNm

Truss modelled as equivalent Euler-Bernoulli beam

Required footprint area=7m^2



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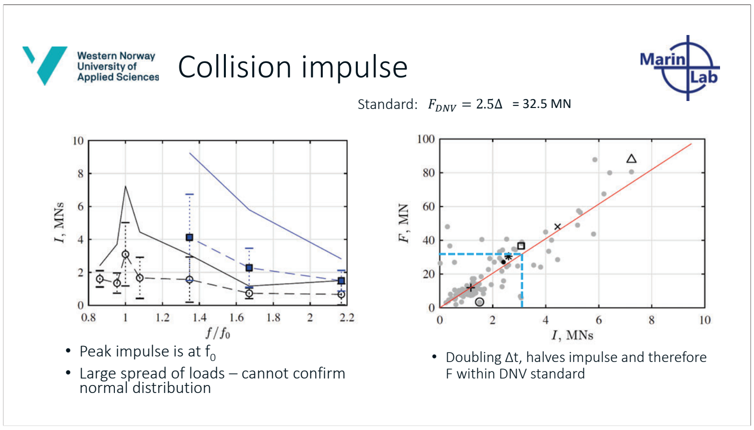
Collisions – full draught

- Electromagnet release time relative to wave phase made no difference.
- Collisions were repeatable.
- Collisions beyond surge period ignored
- Impulse calculated for each collision



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Collision impulse

Standard: $F_{DNV} = 2.5\Delta$ = 32.5 MN

- Peak impulse is at f_0
- Large spread of loads – cannot confirm normal distribution

- Doubling Δt, halves impulse and therefore F within DNV standard

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Conclusions & future work

- Loads from waves and wind can be accommodated
- Vessel with lower eigenfrequency improves operational range of Tp (Hs<2.9 m necessary).
- Use of spring-damper to reduce impulse

- Assess loads on nacelle
- Comparison to collision models
- Test new vessel in wider range of wave headings

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Thank you & questions?

Thank you to Equinor ASA for support in building the model

References:
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[2] Windflip. Tekniske Ukeblad article: https://www.tu.no/artikler/satser-karrieren-pa-windflip/240947
[3] Jiang, Z., et al. (2017) Dynamic response analysis of a catamaran installation vessel during the positioning of a wind turbine assembly onto a spar foundation. In: Marine Structures 61
[4] MODEC Inc. *D-Spar & Fork-on/Float-off installation methods*. Available: http://www.modec.com/fps/offshorewind/d-spar/index.html
[5] Ulstein Group ASA. *Windlifter*. Available: https://ulstein.com/equipment/ulstein-windlifter
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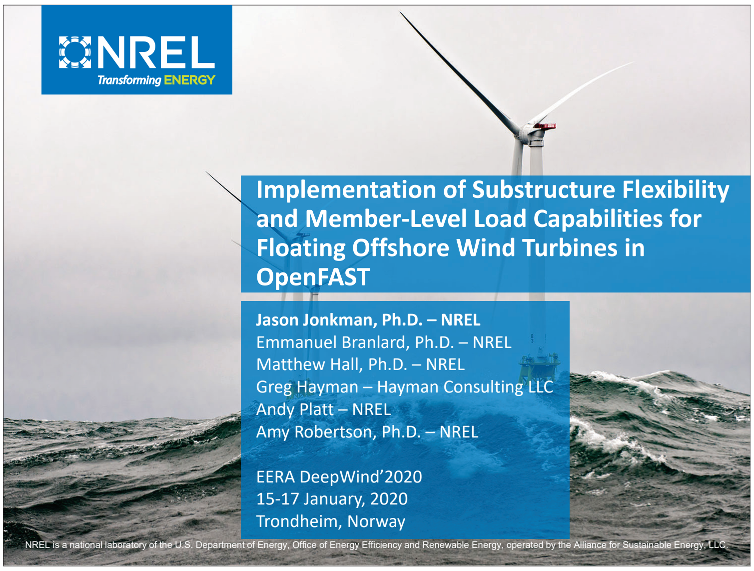

Implementation of Substructure Flexibility and Member-Level Load Capabilities for Floating Offshore Wind Turbines in OpenFAST

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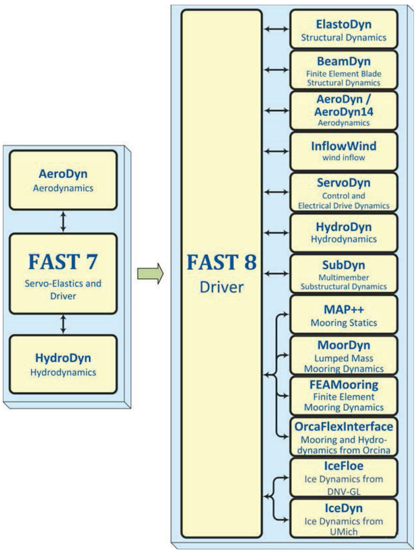
EERA DeepWind’2020
15-17 January, 2020
Trondheim, Norway

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

OpenFAST Overview

- **OpenFAST** is DOE / NREL’s premier open-source wind turbine physics-based engineering tool
- **FAST** has undergone a major restructuring, with a new modularization framework (v8)
- Not only is the framework supporting expanded functionality, but it is facilitating the establishment of an open-source code-development community for physics-based engineering models (**OpenFAST**)



Prior Offshore Functionality

HydroDyn module – Hydrodynamics for fixed & floating substructures:

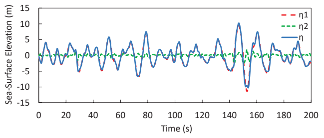
- Waves – 2^{nd} order regular / irregular & directional spreading
- Sea currents
- Hydrodynamic loads – Hybrid combination of strip theory (Morison’s eq.) & potential flow

SubDyn module – Fixed substructure structural dynamics:

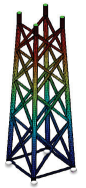
- Linear frame finite-element beam model
- Craig-Bampton dynamic system reduction
- Static-improvement method

MoorDyn & **MAP++** modules – Lumped mass mooring dynamics (MD) or analytical mooring quasi-statics (MAP):

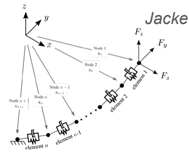
- Multi-segmented taut / catenary lines
- Clump weights & buoyancy tanks
- Elastic stretching & nonlinear geometric restoring
- Structural damping & hydro. drag (MD)
- Apparent weight of lines & added mass (MD)
- Seabed friction



Sea-Surface Elevation (η) from the Summing of 1^{st}- (η_1) & 2^{nd}- (η_2) Order Waves



Jacket Substructure



Lumped-Mass Mooring Dynamics

Objective & Approach

- *Objective*: Introduce substructure flexibility & member-level load calculations in **OpenFAST** to enable design & optimization of floating substructures—especially next-generation platforms that show promise to be streamlined, flexible, & cost-effective
- Prior work (IOWTC 2019):
  - Establish functional requirements
  - Identify modeling approaches that address functional requirements
  - Approach:
    - Meet modeling needs of most FOWT support structures (spar, semi, TLP)
    - Review existing FOWT prototypes & proposed concepts
    - Identify physics-based modeling needs
    - Only consider modeling approaches that maintain computational efficiency
- This work:
  - Mathematical details
  - Changes to **SubDyn**, **HydroDyn**, & **OpenFAST glue code**
- Future work:
  - Source-code implementation (nearing completion)
  - Verification & validation in collaboration w/ Stiesdal
  - Applications

SubDyn – New Element Types (In Addition to Beams)

- Pretensioned cable element:
  - Important for hanging ballast & stiffeners
- Rigid-link element:
  - Important for large-volume members & high natural frequencies
  - Direct elimination of linear multipoint constraints:
    - ODEs instead of DAEs
  - Eliminate 6 DOFs per element

$$\epsilon_0 = \frac{T_0}{EA}$$

$$K_e = \frac{EA}{L_0}\begin{bmatrix} \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 \\ 0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 \\ 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix} \quad f_e = EA\epsilon_0 \begin{Bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ -1 \end{Bmatrix}$$

Pretensioned Cable Element (Mass not Shown)

Full set
Reduced set

$$x = T\tilde{x}$$

Reduction of global mass, stiffness & force

$$\tilde{M} = T^T M T, \quad \tilde{K} = T^T K T, \quad \tilde{F} = T^T F$$

$$T_c = \begin{bmatrix} I_6 \\ A_{12} \\ \vdots \\ A_{1n} \end{bmatrix}, \quad \text{with } A_{1j} = \begin{bmatrix} 1 & 0 & 0 & 0 & (z_j - z_1) & -(y_j - y_1) \\ 0 & 1 & 0 & -(z_j - z_1) & 0 & (x_j - x_1) \\ 0 & 0 & 1 & (y_j - y_1) & -(x_j - x_1) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Rigid-Link Element

SubDyn – New Rotational Joints (In Addition to Cantilevered)

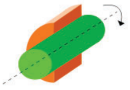
- Introduced 3 new joint types:
  - Important for some floaters (e.g., TetraSpar & SpiderFloat)
  - Direct elimination of linear multipoint constraints:
    - ODEs instead of DAEs
  - Pin – Adds 1 DOF per beam @ joint (minus 1)
  - Universal – Adds 2 DOF per beam @ joint (minus 1)
  - Ball – Adds 3 DOF per beam @ joint (minus 1)

Full set
Reduced set

$$x = T\tilde{x}$$

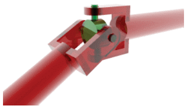
Reduction of global mass, stiffness & force

$$\tilde{M} = T^T M T, \quad \tilde{K} = T^T K T, \quad \tilde{F} = T^T F$$



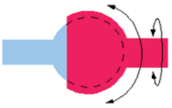
$$T_c = \begin{bmatrix} \hat{p}_1^T/n & \cdots & \hat{p}_1^T/n \\ \hat{p}_2^T/n & \cdots & \hat{p}_2^T/n \\ \hat{p}^t & & 0 \\ & \ddots & \\ 0 & & \hat{p}^t \end{bmatrix}^{-1*}$$

Pin Joint



$$T_c = \begin{bmatrix} \hat{z}_{e_1}^T/n & \cdots & \hat{z}_{e_n}^T/n \\ \hat{x}_{e_1}^T & & 0 \\ \hat{y}_{e_1}^T & & 0 \\ 0 & \ddots & 0 \\ 0 & & \hat{x}_{e_n}^T \\ 0 & \cdots & \hat{y}_{e_n}^T \end{bmatrix}^{-1^*}$$

Universal Joint

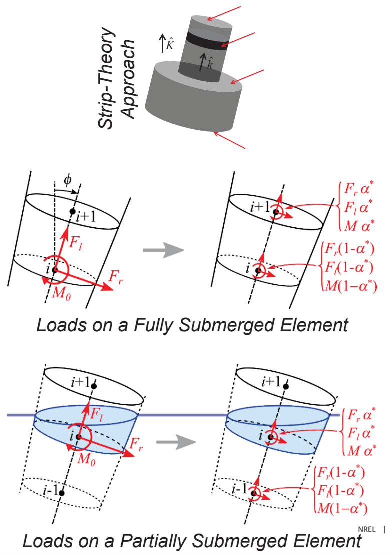


$$T_c = \begin{bmatrix} I_3 & & 0 \\ & \ddots & \\ 0 & & I_3 \end{bmatrix}$$

Ball Joint

HydroDyn – Updated Member-Level Hydrostatics in Strip-Theory

- Important for slender structures @ member level
- Updated strip-theory buoyancy calculation:
  - Exact for cylindrical or tapered members
  - Based on integrated hydrostatic pressure on submerged surface area
  - Dependent on displacement & deflection
  - Forces distributed to analysis nodes, including smoothing to ensure forces don't "step" when crossing SWL



Loads on a Fully Submerged Element

Loads on a Partially Submerged Element

HydroDyn – Support for Multiple Potential Flow Bodies

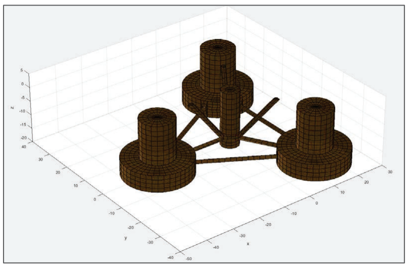
- Important for multiple large-volume bodies w/ radiation & diffraction
- Optional inclusion of hydrodynamic interaction:
  - "NBody" option in **WAMIT** or separate single bodies
- New "NBodyMod" switch:
  1) Full hydrodynamic interaction between bodies
  2) Separate bodies, each centered @ origin:
     - Offsets (phase shift) included in **HydroDyn**
  3) Separate bodies, each located @ correct offset in floater

$$\vec{F}^{Radiation}(t) = -\mathbf{A}^{\infty}\,\ddot{\vec{q}}(t) - \int_0^t \mathbf{K}(t-\tau)\,\dot{\vec{q}}(\tau)\,d\tau$$

$$\begin{bmatrix} \vec{F}_1^{Radiation}(t) \\ \vec{F}_2^{Radiation}(t) \\ \vdots \\ \vec{F}_N^{Radiation}(t) \end{bmatrix} = -\begin{bmatrix} \mathbf{A}_{11}^{\infty} & \mathbf{A}_{12}^{\infty} & \cdots & \mathbf{A}_{1N}^{\infty} \\ \mathbf{A}_{21}^{\infty} & \mathbf{A}_{22}^{\infty} & \cdots & \mathbf{A}_{2N}^{\infty} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_{N1}^{\infty} & \mathbf{A}_{N2}^{\infty} & \cdots & \mathbf{A}_{NN}^{\infty} \end{bmatrix} \begin{bmatrix} \ddot{\vec{q}}_1(t) \\ \ddot{\vec{q}}_2(t) \\ \vdots \\ \ddot{\vec{q}}_N(t) \end{bmatrix} - \int_0^t \begin{bmatrix} \mathbf{K}_{11}(t-\tau) & \mathbf{K}_{12}(t-\tau) & \cdots & \mathbf{K}_{1N}(t-\tau) \\ \mathbf{K}_{21}(t-\tau) & \mathbf{K}_{22}(t-\tau) & \cdots & \mathbf{K}_{2N}(t-\tau) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{K}_{N1}(t-\tau) & \mathbf{K}_{N2}(t-\tau) & \cdots & \mathbf{K}_{NN}(t-\tau) \end{bmatrix} \begin{bmatrix} \dot{\vec{q}}_1(\tau) \\ \dot{\vec{q}}_2(\tau) \\ \vdots \\ \dot{\vec{q}}_N(\tau) \end{bmatrix} d\tau$$

or

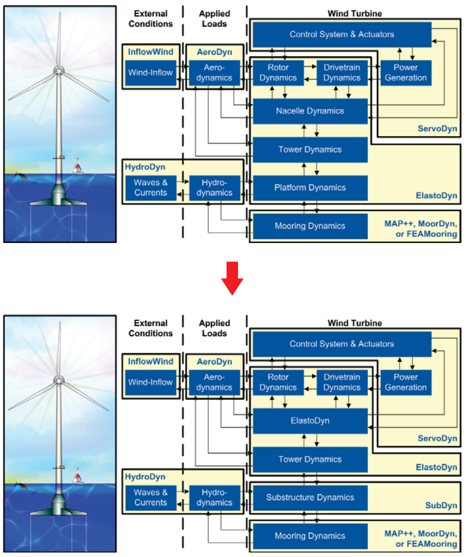
$$\begin{bmatrix} \vec{F}_1^{Radiation}(t) \\ \vec{F}_2^{Radiation}(t) \\ \vdots \\ \vec{F}_N^{Radiation}(t) \end{bmatrix} = -\begin{bmatrix} \mathbf{A}_{11}^{\infty} & 0 & \cdots & 0 \\ 0 & \mathbf{A}_{22}^{\infty} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{A}_{NN}^{\infty} \end{bmatrix} \begin{bmatrix} \ddot{\vec{q}}_1(t) \\ \ddot{\vec{q}}_2(t) \\ \vdots \\ \ddot{\vec{q}}_N(t) \end{bmatrix} - \int_0^t \begin{bmatrix} \mathbf{K}_{11}(t-\tau) & 0 & \cdots & 0 \\ 0 & \mathbf{K}_{22}(t-\tau) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{K}_{NN}(t-\tau) \end{bmatrix} \begin{bmatrix} \dot{\vec{q}}_1(\tau) \\ \dot{\vec{q}}_2(\tau) \\ \vdots \\ \dot{\vec{q}}_N(\tau) \end{bmatrix} d\tau$$



WAMIT Mesh of OC4-DeepCWind Semisubmersible

OpenFAST Glue Code – Updated Module-to-Module Coupling

- Allow **SubDyn** to be enabled for floating (in addition to fixed)
- Couple tower-substructure-hydrodynamic-mooring dynamics (**ElastoDyn** – **SubDyn** – **HydroDyn** – Mooring)



OpenFAST Glue Code – Updated Full-System Linearization

- **OpenFAST** primary used for nonlinear time-domain loads analysis (ultimate & fatigue)
- Linearization is about *understanding*:
  - Useful for eigenanalysis, controls design, stability analysis, gradients for optimization, & development of reduced-order models
- Prior focus:
  - Structuring source code to enable linearization
  - Developing general approach to linearizing mesh-mapping w/n module-to-module input-output coupling relationships, including rotations
  - Linearizing core (but not all) features of **InflowWind**, **ServoDyn**, **ElastoDyn**, **BeamDyn**, **AeroDyn**, **HydroDyn**, & **MAP++** modules & their coupling
  - Verifying implementation
- This work:
  - Expanding linearization of **HydroDyn** to strip-theory hydrostatics & state-space-based wave excitation & radiation for multiple bodies
  - Linearizing all features of **SubDyn**
  - Including linearized **ElastoDyn-SubDyn-HydroDyn-MAP++** coupling in the **OpenFAST glue code**

$$\dot{x} = X(x,z,u,t)$$
$$0 = Z(x,z,u,t) \quad with \left|\frac{\partial Z}{\partial z}\right| \neq 0$$
$$y = Y(x,z,u,t)$$

$$u = u\big|_{op} + \Delta u \quad etc.$$

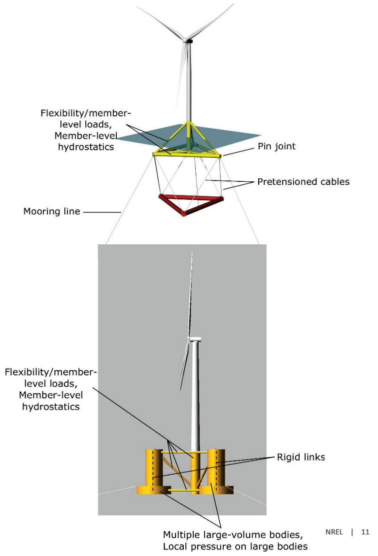
$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u$$

with

$$A = \left[\frac{\partial X}{\partial x} - \frac{\partial X}{\partial z}\left[\frac{\partial Z}{\partial z}\right]^{-1}\frac{\partial Z}{\partial x}\right]\Bigg|_{op} \quad etc.$$

Closing Summary

- Next generation FOWT likely to be more streamlined, flexible, & cost-effective
- Floating flexibility & member-level loads introduced into **OpenFAST**:
  - Substructure flexibility
  - Member-level loads
  - Pretensioned cables
  - Rigid links
  - Pin, universal, & ball joints
  - Distributed buoyancy on slender members
  - Multiple large-volume bodies
  - Time domain & linearization
- Coming soon: Verification, validation, & demonstration in collaboration w/ Stiesdal



Carpe Ventum!

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NREL
Transforming ENERGY

IDL TOWER: LCOE CALCULATION AND LCA

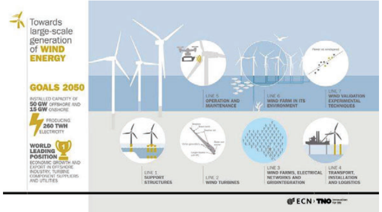
N. Saraswati

sponsored by TKI Wind Op Zee (2017-2019)
Innovation call

AGENDA

- Introduction & Motivation
- LCOE modelling and simulation
  - IDL tower case study: Comparing LCOE steel vs composite tower case
- Life cycle assessment
  - IDL tower case study: Comparing environment impact between steel vs composite tower case
- Conclusions and recommendations

TOWARDS LARGE-SCALE GENERATION OF WIND ENERGY



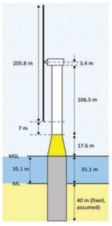
IDL TOWER BACKGROUND

- Continuation of C-Tower: >40% lighter tower concept based on GFRP
- The aim is to evaluate the technical, economic and environmental effects of a lighter, more flexible composite tower, with substantial lower eigen frequencies than a conventional steel tower.
- Alternative for steel tower
  - Energy intensive steel fabrication
  - Less weight in transportation
  - Less maintenance against corrosion and other environmental effects

IDL TOWER SCOPES & WORKS

- Integral Design Study
- Developing production methods
- Prototyping and laboratory testing
- LCoE including effects of installation and O&M
- LCA / end-of-life
- Valorisation, patenting and certification

IDL TOWER DESIGN



- Avatar 10 MW x 77 WT = 770 MW (Borssele area)
- For the integrated tower design, an offshore load set according to IEC 61400-3:2009 was used.
- The composite tower, steel transition piece and steel monopile were optimized using the FOCUS6 software and verified for ultimate, buckling and fatigue strength and eigenfrequency constraints
- Layup composite tower
  (GFRP polyester)

	Steel	IDL	Red
Material price (€/kg)	1.80	4.63	
Tower mass (mT)	790.3	320.5	-59.4%
MP Mass (mT)	1186.0	788.6	-33.5%
TP Mass (mT)	251.0	162.2	-35.4%

LCOE CALCULATION

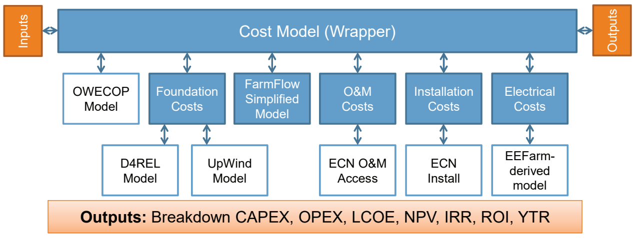
ECN COST MODEL

- The cost model is developed with the idea to provide an economic evaluation of an offshore wind farm:
- Currently is tuned for “traditional” OWF, but flexible enough to be expanded with new technologies/knowledge
  - Wind turbine with a single (3 bladed) rotor
  - Monopile support structure
  - Rectangular or square shape farm
  - Installation and O&M with SOVs and/or CTVs that are used in today’s market
  - Typical electrical infrastructure

$$LCoE = \frac{\left(\frac{CapEx}{a} + OpEx\right)}{AEP}$$

- Next development are: floating support structure, multi-rotor/airborne technology, etc.

ECN COST MODEL



Inputs

Cost Model (Wrapper)

Outputs

OWECOP Model

Foundation Costs

FarmFlow Simplified Model

O&M Costs

Installation Costs

Electrical Costs

D4REL Model

UpWind Model

ECN O&M Access

ECN Install

EEFarm-derived model

Outputs: Breakdown CAPEX, OPEX, LCOE, NPV, IRR, ROI, YTR

STEEL VS. IDL TOWER CASES

Installation

- *Deck space: 3600m2*
- *Crane: 1000 mT*
- *Cargo 6000 mT*
- *Cases:*
  - Steel: 3 WTs or 3 foundations per trips
  - IDL: 4 WTs or 4 foundations per trips

A: 100%

- *Deck space: 4600m2*
- *Crane: 1500 mT*
- *Cargo 8000 mT*
- *Cases:*
  - IDL: 6 WTs or 6 foundations per trips

B: 160%

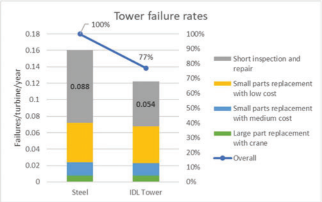
- *Deck space: 3200m2*
- *Crane: 600 mT*
- *Cargo 4000 mT*
- *Cases:*
  - IDL: 12 towers/trip
  - Add vessel type A to carry 5 nacelles, hubs and blades

C: 50%

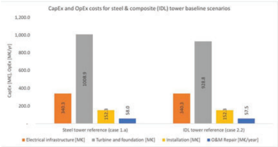
STEEL VS. IDL TOWER CASES

O&M

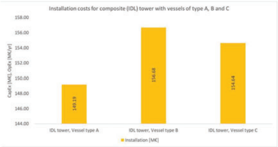
- Changes only in UMD – Turbine Structure / Tower failure rates
  - Reduction in short inspection and repair (bolts and welding)
- Same maintenance response as default
  - Short inspection and small repair
    - 4 hours
    - Using consumables
    - 3 technicians



RESULTS

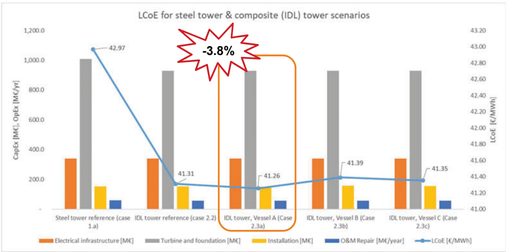


- Reductions
  - Tower & foundation costs: 80M€
  - O&M costs: ~0.5 M€/year



- Using vessel A (Carry 4 sets of WTs/trip and 4 sets of foundations/trip) is the cheapest
- Reduction of 3.1M€ or 2% of installation costs

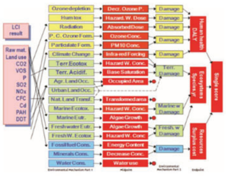
SUMMARY

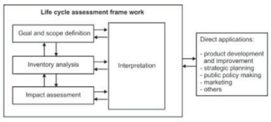


LIFE CYCLE ASSESSMENT

LIFE CYCLE ASSESSMENT

- LCA is a methodology used to evaluate the environmental impacts associated with a product or service throughout their life cycle, by
  - Compiling the environmental inputs and outputs
  - Evaluating their potential environment impacts
  - Considering their life cycle

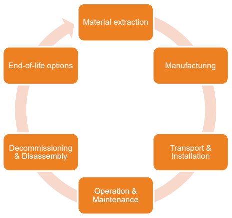




Direct applications:
- product development and improvement
- strategic planning
- public policy making
- marketing
- others

IDL VS STEEL CASE LCA

- Scope
  - Components:
    - Foundations: monopile + TP
    - Tower: steel vs composite
  - Process (see pictures)
- Functional unit: 1 piece of each component
- Methodology
  - ReCiPe 2016 Mid point / End point (E)
  - Energy cumulative demand
- Tool: SimaPro



MATERIAL & MANUFACTURING

- Foundations (monopile + TP)

Figure: © COWI A/S.

Steel case	IDL Case
• 99% steel (incl. rolling & welding) • 1% aluminium, alkyl resin, powder coating, copper, lead	
TP: 251 mT MP: 1186 mT	TP: 162.2 mT MP: 788.6 mT

  - 33.8% reduction in weight (foundations)
  - Add: heat, tap water, electricity mix based in NL

- Tower

Steel case	IDL Case
• 98.2% steel (incl. rolling, welding) • Rest: copper, steel coating, alkyl resin, etc.	• 62% glass fibres • 37% polyester resin • Organic chemical for curing agent and coating • Emission: 0.25%-w styrene
790.3 mT	320.5 mT

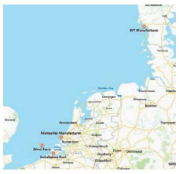
OTHER PHASES

Installation
- Perform by jack-up vessel “Transport, freight, sea, transoceanic ship”tonnes.km
- tonnes.km
  - Vessel usage
  - Fuel consumption
  - Maintenance
  - Port facilities
  - Emissions
  - Waste and waste treatments

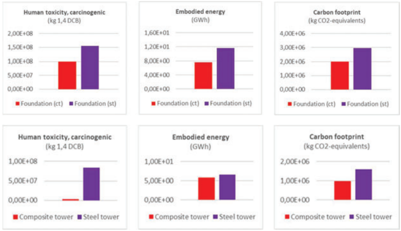
O&M
- No large replacement (foundations, towers)
- Almost no difference in vessel use
- Calculation is excluded

Decommissioning
- Perform by same type of vessels as installation
- Decommissioning = installation port distance

End of Life
- Steel, copper, and aluminium are recycled (80-90%) based on TNO’s model
- GFRP is incinerated
- Other is sorted, incinerated, or landfill



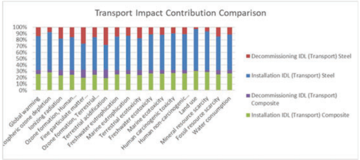
LCA RESULTS: MATERIAL COMPARISON



- Foundations: factors of the weight (reductions of 33.8%)
- Embodied energy difference is marginal (tower)
- Almost all impact categories, IDL tower < steel towers
  - Except 2/18 (stratospheric ozone depletion and land use)

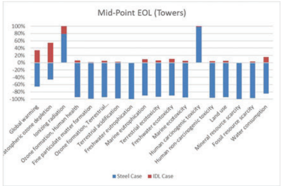
LCA RESULTS: TRANSPORT RELATED

- IDL tower case has less impact than the steel tower as it's less weight to carry (all proportional)
- Installation & Decommissioning contribution is very small compared to overall life cycle (<5%)

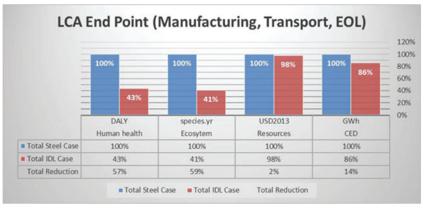


LCA RESULTS: END OF LIFE

- Steel is relatively easy to recycle → potential environment benefit or credit in the future
- For foundations, steel case gives higher benefit
- For towers
  - Steel tower gives high benefits as MP + TP
  - Composite tower is not recycled hence
    - Additional impacts at the end-of-life



OVERALL LCA COMPARISON



	DALY Human health	species.yr Ecosytem	USD2013 Resources	GWh CED
■ Total Steel Case	100%	100%	100%	100%
■ Total IDL Case	43%	41%	98%	86%
Total Reduction	57%	59%	2%	14%

CONCLUSION

CONCLUSIONS

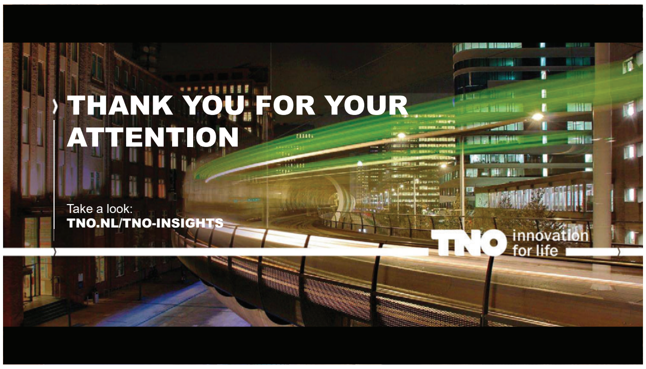
- IDL Tower: reductions of 59.4% and 33.8% mass reduction in tower and foundation
- Costs and environment impacts/benefits can be evaluated,
  - ECN Cost model is used to get insight in LCOE or costs breakdown
  - LCA is used to evaluate technology beyond their economic values
- IDL tower case led to ~3.9% LCOE reduction, mostly come from weight reduction but also installation
- IDL tower case led to lower environment impacts in total, even though at EoL composite tower shows higher impacts,
  - Steel is highly and easily recycled hence at the EoL there is potential environment credit
  - Potential benefit (not included) if composite is recycled

RECOMMENDATION & NEXT STEPS

- Further validation in the manufacturing, usage related to the O&M, and certification.
- Further roll out: real life demonstration to monitor the performance, degradation, load and vibration measurements

- Sensitivity (LCOE and LCA) when using IDL tower with current and future turbine sizes
- CAPEX of IDL tower will be influenced by economies of scale and production capacity

- Development of composite recycling within the wind industry
- When viable recycling processes are included, it is expected that the composite case will have potential environmental benefit as in steel tower case.



THANK YOU FOR YOUR ATTENTION

Take a look:
TNO.NL/TNO-INSIGHTS

F) Wind farm optimization

Effect of wind direction on wind park performance using Actuator Surface Modelling (ASM) with and without nacelle effects, B.Panjwani, SINTEF

Design Optimization of Spar Floating Wind Turbines Considering Different Control Strategies, J.M.Hegseth, NTNU

Far off-shore wind energy-based hydrogen production: Technological assessment and market valuation designs, M.Woznicki, CEA

Optimising the utilisation of subsea cables in GW scale offshore wind farm collector networks using energy storage, P.Taylor, University of Strathclyde

Effect of wind direction on wind park performance using Actuator Surface Modelling (ASM) approach

Balram Panjwani and Jon Samseth
SINTEF, Norway

EERA DeepWind 2020 conference
Trondheim January 15th-17th, 2020

Outline

- Introduction
- H2020 project: UPWARDS
- Theoretical background of Actuator surface model
- Model verification
  - Power curve
  - Wake deficits
  - Park
- Effect of wind direction on power
- Conclusions and future work

Introduction

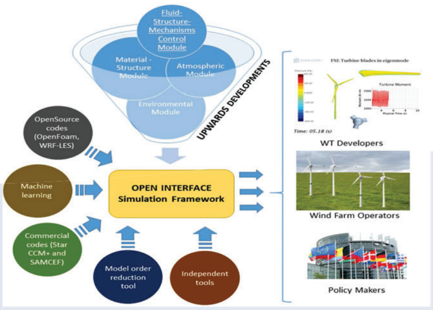
- A full CFD method (resolving wind turbines on the grid scales)
- Virtual turbine methods
  - Actuator Disk model (ADM)
  - Actuator Line model (ALM)
  - Actuator Surface Model (ASM)
- Actuator disk assume turbine as a porous disk and forces are estimated using thrust coefficient
- ALM method assume each blade as line and forces are estimated from lift and drag coefficient of the blades

---

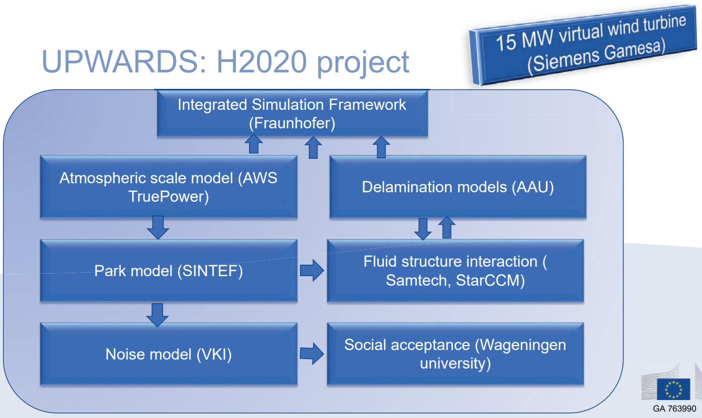
Challenges with ALM

- The actuator line model can incorporate rotational effects, tip loses, 3D stall effects, and the effect of non-uniform force distribution in the azimuthal direction.
- The ALM is unable to resolve the detailed geometrical features of turbine blades on a mesh.
- There are two major limitations with the standard ALM:
  1) The lack of an effective nacelle model
  2) A finer mesh (i.e. Large Eddy Simulation) cannot resolve more geometrical features of the turbine blade.
- Need of ASM

Brief description of UPWARDS project



UPWARDS: H2020 project


15 MW virtual wind turbine (Siemens Gamesa)

Integrated Simulation Framework (Fraunhofer)

Atmospheric scale model (AWS TruePower)

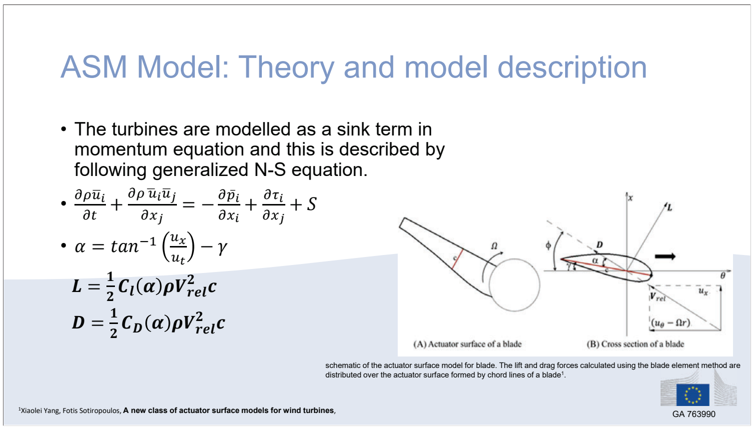
Delamination models (AAU)

Park model (SINTEF)

Fluid structure interaction (Samtech, StarCCM)

Noise model (VKI)

Social acceptance (Wageningen university)



ASM Model: Theory and model description

- The turbines are modelled as a sink term in momentum equation and this is described by following generalized N-S equation.
- $\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho\, \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}_i}{\partial x_i} + \frac{\partial \tau_i}{\partial x_j} + S$
- $\alpha = tan^{-1}\left(\frac{u_x}{u_t}\right) - \gamma$

$$\boldsymbol{L = \frac{1}{2} C_l(\alpha) \rho V_{rel}^2 c}$$

$$\boldsymbol{D = \frac{1}{2} C_D(\alpha) \rho V_{rel}^2 c}$$

schematic of the actuator surface model for blade. The lift and drag forces calculated using the blade element method are distributed over the actuator surface formed by chord lines of a blade[1].

[1]Xiaolei Yang, Fotis Sotiropoulos, **A new class of actuator surface models for wind turbines**,

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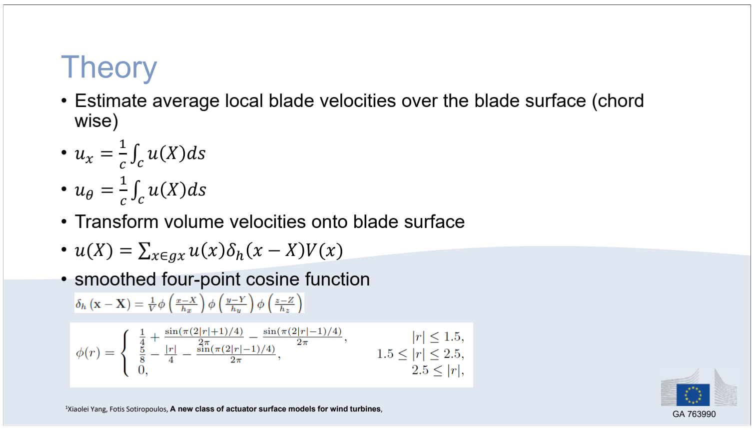

Theory

- Estimate average local blade velocities over the blade surface (chord wise)
- $u_x = \frac{1}{c}\int_c u(X)ds$
- $u_\theta = \frac{1}{c}\int_c u(X)ds$
- Transform volume velocities onto blade surface
- $u(X) = \sum_{x \in gx} u(x)\delta_h(x - X)V(x)$
- smoothed four-point cosine function

$$\delta_h(\mathbf{x} - \mathbf{X}) = \frac{1}{V}\phi\left(\frac{x-X}{h_x}\right)\phi\left(\frac{y-Y}{h_y}\right)\phi\left(\frac{z-Z}{h_z}\right)$$

$$\phi(r) = \begin{cases} \frac{1}{4} + \frac{\sin(\pi(2|r|+1)/4)}{2\pi} - \frac{\sin(\pi(2|r|-1)/4)}{2\pi}, & |r| \le 1.5, \\ \frac{5}{8} - \frac{|r|}{4} - \frac{\sin(\pi(2|r|-1)/4)}{2\pi}, & 1.5 \le |r| \le 2.5, \\ 0, & 2.5 \le |r|, \end{cases}$$

[1]Xiaolei Yang, Fotis Sotiropoulos, **A new class of actuator surface models for wind turbines**,

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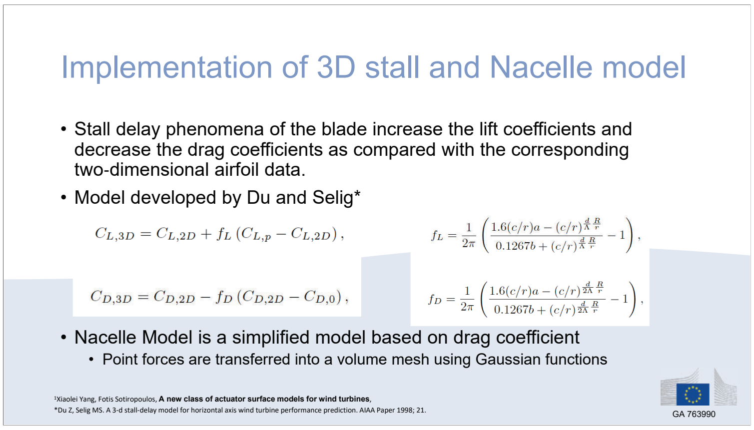

Implementation of 3D stall and Nacelle model

- Stall delay phenomena of the blade increase the lift coefficients and decrease the drag coefficients as compared with the corresponding two-dimensional airfoil data.
- Model developed by Du and Selig*

$$C_{L,3D} = C_{L,2D} + f_L\left(C_{L,p} - C_{L,2D}\right),$$

$$f_L = \frac{1}{2\pi}\left(\frac{1.6(c/r)a - (c/r)^{\frac{d}{\Lambda}\frac{R}{r}}}{0.1267b + (c/r)^{\frac{d}{\Lambda}\frac{R}{r}}} - 1\right),$$

$$C_{D,3D} = C_{D,2D} - f_D\left(C_{D,2D} - C_{D,0}\right),$$

$$f_D = \frac{1}{2\pi}\left(\frac{1.6(c/r)a - (c/r)^{\frac{d}{2\Lambda}\frac{R}{r}}}{0.1267b + (c/r)^{\frac{d}{2\Lambda}\frac{R}{r}}} - 1\right),$$

- Nacelle Model is a simplified model based on drag coefficient
  - Point forces are transferred into a volume mesh using Gaussian functions

[1]Xiaolei Yang, Fotis Sotiropoulos, **A new class of actuator surface models for wind turbines**,
*Du Z, Selig MS. A 3-d stall-delay model for horizontal axis wind turbine performance prediction. AIAA Paper 1998; 21.

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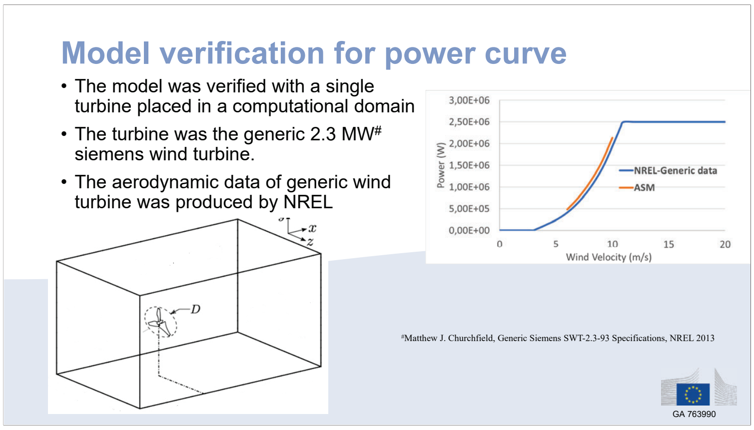

Model verification for power curve

- The model was verified with a single turbine placed in a computational domain
- The turbine was the generic 2.3 MW[#] siemens wind turbine.
- The aerodynamic data of generic wind turbine was produced by NREL

[#]Matthew J. Churchfield, Generic Siemens SWT-2.3-93 Specifications, NREL 2013

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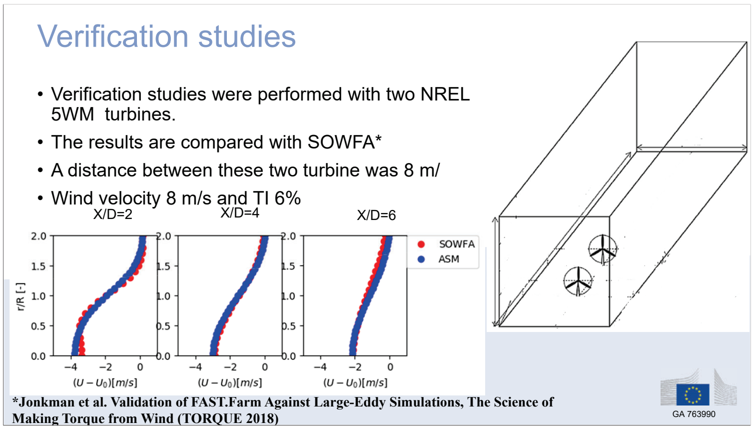

Verification studies

- Verification studies were performed with two NREL 5WM turbines.
- The results are compared with SOWFA*
- A distance between these two turbine was 8 m/
- Wind velocity 8 m/s and TI 6%

***Jonkman et al. Validation of FAST.Farm Against Large-Eddy Simulations, The Science of Making Torque from Wind (TORQUE 2018)**

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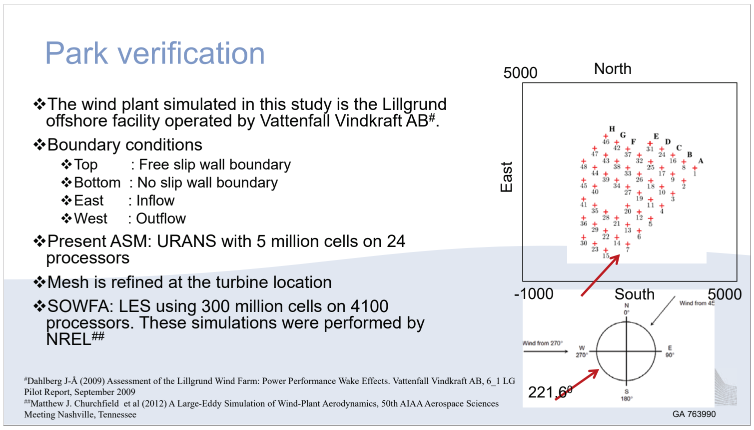

Park verification

- ❖The wind plant simulated in this study is the Lillgrund offshore facility operated by Vattenfall Vindkraft AB[#].
- ❖Boundary conditions
  - ❖Top : Free slip wall boundary
  - ❖Bottom : No slip wall boundary
  - ❖East : Inflow
  - ❖West : Outflow
- ❖Present ASM: URANS with 5 million cells on 24 processors
- ❖Mesh is refined at the turbine location
- ❖SOWFA: LES using 300 million cells on 4100 processors. These simulations were performed by NREL[##]

[#]Dahlberg J-Å (2009) Assessment of the Lillgrund Wind Farm: Power Performance Wake Effects. Vattenfall Vindkraft AB, 6_1 LG Pilot Report, September 2009
[##]Matthew J. Churchfield et al (2012) A Large-Eddy Simulation of Wind-Plant Aerodynamics, 50th AIAA Aerospace Sciences Meeting Nashville, Tennessee

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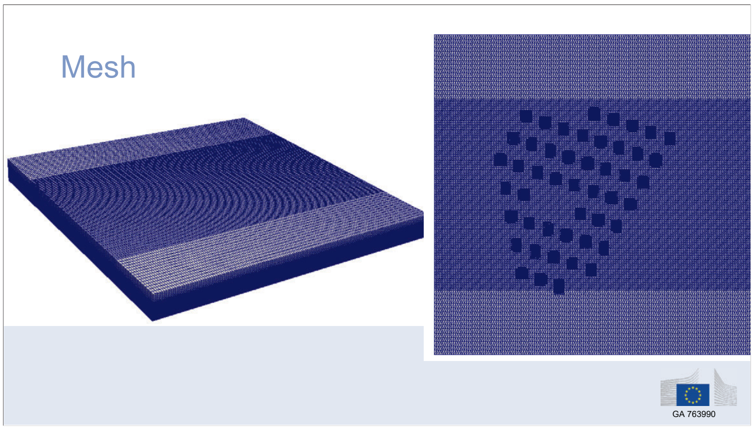
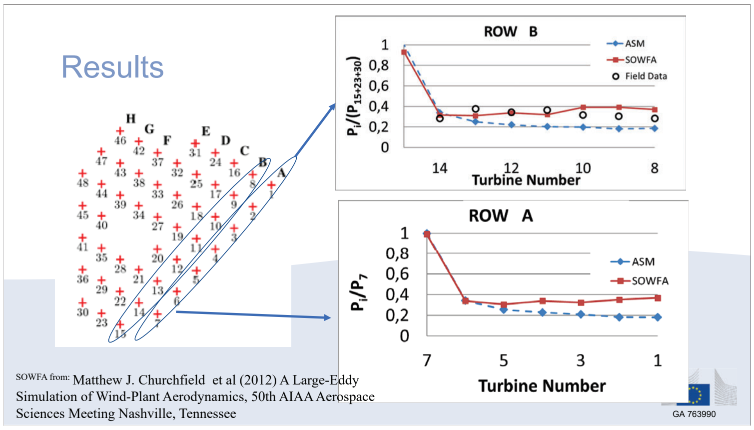
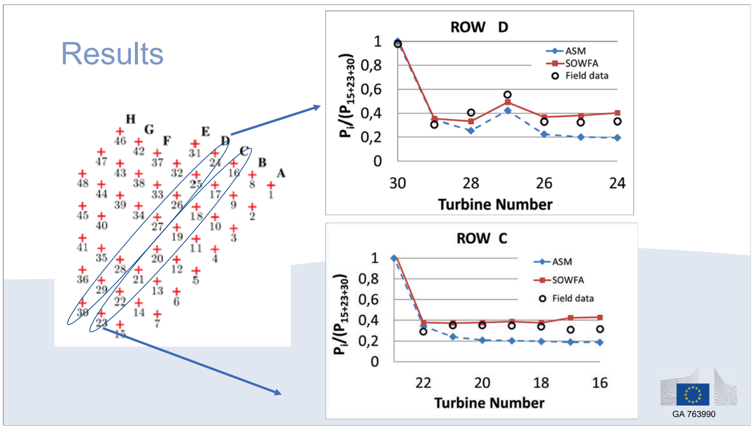


Mesh

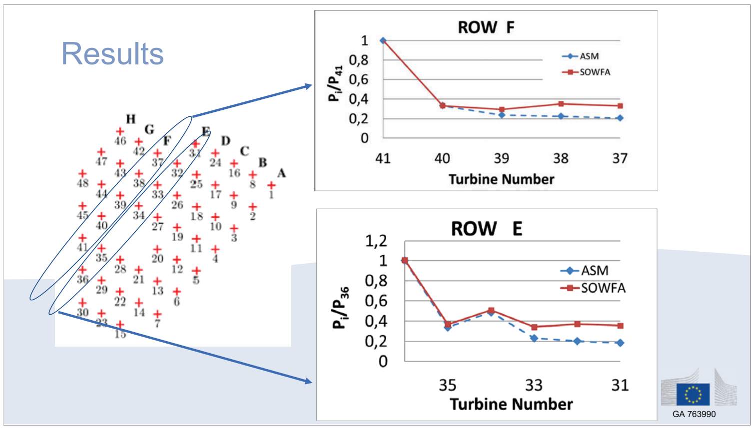


Results

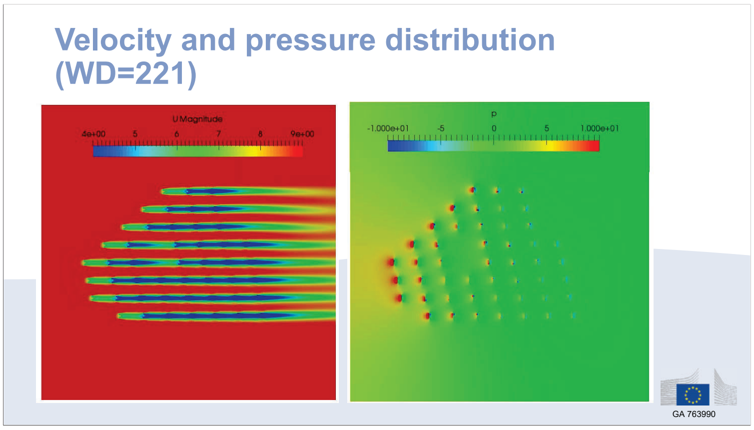
SOWFA from: Matthew J. Churchfield et al (2012) A Large-Eddy Simulation of Wind-Plant Aerodynamics, 50th AIAA Aerospace Sciences Meeting Nashville, Tennessee



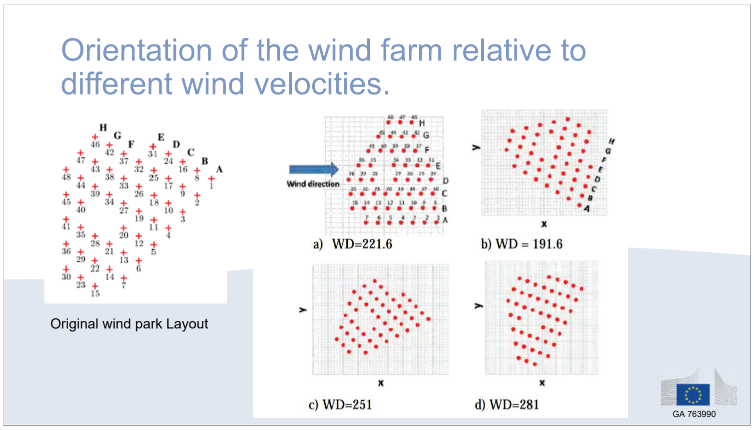
Results



Results



Velocity and pressure distribution (WD=221)



Orientation of the wind farm relative to different wind velocities.

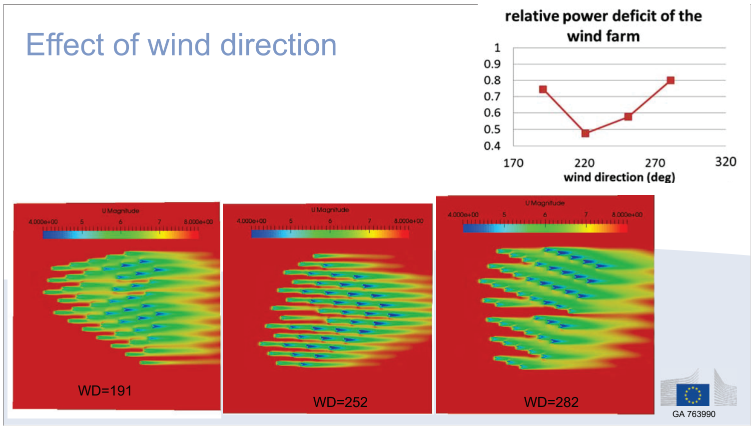
Original wind park Layout

a) WD=221.6

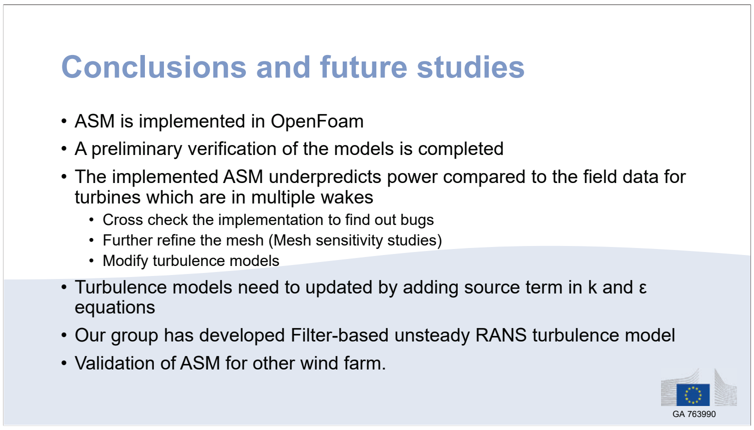
b) WD = 191.6

c) WD=251

d) WD=281



Effect of wind direction



Conclusions and future studies

- ASM is implemented in OpenFoam
- A preliminary verification of the models is completed
- The implemented ASM underpredicts power compared to the field data for turbines which are in multiple wakes
  - Cross check the implementation to find out bugs
  - Further refine the mesh (Mesh sensitivity studies)
  - Modify turbulence models
- Turbulence models need to updated by adding source term in k and ε equations
- Our group has developed Filter-based unsteady RANS turbulence model
- Validation of ASM for other wind farm.

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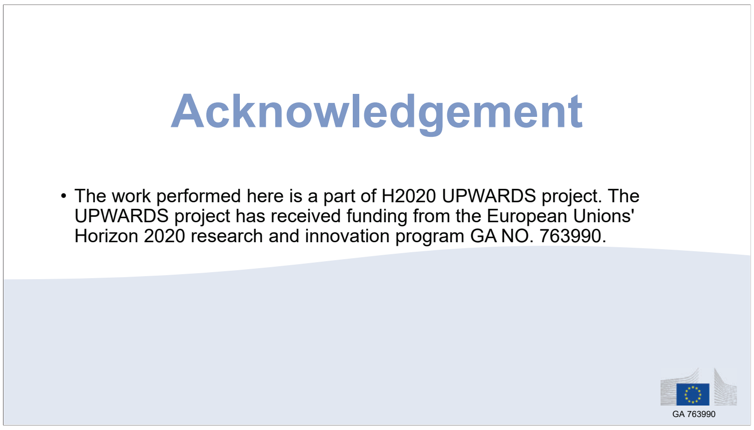

Acknowledgement

- The work performed here is a part of H2020 UPWARDS project. The UPWARDS project has received funding from the European Unions' Horizon 2020 research and innovation program GA NO. 763990.

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NTNU – Trondheim
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Design optimization of spar floating wind turbines considering different control strategies

John Marius Hegseth, Erin E. Bachynski
Department of Marine Technology, NTNU

Joaquim R. R. A. Martins
Department of Aerospace Engineering, University of Michigan

DeepWind 2020
Trondheim, 17 January 2020

Larsen and Hanson (2007)

Motivation

- Controller design is challenging for FWTs
- Several control strategies suggested
  - Trade-offs between structural loads, rotor speed tracking, and blade-pitch actuator use
  - Non-trivial to find optimal control parameters
- Interactions between controller and structure
  - Should be designed together for fair comparison between solutions
- **Simultaneous design optimization with realistic design limits**

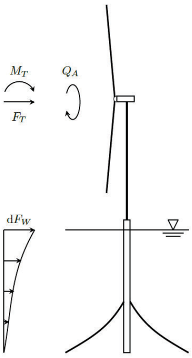
Linearized FWT model

- Linearized model
  - aero-hydro-servo-elastic
  - frequency-domain
  - stochastic wind/wave input

$$\mathbf{x} = \mathbf{x}_0 + \Delta\mathbf{x}, \quad \mathbf{u} = \mathbf{u}_0 + \Delta\mathbf{u}$$

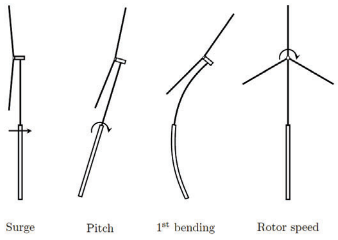
$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$

- External loads
  - wave excitation
  - thrust
  - tilting moment
  - torque
- Control inputs
  - generator torque
  - collective blade pitch angle



Linearized FWT model

- Four structural DOFs
- Rigid blades
- Internal forces from dynamic equilibrium
- Valid for spar platforms (circular cross section) with catenary mooring



$$\mathbf{x}_s = \begin{bmatrix} \xi_1 \\ \xi_5 \\ \xi_7 \\ \dot{\xi}_1 \\ \dot{\xi}_5 \\ \dot{\xi}_7 \\ \dot{\varphi} \end{bmatrix}$$

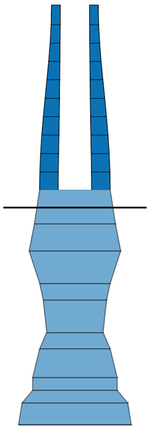
Blade-pitch control strategies

- CS1: PI
- CS2: PI + platform pitch velocity feedback
- CS3: PI + nacelle velocity feedback
- CS4: PI + nacelle velocity feedback + WF low-pass filter
- Modified rotor speed reference in CS2-4:

$$\dot{\varphi}_0' = \dot{\varphi}_0(1 + k_f \dot{x}_f)$$

Optimization problem

- Objective
  - Minimize cost of platform + tower
  - Material and manufacturing
- Design variables, structure
  - Tower/hull dimensions
  - Hull scantling design not considered



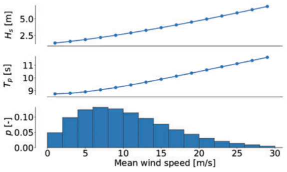
Optimization problem

- Objective
  - Minimize cost of platform + tower
  - Material and manufacturing
- Design variables, structure
  - Tower/hull dimensions
  - Hull scantling design not considered
- Design variables, control
  - PI gains (k_p and k_i)
  - Velocity feedback gain (k_f)
  - Low-pass filter corner frequency (ω_f)
- 47 design variables in total

Design variable	k_p	k_i	k_f	ω_f
CS1	✓	✓		
CS2	✓	✓	✓	
CS3	✓	✓	✓	
CS4	✓	✓	✓	✓

Environmental conditions

- Long-term fatigue
  - 15 ECs
  - 1-30 m/s with 2 m/s step
  - Most probable H_s and T_p



- Short-term extreme response
  - 3 ECs
  - 50-year contour

Condition	1	2	3
Mean wind speed [m/s]	13.0	21.0	50.0
Significant wave height [m]	8.1	9.9	15.1
Spectral peak period [s]	14.0	15.0	16.0

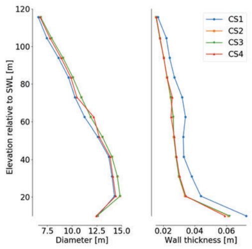
Optimization problem

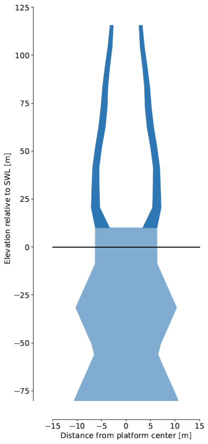
- Constraints, structure
  - Fatigue damage and buckling in tower
  - Maximum platform pitch angle, < 15°
  - Heave natural period, > 25 s
  - Most probable 1-h maximum value used as extreme response
- Constraints, control
  - Rotor speed variation (std.dev.), blade pitch actuator use (ADC)
  - Constraint values based on land-based DTU 10 MW
  - Weighted average of short-term values

$$\mathrm{ADC}_i = \frac{1}{T}\int_0^T \frac{|\dot{\theta}_i(t)|}{\dot{\theta}_{\max}}\mathrm{d}t, \qquad \mathrm{ADC} = \sum_{i=1}^{N_{EC}} p_i \mathrm{ADC}_i$$

- Gradient-based optimization
  - OpenMDAO framework
  - Analytic derivatives

Design solutions

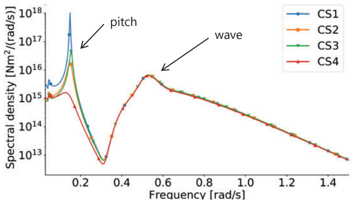




- Below wave zone
  - Heighten CoB, lower CoG
  - Increases pitch restoring stiffness
- Intersection platform/tower
  - Balance between wave loads and fatigue resistance

Structural response

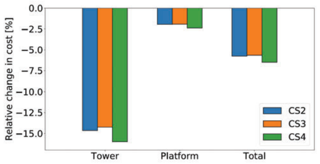
- Controller primarily affects resonant pitch response
  - More aerodynamic damping
  - Tower base bending moment spectrum, 15 m/s mean wind speed

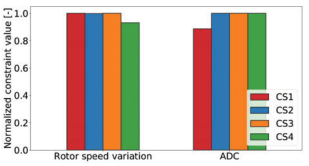


- Most critical extreme response found above cut-out
  - No impact from controller

Cost and performance comparison

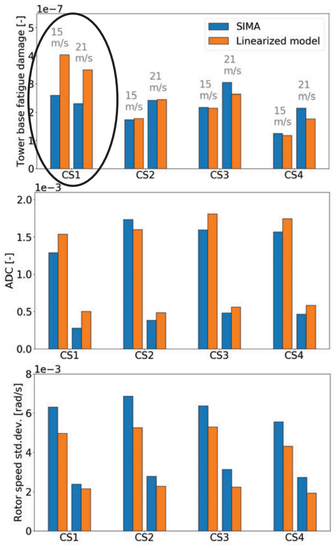
- Cost reduction mainly in tower due to lower fatigue loads
  - Some reduction in platform costs, coupling with tower
- CS1 unable to fully utilize available actuator capacity
- CS4 does not offer much additional reduction in cost, but
  - Less rotor speed variation
  - Larger improvements likely for designs with more WF response
- Cost comparison strongly dependent on chosen constraint values





Verification

- Comparison with nonlinear time domain simulations
- Mostly, trends are captured with reasonable accuracy
- Fatigue damage for CS1 significantly overpredicted
  - Optimal design has small aerodynamic damping in pitch
  - Does not occur with velocity feedback control
- Rotor speed variation quite consistently underestimated
  - Can be considered by lowering constraint value



Conclusions

- Integrated optimization of a spar FWT
  - Evaluation of trade-off effects in a lifetime perspective
- Linearized model captures trends, but
  - Overestimates pitch response if aerodynamic damping is low
- Controller mainly affects resonant pitch response
  - Cost reductions in tower due to lower fatigue loads
  - Actual values depend on rotor speed variation and ADC constraints
  - Alternative to use multi-objective approach
- No effect from controller on extreme response
  - Limited coupling effects
  - Small variations for the platform design

Limitations/future work

- Transient and nonlinear events
  - Extreme rotor speed excursions
- Consider impact of controller on
  - Blades
  - Drivetrain
  - Mooring system
- Additional modifications
  - Torque controller
  - IPC

Thank you for your attention!

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FAR OFF-SHORE WIND ENERGY-BASED HYDROGEN PRODUCTION: TECHNOLOGICAL ASSESSMENT AND MARKET VALUATION DESIGNS

M. Woznicki, G. Le Solliec, R. Loisel

CONTENT

- Context
- MHyWind Overview
- Components Models Overview
- Case Studies
- Future work
- Questions ?

CONTEXT

- Offshore wind **capacity** is **increasing**, **turbines** are growing **bigger**, and **floating** technologies are on their way
- Going further offshore will unlock access to a **tremendous amount of energy**
- **Transmission** over long distances may be an **issue**

- **98%** of **H_2** is produced from **fossil** fuels => Production of **1 kg** emits **10 kg of CO_2** (for oil refining, ammonia and fertilizers production, metallurgy, etc...)
- H_2 is an **energy vector** and can provide, via **fuel cells** (+storage vessels), various **electrical services** : grid services, energy storage, mobility...
- When produced via **water electrolysis** with renewable energy sources, **orders of magnitude**:

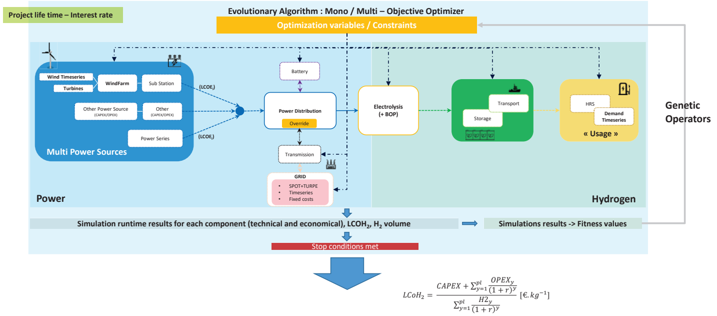
H_2 Energy content (LHV)	33.3 kWh.kg^{-1}
Energy requirements (η = 0.6) for production	55.5 kWh.kg^{-1}
Compression energy for storage	350bar: 2.1 kWh.kg^{-1} 700bar: 3.5 kWh.kg^{-1}

Exemple	**ICE (gasoline) car**	**Fuel cell car (H_2 from RE source)**
Fuel energy content	12.06 kWh.kg^{-1}	33.3 kWh.kg^{-1}
Engine efficiency	≈0.35	≈0.6 . 0.95 ($\eta_{FC} \cdot \eta_{EM}$)
Fuel consumption (100km)	5L / 3.68kg	1kg
CO_2 emissions (100km)	**≈10kg**	≈0g

How wind energy can be used to avoid these emissions ?
Can coupling of Hydrogen and Wind be mutually beneficial ?

- **Questions**:
  - How much H_2 can be produced with Offshore Wind ?
  - How to size the plants (OWF, water electrolysis system (WE)) and define their architectures?
  - What WE technologies could be used ?
  - What strategies and levers could help minimizing H_2 production costs ?

MHYWIND OVERVIEW



$$LCoH_2 = \frac{CAPEX + \sum_{y=1}^{pl} \frac{OPEX_y}{(1+r)^y}}{\sum_{y=1}^{pl} \frac{H2_y}{(1+r)^y}} \ [€.kg^{-1}]$$

Optimization/simulations results
SIZING, Min ($LCoH_2$), Volume, Production aligned to forecasted demand, etc...

COMPONENTS MODELS – OVERVIEW – WIND FARM

Offshore wind farm power

$$U_{HH}(z,t) = U_{z_0}(t).\left(\frac{z}{z_0}\right)^{\alpha} \quad [m.s^{-1}]$$

Wind Speed Correction (DAVENPORT)

$$P_T\big(U_{HH}(z,t)\big) = \delta + \frac{\alpha - \delta}{\left(\varepsilon + e^{(-\beta.(U-v_0))}\right)^{\frac{1}{\gamma}}} \quad [kW]$$

(6 parameters logistic function fit)

Turbine Output Power

$$P_{owf}\big(U_{HH}(z,t)\big) = Nb_T \, .P_T\big(U_{HH}(z,t)\big) \quad [kW]$$

Wind farm Output Power

$capex(distance, P_{rated})$ [€]

$opex(distance, capex, P_{rated})$ [€/y]

Available models :
- LEANWIND 8MW reference offshore turbine
- MHI VESTAS 4.2MW offshore turbine
- NORDEX N90 2.5MW onshore turbine
- ENERCON E53 800kW onshore turbine

Offshore Substation

$$P_{substation}(t) = \eta\left(\frac{P_{owf}(t)}{P^{rated}_{substation}}\right).P_{owf}(t) \ [kW]$$

Substation Output Power

$capex(distance, P_{rated})$ [€]

$opex(distance, capex, P_{rated})$ [€/y]

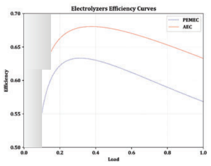
COMPONENTS MODELS – OVERVIEW – ELECTROLYZER

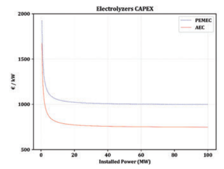
- Total electrolysis power P_{we}^{rated}
- Number of electrolyzers
- Electrolyzer technology
- $capex\big(distance, P_{we}^{rated}\big)$ [€]
- $opex\big(distance, capex, P_{we}^{rated}\big)$ [€/y]

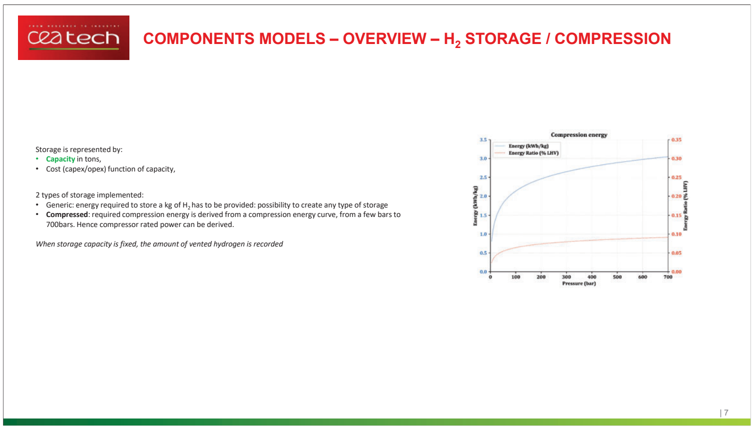
Ageing (for efficiency degradation) is included and replacement costs are added to project OPEX

	AEC	PEMEC
Efficiency η	Cf. graph	Cf. graph
Working range (% nominal load)	15-100	10-100
Life time (kh)	60	50
Efficiency degradation (%/y)	0.01	0.015

$$\begin{cases} P_{we}^{out}(t) = P_{we}^{in}(t).\eta\left(\frac{P_{we}^{in}(t)}{P_{we}^{rated}}\right), P_{we}^{min} \le P_{we}^{in}(t) \le P_{we}^{max} \\ \dot{m}_{H2}(t) = \frac{P_{we}^{out}(t)}{LHV_{H2}} \end{cases}$$





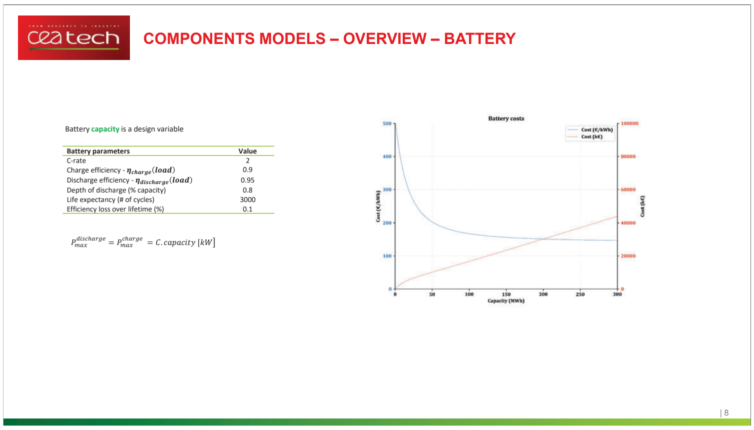


COMPONENTS MODELS – OVERVIEW – H_2 STORAGE / COMPRESSION

Storage is represented by:
- **Capacity** in tons,
- Cost (capex/opex) function of capacity,

2 types of storage implemented:
- Generic: energy required to store a kg of H_2 has to be provided: possibility to create any type of storage
- **Compressed**: required compression energy is derived from a compression energy curve, from a few bars to 700bars. Hence compressor rated power can be derived.

When storage capacity is fixed, the amount of vented hydrogen is recorded

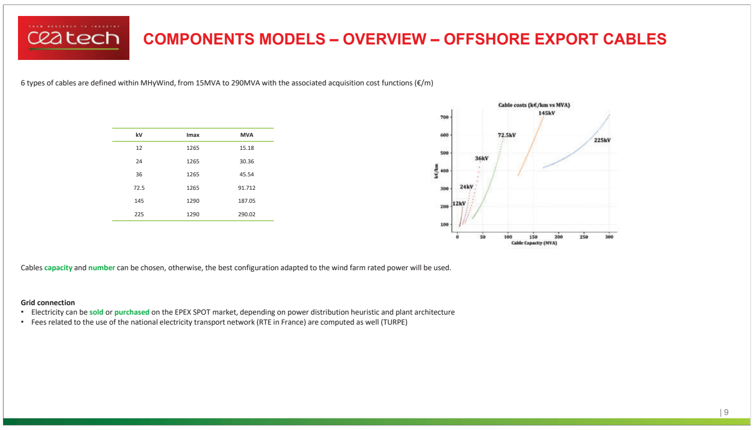


COMPONENTS MODELS – OVERVIEW – BATTERY

Battery **capacity** is a design variable

Battery parameters	Value
C-rate	2
Charge efficiency - $\eta_{charge}(load)$	0.9
Discharge efficiency - $\eta_{discharge}(load)$	0.95
Depth of discharge (% capacity)	0.8
Life expectancy (# of cycles)	3000
Efficiency loss over lifetime (%)	0.1

$$P_{max}^{discharge} = P_{max}^{charge} = C.capacity\ [kW]$$



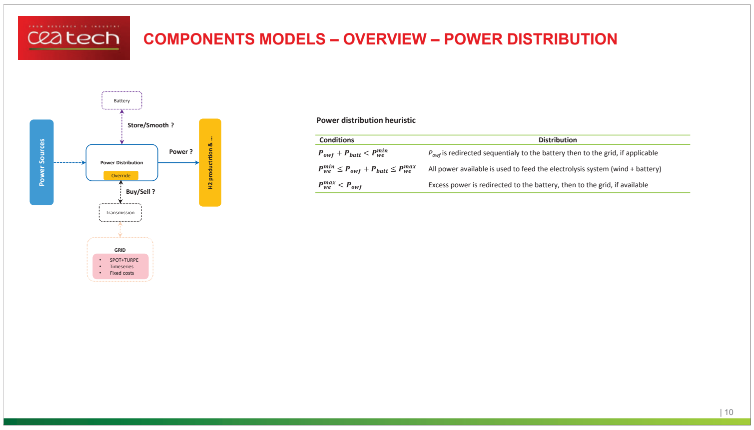
COMPONENTS MODELS – OVERVIEW – OFFSHORE EXPORT CABLES

6 types of cables are defined within MHyWind, from 15MVA to 290MVA with the associated acquisition cost functions (€/m)

kV	Imax	MVA
12	1265	15.18
24	1265	30.36
36	1265	45.54
72.5	1265	91.712
145	1290	187.05
225	1290	290.02

Cables **capacity** and **number** can be chosen, otherwise, the best configuration adapted to the wind farm rated power will be used.

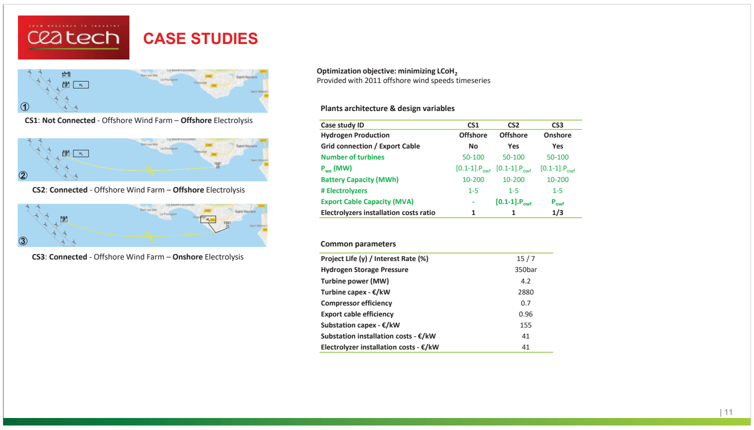
Grid connection
- Electricity can be **sold** or **purchased** on the EPEX SPOT market, depending on power distribution heuristic and plant architecture
- Fees related to the use of the national electricity transport network (RTE in France) are computed as well (TURPE)



COMPONENTS MODELS – OVERVIEW – POWER DISTRIBUTION

Power distribution heuristic

Conditions	Distribution
$P_{owf} + P_{batt} < P_{we}^{min}$	P_{owf} is redirected sequentialy to the battery then to the grid, if applicable
$P_{we}^{min} \leq P_{owf} + P_{batt} \leq P_{we}^{max}$	All power available is used to feed the electrolysis system (wind + battery)
$P_{we}^{max} < P_{owf}$	Excess power is redirected to the battery, then to the grid, if available



CASE STUDIES

① CS1: **Not Connected** - Offshore Wind Farm – **Offshore** Electrolysis

② CS2: **Connected** - Offshore Wind Farm – **Offshore** Electrolysis

③ CS3: **Connected** - Offshore Wind Farm – **Onshore** Electrolysis

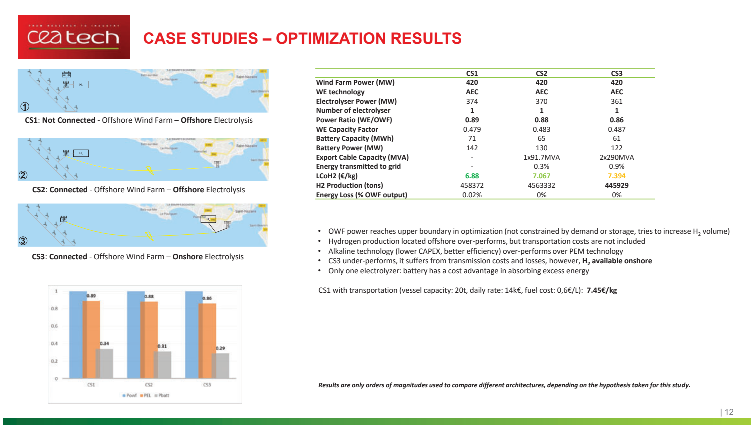
Optimization objective: minimizing $LCoH_2$
Provided with 2011 offshore wind speeds timeseries

Plants architecture & design variables

Case study ID	CS1	CS2	CS3
Hydrogen Production	Offshore	Offshore	Onshore
Grid connection / Export Cable	No	Yes	Yes
Number of turbines	50-100	50-100	50-100
P_{we} (MW)	$[0.1\text{-}1].P_{owf}$	$[0.1\text{-}1].P_{owf}$	$[0.1\text{-}1].P_{owf}$
Battery Capacity (MWh)	10-200	10-200	10-200
# Electrolyzers	1-5	1-5	1-5
Export Cable Capacity (MVA)	-	$[0.1\text{-}1].P_{owf}$	P_{owf}
Electrolyzers installation costs ratio	1	1	1/3

Common parameters

Project Life (y) / Interest Rate (%)	15 / 7
Hydrogen Storage Pressure	350bar
Turbine power (MW)	4.2
Turbine capex - €/kW	2880
Compressor efficiency	0.7
Export cable efficiency	0.96
Substation capex - €/kW	155
Substation installation costs - €/kW	41
Electrolyzer installation costs - €/kW	41



CASE STUDIES – OPTIMIZATION RESULTS

① CS1: **Not Connected** - Offshore Wind Farm – **Offshore** Electrolysis

② CS2: **Connected** - Offshore Wind Farm – **Offshore** Electrolysis

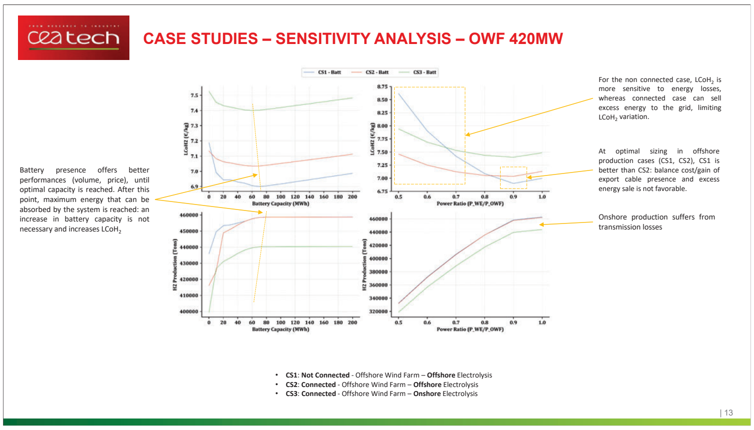
③ CS3: **Connected** - Offshore Wind Farm – **Onshore** Electrolysis

	CS1	CS2	CS3
Wind Farm Power (MW)	**420**	**420**	**420**
WE technology	**AEC**	**AEC**	**AEC**
Electrolyser Power (MW)	374	370	361
Number of electrolyser	**1**	**1**	**1**
Power Ratio (WE/OWF)	**0.89**	**0.88**	**0.86**
WE Capacity Factor	0.479	0.483	0.487
Battery Capacity (MWh)	71	65	61
Battery Power (MW)	142	130	122
Export Cable Capacity (MVA)	-	1x91.7MVA	2x290MVA
Energy transmitted to grid	-	0.3%	0.9%
LCoH2 (€/kg)	**6.88**	**7.067**	**7.394**
H2 Production (tons)	458372	4563332	**445929**
Energy Loss (% OWF output)	0.02%	0%	0%

- OWF power reaches upper boundary in optimization (not constrained by demand or storage, tries to increase H_2 volume)
- Hydrogen production located offshore over-performs, but transportation costs are not included
- Alkaline technology (lower CAPEX, better efficiency) over-performs over PEM technology
- CS3 under-performs, it suffers from transmission costs and losses, however, **H_2 available onshore**
- Only one electrolyzer: battery has a cost advantage in absorbing excess energy

CS1 with transportation (vessel capacity: 20t, daily rate: 14k€, fuel cost: 0,6€/L): **7.45€/kg**

Results are only orders of magnitudes used to compare different architectures, depending on the hypothesis taken for this study.



CASE STUDIES – SENSITIVITY ANALYSIS – OWF 420MW

Battery presence offers better performances (volume, price), until optimal capacity is reached. After this point, maximum energy that can be absorbed by the system is reached: an increase in battery capacity is not necessary and increases $LCoH_2$

For the non connected case, $LCoH_2$ is more sensitive to energy losses, whereas connected case can sell excess energy to the grid, limiting $LCoH_2$ variation.

At optimal sizing in offshore production cases (CS1, CS2), CS1 is better than CS2: balance cost/gain of export cable presence and excess energy sale is not favorable.

Onshore production suffers from transmission losses

- **CS1**: **Not Connected** - Offshore Wind Farm – **Offshore** Electrolysis
- **CS2**: **Connected** - Offshore Wind Farm – **Offshore** Electrolysis
- **CS3**: **Connected** - Offshore Wind Farm – **Onshore** Electrolysis

FUTURE WORK

- **Optimized power distribution** (perfect knowledge of wind speeds and electricity costs at given horizons (hours/days)): battery usage, electrolysis load, hydrogen production volume, electricity purchase costs and electricity sale revenues that finds the best trade-offs in power use
- Include electrolyzers **startup** times
- Optimal electrolyzer use and control
- Turbine **generator downsizing**: influences costs: turbines, substation and transmission

QUESTIONS ?

THANK YOU

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Optimising the utilisation of subsea cables in offshore wind farm collector networks

Considering energy storage and GW scale wind farms

Peter Taylor[1]
Olimpo Anaya-Lara[1], David Campos Gaona[1], Hong Yue[1]
Chunjiang Jia[2], Chong Ng[2]
[1] – University of Strathclyde, [2] – Offshore Renewable Energy Catapult

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Contents

- Wind farm design optimisation
  - How and why?
- Energy storage system (ESS) hypothesis
- Case study at Lillgrund offshore wind farm
- Scaling up to GW wind farms

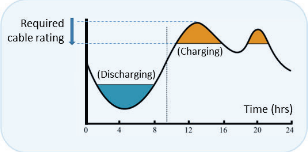
Wind farm optimisation

- Design factors to optimise
  - Turbine placement
  - Cable layout
- Aims
  - Increased energy capture
  - Lower investment costs
  - Reduced electrical losses
  - Reduced LCOE

Image: Wiser, Ryan & Jenni, Karen & Seel, Joachim & Baker, Erin & Hand, Maureen & Lantz, Eric & Smith, Aaron. (2016). Expert elicitation survey on future wind energy costs. Nature Energy. 1. 16135. 10.1038/nenergy.2016.135.

ESS hypothesis

- Cable rating must be high enough to deliver rated power
- Energy storage can charge at times of peak power and discharge at times of low power
- Peak power in the cable is reduced



Case Study

- 48 turbines
- 2.3MW rated power
- 3 cable sizes used
  - 95mm^2, 185mm^2, 240mm^2

Lillgrund Offshore Wind Farm

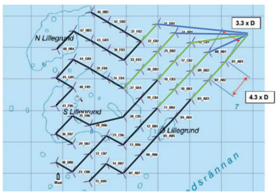
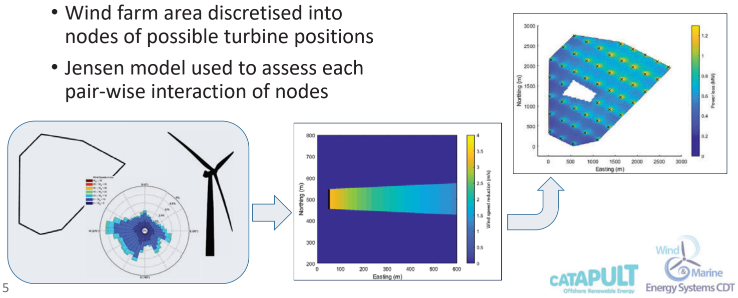
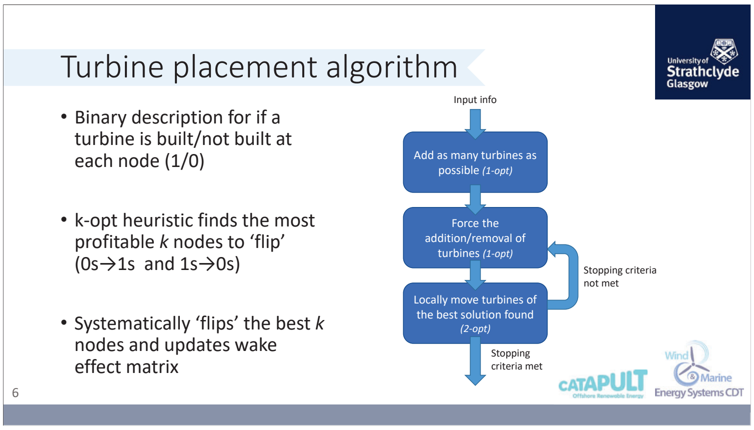


Image courtesy of – Vattenfall – "Assessment of the Lillgrund Windfarm"

Turbine placement pre-processing

- Wind farm area discretised into nodes of possible turbine positions
- Jensen model used to assess each pair-wise interaction of nodes





Turbine placement algorithm

- Binary description for if a turbine is built/not built at each node (1/0)
- k-opt heuristic finds the most profitable *k* nodes to 'flip' (0s→1s and 1s→0s)
- Systematically 'flips' the best *k* nodes and updates wake effect matrix

Input info

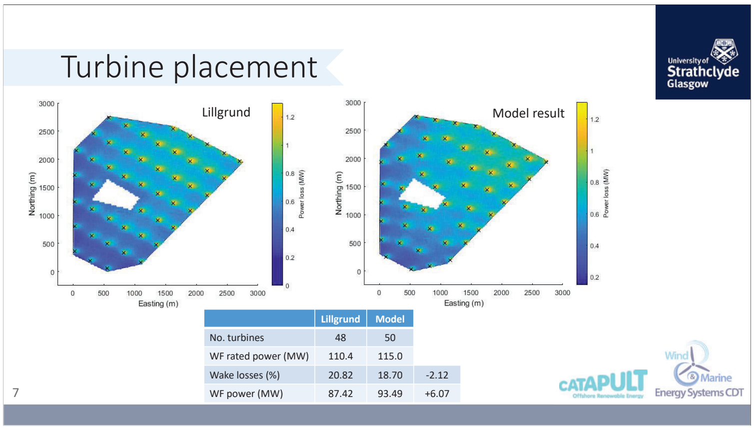
Add as many turbines as possible *(1-opt)*

Force the addition/removal of turbines *(1-opt)*

Locally move turbines of the best solution found *(2-opt)*

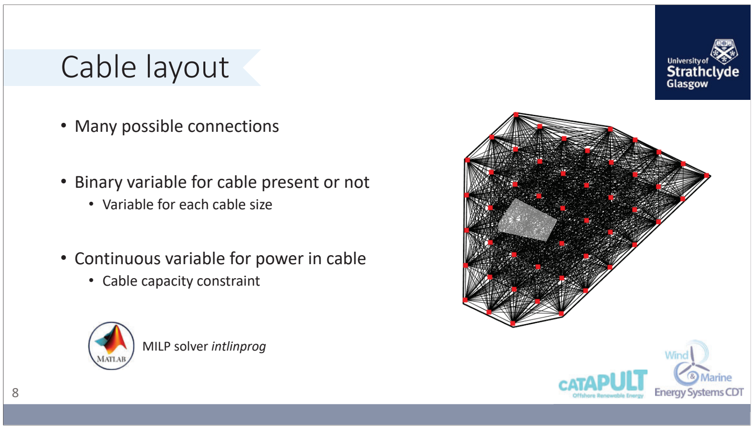
Stopping criteria not met

Stopping criteria met



Turbine placement

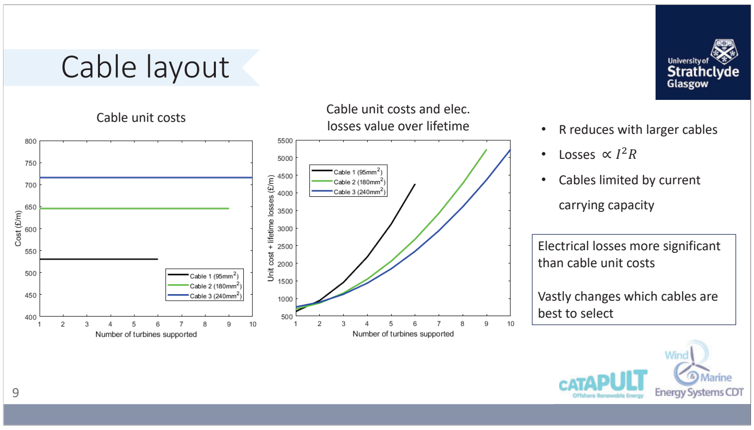
	Lillgrund	Model	
No. turbines	48	50	
WF rated power (MW)	110.4	115.0	
Wake losses (%)	20.82	18.70	-2.12
WF power (MW)	87.42	93.49	+6.07



Cable layout

- Many possible connections
- Binary variable for cable present or not
  - Variable for each cable size
- Continuous variable for power in cable
  - Cable capacity constraint

MILP solver *intlinprog*



Cable layout

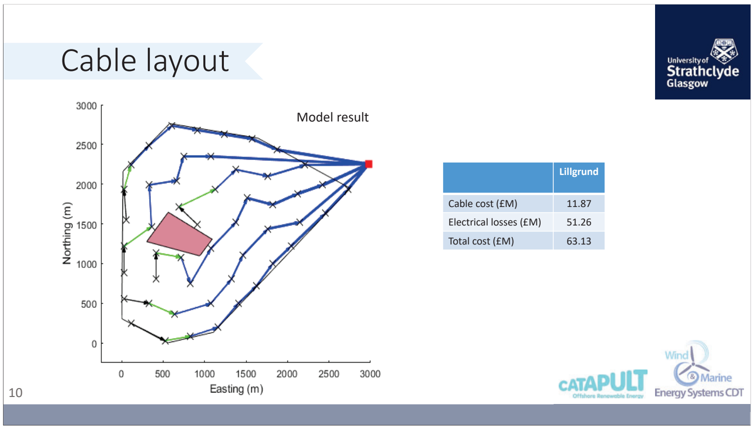
Cable unit costs

Cable unit costs and elec. losses value over lifetime

- R reduces with larger cables
- Losses $\propto I^2 R$
- Cables limited by current carrying capacity

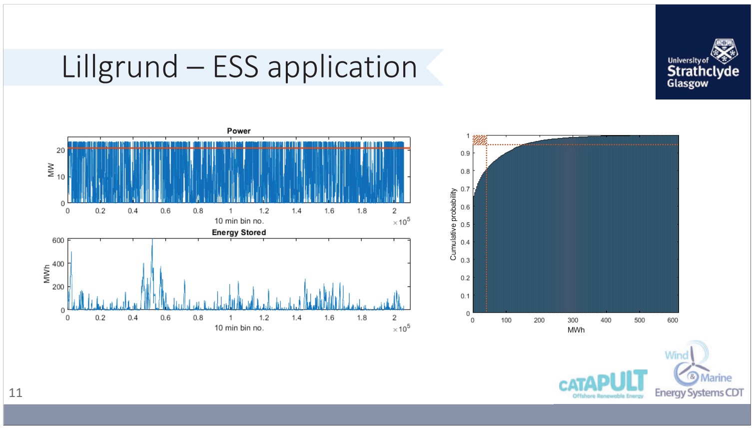
Electrical losses more significant than cable unit costs

Vastly changes which cables are best to select



Cable layout

	Lillgrund
Cable cost (£M)	11.87
Electrical losses (£M)	51.26
Total cost (£M)	63.13



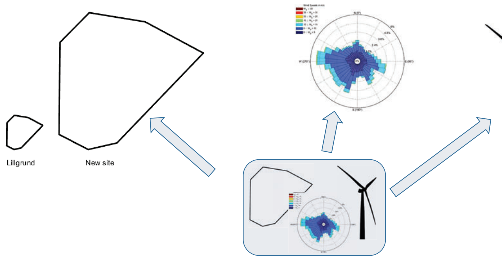
Lillgrund – ESS application

Limitations & improvements

- Loss of the grid structure of the layout
  - Navigation and search and rescue issues
- Computationally complex at large scale
  - Pre-processing wake effects for all node pairs
  - Constraint eq.s for MILP formulation of cable layout problem
- Not suitable for realistic larger scale WFs

Scaling up to GWs

Same wind conditions



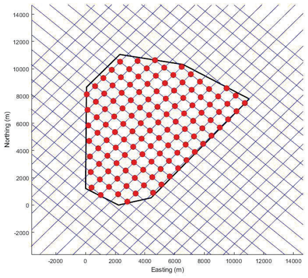
Model inputs

Vestas V164	
Rated power	7-10MW
Rotor Diam.	164m
Cut in speed	4ms^{-1}
Cut out speed	25ms^{-1}
Hub height	138m

Scaling up – turbine placement

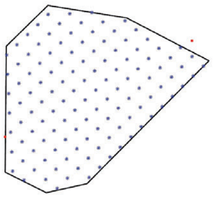
- Particle swarm optimisation algorithm
- 8 variables
  - No longer a func of no. turbines
- Larsen wake model
- Much quicker run time

Variables	
m_1	Angle of rows
dm_1	Angle between rows
s_1	Spacing of rows
m_2	Angle of cols
dm_2	Angle between cols
s_2	Spacing of cols
x	Horizontal disp.
y	Vertical disp.



Scaling up – cable layout

- Ant colony optimisation algorithm
  - 'Tidy-up' messy random routes
  - With multiple-travelling-salesman-problem approach for cable routing
- Able to deal with more complex problems
  - Computationally efficient



Conclusions

- Clear benefits in considering WF optimisation in design phase
  - Savings can be made if aiming at lifetime cost reduction
- Energy storage systems are not profitable/practical for cable loss reduction and cable de-rating
- Scaling up to GW scale can lead to a huge increase in computational complexity
- Practical design tools are needed to cope with these problems

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Thank you

This research is conducted under the **Electrical Infrastructure Research Hub** (EIRH). The EIRH is a 5-year collaboration between ORE Catapult and the Universities of Strathclyde and Manchester.

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Sources and references

Position data: *Vattenfall – Assessment of the Lillgrund Windfarm*

Windfarm information: *Vattenfall – Technical description Lillgrund wind power plant*

Wind data: *BMWi and PTJ – FINO1 project* & *Vattenfall – Meteorological conditions at Lillgrund*

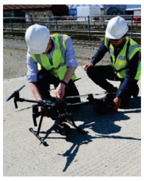
G1) Experimental Testing and Validation

RAVE (Research at alpha ventus) offers its 10 years of measurement data to support research in offshore wind power, B.Lange, Fraunhofer IWES – *Presentation not available*

Managing data to develop digital twins, demonstrate new technology and provide improved wind turbine/wind farm control during operation, P.McKeever, ORE Catapult

Experimental Investigations on the Fatigue Resistance of Automatically Welded Tubular X-Joints for Jacket Support Structures, K.Schürmann, Leibniz University Hannover

Determination of the Yaw Moment of a Downwind-coned Rotor under Yawed Conditions: Limitations of a Blade Element Momentum Theory Method, C.W.Schulz, Hamburg University of Technology



7MW Levenmouth Demonstration Turbine - Managing data and the asset to develop research and demonstration projects during turbine operation

16 January 2020 | Paul McKeever – Head of Electrical Research

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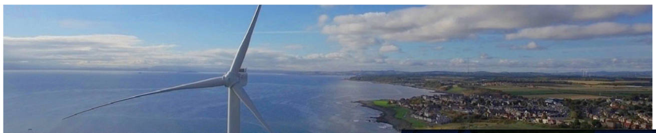
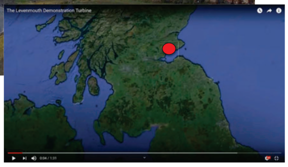
Agenda

- 7MW Levenmouth Demonstration Turbine (LDT) Summary
  - The LDT in numbers
  - Operation of the LDT - Challenges
- LDT Asset Usage
  - Management & Utilisation of Data
    - The Platform for Operational Data (POD) Service
  - Developing a Turbine Model
    - The LDT Model
  - LDT as a Demonstration Platform
    - Case Studies
      - Non-intrusive demonstrations
      - Offshore Demonstration Blade (ODB) and TotalControl Projects
- Conclusions

7MW Levenmouth Demonstration Turbine (LDT) Summary

- Short Video - https://youtu.be/-j3hZvQIEWI

- Located in Fife, Scotland
- Acquired by ORE Catapult in November, 2015
- One of the world's most advanced open access offshore wind turbines
  - Dedicated to research and product validation/demonstration

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The LDT in numbers

Features

Wind class
IEC Class I_A/ S_B

Rotor dia.
171.2m

Capacity
7MW at grid side

Hub height
110.6m

Blade length
83.5m

Total height
196m blade tip to sea level

Generator
Medium voltage PMG (3.3kV)

Converter
Full power conversion

Drive train
Medium speed (400rpm)

Rated frequency
50Hz

Rotor speed
5.9 ~ 10.6rpm

Wind speed
3.5 ~ 25m/s

Temp. range
Survival
-20°C to +50°C
Operating
-10°C to +25°C

Lightning protection level
Level 1 (IEC 62305-1)

Corrosion category (ISO 12944-5)
Inside : C4
Outside : C5-M

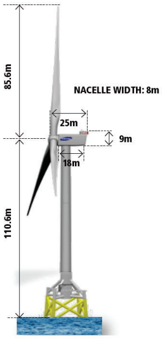
Design life
25 years

Control system features

- Independent and collective pitch control modes
- Active drivetrain damping
- Active load control
- Blade load monitoring

Complementary measurement opportunities

- Access hatches on roof
- Land-side flat locations for lidar installation (including 1 pad with electrical connections)
- On-site IEC met mast with cup anemometry currently installed
- Deck space on transition piece for small instruments



Operation of the LDT

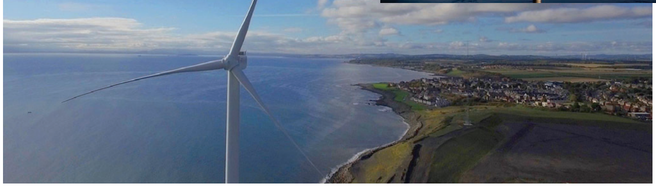
List of Activities (non-exhaustive)

- Product validation of new concepts and technology (including power performance measurements)
  - Demonstrate remote inspection methods and technologies
- Improve wind resource estimation and standardisation
- Holistic control system development, including control algorithm optimisation
- Prognostic condition monitoring system (CMS) development
- Measurement system development (DAQ, sensors)
- Measure and compare real-life data against a controlled test programme
- Structural mechanics
- Aeroelastic modelling
- Aerodynamic modelling
- Design and analysis tool evaluation
- Evaluate environmental conditions, data and/or impact

Enables vital testing, verification and validation of remote sensing and other innovative technologies in order to prove reliability and performance (and facilitate data availability) for next generation offshore wind turbine technologies.

Operation of the LDT - Challenges

1. Proximity to land
   1. Great for turbine access
   2. Still provides offshore environment
   3. Care regarding interaction with local community
   4. Effects on wind resource assessment

Operation of the LDT - Challenges

1. Spare parts
2. Major alterations
    1. Logistics
    2. Turbine Financial Model
    3. Consenting
3. Mother nature

LDT Asset Usage

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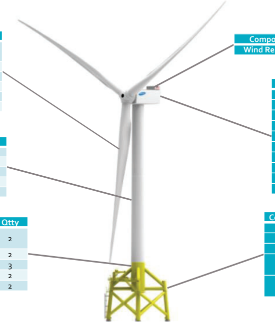
Management & Utilisation of Data

In addition to standard SCADA controller signals and existing condition monitoring systems (see summary table below), ORE Catapult has been working on the CLOWT (Clone of the Levenmouth Offshore Wind Turbine) Project.

- Project ultimately aims to develop a validated virtual model of the Levenmouth Demonstration Turbine (LDT)
- Validated using measurement campaign data from a comprehensive package of instrumentation

Component	High-Level Measurement Description
Hub	Temperature, rotational speed, azimuth
Pitch	Pitch position, pitch rate, pitch demand, motor current, motor temperature
Nacelle	Yaw position, wind direction, wind speed, yaw error, yaw speed, temperature (inside and outside), vibrations (accelerations)
Drive-train	Oil pressure, oil temperature, vibrations (accelerations), gearbox temperature
Main bearing	Temperature
Tower	Vibrations (accelerations)
Electrical	IGCT temperature, current (generator, grid), voltage (grid, generator), temperature (generator), reactive power (generator, grid), torque, generator speed, active power (grid, generator), grid frequency, grid phase, power factor
Protective relay (IPR)	Line current, frequency, power (real, reactive and apparent)

CLOWT Project Sensors



Component	Sensor	Location	Qtty
Blade	Strain Gauge	Blade root	4 x 3 blades
		¼ Blade length	4
		.4 Blade length	4
		½ Blade length	4
		.6 Blade length	4
		¾ Blade length	4

Component	Sensor	Location	Qtty
Tower	Strain Gauge	Tower top	2
		Tower base	2
		Tower middle	2
	Accelerometer	Tower top	1
		1/3 from top	1

Component	Sensor	Location	Qtty
Transition Piece	Strain Gauge	Diagonal Leg (side 1)	2
		Horizontal Leg (side 1)	2
		Tower	3
		Diagonal Leg (Side 2)	2
		Horizontal Leg (Side 2)	2

Component	Equipment	Location	Qtty
Wind Resource	ZephIR Lidar	Nacelle (Forward Facing)	1

Component	Sensor	Location	Qtty
Power Train	Speed	Various	Multiple
	Torque		
	Temperature		
	Current		
	Voltage		
	Humidity		
Pitch System	Temperature		
	Current		
	Voltage		
	Humidity		

Component	Sensors	Location	Qtty
Jacket	Strain Gauge	Jacket Brace 1	2
		Jacket Brace 2	2
		Jacket Leg	2
		Jacket Brace 1 (alternate side)	2
		Jacket Brace 2 (alternate side)	2

The Platform for Operational Data (POD) Service

What is POD?

- POD enables you to access and request data sets for the LDT

How does it work?

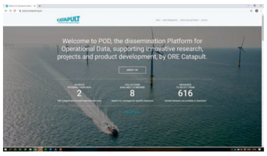
- Browse the POD catalogue and request your required datasets
    - Samples of each data collection are available for you to view
- Choose the data collections/time periods you are interested in
- Briefly describe your intended use of the data

*There is a small charge to cover the data retrieval, depending on the size or complexity of the request, and this will be calculated after receipt of the request and discussion around an appropriate solution.

Data Storage & Availability

Data Set	Frequency of Capture
LDT Met Mast SCADA	1 sec & 10 min
LDT Substation SCADA	1 sec & 10 min
LDT Turbine SCADA	1 sec & 10 min
LDT Alarm Log	

All data sources are collected in a bespoke Data Acquisition System (DAQ) and are stored on a local server at the LDT site. Data transfer to remote users can be provided where appropriate.



Welcome to POD, the dissemination Platform for Operational Data, supporting innovative research, projects and product development, by ORE Catapult.

Developing a Turbine Model

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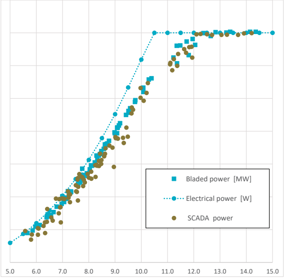
Developing the LDT Digital Twin

Enhancing Modelling (using real data)

Power Curve now matches real measurements



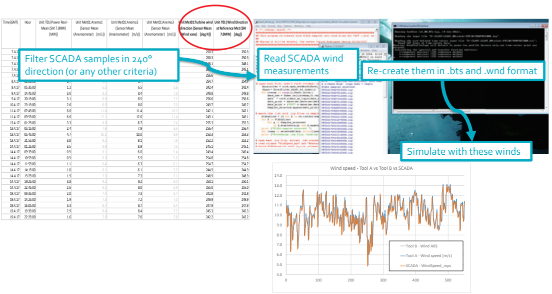
Started with aeroelastic model, but this is being expanded to powertrain and grid connection modelling

Managing Data on the Project

- **1st step in process: choose your data**
- We have filtered SCADA samples where wind direction is aligned with the met mast
  - Using only samples where all wind measurements (met mast, WT) coincide

Managing Data on the Project

- **2nd step: run some simulations**
- Used a bespoke python script - wind measurements are being easily translated into simulations:



Filter SCADA samples in 240° direction (or any other criteria)

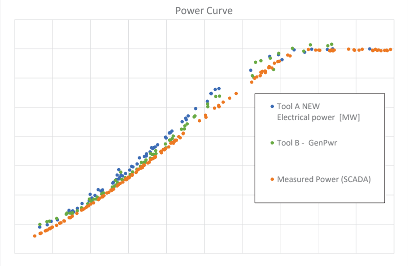
Read SCADA wind measurements

Re-create them in .bts and .wnd format

Simulate with these winds

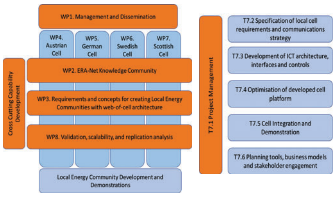
Managing Data on the Project

- **3rd step: compare simulations to reality – power curve (also compared pitch, rotor speed & torque)**
- Re-created wind fields measured on the nacelle, and using original controller, we have more reliably evaluated aero-elastic code performance. In this graphic, Tool A vs. Tool B vs. SCADA



Future Use of the LDT

- **CLOWT Sensors –** Additional sensors recently fitted to the LDT will enable a number of new R&D projects
- **Expansion into Energy Systems Research – Project CLUE**
- Concepts, Planning, Demonstration and Replication of Local User-friendly Energy Communities (CLUE) - €7million project delivered over 3 years from December 2019
- CLUE will develop and validate a tool kit supporting the implementation of sustainable local energy systems and will close the gap of missing control and monitoring tools
- The different types of Local Energy Community (LEC) stakeholders (cooperatives, project developers, DSOs, owners, operators of LECs, utilities, supplier) will participate in CLUE



WP1. Management and Dissemination

WP4. Austrian Cell

WP5. German Cell

WP6. Swedish Cell

WP7. Scottish Cell

Cross Cutting Capability Development

WP2. ERA-Net Knowledge Community

WP3. Requirements and concepts for creating Local Energy Communities with web-of-cell architecture

WP8. Validation, scalability, and replication analysis

Local Energy Community Development and Demonstrations

T7.1 Project Management

T7.2 Specification of local cell requirements and communications strategy

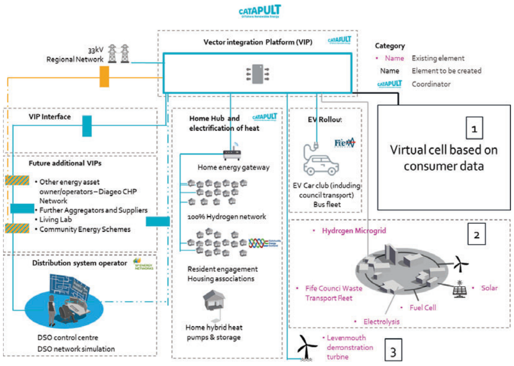
T7.3 Development of ICT architecture, interfaces and controls

T7.4 Optimisation of developed cell platform

T7.5 Cell Integration and Demonstration

T7.6 Planning tools, business models and stakeholder engagement

Project CLUE



33kV Regional Network

Vector integration Platform (VIP)

Category
- Name — Existing element
- Name — Element to be created
- Coordinator

VIP Interface

Future additional VIPs
- Other energy asset owner/operators – Diageo CHP Network
- Further Aggregators and Suppliers
- Living Lab
- Community Energy Schemes

Distribution system operator

DSO control centre
DSO network simulation

Home Hub and electrification of heat

Home energy gateway

100% Hydrogen network

Resident engagement
Housing associations

Home hybrid heat pumps & storage

EV Rollout

EV Car club (including council transport)
Bus fleet

1 Virtual cell based on consumer data

2
- Hydrogen Microgrid
- Fife Counci Waste Transport Fleet
- Solar
- Fuel Cell
- Electrolysis

3
- Levenmouth demonstration turbine

LDT as a Demonstration Platform

Non-Intrusive Demonstrations

List of Activities (non-exhaustive)

- Product validation of new concepts and technology (including power performance measurements)
  - Demonstrate remote inspection methods and technologies
- Improve wind resource estimation and standardisation
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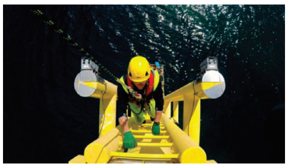
- Evaluate environmental conditions, data and/or impact

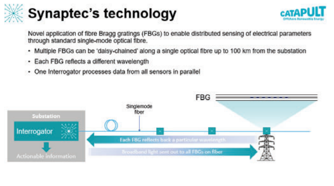
Enables vital testing, verification and validation of remote sensing and other innovative technologies in order to prove reliability and performance (and facilitate data availability) for next generation offshore wind turbine technologies.

Limpet – Height Safety and Access Systems



- Getting onto and off the turbines from a boat is among the most stressful and dangerous parts of offshore turbine maintenance
  - When waves are higher than 1.5 metres, transfers are considered too risky
- Failed transfers and lost energy production are hugely expensive for operators
  - Problem is set to become worse as the industry pushes into sites that are further from shore
- Limpet Technology has developed an offshore personnel transfer system aimed at alleviating this problem
  - Dynamic hoist and fall arrest system uses in-built lasers to track the vessel's deck, adjusting the height of the hoist in real time
  - Compensates for the motion of the vessel and allows the technician to clip in and transfer onto the turbine more easily
- Limpet's system can make safe transfers possible in 3m waves
  - Aims to increase access to far offshore turbines from 50% of the year to 80%

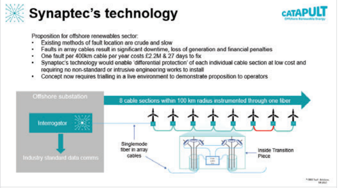
Synaptec – Cable Monitoring Utilising Existing Cable Optical Fibres



Synaptec's technology

Novel application of fibre Bragg gratings (FBGs) to enable distributed sensing of electrical parameters through standard single-mode optical fibre.

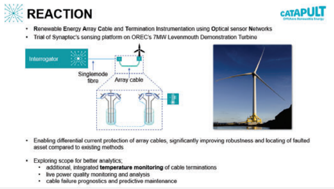
- Multiple FBGs can be 'daisy-chained' along a single optical fibre up to 100 km from the substation
- Each FBG reflects a different wavelength
- One Interrogator processes data from all sensors in parallel



Synaptec's technology

Proposition for offshore renewables sector:

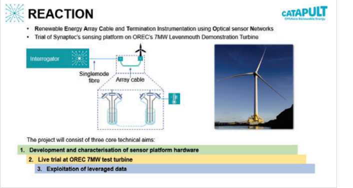
- Existing methods of fault location are crude and slow
- Faults in array cables result in significant downtime, loss of generation and financial penalties
- One fault per 400km cable per year costs £2.2M & 27 days to fix
- Synaptec's technology would enable 'differential protection' of each individual cable section at low cost and requiring no non-standard or intrusive engineering works to install
- Concept now requires trialling in a live environment to demonstrate proposition to operators



REACTION

- **R**enewable **E**nergy **A**rray **C**able and **T**ermination **I**nstrumentation using **O**ptical sensor **N**etworks
- Trial of Synaptec's sensing platform on OREC's 7MW Levenmouth Demonstration Turbine

- Enabling differential current protection of array cables, significantly improving robustness and locating of faulted asset compared to existing methods
- Exploring scope for better analytics;
  - additional, integrated **temperature monitoring** of cable terminations
  - live power quality monitoring and analysis
  - cable failure prognostics and predictive maintenance



REACTION

- **R**enewable **E**nergy **A**rray **C**able and **T**ermination **I**nstrumentation using **O**ptical sensor **N**etworks
- Trial of Synaptec's sensing platform on OREC's 7MW Levenmouth Demonstration Turbine

The project will consist of three core technical aims:

1. **Development and characterisation of sensor platform hardware**
2. **Live trial at OREC 7MW test turbine**
3. **Exploitation of leveraged data**

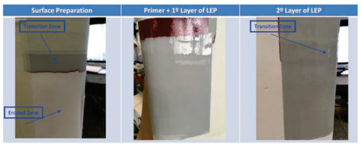
Intrusive Demonstrations - Offshore Demonstration Blade (ODB)

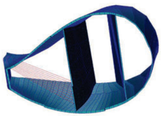
- 2-year DemoWind-funded project forming a €4 million research collaboration between 10 European partners
  - Coordinated by the ORE Catapult commercial arm (ODSL)
- Led the development of seven novel offshore wind turbine blade technologies, which collectively could lower the levelised cost of energy (LCOE) of offshore wind by as much as 4.7%.
- The Offshore Demonstration Blade (ODB) project supported the research, development and demonstration of wind turbine blade innovations, including aerodynamic and structural enhancements, blade monitoring systems and blade erosion protection solutions
  - A number of these innovations were demonstrated on the Levenmouth Demonstration Turbine

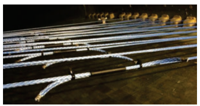
The Impact

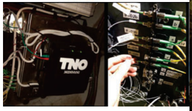
- O&M costs represent almost a quarter of the total LCOE of an offshore wind turbine
  - Rotor O&M (specifically blade erosion and blade structural integrity) represents a large share of these costs
- Improving the performance and operational lifetime of turbine blades is therefore a key factor in lowering LCOE.

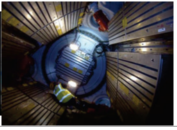
ODB Demonstrations at Levenmouth (LDT)









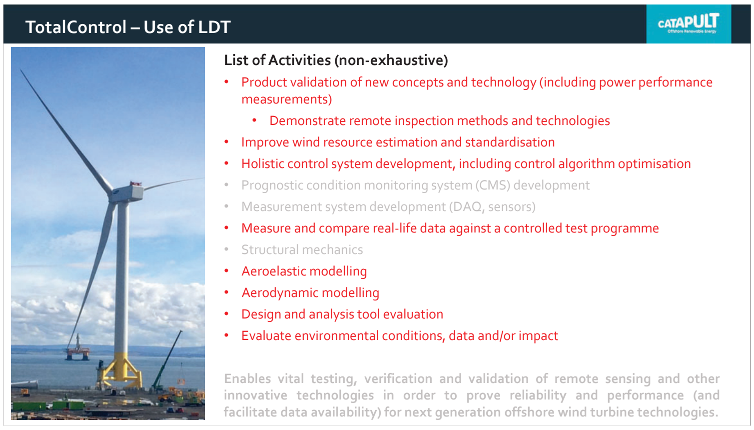


- Aerox Advanced Polymers - Leading Edge Protection Coating
  - Installed on LDT in May 2019
  - Applied successfully to blade area that had previously had a repair due to some minor lightning damage
  - Performance of the coating continues to be monitored
- GEV Windpower – X-Stiffener
  - Installed on LDT in May 2019 with support from Bladena
  - Explain where fitted inside the blade
- TNO – Cross Sectional Shear Distortion Sensor (CSSDS)
  - Installed on LDT in May 2019 with support from GEV Windpower
  - Designed to monitor X-Stiffener performance
  - X-Stiffener and the CSSDS were decommissioned in late 2019 after a few months of trial

Intrusive Demonstrations - The TotalControl Project

- TotalControl is a project within the Horizon 2020 framework funded by the European Union (Project Number 727680)
- The project runs for four years, from 1 January 2018 to 31 December 2021
- The total project budget is EUR 4 876 482,50

- The ambition of the TotalControl project is to develop the next generation of wind power plant (WPP) control tools, improving both WPP control itself and the link between wind turbine (WT) and WPP control
- TotalControl uses high-fidelity simulation and design environments including time resolved flow field modelling, nonlinear flexible multi-body representations of turbines, and detailed power grid models



TotalControl – Use of LDT

List of Activities (non-exhaustive)

- Product validation of new concepts and technology (including power performance measurements)
  - Demonstrate remote inspection methods and technologies
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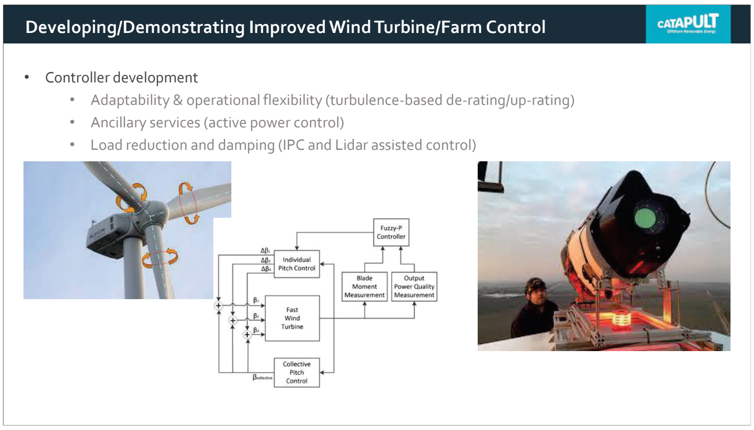
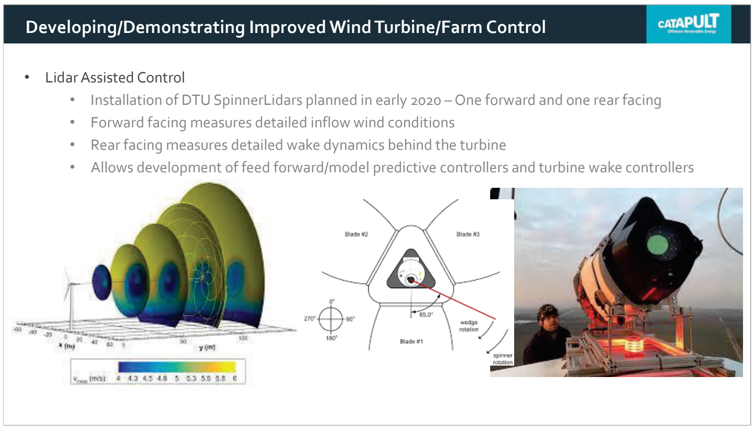


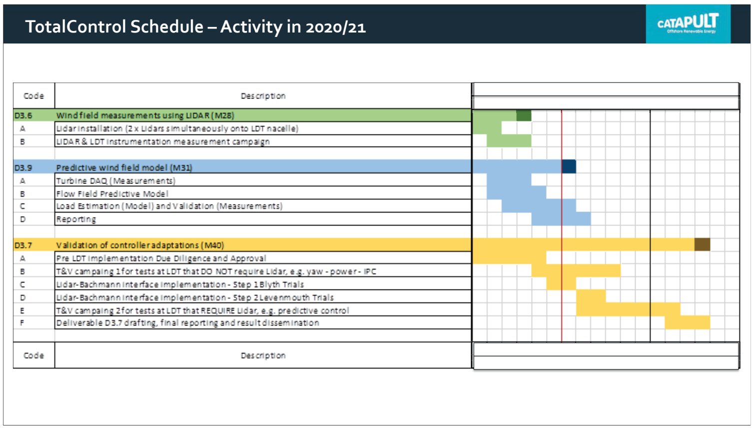
Developing/Demonstrating Improved Wind Turbine/Farm Control

- Controller development
  - Adaptability & operational flexibility (turbulence-based de-rating/up-rating)
  - Ancillary services (active power control)
  - Load reduction and damping (IPC and Lidar assisted control)



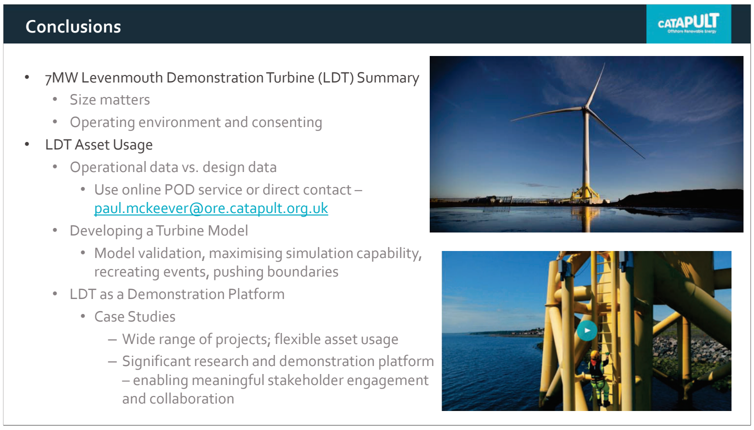
Developing/Demonstrating Improved Wind Turbine/Farm Control

- Lidar Assisted Control
  - Installation of DTU SpinnerLidars planned in early 2020 – One forward and one rear facing
  - Forward facing measures detailed inflow wind conditions
  - Rear facing measures detailed wake dynamics behind the turbine
  - Allows development of feed forward/model predictive controllers and turbine wake controllers



TotalControl Schedule – Activity in 2020/21

Code	Description
D3.6	Wind field measurements using LIDAR (M28)
A	Lidar installation (2 x Lidars simultaneously onto LDT nacelle)
B	LIDAR & LDT instrumentation measurement campaign
D3.9	Predictive wind field model (M31)
A	Turbine DAQ (Measurements)
B	Flow Field Predictive Model
C	Load Estimation (Model) and Validation (Measurements)
D	Reporting
D3.7	Validation of controller adaptations (M40)
A	Pre LDT implementation Due Diligence and Approval
B	T&V campaing 1 for tests at LDT that DO NOT require Lidar, e.g. yaw - power - IPC
C	Lidar-Bachmann interface implementation - Step 1 Blyth Trials
D	Lidar-Bachmann interface implementation - Step 2 Levenmouth Trials
E	T&V campaing 2 for tests at LDT that REQUIRE Lidar, e.g. predictive control
F	Deliverable D3.7 drafting, final reporting and result dissemination
Code	Description



Conclusions

- 7MW Levenmouth Demonstration Turbine (LDT) Summary
  - Size matters
  - Operating environment and consenting
- LDT Asset Usage
  - Operational data vs. design data
    - Use online POD service or direct contact – paul.mckeever@ore.catapult.org.uk
  - Developing a Turbine Model
    - Model validation, maximising simulation capability, recreating events, pushing boundaries
  - LDT as a Demonstration Platform
    - Case Studies
      - – Wide range of projects; flexible asset usage
      - – Significant research and demonstration platform – enabling meaningful stakeholder engagement and collaboration

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EERA DeepWind'2020
15 - 17 January 2020, Trondheim, Norway

Experimental investigations on the fatigue resistance of automatically welded tubular X-joints for jacket support structures

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Dr. Andreas Pittner, BAM
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Institute for Steel Construction
Prof. Dr.-Ing. Peter Schaumann

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Center for Wind Energy Research

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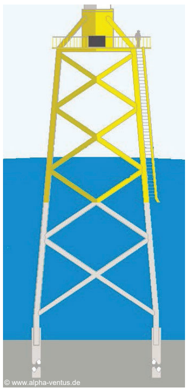
Motivation

- Innovative standardised jacket foundations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Motivation

- Innovative standardised jacket foundations


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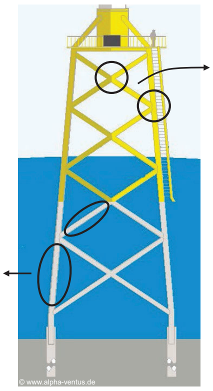
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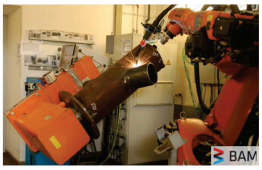
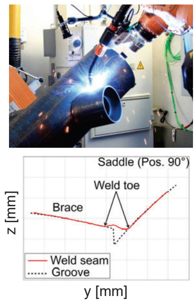


Outline

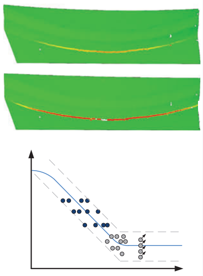
Automatically Welding Procedure



BAM

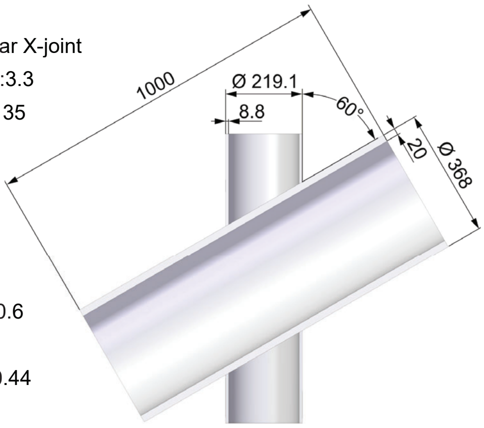
Axial Fatigue Tests

Fatigue Test Analysis



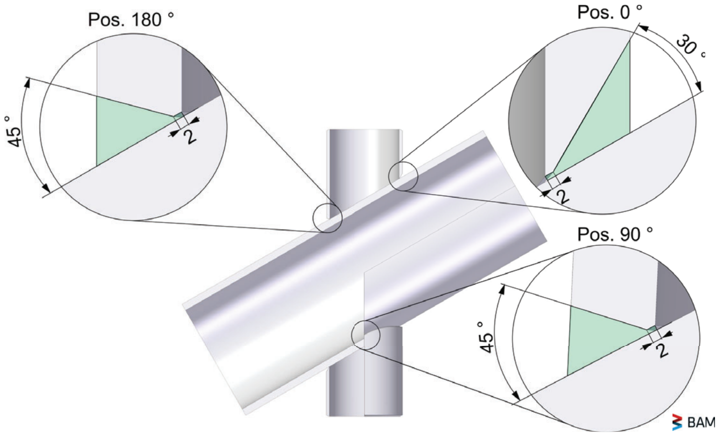
Geometrical Dimensions

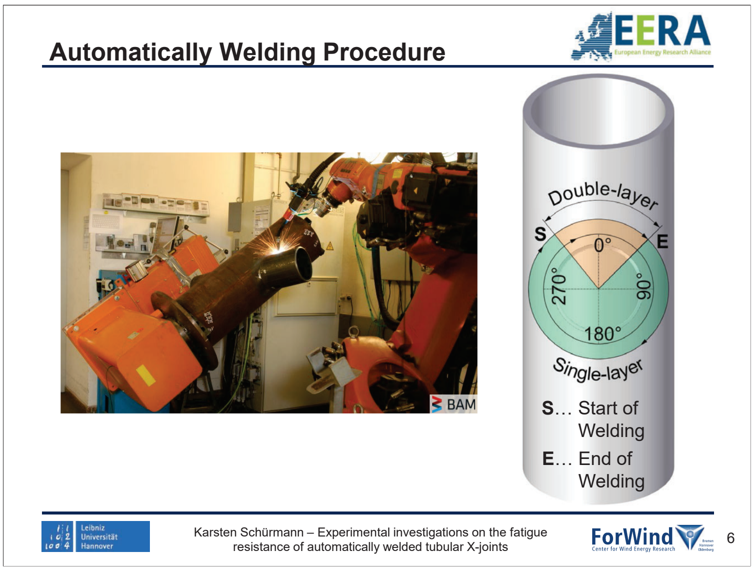
- Scaled tubular X-joint
  - Scaling 1:3.3
- S355 J2 + Z 35



- $\beta = \frac{d_{Brace}}{D_{Chord}} = 0.6$
- $\tau = \frac{t_{Brace}}{T_{Chord}} = 0.44$

Weld Seam Preparation

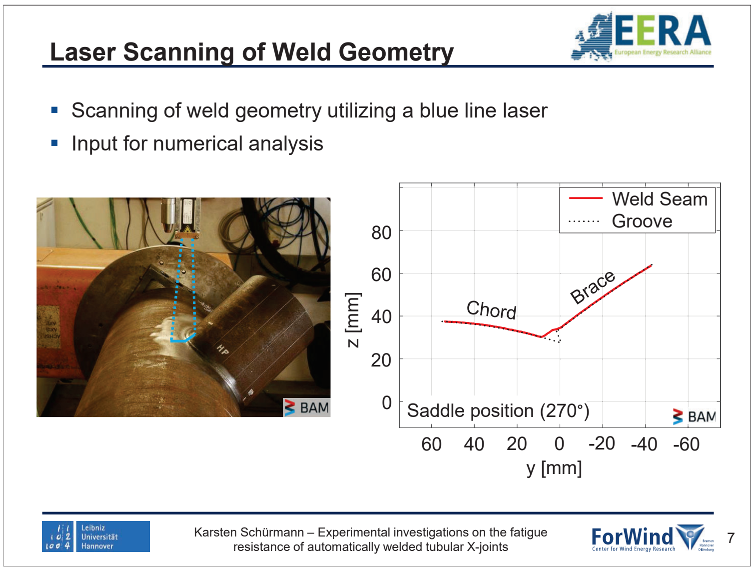




Automatically Welding Procedure

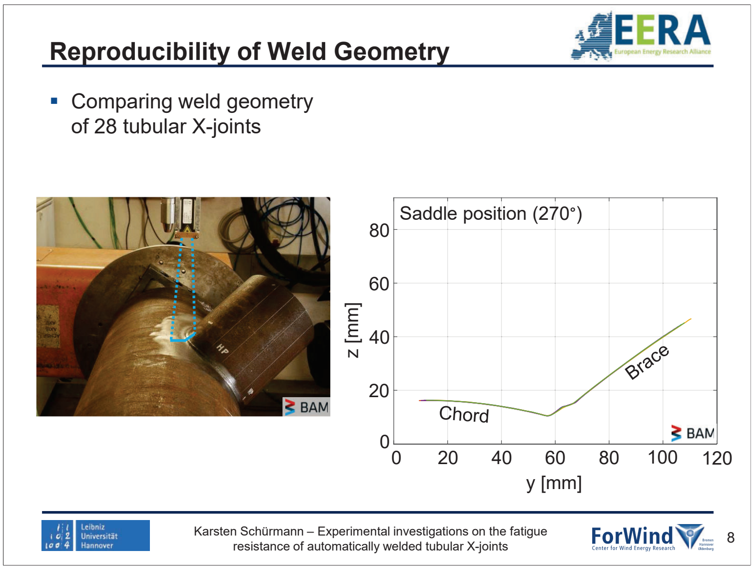
S… Start of Welding

E… End of Welding



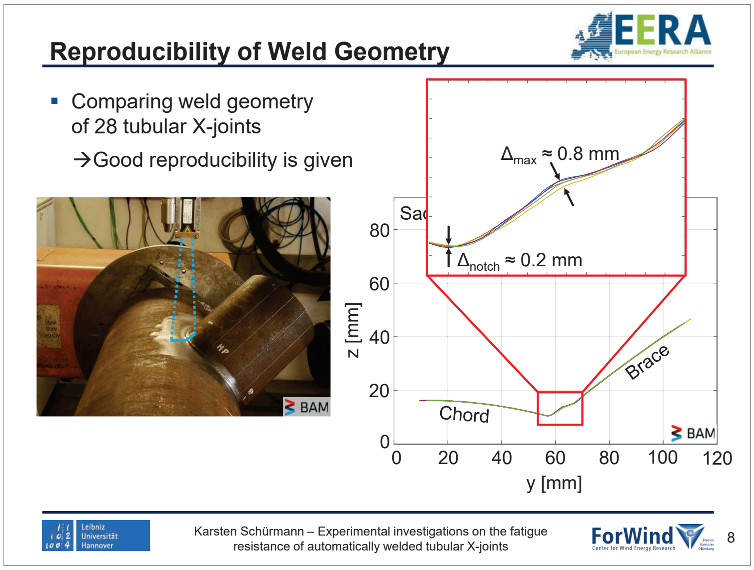
Laser Scanning of Weld Geometry

- Scanning of weld geometry utilizing a blue line laser
- Input for numerical analysis



Reproducibility of Weld Geometry

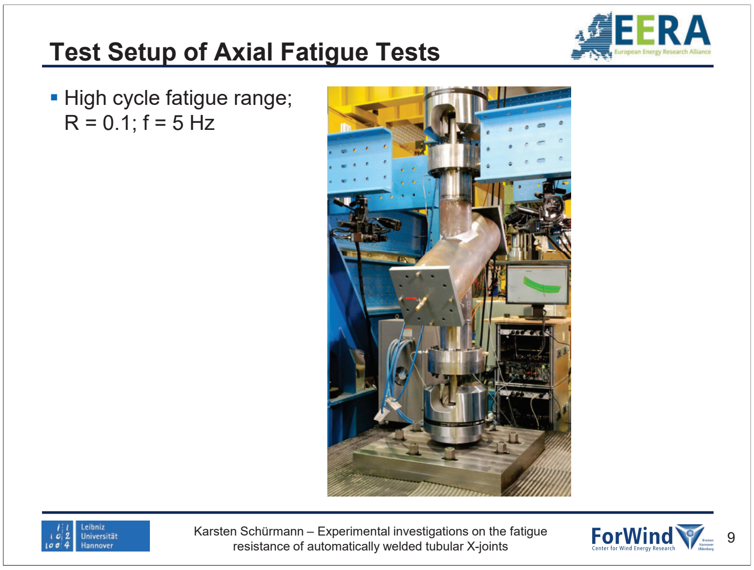
- Comparing weld geometry of 28 tubular X-joints



Reproducibility of Weld Geometry

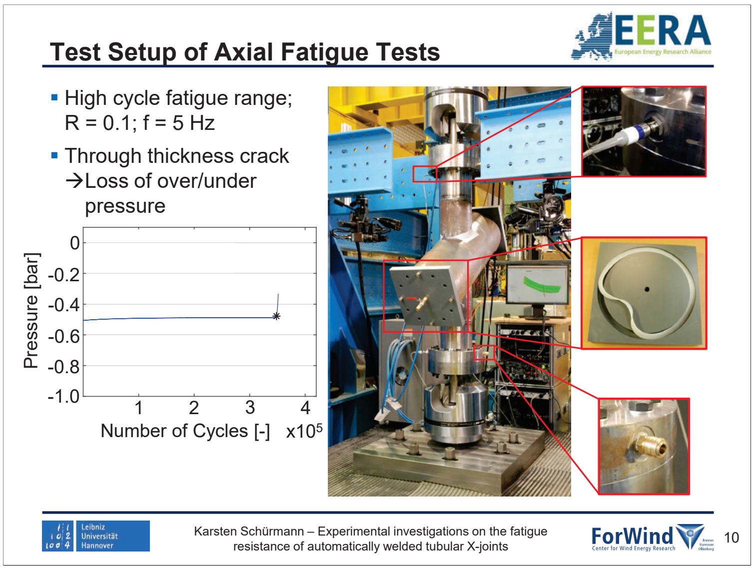
- Comparing weld geometry of 28 tubular X-joints

  →Good reproducibility is given



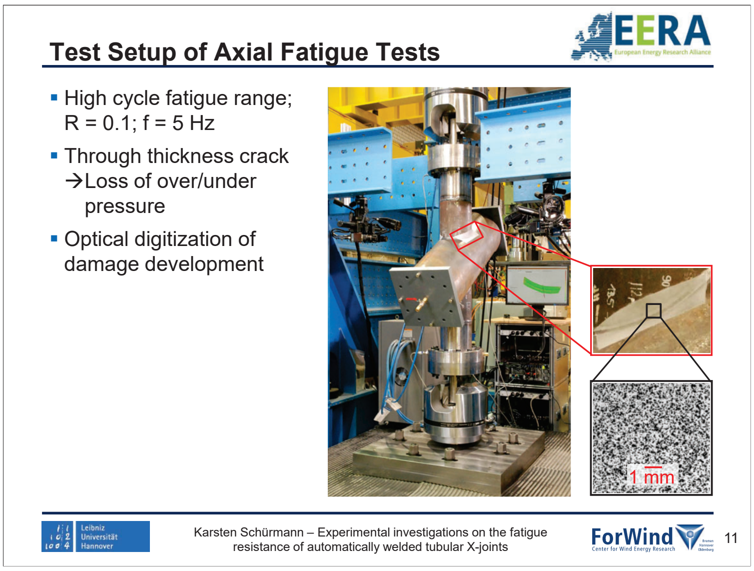
Test Setup of Axial Fatigue Tests

- High cycle fatigue range; R = 0.1; f = 5 Hz



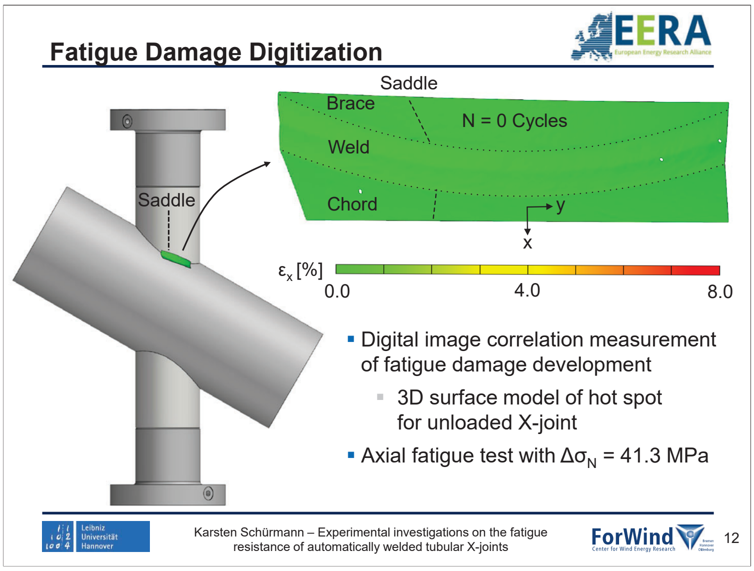
Test Setup of Axial Fatigue Tests

- High cycle fatigue range; R = 0.1; f = 5 Hz
- Through thickness crack →Loss of over/under pressure



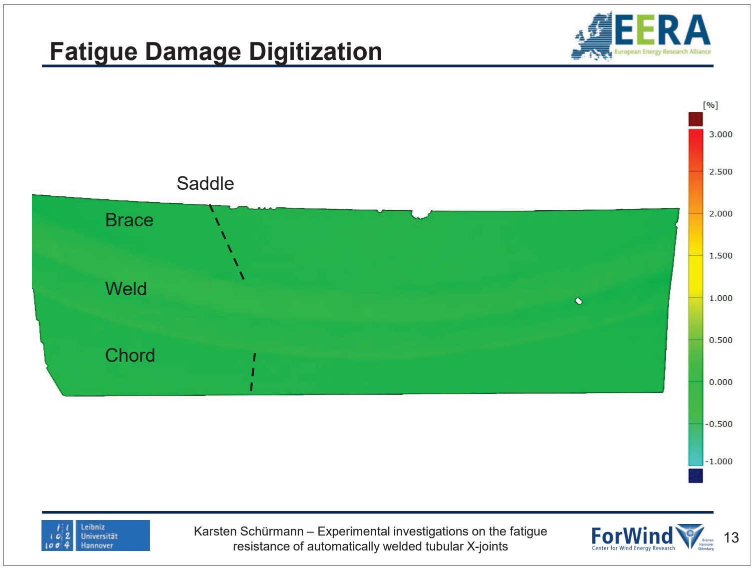
Test Setup of Axial Fatigue Tests

- High cycle fatigue range; R = 0.1; f = 5 Hz
- Through thickness crack
  →Loss of over/under pressure
- Optical digitization of damage development

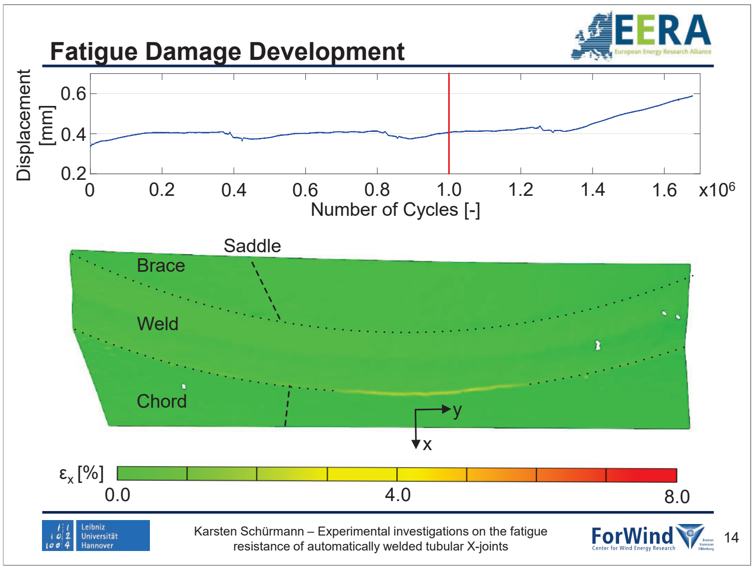


Fatigue Damage Digitization

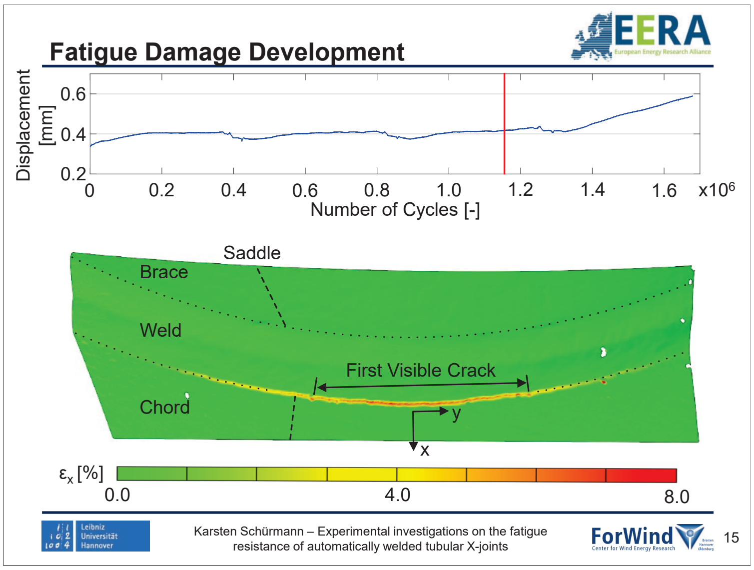
- Digital image correlation measurement of fatigue damage development
  - 3D surface model of hot spot for unloaded X-joint
- Axial fatigue test with $\Delta\sigma_N$ = 41.3 MPa



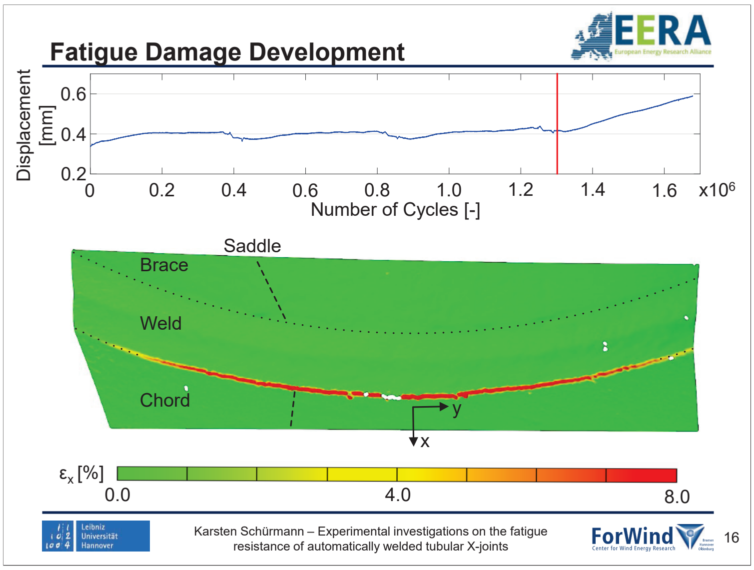
Fatigue Damage Digitization



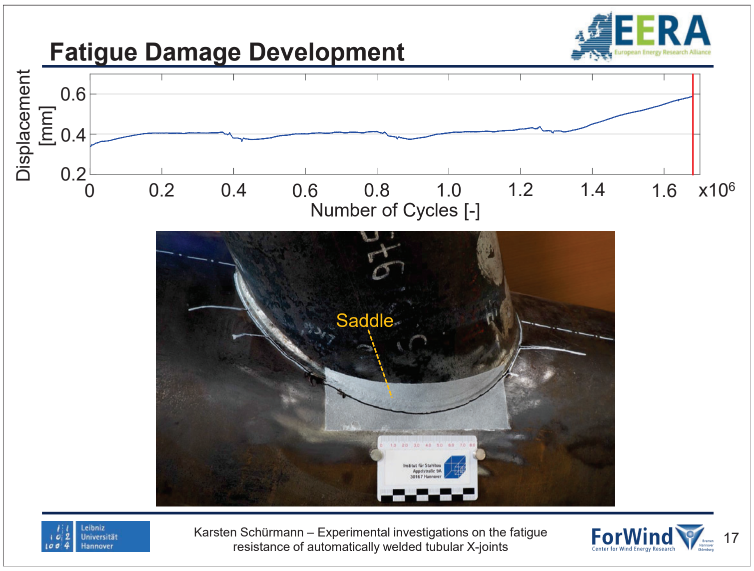
Fatigue Damage Development



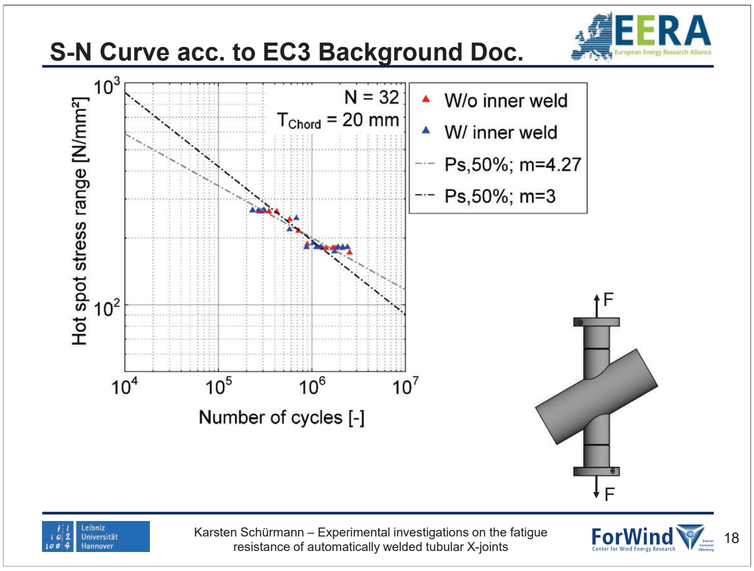
Fatigue Damage Development



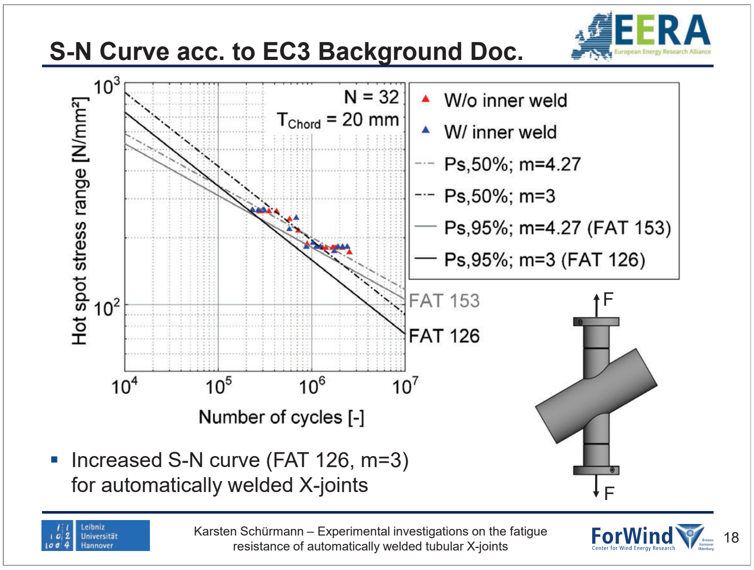
Fatigue Damage Development



Fatigue Damage Development

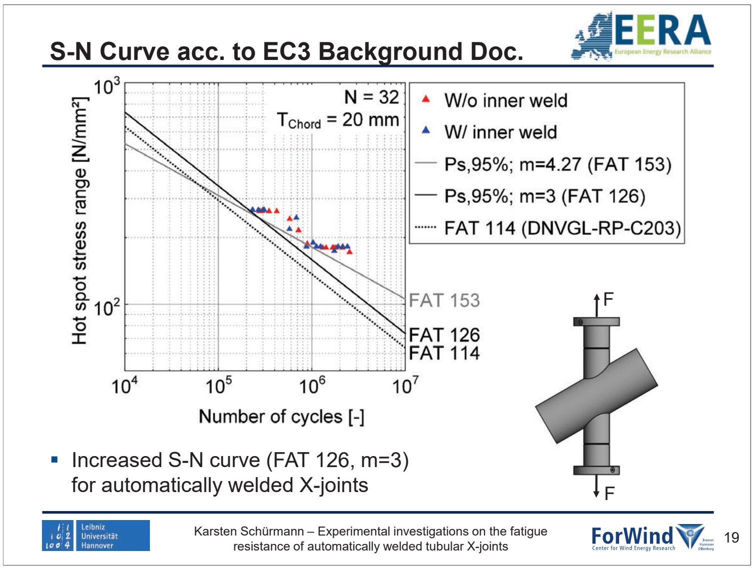


S-N Curve acc. to EC3 Background Doc.



S-N Curve acc. to EC3 Background Doc.

- Increased S-N curve (FAT 126, m=3) for automatically welded X-joints



S-N Curve acc. to EC3 Background Doc.

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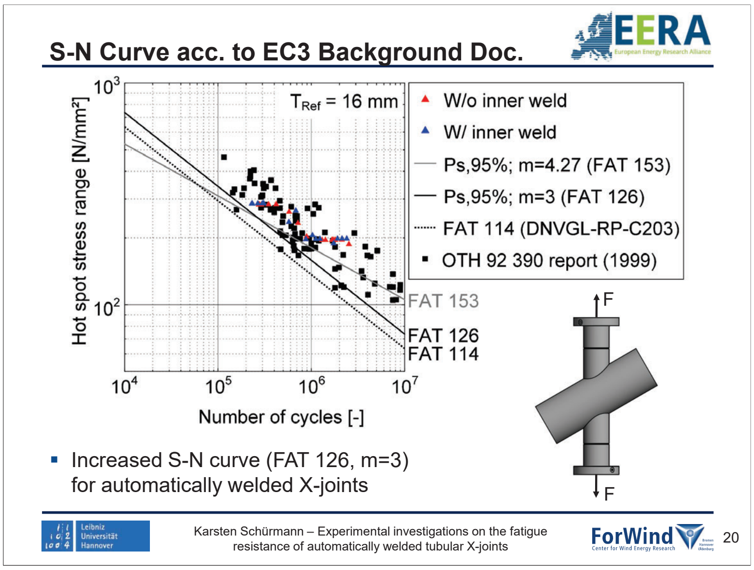

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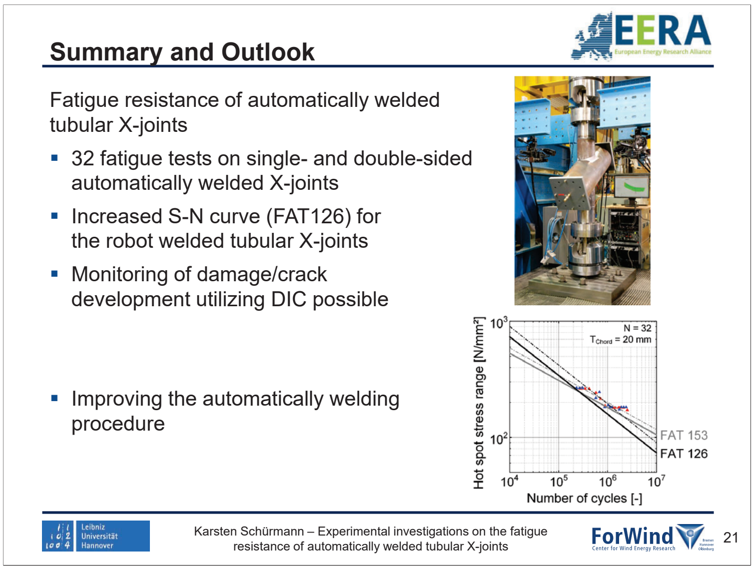

Summary and Outlook

Fatigue resistance of automatically welded tubular X-joints

- 32 fatigue tests on single- and double-sided automatically welded X-joints
- Increased S-N curve (FAT126) for the robot welded tubular X-joints
- Monitoring of damage/crack development utilizing DIC possible
- Improving the automatically welding procedure

Thank you for your attention!

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Thank you to our project partners and supporters!

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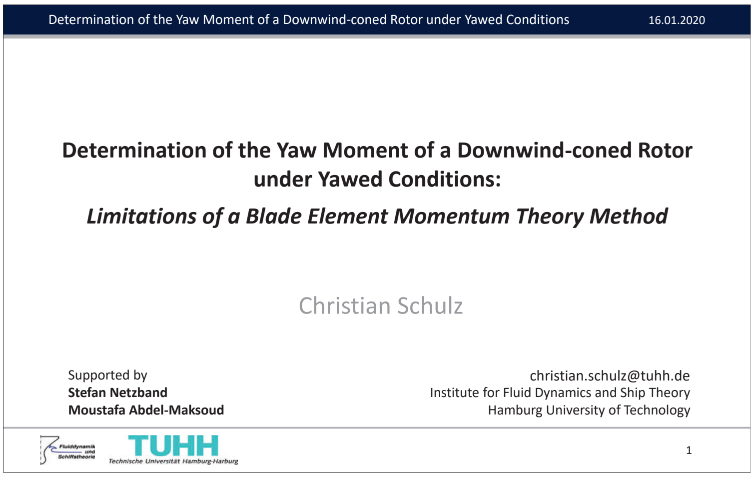
on the basis of a decision
by the German Bundestag

The IGF project 19104 N of the FOSTA was supported via AiF within the programme for promoting the Industrial Collective Research (IGF) of the German Ministry of Economic Affairs and Energy (BMWi), based on a resolution of the German Parliament.



Determination of the Yaw Moment of a Downwind-coned Rotor under Yawed Conditions:

Limitations of a Blade Element Momentum Theory Method

Christian Schulz

Supported by
Stefan Netzband
Moustafa Abdel-Maksoud

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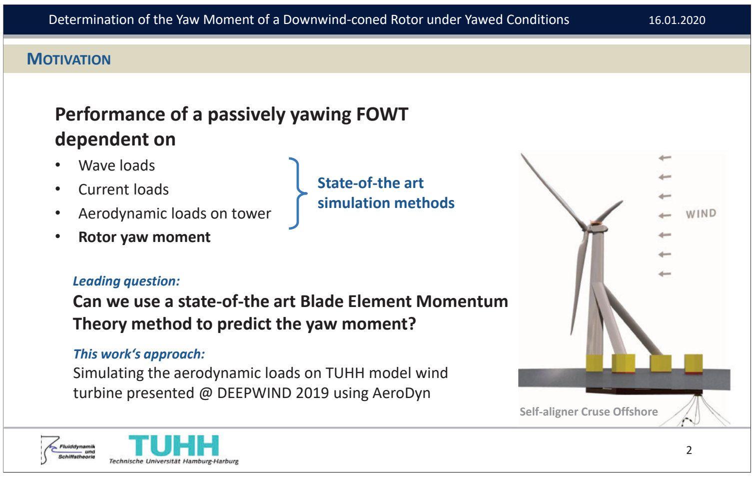
Institute for Fluid Dynamics and Ship Theory
Hamburg University of Technology



MOTIVATION

Performance of a passively yawing FOWT dependent on

- Wave loads
- Current loads
- Aerodynamic loads on tower
- **Rotor yaw moment**

} **State-of-the art simulation methods**

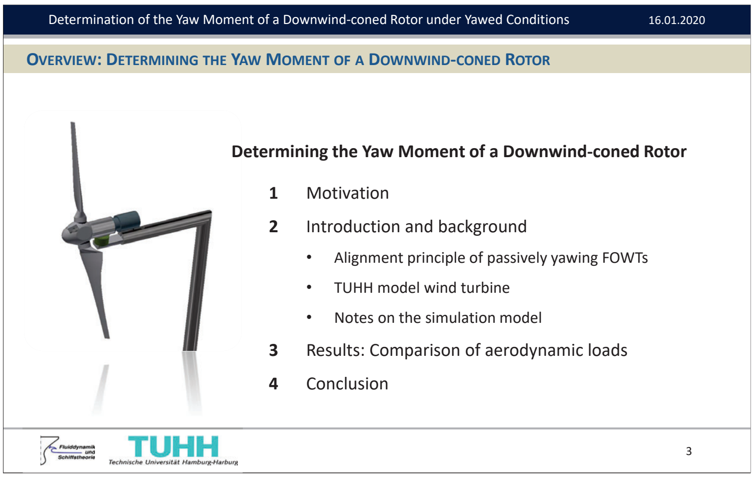
Leading question:

Can we use a state-of-the art Blade Element Momentum Theory method to predict the yaw moment?

This work's approach:

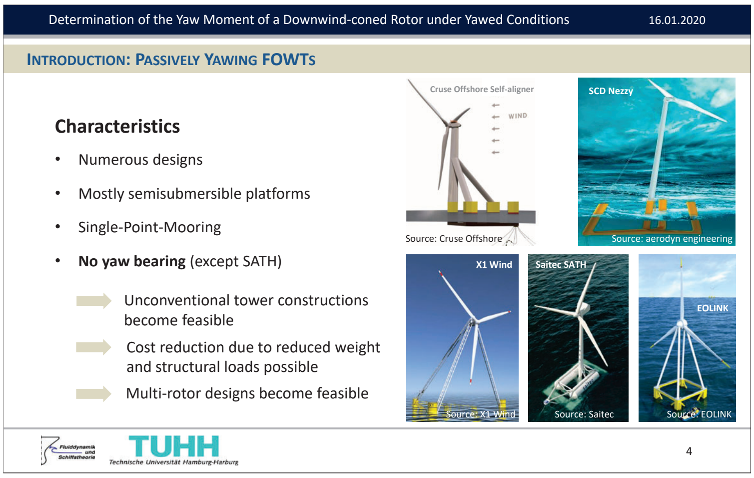
Simulating the aerodynamic loads on TUHH model wind turbine presented @ DEEPWIND 2019 using AeroDyn

Self-aligner Cruse Offshore



OVERVIEW: DETERMINING THE YAW MOMENT OF A DOWNWIND-CONED ROTOR

Determining the Yaw Moment of a Downwind-coned Rotor



INTRODUCTION: PASSIVELY YAWING FOWTS

Characteristics

- Numerous designs
- Mostly semisubmersible platforms
- Single-Point-Mooring
- **No yaw bearing** (except SATH)

⇨ Unconventional tower constructions become feasible

⇨ Cost reduction due to reduced weight and structural loads possible

⇨ Multi-rotor designs become feasible

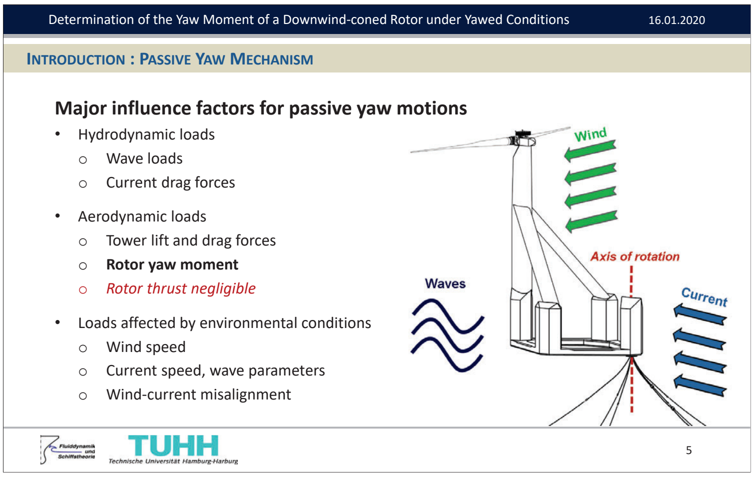
Source: Cruse Offshore

Source: aerodyn engineering

Source: X1 Wind

Source: Saitec

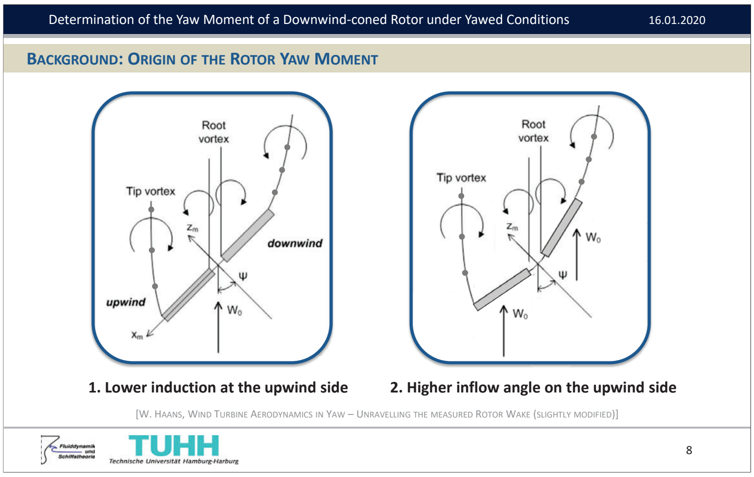
Source: EOLINK



INTRODUCTION : PASSIVE YAW MECHANISM

Major influence factors for passive yaw motions

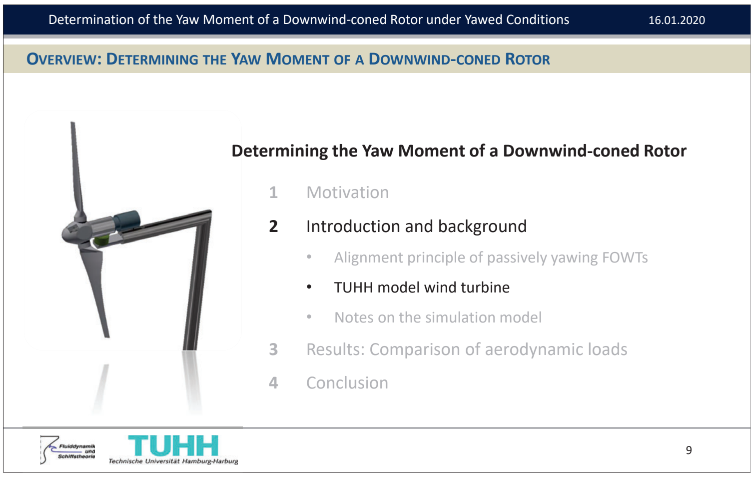
- Hydrodynamic loads
  - Wave loads
  - Current drag forces
- Aerodynamic loads
  - Tower lift and drag forces
  - **Rotor yaw moment**
  - *Rotor thrust negligible*
- Loads affected by environmental conditions
  - Wind speed
  - Current speed, wave parameters
  - Wind-current misalignment



BACKGROUND: ORIGIN OF THE ROTOR YAW MOMENT

1. Lower induction at the upwind side **2. Higher inflow angle on the upwind side**

[W. HAANS, WIND TURBINE AERODYNAMICS IN YAW – UNRAVELLING THE MEASURED ROTOR WAKE (SLIGHTLY MODIFIED)]



Overview: Determining the Yaw Moment of a Downwind-coned Rotor

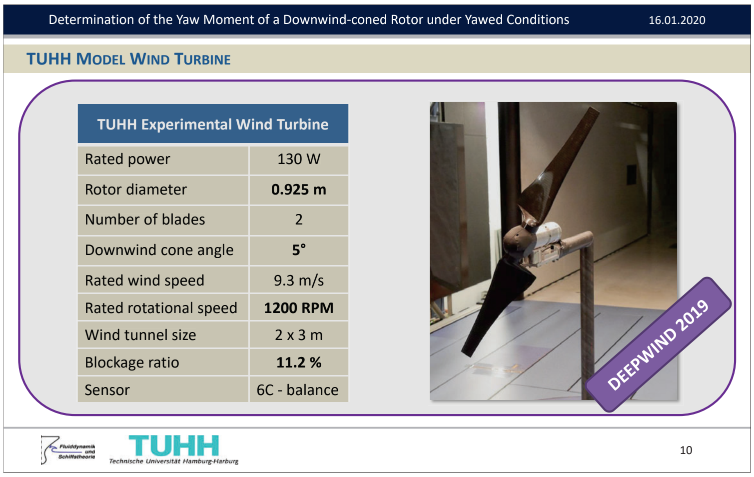
Determining the Yaw Moment of a Downwind-coned Rotor

1 Motivation

2 Introduction and background
- Alignment principle of passively yawing FOWTs
- TUHH model wind turbine
- Notes on the simulation model

3 Results: Comparison of aerodynamic loads

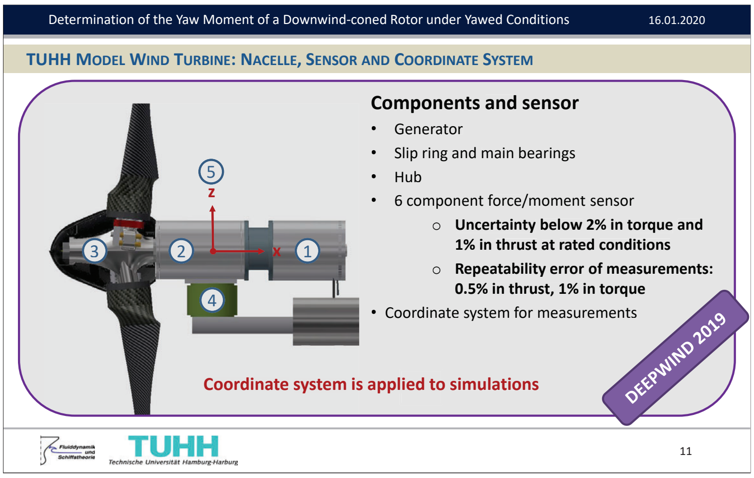
4 Conclusion



TUHH Model Wind Turbine

TUHH Experimental Wind Turbine	
Rated power	130 W
Rotor diameter	**0.925 m**
Number of blades	2
Downwind cone angle	**5°**
Rated wind speed	9.3 m/s
Rated rotational speed	**1200 RPM**
Wind tunnel size	2 x 3 m
Blockage ratio	**11.2 %**
Sensor	6C - balance

DEEPWIND 2019

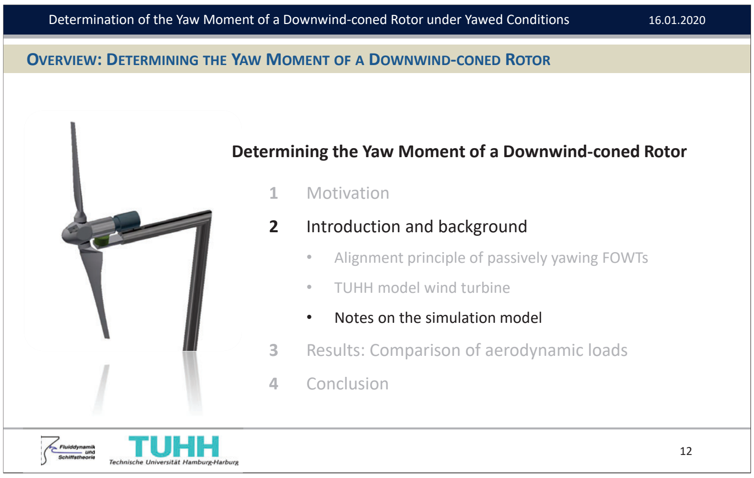


TUHH Model Wind Turbine: Nacelle, Sensor and Coordinate System

Components and sensor
- Generator
- Slip ring and main bearings
- Hub
- 6 component force/moment sensor
  - **Uncertainty below 2% in torque and 1% in thrust at rated conditions**
  - **Repeatability error of measurements: 0.5% in thrust, 1% in torque**
- Coordinate system for measurements

Coordinate system is applied to simulations

DEEPWIND 2019



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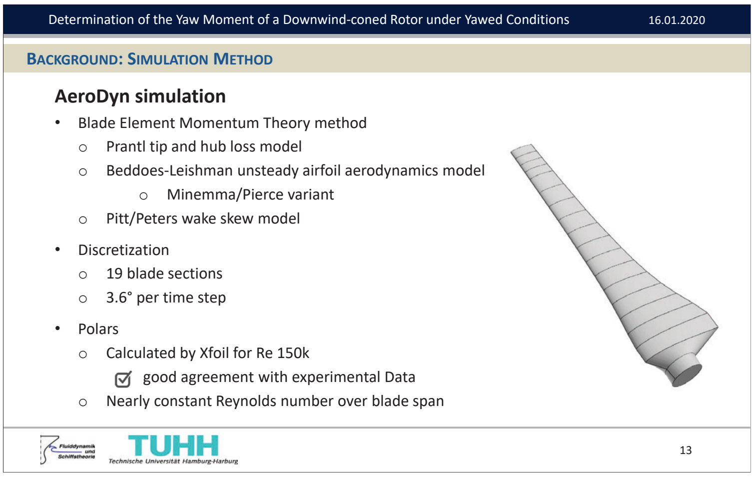
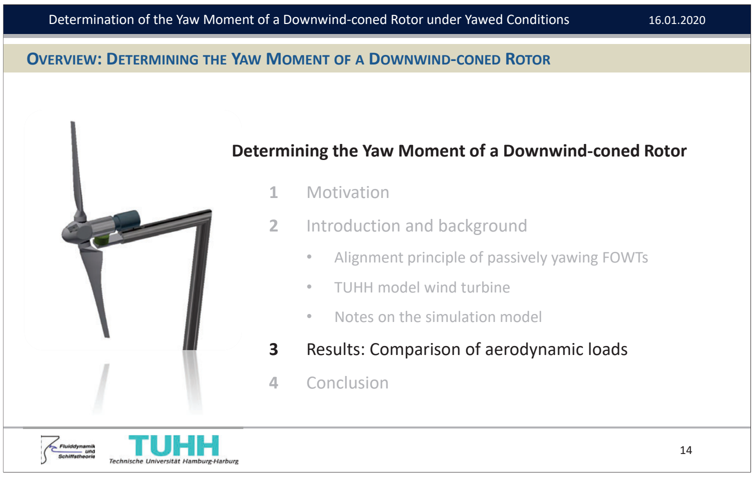


Background: Simulation Method

AeroDyn simulation
- Blade Element Momentum Theory method
  - Prantl tip and hub loss model
  - Beddoes-Leishman unsteady airfoil aerodynamics model
    - Minemma/Pierce variant
  - Pitt/Peters wake skew model
- Discretization
  - 19 blade sections
  - 3.6° per time step
- Polars
  - Calculated by Xfoil for Re 150k
    - ☑ good agreement with experimental Data
  - Nearly constant Reynolds number over blade span



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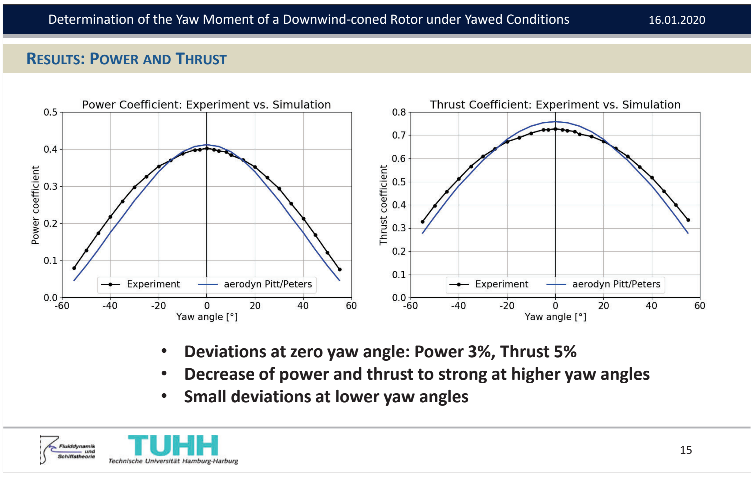
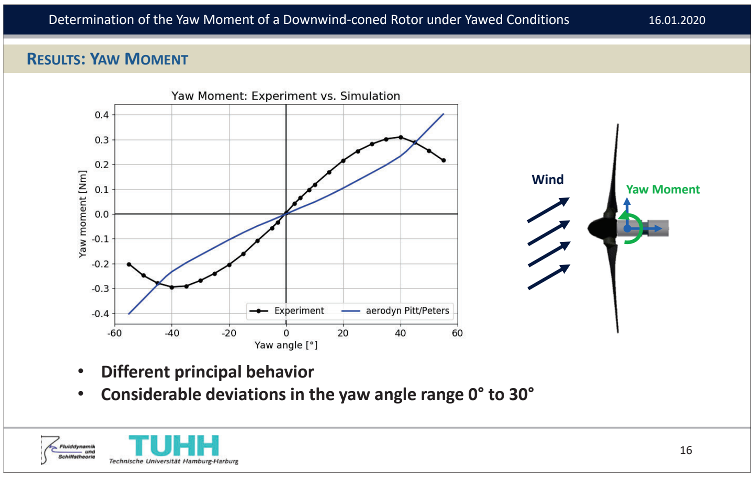


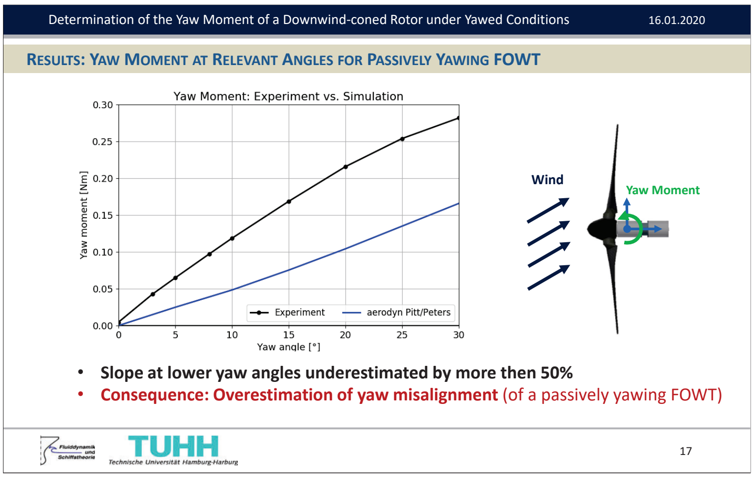
RESULTS: POWER AND THRUST

- **Deviations at zero yaw angle: Power 3%, Thrust 5%**
- **Decrease of power and thrust to strong at higher yaw angles**
- **Small deviations at lower yaw angles**



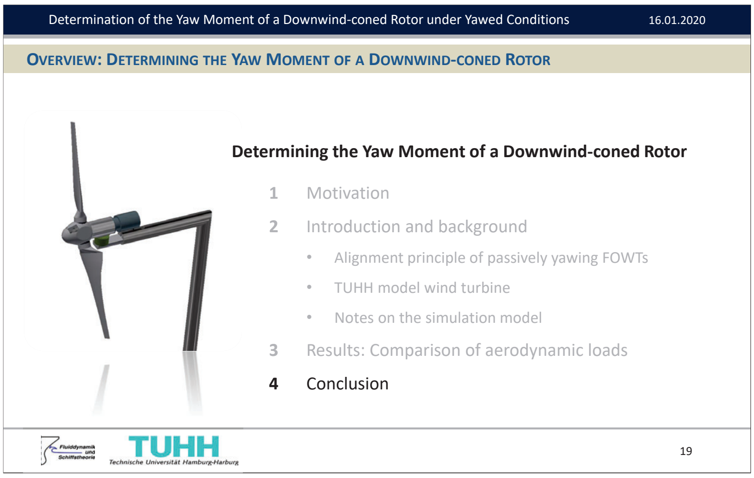
RESULTS: YAW MOMENT

- **Different principal behavior**
- **Considerable deviations in the yaw angle range 0° to 30°**



RESULTS: YAW MOMENT AT RELEVANT ANGLES FOR PASSIVELY YAWING FOWT

- **Slope at lower yaw angles underestimated by more then 50%**
- **Consequence: Overestimation of yaw misalignment** (of a passively yawing FOWT)



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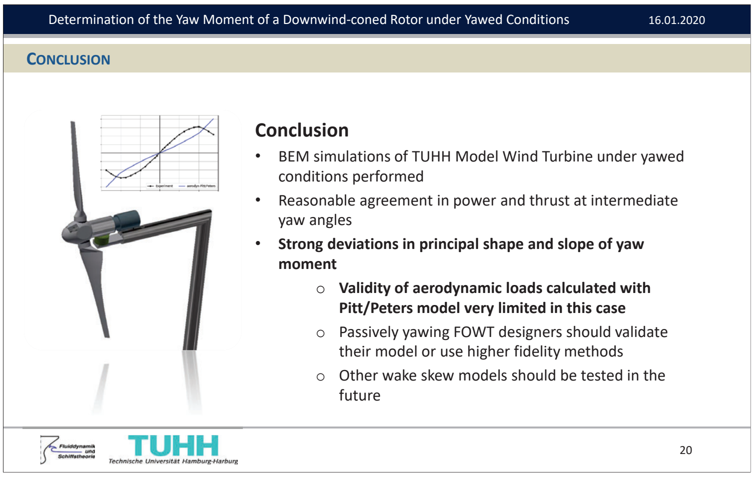
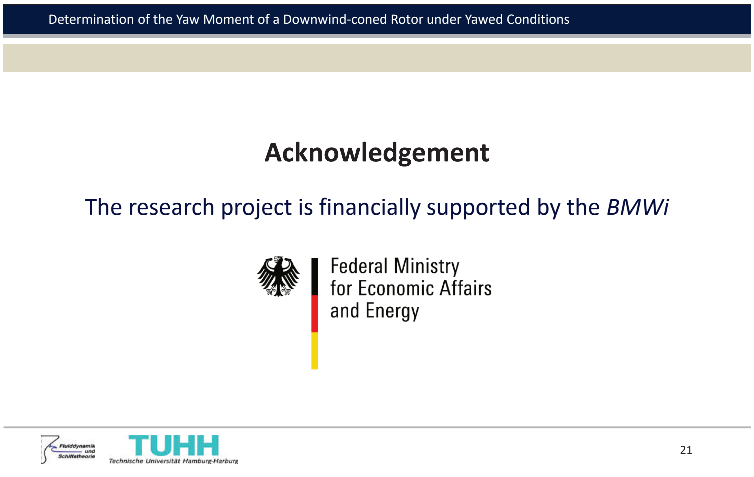


CONCLUSION

Conclusion

- BEM simulations of TUHH Model Wind Turbine under yawed conditions performed
- Reasonable agreement in power and thrust at intermediate yaw angles
- **Strong deviations in principal shape and slope of yaw moment**
    - **Validity of aerodynamic loads calculated with Pitt/Peters model very limited in this case**
    - Passively yawing FOWT designers should validate their model or use higher fidelity methods
    - Other wake skew models should be tested in the future



Acknowledgement

The research project is financially supported by the *BMWi*

Federal Ministry
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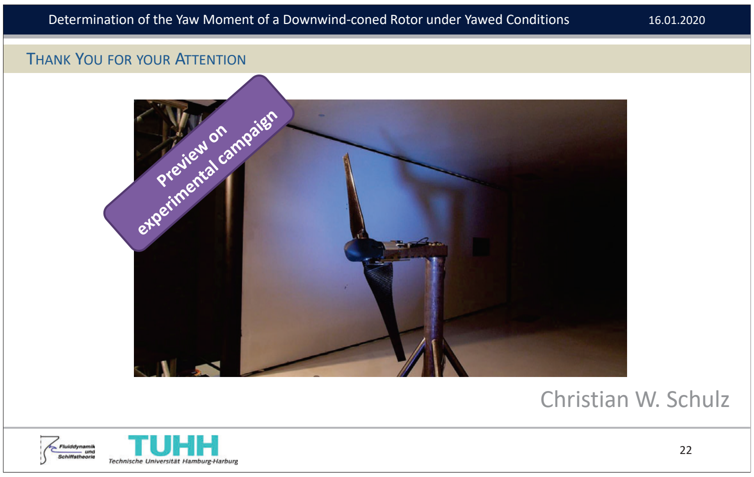
and Energy



Determination of the Yaw Moment of a Downwind-coned Rotor under Yawed Conditions 16.01.2020

THANK YOU FOR YOUR ATTENTION

Preview on experimental campaign

Christian W. Schulz

Fluiddynamik und Schiffstheorie

TUHH Technische Universität Hamburg-Harburg

G2) Experimental Testing and Validation

Hydrodynamic testing of a flexible, large-diameter monopile in regular and irregular waves: observations and effects of wave generation techniques, E.Bachynski, NTNU

Validation of Drift Motions for a Semi-submersible Floating Wind Turbine and the Associated Challenges, M.Y.Mahfouz, Stuttgart Wind Energy

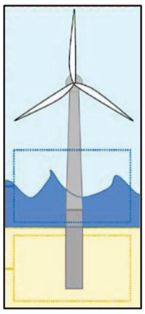
Hybrid Modelling for Engineering Design of Floating Offshore Wind Turbine Foundations – Model Coupling and Validation, P.D.Tomaselli, DHI

On the real time hybrid modelling of floating offshore wind turbine using ducted fan(s), F.Petrie, Oceanide

Observations from hydrodynamic testing of a flexible, large-diameter monopile in irregular waves

Erin Bachynski, NTNU (erin.bachynski@ntnu.no)
Maxime Thys, SINTEF Ocean
Fatemeh Hoseini Dadmarzi, NTNU

Norwegian University of Science and Technology



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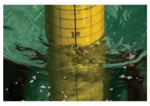
https://www.sintef.no/projectweb/was-xl

Background

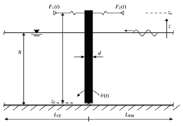
- Larger wind turbines, deeper water, larger monopiles
  - Concerns about dynamic responses to severe waves (ULS)
- Need for validation of numerical models
  - Experimental campaigns

Rigid model



Kristiansen and Faltinsen, 2017

Pitching model



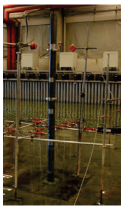
Riise et al., 2018

Bachynski et al. 2017

Flexible model

de Ridder et al., 2011

Bachynski et al. 2019



Bredmose et al., 2013

What's new?

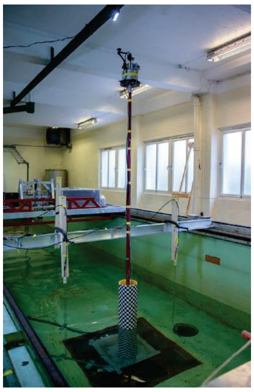
- Larger diameter, larger top mass
- More realizations
- More repetitions
- Measurements of both base shear and bending moment
- Variations in damping level (1.14% and 1.7%)

	Scale	h (m)	D (m)	f_1 (Hz)	f_2 (Hz)	ξ_1 (%)	ξ_2(%)
WiFi[1]	1:30	30	5.8-7.0	0.29	1.21	1.1	1.1
WaveLoads[2]	1:80	20.8-40.8	6.0	0.28	2.0	1.7	1.7
NOWITECH[3]	1:40	30	7.0	0.22	0.85	0.5	-
WAS-XL Phase II	1:50	27	9.0	0.25	1.58	1.1	0.4

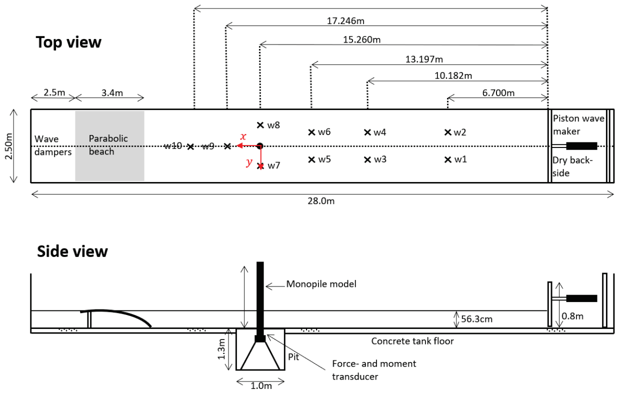
1. Suja-Thauvin et al. 2017, de Ridder et al. 2011, de Ridder et al. 2017
2. Nielsen et al. 2012, Bredmose et al. 2013, Hansen et al. 2012
3. Bachynski et al. 2019

Outline

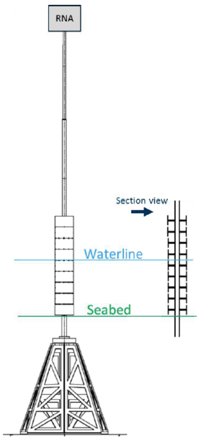
- Experimental design
- Decay tests
- Irregular wave test results
  - Distributions of extreme responses
  - Frequency content of extreme responses
  - Repeatability

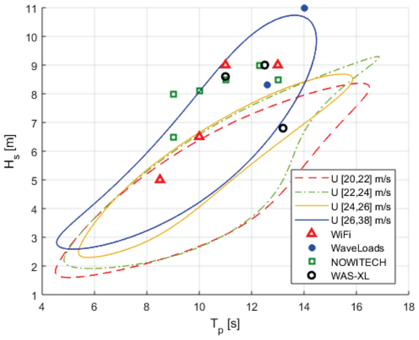


Experimental design

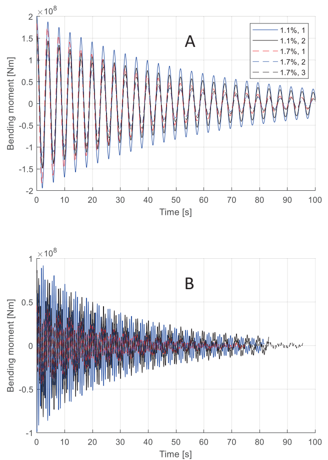


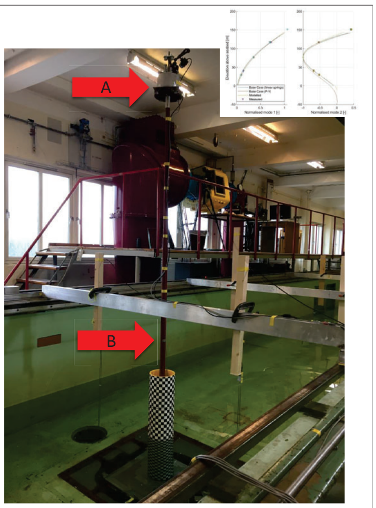
Experimental design



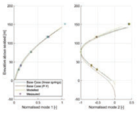


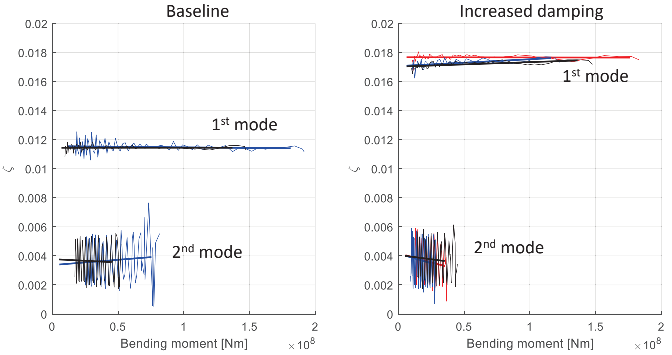
Decay tests



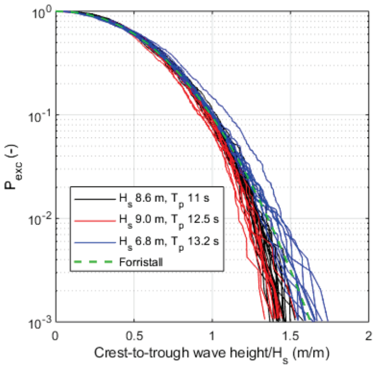


Damping



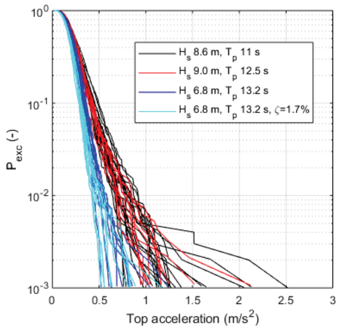


Probability of exceedance: crest-to-trough wave height



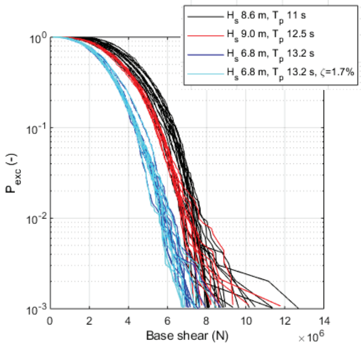
(Compare to Hansen et al. 2012)

Probability of exceedance: accelerations



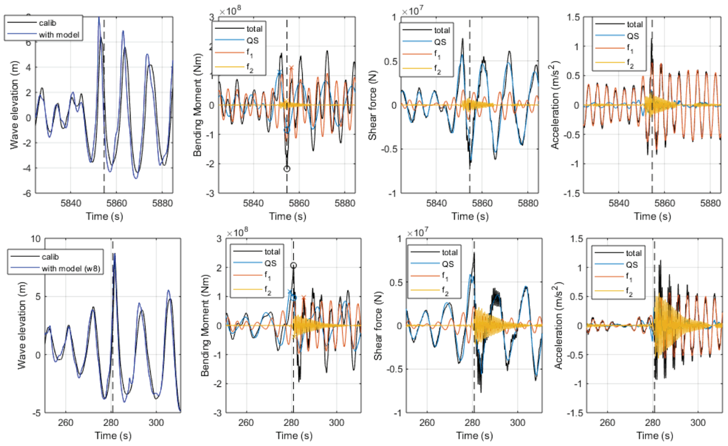
(Compare to Bredmose et al., 2013)

Probability of exceedance: base shear



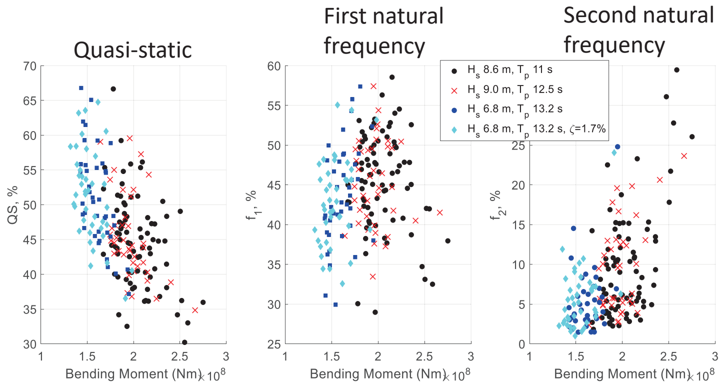
Compare to Bredmose et al., 2013

Frequency content of extreme responses

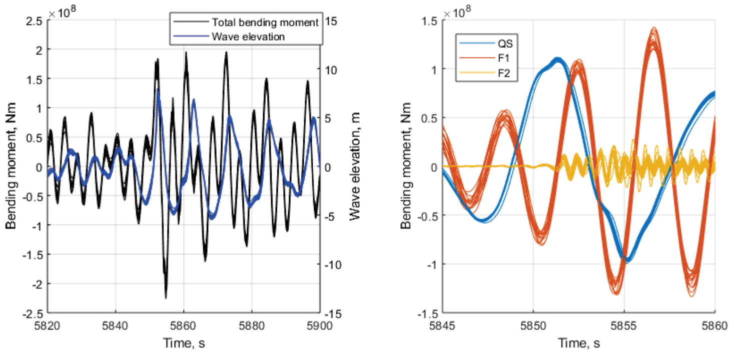


Compare to Suja-Thauvin et al. 2018

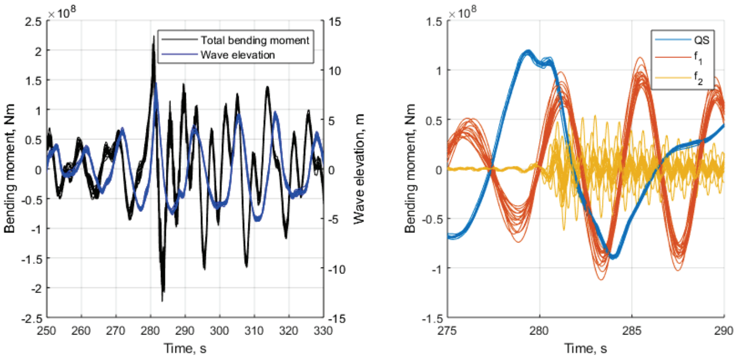
Frequency content of extreme responses



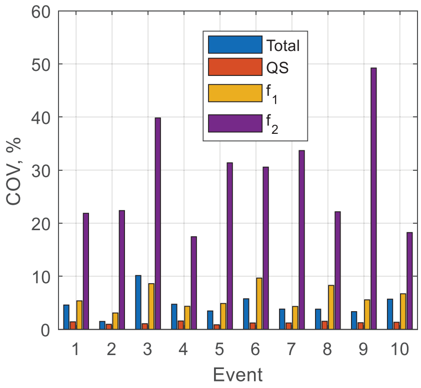
Repeatability: example 1



Repeatability: example 2



Repeatability: 10 events, 15 repetitions



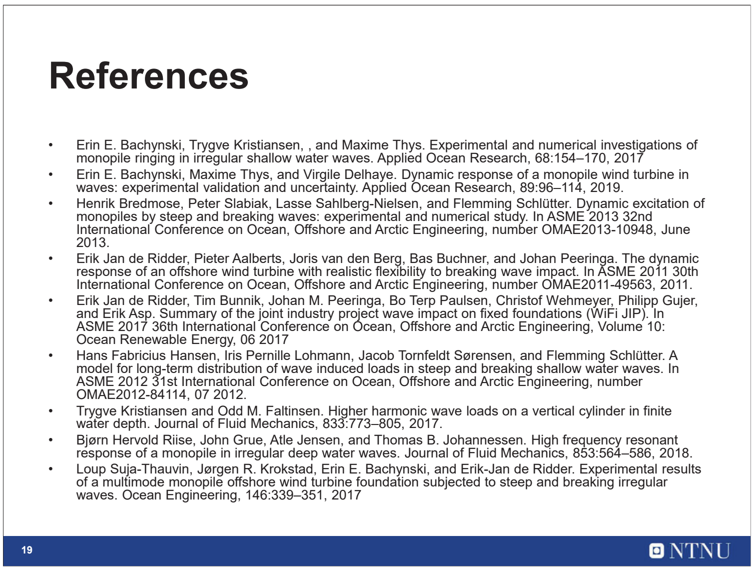
Summary

- Experimental campaign with a flexible monopile in severe waves
  - Larger diameter, larger top mass
  - More realizations and repetitions
  - Measurements of both base shear and bending moment
  - Variations in damping level (1.14% and 1.7%)
- Compared to previous experiments
  - Differences in distributions of responses
  - Similar relative contributions from different frequency bands
  - Larger damping appears to give better repeatability, but higher modes are less repeatable
  - (Not shown) more observations of large accelerations far from wave breaking limit
  - Additional results in the paper!

Acknowledgments

- This work is part of the Wave Loads and Soil Support for Extra Large Monopiles (WAS-XL) project, funded by NFR grant 26818 and industry partners

https://www.sintef.no/projectweb/was-xl



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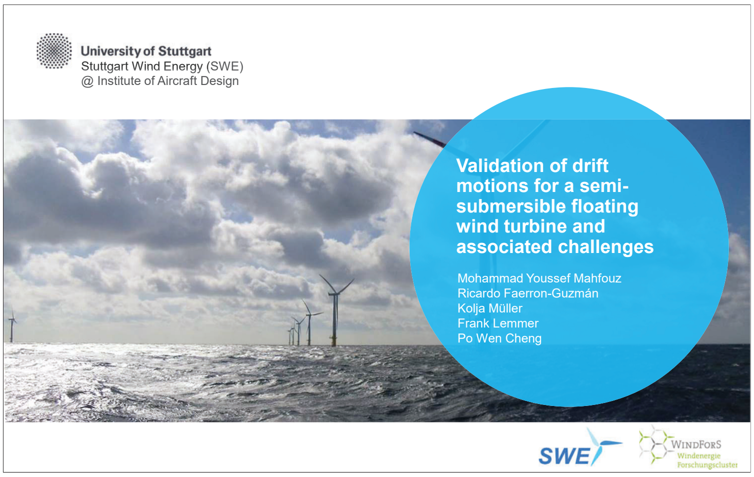
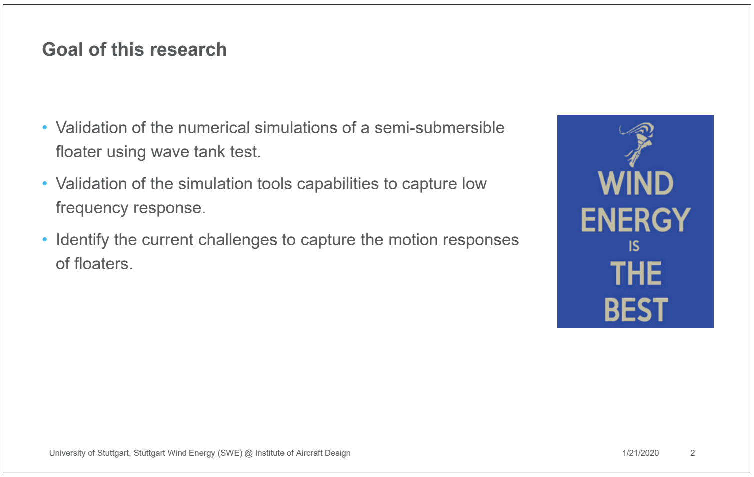


University of Stuttgart
Stuttgart Wind Energy (SWE)
@ Institute of Aircraft Design

Validation of drift motions for a semi-submersible floating wind turbine and associated challenges

Mohammad Youssef Mahfouz
Ricardo Faerron-Guzmán
Kolja Müller
Frank Lemmer
Po Wen Cheng



Goal of this research

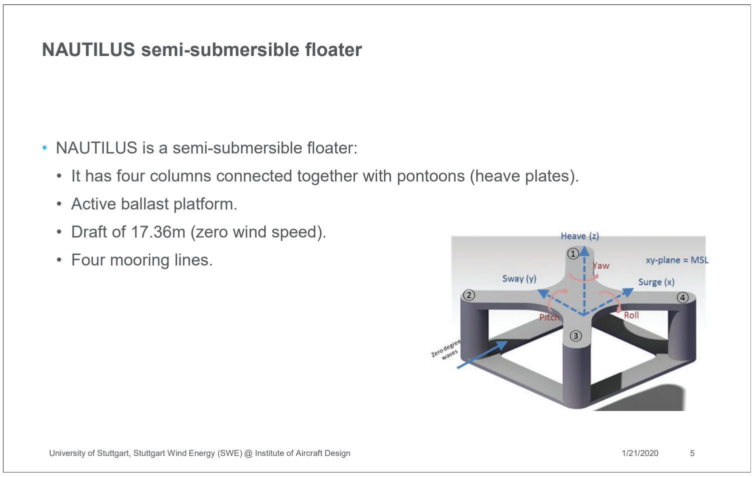
- Validation of the numerical simulations of a semi-submersible floater using wave tank test.
- Validation of the simulation tools capabilities to capture low frequency response.
- Identify the current challenges to capture the motion responses of floaters.

Work flow

- Choose relevant tests to achieve the research goals
- Calibrate the FAST model to match the experiments
- Damping properties for the platform
- Identification tests (decay and pullout tests)
- Load cases tests (pink wave and extreme irregular wave spectra)

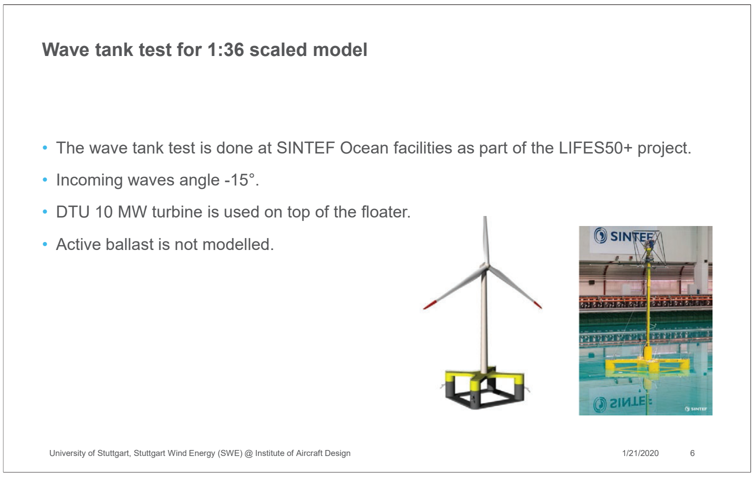
Tools used in the research

- FAST8 is used for numerical simulations.
  - First order radiation diffraction hydrodynamics using Cummins' equation.
  - RAOs are calculated using Ansys-AQWA.
  - Morison drag coefficients to capture viscous effects.
  - Second order difference frequency forces QTF.
- Mooring lines modelling
  - Static model using MAP++



NAUTILUS semi-submersible floater

- NAUTILUS is a semi-submersible floater:
  - It has four columns connected together with pontoons (heave plates).
  - Active ballast platform.
  - Draft of 17.36m (zero wind speed).
  - Four mooring lines.



Wave tank test for 1:36 scaled model

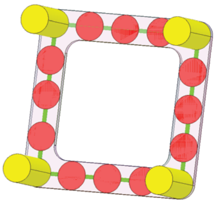
- The wave tank test is done at SINTEF Ocean facilities as part of the LIFES50+ project.
- Incoming waves angle -15°.
- DTU 10 MW turbine is used on top of the floater.
- Active ballast is not modelled.

Tests used in this study

- All the test used are in the absence of wind. The main focus in this study is the hydrodynamic response of the floater.
- The tests used are:
  - Heave and pitch decay tests without mooring.
  - All platform's degrees of freedom with mooring.
  - Pull out tests in the surge direction.
  - Pink noise wave spectra test (H_s=2m and T_p between 4.5-18.2 sec)
  - Extreme wave (Pierson-Moskowitz spectrum H_s=10.9 and T_p=15 sec)

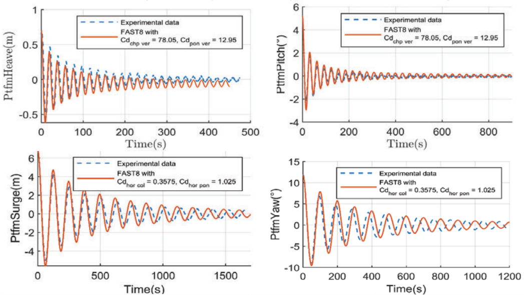
Platform's drag coefficients

- The damping discretization of the platform is done using four damping coefficients:
  - Vertical damping pontoon $Cd_{\text{ver pon}}$ (red circles)
  - Vertical drag coef. column $Cd_{\text{ver col}}$ (yellow)
  - Horizontal drag coef. column $Cd_{\text{hor col}}$ (yellow)
  - Horizontal drag coef. Pontoon $Cd_{\text{hor pon}}$ (green)



Decay tests

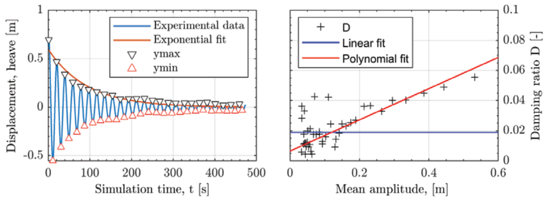
Heave, pitch, surge, and yaw decay tests with mooring



- Heave, pitch and roll responses are affected by vertical drag
- Surge, sway and yaw responses are affected by horizontal drag

	$Cd_{\text{ver col}}$	$Cd_{\text{ver pon}}$	$Cd_{\text{hor col}}$	$Cd_{\text{hor pon}}$	Specific weight mooring line (kg/m)
FAST8 decay tuned	78.05	12.95	0.3575	1.025	157.172

Experimental behavior of damping



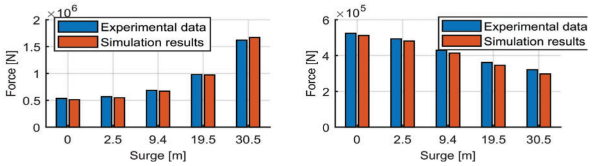
- Nonlinear damping behaviour.
- Dependency on both Keulegan-Carpenter (KC) number and Reynolds number.
- Hard to fit in a simple model.

Decay results discussions

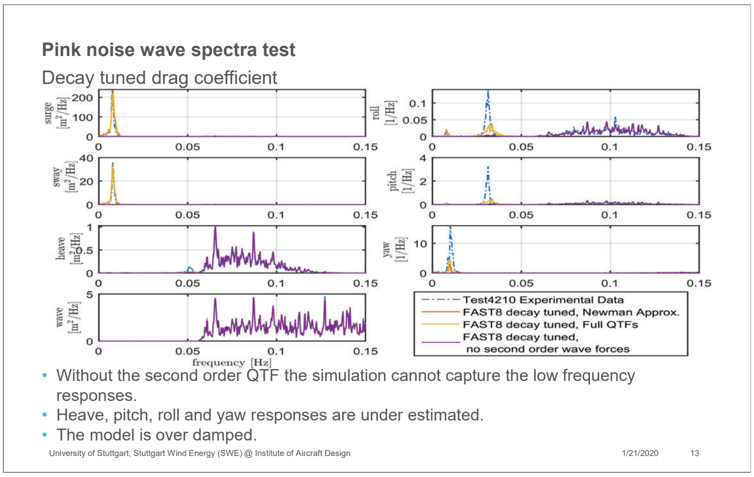
- This good match was only reached after decreasing the mooring lines specific mass.
- Pull out tests are simulated later to make sure that the mooring lines of the model are representative.

	Surge Moored	Heave Moored	Pitch Moored	Yaw Moored
Test (Hz)	0.0079	0.0527	0.0314	0.0110
FAST8 decay tuned (Hz)	0.0082	0.0533	0.0322	0.0100

Pull-out test



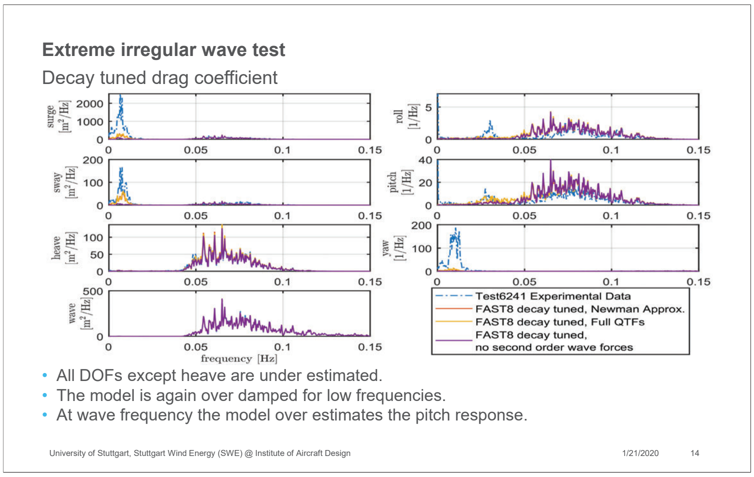
- Pull-out tests to check if the mooring lines used in the simulation model are representative to the wave test model.
- The tension of two different lines show that the model is representative.
- The changes in the mooring lines specific mass is acceptable.



Pink noise wave spectra test

Decay tuned drag coefficient

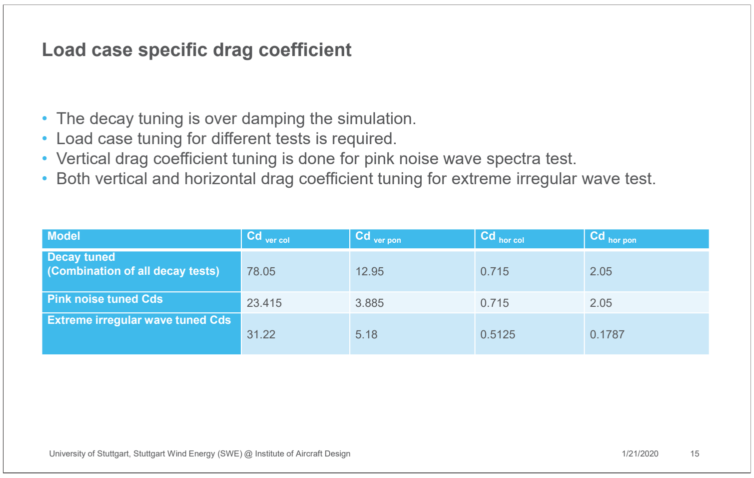
- Without the second order QTF the simulation cannot capture the low frequency responses.
- Heave, pitch, roll and yaw responses are under estimated.
- The model is over damped.



Extreme irregular wave test

Decay tuned drag coefficient

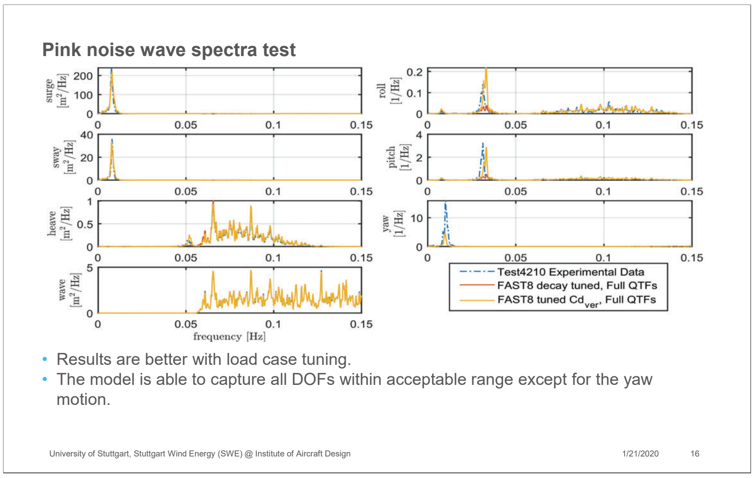
- All DOFs except heave are under estimated.
- The model is again over damped for low frequencies.
- At wave frequency the model over estimates the pitch response.



Load case specific drag coefficient

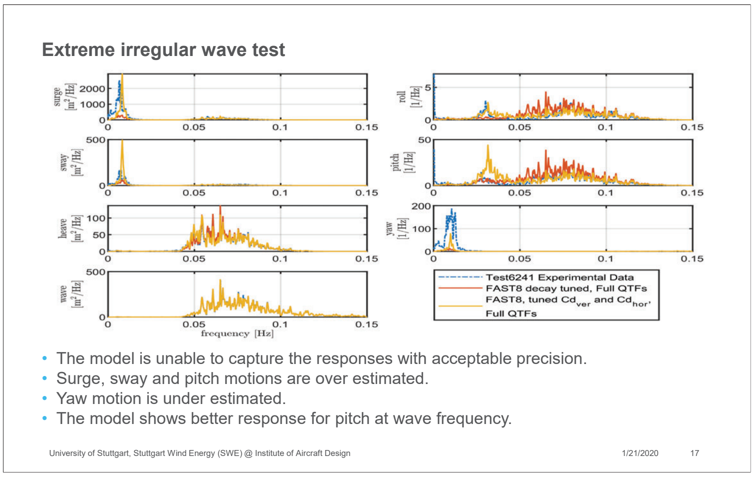
- The decay tuning is over damping the simulation.
- Load case tuning for different tests is required.
- Vertical drag coefficient tuning is done for pink noise wave spectra test.
- Both vertical and horizontal drag coefficient tuning for extreme irregular wave test.

Model	$Cd_{ver\ col}$	$Cd_{ver\ pon}$	$Cd_{hor\ col}$	$Cd_{hor\ pon}$
Decay tuned (Combination of all decay tests)	78.05	12.95	0.715	2.05
Pink noise tuned Cds	23.415	3.885	0.715	2.05
Extreme irregular wave tuned Cds	31.22	5.18	0.5125	0.1787



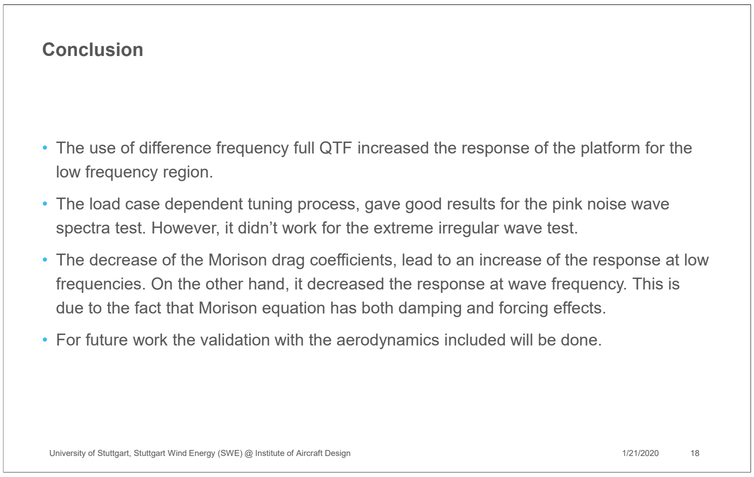
Pink noise wave spectra test

- Results are better with load case tuning.
- The model is able to capture all DOFs within acceptable range except for the yaw motion.



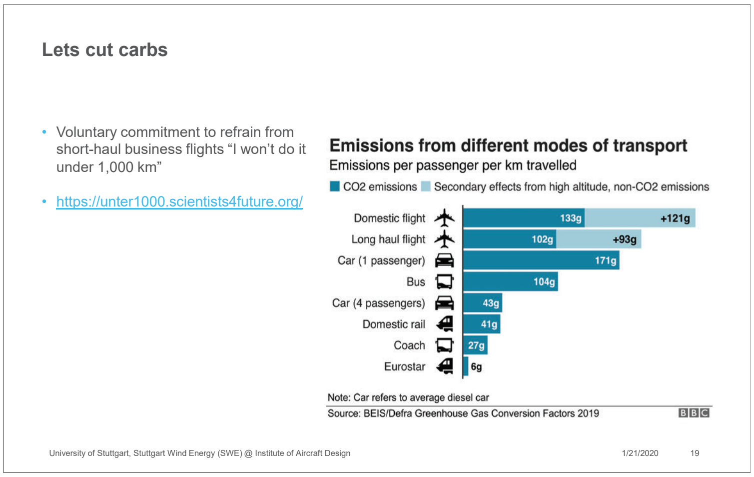
Extreme irregular wave test

- The model is unable to capture the responses with acceptable precision.
- Surge, sway and pitch motions are over estimated.
- Yaw motion is under estimated.
- The model shows better response for pitch at wave frequency.



Conclusion

- The use of difference frequency full QTF increased the response of the platform for the low frequency region.
- The load case dependent tuning process, gave good results for the pink noise wave spectra test. However, it didn't work for the extreme irregular wave test.
- The decrease of the Morison drag coefficients, lead to an increase of the response at low frequencies. On the other hand, it decreased the response at wave frequency. This is due to the fact that Morison equation has both damping and forcing effects.
- For future work the validation with the aerodynamics included will be done.



Lets cut carbs

- Voluntary commitment to refrain from short-haul business flights “I won’t do it under 1,000 km”
- https://unter1000.scientists4future.org/

Emissions from different modes of transport

Emissions per passenger per km travelled

Note: Car refers to average diesel car

Source: BEIS/Defra Greenhouse Gas Conversion Factors 2019

University of Stuttgart, Stuttgart Wind Energy (SWE) @ Institute of Aircraft Design 1/21/2020 19

University of Stuttgart

Thank you!

The research leading to these results has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement 640741 (LIFES50+).

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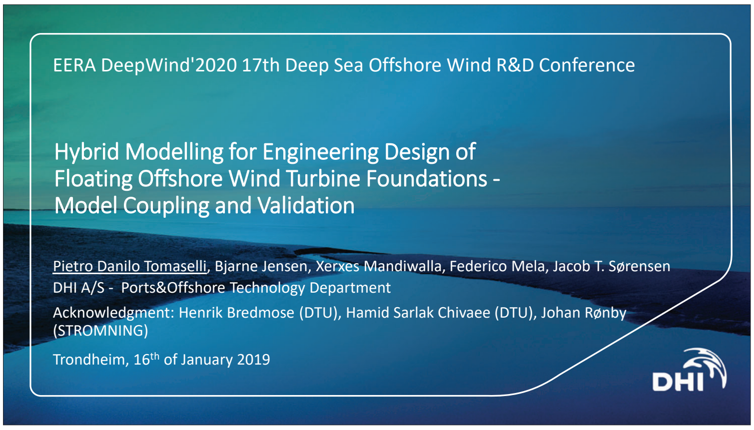

EERA DeepWind'2020 17th Deep Sea Offshore Wind R&D Conference

Hybrid Modelling for Engineering Design of Floating Offshore Wind Turbine Foundations - Model Coupling and Validation

Pietro Danilo Tomaselli, Bjarne Jensen, Xerxes Mandiwalla, Federico Mela, Jacob T. Sørensen
DHI A/S - Ports&Offshore Technology Department

Acknowledgment: Henrik Bredmose (DTU), Hamid Sarlak Chivaee (DTU), Johan Rønby (STROMNING)

Trondheim, 16th of January 2019

FloatStep research project

Support commercial breakthrough of Offshore Floating Wind technology by:

- Reducing cost by structural optmization
- Enabling accurate design by validated engineering tools
- Reducing risk from extreme waves by detailed flow simulations
- Reducing risk during installation and operation by lab tests and full scale data

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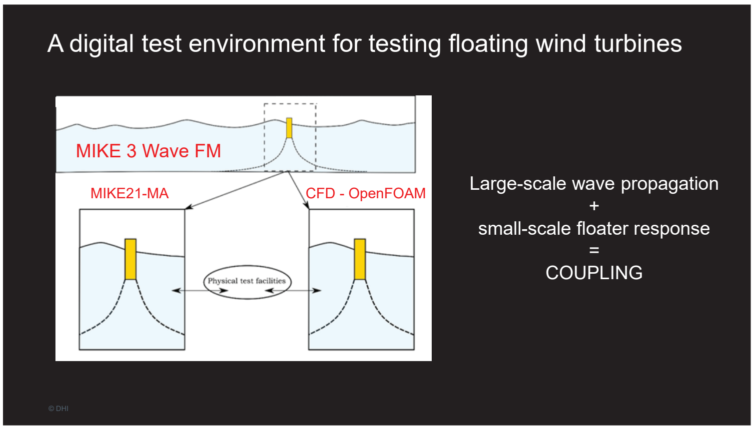
A digital test environment for testing floating wind turbines



Large-scale wave propagation
+
small-scale floater response
=
COUPLING

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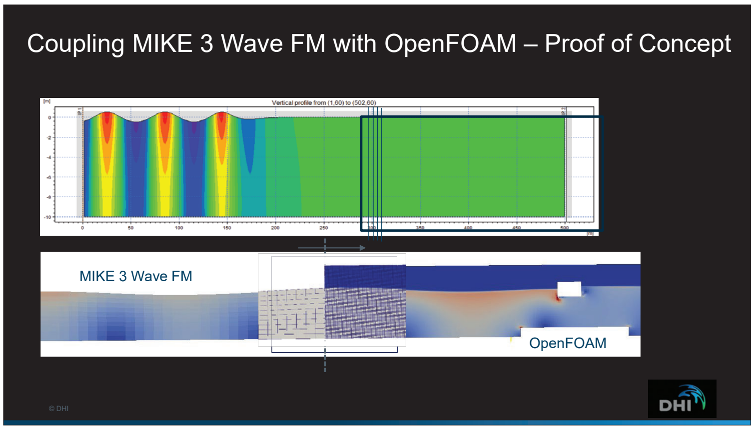
Coupling MIKE 3 Wave FM with OpenFOAM – Proof of Concept



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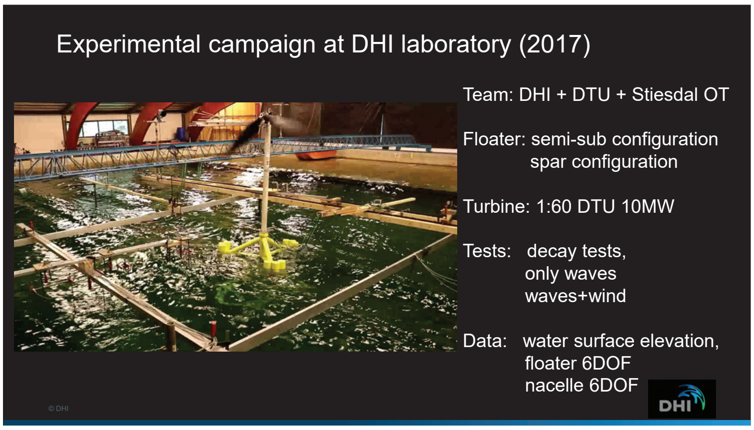
Experimental campaign at DHI laboratory (2017)



Team: DHI + DTU + Stiesdal OT

Floater: semi-sub configuration
spar configuration

Turbine: 1:60 DTU 10MW

Tests: decay tests,
only waves
waves+wind

Data: water surface elevation,
floater 6DOF
nacelle 6DOF

© DHI

CFD model validation - plan

Experimental test	Numerical model
• Regular waves Parameters: Hs=0.175 m, Tp=1.83 s Duration of the test = 1500 s • Focused waves Parameters: Hs=0.175 m, Tp=1.83 s Duration of the test = 60 s	Open source `interIsoFoam` 2-fluid transient solver Free surface tracking with isoAdvector Morphing mesh capability Suitable for parallel computation Standard 6 DoF- rigid body coupling (*on-going improvement!)

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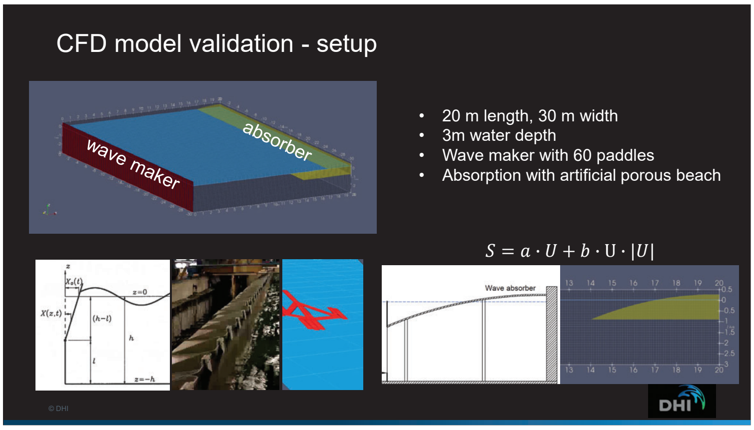
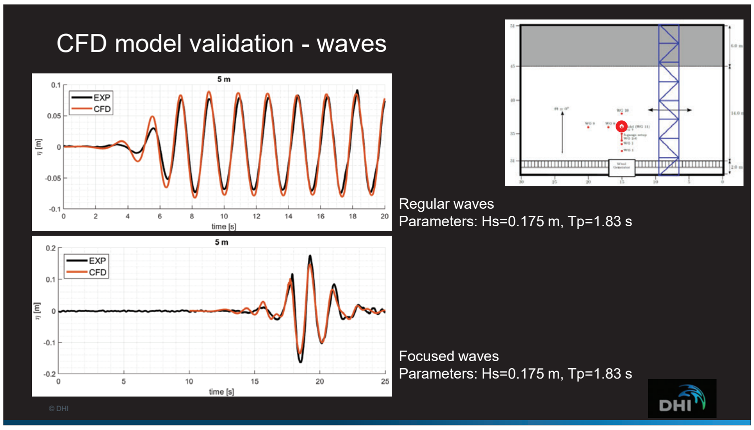


CFD model validation - setup

- 20 m length, 30 m width
- 3m water depth
- Wave maker with 60 paddles
- Absorption with artificial porous beach

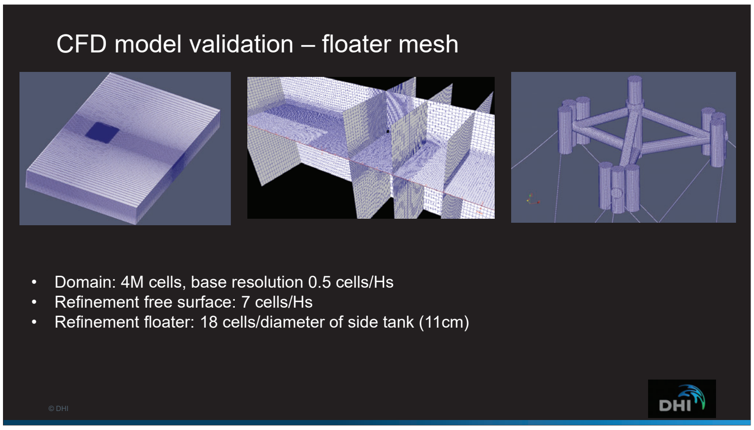
$S = a \cdot U + b \cdot U \cdot |U|$



CFD model validation - waves

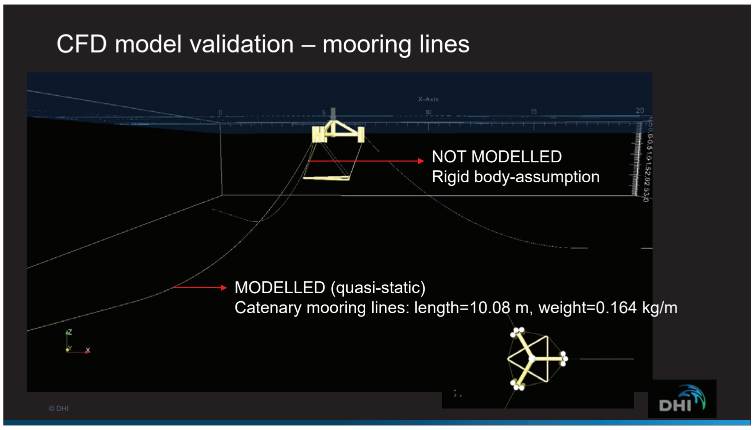
Regular waves
Parameters: Hs=0.175 m, Tp=1.83 s

Focused waves
Parameters: Hs=0.175 m, Tp=1.83 s



CFD model validation – floater mesh

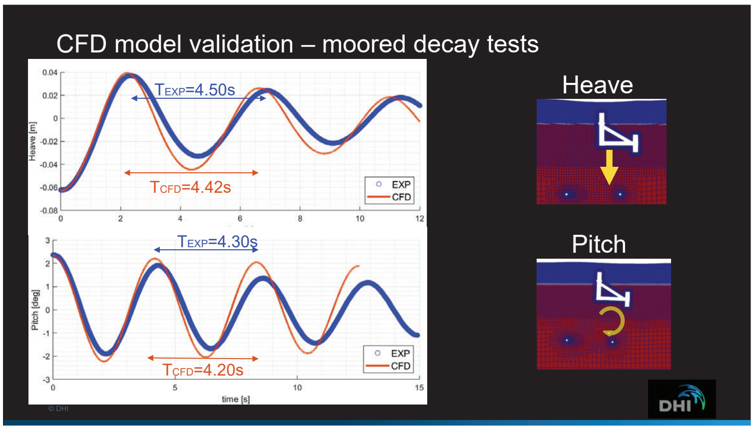
- Domain: 4M cells, base resolution 0.5 cells/Hs
- Refinement free surface: 7 cells/Hs
- Refinement floater: 18 cells/diameter of side tank (11cm)



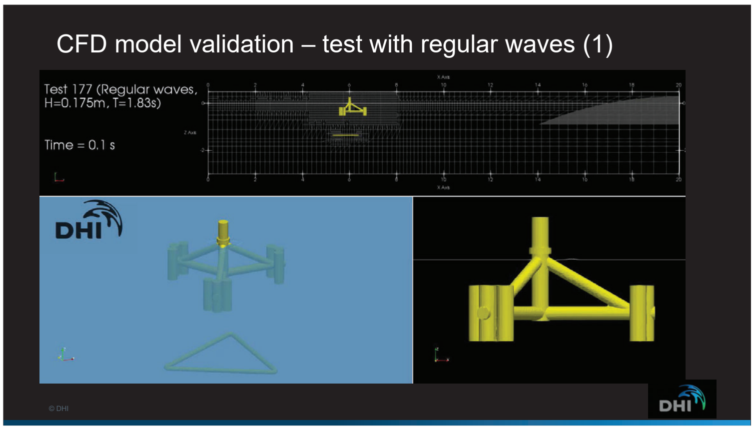
CFD model validation – mooring lines

NOT MODELLED
Rigid body-assumption

MODELLED (quasi-static)
Catenary mooring lines: length=10.08 m, weight=0.164 kg/m



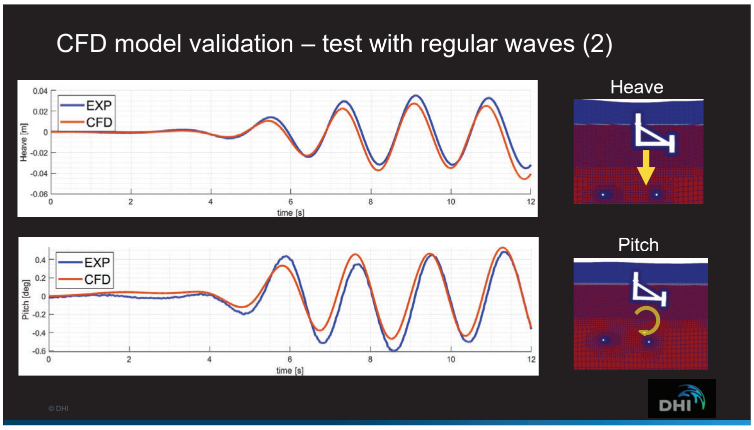
CFD model validation – moored decay tests



CFD model validation – test with regular waves (1)

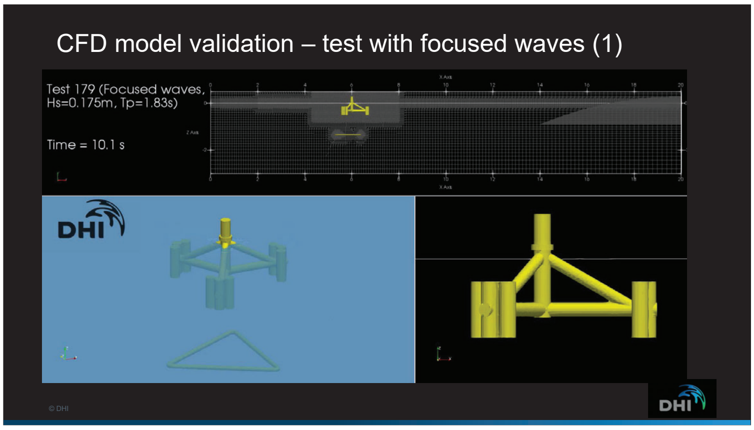
Test 177 (Regular waves, H=0.175m, T=1.83s)

Time = 0.1 s



CFD model validation – test with regular waves (2)

© DHI

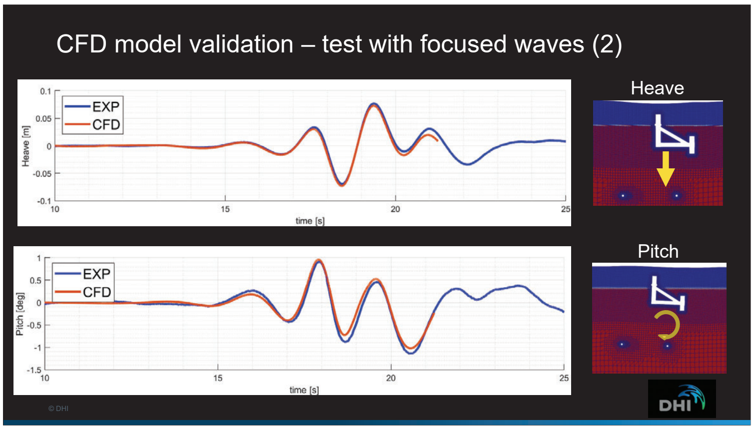


CFD model validation – test with focused waves (1)

Test 179 (Focused waves, Hs=0.175m, Tp=1.83s)

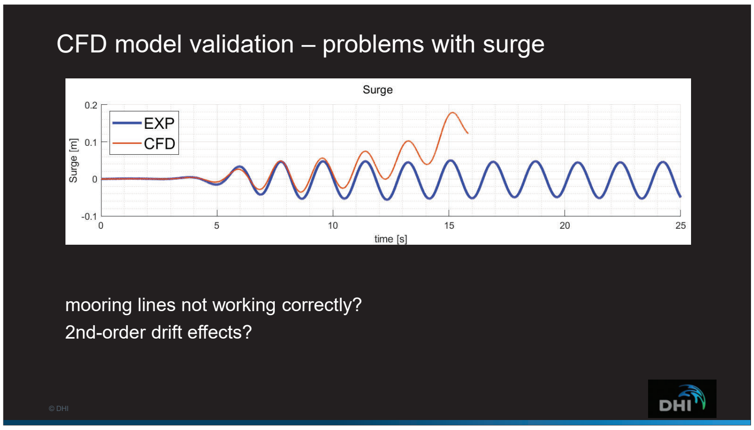
Time = 10.1 s

© DHI



CFD model validation – test with focused waves (2)

© DHI



CFD model validation – problems with surge

mooring lines not working correctly?
2nd-order drift effects?

© DHI

Lessons learnt/Future work

- Results are in a good agreement with the experiments for surface elevation, heave and pitch
- Solver is stable, but time-consuming to setup.
  Example: Mesh resolution of floater ⟷ Volume ⟷ Mass ⟷ Response
- Solver is computational time-demanding. Examples:
  10 hours = one period of regular waves on 32 cores
  96 hours = focused test on 32 cores
- Future work: fix surge, tests with wind, added mass issue, test the coupling

© DHI

Thank you

My e-mail address: dto@dhigroup.com

© DHI A/S

REAL TIME HYBRID MODELLING

APPLIED TO A FLOATING OFFSHORE WIND TURBINE

USING A DUCTED FAN

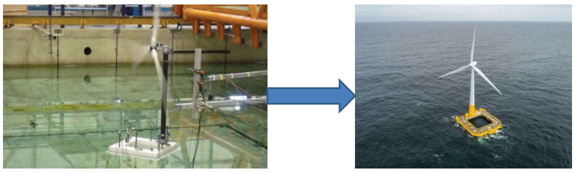
François PETRIE (fpetrie@oceanide.net)

Oceanide

16th of January 2020

INTRODUCTION

- Basin model tests consist in
  - Modelling the complete system at a reduced scale
  - Submit it to site environmental conditions (waves, wind & current)
  - Measure quantities of interest (motions, accelerations, mooring tensions…)
- They are usually carried out at FOWT design stage to
  1. Measure quantities difficult to capture numerically (viscous effects…)
  2. Validate the design



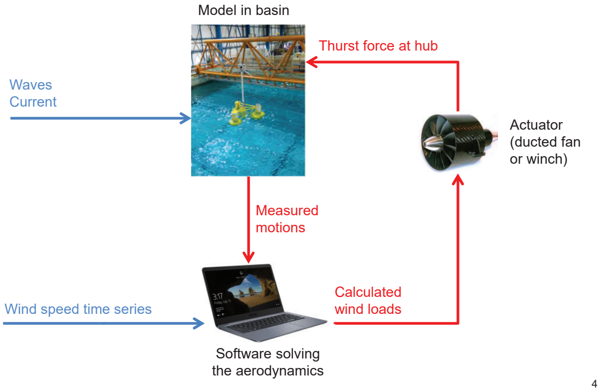
INTRODUCTION

- For FOWT modelling in basin, 2 scaling laws shall be used but are not compatible
  - Froude similitude for the hydrodynamics (submerged part)
  - Reynolds similitude for the aerodynamics (emerged part)
- 3 alternatives can be used

Hydro	Aero	Pro & Cons
In basin	In basin With wind	Uncertain
In basin	Numerically Afterwards	Does not allow « third party » control
In basin	In basin Numerically	So called « RTHM » The best technical choice

---

RTHM APPLIED TO FOWT



Model in basin

Waves
Current

Thurst force at hub

Actuator
(ducted fan
or winch)

Measured
motions

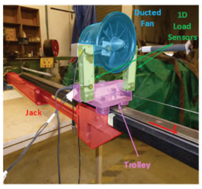
Wind speed time series

Calculated
wind loads

Software solving
the aerodynamics

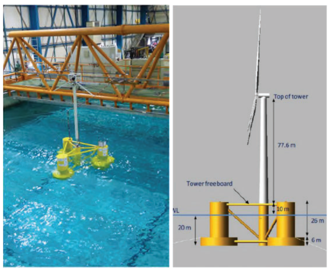
THE JIP

- RTHM has already been applied to FOWT's
- But more "feedbacks" are still needed
- A JIP was initiated by OCEANIDE & PRINCIPIA in 2019 to clarify
  - How reliable and robust such a methodology is
  - How it shall be specified / controlled
  - Which accuracy / gain compared to other methodologies can be expected
  - …
- The program included
  - Development
  - Qualification on a bench outside basin (static + dynamic tests)
  - Application to a "real" case (tests in basin)
  - Synthesis & recommendations
- The presentation will focus on a few results



CASE STUDY

- Floater : DeepCwind (OC4)
- Turbine : NREL 5MW
- Actuator : ducted fan
- Scale : 1/32
- Software : DeepLinesWind



	Global COG location			Mass	Inertia at global COG	Radius of gyration
	X (m)	Y (m)	Z (m)	(t)	I_{yy} (t.m²)	(m)
Floater	0.00	0.00	6.52	13 659	7.070E+06	-
Tower	0.00	0.00	63.38	245	8.650E+05	-
RNA	-0.46	0.00	110.11	349	3.522E+06	-
Total measured	-0.01	0.00	10.04	14 253	1.146E+07	28.35
Total specified	-0.01	0.00	10.06	14 260	1.129E+07	28.14
Deviation (%)	-	-	-0.2%	0.0%	1.5%	0.8%

OCEANIDE FACILITY DESCRIPTION

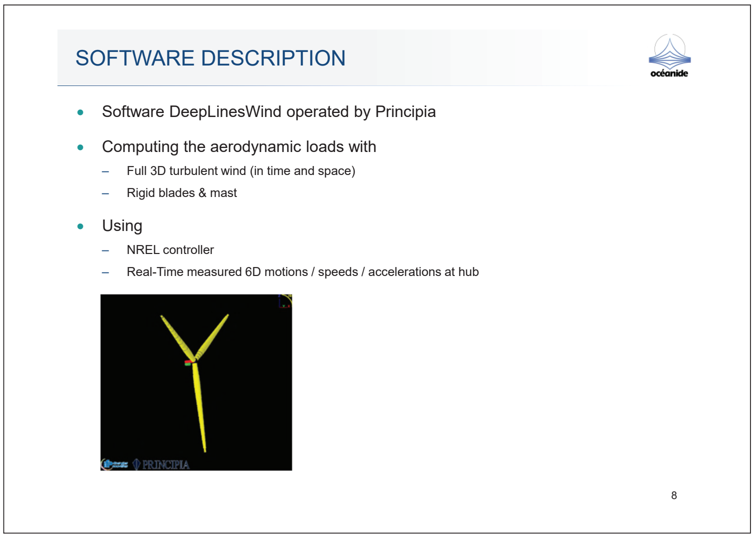
- BGO FIRST basin : 40m x 16m x 0 to 4,8m
- Waves + Current + Wind capabilities
- Operated by Oceanide since 1998
- Located France, in « Côte d'Azur »

Eolfloat

PGL

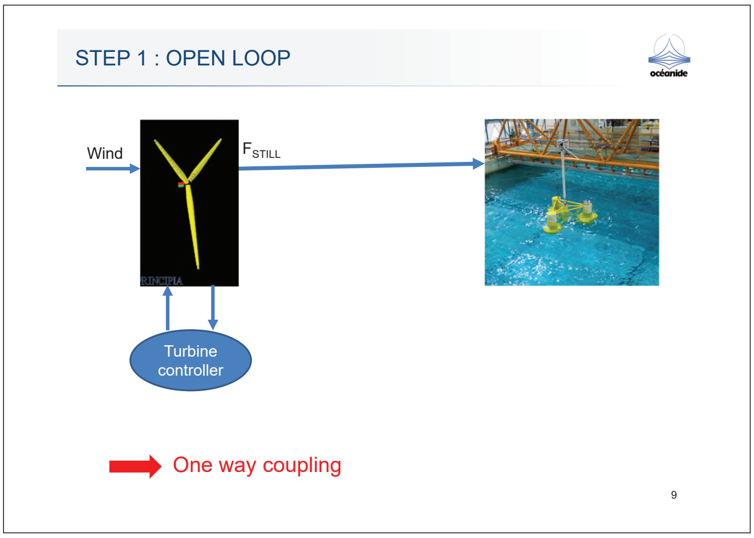
Kieggers Flak

Fécamp



SOFTWARE DESCRIPTION

- Software DeepLinesWind operated by Principia
- Computing the aerodynamic loads with
  - Full 3D turbulent wind (in time and space)
  - Rigid blades & mast
- Using
  - NREL controller
  - Real-Time measured 6D motions / speeds / accelerations at hub



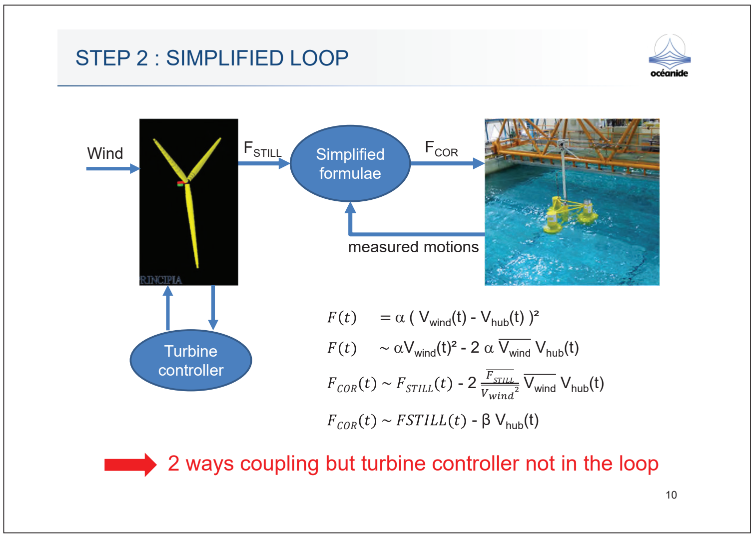
STEP 1 : OPEN LOOP

Wind

F_{STILL}

Turbine controller

One way coupling



STEP 2 : SIMPLIFIED LOOP

Wind

F_{STILL}

Simplified formulae

F_{COR}

measured motions

Turbine controller

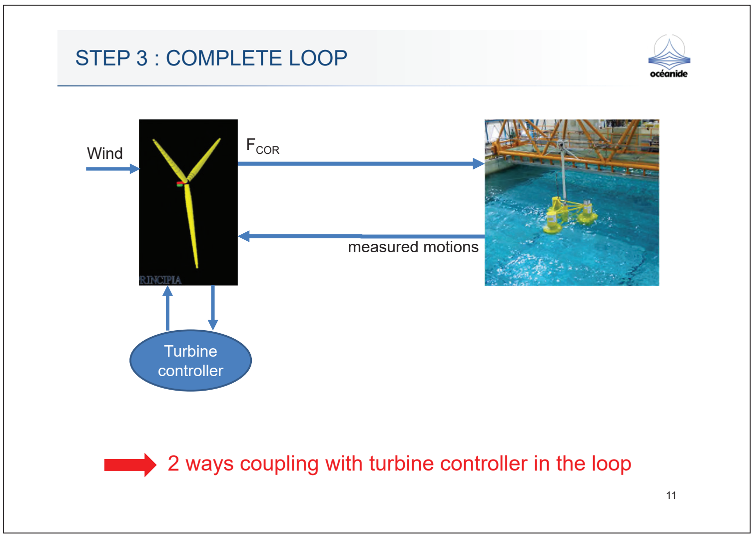
$$F(t) = \alpha\,(V_{wind}(t) - V_{hub}(t))^2$$

$$F(t) \sim \alpha V_{wind}(t)^2 - 2\,\alpha\,\overline{V_{wind}}\,V_{hub}(t)$$

$$F_{COR}(t) \sim F_{STILL}(t) - 2\,\frac{\overline{F_{STILL}}}{\overline{V_{wind}}^2}\,\overline{V_{wind}}\,V_{hub}(t)$$

$$F_{COR}(t) \sim FSTILL(t) - \beta\,V_{hub}(t)$$

2 ways coupling but turbine controller not in the loop



STEP 3 : COMPLETE LOOP

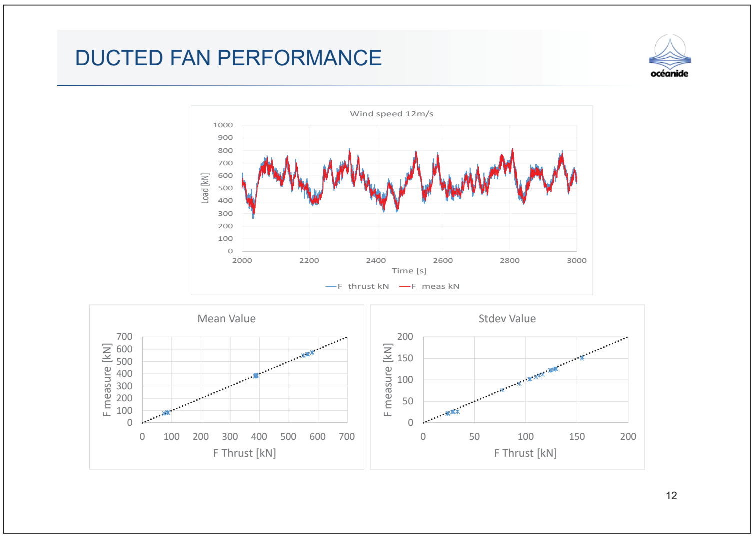
Wind

F_{COR}

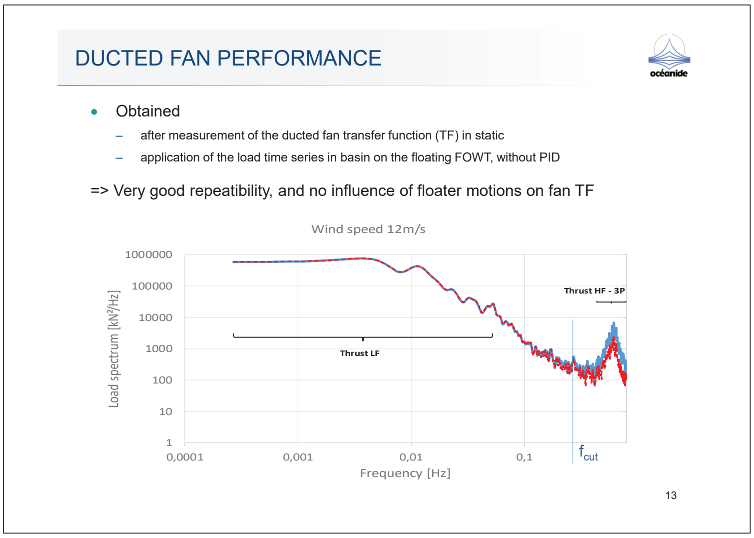
measured motions

Turbine controller

2 ways coupling with turbine controller in the loop



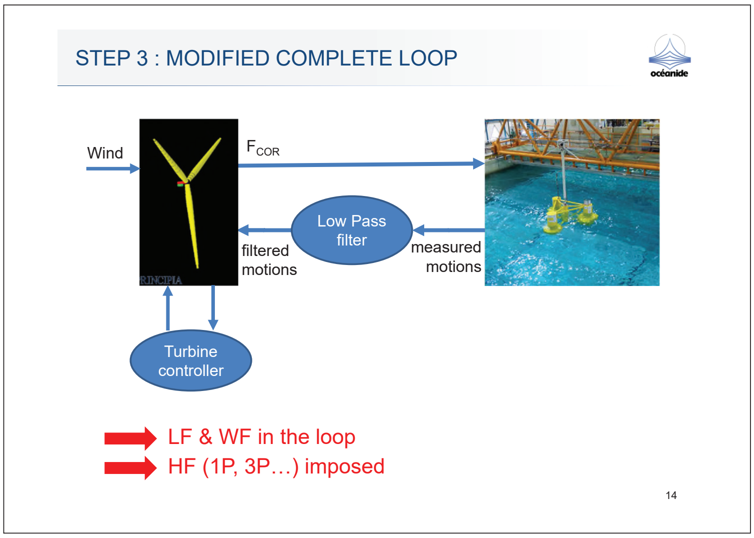
DUCTED FAN PERFORMANCE



DUCTED FAN PERFORMANCE

- Obtained
  - after measurement of the ducted fan transfer function (TF) in static
  - application of the load time series in basin on the floating FOWT, without PID

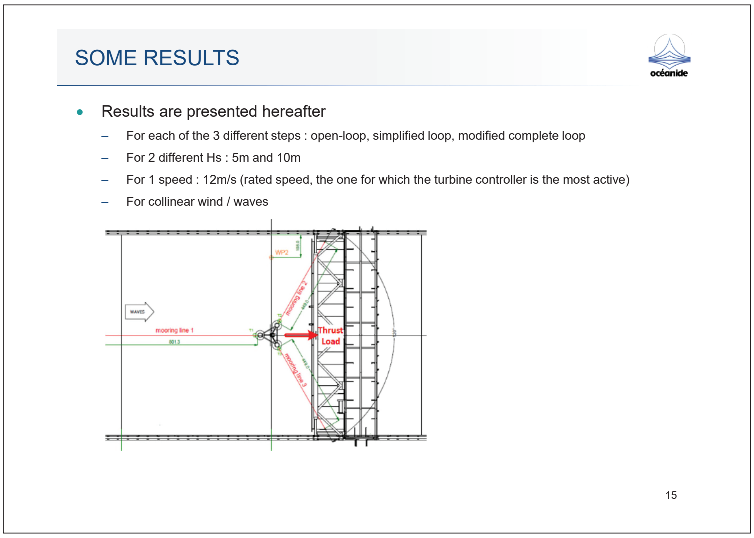
=> Very good repeatability, and no influence of floater motions on fan TF



STEP 3 : MODIFIED COMPLETE LOOP

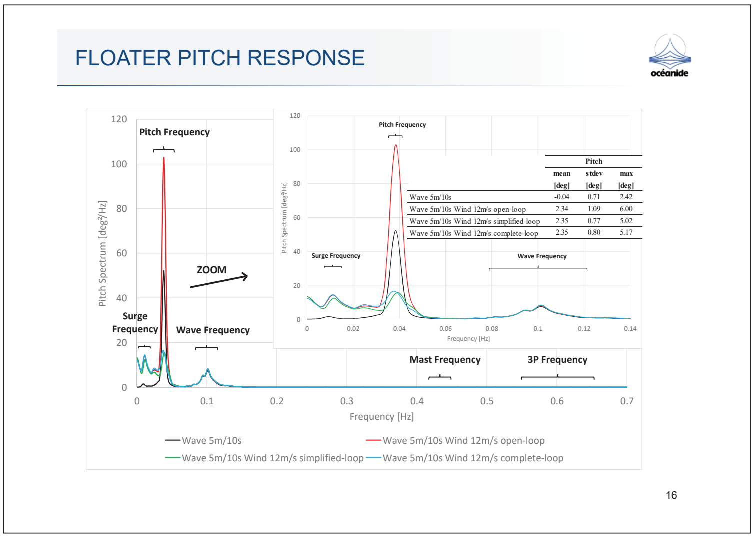
LF & WF in the loop

HF (1P, 3P…) imposed



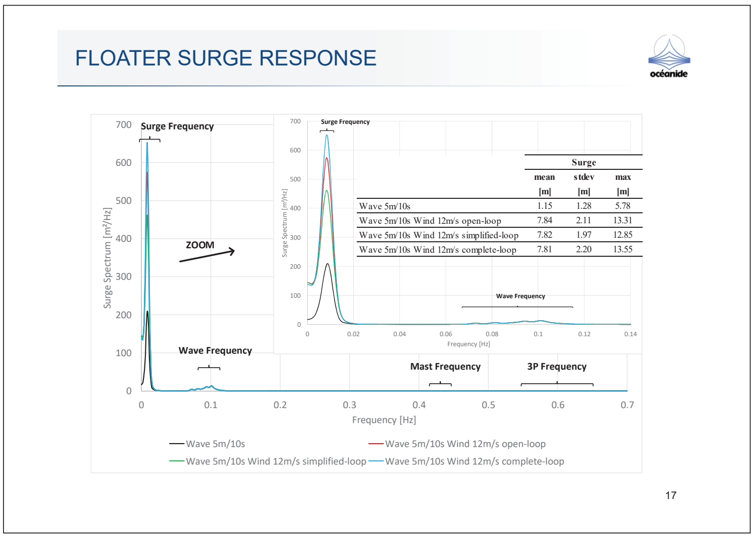
SOME RESULTS

- Results are presented hereafter
  - For each of the 3 different steps : open-loop, simplified loop, modified complete loop
  - For 2 different Hs : 5m and 10m
  - For 1 speed : 12m/s (rated speed, the one for which the turbine controller is the most active)
  - For collinear wind / waves



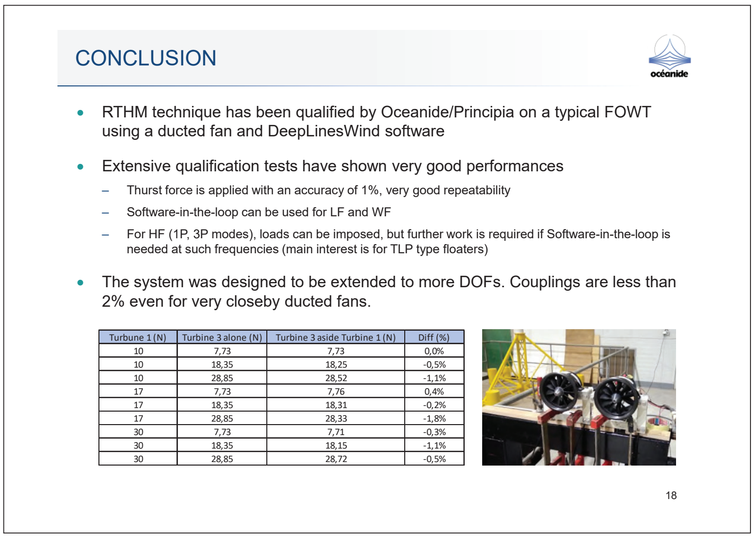
FLOATER PITCH RESPONSE

	Pitch		
	mean [deg]	stdev [deg]	max [deg]
Wave 5m/10s	-0.04	0.71	2.42
Wave 5m/10s Wind 12m/s open-loop	2.34	1.09	6.00
Wave 5m/10s Wind 12m/s simplified-loop	2.35	0.77	5.02
Wave 5m/10s Wind 12m/s complete-loop	2.35	0.80	5.17



FLOATER SURGE RESPONSE

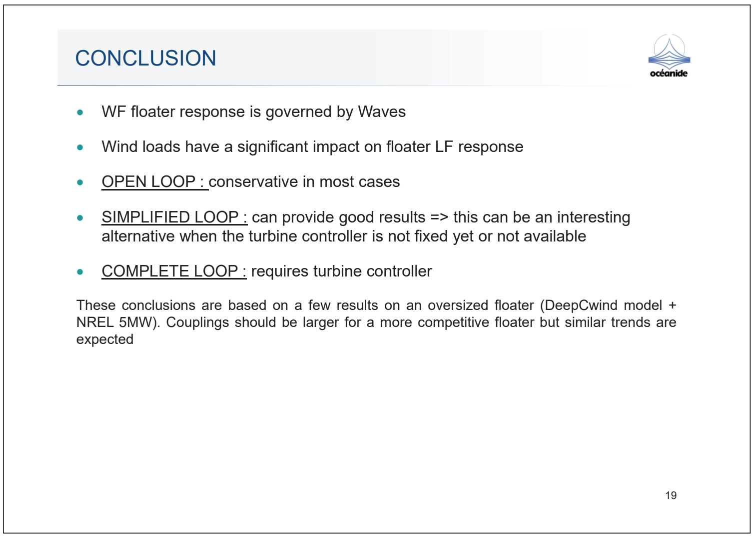
	Surge		
	mean [m]	stdev [m]	max [m]
Wave 5m/10s	1.15	1.28	5.78
Wave 5m/10s Wind 12m/s open-loop	7.84	2.11	13.31
Wave 5m/10s Wind 12m/s simplified-loop	7.82	1.97	12.85
Wave 5m/10s Wind 12m/s complete-loop	7.81	2.20	13.55



CONCLUSION

- RTHM technique has been qualified by Oceanide/Principia on a typical FOWT using a ducted fan and DeepLinesWind software
- Extensive qualification tests have shown very good performances
  - Thurst force is applied with an accuracy of 1%, very good repeatability
  - Software-in-the-loop can be used for LF and WF
  - For HF (1P, 3P modes), loads can be imposed, but further work is required if Software-in-the-loop is needed at such frequencies (main interest is for TLP type floaters)
- The system was designed to be extended to more DOFs. Couplings are less than 2% even for very closeby ducted fans.

Turbune 1 (N)	Turbine 3 alone (N)	Turbine 3 aside Turbine 1 (N)	Diff (%)
10	7,73	7,73	0,0%
10	18,35	18,25	-0,5%
10	28,85	28,52	-1,1%
17	7,73	7,76	0,4%
17	18,35	18,31	-0,2%
17	28,85	28,33	-1,8%
30	7,73	7,71	-0,3%
30	18,35	18,15	-1,1%
30	28,85	28,72	-0,5%



CONCLUSION

- WF floater response is governed by Waves
- Wind loads have a significant impact on floater LF response
- OPEN LOOP : conservative in most cases
- SIMPLIFIED LOOP : can provide good results => this can be an interesting alternative when the turbine controller is not fixed yet or not available
- COMPLETE LOOP : requires turbine controller

These conclusions are based on a few results on an oversized floater (DeepCwind model + NREL 5MW). Couplings should be larger for a more competitive floater but similar trends are expected

CONCLUSION

- This project was initiated in April. 2019 and will be completed in March. 2020
- The authors wish to thank **Doris Group, Engie, Saipem** and **Technip France** for their financial & technical support during this JIP
- A second phase is under discussion, new comers are welcome
- See also OMAE2020-18076
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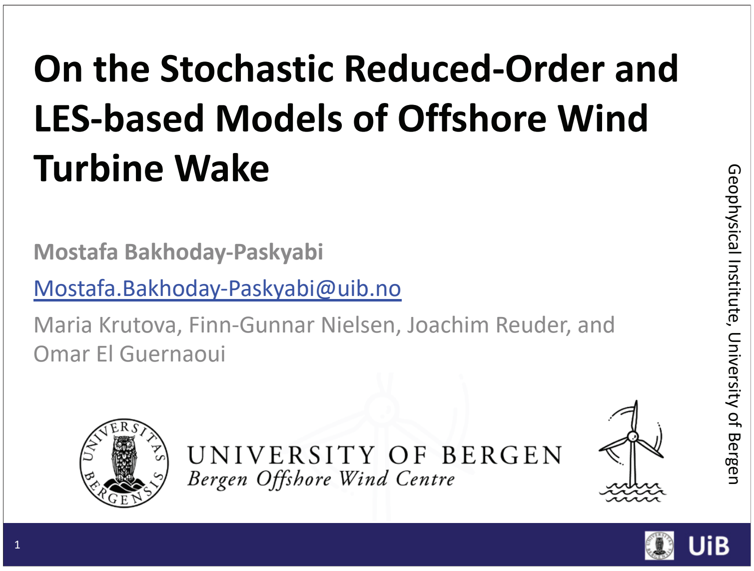
H) Wind farm control systems

Model predictive control on a wind turbine using a reduced order model based on STAS,
A.Skibelid, NTNU – *Presentation not available*

On the Stochastic Reduced-Order and LES-based Models of Offshore Wind Farm Wake,
M.B.Paskyabi, UiB

Consequences of load mitigation control strategies for a floating wind turbine,
E.Bachynski, NTNU



On the Stochastic Reduced-Order and LES-based Models of Offshore Wind Turbine Wake

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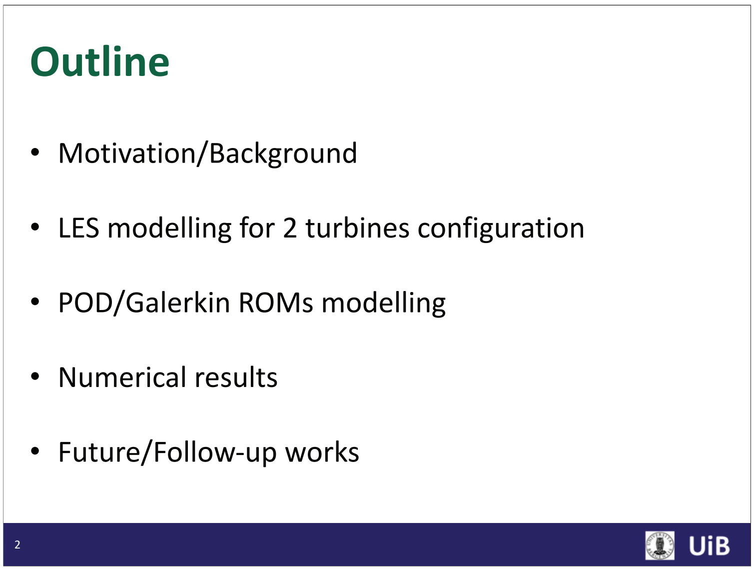
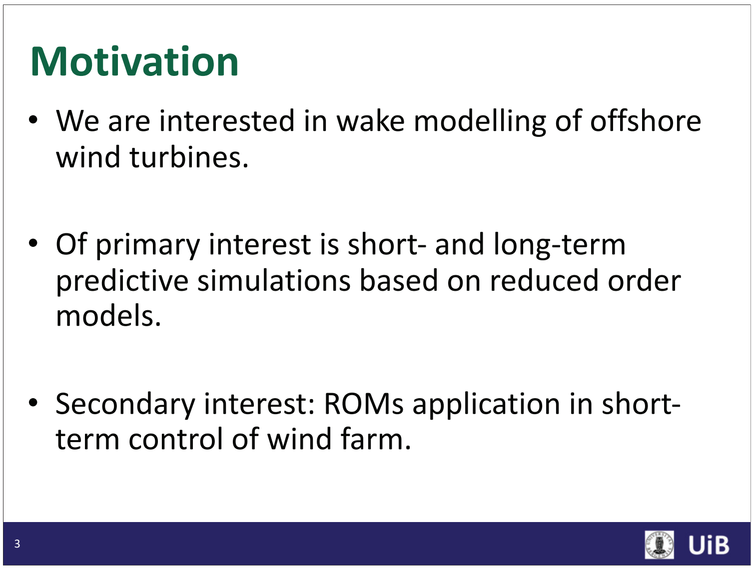


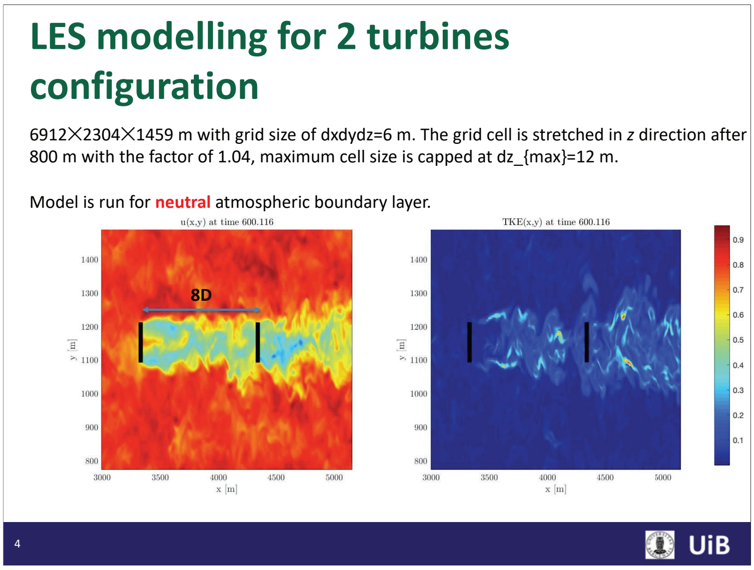
Outline

- Motivation/Background
- LES modelling for 2 turbines configuration
- POD/Galerkin ROMs modelling
- Numerical results
- Future/Follow-up works



Motivation

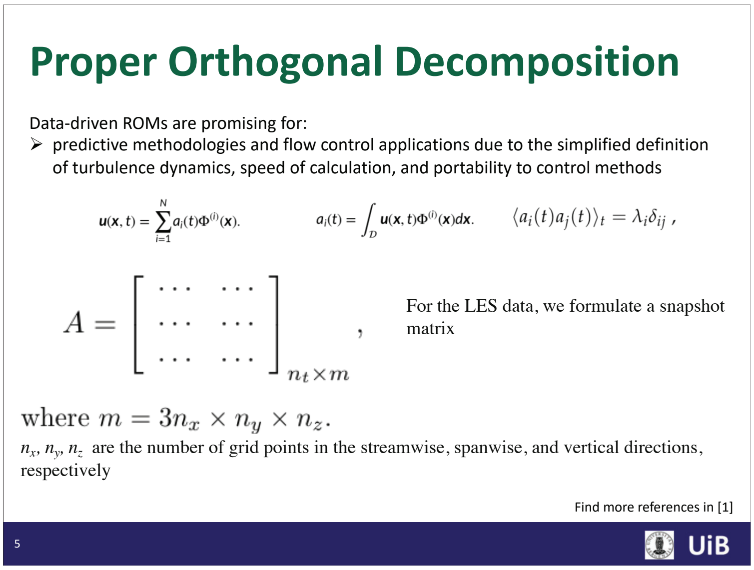
- We are interested in wake modelling of offshore wind turbines.
- Of primary interest is short- and long-term predictive simulations based on reduced order models.
- Secondary interest: ROMs application in short-term control of wind farm.



LES modelling for 2 turbines configuration

6912×2304×1459 m with grid size of dxdydz=6 m. The grid cell is stretched in *z* direction after 800 m with the factor of 1.04, maximum cell size is capped at dz_{max}=12 m.

Model is run for **neutral** atmospheric boundary layer.



Proper Orthogonal Decomposition

Data-driven ROMs are promising for:

- predictive methodologies and flow control applications due to the simplified definition of turbulence dynamics, speed of calculation, and portability to control methods

$$\mathbf{u}(\mathbf{x},t)=\sum_{i=1}^{N}a_i(t)\Phi^{(i)}(\mathbf{x}). \qquad a_i(t)=\int_D \mathbf{u}(\mathbf{x},t)\Phi^{(i)}(\mathbf{x})d\mathbf{x}. \qquad \langle a_i(t)a_j(t)\rangle_t=\lambda_i\delta_{ij}\,,$$

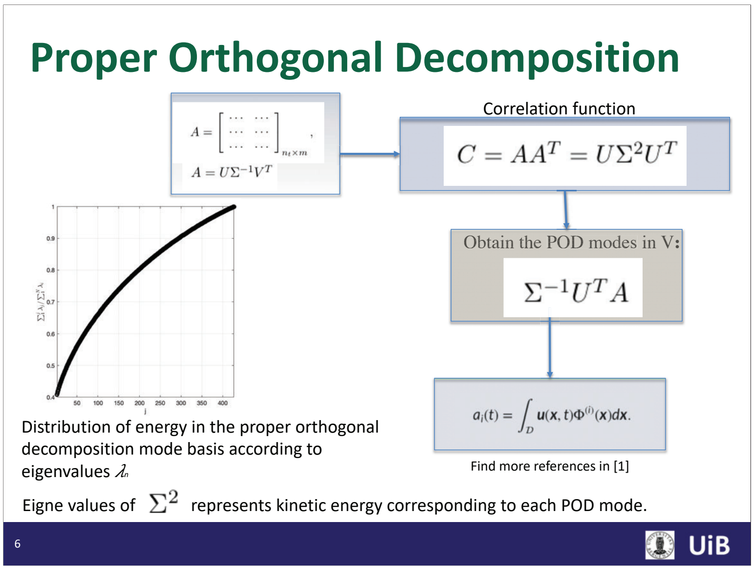
$$A=\begin{bmatrix}\cdots & \cdots\\ \cdots & \cdots\\ \cdots & \cdots\end{bmatrix}_{n_t\times m},$$

For the LES data, we formulate a snapshot matrix

where $m = 3n_x \times n_y \times n_z$.

n_x, n_y, n_z are the number of grid points in the streamwise, spanwise, and vertical directions, respectively

Find more references in [1]



Proper Orthogonal Decomposition

$$A=\begin{bmatrix}\cdots & \cdots\\ \cdots & \cdots\\ \cdots & \cdots\end{bmatrix}_{n_t\times m},$$

$$A=U\Sigma^{-1}V^T$$

Correlation function

$$C=AA^T=U\Sigma^2U^T$$

Obtain the POD modes in V:

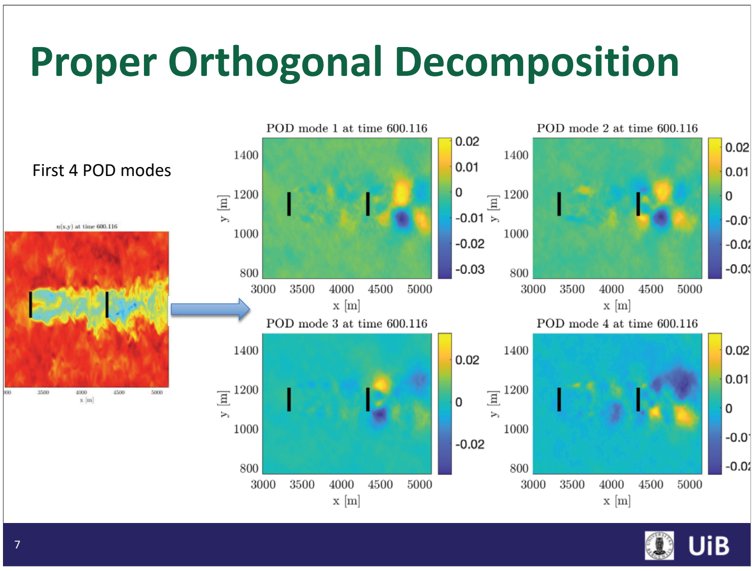
$$\Sigma^{-1}U^TA$$

$$a_i(t)=\int_D \mathbf{u}(\mathbf{x},t)\Phi^{(i)}(\mathbf{x})d\mathbf{x}.$$

Find more references in [1]

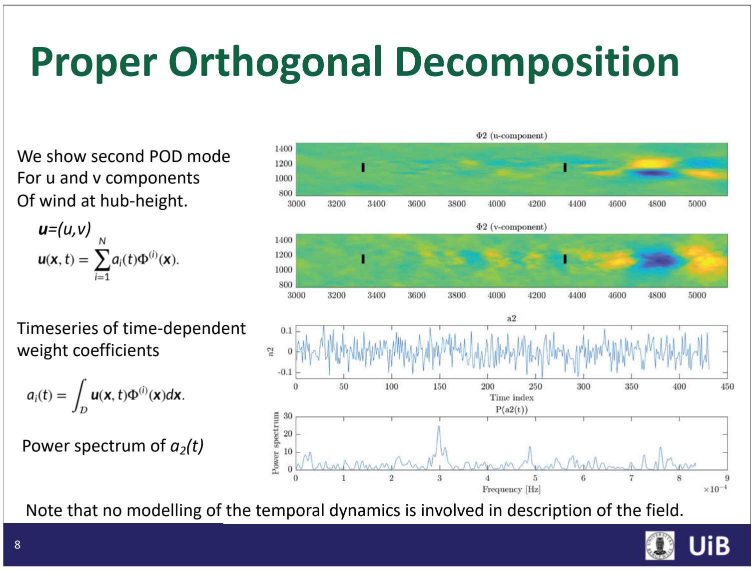
Distribution of energy in the proper orthogonal decomposition mode basis according to eigenvalues λ_n

Eigne values of $\sum^2$ represents kinetic energy corresponding to each POD mode.



Proper Orthogonal Decomposition

First 4 POD modes



Proper Orthogonal Decomposition

We show second POD mode
For u and v components
Of wind at hub-height.

u=(u,v)

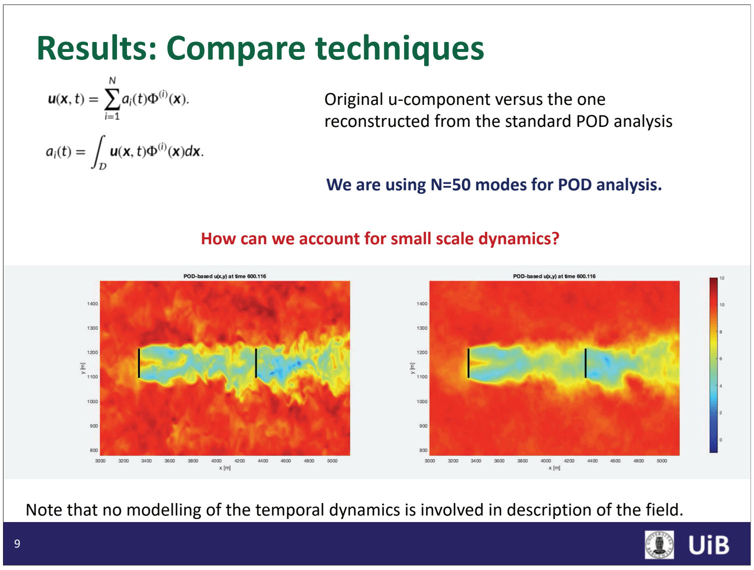
$$\mathbf{u}(\mathbf{x},t)=\sum_{i=1}^{N} a_i(t)\Phi^{(i)}(\mathbf{x}).$$

Timeseries of time-dependent weight coefficients

$$a_i(t)=\int_D \mathbf{u}(\mathbf{x},t)\Phi^{(i)}(\mathbf{x})d\mathbf{x}.$$

Power spectrum of *$a_2(t)$*

Note that no modelling of the temporal dynamics is involved in description of the field.



Results: Compare techniques

$$\mathbf{u}(\mathbf{x},t)=\sum_{i=1}^{N} a_i(t)\Phi^{(i)}(\mathbf{x}).$$

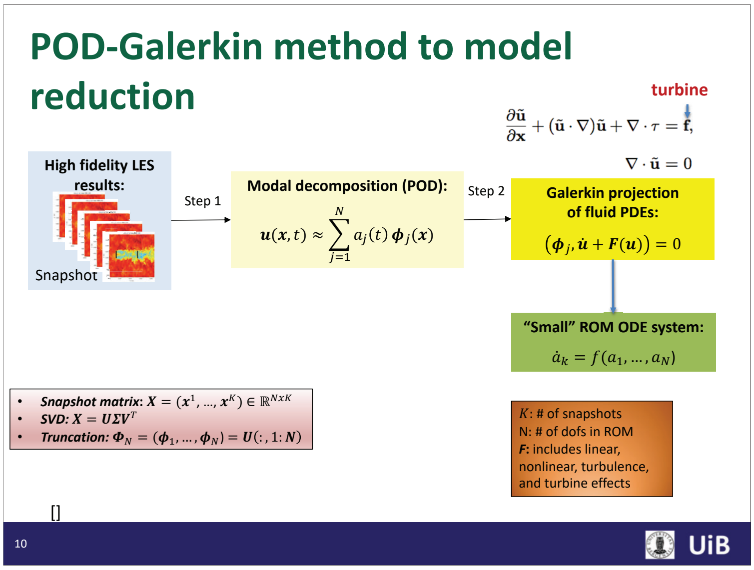
$$a_i(t)=\int_D \mathbf{u}(\mathbf{x},t)\Phi^{(i)}(\mathbf{x})d\mathbf{x}.$$

Original u-component versus the one reconstructed from the standard POD analysis

We are using N=50 modes for POD analysis.

How can we account for small scale dynamics?

Note that no modelling of the temporal dynamics is involved in description of the field.



POD-Galerkin method to model reduction

turbine

$$\frac{\partial \tilde{\mathbf{u}}}{\partial \mathbf{x}}+(\tilde{\mathbf{u}}\cdot\nabla)\tilde{\mathbf{u}}+\nabla\cdot\tau=\tilde{\mathbf{f}},$$

$$\nabla\cdot\tilde{\mathbf{u}}=0$$

High fidelity LES results:

Snapshot

Step 1

Modal decomposition (POD):

$$\boldsymbol{u}(\boldsymbol{x},t)\approx\sum_{j=1}^{N} a_j(t)\,\boldsymbol{\phi}_j(\boldsymbol{x})$$

Step 2

Galerkin projection of fluid PDEs:

$$\left(\boldsymbol{\phi}_j,\dot{\boldsymbol{u}}+\boldsymbol{F}(\boldsymbol{u})\right)=0$$

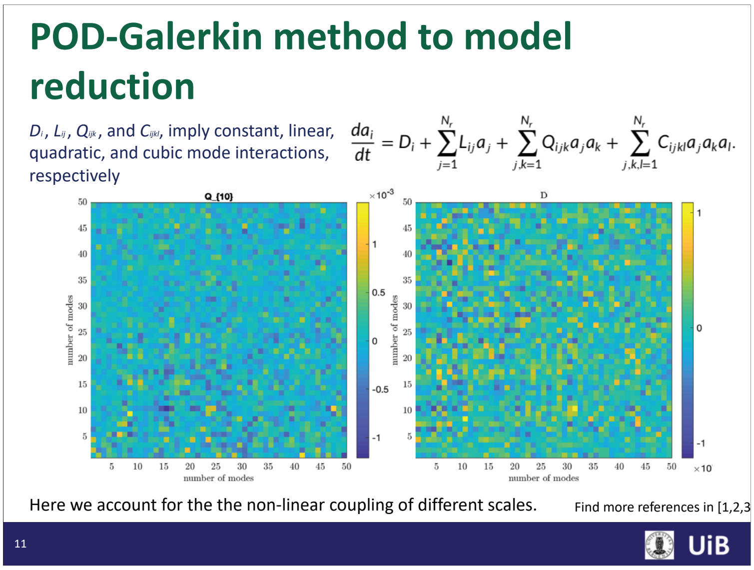
"Small" ROM ODE system:

$$\dot{a}_k=f(a_1,\dots,a_N)$$

- ***Snapshot matrix***: $\boldsymbol{X}=(\boldsymbol{x}^1,\dots,\boldsymbol{x}^K)\in\mathbb{R}^{NxK}$
- ***SVD:*** $\boldsymbol{X}=\boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^T$
- ***Truncation:*** $\boldsymbol{\Phi}_N=(\boldsymbol{\phi}_1,\dots,\boldsymbol{\phi}_N)=\boldsymbol{U}(:,1:\boldsymbol{N})$

K: # of snapshots
N: # of dofs in ROM
F: includes linear, nonlinear, turbulence, and turbine effects

[]



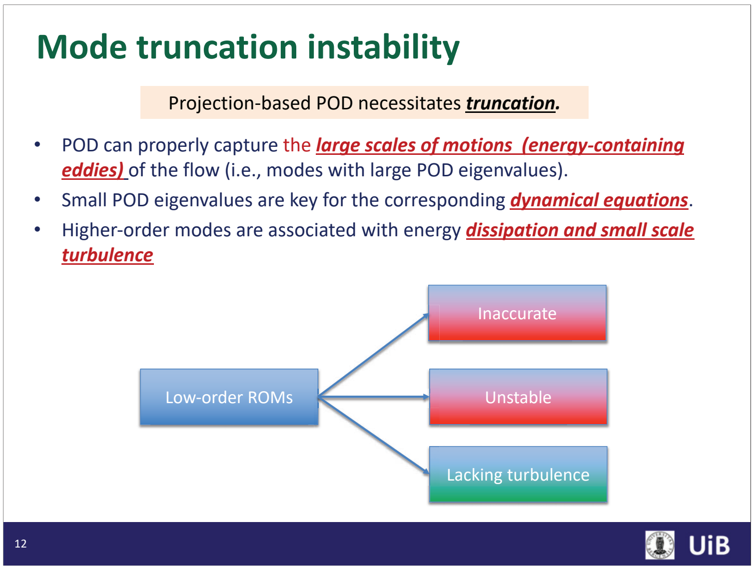
POD-Galerkin method to model reduction

D_i, *L_{ij}*, *Q_{ijk}*, and *C_{ijkl}*, imply constant, linear, quadratic, and cubic mode interactions, respectively

$$\frac{da_i}{dt}=D_i+\sum_{j=1}^{N_r}L_{ij}a_j+\sum_{j,k=1}^{N_r}Q_{ijk}a_ja_k+\sum_{j,k,l=1}^{N_r}C_{ijkl}a_ja_ka_l.$$

Here we account for the the non-linear coupling of different scales.

Find more references in [1,2,3



Mode truncation instability

Projection-based POD necessitates ***truncation***.

- POD can properly capture the ***large scales of motions (energy-containing eddies)*** of the flow (i.e., modes with large POD eigenvalues).
- Small POD eigenvalues are key for the corresponding ***dynamical equations***.
- Higher-order modes are associated with energy ***dissipation and small scale turbulence***

Low-order ROMs

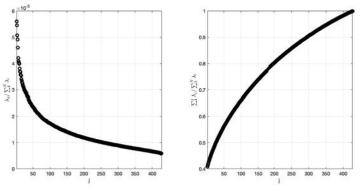
Inaccurate

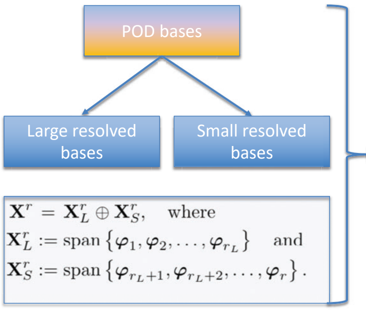
Unstable

Lacking turbulence

POD Closure Models: Overview

- ➢ Mixing Length (ML)
- ➢ Smagorinsky (S)
- ➢ Variational Multi-Scale (VMS)
- ➢ Dynamic Subgrid (DS)



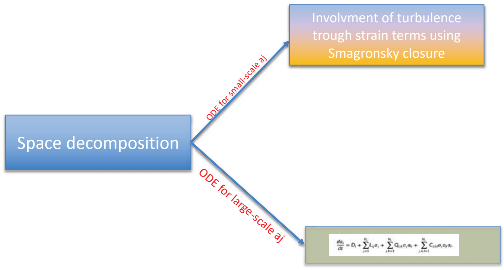


$$\mathbf{X}^r = \mathbf{X}^r_L \oplus \mathbf{X}^r_S, \quad \text{where}$$
$$\mathbf{X}^r_L := \operatorname{span}\{\varphi_1, \varphi_2, \ldots, \varphi_{r_L}\} \quad \text{and}$$
$$\mathbf{X}^r_S := \operatorname{span}\{\varphi_{r_L+1}, \varphi_{r_L+2}, \ldots, \varphi_r\}.$$

$$\boldsymbol{u}(\boldsymbol{x},t) \approx \boldsymbol{u}_L + \boldsymbol{u}_H$$
$$\boldsymbol{u}_L(\boldsymbol{x},t) \approx \boldsymbol{U} + \sum_{j=1}^{r_L} a_j(t)\,\boldsymbol{\phi}_j(\boldsymbol{x})$$
$$\boldsymbol{u}_H(\boldsymbol{x},t) \approx \boldsymbol{U} + \sum_{j=r_L+1}^{r} a_j(t)\,\boldsymbol{\phi}_j(\boldsymbol{x})$$

POD Closure Models: Overview

Applying previous slide's decomposition leads to two sets of Ordinary Differential Equations (ODEs). The one related to the small scales of motion accounts for turbulence, For example through the Smagronsky representation.

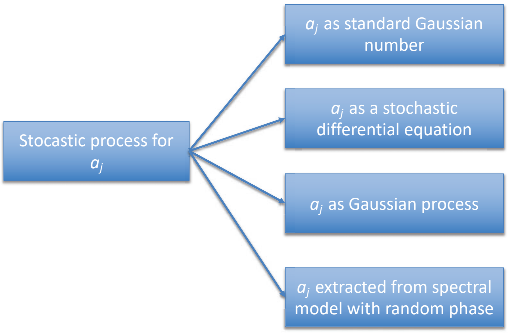


$$\frac{da_i}{dt} = D_i + \sum_{j=1}^{N_r} L_{ij}a_j + \sum_{j,k=1}^{N_r} Q_{ijk}a_ja_k + \sum_{j,k,l=1}^{N_r} C_{ijkl}a_ja_ka_l.$$

Stochastic POD

Can we describe *N time-dependent* weighting coefficients ($a_j(t)$) as a stochastic system?

By assuming, a_j are statistically independent, we are able to consider them as stochastic process.



Stochastic POD

Can we describe *N time-dependent* weighting coefficients ($a_j(t)$) as a stochastic system?

By assuming, a_j are statistically independent, we are able to consider them as stochastic process.

$$da_j(t) = f(a_j(t),t)\cdot dt + g(a_j(t),t)\cdot dW(t),$$

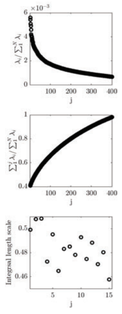
W denotes Brownien motion

$$da_j(t) = -\alpha_j(\mu_j - a_j(t))\cdot dt + \overbrace{\sigma_j\sqrt{2\alpha_j}\cdot dW(t)}^{d\gamma(t)},$$

μ_j and σ_j are mean and standard deviation of $a_j(t)$

autocorrelation is governed by an exponential-decaying function with decay rate of α as follows

$$\rho(\tau) = \overline{a_j(t)a_j(t+\tau)} = e^{-\alpha\cdot\tau},$$



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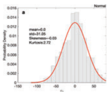
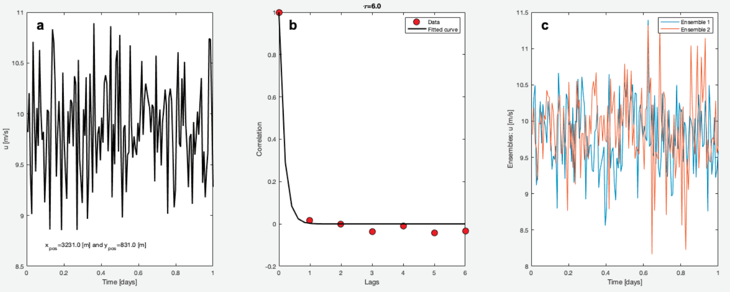
Stochastic POD: Brownian motion & a_j autocorrelation

a_j are normally distributed



Two stochastic trajectories



Stochastic POD

Comparisons between three different

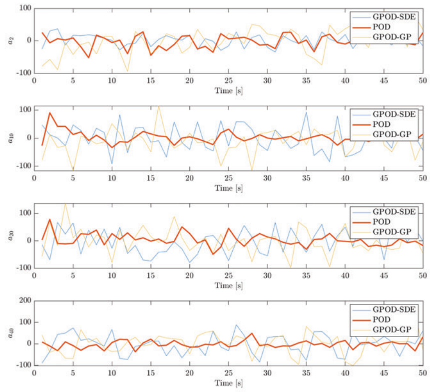
Values of a based on:

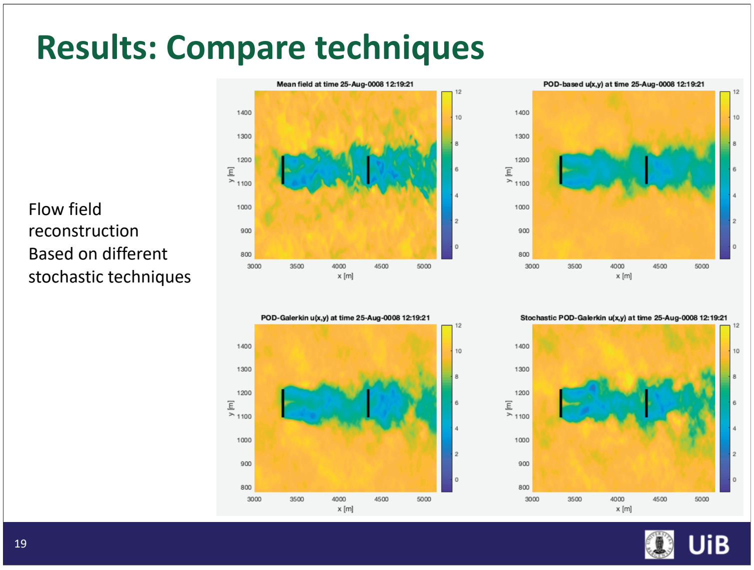
(1) POD eignvalues

(2) Gaussian random process

(3) SDE

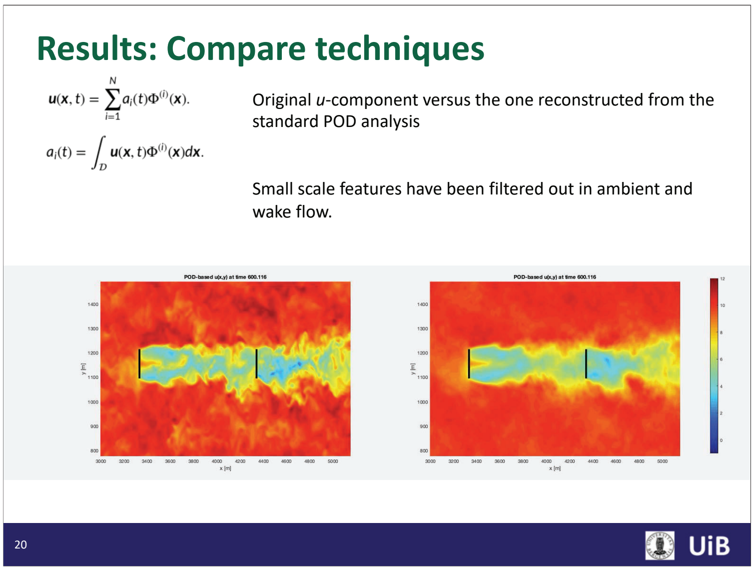
Note that for case 2 & 3, we Use GPOD.





Results: Compare techniques

Flow field reconstruction
Based on different stochastic techniques



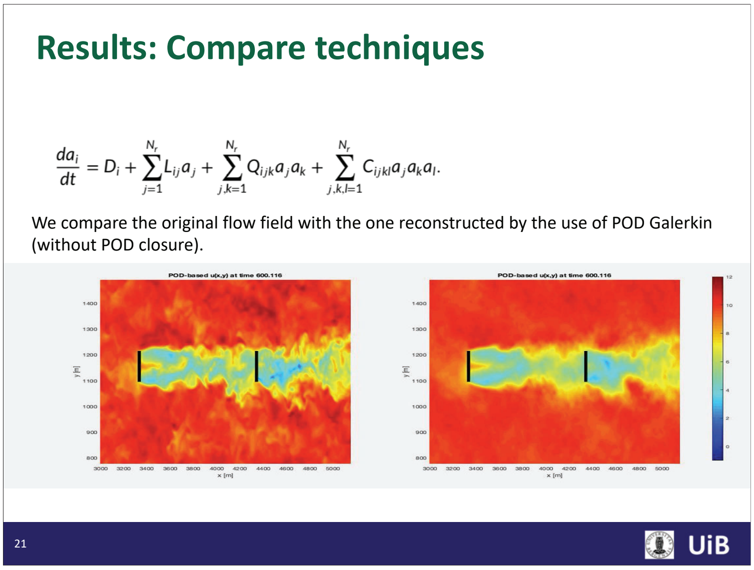
Results: Compare techniques

$$u(\mathbf{x},t) = \sum_{i=1}^{N} a_i(t)\Phi^{(i)}(\mathbf{x}).$$

$$a_i(t) = \int_D \mathbf{u}(\mathbf{x},t)\Phi^{(i)}(\mathbf{x})d\mathbf{x}.$$

Original *u*-component versus the one reconstructed from the standard POD analysis

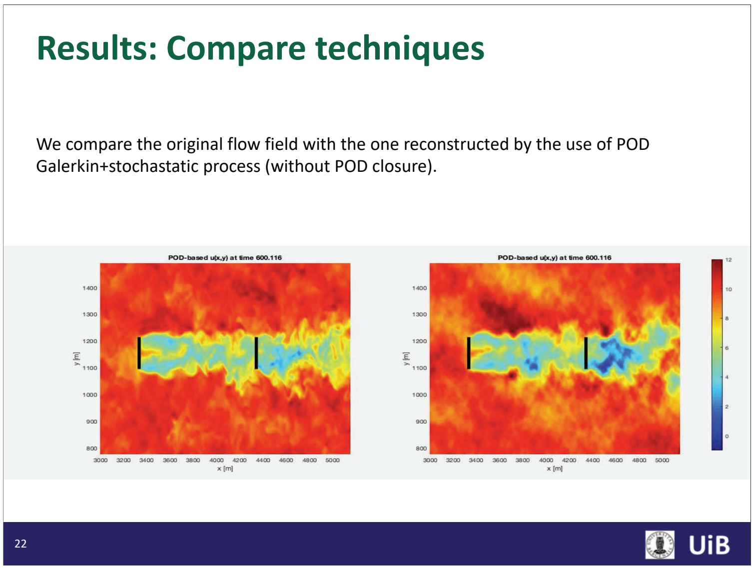
Small scale features have been filtered out in ambient and wake flow.



Results: Compare techniques

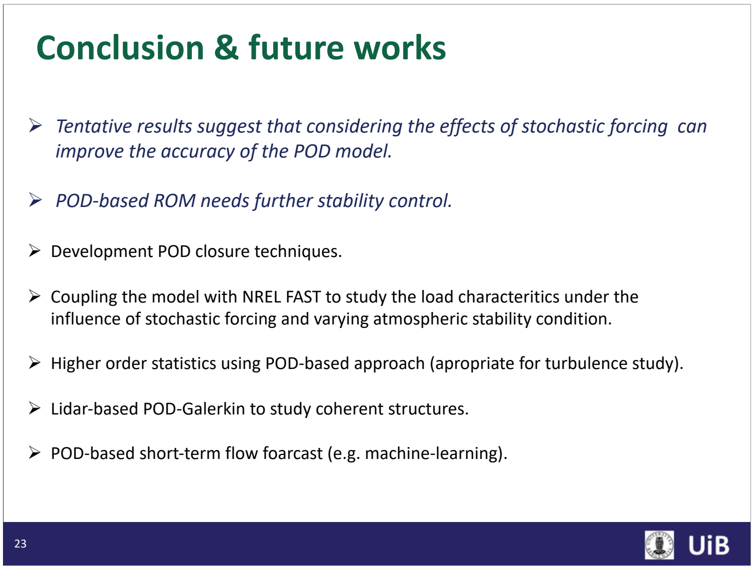
$$\frac{da_i}{dt} = D_i + \sum_{j=1}^{N_r} L_{ij}a_j + \sum_{j,k=1}^{N_r} Q_{ijk}a_j a_k + \sum_{j,k,l=1}^{N_r} C_{ijkl}a_j a_k a_l.$$

We compare the original flow field with the one reconstructed by the use of POD Galerkin (without POD closure).



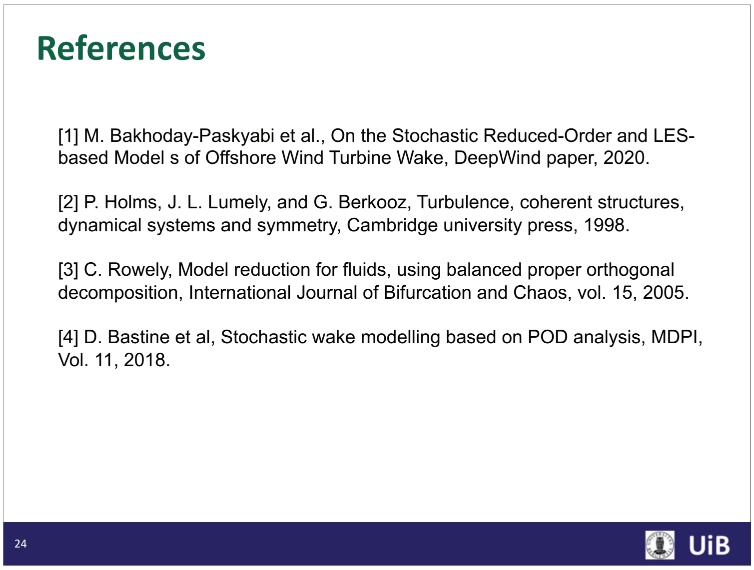
Results: Compare techniques

We compare the original flow field with the one reconstructed by the use of POD Galerkin+stochastatic process (without POD closure).



Conclusion & future works

- ➢ *Tentative results suggest that considering the effects of stochastic forcing can improve the accuracy of the POD model.*
- ➢ *POD-based ROM needs further stability control.*
- ➢ Development POD closure techniques.
- ➢ Coupling the model with NREL FAST to study the load characteritics under the influence of stochastic forcing and varying atmospheric stability condition.
- ➢ Higher order statistics using POD-based approach (apropriate for turbulence study).
- ➢ Lidar-based POD-Galerkin to study coherent structures.
- ➢ POD-based short-term flow foarcast (e.g. machine-learning).



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[1] M. Bakhoday-Paskyabi et al., On the Stochastic Reduced-Order and LES-based Model s of Offshore Wind Turbine Wake, DeepWind paper, 2020.

[2] P. Holms, J. L. Lumely, and G. Berkooz, Turbulence, coherent structures, dynamical systems and symmetry, Cambridge university press, 1998.

[3] C. Rowely, Model reduction for fluids, using balanced proper orthogonal decomposition, International Journal of Bifurcation and Chaos, vol. 15, 2005.

[4] D. Bastine et al, Stochastic wake modelling based on POD analysis, MDPI, Vol. 11, 2018.

Thanks

Consequences of load mitigation control strategies for a floating wind turbine

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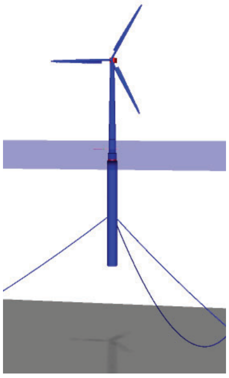
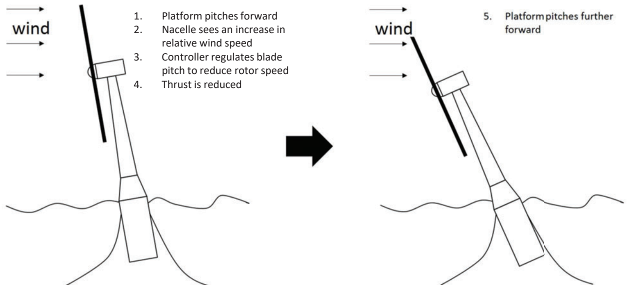


Norwegian University of Science and Technology

Control-induced resonance

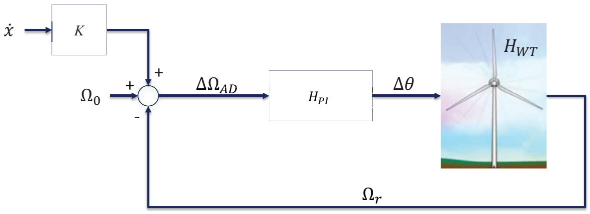


1. Platform pitches forward
2. Nacelle sees an increase in relative wind speed
3. Controller regulates blade pitch to reduce rotor speed
4. Thrust is reduced

5. Platform pitches further forward

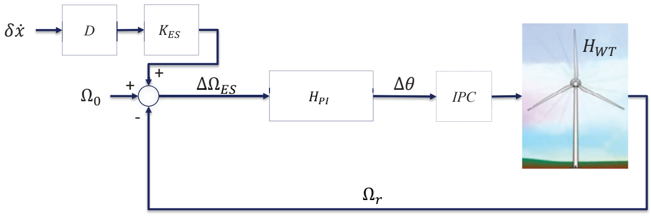
Load-mitigation control strategies for FWTs

- AD: Nacelle velocity feedback (added damping)
  - Lackner, 2007
  - Modify rotor speed reference with nacelle velocity measurement



Load-mitigation control strategies for FWTs

- ES: Energy shaping controller
  - Pedersen, 2017
  - Modify rotor speed reference using the deviation of nacelle velocity from its value in equilibrium



Load-mitigation control strategies for FWTs

- AD: Nacelle velocity feedback (added damping)
  - Lackner, 2007
  - Modify rotor speed reference with nacelle velocity measurement
- ES w/o IPC: Energy shaping controller
  - Pedersen, 2017
- ES w/IPC: Energy shaping controller with IPC
  - Try to reduce individual blade root bending moments
  - IPC follows Lackner and van Kuik, 2009

Known consequences of load-mitigating control strategies

- AD: reduction in pitch motion, increased variations in power and rotor speed
- ES: stable control, expected reductions in pitch motions
- IPC: reduce blade root bending moments, increase pitch actuator use

What about the drivetrain?

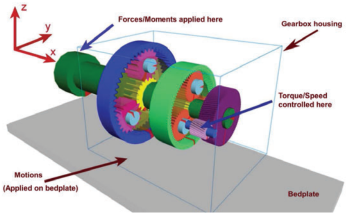


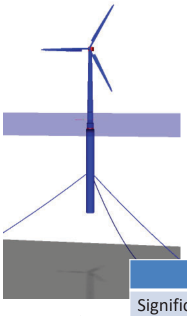
Image: Nejad et al., 2016

Outline

- Methodology
- Global analysis results
- Drivetrain loads
- Conclusions

Methodology: Decoupled simulations

Global analysis: SIMA



6x1hr

Drivetrain analysis: SIMPACK

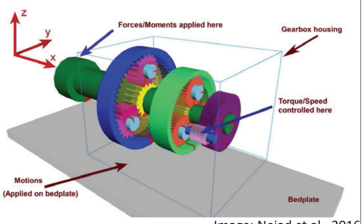


Image: Nejad et al., 2016

1x1hr

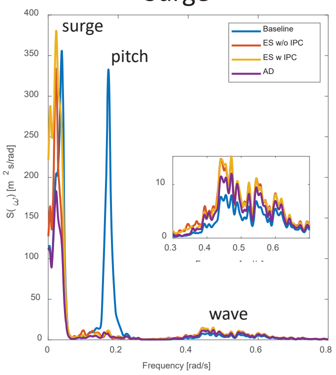
	EC 1	EC 2	EC 3
Significant wave height, H_s [m]	5.0	4.0	5.5
Peak period, T_p [s]	12.0	10.0	14.0
Mean wind speed, U [m/s]	12.0	14.0	20.0
Turbulence intensity, I [-]	0.15	0.14	0.12

Performance indicators

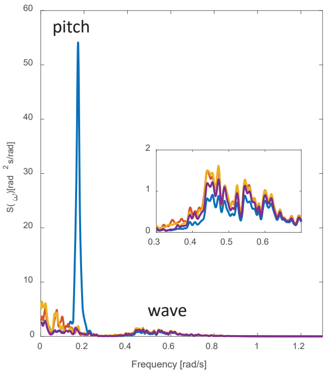
- Tower base 1-hr fatigue damage
  - Stresses from global analysis, rainflow counting, SN curve, Miner's rule
- Gear root 1-hr fatigue damage
  - Forces from MBS analysis, load duration distribution method
- Bearing 1-hr fatigue damage
  - Forces from MBS analysis, load duration distribution method
- Standard deviation of power output
  - Direct result from global analysis

Global motions, EC1

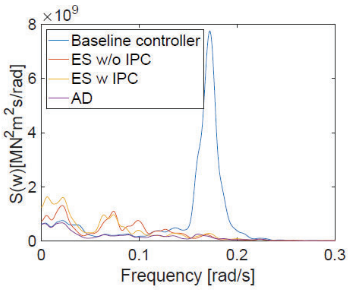
Surge

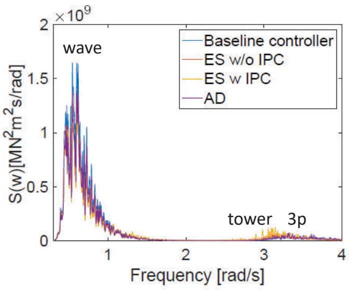


Pitch



Tower base fore-aft bending moments





Gearbox topology

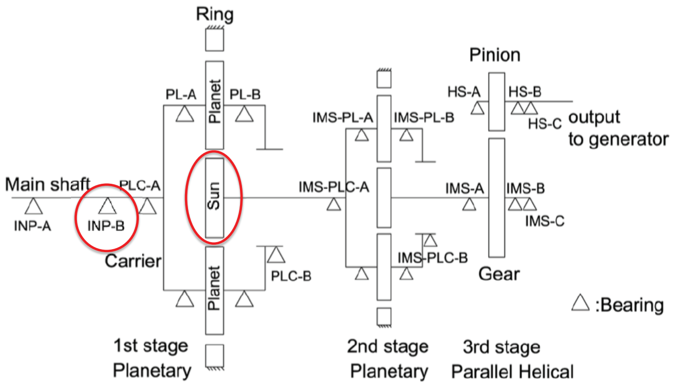
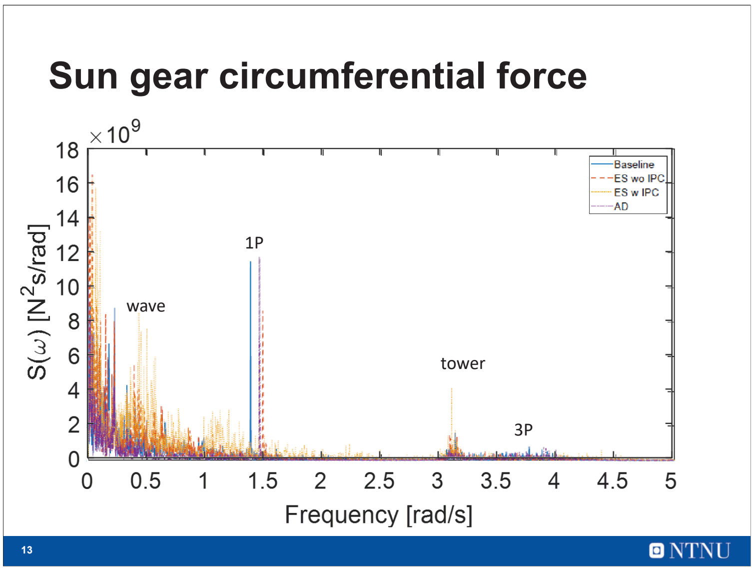
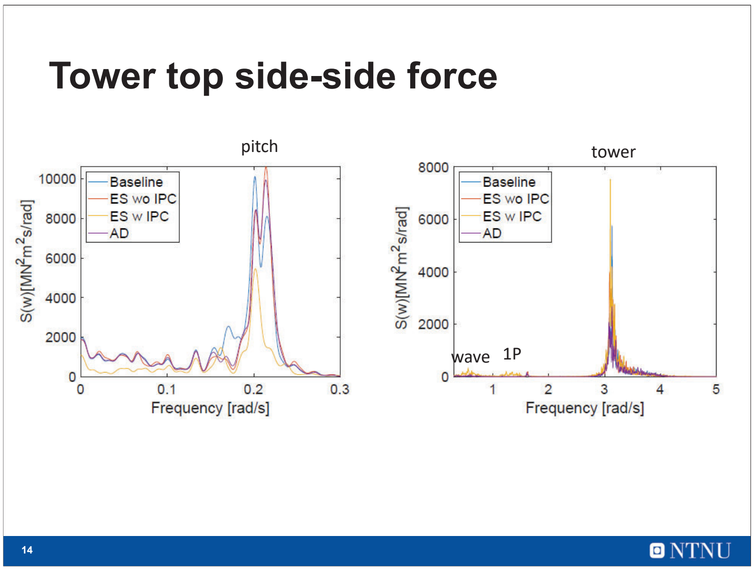


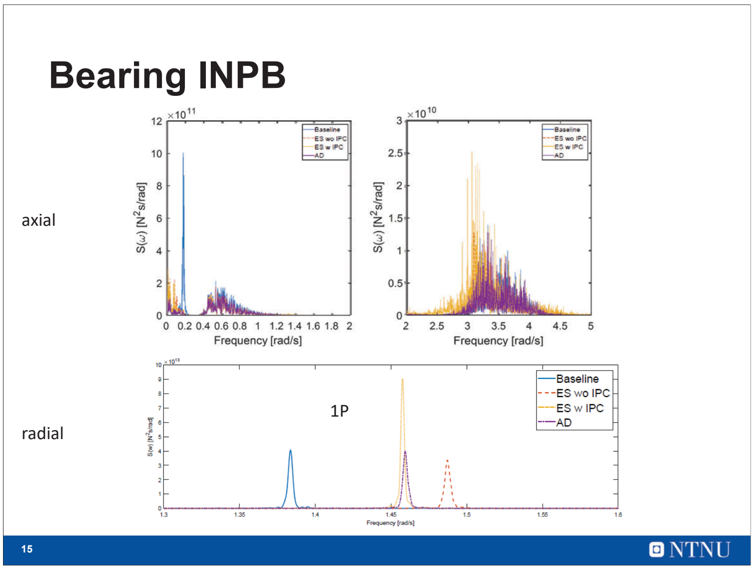
Image: Nejad et al., 2016



Sun gear circumferential force



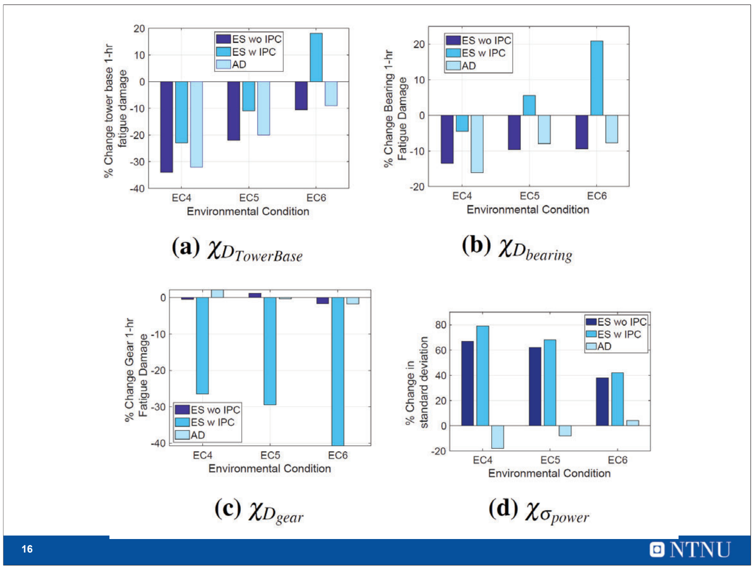
Tower top side-side force



Bearing INPB

axial

radial



(a) $\chi_{D_{TowerBase}}$

(b) $\chi_{D_{bearing}}$

(c) $\chi_{D_{gear}}$

(d) $\chi_{\sigma_{power}}$

Conclusions

- Global and drivetrain responses of a spar floating wind turbine
- Three control modifications
  - active damping (AD)
  - energy shaping control (ES w/o IPC),
  - energy shaping control with individual blade pitch (ES w/IPC).
- Improved platform motion responses in surge and pitch
- ES adds some responses at i.e. wave frequency
- IPC reduces blade root flap-wise bending, but introduces excitation of tower top shear force at rotor frequency.
- The reduced blade root moment therefore comes with a cost of increased radial load resonance in drivetrain gears and bearings.
- Drivetrain should be considered when assessing control performance

Closing session – Strategic Outlook

Offshore wind is going big, Kristian Holm, Head of wind turbine technology, Equinor

Zero Emission Energy Distribution at Sea (ZEEDS), Jim Stian Olsen, Innovation Program Manager, Aker Solutions

Status and outlook of European offshore wind research and innovation; Dr. Carlos Eduardo Lima Da Cunha, Policy Officer, European Commission, DG Research & Innovation

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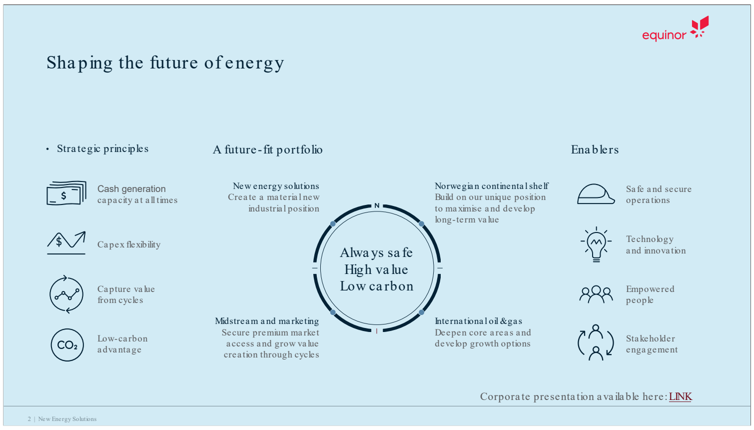
Delivering a safe and profitable renewable business

Kristian Holm
Head of Wind Turbine Technology



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Shaping the future of energy

- Strategic principles

Cash generation capacity at all times

Capex flexibility

Capture value from cycles

Low-carbon advantage

A future-fit portfolio

New energy solutions
Create a material new industrial position

Norwegian continental shelf
Build on our unique position to maximise and develop long-term value

Always safe
High value
Low carbon

Midstream and marketing
Secure premium market access and grow value creation through cycles

International oil & gas
Deepen core areas and develop growth options

Enablers

Safe and secure operations

Technology and innovation

Empowered people

Stakeholder engagement

Corporate presentation available here: LINK

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Equinor's renewables strategy

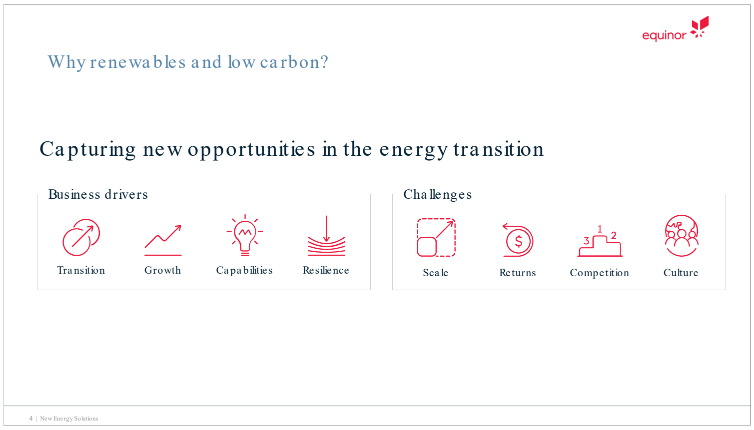
1 Global offshore wind major

Accelerate offshore wind business to close gap(s) and achieve scale in 4-5 clusters

2 Market-driven power producer

Focus on 3-5 attractive markets with a selective approach fitting each market, capitalizing on ability to take merchant risk

Diversify offshore wind business to de-risk and pursue additional growth



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Why renewables and low carbon?

Capturing new opportunities in the energy transition

Business drivers

Transition

Growth

Capabilities

Resilience

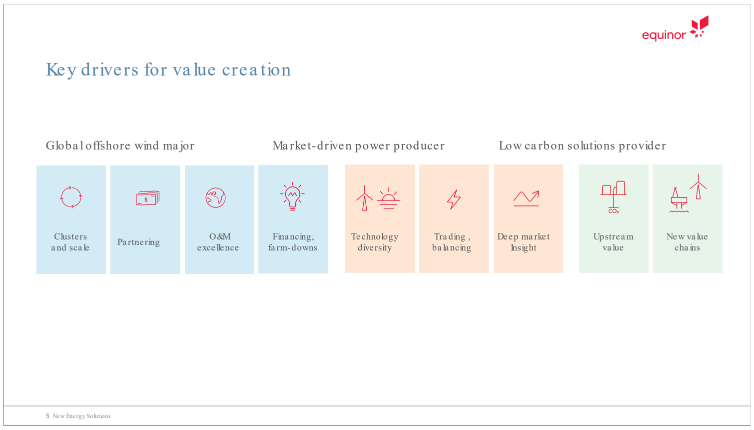
Challenges

Scale

Returns

Competition

Culture



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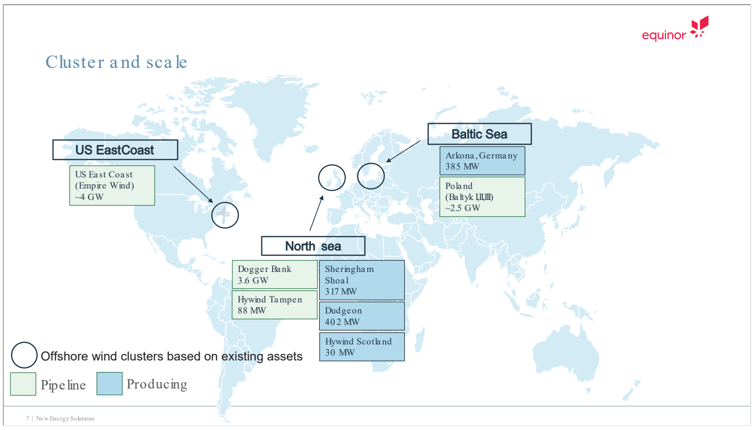
Key drivers for value creation

Global offshore wind major				Market-driven power producer			Low carbon solutions provider	
Clusters and scale	Partnering	O&M excellence	Financing, farm-downs	Technology diversity	Trading, balancing	Deep market Insight	Upstream value	New value chains

equinor

Leveraging five decades of oil and gas experience

Safety is our first priority	Large complex projects and supplier relations	Financial strength & risk management	Leverage local presence & corporate capabilities	Marine operations & maintenance	Technology & innovation



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Cluster and scale

US EastCoast

US East Coast
(Empire Wind)
~4 GW

Baltic Sea

Arkona, Germany
385 MW

Poland
(Baltyk I,II,III)
~2.5 GW

North sea

Dogger Bank
3.6 GW

Hywind Tampen
88 MW

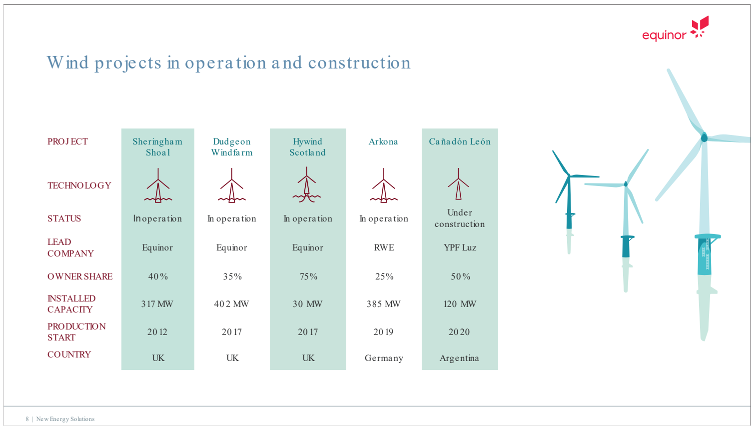
Sheringham
Shoal
317 MW

Dudgeon
402 MW

Hywind Scotland
30 MW

○ Offshore wind clusters based on existing assets

🟩 Pipeline 🟦 Producing



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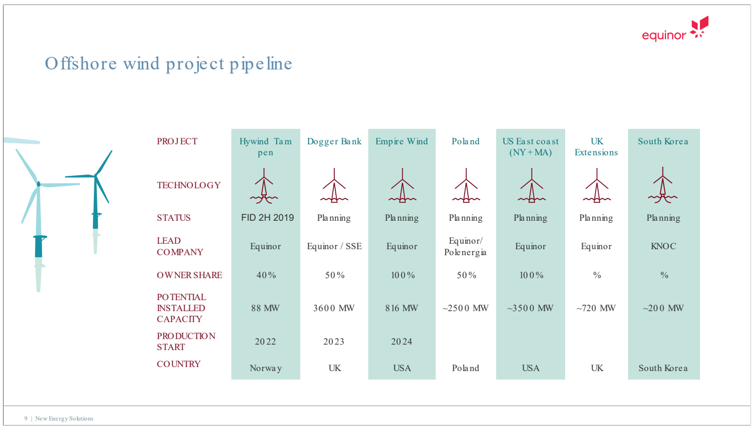
Wind projects in operation and construction

PROJECT	Sheringham Shoal	Dudgeon Windfarm	Hywind Scotland	Arkona	Cañadón León
TECHNOLOGY					
STATUS	In operation	In operation	In operation	In operation	Under construction
LEAD COMPANY	Equinor	Equinor	Equinor	RWE	YPF Luz
OWNER SHARE	40%	35%	75%	25%	50%
INSTALLED CAPACITY	317 MW	402 MW	30 MW	385 MW	120 MW
PRODUCTION START	2012	2017	2017	2019	2020
COUNTRY	UK	UK	UK	Germany	Argentina



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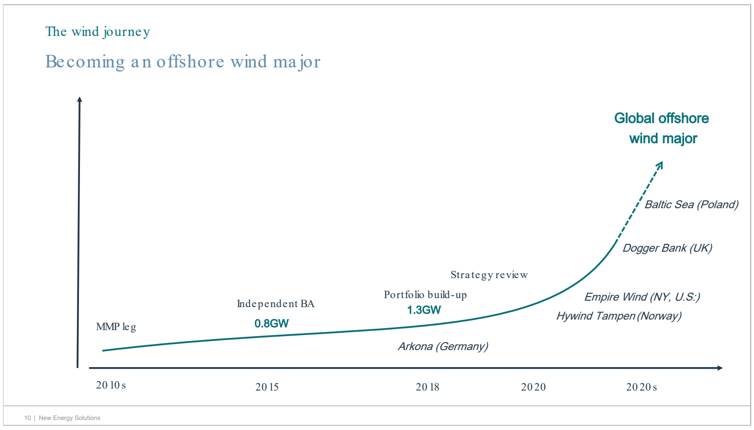
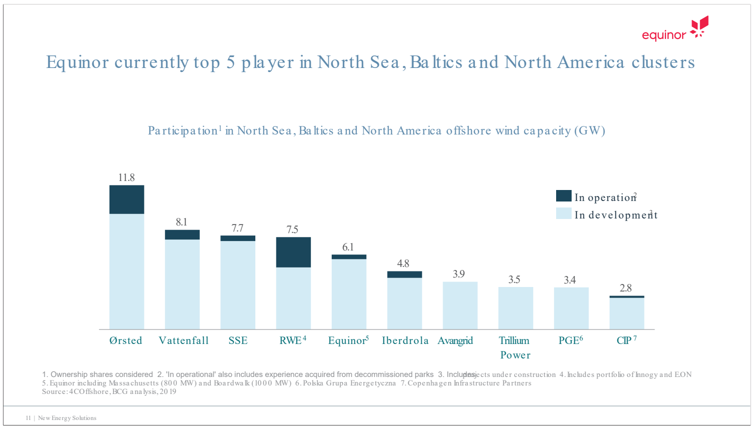
Offshore wind project pipeline

PROJECT	Hywind Tampen	Dogger Bank	Empire Wind	Poland	US East coast (NY + MA)	UK Extensions	South Korea
TECHNOLOGY							
STATUS	FID 2H 2019	Planning	Planning	Planning	Planning	Planning	Planning
LEAD COMPANY	Equinor	Equinor / SSE	Equinor	Equinor/ Polenergia	Equinor	Equinor	KNOC
OWNER SHARE	40%	50%	100%	50%	100%	%	%
POTENTIAL INSTALLED CAPACITY	88 MW	3600 MW	816 MW	~2500 MW	~3500 MW	~720 MW	~200 MW
PRODUCTION START	2022	2023	2024				
COUNTRY	Norway	UK	USA	Poland	USA	UK	South Korea



The wind journey

Becoming an offshore wind major



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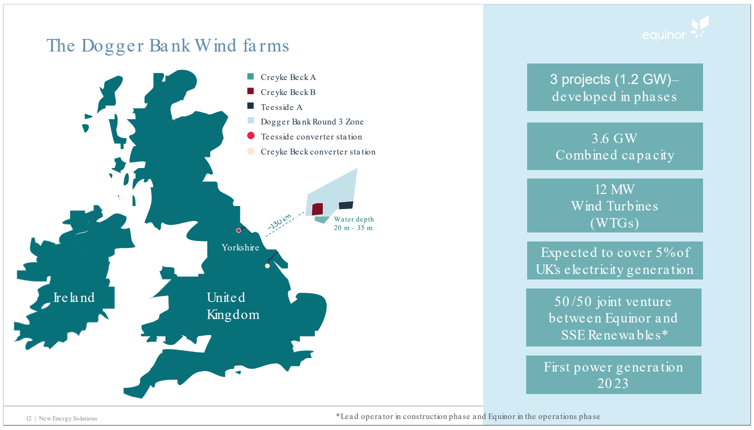
Equinor currently top 5 player in North Sea, Baltics and North America clusters

Participation[1] in North Sea, Baltics and North America offshore wind capacity (GW)

1. Ownership shares considered 2. 'In operational' also includes experience acquired from decommissioned parks 3. Includes projects under construction 4. Includes portfolio of Innogy and EON
5. Equinor including Massachusetts (800 MW) and Boardwalk (1000 MW) 6. Polska Grupa Energetyczna 7. Copenhagen Infrastructure Partners
Source: 4COffshore, BCG analysis, 2019



equinor

The Dogger Bank Wind farms

3 projects (1.2 GW)– developed in phases

3.6 GW
Combined capacity

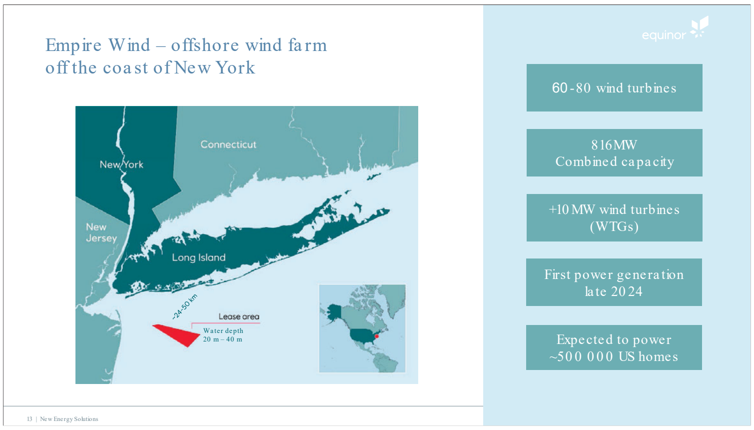
12 MW
Wind Turbines
(WTGs)

Expected to cover 5% of UK's electricity generation

50/50 joint venture between Equinor and SSE Renewables*

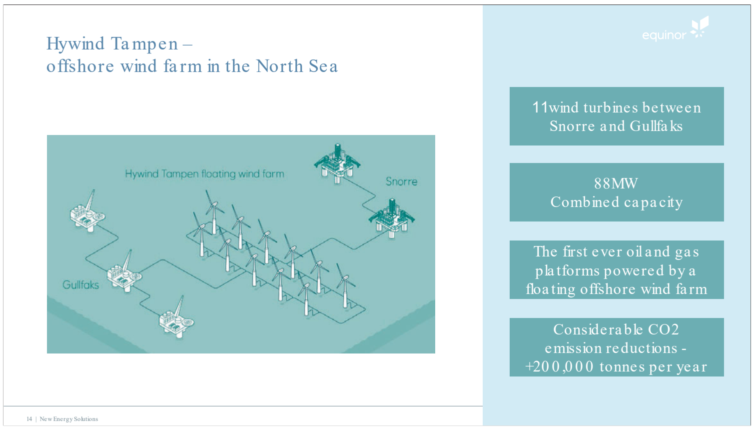
First power generation 2023

*Lead operator in construction phase and Equinor in the operations phase



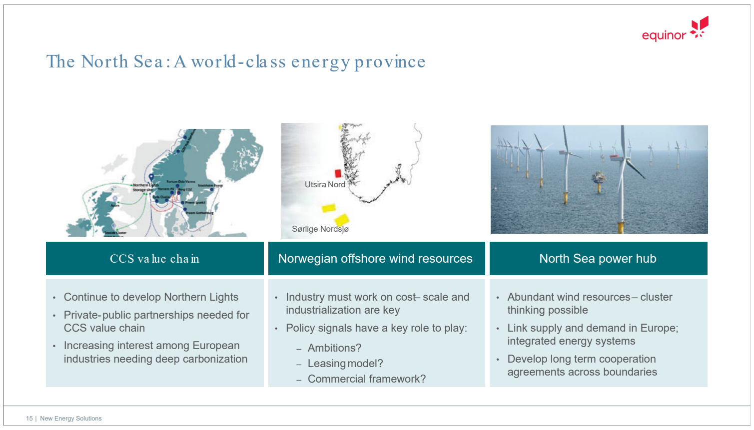
Empire Wind – offshore wind farm off the coast of New York

- 60-80 wind turbines
- 816MW
  Combined capacity
- +10 MW wind turbines (WTGs)
- First power generation late 2024
- Expected to power ~500 000 US homes



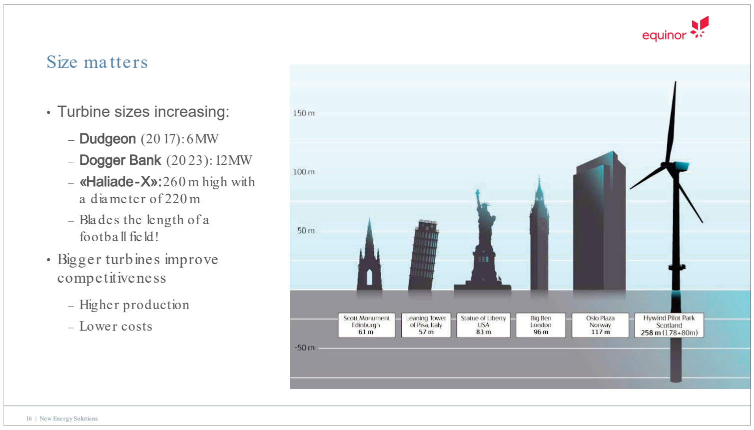
Hywind Tampen – offshore wind farm in the North Sea

- 11wind turbines between Snorre and Gullfaks
- 88MW
  Combined capacity
- The first ever oil and gas platforms powered by a floating offshore wind farm
- Considerable CO2 emission reductions - +200,000 tonnes per year



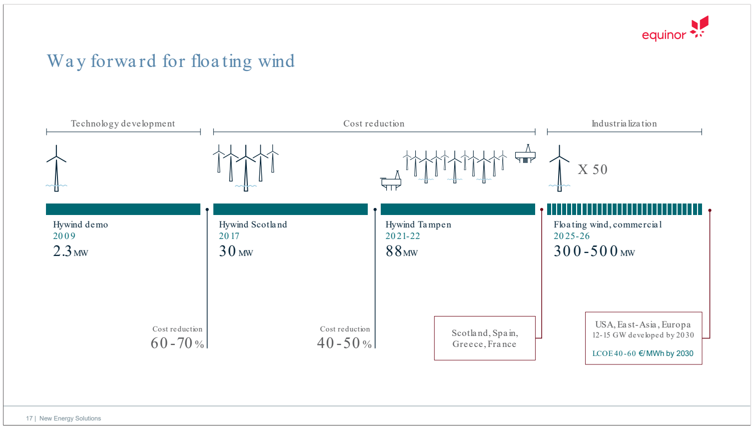
The North Sea: A world-class energy province

CCS value chain	Norwegian offshore wind resources	North Sea power hub
• Continue to develop Northern Lights • Private-public partnerships needed for CCS value chain • Increasing interest among European industries needing deep carbonization	• Industry must work on cost– scale and industrialization are key • Policy signals have a key role to play: – Ambitions? – Leasing model? – Commercial framework?	• Abundant wind resources – cluster thinking possible • Link supply and demand in Europe; integrated energy systems • Develop long term cooperation agreements across boundaries



Size matters

- Turbine sizes increasing:
  - **Dudgeon** (2017): 6MW
  - **Dogger Bank** (2023): 12MW
  - **«Haliade-X»:** 260 m high with a diameter of 220 m
  - Blades the length of a football field!
- Bigger turbines improve competitiveness
  - Higher production
  - Lower costs



Way forward for floating wind

Hywind demo
2009
2.3 MW

Hywind Scotland
2017
30 MW

Hywind Tampen
2021-22
88MW

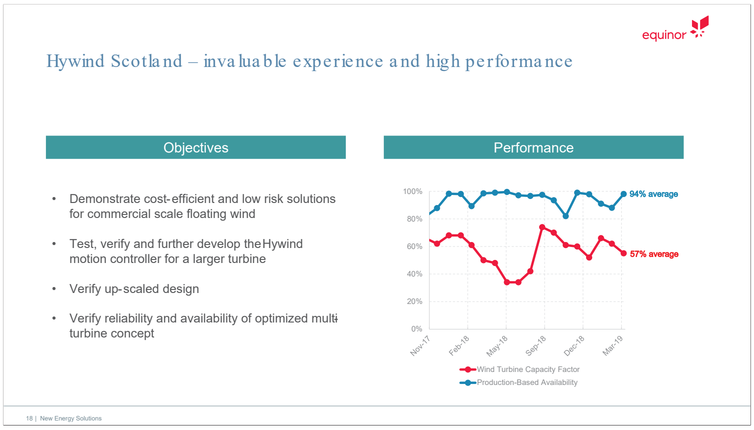
Floating wind, commercial
2025-26
300-500 MW

Cost reduction
60-70 %

Cost reduction
40-50 %

Scotland, Spain, Greece, France

USA, East-Asia, Europa
12-15 GW developed by 2030
LCOE 40-60 €/MWh by 2030



Hywind Scotland – invaluable experience and high performance

Objectives

- Demonstrate cost-efficient and low risk solutions for commercial scale floating wind
- Test, verify and further develop the Hywind motion controller for a larger turbine
- Verify up-scaled design
- Verify reliability and availability of optimized multi-turbine concept

Performance

equinor

The next big thing globally

- Vast potential: 12-15 GW market by 2030
- Innovative applications
- Choice of substructure and design will vary depending on local conditions
- Equinor is a technology agnostic developer
- Targeting the «big four» regions

equinor

Solar - Building capabilities and capturing opportunities through partnership

Apodi project
Brazil
162 MW*

Guanizul 2A project
Argentina
117 MW*

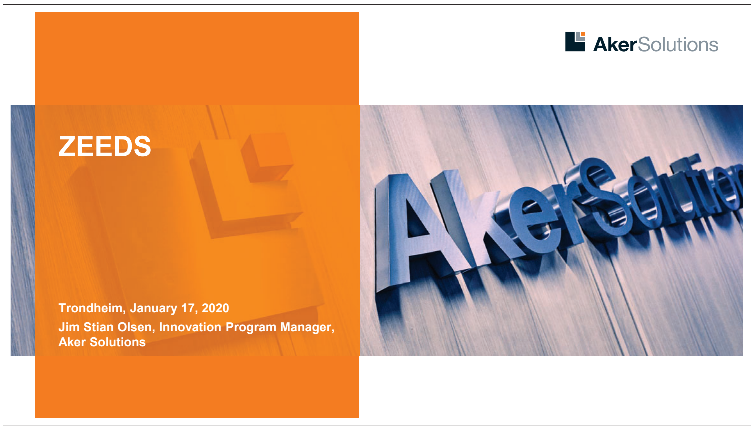
Exploring opportunities
Latin America and other regions with Equinor presence

Combining solutions
Bundling technologies

- Installed capacity, 100% basis.

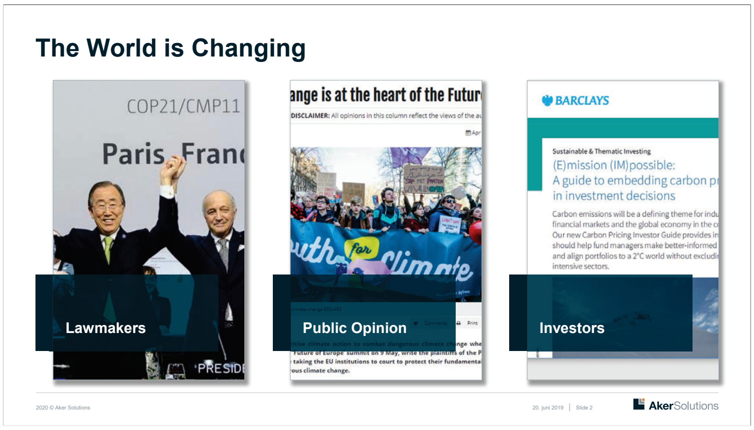
Shaping the future of energy

Thank you for your attention



ZEEDS

Trondheim, January 17, 2020
Jim Stian Olsen, Innovation Program Manager,
Aker Solutions



The World is Changing

Lawmakers

Public Opinion

Investors

2020 © Aker Solutions

20. juni 2019 | Slide 2

20/25/30

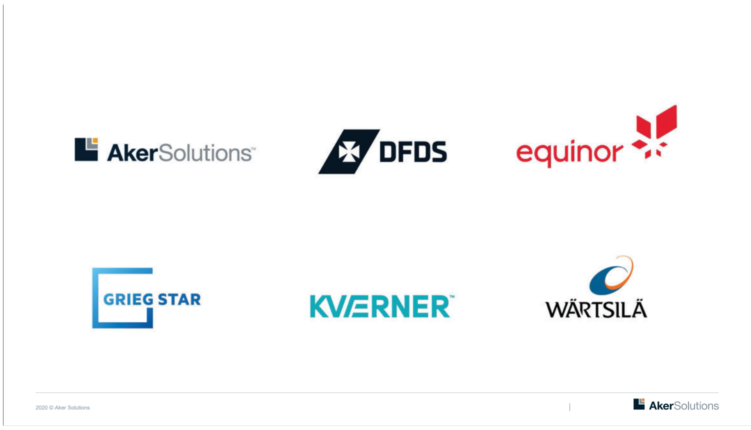
Leading a **Sustainable** Energy Future

Aker Solutions will **lead the industrialization** of offshore wind energy solutions

New Era of Ocean Economy Opportunities

SHIPPING

1 BILLON TONS CO_2



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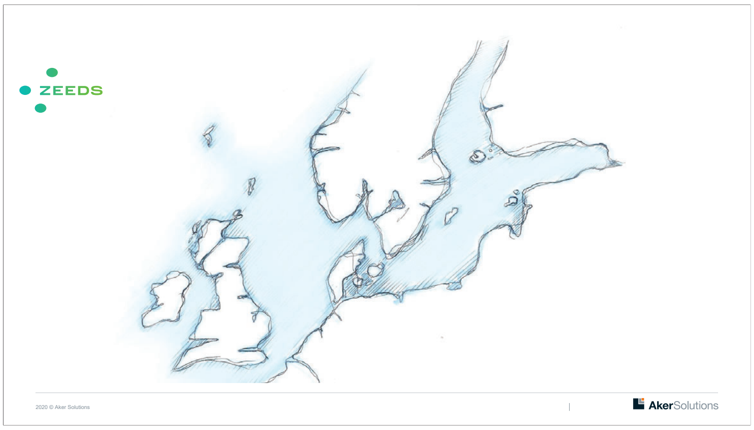
ASSIGNMENT

Explore if zero emission energy distribution at sea can accelerate the development of zero emission shipping



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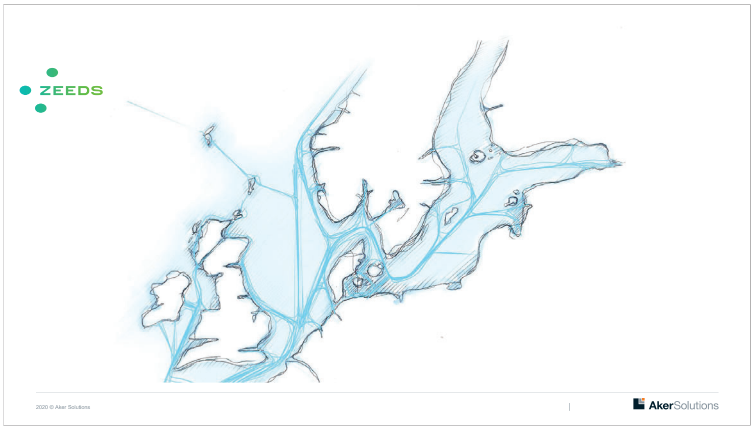

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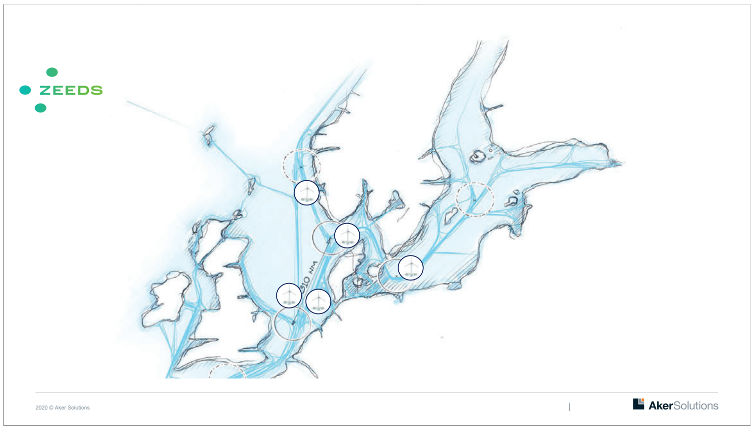

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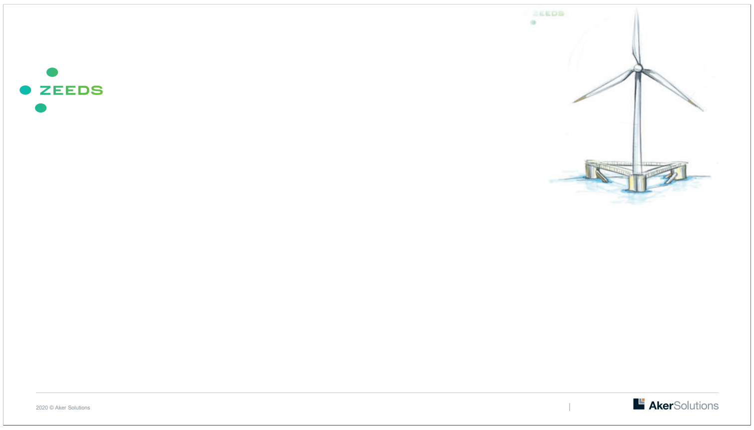

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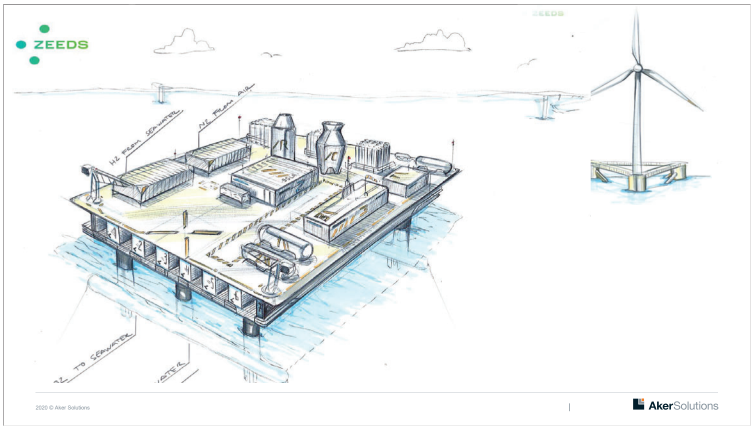

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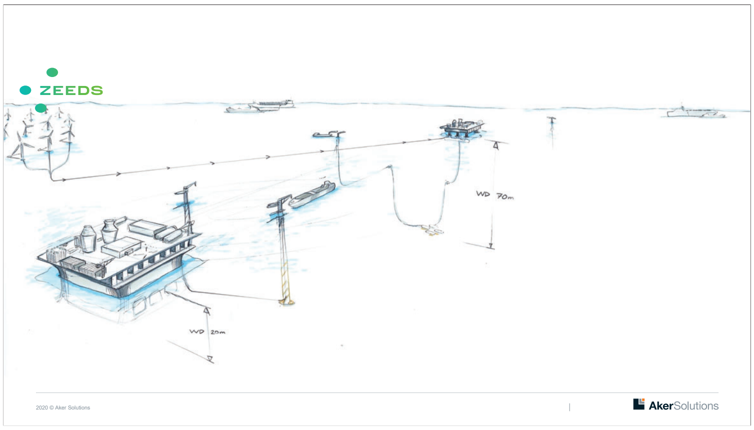

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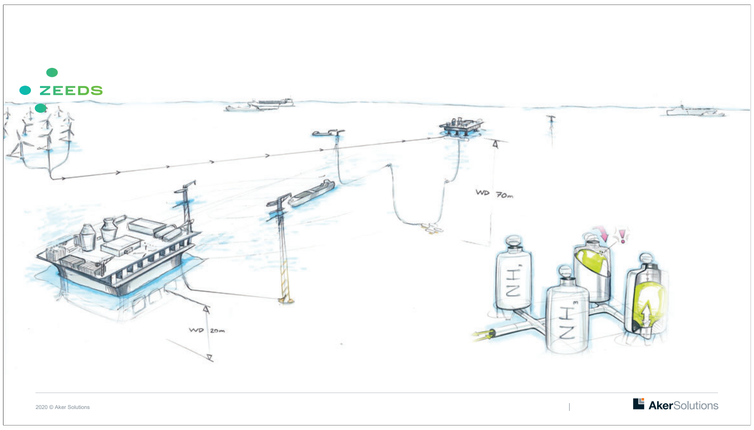

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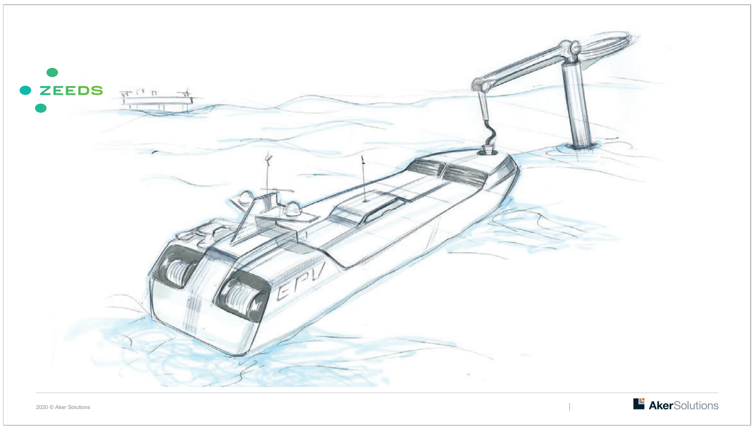

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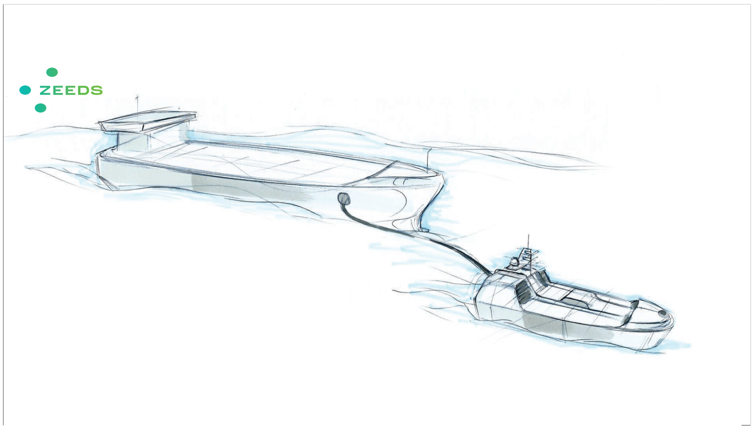

74 Windturbines

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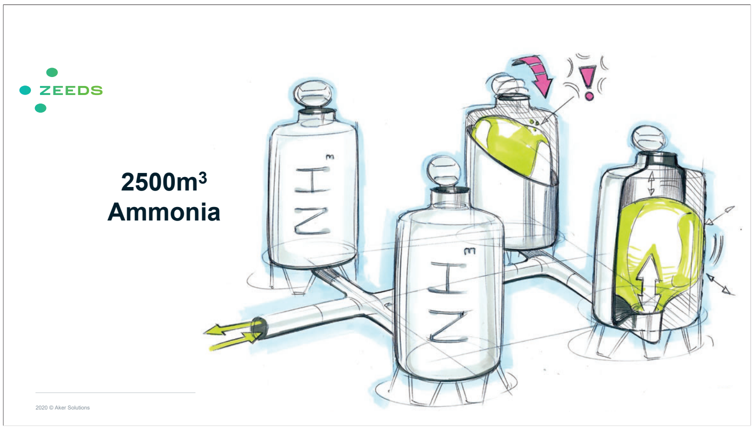

ZEEDS

$2500m^3$ Ammonia

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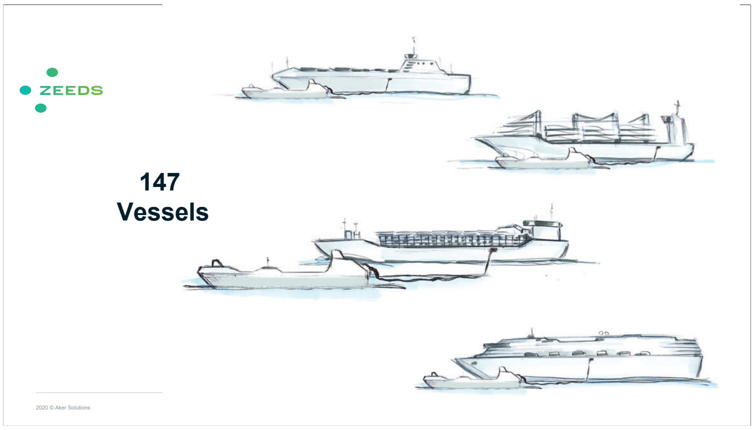

ZEEDS

147 Vessels

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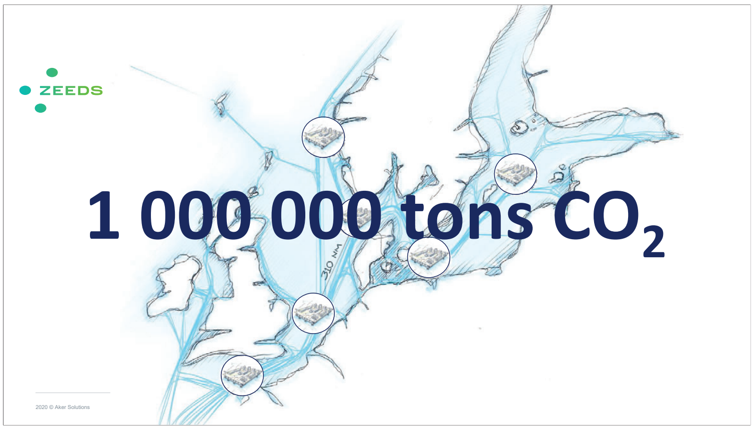

ZEEDS

1 000 000 tons CO_2

2020 © Aker Solutions

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Offshore Wind R&I:
The now and the future

Dr. Carlos Eduardo Lima da Cunha
DG Research & Innovation

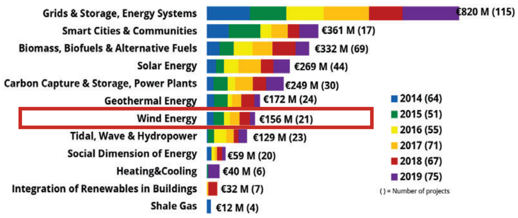
Trondheim/NO

Current state-of-affairs

Numbers and figures in wind energy

H2020 Energy Projects*

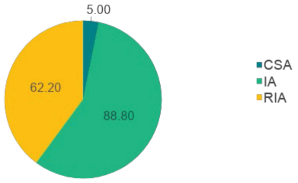
In total over **380 projects (€2.6B)**



*numbers from INEA

H2020 Wind Energy Projects*

21 projects: 12 RIA - 6 IA - 3 CSA
EU funding: €156M



EU funds of the 21 projects,
per type of action (Mio Euro)

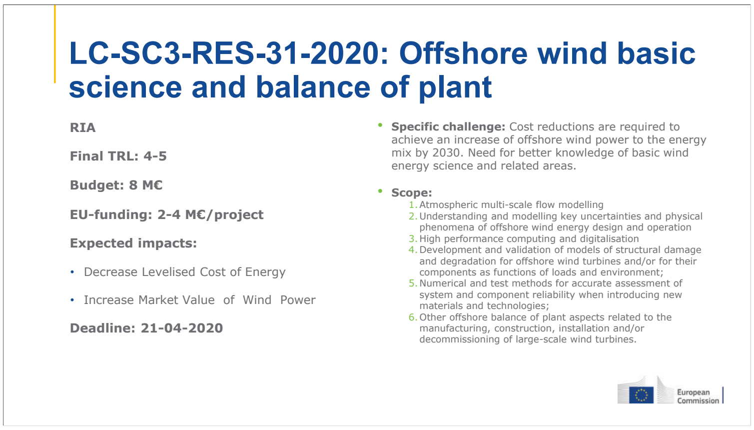
*numbers from INEA

Closing Horizons 2020

Last calls of this Work Programme

Closing calls

- Secure, clean and efficient energy programme
  - LC-SC3-RES-31-2020 Offshore wind basic science and balance of plant
  - LC-SC3-RES-19-2020 Demonstration of innovative technologies for floating wind farms
- NMBP Programme
  - DT-FOF-10-2020 Pilot lines for large-part high-precision manufacturing
  - LC-NMBP-31-2020 Materials for offshore energy
- General topics
  - LC-SC3-RES-1-2019-2020 Developing the next generation of renewable energy technologies
  - H2020-EIC-SMEInst-2018-2020 EIC Accelerator pilot



LC-SC3-RES-31-2020: Offshore wind basic science and balance of plant

RIA

Final TRL: 4-5

Budget: 8 M€

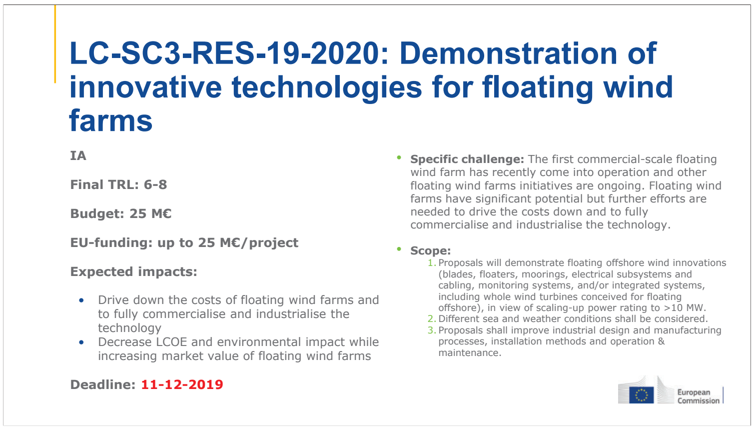
EU-funding: 2-4 M€/project

Expected impacts:

- Decrease Levelised Cost of Energy
- Increase Market Value of Wind Power

Deadline: 21-04-2020

- **Specific challenge:** Cost reductions are required to achieve an increase of offshore wind power to the energy mix by 2030. Need for better knowledge of basic wind energy science and related areas.
- **Scope:**
  1. Atmospheric multi-scale flow modelling
  2. Understanding and modelling key uncertainties and physical phenomena of offshore wind energy design and operation
  3. High performance computing and digitalisation
  4. Development and validation of models of structural damage and degradation for offshore wind turbines and/or for their components as functions of loads and environment;
  5. Numerical and test methods for accurate assessment of system and component reliability when introducing new materials and technologies;
  6. Other offshore balance of plant aspects related to the manufacturing, construction, installation and/or decommissioning of large-scale wind turbines.



LC-SC3-RES-19-2020: Demonstration of innovative technologies for floating wind farms

IA

Final TRL: 6-8

Budget: 25 M€

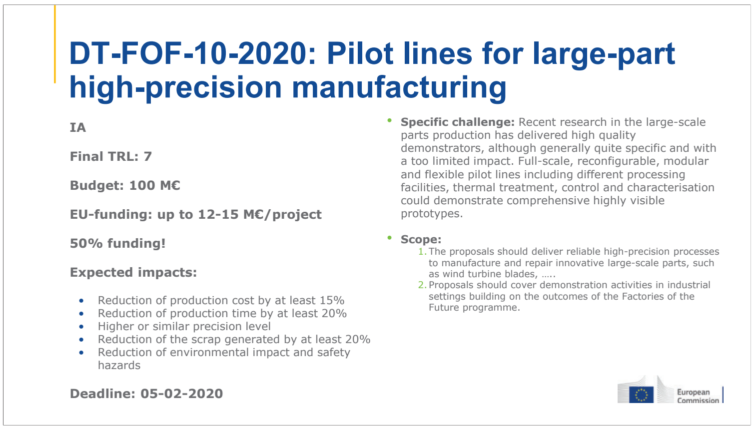
EU-funding: up to 25 M€/project

Expected impacts:

- Drive down the costs of floating wind farms and to fully commercialise and industrialise the technology
- Decrease LCOE and environmental impact while increasing market value of floating wind farms

Deadline: 11-12-2019

- **Specific challenge:** The first commercial-scale floating wind farm has recently come into operation and other floating wind farms initiatives are ongoing. Floating wind farms have significant potential but further efforts are needed to drive the costs down and to fully commercialise and industrialise the technology.
- **Scope:**
  1. Proposals will demonstrate floating offshore wind innovations (blades, floaters, moorings, electrical subsystems and cabling, monitoring systems, and/or integrated systems, including whole wind turbines conceived for floating offshore), in view of scaling-up power rating to >10 MW.
  2. Different sea and weather conditions shall be considered.
  3. Proposals shall improve industrial design and manufacturing processes, installation methods and operation & maintenance.



DT-FOF-10-2020: Pilot lines for large-part high-precision manufacturing

IA

Final TRL: 7

Budget: 100 M€

EU-funding: up to 12-15 M€/project

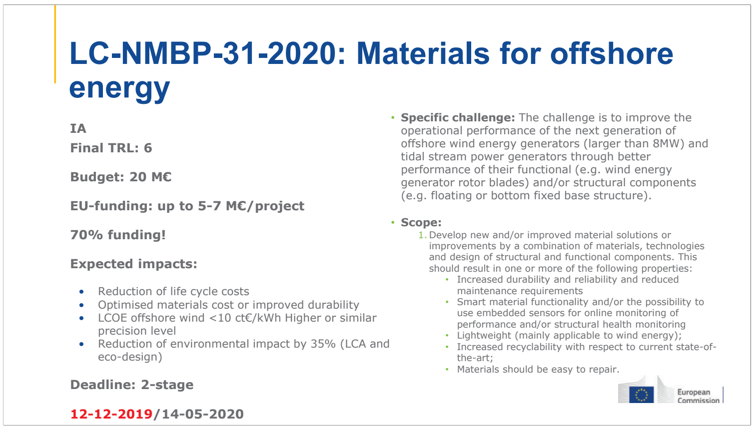
50% funding!

Expected impacts:

- Reduction of production cost by at least 15%
- Reduction of production time by at least 20%
- Higher or similar precision level
- Reduction of the scrap generated by at least 20%
- Reduction of environmental impact and safety hazards

Deadline: 05-02-2020

- **Specific challenge:** Recent research in the large-scale parts production has delivered high quality demonstrators, although generally quite specific and with a too limited impact. Full-scale, reconfigurable, modular and flexible pilot lines including different processing facilities, thermal treatment, control and characterisation could demonstrate comprehensive highly visible prototypes.
- **Scope:**
  1. The proposals should deliver reliable high-precision processes to manufacture and repair innovative large-scale parts, such as wind turbine blades, …..
  2. Proposals should cover demonstration activities in industrial settings building on the outcomes of the Factories of the Future programme.



LC-NMBP-31-2020: Materials for offshore energy

IA

Final TRL: 6

Budget: 20 M€

EU-funding: up to 5-7 M€/project

70% funding!

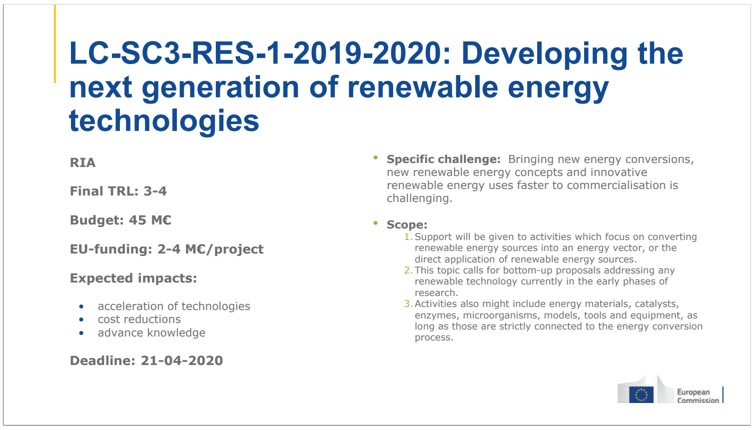
Expected impacts:

- Reduction of life cycle costs
- Optimised materials cost or improved durability
- LCOE offshore wind <10 ct€/kWh Higher or similar precision level
- Reduction of environmental impact by 35% (LCA and eco-design)

Deadline: 2-stage

12-12-2019/14-05-2020

- **Specific challenge:** The challenge is to improve the operational performance of the next generation of offshore wind energy generators (larger than 8MW) and tidal stream power generators through better performance of their functional (e.g. wind energy generator rotor blades) and/or structural components (e.g. floating or bottom fixed base structure).
- **Scope:**
  1. Develop new and/or improved material solutions or improvements by a combination of materials, technologies and design of structural and functional components. This should result in one or more of the following properties:
     - Increased durability and reliability and reduced maintenance requirements
     - Smart material functionality and/or the possibility to use embedded sensors for online monitoring of performance and/or structural health monitoring
     - Lightweight (mainly applicable to wind energy);
     - Increased recyclability with respect to current state-of-the-art;
     - Materials should be easy to repair.



LC-SC3-RES-1-2019-2020: Developing the next generation of renewable energy technologies

RIA

Final TRL: 3-4

Budget: 45 M€

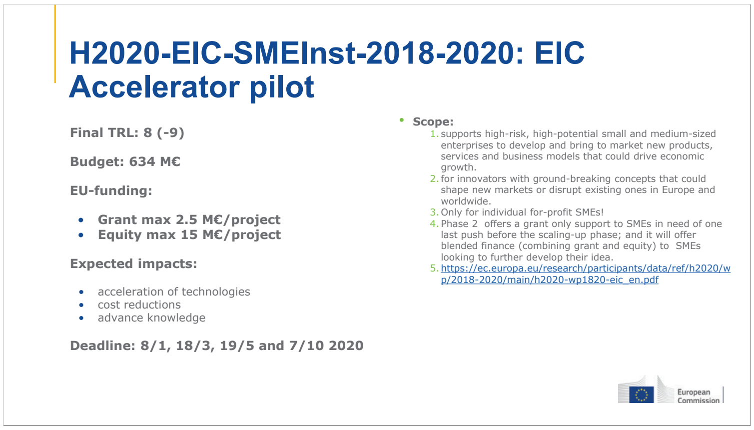
EU-funding: 2-4 M€/project

Expected impacts:

- acceleration of technologies
- cost reductions
- advance knowledge

Deadline: 21-04-2020

- **Specific challenge:** Bringing new energy conversions, new renewable energy concepts and innovative renewable energy uses faster to commercialisation is challenging.
- **Scope:**
  1. Support will be given to activities which focus on converting renewable energy sources into an energy vector, or the direct application of renewable energy sources.
  2. This topic calls for bottom-up proposals addressing any renewable technology currently in the early phases of research.
  3. Activities also might include energy materials, catalysts, enzymes, microorganisms, models, tools and equipment, as long as those are strictly connected to the energy conversion process.



H2020-EIC-SMEInst-2018-2020: EIC Accelerator pilot

Final TRL: 8 (-9)

Budget: 634 M€

EU-funding:

- **Grant max 2.5 M€/project**
- **Equity max 15 M€/project**

Expected impacts:

- acceleration of technologies
- cost reductions
- advance knowledge

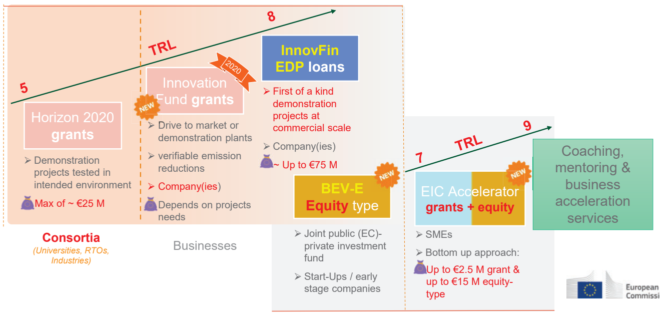
Deadline: 8/1, 18/3, 19/5 and 7/10 2020

- **Scope:**
  1. supports high-risk, high-potential small and medium-sized enterprises to develop and bring to market new products, services and business models that could drive economic growth.
  2. for innovators with ground-breaking concepts that could shape new markets or disrupt existing ones in Europe and worldwide.
  3. Only for individual for-profit SMEs!
  4. Phase 2 offers a grant only support to SMEs in need of one last push before the scaling-up phase; and it will offer blended finance (combining grant and equity) to SMEs looking to further develop their idea.
  5. https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-eic_en.pdf

Exploring Other Possibilities

There is more beyond RIA, IA, CSA…

Other EU funding options for clean energy innovation



Horizon 2020 grants
- Demonstration projects tested in intended environment

Max of ~ €25 M

Consortia
(Universities, RTOs, Industries)

Innovation Fund grants
- Drive to market or demonstration plants
- verifiable emission reductions
- Company(ies)

Depends on projects needs

Businesses

InnovFin EDP loans
- First of a kind demonstration projects at commercial scale
- Company(ies)

~ Up to €75 M

BEV-E Equity type
- Joint public (EC)-private investment fund
- Start-Ups / early stage companies

EIC Accelerator grants + equity
- SMEs
- Bottom up approach:

Up to €2.5 M grant & up to €15 M equity-type

Coaching, mentoring & business acceleration services

InnoVFin
Energy Demo Projects

Risk-finance instrument
Pilot launched in June 2015

Criteria I:
- Innovativeness
- Replicability

Criteria II:
- Bankability during operations
- Commitment by promoters

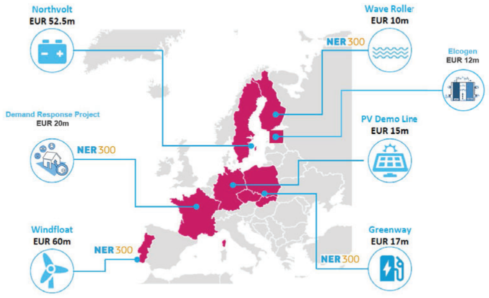
Targets first-of-a-kind demonstrations of innovative technologies at commercial scale

Support via **loans and quasi-equity**

Budget: over € 700M
- Energy Challenge: **€** 125M
- Access to Risk Finance: **€** 165M
- Undisbursed NER300: over **€** 436M

Current Portfolio: 7 projects
- **€ 186M of EU support (Jan 2020)**
- € 393M project costs

Portfolio



EIB

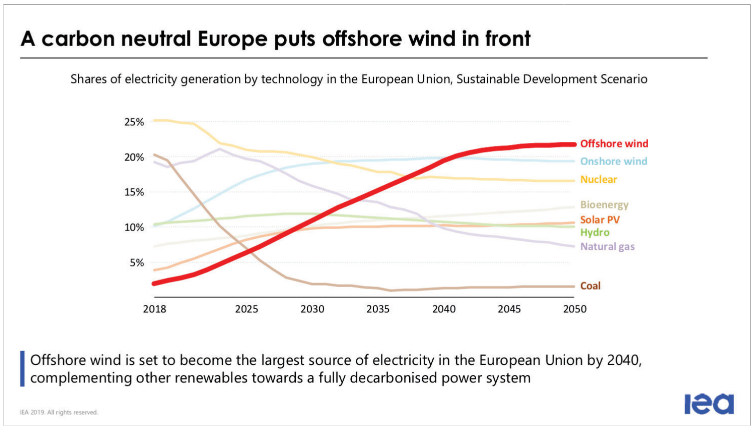
WindFloat

- **Project characteristics**
  - Floating offshore wind farm in Portugal
  - Semi-submersible floating structure
  - 3 x 8,3 MW
  - 20 km from shore, water depth 85-100 m
- **Risks and opportunities**
  - Risks: new turbine, upscaling, structural integrity, wind resources
  - Opportunities: deep seas, assembly in port, transport by tugboats
- **Technological development**
  - 2011-2014 – FP7 "DEMOWFLOAT" project: pilot installation of 2 MW
- **Finance**
  - Support: €60M InnovFin EDP loan + €30M NER300 grant
  - Total project cost: €131M

The road ahead

What will Horizons Europe bring us?

Circular Economy · Sustainability · Carbon Neutrality by 2050 · Global Competitiveness with Global Consequences



A carbon neutral Europe puts offshore wind in front

Shares of electricity generation by technology in the European Union, Sustainable Development Scenario

Offshore wind is set to become the largest source of electricity in the European Union by 2040, complementing other renewables towards a fully decarbonised power system

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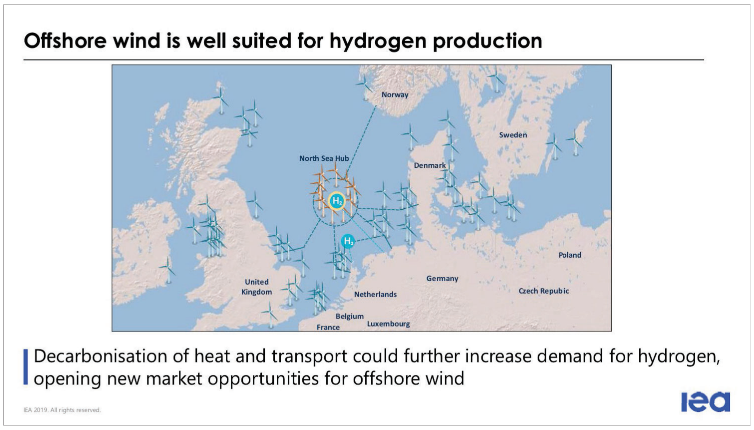

Offshore wind is well suited for hydrogen production

Decarbonisation of heat and transport could further increase demand for hydrogen, opening new market opportunities for offshore wind

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Horizons Europe and the Green Deal

- Horizons Europe will support the Green Deal.
  - Expected budget: €100B
  - Missions & Partnerships
  - Co-creation with other financial instruments
- Beyond Horizons Europe
  - Private Public Initiatives focused on climate and environment
  - Just Transition Mechanism
    - Leveling the playfield
    - Expected budget: at least €100B
  - Sustainable Europe Investment Plan
    - European Investment Bank = European Green Bank
    - InvestEU (consolidated InnovFin)
    - Expected budget: at least €1T

European Commission

Clean energy
Sustainable industry
Building and renovating
Sustainable mobility
Biodiversity
From Farm to Fork
Eliminating pollution

European Commission

Thanks. Danke. Merci. Obrigado.

More info at:

https://ec.europa.eu/research/
https://ec.europa.eu/energy/

European Commission

Poster session - link to posters

1. Multi-objective model predictive control for a multi-rotor wind turbine, Jørgen Urdal, NTNU
2. Wave-modified two-equation model to study wave-wind interaction in shallow waters, Mostafa Bakhoday Paskyabi, UiB
3. Vertical profiles of wind velocity, turbulence intensity and temperature beyond the surface layer, Piotr Domagalski, WindTak
4. COTUR - estimating the COherence of TURbulence with wind lindar technology, Martin Flügge, NORCE
5. Polymorphic uncertainty in met-ocean conditions and the influence on fatigue loads, Clemens Hübler, ForWind
6. Evaluation of Gaussian wake models under different atmospheric stability conditions: comparison with large eddy simulation results, Maria Krutova, UiB
7. A novel approach to computing super observations for probabilistic wave model validation, Patrik Bohlinger, Norwegian Meteorological Inst.
8. Hub-based vectoral reduction of turbulent wind fields for actuator-disc wind turbine models, Valentin Chabaud, SINTEF
9. Comparison of Weather Window Statistics and Time Series Based Methods Considering Risk Measures, Julia Lübsen, Fraunhofer IWES
10. A Conceptual Framework for Data-driven Reliability-centred Evolutionary and Automated Maintenance of Offshore Wind Farms, Koorosh Aslansefat, University of Hull
11. Applications and platforms in digitalisation of wind farm O&M – community feedback and survey results, Volker Berkhout, Fraunhofer IEE
12. Identification and prioritization of low performing wind turbines using a power curve health value approach, Sebastian Pfaffel, Fraunhofer IEE
13. Innovative, Low Cost, Low Weight and Safe Floating Wind Technology Optimized for Deep Water Wind Sites: The FLOTANT Project, Ayoze Castro, The Oceanic Platform of the Canary Islands
14. Short-term Offshore Wind Speed Forecasting with an Efficient Machine Learning Approach, Mostafa Bakhoday Paskyabi, UiB
15. Vortex interaction in the wake of a two- and three-bladed wind turbine, Ludwig Kuhn, NTNU
16. Sensitivity analysis of cost parameters for floating offshore wind farms, Carmela Maienza, Univ of Campania
17. Flow model integration into the STAS framework for optimal control of wind power plant, Stefan Dankelman, SINTEF
18. A Numerical Study on the Effect of Wind Turbine Wake Meandering on Power Production of Hywind Tampen, Endre Tenggren, NTNU
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