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Report

Wind Power R&D seminar – deep sea offshore wind – Trondheim, Norway, 20-21 January 2011

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KEYWORDS:
Wind turbine; Generators; Offshore; Grid connection; Met-ocean conditions; Operation and maintenance; Installation and sub-structures; Wind farm modelling

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ABSTRACT

This report includes the presentations from the wind power R&D seminar 20-21 January 2011 in Trondheim, Norway. The research and development on deep sea offshore wind power is addressed through invited presentations by industry and research. Emphasis is on presenting results from the strong Norwegian research programmes on offshore wind power.

The seminar has been arranged every year since 2004, and has been established as an important venue for the wind power sector in Norway and internationally. 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) Operation and maintenance
e) Installation and sub-structures
f) Wind farm modelling

Plenary presentations include offshore wind opportunities and success stories.

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Closing session – Success stories from Offshore Wind Research, Development and Deployment

Wind Power R&D seminar – deep sea offshore wind
20-21 January 2011, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY

	Thursday 20 January		
09.00	Registration & coffee		
	Opening session – offshore wind opportunities Chairs: John Olav Tande, SINTEF/NOWITECH and Kristin Guldbrandsen Frøysa, CMR/NORCOWE		
09.30	Opening and welcome by chair		
09.40	*Norway as a battery for Europe – prospects for supply of technology and services* Jon Dugstad, Regional Director INTPOW		
10.10	*Potential supplies from Norwegian industry to offshore wind developments* Asle Lygre, Arena NOW		
10.30	*New research initiatives for advancing development of deep sea offshore wind technology* John Olav Giæver Tande, Director NOWITECH / Senior Scientist SINTEF Energy Research		
11.00	*Norwegian met/ocean infrastructure for offshore wind energy research* Prof. Joachim Reuder, University of Bergen		
11.30	*Plans for Havsul offshore wind farm* Tore Engevik, Vestavind Offshore		
11.50	Summary and discussions by chair		
12.00	Lunch		
	Parallel sessions		
	A1) New turbine technology Chairs: Jasna B. Jakobsen, Uni. of Stavanger, Roy Stenbro, IFE	**B1) Power system integration** Chairs: Prof Tore Undeland, NTNU, Prof Kjetil Uhlen, NTNU	**C1) Met-ocean conditions** Chairs: Prof Jochen Reuder, Uni. of Bergen, Erik Berge, IFE
13.00	Introduction by Chair	Introduction by Chair	Introduction by Chair
13.10	*Development of the SWAY tower concept;* Michal Forland, SWAY	*Offshore Wind farm Grid Integration challenges, Doggerbank;* Sharifabadi Kamran, Statkraft	*Conditions for Offshore Wind Energy Use*; Prof D Heinemann, Uni. Oldenburg
13.30	*Loads analysis of selected floating designs;* Amy Robertson, NREL	*Offshore grid developments;* Kjartan Hauglum, Statnett	*Atmospheric profiling by lidar for wind energy research;* Torben Mikkelsen, DTU Risø
14.00	*Aluminium as a viable solution for offshore wind turbines*; Simon Jupp, Hydro Aluminium	*Characterization and modelling of the power output variability of wind farms;* Prof Hans Georg Beyer, Uni of Agder	*From tower to tower;* Svein Erling Hansen, Fugro Oceanor
14.20	*HiPRWind – large floating turbines for intermediate water depths*; Jochen Bard, Fraunhofer IWES	*Supply of offshore wind energy to oil and gas installations;* Harald Svendsen, SINTEF	*The effects of ocean waves on offshore wind generators;* Alastair Jenkins, Uni Research
14.40	*Prospects of large floating vertical axis wind turbines;* Uwe Schmidt Paulsen, Risø DTU	*Balancing offshore wind;* Post Doc Steve Völler, NTNU	*Large Eddy Simulation;* Alla Sapronova, Uni Research
15.00	Refreshments		
	A2) New turbine technology Chairs: Conrad Carstensen, Uni. of Stavanger, BW Tveiten, SINTEF	**B2) Grid connection** Chairs: Prof Tore Undeland, NTNU, Prof K Uhlen, NTNU	**C2) Met-ocean conditions** Chairs: Prof Jochen Reuder, Uni. of Bergen, Erik Berge, IFE
15.30	Introduction by Chair	Introduction by Chair	Introduction by Chair
15.35	*Novel PM generators for large wind turbines*; Alexey Matveev, SmartMotor	*Challenges and design of offshore substations;* C. Olerud, Goodtech Projects & Services	*Wave extremes in the Northeast Atlantic;* Ole Johan Aarnes, met.no
15.55	*Novel methodology for fatigue design of wind turbine components of ductile cast iron;* Prof G Härkegård, NTNU	*Voltage control of wind power plants with DFIG;* Jorge Martínez García, Vestas	*The HyWind forecasting project;* Birgitte Furevik, met.no
16.15	*New power electronic schemes for large wind turbines*; Prof Marta Molinas, NTNU	*Wind farm measurements and model validation;* Prof Kjetil Uhlen, NTNU	*A comparison of sonic and lidar-sensed wind velocity*; PhD stud Fabio Pierella, NTNU
16.35	*Need for international standards on floating offshore wind turbines;* Johan Sandberg, DNV	*Transient analysis of transformers and cables for offshore wind connection*; Bjørn Gustavsen, SINTEF	*Design and operation of floating met-masts;* Israel Pinto Grijuela, Grupo APIAXXI
16.55	Closing by Chair	Closing by Chair	Closing by Chair
17.00	**Poster Session with refreshments and presentation of PhD students on offshore wind**		
19.00	Dinner		

Wind Power R&D seminar – deep sea offshore wind **20-21 January 2010, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY**			
	Friday 21 January		
	Parallel sessions		
	D) Operations & maintenance Chairs: Jørn Heggset, SINTEF, Hans Georg Beyer, Uni. of Agder	**E) Installation & sub-structures** Chairs: Prof Geir Moe, NTNU, Prof Ivar Langen, Uni of Stavanger	**F) Wind farm modelling** Chairs: Prof Trond Kvamsdal, NTNU, Lene Sælen, CMR Gexcon
09.00	Introduction by Chair	Introduction by Chair	Introduction by Chair
09.05	*The German wind turbine reliability database (WMEP)*; Jochen Bard, Fraunhofer IWES	*Coupled analysis of floating wind turbines*; Elizabeth Passano, MARINTEK	*Wakes between large wind farms;* Idar Barstad, Uni Research
09.25	*Framework for risk-based O&M planning for offshore wind turbines*; Prof John D Sørensen, Uni. of Aalborg	*The effects of breaking wave-induced currents;* PhD stud Sung-Jin Choi, Uni of Stavanger	*Wake models compared with measurements;* Jennifer van Rij, IFE
09.45	*Cooperation on O&M and LCC analysis with Vattenfall;* F. Besnard, Chalmers Uni. Technology	*Analysis of piled foundations by means of various soil models*; PhD stud Eric van Buren, NTNU	*Wind and wake modelling using CFD*; Jens A Melheim, CMR GexCon
10.05	*HSE challenges of installing and operating offshore wind farms*; Camilla Tveiten, SINTEF	*Installation of bottom supported wind turbines at Sheringham Shoal*; Jan Ingar Knutsen, Master Marine	*A model study of wind turbine interference;* Prof Per Åge Krogstad, NTNU
10.25	Closing by Chair	Closing by Chair	Closing by Chair
10.30	Refreshments		
	Closing session – Success stories from Offshore Wind Research, Development and Deployment Chairs: John Olav Tande, SINTEF/NOWITECH and Kristin Guldbrandsen Frøysa, CMR/NORCOWE		
11.00	Introduction by Chair		
11.05	*Carbon Trust's Offshore Wind Accelerator,* Phil de Villiers, Carbon Trust		
11.25	*From Scanwind to GE – becoming a global player anchored in Mid-Norway* Martin Degen, GE		
11.45	*HyWind – A success story – A catalyst with Access as an example,* Sjur Bratland, Statoil		
12.05	*Offshore wind farm forecasting and energy production,* Jostein Mælan, StormGeo		
12.25	*Using research experiences in marine technology for advancing offshore wind technology* Prof. Torgeir Moan, NTNU		
12.45	*Research gives results* Espen B Christophersen, Research Council of Norway		
13.05	Closing by Chair		
13.10	Lunch		

List of participants
Wind Power R&D Seminar – Deep Sea Offshore Wind 20 – 21 January 2011

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Aarnes, Ole Johan	Meteorologisk institutt	NO
Abrahamsen, Odd Henning	Lyse Produksjon AS	NO
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Svendsen, Harald G.	SINTEF Energi as	NO
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Opening Session – offshore wind opportunities

Norway as a battery for Europe – prospects for supply of technology and services
Jon Dugstad, Regional Director INTPOW

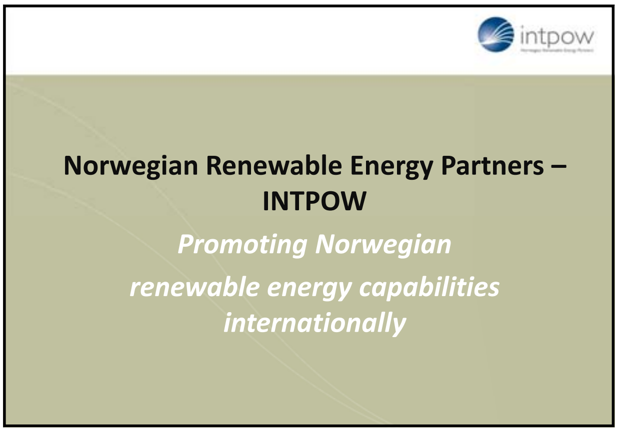
Potential supplies from Norwegian industry to offshore wind developments,
Asle Lygre, Arena NOW

New research initiatives for advancing development of deep sea offshore wind technology, John Olav Giæver Tande, Director NOWITECH / Senior Scientist SINTEF Energy Research

Norwegian met/ocean infrastructure for offshore wind energy research,
Prof. Joachim Reuder, University of Bergen

Plans for Havsul offshore wind farm,
Tore Engevik, Vestavind Offshore

Norway as a battery for Europe – prospects for supply of technology and services

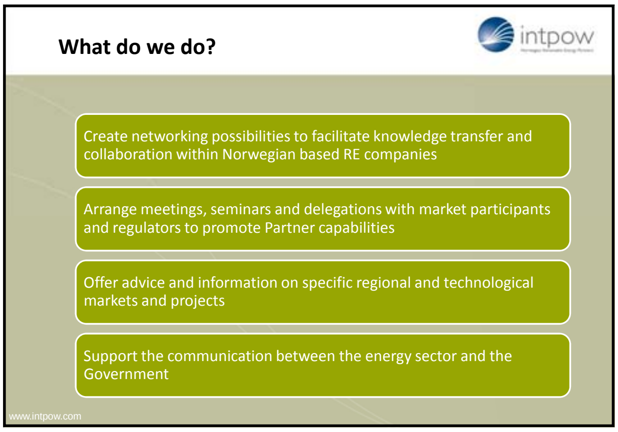


Norwegian Renewable Energy Partners – INTPOW

Promoting Norwegian

renewable energy capabilities internationally

ABB
energi
baze
BKK
EKSPORT FINANS
GIEK Garanti-instituttet for eksportkreditt
HAVGUL clean energy
HYDROENERGI
ITS INNOTECH SOLAR
Jacobsen Elektro
MULTICONSULT
navita
Nexans
Norconsult
norges varemesse norway trade fairs
NORPLAN
ONS
powel
SEAPROOF SOLUTIONS
SN POWER
Statkraft
Solkraft
RAINPOWER
SWECO
Statoil
teksal
TrønderEnergi
WAVEenergy



What do we do?

- Create networking possibilities to facilitate knowledge transfer and collaboration within Norwegian based RE companies
- Arrange meetings, seminars and delegations with market participants and regulators to promote Partner capabilities
- Offer advice and information on specific regional and technological markets and projects
- Support the communication between the energy sector and the Government

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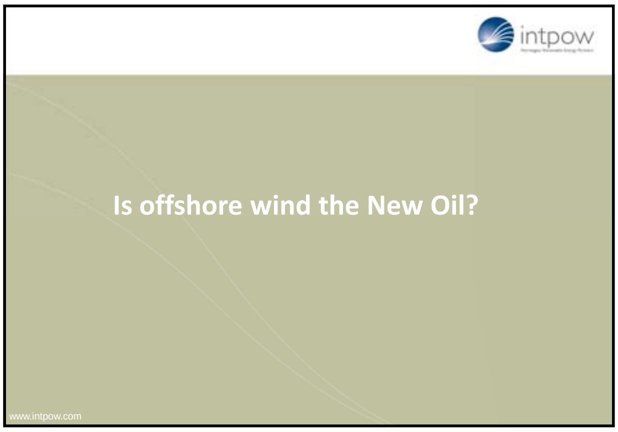
Hydro Power Markets
Priority : South East Europe with initial focus on Turkey
Secondary : Southern Africa (sub-Saharan Africa)

Offshore Wind Markets
Priority : North Sea with initial focus on UK-projects
Secondary : Asia, USA, North-Europe

Solar PV Market:
Priority : Southern Europe bordering the Mediterranean Sea
Secondary : Asia, USA, North Africa

Norway – An Energy Nation



Is offshore wind the New Oil?

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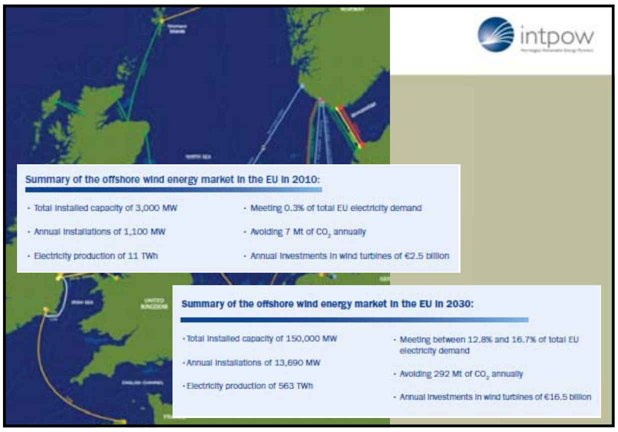
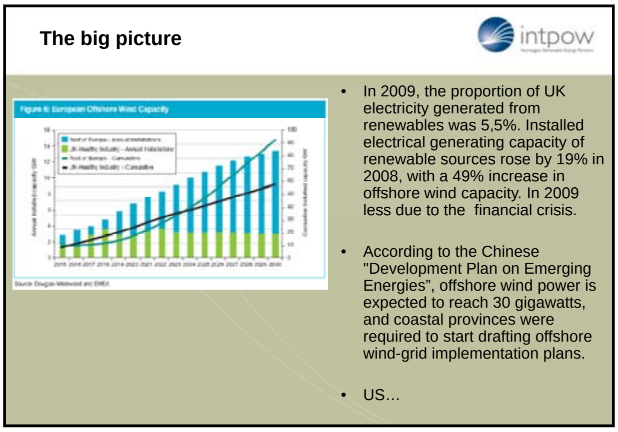


Summary of the offshore wind energy market in the EU in 2010:

- Total installed capacity of 3,000 MW
- Annual installations of 1,100 MW
- Electricity production of 11 TWh
- Meeting 0.3% of total EU electricity demand
- Avoiding 7 Mt of CO_2 annually
- Annual investments in wind turbines of €2.5 billion

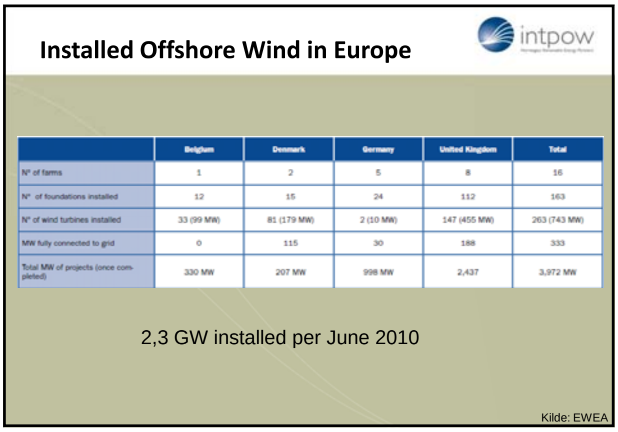
Summary of the offshore wind energy market in the EU in 2030:

- Total installed capacity of 150,000 MW
- Annual installations of 13,690 MW
- Electricity production of 563 TWh
- Meeting between 12.8% and 16.7% of total EU electricity demand
- Avoiding 292 Mt of CO_2 annually
- Annual investments in wind turbines of €16.5 billion



The big picture

- In 2009, the proportion of UK electricity generated from renewables was 5,5%. Installed electrical generating capacity of renewable sources rose by 19% in 2008, with a 49% increase in offshore wind capacity. In 2009 less due to the financial crisis.
- According to the Chinese "Development Plan on Emerging Energies", offshore wind power is expected to reach 30 gigawatts, and coastal provinces were required to start drafting offshore wind-grid implementation plans.
- US…

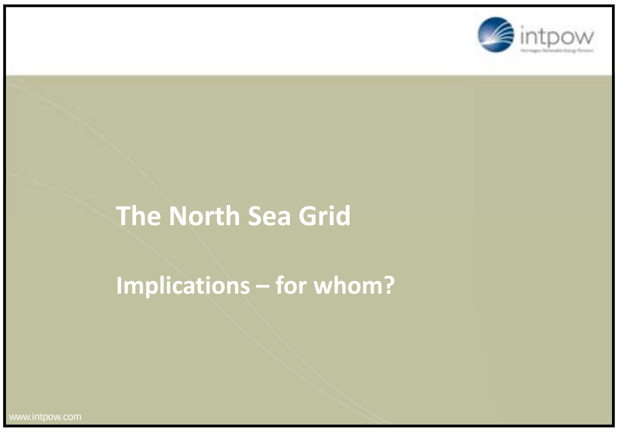


Installed Offshore Wind in Europe

	Belgium	Denmark	Germany	United Kingdom	Total
N° of farms	1	2	5	8	16
N° of foundations installed	12	15	24	112	163
N° of wind turbines installed	33 (99 MW)	81 (179 MW)	2 (10 MW)	147 (455 MW)	263 (743 MW)
MW fully connected to grid	0	115	30	188	333
Total MW of projects (once completed)	330 MW	207 MW	998 MW	2,437	3,972 MW

2,3 GW installed per June 2010

Kilde: EWEA



The North Sea Grid

Implications – for whom?

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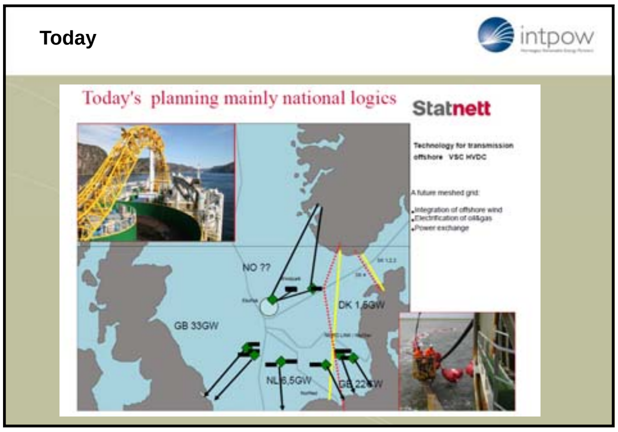


Today

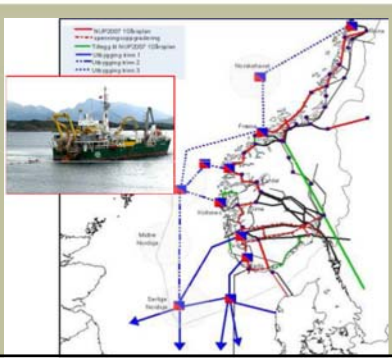
Today's planning mainly national logics

Technology for transmission offshore VSC HVDC

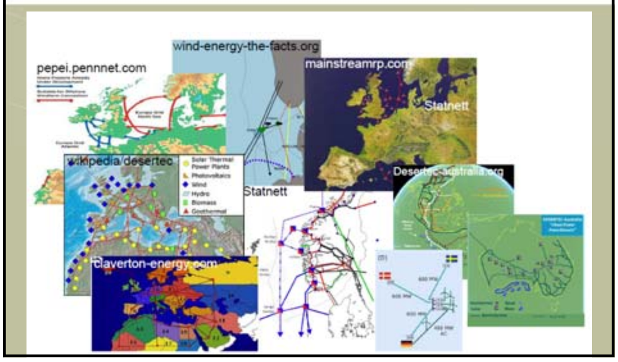
A future meshed grid:

- Integration of offshore wind
- Electrification of oil&gas
- Power exchange

Statnett vision for 2020 onwards…



.. And a number of other concepts...



Benefiting the European electricity market

Securing supply
- Improve the connection between big load centres around the North Sea
- Reduce dependency on gas and oil from unstable regions
- Transmit indigenous offshore renewable electricity to where it can be used onshore
- Bypass onshore electricity transmission bottlenecks

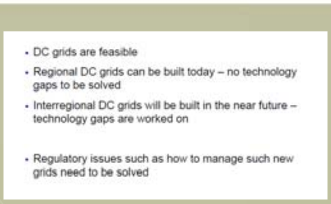
Increasing the competition and Market opportunities
- Development of more interconnection between countries and power systems enhances trade and improves competition on the European energy market
- Increased possibilities for arbitrage and limitation of price spikes

Facilitating the integration of renewable energy
- Facilitation of large scale offshore wind power plants and other marine technologies
- Enabling wind power and other renewable power's spatial smoothing effects, thus reducing variability and the resulting flexibility needs
- Connection to large hydropower capacity in Scandinavia, introducing flexibility in the power system for compensation of variability from wind power and other renewable power
- Contribution to Europe's 2020 targets for renewables and CO2 emission reductions

The Challenges

- Cost
  - Financing
- Grid Technology
  - Solved?
- International North Sea cooperation on North sea grid
  - Three working Groups established
    - Technology
    - Policy
    - Regulatory

Is it feasible?



- DC grids are feasible
- Regional DC grids can be built today – no technology gaps to be solved
- Interregional DC grids will be built in the near future – technology gaps are worked on
- Regulatory issues such as how to manage such new grids need to be solved

Europe's battery?

The Norwegian benefits

- Balancing the Norwegian power demand
  - Increasing value of offshore wind power generation
- Better utilisation of hydro power storage capacity
  - Enhancing value of generation facilities
- Electrification of the oil & gas installations
  - Competitive?
- Trading opportunities
  - Stratkraft already the largest cross-border trader of power in Europe
- Supply of products and services
  - Cable
  - Engineering
  - Umbilicals - electricals

.. or supplier?

We are not about to give up on oil & gas………

….but to utilise our strong maritime and offshore expertise in this new and exiting market!

The Norwegian Offshore Wind Industry

Excellent offshore experience

- Advanced project development experience – RISK MANAGEMENT
- Logistics
- Installation
- O&M
- Environmental
- H&S
- Materials (steel & concrete)
- Innovative Financing – Debt, Equity, Venture Capital

integrated numerical design tools

- energy conversion systems
- grid connection and system integration
- operation and maintenance
- Wind and ocean conditions
- Offshore wind technology and innovative concepts
- Offshore deployment and operation
- Wind farm optimisation
  Common themes: education, safety, environmental impact assessment and test facilities and infrastructure

Public technology development and industry support

- Innovation Norway, Enova
- Arena NOW, Arena Wind

Challenges to Norwegian Supply Chain

- Insecurity of market
- Lack of domestic market
- Fast growth
  - Lack of resources
  - Size and balance sheet
- Large number of contractors with developers prefering a strategy of multi-contracting
  - Need of large legal resources
  - But – emerging EPC contractors
- Cost requirements
  - technology development
  - Industrialization

Trends

- Speed and lack of resource
- Needed offshore expertise finding its place in wind
- Cost and learning curves remain steep – innovations
- Value chain positioning business model
- Norwegian Statoil and Statkraft have taken project stakes - Forewind
- EPC, supply chain players take on crucial development role – The German connection?
- Partnering strategies - "compatimates"

INTPOW activities & initiatives

- Past:
  - *Networking event in Turkey*
  - *Visit to Washington*
  - *State visit to South-Africa*
  - *INTPOW Solar Day*
  - *INTPOW 1st Offshore Wind Supply Chain Conference*
  - *EXPO 2010 Shanghai*
  - *RenewableUK Offshore Wind 2010*
  - *ONS 2010*
  - *Hydro 2010*
  - *Delegation to Turkey*
  - *DIREC – India*
  - *US DEC Video Conference*
  - *Visit to Etiopia/Uganda*
  - *Offshore Wind coordination meeting*
- In planning:
  - *INTPOW Solar day*
  - *Offshore wind competence and supply chain mapping*
  - *EWEA 2011 – Brussels?*
  - *INTPOW's 2nd offshore wind supply chain conference*
  - *Offshore Wind visit to Germany*
  - *UK Offshore wind supply chain charter – workshop with RenewableUK*
  - *Solar Valley visit and intersolar*
  - *Siemens/Vestas visits Denmark*
  - *Hydro 2011 – Praha*
  - *Offshore Wind UK 2011 - Liverpool*
  - *RenewableUK 2011 – Manchester*
  - *AWEA Offshore Wind - Baltimore*
  - *Offshore Wind 2011 Amsterdam*

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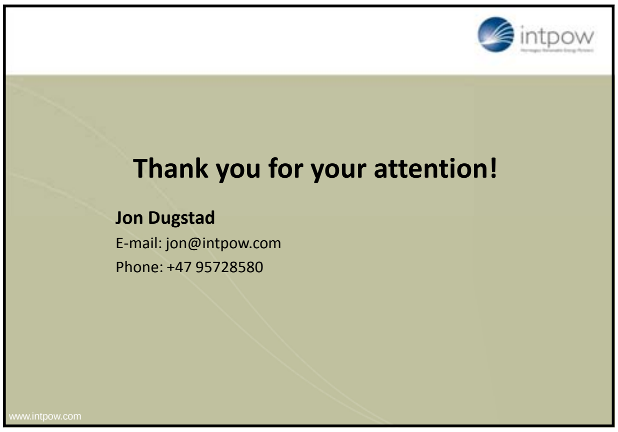

Thank you for your attention!

Jon Dugstad

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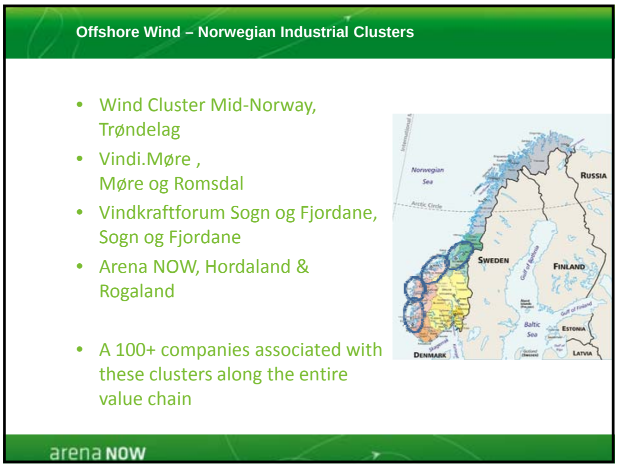
Phone: +47 95728580

www.intpow.com

Potential Supplies from Norwegian Industry to offshore Wind Developments

Trondheim 20-21 January 2011

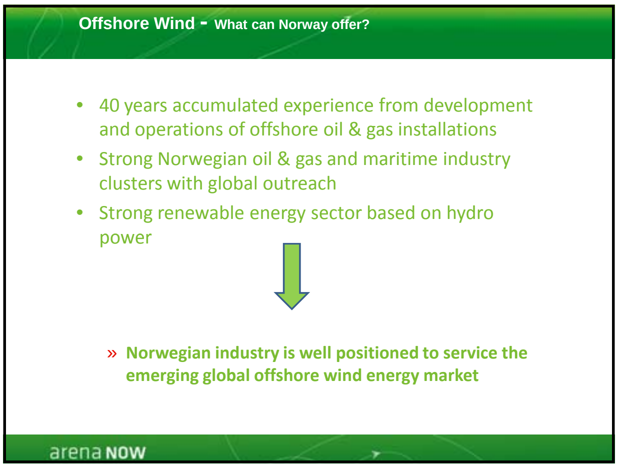
Asle Lygre, General Manager, Arena NOW



Offshore Wind – Norwegian Industrial Clusters

- Wind Cluster Mid-Norway, Trøndelag
- Vindi.Møre , Møre og Romsdal
- Vindkraftforum Sogn og Fjordane, Sogn og Fjordane
- Arena NOW, Hordaland & Rogaland

- A 100+ companies associated with these clusters along the entire value chain



Offshore Wind - What can Norway offer?

- 40 years accumulated experience from development and operations of offshore oil & gas installations
- Strong Norwegian oil & gas and maritime industry clusters with global outreach
- Strong renewable energy sector based on hydro power

» **Norwegian industry is well positioned to service the emerging global offshore wind energy market**

Offshore Wind Supplier Segments

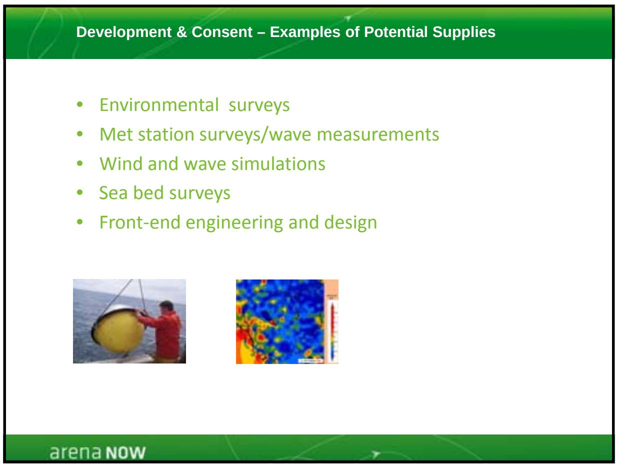
Development & Consent

Offshore Wind Turbines

Balance of Plant

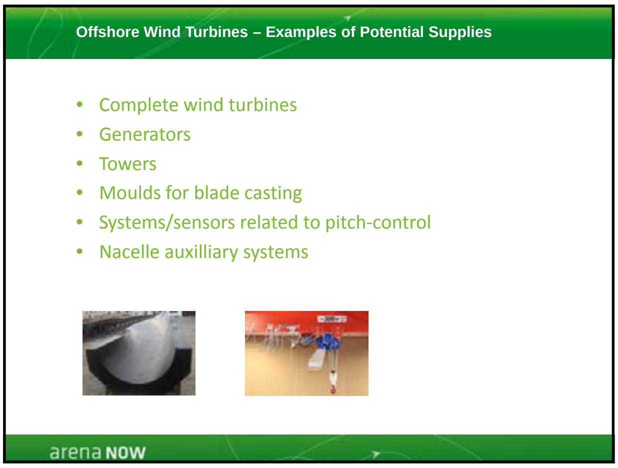
Installation & Commissioning

Operations & Maintenence



Development & Consent – Examples of Potential Supplies

- Environmental surveys
- Met station surveys/wave measurements
- Wind and wave simulations
- Sea bed surveys
- Front-end engineering and design



Offshore Wind Turbines – Examples of Potential Supplies

- Complete wind turbines
- Generators
- Towers
- Moulds for blade casting
- Systems/sensors related to pitch-control
- Nacelle auxilliary systems

Balance of Plant – Examples of Potential Supplies

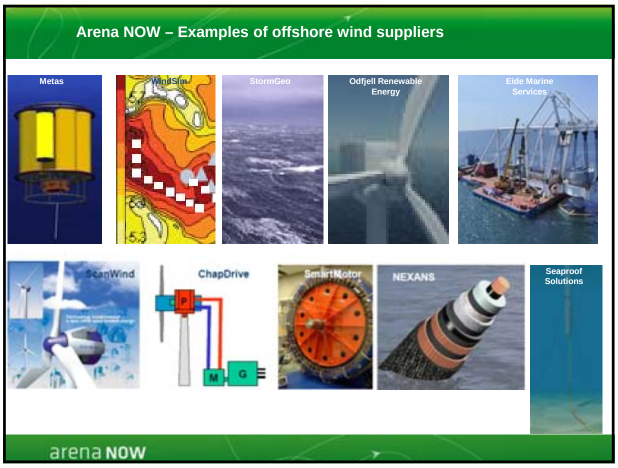
- Cables, export and inter array
- Complete Substations
- Foundations
- Crew access systems
- Floaters & moorings

Installation & Commissioning – Examples of Supplies

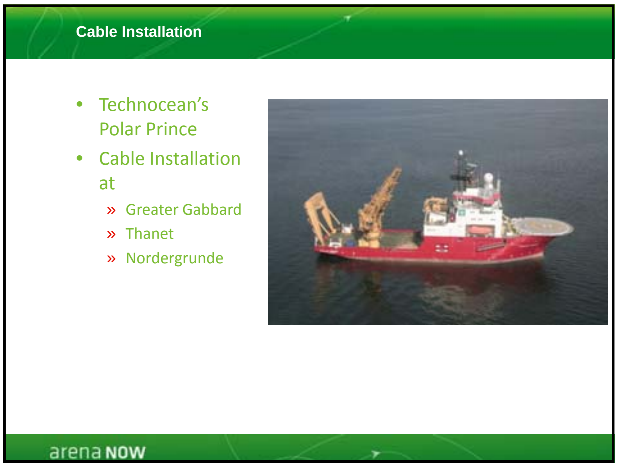
- Logistics and base services
- Export and inter array cable laying (trenching and laying)
- Foundation installation
- Offshore substation installation
- Turbine installation

Operations & Maintenance – Examples of Supplies

- Logistics & base services
- Operation of service vessels
- Large component refurbishment, replacement and repair
- Weather forecasts/production forecasts
- Environmental monitoring

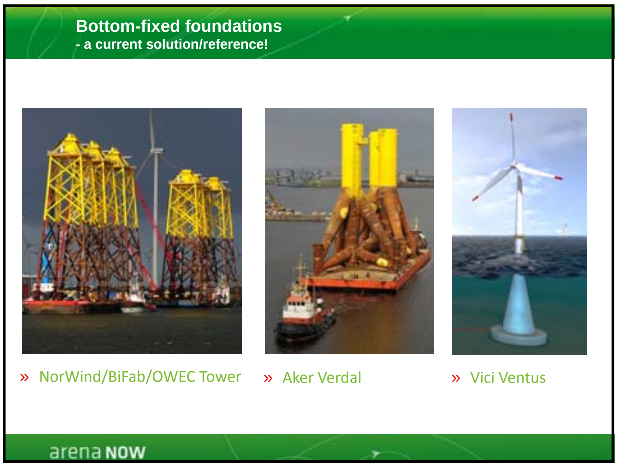


Arena NOW – Examples of offshore wind suppliers



Cable Installation

- Technocean's Polar Prince
- Cable Installation at
  - Greater Gabbard
  - Thanet
  - Nordergrunde



Bottom-fixed foundations
- a current solution/reference!

- NorWind/BiFab/OWEC Tower
- Aker Verdal
- Vici Ventus

Installation Vessels - Examples

» Master Marine – Installation vessel «NORA» to be delivered in 2011

» NorWind – DP floating jacket foundation installation vessel

Offshore wind substations

- Turn key solution for Offshore Substation
  - » Flexible design – easy to accommodate client requirements
  - » Minimum maintenance for primary electrical components
  - » Minimised offshore hoop-up work
  - » Safe an innovative solutions for all interfaces

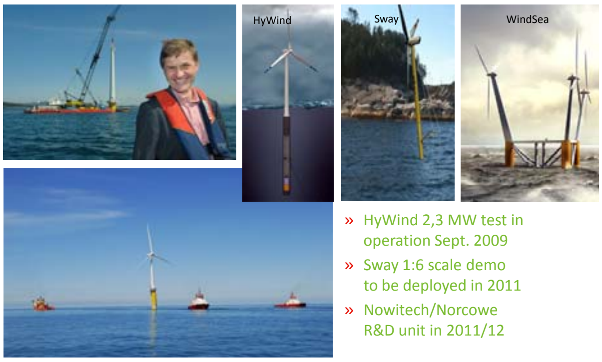
Troll Rosenberg Offshore Substation

Wind Turbine Generators

- SWAY
  - » New 10 MW WTG prototype under development and to be tested on land near Bergen.
- GE/ScanWind
  - » 4MW WTG developed and tested on land, further developments taking place in Verdal.

Courtesy SWAY

Floating wind turbines
- a solution for the future!



» HyWind 2,3 MW test in operation Sept. 2009

» Sway 1:6 scale demo to be deployed in 2011

» Nowitech/Norcowe R&D unit in 2011/12

Wind cluster Mid-Norway

"Building Norway's Bremerhaven"

Arena NOW
Member organization

TECHNOCEAN
INWIND
ODFJELL DRILLING TECHNOLOGY
INNOWIND
NORDNORSK HAVKRAFT
INNOVA
windsim
SEAPROOF SOLUTIONS
TROLL WINDPOWER
Vestavind OFFSHORE
Lyse
innovasjon norge
FJELLSTRAND
umoe mandal
NorWind
Anglewind
POLYTEC
UTSIRA servicesenter
keypex
NOR-OCEAN OFFSHORE
maritimecolours
GRIEG
METCentre
LUTELANDET
CONNECT
seatower
FIRMUS INNOVATION
GREATER STAVANGER
idevekst
BERGEN GROUP
vici ventus
SWAY

» Currently 37 member organizations

Arena NOW

Partners

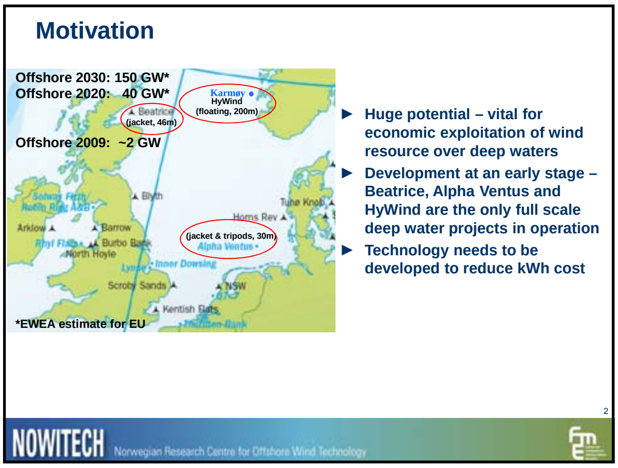
SparebankenVest
Vestavind OFFSHORE
NorWind
TROLL
BERGEN
Lyse
Forskningsrådet
SIVA
arena PROGRAMMET
innovasjon norge

An industrial cluster of suppliers and operators working together to develop and deliver complete wind power park solutions offshore

www.arenanow.no

New Research Initiatives for Advancing the Development of Deep Sea Offshore Wind Technology

John Olav Giæver Tande
Director NOWITECH
Senior Research Scientist
SINTEF Energy Research
John.tande@sintef.no
www.nowitech.no



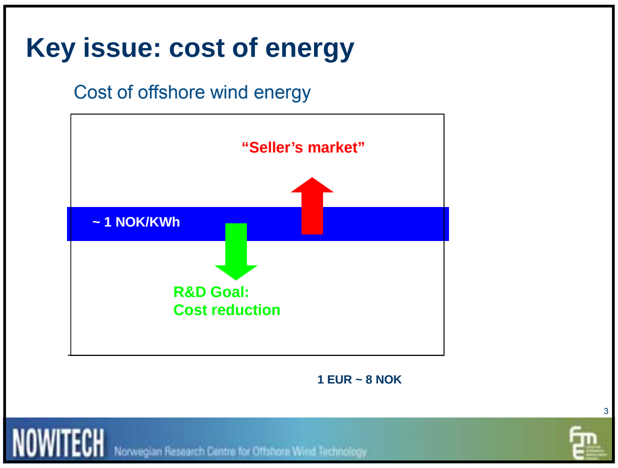
Motivation

Offshore 2030: 150 GW*
Offshore 2020: 40 GW*

Offshore 2009: ~2 GW

*EWEA estimate for EU

- Huge potential – vital for economic exploitation of wind resource over deep waters
- Development at an early stage – Beatrice, Alpha Ventus and HyWind are the only full scale deep water projects in operation
- Technology needs to be developed to reduce kWh cost



Key issue: cost of energy

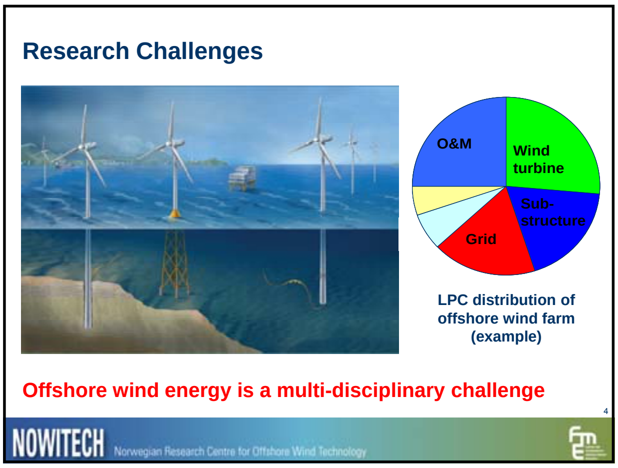
Cost of offshore wind energy

"Seller's market"

~ 1 NOK/KWh

R&D Goal:
Cost reduction

1 EUR ~ 8 NOK

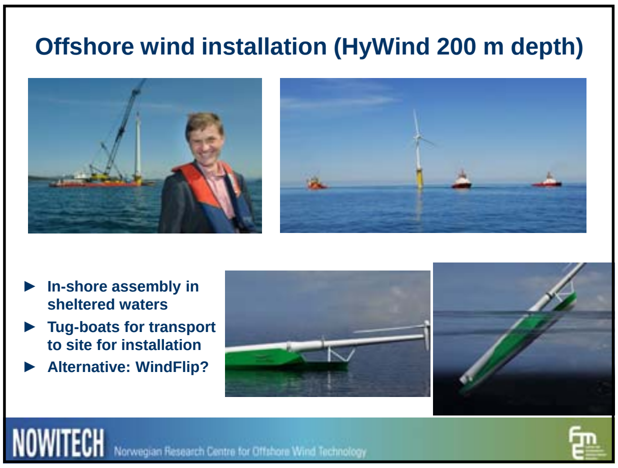


Research Challenges

LPC distribution of offshore wind farm (example)

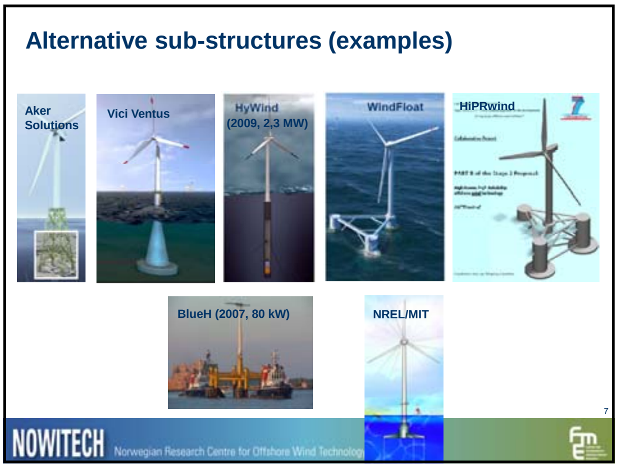
Offshore wind energy is a multi-disciplinary challenge

Offshore wind installation (Beatrice 45 m depth)



Offshore wind installation (HyWind 200 m depth)

- In-shore assembly in sheltered waters
- Tug-boats for transport to site for installation
- Alternative: WindFlip?



Alternative sub-structures (examples)

7

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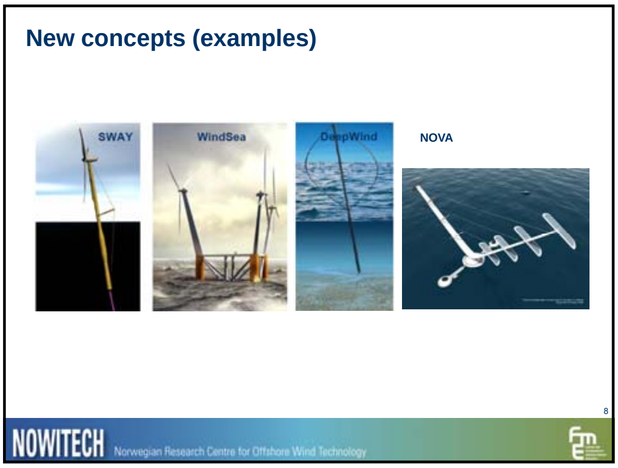

New concepts (examples)

8

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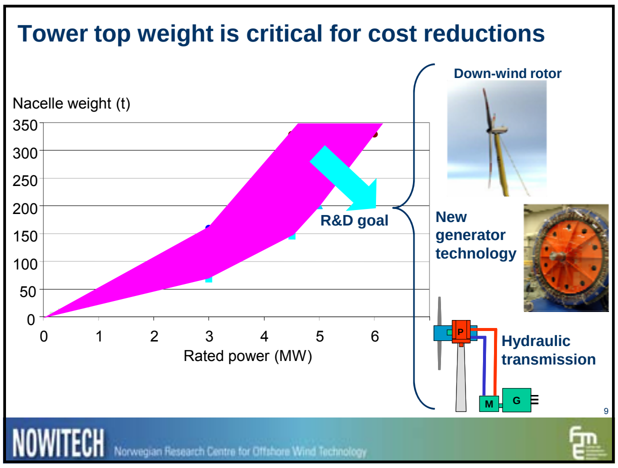

Tower top weight is critical for cost reductions

9

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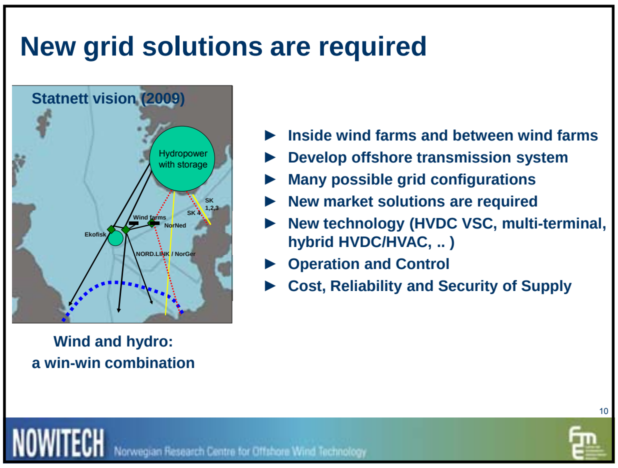

New grid solutions are required

Statnett vision (2009)

Wind and hydro:
a win-win combination

- Inside wind farms and between wind farms
- Develop offshore transmission system
- Many possible grid configurations
- New market solutions are required
- New technology (HVDC VSC, multi-terminal, hybrid HVDC/HVAC, ..)
- Operation and Control
- Cost, Reliability and Security of Supply

10

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Why bother with all this new, when there are plenty of challenges in need for urgent attention?

- Need for both; long term R&D are the answer to be prepared for the urgencies of tomorrow
- New solutions should be robust
- Systems for remote monitoring, state estimation and control should be developed
- Improved systems for access and HSE must be developed
- Much can be learnt from the offshore oil and gas sector

Copy from Recharge June 2010

11

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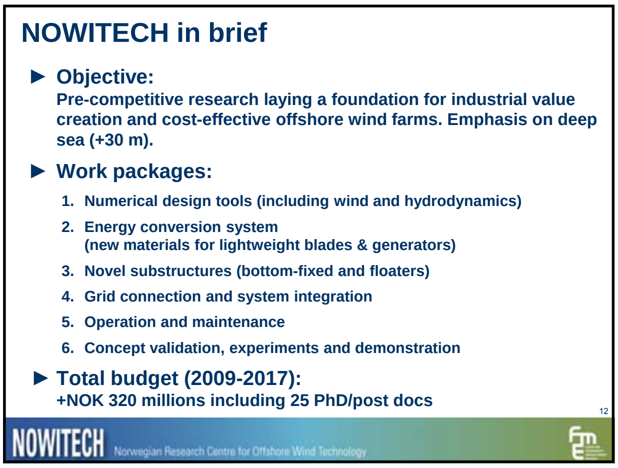


NOWITECH in brief

- **Objective:**
  Pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms. Emphasis on deep sea (+30 m).
- **Work packages:**
  1. **Numerical design tools (including wind and hydrodynamics)**
  2. **Energy conversion system**
     (new materials for lightweight blades & generators)
  3. **Novel substructures (bottom-fixed and floaters)**
  4. **Grid connection and system integration**
  5. **Operation and maintenance**
  6. **Concept validation, experiments and demonstration**
- **Total budget (2009-2017):**
  +NOK 320 millions including 25 PhD/post docs

12

NOWITECH Norwegian Research Centre for Offshore Wind Technology

R&D partners

SINTEF

NTNU – Trondheim Norwegian University of Science and Technology

IFE Institute for Energy Technology

Associate R&D partners

Risø DTU National Laboratory for Sustainable Energy

Fraunhofer IWES

University of Strathclyde Glasgow

Massachusetts Institute of Technology

NREL

TU Delft

Industry partners

Vestas

Vestavind Offshore

NTE

Statkraft

Lyse

Fugro Oceanor

GE

Statoil

DONG energy

EDF

Statnett

Devold AMT

SmartMotor

AkerSolutions

DNV

Associate industry partners

NORWEA Norsk vindkraftforening

EnergiNorge

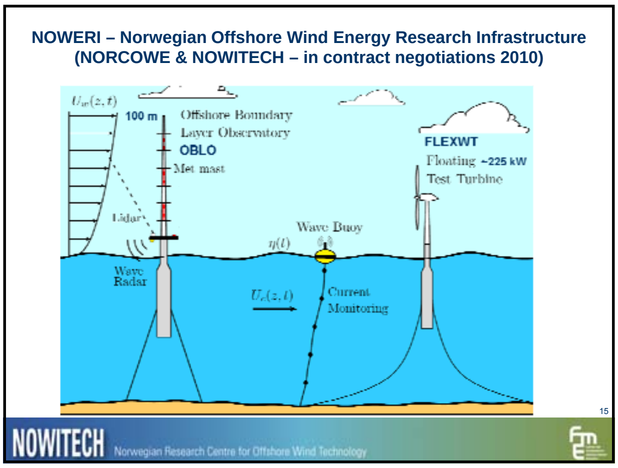
Navitas Network

NCE Instrumentation

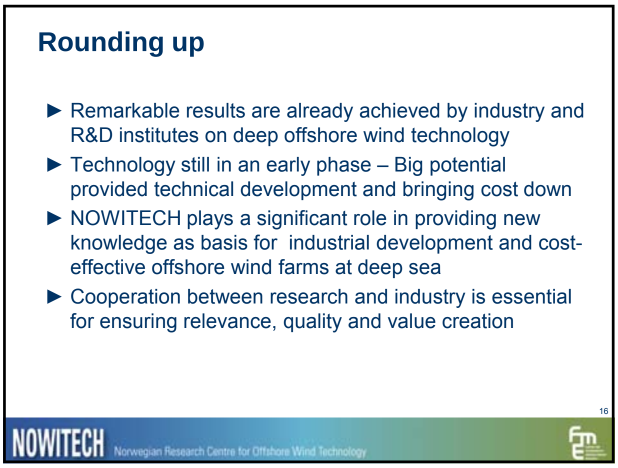
enova

Innovation Norway

NVE



NOWERI – Norwegian Offshore Wind Energy Research Infrastructure (NORCOWE & NOWITECH – in contract negotiations 2010)



Rounding up

- Remarkable results are already achieved by industry and R&D institutes on deep offshore wind technology
- Technology still in an early phase – Big potential provided technical development and bringing cost down
- NOWITECH plays a significant role in providing new knowledge as basis for industrial development and cost-effective offshore wind farms at deep sea
- Cooperation between research and industry is essential for ensuring relevance, quality and value creation

Norwegian Met-Ocean Infrastructure for Offshore Wind Energy Research

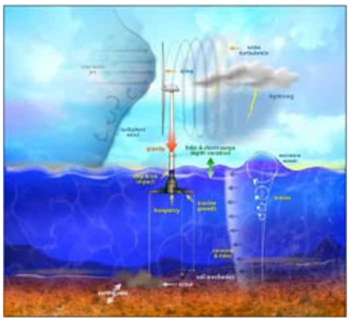
Prof. Joachim Reuder
Geophysical Institute, University of Bergen & Christian Michelsen Research (CMR)
joachim.reuder@gfi.uib.no

Wind Power R&D seminar – deep sea offshore wind
20-21 January 2011, Trondheim

Outline

- Introduction
- The marine atmospheric boundary layer (MABL)
  - ❑ Specific characteristics of the MABL
  - ❑ Knowledge gaps
- The Norwegian Offshore Wind Energy Research Infrastructure (NOWERI)
  - ❑ OBLO: The Oceanic Boundary Layer Obsevatory
  - ❑ Land based super-sites
- Outlook and conclusion

Marine Atmospheric Boundary Layer (MABL)



Of interest:
- ❑ Average wind speed
- ❑ Wind shear over the rotor disk
- ❑ Turbulence intensity

These parameters depend on:
- ❑ Synoptic situation
- ❑ Temperature stratification
- ❑ Underlying ocean wave field
- ❑ Proximity to land

The main problem:
- ❑ Massive lack of observational data in the relevant altitude range (30-150 m)

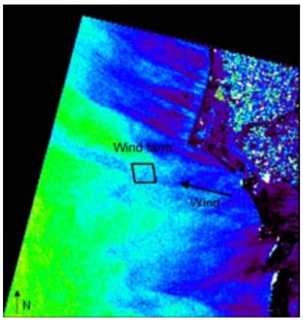
Source: http://www.ieawind.org/GWEC_PDF/GWEC%20Annex23.pdf

Only few offshore measurements

Measurements up to 100 m
Shallow waters (~ 20 m)

Deep water measurements possible
Measurements only up to ~ 20 m

Satellite data (SAR, QuickScat)



Ocean wind speed map from ERS SAR from Horns Rev in the North Sea, Denmark observed 6 October 2004. The Horns Rev offshore wind farm is located in the trapezoid.

Shortcomings:
- limited temporal resolution
- uncertainty in determination of relevant wind speed over the rotor disk

Source: http://galathea3.emu.dk/satelliteeye/projekter/wind/back_uk.html

---

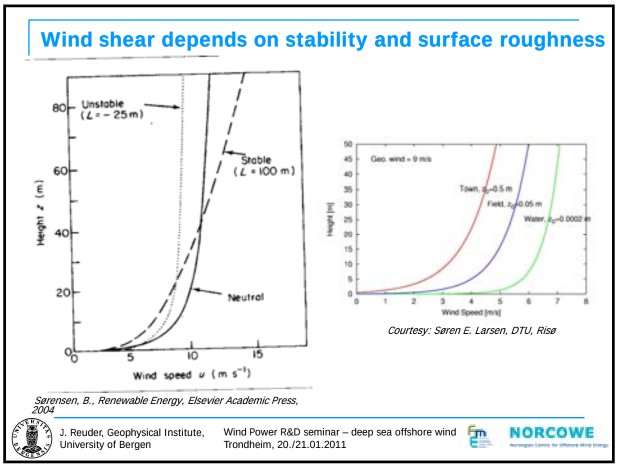
Description of wind shear

The wind power community is mainly working with an empirical power law description of the vertical wind shear:

$$\overline{u(z)} = u_{ref} \left(\frac{z}{z_{ref}} \right)^{\alpha}$$

Meteorologists use the physically based approach of the logarithmic wind profile (only valid for neutral conditions !!!):

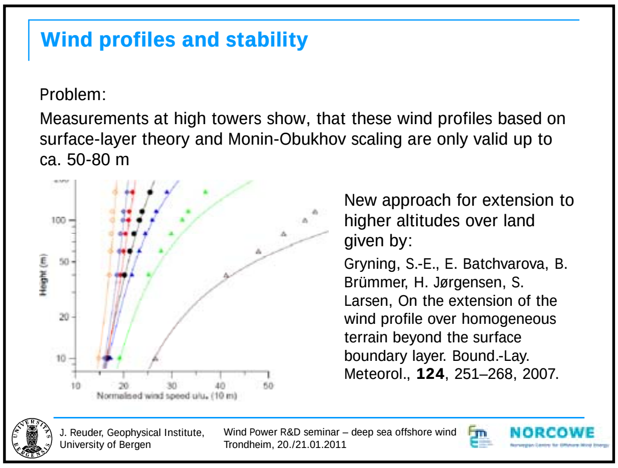
$$\overline{u(z)} = \frac{u_*}{k} \ln \frac{z}{z_0}$$



Wind shear depends on stability and surface roughness

Courtesy: Søren E. Larsen, DTU, Risø

Sørensen, B., Renewable Energy, Elsevier Academic Press, 2004



Wind profiles and stability

Problem:

Measurements at high towers show, that these wind profiles based on surface-layer theory and Monin-Obukhov scaling are only valid up to ca. 50-80 m

New approach for extension to higher altitudes over land given by:

Gryning, S.-E., E. Batchvarova, B. Brümmer, H. Jørgensen, S. Larsen, On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer. Bound.-Lay. Meteorol., **124**, 251–268, 2007.

Wind profiles and stability

Splitting of the relevant length scale:

$$\frac{1}{l} = \underbrace{\frac{1}{L_{SL}}}_{\text{I}} + \underbrace{\frac{1}{L_{MBL}}}_{\text{II}}$$

Neutral:

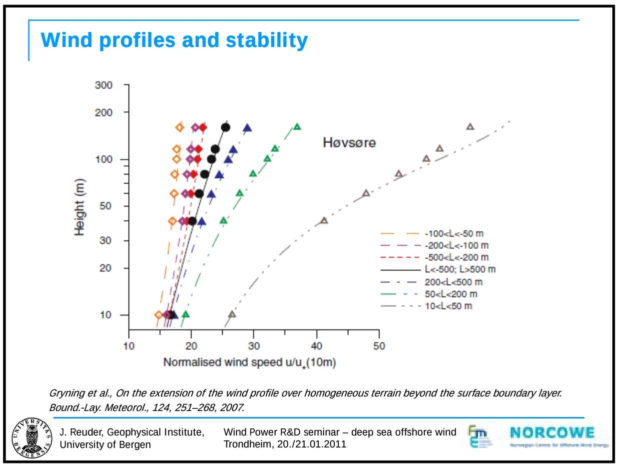
$$u(z) = \frac{u_{*0}}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) + \frac{z}{L_{MBL,N}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL,N}}\right)\right)$$

Stable:

$$\frac{u(z)}{u_{*0}} = \frac{1}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) + \frac{bz}{L}\left(1 - \frac{z}{2z_i}\right) + \frac{z}{L_{MBL}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL}}\right)\right)$$

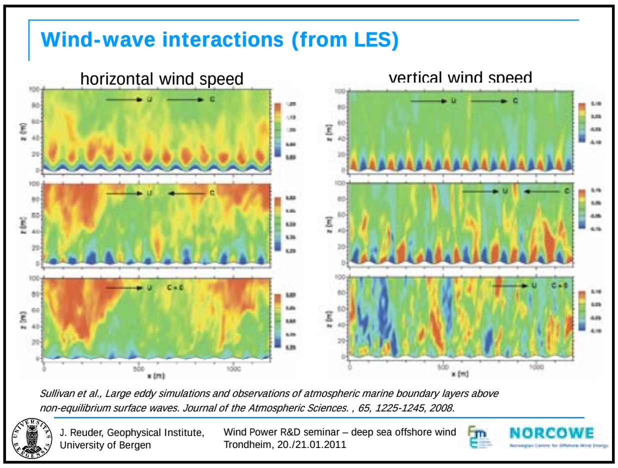
Unstable:

$$\frac{u(z)}{u_{*0}} = \frac{1}{\kappa}\left(\ln(\frac{z}{z_0}) - \psi\left(\frac{z}{L}\right) + \frac{z}{L_{MBL}} - \frac{z}{z_i}\left(\frac{z}{2L_{MBL}}\right)\right)$$



Wind profiles and stability

Gryning et al., On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer. Bound.-Lay. Meteorol., 124, 251–268, 2007.



Wind-wave interactions (from LES)

Sullivan et al., Large eddy simulations and observations of atmospheric marine boundary layers above non-equilibrium surface waves. Journal of the Atmospheric Sciences. , 65, 1225-1245, 2008.

Plans for national infrastructure

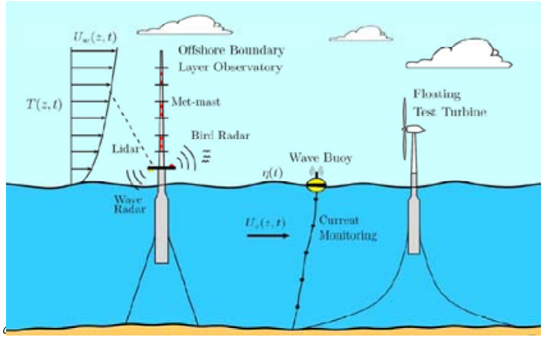
Floating Offshore Boundary Layer Observatory (OBLO)
Floating Experimental Wind Turbine (FLEXWT)

- Scale 1:4; ca. 250 kW; 30 m

In a next step:
3-4 onshore “super-sites”

- 100 m meteorological mast with advanced (in particular turbulence) instrumentation
- Wind Lidar and/or Sodar RASS
- Met-ocean buoy system
- in close cooperation with industry partners with interest at specific sites
- upgrade/standardization/interconnection of existing infrastructure and connection/co-location to technical test facilities

Components of NOWERI



Motivation for NOWERI

Vision:

easily accessible Norwegian offshore wind energy related research infrastructure for the measurement of:

- ❑ the state of the atmospheric and oceanic boundary layer with focus on specific offshore conditions
- ❑ the resulting atmospheric and oceanic forcing on the foundation, tower and rotor structures for offshore wind energy production
- ❑ the effects of the forcing on the structures for strength and fatigue investigations
- ❑ the potential environmental impact of offshore wind installations

NOWERI

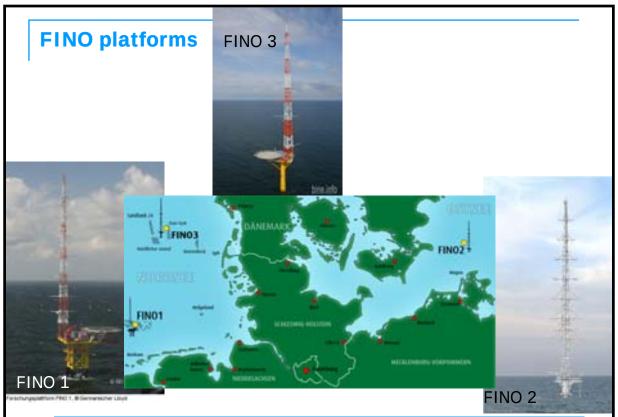
NOWERI: Norwegian Offshore Wind Energy Infrastructure (77 MNOK, ca. 10 M€)

- ❑ NFR: national research infrastructure programme
- ❑ Joint application NORCOWE, NOWITECH and CEDREN
- ❑ Advanced platforms and instrumentation (OBLO, FLEXWT)
- ❑ Funding of 66 MNOK approved
- ❑ Contract negotiations with NFR started on 10.06.2010
- ❑ Drift and ownership model under development
- ❑ Pre-design project is ongoing.

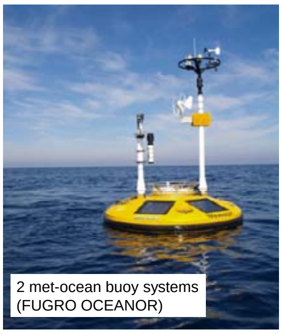
OBLO (Oceanic Boundary Layer Observatory)

- Observatory for the advanced characterization of all relevant atmospheric and oceanic parameters
- Measurement mast with top at around 100 m a.s.l; (dense profiles of temperature and wind; direct turbulence measurements by sonic anemometers)
- Platform for additional instrumentation (e.g. lidar, sodar, avian radar, etc.)
- Additional buoy system for characterization of the waves and currents
- Dedicated both to basic and applied research on offshore wind energy
  - ❑ Improvement of the understanding of the offshore marine boundary layers in atmosphere and ocean, e.g.
    - wave atmosphere interactions
    - turbulence structure
    - key for validation and improvement of corresponding models
  - ❑ Basis for applied research on forcing and effects by co-location with FLEXWT

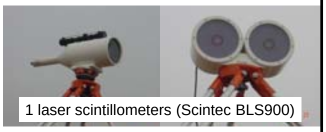
FINO platforms

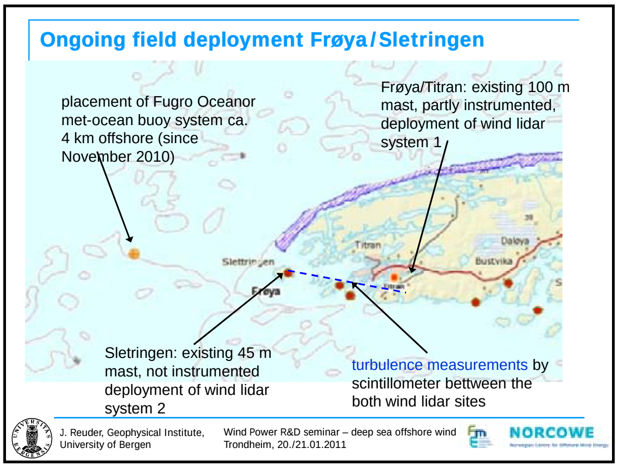


EFOWI (Equipment for Offshore Wind Energy Infrastructure)


2 met-ocean buoy systems (FUGRO OCEANOR)


2 laser wind profilers (WindCube, Leosphere)


1 laser scintillometers (Scintec BLS900)



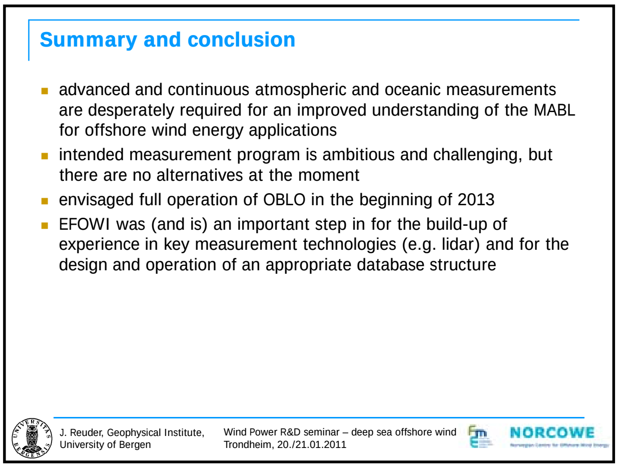
Ongoing field deployment Frøya / Sletringen

placement of Fugro Oceanor met-ocean buoy system ca. 4 km offshore (since November 2010)

Frøya/Titran: existing 100 m mast, partly instrumented, deployment of wind lidar system 1

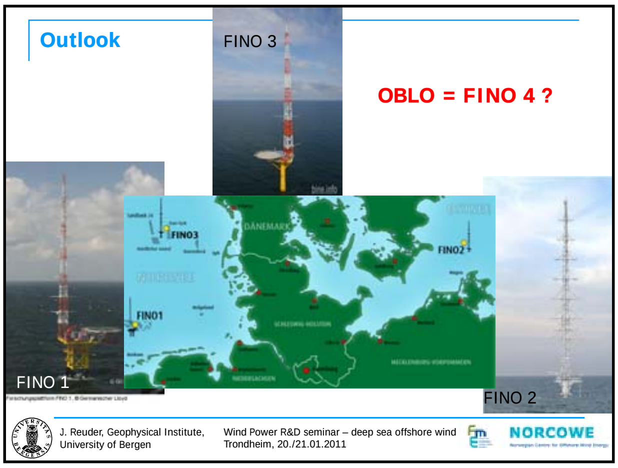
Sletringen: existing 45 m mast, not instrumented deployment of wind lidar system 2

turbulence measurements by scintillometer betweeen the both wind lidar sites



Summary and conclusion

- advanced and continuous atmospheric and oceanic measurements are desperately required for an improved understanding of the MABL for offshore wind energy applications
- intended measurement program is ambitious and challenging, but there are no alternatives at the moment
- envisaged full operation of OBLO in the beginning of 2013
- EFOWI was (and is) an important step in for the build-up of experience in key measurement technologies (e.g. lidar) and for the design and operation of an appropriate database structure



Outlook

OBLO = FINO 4 ?

Outlook

FI⁴NO

Floating Infrastructure for Norwegian Offshore Wind Energy Research

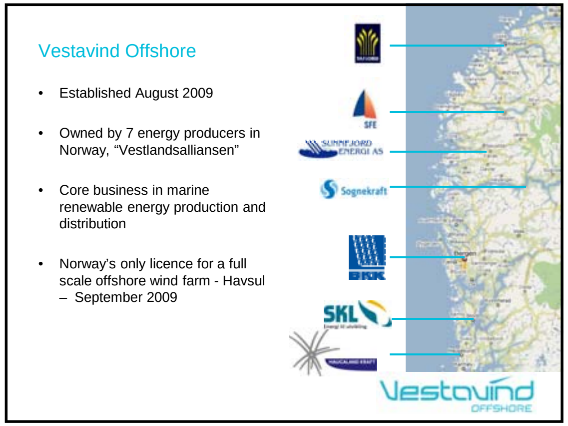
or

Floating Instrumentation for Norwegian Offshore Wind Energy Research

© M. Durstewitz, 2010

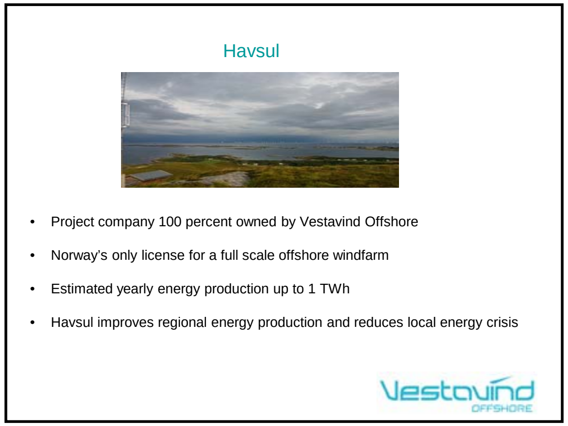
Havsul offshore wind farm

Trondheim, 20.01.2011
Tore Engevik, President, Vestavind Offshore



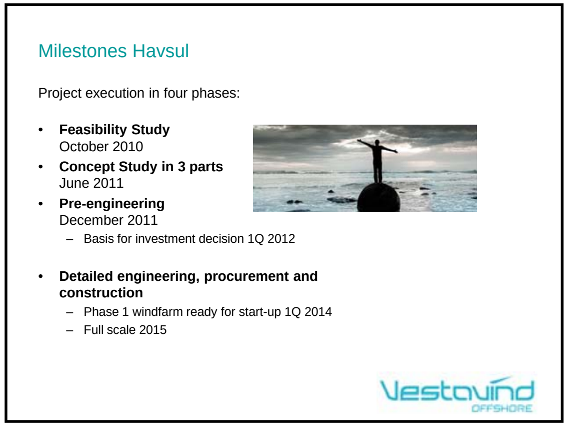
Vestavind Offshore

- Established August 2009
- Owned by 7 energy producers in Norway, “Vestlandsalliansen”
- Core business in marine renewable energy production and distribution
- Norway's only licence for a full scale offshore wind farm - Havsul – September 2009



Havsul

- Project company 100 percent owned by Vestavind Offshore
- Norway's only license for a full scale offshore windfarm
- Estimated yearly energy production up to 1 TWh
- Havsul improves regional energy production and reduces local energy crisis



Milestones Havsul

Project execution in four phases:

- **Feasibility Study**
  October 2010
- **Concept Study in 3 parts**
  June 2011
- **Pre-engineering**
  December 2011
  - Basis for investment decision 1Q 2012
- **Detailed engineering, procurement and construction**
  - Phase 1 windfarm ready for start-up 1Q 2014
  - Full scale 2015

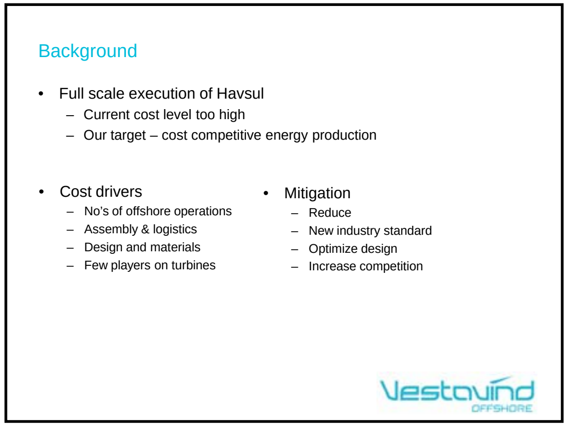
Concept competition substructure, inshore assembly total windmill and offshore installation of same

Scope:

- Technology and construction substructure
- Inshore assembly of complete windmill including substructure, tower, nacelle and blades and located assembly site
- Offshore installation targeted in 1 offshore operation
- Cost estimate

If pre-engineering phase is decided in Q3 2011

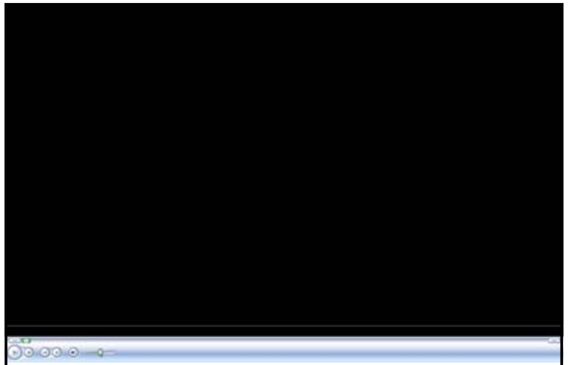
- 1-3 players for further pre-engineering



Background

- Full scale execution of Havsul
  - Current cost level too high
  - Our target – cost competitive energy production

- Cost drivers
  - No's of offshore operations
  - Assembly & logistics
  - Design and materials
  - Few players on turbines
- Mitigation
  - Reduce
  - New industry standard
  - Optimize design
  - Increase competition



Metmast Skråpen

Milestones / Plan

May - Sep 2010	Feasibility study completed
Sep - Oct 2010	Develop design basis for concept studies
Oct - Nov 2010	Prequalification (30 companies applied)
Nov - Dec 2010	Tender competition (16 tenders of 17 prequal.)
Dec - Jan 2011	Evaluation – qualification meetings
Jan - May 2011	Execute concept study (4 companies)
May - Jun 2011	Evaluation – concept selection (1-3) Internal total cost estimate +/- 30%

Tender competition process

- Prequalification – announced on TED / Doffin
- Prequalified candidates received ITT
- Shortlisting of candidates
- Clarifications with shortlisted candidates
- Recommendation
- Selection (4 companies/Industrial Groups)

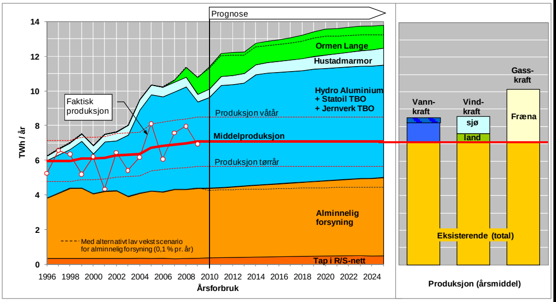
Strong companies/industrial groups as winners

- **Reinertsen** (concrete and steel)
  - Vattenfall power consultant AB
- **Technip** (steel)
- **Vici Ventus** (concrete)
  - AF-Gruppen ASA
  - Dr.techn.Olav Olsen AS
  - Lyse AS
- **Westcon** (concrete)
  - Eide Marine Services AS
  - Kruse Smith Entreprenører AS
  - Norconsult AS

Market Dimensions

Adding 30,000 MW offshore wind capacity requires to build 2 large offshore wind turbines per day until 2020

Prognosis energy consumption Mid-Norway



Regional kraftsystemutredning Møre og Romsdal 2010
Istad Nett / TRT / 28.05.2010

12

VESTAVIND Offshore's "Kinderegg"

- **Energy crisis in Mid-Norway**
  - Part of permanent solution
  - New production renewable energy from 2013/2014
  - Local energy production – SHORT TRAVELLED!
- **Climate friendly**
  - Renewable energy
  - Short travelled
  - Paradigm shift, from Onshore to Offshore approach
- **New industrial approach**
  - New innovative solutions based on proven technology
  - Capitalize on offshore Petromarine core competence
  - Cost-effective, sound solutions

Vestavind Offshore's goals in offshore wind:

- Create tomorrows global solutions in offshore wind together with the industry in a 'wind – wind' approach
- Utilize unique offshore Petromarine competence in marine renewable energy production
- New market opportunities for the industry

A1) New turbine technology

Development of the SWAY tower concept, Michal Forland, SWAY

Loads analysis of selected floating designs, Amy Robertson, NREL

Aluminium as a viable solution for offshore wind turbines,
Simon Jupp, Hydro Aluminium

HiPRWind – large floating turbines for intermediate water depths,
Jochen Bard, Fraunhofer IWES

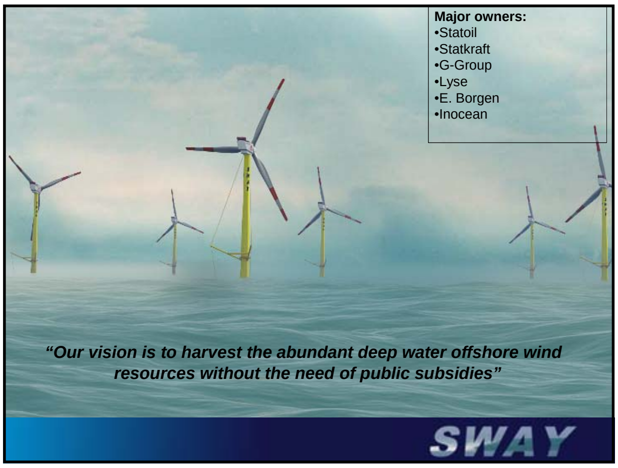
Prospects of large floating vertical axis wind turbines,
Uwe Schmidt Paulsen, Risø DTU

Wind Power R&D seminar

-deep sea offshore wind

Development of the Sway floating tower

Michal Forland
CEO



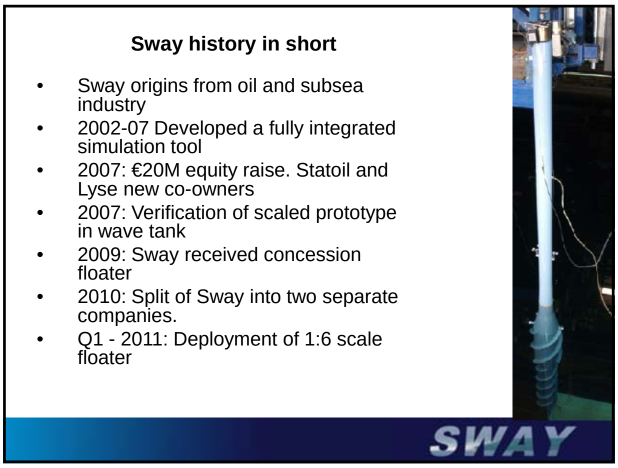
Major owners:
- •Statoil
- •Statkraft
- •G-Group
- •Lyse
- •E. Borgen
- •Inocean

"Our vision is to harvest the abundant deep water offshore wind resources without the need of public subsidies"

Sway business strategy:

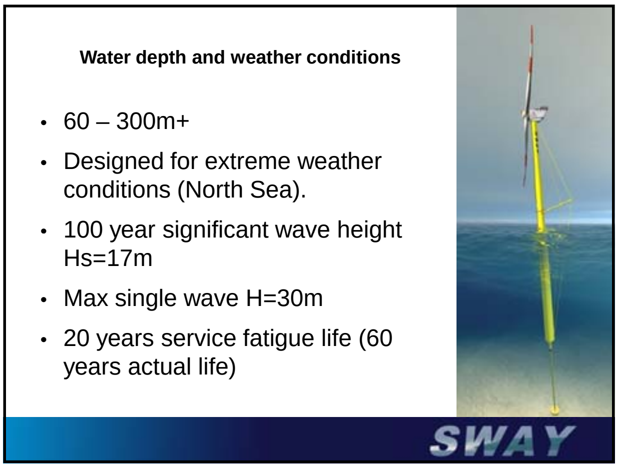
The four key factors for success will be qualification of the technology through:

- *1:6 floating model Q1 2011*
- *Full scale pilot 2013*
- *Thereafter use the existing industry and their industrial and financial muscles by licensing the technology*
- *Use local manufacturers in the major home markets*



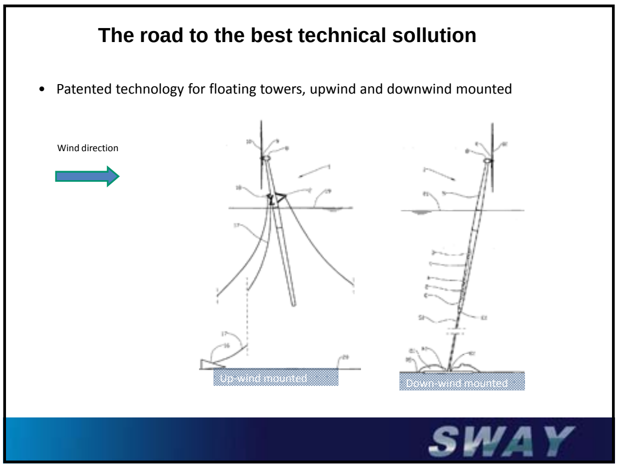
Sway history in short

- Sway origins from oil and subsea industry
- 2002-07 Developed a fully integrated simulation tool
- 2007: €20M equity raise. Statoil and Lyse new co-owners
- 2007: Verification of scaled prototype in wave tank
- 2009: Sway received concession floater
- 2010: Split of Sway into two separate companies.
- Q1 - 2011: Deployment of 1:6 scale floater



Water depth and weather conditions

- 60 – 300m+
- Designed for extreme weather conditions (North Sea).
- 100 year significant wave height Hs=17m
- Max single wave H=30m
- 20 years service fatigue life (60 years actual life)



The road to the best technical sollution

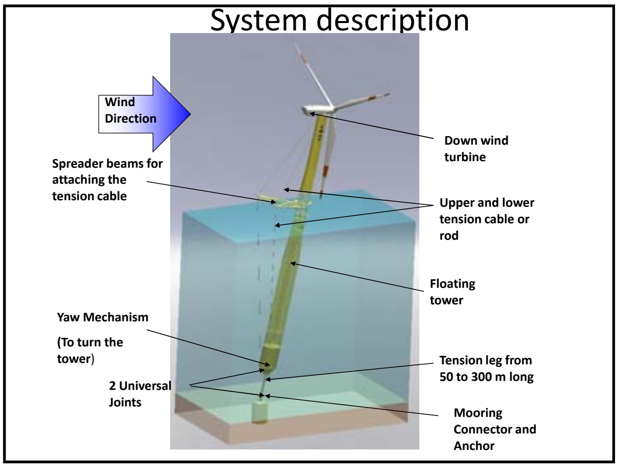
- Patented technology for floating towers, upwind and downwind mounted

Wind direction

Up-wind mounted

Down-wind mounted

SWAY



System description

Wind Direction

Spreader beams for attaching the tension cable

Yaw Mechanism

(To turn the tower)

2 Universal Joints

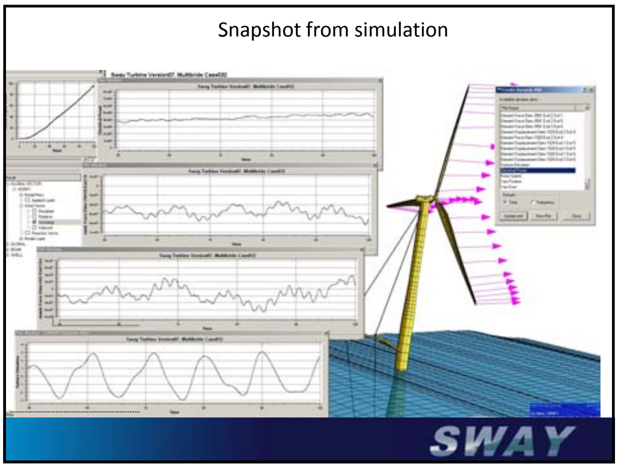
Down wind turbine

Upper and lower tension cable or rod

Floating tower

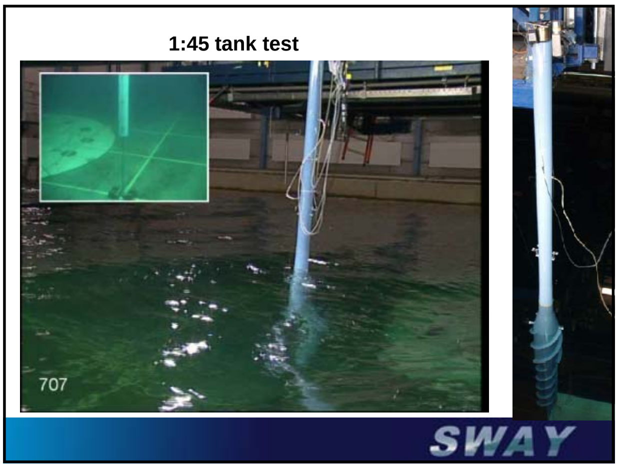
Tension leg from 50 to 300 m long

Mooring Connector and Anchor



Snapshot from simulation

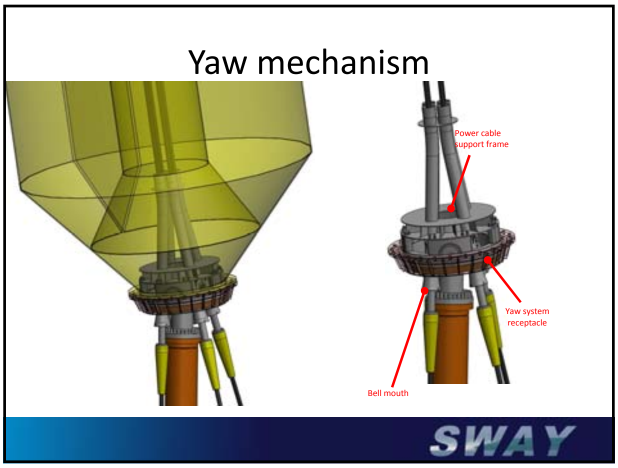
SWAY



1:45 tank test

707

SWAY



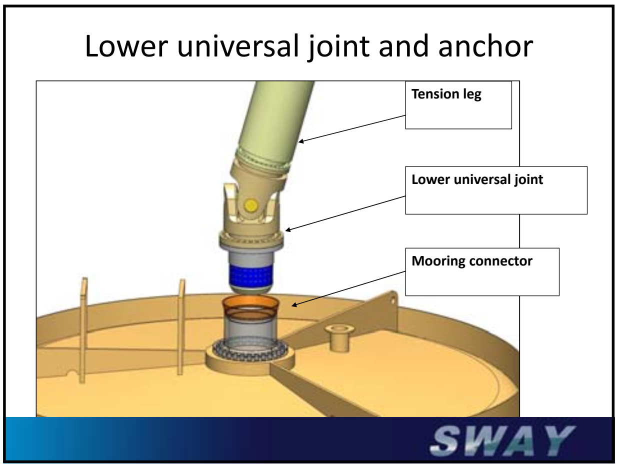
Yaw mechanism

Power cable support frame

Yaw system receptacle

Bell mouth

SWAY



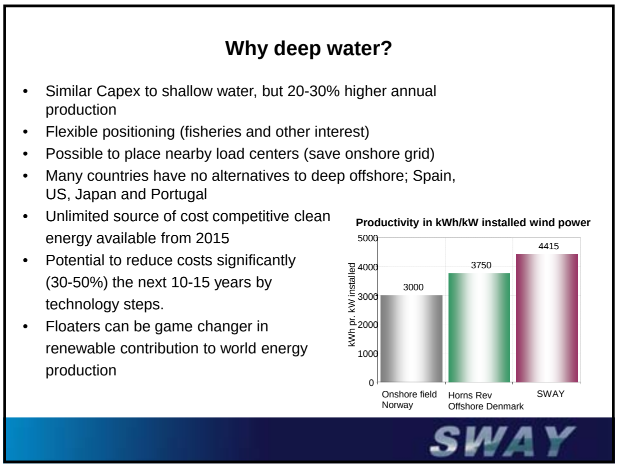
Lower universal joint and anchor

Tension leg

Lower universal joint

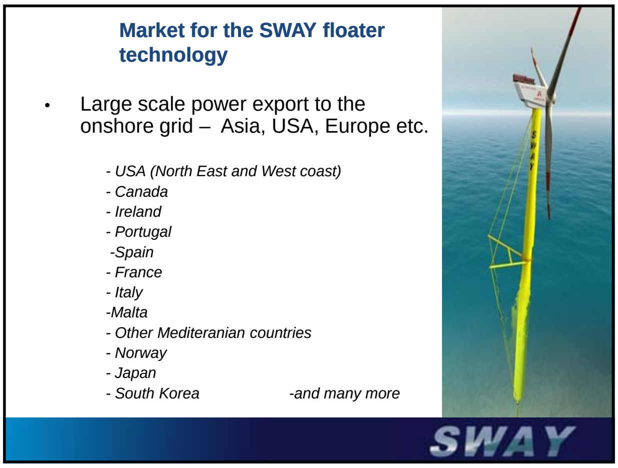
Mooring connector

SWAY



Why deep water?

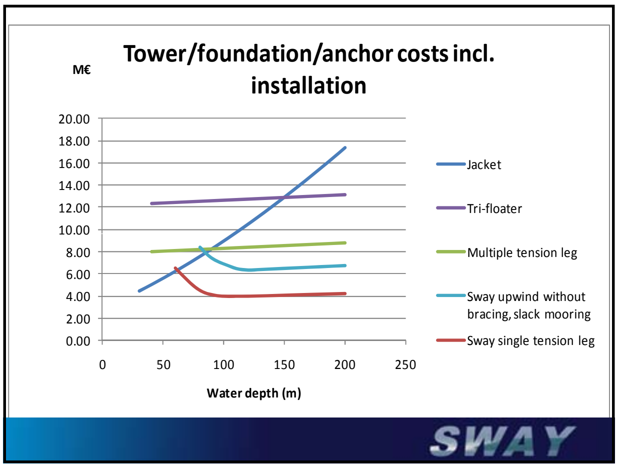
- Similar Capex to shallow water, but 20-30% higher annual production
- Flexible positioning (fisheries and other interest)
- Possible to place nearby load centers (save onshore grid)
- Many countries have no alternatives to deep offshore; Spain, US, Japan and Portugal
- Unlimited source of cost competitive clean energy available from 2015
- Potential to reduce costs significantly (30-50%) the next 10-15 years by technology steps.
- Floaters can be game changer in renewable contribution to world energy production



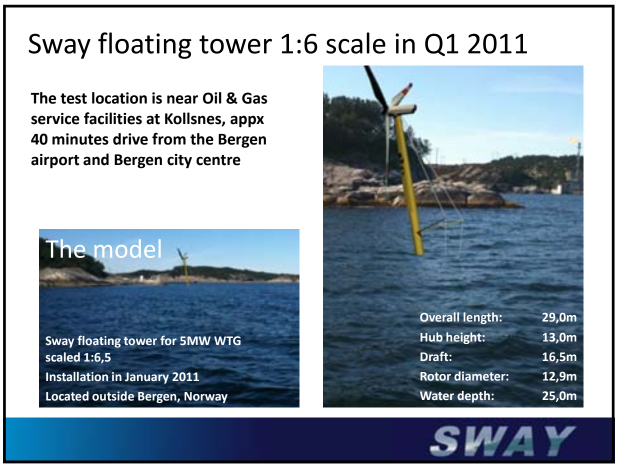
Market for the SWAY floater technology

- Large scale power export to the onshore grid – Asia, USA, Europe etc.

- USA (North East and West coast)
- Canada
- Ireland
- Portugal
-Spain
- France
- Italy
-Malta
- Other Mediteranian countries
- Norway
- Japan
- South Korea *-and many more*



Tower/foundation/anchor costs incl. installation



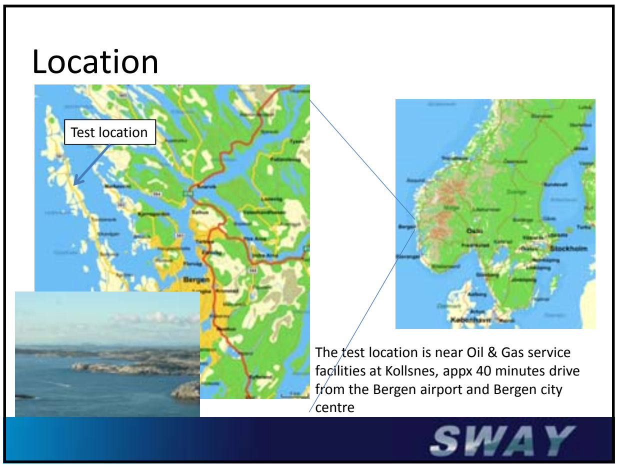
Sway floating tower 1:6 scale in Q1 2011

The test location is near Oil & Gas service facilities at Kollsnes, appx 40 minutes drive from the Bergen airport and Bergen city centre

The model

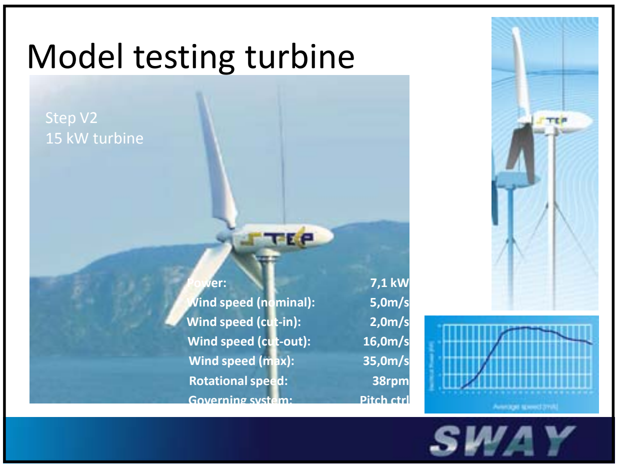
Sway floating tower for 5MW WTG scaled 1:6,5
Installation in January 2011
Located outside Bergen, Norway

Overall length:	**29,0m**
Hub height:	**13,0m**
Draft:	**16,5m**
Rotor diameter:	**12,9m**
Water depth:	**25,0m**



Location

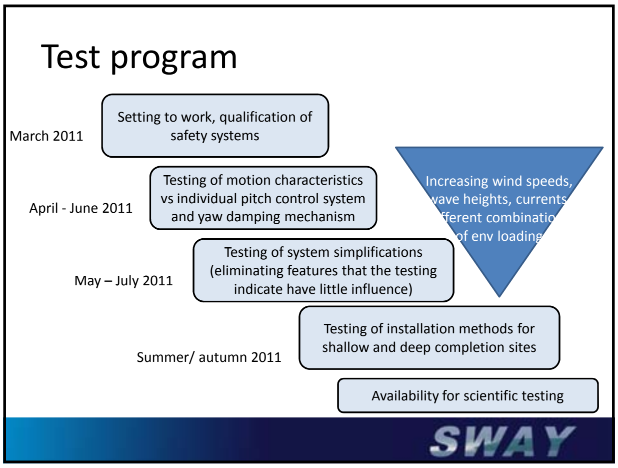
The test location is near Oil & Gas service facilities at Kollsnes, appx 40 minutes drive from the Bergen airport and Bergen city centre



Model testing turbine

Step V2
15 kW turbine

Power:	7,1 kW
Wind speed (nominal):	5,0m/s
Wind speed (cut-in):	2,0m/s
Wind speed (cut-out):	16,0m/s
Wind speed (max):	35,0m/s
Rotational speed:	38rpm
Governing system:	Pitch ctrl



Test program

March 2011 — Setting to work, qualification of safety systems

April - June 2011 — Testing of motion characteristics vs individual pitch control system and yaw damping mechanism

May – July 2011 — Testing of system simplifications (eliminating features that the testing indicate have little influence)

Summer/ autumn 2011 — Testing of installation methods for shallow and deep completion sites

Availability for scientific testing

Increasing wind speeds,
wave heights, currents
fferent combinatio
of env loading

Muchas gracias por su atenciòn!

Learn more about Sway at:

www.sway.no

Offshore Wind Power in the United States

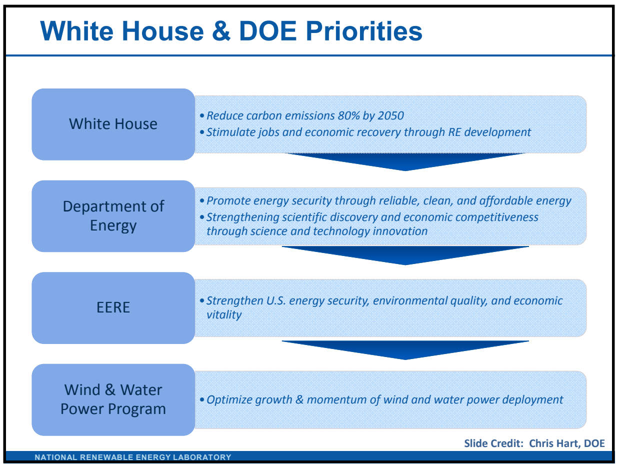
Wind Power R&D Seminar – Deep Sea Offshore Wind

Amy Robertson

January 20, 2011

Outline

- U.S. government priorities
- U.S. Offshore wind resource
- Roadmap for developing resource
- DOE's role
- Offshore wind projects in the U.S.
- NREL work in offshore wind
  - International Collaborations
  - Design concept loads analysis



White House & DOE Priorities

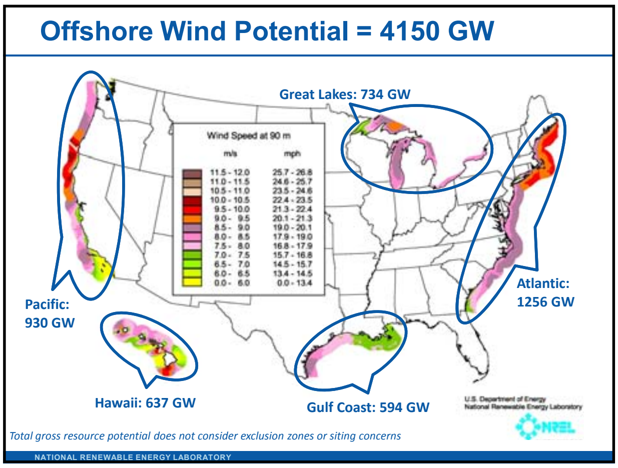
White House
- *Reduce carbon emissions 80% by 2050*
- *Stimulate jobs and economic recovery through RE development*

Department of Energy
- *Promote energy security through reliable, clean, and affordable energy*
- *Strengthening scientific discovery and economic competitiveness through science and technology innovation*

EERE
- *Strengthen U.S. energy security, environmental quality, and economic vitality*

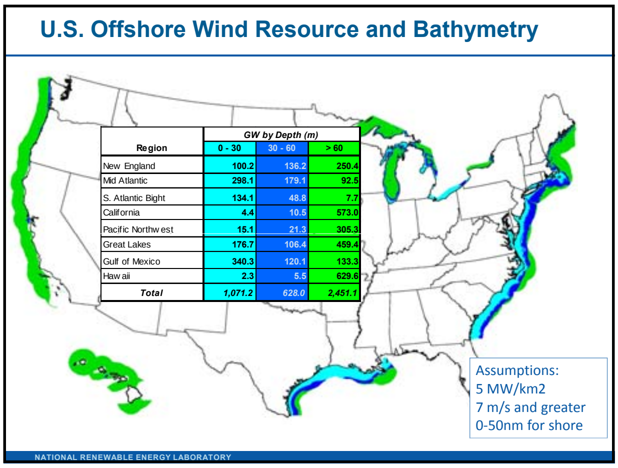
Wind & Water Power Program
- *Optimize growth & momentum of wind and water power deployment*

Slide Credit: Chris Hart, DOE



Offshore Wind Potential = 4150 GW

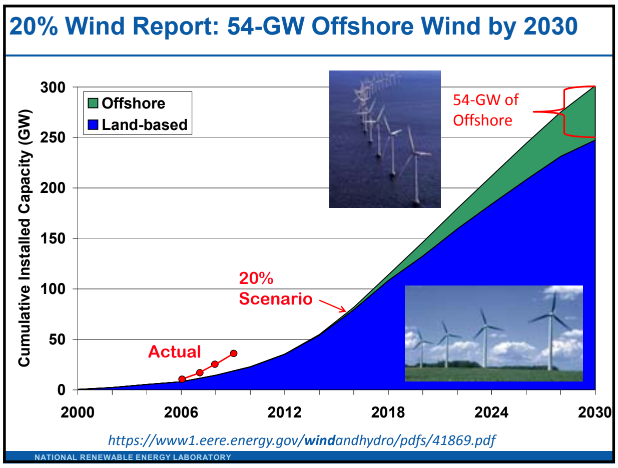
Total gross resource potential does not consider exclusion zones or siting concerns



U.S. Offshore Wind Resource and Bathymetry

Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

Assumptions:
5 MW/km2
7 m/s and greater
0-50nm for shore

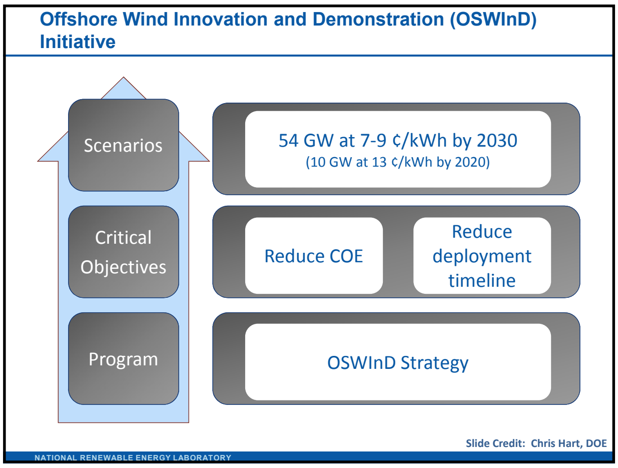


20% Wind Report: 54-GW Offshore Wind by 2030

*https://www1.eere.energy.gov/**wind**andhydro/pdfs/41869.pdf*

NREL Releases Report on Offshore Wind in U.S.

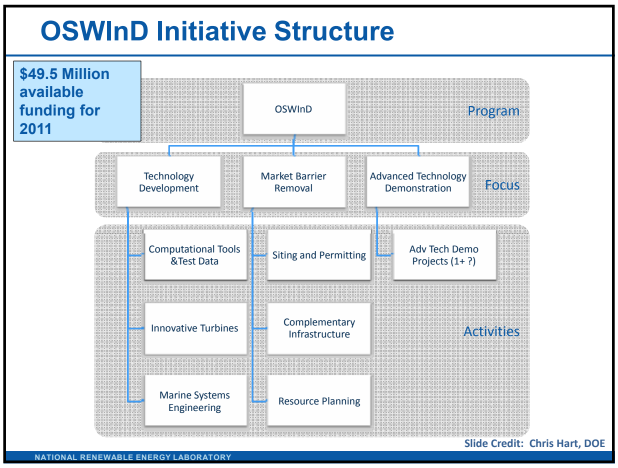
- Detailed assessment of the Nation's offshore wind resources and wind industry
  - Estimated 4000 GW offshore wind resource over 7.0 m/s
- Analyzes:
  - Technology challenges
  - Economics
  - Permitting procedures
  - Potential risks/benefits
- Report will be used to help guide the U.S. efforts in offshore wind



Offshore Wind Innovation and Demonstration (OSWInD) Initiative

Scenarios	54 GW at 7-9 ¢/kWh by 2030 (10 GW at 13 ¢/kWh by 2020)
Critical Objectives	Reduce COE Reduce deployment timeline
Program	OSWInD Strategy

Slide Credit: Chris Hart, DOE



OSWInD Initiative Structure

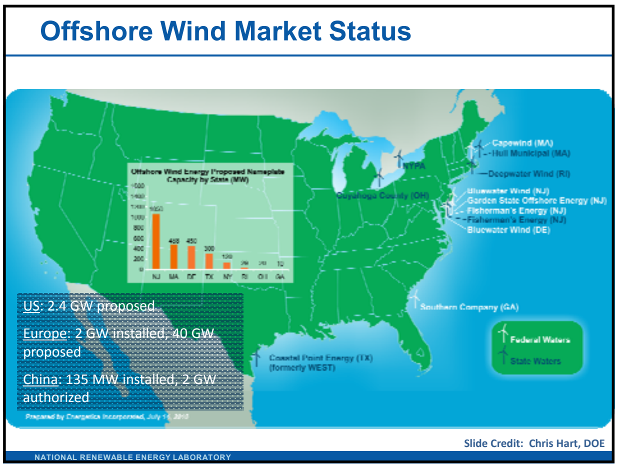
$49.5 Million available funding for 2011

Program: OSWInD

Focus:
- Technology Development
- Market Barrier Removal
- Advanced Technology Demonstration

Activities:
- Computational Tools &Test Data
- Innovative Turbines
- Marine Systems Engineering
- Siting and Permitting
- Complementary Infrastructure
- Resource Planning
- Adv Tech Demo Projects (1+ ?)

Slide Credit: Chris Hart, DOE



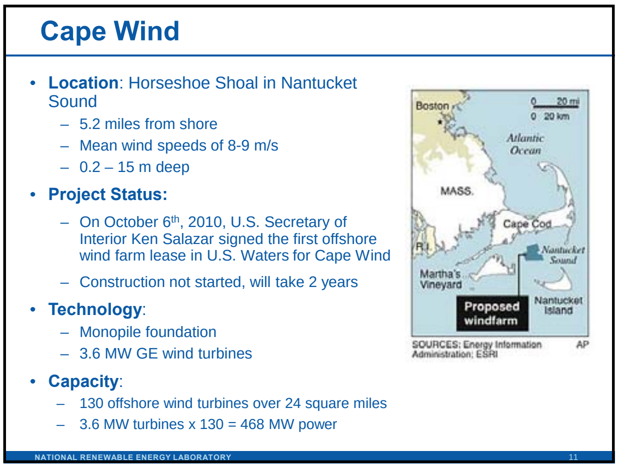
Offshore Wind Market Status

US: 2.4 GW proposed

Europe: 2 GW installed, 40 GW proposed

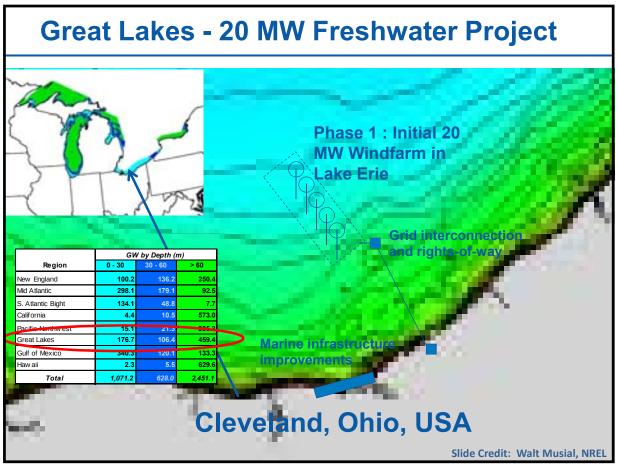
China: 135 MW installed, 2 GW authorized

Slide Credit: Chris Hart, DOE



Cape Wind

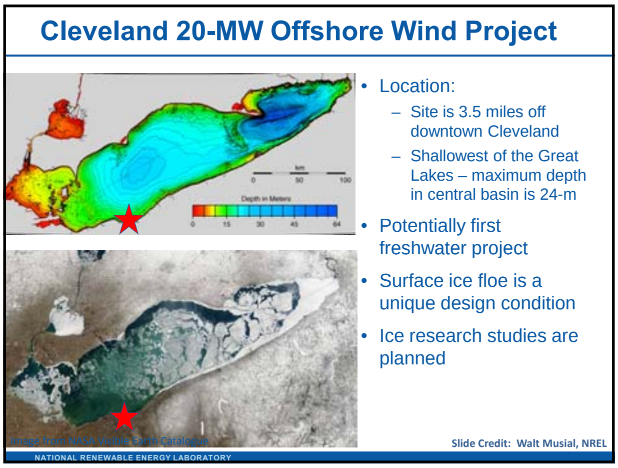
- **Location**: Horseshoe Shoal in Nantucket Sound
  - 5.2 miles from shore
  - Mean wind speeds of 8-9 m/s
  - 0.2 – 15 m deep
- **Project Status:**
  - On October 6th, 2010, U.S. Secretary of Interior Ken Salazar signed the first offshore wind farm lease in U.S. Waters for Cape Wind
  - Construction not started, will take 2 years
- **Technology**:
  - Monopile foundation
  - 3.6 MW GE wind turbines
- **Capacity**:
  - 130 offshore wind turbines over 24 square miles
  - 3.6 MW turbines x 130 = 468 MW power



Great Lakes - 20 MW Freshwater Project

Region	GW by Depth (m)		
	0 - 30	30 - 60	> 60
New England	100.2	136.2	250.4
Mid Atlantic	298.1	179.1	92.5
S. Atlantic Bight	134.1	48.8	7.7
California	4.4	10.5	573.0
Pacific Northwest	15.1	21.3	305.3
Great Lakes	176.7	106.4	459.4
Gulf of Mexico	340.3	120.1	133.3
Hawaii	2.3	5.5	629.6
Total	*1,071.2*	*628.0*	*2,451.1*

Slide Credit: Walt Musial, NREL

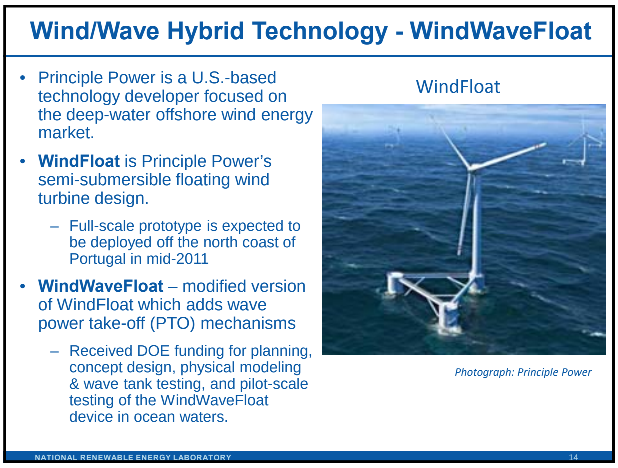


Cleveland 20-MW Offshore Wind Project

Image from NASA Visible Earth Catalogue

- Location:
  - Site is 3.5 miles off downtown Cleveland
  - Shallowest of the Great Lakes – maximum depth in central basin is 24-m
- Potentially first freshwater project
- Surface ice floe is a unique design condition
- Ice research studies are planned

Slide Credit: Walt Musial, NREL

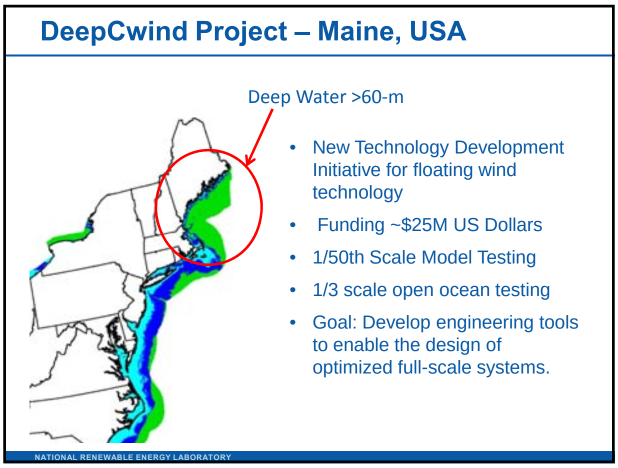


Wind/Wave Hybrid Technology - WindWaveFloat

- Principle Power is a U.S.-based technology developer focused on the deep-water offshore wind energy market.
- **WindFloat** is Principle Power's semi-submersible floating wind turbine design.
  - Full-scale prototype is expected to be deployed off the north coast of Portugal in mid-2011
- **WindWaveFloat** – modified version of WindFloat which adds wave power take-off (PTO) mechanisms
  - Received DOE funding for planning, concept design, physical modeling & wave tank testing, and pilot-scale testing of the WindWaveFloat device in ocean waters.

WindFloat

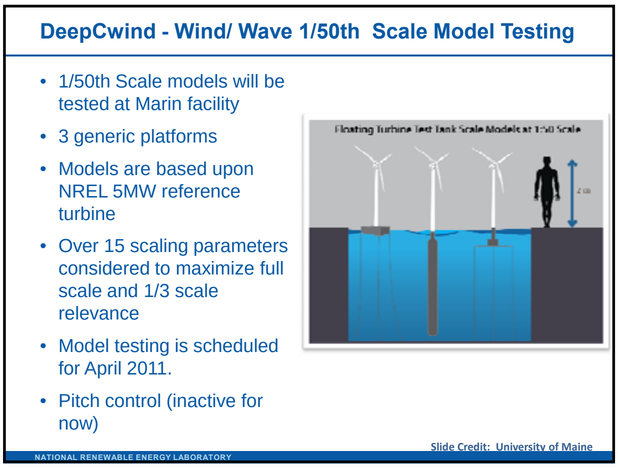
Photograph: Principle Power



DeepCwind Project – Maine, USA

Deep Water >60-m

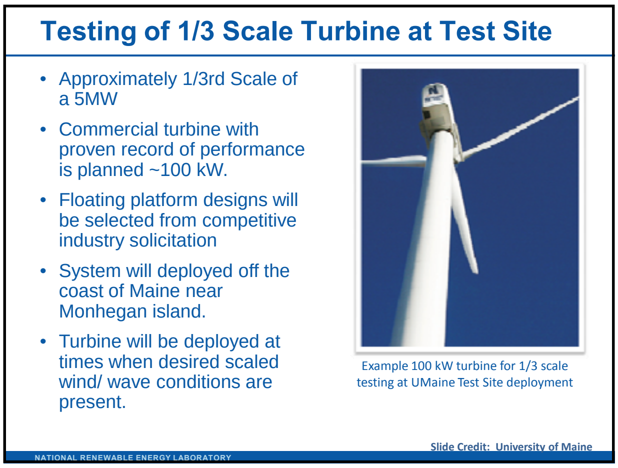
- New Technology Development Initiative for floating wind technology
- Funding ~$25M US Dollars
- 1/50th Scale Model Testing
- 1/3 scale open ocean testing
- Goal: Develop engineering tools to enable the design of optimized full-scale systems.



DeepCwind - Wind/ Wave 1/50th Scale Model Testing

- 1/50th Scale models will be tested at Marin facility
- 3 generic platforms
- Models are based upon NREL 5MW reference turbine
- Over 15 scaling parameters considered to maximize full scale and 1/3 scale relevance
- Model testing is scheduled for April 2011.
- Pitch control (inactive for now)

Slide Credit: University of Maine

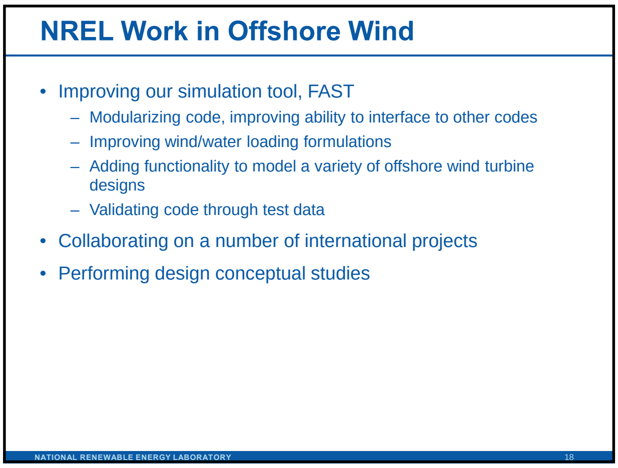


Testing of 1/3 Scale Turbine at Test Site

- Approximately 1/3rd Scale of a 5MW
- Commercial turbine with proven record of performance is planned ~100 kW.
- Floating platform designs will be selected from competitive industry solicitation
- System will deployed off the coast of Maine near Monhegan island.
- Turbine will be deployed at times when desired scaled wind/ wave conditions are present.

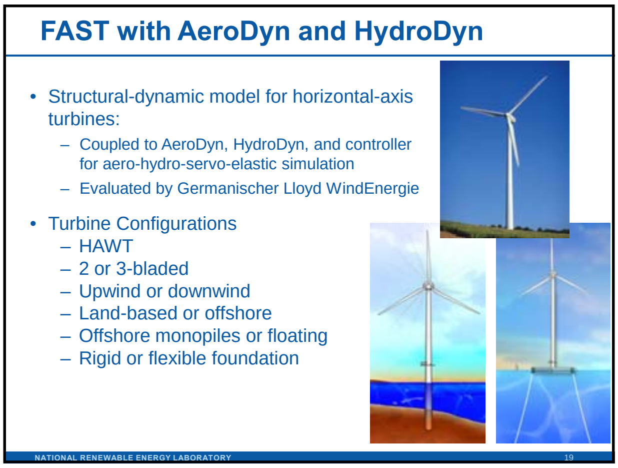
Example 100 kW turbine for 1/3 scale testing at UMaine Test Site deployment

Slide Credit: University of Maine



NREL Work in Offshore Wind

- Improving our simulation tool, FAST
  - Modularizing code, improving ability to interface to other codes
  - Improving wind/water loading formulations
  - Adding functionality to model a variety of offshore wind turbine designs
  - Validating code through test data
- Collaborating on a number of international projects
- Performing design conceptual studies

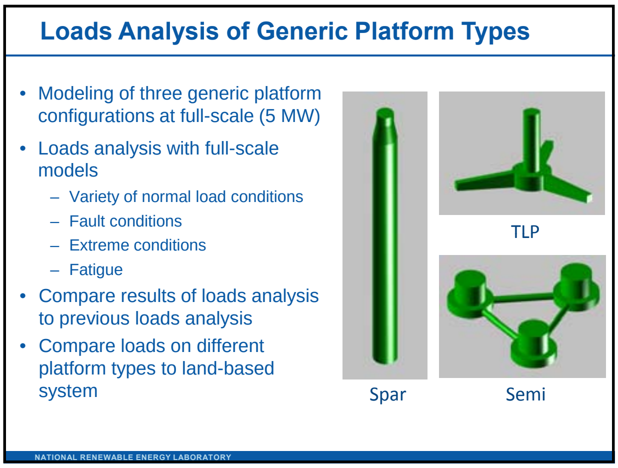


FAST with AeroDyn and HydroDyn

- Structural-dynamic model for horizontal-axis turbines:
  - Coupled to AeroDyn, HydroDyn, and controller for aero-hydro-servo-elastic simulation
  - Evaluated by Germanischer Lloyd WindEnergie
- Turbine Configurations
  - HAWT
  - 2 or 3-bladed
  - Upwind or downwind
  - Land-based or offshore
  - Offshore monopiles or floating
  - Rigid or flexible foundation

International Collaborations

Project Name	Description
DeepCWind	Floating offshore wind project in U.S. – includes scale model testing and 1/3 scale demonstration project
Risø	Collaboration to share information on a variety of wind-turbine related topics
OC4	IEA Offshore Codes Comparison Collaboration, Continued – jacket and semi (co-leading project)
ORECCA	EU development of offshore renewables roadmap
Nowitech	Norwegian research group on deep offshore wind. Strong emphasis on supporting PhD and post-doctoral research.
HiPRWind	5-yr project to help development of deep-water offshore wind. Will deploy a 1-MW demonstration turbine.
DeepWind	Examination of vertical-axis offshore WT
UpWind	Assessing requirements for design of very large turbines

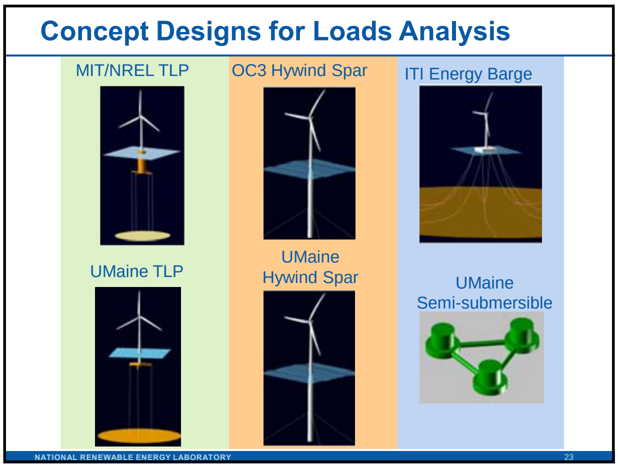


Loads Analysis of Generic Platform Types

- Modeling of three generic platform configurations at full-scale (5 MW)
- Loads analysis with full-scale models
  - Variety of normal load conditions
  - Fault conditions
  - Extreme conditions
  - Fatigue
- Compare results of loads analysis to previous loads analysis
- Compare loads on different platform types to land-based system

Loads Analysis

DLC	Winds		Waves			Controls / Events	Type	Load
	Model	Speed	Model	Height	Direction			Factor
1) Power Production								
1.1	NTM	$V_{in} < V_{hub} < V_{out}$	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Normal operation	U	1.25×1.2
1.2	NTM	$V_{in} < V_{hub} < V_{out}$	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Normal operation	F	1.00
1.3	ETM	$V_{in} < V_{hub} < V_{out}$	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Normal operation	U	1.35
1.4	ECD	$V_{hub} = V_r$, V_r±2m/s	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Normal operation; ±Δ wind dir'n.	U	1.35
1.5	EWS	$V_{in} < V_{hub} < V_{out}$	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Normal operation; ±Δ ver. & hor. shr.	U	1.35
1.6a	NTM	$V_{in} < V_{hub} < V_{out}$	ESS	$H_s = 1.09 \times H_{s50}$	$\beta = 0^o$	Normal operation	U	1.35
2) Power Production Plus Occurrence of Fault								
2.1	NTM	$V_{hub} = V_r$, V_{out}	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Pitch runaway → Shutdown	U	1.35
2.3	EOG	$V_{hub} = V_r$, V_r±2m/s, V_{out}	NSS	$H_s = E[H_s \mid V_{hub}]$	$\beta = 0^o$	Loss of load → Shutdown	U	1.10
6) Parked (Idling)								
6.1a	EWM	$V_{hub} = 0.95 \times V_{50}$	ESS	$H_s = 1.09 \times H_{s50}$	$\beta = 0^o, \pm 30^o$	Yaw = 0º, ±8º	U	1.35
6.2a	EWM	$V_{hub} = 0.95 \times V_{50}$	ESS	$H_s = 1.09 \times H_{s50}$	$\beta = 0^o, \pm 30^o$	Loss of grid → -180º < Yaw < 180º	U	1.10
6.3a	EWM	$V_{hub} = 0.95 \times V_1$	ESS	$H_s = 1.09 \times H_{s1}$	$\beta = 0^o, \pm 30^o$	Yaw = 0º, ±20º	U	1.35
7) Parked (Idling) and Fault								
7.1a	EWM	$V_{hub} = 0.95 \times V_1$	ESS	$H_s = 1.09 \times H_{s1}$	$\beta = 0^o, \pm 30^o$	Seized blade; Yaw = 0º, ±8º	U	1.10

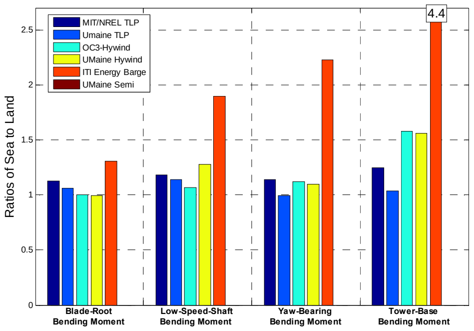


Concept Designs for Loads Analysis

Summary of Properties: 6 Floating Systems

	MIT/NREL TLP	UMaine TLP	OC3-Hywind Spar Buoy 320 m Depth	OC3-Hywind Spar Buoy 200 m Depth	ITI Energy Barge	UMaine Semi-Submersible
Diameter or width × length (m)	18	15	6.5 to 9.4 (is tapered)	6.5 to 9.4 (is tapered)	40 × 40	13.5 and 20 (diameters)
Draft (m)	47.89	24	120	120	4	20
Water displacement (m^3)	12,180	2,767	8,029	8,029	6,000	6232
Mass, including ballast (kg)	8,600,000	774,940	7,466,000	7,466,000	5,452,000	5,591,400
CM location of the platform below SWL (m)	40.61	19.72	89.92	89.92	0.2818	5.11
Roll inertia about CM(kg • m^2)	571,600,000	150,780,000	4,229,000,000	4,229,000,000	726,900,000	3,062,000,000
Pitch inertia about CM (kg • m^2)	571,600,000	150,780,000	4,229,000,000	4,229,000,000	726,900,000	3,062,000,000
Yaw inertia about CM (kg • m^2)	361,400,000	98,850,000	164,200,000	164,200,000	1,454,000,000	3,673,000,000
Number of mooring lines	8 (4 pairs)	3	3	3	8	3
Depth to fairleads, anchors	47.89 200	28.5 200	70 320	70 200	4 150	7 200
Radius to fairleads, anchors (m)	27 27	30 30	5.2 853.9	5.2 445	28.28 423.4	36.558 1013
Unstretched line length (m)	151.7	171.4	902.2	468	473.3	1017
Line diameter (m)	0.127	0.222	0.09	0.09	0.0809	0.0766
Line mass density (kg/m)	116	302.89	77.71	145	130.4	113.4
Line extensional stiffness (N)	1,500,000,000	7,720,000,000	384,200,000	384,200,000	589,000,000	753,600,000

Sea-to-Land Ratios of Ultimate Loads
(DLCs 1.1, 1.3, 1.4, 1.5)



Extreme Event Comparison

Ultimate Load	Land-Based System	MIT/NREL TLP System	UMaine TLP System	OC3-Hywind Spar Buoy System	Umaine Hywind Spar Buoy System	ITI Energy Barge System
Blade-root bending moment	DLC 1.4	DLC 1.4	DLC 1.4	DLC 1.3	DLC 1.3	DLC 1.1
Low-speed-shaft bending moment	DLC 1.4	DLC 1.4	DLC 1.4	DLC 1.3	DLC 1.3	DLC 1.1
Yaw-bearing bending moment	DLC 1.3	DLC 1.4	DLC 1.3	DLC 1.3	DLC 1.3	DLC 1.1
Tower-base bending moment	DLC 1.3	DLC 1.1	DLC 1.1	DLC 1.3	DLC 1.1	DLC 1.1

Summary of Ultimate Loads – Land vs. Offshore

- Land-based system
  - Many of the greatest loads on blades and shaft from gust of DLC1.4
  - Most other large loads driven by DLC 1.3 (extreme turbulence) at rated wind speed.
- Offshore systems
  - Larger motion of offshore systems in general results in larger loads
  - Increased loads caused by inertial forces on the system.
  - These loads get greater as you move from the top of the turbine to the platform
  - Yaw errors allow for more side-to-side excitation in the system

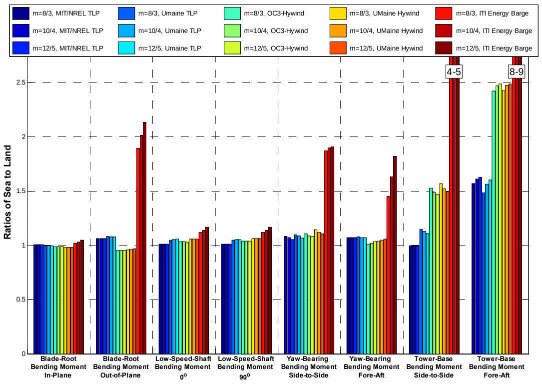
Summary of System Ultimate Loads

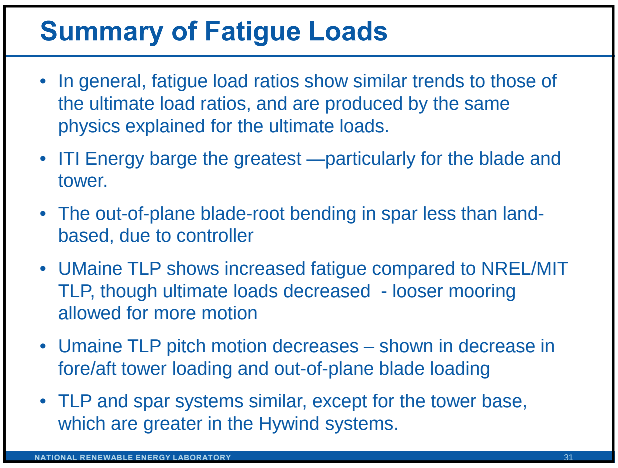
- ITI Energy Barge
  - Affected more by the waves than the wind
  - Since waves are same for DLCs, DLC 1.1 dominates large loads due to higher safety factor
- TLPs
  - TLPs have much less motion than the barge, and therefore lower loads (especially pitch, roll), but more than land-based
  - Greatest loads are in the same DLC as land-based, DLC 1.4
  - Umaine TLP much smaller and lighter than NREL/MIT TLP, but motions remain similar - TLP motion different than other concepts
  - Slight decrease in Umaine TLP loads due to surge motion at time of gust

Summary of System Ultimate Loads, cont.

- Hywind Spar Buoy
  - Spar system has greater motion than TLP in pitch and roll, but less in yaw (damping from tests)
  - Load increases are somewhat compensated for by a control system that limits blade and tower loads
  - Result is that some loads increase in spar system and some decrease compared to TLP
  - DLC 1.3 was the force driver rather than 1.4 due to controller limiting load on blades
  - UMaine Hywind very similar to OC3 Hywind

Sea-to-Land Ratios of Fatigue Loads





Summary of Fatigue Loads

- In general, fatigue load ratios show similar trends to those of the ultimate load ratios, and are produced by the same physics explained for the ultimate loads.
- ITI Energy barge the greatest —particularly for the blade and tower.
- The out-of-plane blade-root bending in spar less than land-based, due to controller
- UMaine TLP shows increased fatigue compared to NREL/MIT TLP, though ultimate loads decreased - looser mooring allowed for more motion
- Umaine TLP pitch motion decreases – shown in decrease in fore/aft tower loading and out-of-plane blade loading
- TLP and spar systems similar, except for the tower base, which are greater in the Hywind systems.

Thank You for Your Attention

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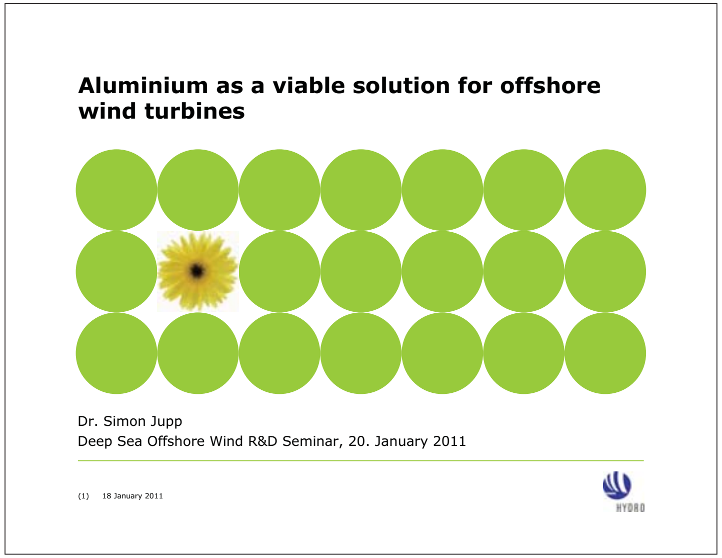
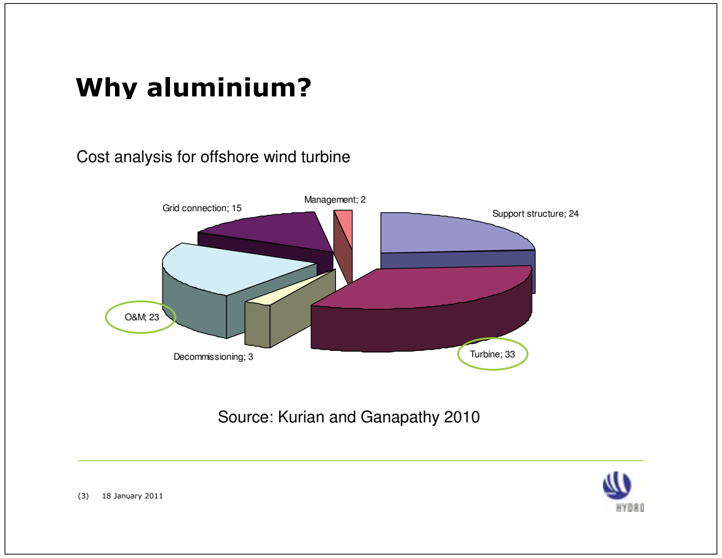


Aluminium as a viable solution for offshore wind turbines

Dr. Simon Jupp
Deep Sea Offshore Wind R&D Seminar, 20. January 2011

Climate matters

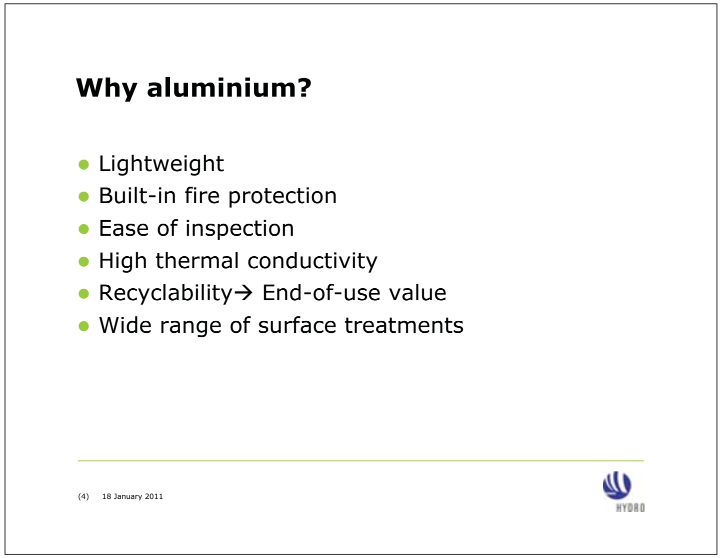
- Hydro's mission – to create a more viable society – implies making solutions to the climate challenge an inherent part of our business model
- **The Business Opportunity: Reduce emissions and improve energy efficiency**
- Technology a key driver



Why aluminium?

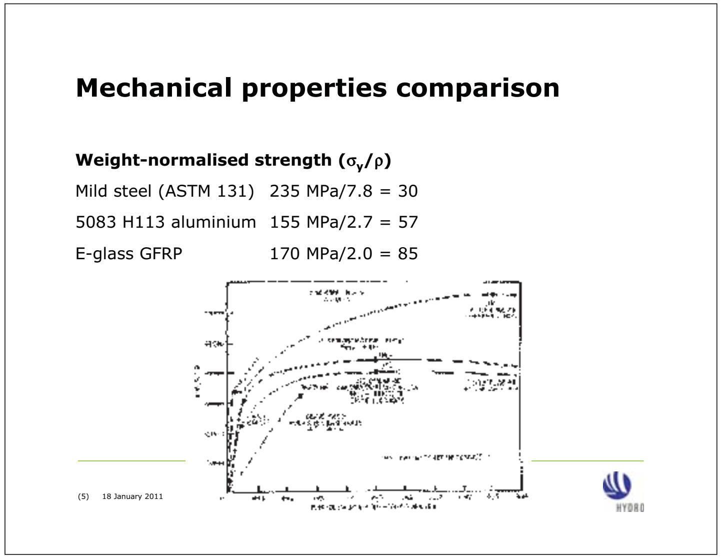
Cost analysis for offshore wind turbine

Source: Kurian and Ganapathy 2010



Why aluminium?

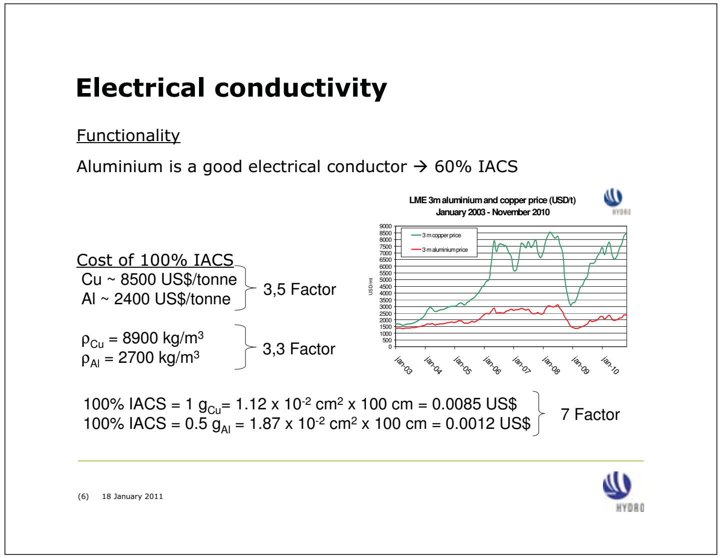
- Lightweight
- Built-in fire protection
- Ease of inspection
- High thermal conductivity
- Recyclability→ End-of-use value
- Wide range of surface treatments



Mechanical properties comparison

Weight-normalised strength (σ_y/ρ)

Mild steel (ASTM 131)	235 MPa/7.8 = 30
5083 H113 aluminium	155 MPa/2.7 = 57
E-glass GFRP	170 MPa/2.0 = 85



Electrical conductivity

Functionality

Aluminium is a good electrical conductor → 60% IACS

Cost of 100% IACS
Cu ~ 8500 US\$/tonne
Al ~ 2400 US\$/tonne
} 3,5 Factor

ρ_{Cu} = 8900 kg/m^3
ρ_{Al} = 2700 kg/m^3
} 3,3 Factor

100% IACS = 1 g_{Cu}= 1.12 x 10^{-2} cm^2 x 100 cm = 0.0085 US\$
100% IACS = 0.5 g_{Al} = 1.87 x 10^{-2} cm^2 x 100 cm = 0.0012 US\$
} 7 Factor

Lightweight structure (e.g. nacelle)

- Aluminium stiffeners weigh 40%-50% less than steel stiffeners with the same deflection resistance
- The weight disadvantage to GRP is equalized by the advantage in stiffness.

	Steel	Aluminium	Aluminium	Aluminium
Moment in inertia in mm^4	$38.9\ 10^6$	$116.6\ 10^6$	$116.7\ 10^6$	$117.3\ 10^6$
E x I (N/mm^2)	$8.17\ 10^{12}$	$8.16\ 10^{12}$	$8.17\ 10^{12}$	$8.21\ 10^{12}$
h (mm)	240	240	300	330
b(mm)	120	240	200	200
w (mm)	6.2	12	6	6
t (mm)	9.8	18.3	12.9	10
Unit weight (kg/m)	30.7	30.3	18.4	15.8
Weight in % of the steel beam	100 %	99 %	60 %	51 %

Lightweight in nacelle equipment

The weight advantage of aluminium can also be used in nacelle equipment parts:

- Helicopter Hoist Platforms
- Electrical cabinets
- Floor sheets
- Steps and ladders
- Ventilation channels
- Transformers
- Cabling

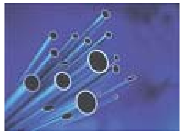
Built-in fire protection

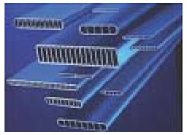
- Aluminium is incombustible and does not contribute to a fire
  - Wide use of aluminium profiles in fire protection doors
- There is no need for additional lightning protection (an aluminium skin builds a natural Faraday´s cage)
- Aluminium has no electrostatic potential

High thermal conductivity

- Aluminium's thermal conductivity is 3-4 times that of steel and more than 100 times that of plastics
- Enables better heat dissipation through the outer skin of a nacelle and therefore allows smaller cooler sizes

- Aluminium is also extensively used in heat exchangers, both as tubes and for fins





Recyclability

- Aluminium can be infinitely recycled without a loss in quality with a saving of 95% of energy compared to its primary production
- Aluminium keeps a commercial value along its whole lifetime; e.g. the „scrap value" is typically in the range of 1.000-1.500 EUR/tonne (Note: as of 5 Jan 2011, LME Al scrap price >1800€/tonne).

Longevity

- 75% of all aluminium produced so far is still in use
- Aluminium can be kept unpainted in normal environmental conditions
  - Oldest aluminium roof in the world: San Gioacchino church of 1896
- Aluminium survives harshest marine conditions:
  - Wide use in helicopter decks and living quarters of offshore platforms

Ease of inspection

As aluminium does not need to be painted and is rust- free, it can easily be inspected with visual means. Any other inspection methods for other metals can also be applied on aluminium.

This is expected to reduce the need for costly and intensive maintenance – especially when used in offshore wind turbines.

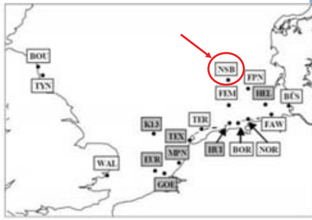
Source: ZDF

Wide range of surface treatments

- Due to its natural oxide layer, an aluminium surface does not corrode and does not need to be painted for surface protection
- For aesthetical reasons and to gain a certain appearance, an aluminium surface can be:
  - Sand- or shot-blasted
  - Painted
  - Brushed or polished
  - Anodized

North Sea Buoy II

- Container with measuring equipment
  - Made of painted aluminium
  - Mounted on top of the buoy during operation



  - NSB II is part of a network of meteorological measurement stations in the North Sea

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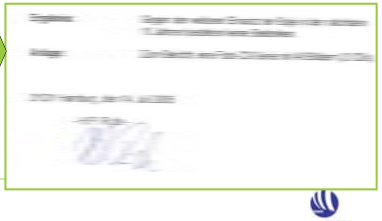
North Sea Buoy II

- NSB II has been operated in the open sea for 32 years with no maintenance other than occasional cleaning
  - Maintenance was necessary in June 2010 due to collision damage
  - Buoy was cleaned with 80 bar high pressure water jet
  - NSB II is in operation again

North Sea Buoy II
Technical survey in 2005

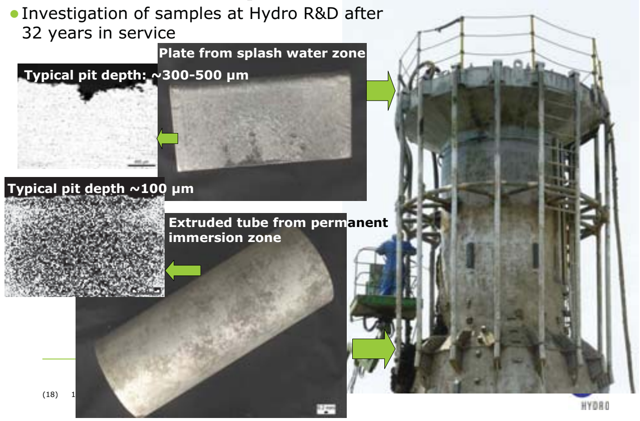
- **No substantial wall thickness reduction** on any part of the buoy
- **No cracks** in base material or weld seams
- **Weldability** identical to new material
- **Joints with stainless steel screws** (1.4571) fully intact without galvanic isolation

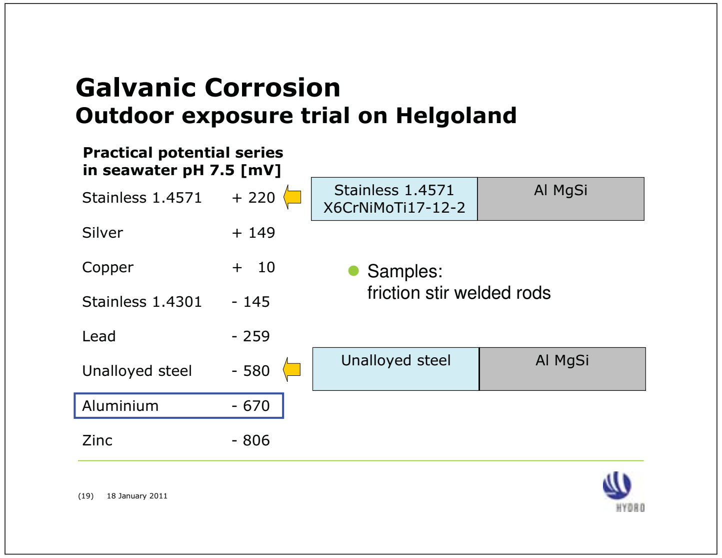
Result:
No objection against
another 10 years
of operation



North Sea Buoy II

- Investigation of samples at Hydro R&D after 32 years in service



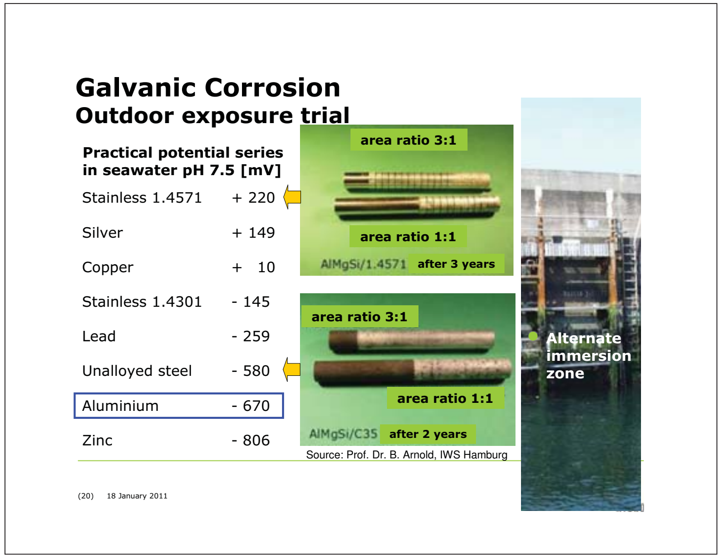


Galvanic Corrosion
Outdoor exposure trial on Helgoland

Practical potential series in seawater pH 7.5 [mV]

Stainless 1.4571	+ 220
Silver	+ 149
Copper	+ 10
Stainless 1.4301	- 145
Lead	- 259
Unalloyed steel	- 580
Aluminium	- 670
Zinc	- 806

- Samples:
  friction stir welded rods

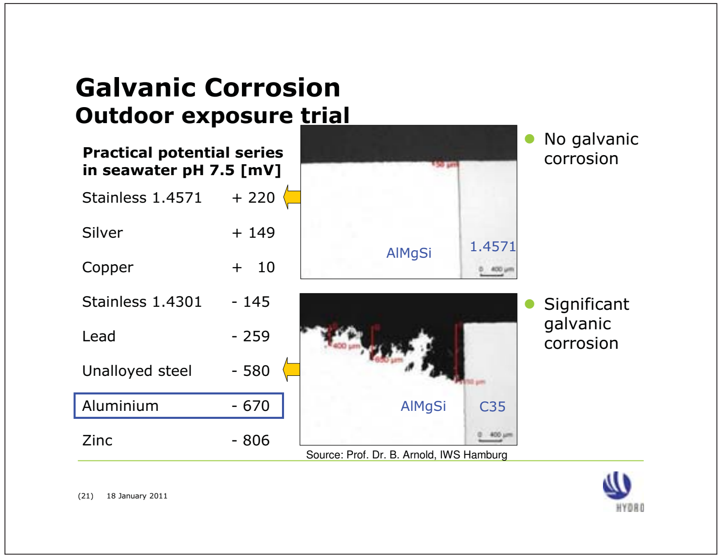


Galvanic Corrosion
Outdoor exposure trial

Practical potential series in seawater pH 7.5 [mV]

Stainless 1.4571	+ 220
Silver	+ 149
Copper	+ 10
Stainless 1.4301	- 145
Lead	- 259
Unalloyed steel	- 580
Aluminium	- 670
Zinc	- 806

Source: Prof. Dr. B. Arnold, IWS Hamburg



Galvanic Corrosion
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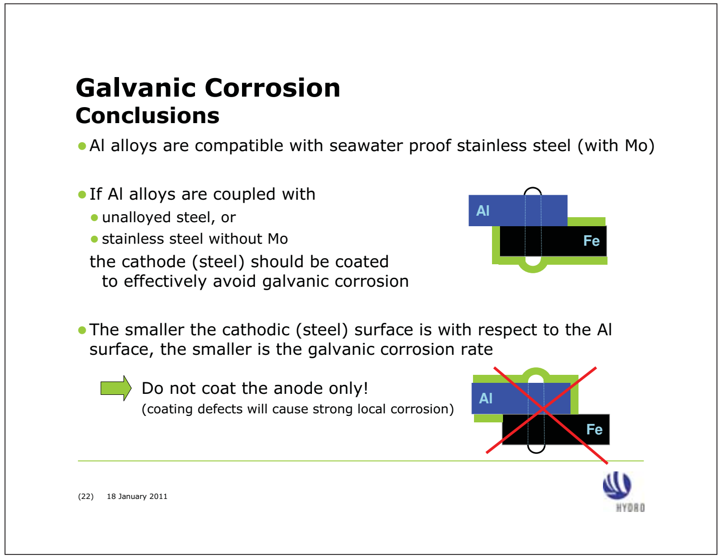
Stainless 1.4301	- 145
Lead	- 259
Unalloyed steel	- 580
Aluminium	- 670
Zinc	- 806

- No galvanic corrosion
- Significant galvanic corrosion

Source: Prof. Dr. B. Arnold, IWS Hamburg



Galvanic Corrosion
Conclusions

- Al alloys are compatible with seawater proof stainless steel (with Mo)
- If Al alloys are coupled with
  - unalloyed steel, or
  - stainless steel without Mo

  the cathode (steel) should be coated to effectively avoid galvanic corrosion

- The smaller the cathodic (steel) surface is with respect to the Al surface, the smaller is the galvanic corrosion rate

➡ Do not coat the anode only!
(coating defects will cause strong local corrosion)

Lille Frigg Protection Cover after removal

Steel structure with protection cover at top of aluminium extrusions

Lille Frigg Protection Cover after removal

Aluminium top cover of aluminium extrusions

Lille Frigg Protection Cover after removal

Hinge for aluminium protection cover and steel structure

Lille Frigg Protection Cover

For corrosion protection, galvanic anodes are used. The need for galvanic anodes is ~10% of what is needed for steel structures.

Summary

- Lightweight
  - Typical weight savings of 50% for both mechanical and electrical applications
- Built-in fire protection
  - Inherent lightning protection
- Ease of inspection
  - Unpainted surfaces for simplified visual inspection
- High thermal conductivity
  - Further weight reductions through reduced cooling requirements
- Recyclability
  - End-of-use value helps to offset decommissioning costs
- Wide range of surface treatments
- Combination of steel and aluminium possible through appropriate design and surface coating of steel.

An opportunity for the Wind Industry?

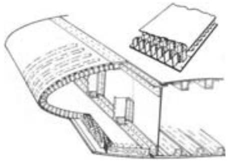
A major issue regarding life cycle costs of wind turbines, is durability and end of life scrapping of fibreglass/CFRP rotor blades.

It has been suggested by several turbine manufacturers that an Al solution would be desirable.

Experience from the aerospace industries suggests that this would be possible.

However, the development and testing of a full scale blade is a major investment and would require industry-wide interest and support.

A solution would be to form an industry-wide consortium, including Hydro Aluminium as partner.



Sandwich core structure for aircraft wings

Aircraft Wing Box

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www.hydro.com

Thank you for your attention

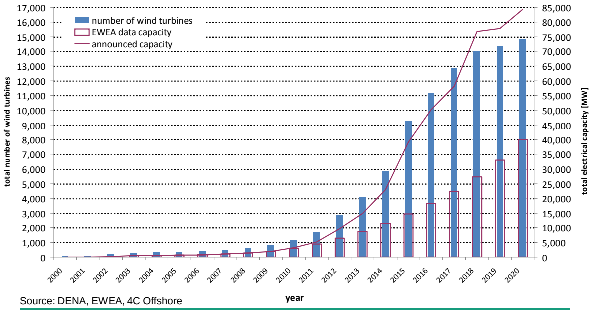
Contact: Dr. Simon Jupp
simon.jupp@hydro.com

HiPRWind
Large floating turbines for intermediate water depths

Jochen Bard[1], Louis Quesnel[1], Jan Erik Hanssen[2]

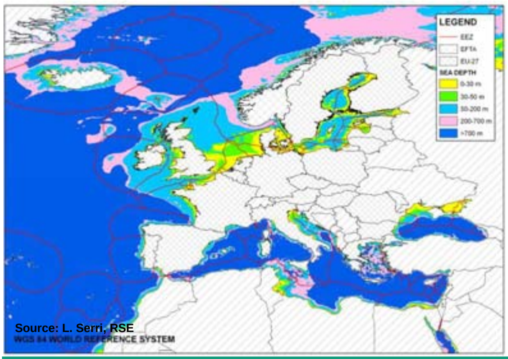
[1] Fraunhofer Institute for Wind Energy and Energy Systems Technology
[2] 1-Tech, Brussels

European offshore wind market development: EWEA scenario and “project pipeline”



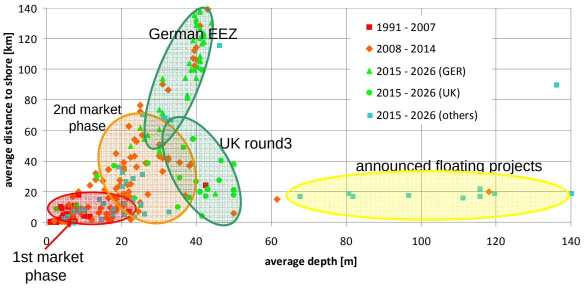
Source: DENA, EWEA, 4C Offshore

European EEZs and bathymetry map



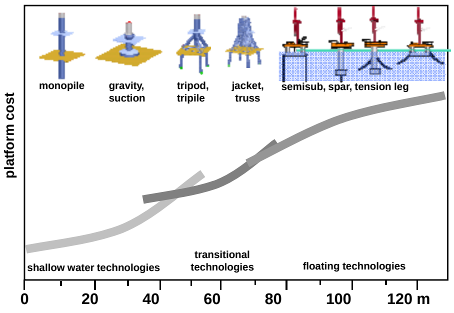
Source: L. Serri, RSE

Development phases of the EU offshore wind market in terms of water depth (m) and distance to shore (km) up to 2025



WWW.ORECCA.EU

Platform technologies change with water depth



Source: NREL, NTNU

Floating concepts: project examples

…and many more…

Call FP7-ENERGY-2010-1

- Topic ENERGY.2010.2.3-1: Cross-sectoral approach to the development of very large offshore wind turbines
- Collaborative project, where „the active participation of stakeholders involved in harsh environment industrial developments is essential to achieving the full impact of the project."
- Scope
  - Testing at industrial prototype scale to develop 10 MW range OWT
  - Treat bottleneck issues such as maintenance, power stability, weight/size limitations
  - Advanced power electronics and ICT sub-systems
- 1st deadline on 15th October 2009
- 35 M€ available for 6 distinct topics in 3 different research areas

HiPRwind: key facts and figures

„High Power, high Reliability offshore wind technology"

Project coordinator: Fraunhofer IWES

- Funded under the European Commission's 7th Framework Programme
  - Main source for European R&D funding, 50+ billions € over 7 years
  - Theme ENERGY.2010.2.3-1: Cross-sectoral approach to the development of very large offshore wind turbines
  - Involvement of offshore industry stakeholders required
- Project start date: November 1, 2010. End date: October 31, 2015
- Total budget ~ 20 million €, total EC-funding 11 million €
- 1130 man months over 5 years

Programme

- **Aim:**
  install and operate a floating MW-class wind turbine for research purpose
- **Potential Location:**
  Bay of Biscay, off Bilbao in Spain
- **Industrial challenge: design, procurement, construction and installation of the floating WT within three years of project start and within the available budget**
- **Research prospects: „unrestricted" access to data from experiments on a real wind turbine in harsh offshore conditions during at least two years**

Work plan

Main research topics:

- Floater and mooring systems
- Controls, power and grid
- Condition and structural health monitoring
- Advanced rotor concepts

Timing:

- 1st year: design of the floating platform and of the research equipment
- 2nd and 3rd year: procurement, construction and installation of the floating WT
- 4th and 5th year: WT operation and maintenance for experimental research

Consortium: Partners

A strong consortium with experience in offshore developments:

Industry

Acciona Energia (Spain)
Acciona Wind Power (Spain)
Technip (France)
ABB (Switzerland)
Bureau Véritas (France)
Mammoet (Netherlands)
IDESA (Spain)
Vicinay Cadenas (Spain)

R&D SMEs

Olav Olsen (Norway)
Tecnalia-Robotiker (Spain)
The Welding Institute (UK)
Wölfel berat. Ing. (Germany)
Micromega (Belgium)
1-Tech (Belgium)

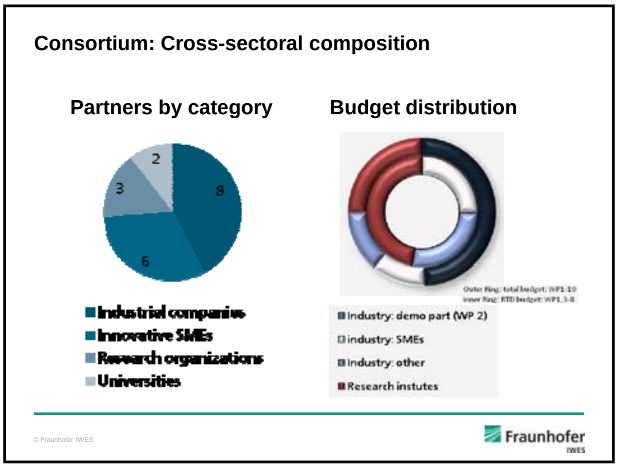
Universities

NTNU (Norway)
Universität Siegen (Germany)

Research organisations

Fraunhofer IWES and IZFP
SINTEF (Norway)
Narec (UK)

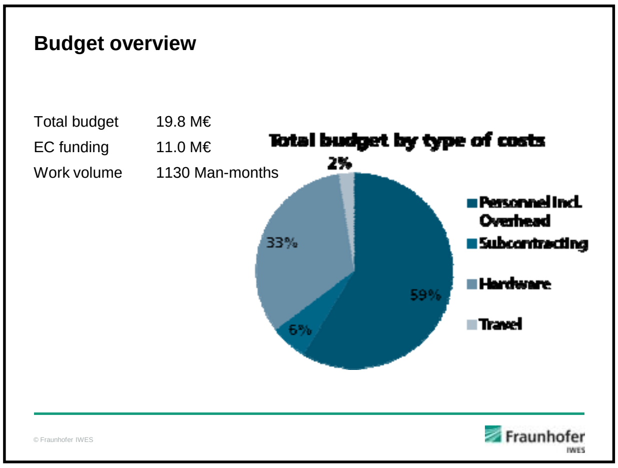
Consortium: Nationalities and partners/country



Consortium: Cross-sectoral composition

Partners by category

Budget distribution



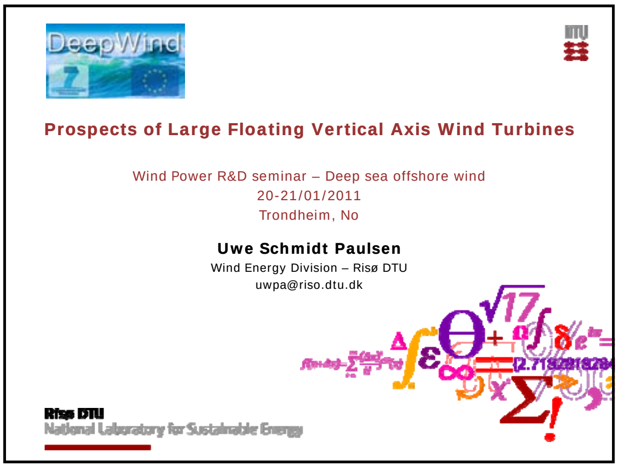
Budget overview

Total budget	19.8 M€
EC funding	11.0 M€
Work volume	1130 Man-months

Challenges in the design process

- Iterative design process
- Competences, contributions and roles of the partners
- Available software tools, interfaces between the tools and partners
- Design framework (Metocean, wind turbine, budget, …)
- Requirements for wave tank testing of a physical model
- Turbine modification vs platform stability; Moorings and station keeping
- Assembly, Installation and Commissioning Procedures
- Operation and Maintenance concept
- Generation of a reliable budget for manufacturing, assembly, installation and operation
- Certification and Permitting requirements for the offshore site
- ….

www.hyperwind.eu



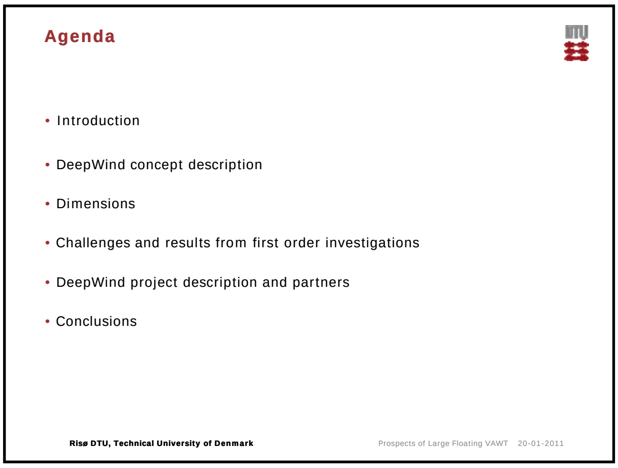
DeepWind

Prospects of Large Floating Vertical Axis Wind Turbines

Wind Power R&D seminar – Deep sea offshore wind
20-21/01/2011
Trondheim, No

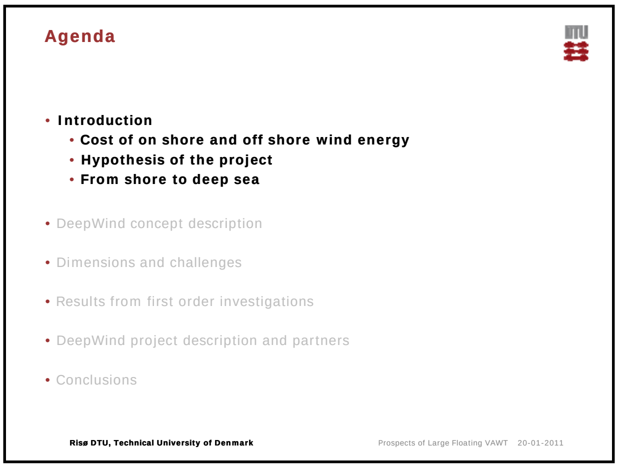
Uwe Schmidt Paulsen
Wind Energy Division – Risø DTU
uwpa@riso.dtu.dk

Risø DTU
National Laboratory for Sustainable Energy



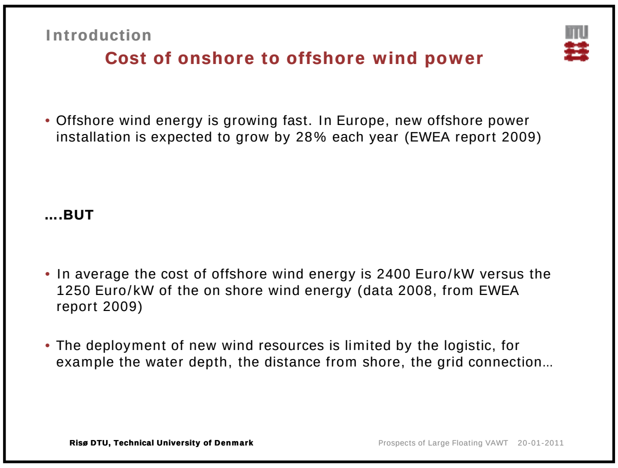
Agenda

- Introduction
- DeepWind concept description
- Dimensions
- Challenges and results from first order investigations
- DeepWind project description and partners
- Conclusions



Agenda

- **Introduction**
  - **Cost of on shore and off shore wind energy**
  - **Hypothesis of the project**
  - **From shore to deep sea**
- DeepWind concept description
- Dimensions and challenges
- Results from first order investigations
- DeepWind project description and partners
- Conclusions



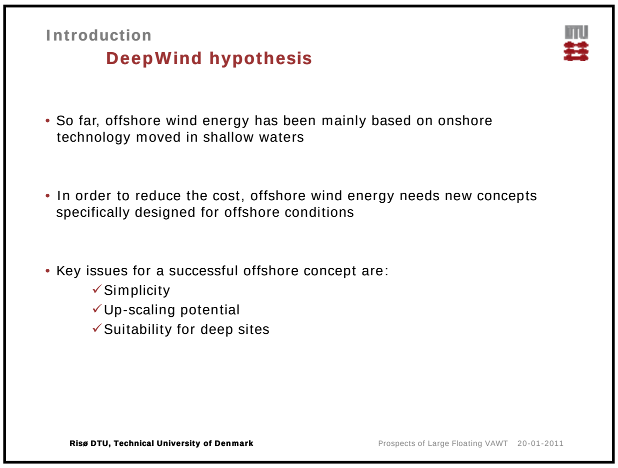
Introduction

Cost of onshore to offshore wind power

- Offshore wind energy is growing fast. In Europe, new offshore power installation is expected to grow by 28% each year (EWEA report 2009)

....BUT

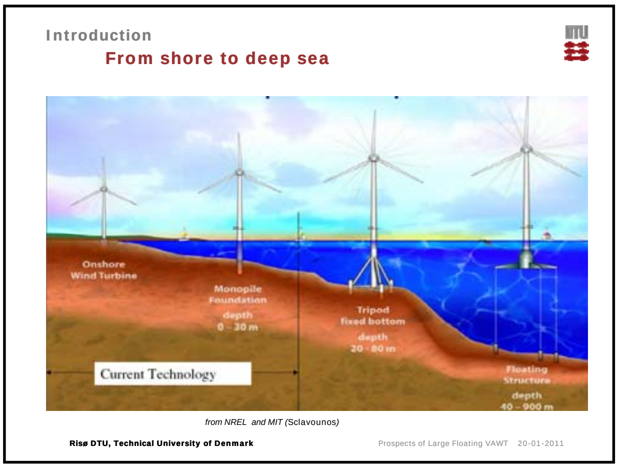
- In average the cost of offshore wind energy is 2400 Euro/kW versus the 1250 Euro/kW of the on shore wind energy (data 2008, from EWEA report 2009)
- The deployment of new wind resources is limited by the logistic, for example the water depth, the distance from shore, the grid connection…



Introduction

DeepWind hypothesis

- So far, offshore wind energy has been mainly based on onshore technology moved in shallow waters
- In order to reduce the cost, offshore wind energy needs new concepts specifically designed for offshore conditions
- Key issues for a successful offshore concept are:
  - ✓Simplicity
  - ✓Up-scaling potential
  - ✓Suitability for deep sites



Introduction

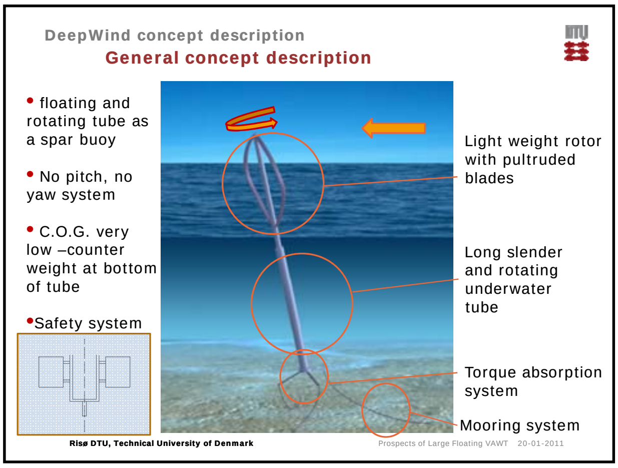
From shore to deep sea

from NREL and MIT (Sclavounos)

Agenda

- Introduction
- **DeepWind concept description**
  - **General concept description**
  - **Components description**
  - **Upscaling**
  - **Installation and O&M strategies**
- Dimensions and challenges
- Results from first order investigations
- DeepWind project description and partners
- Conclusions

Risø DTU, Technical University of Denmark Prospects of Large Floating VAWT 20-01-2011

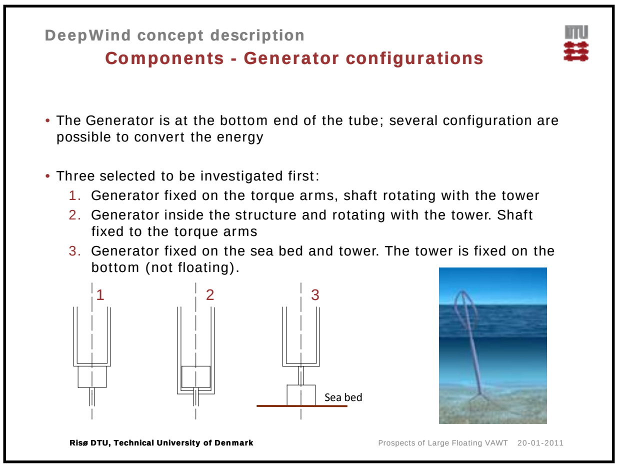


DeepWind concept description

General concept description

- floating and rotating tube as a spar buoy
- No pitch, no yaw system
- C.O.G. very low –counter weight at bottom of tube
- Safety system

Risø DTU, Technical University of Denmark Prospects of Large Floating VAWT 20-01-2011

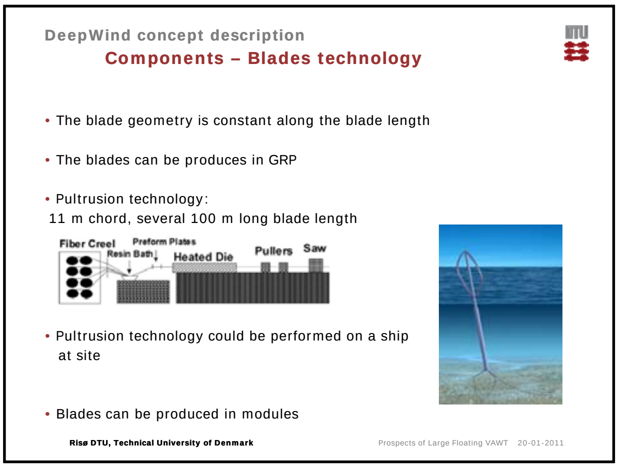


DeepWind concept description

Components - Generator configurations

- The Generator is at the bottom end of the tube; several configuration are possible to convert the energy
- Three selected to be investigated first:
  1. Generator fixed on the torque arms, shaft rotating with the tower
  2. Generator inside the structure and rotating with the tower. Shaft fixed to the torque arms
  3. Generator fixed on the sea bed and tower. The tower is fixed on the bottom (not floating).

Risø DTU, Technical University of Denmark Prospects of Large Floating VAWT 20-01-2011



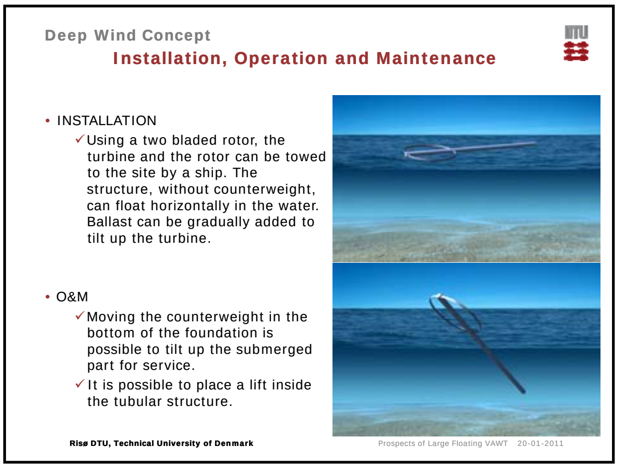
DeepWind concept description

Components – Blades technology

- The blade geometry is constant along the blade length
- The blades can be produces in GRP
- Pultrusion technology:
  11 m chord, several 100 m long blade length

- Pultrusion technology could be performed on a ship at site
- Blades can be produced in modules

Risø DTU, Technical University of Denmark Prospects of Large Floating VAWT 20-01-2011

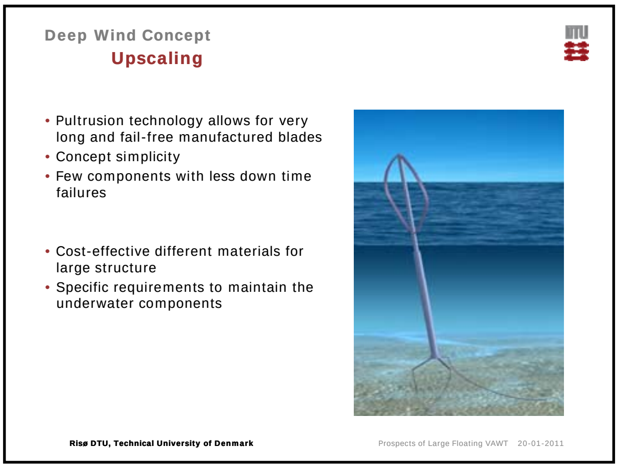


Deep Wind Concept

Installation, Operation and Maintenance

- INSTALLATION
  - ✓Using a two bladed rotor, the turbine and the rotor can be towed to the site by a ship. The structure, without counterweight, can float horizontally in the water. Ballast can be gradually added to tilt up the turbine.
- O&M
  - ✓Moving the counterweight in the bottom of the foundation is possible to tilt up the submerged part for service.
  - ✓It is possible to place a lift inside the tubular structure.

Risø DTU, Technical University of Denmark Prospects of Large Floating VAWT 20-01-2011

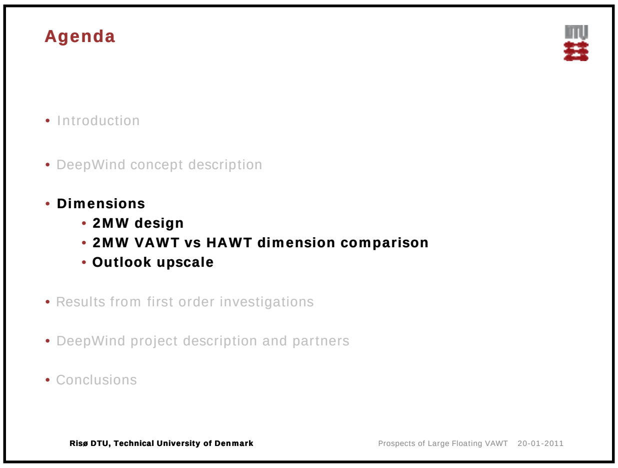


Deep Wind Concept

Upscaling

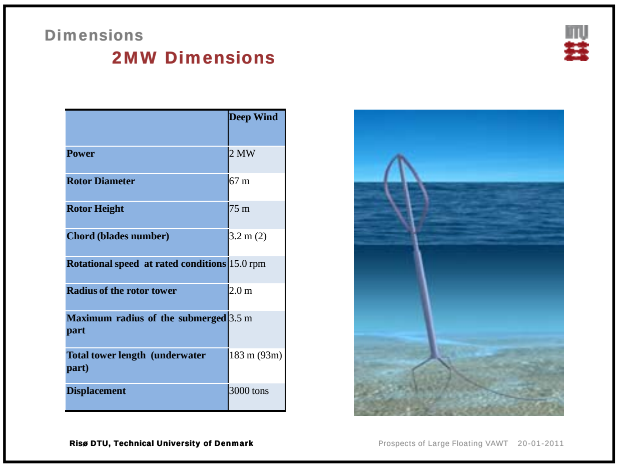
- Pultrusion technology allows for very long and fail-free manufactured blades
- Concept simplicity
- Few components with less down time failures
- Cost-effective different materials for large structure
- Specific requirements to maintain the underwater components

Risø DTU, Technical University of Denmark Prospects of Large Floating VAWT 20-01-2011



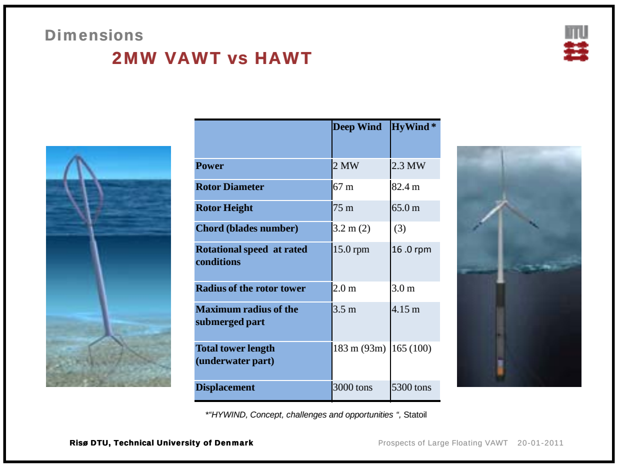
Agenda

- Introduction
- DeepWind concept description
- **Dimensions**
  - **2MW design**
  - **2MW VAWT vs HAWT dimension comparison**
  - **Outlook upscale**
- Results from first order investigations
- DeepWind project description and partners
- Conclusions



Dimensions
2MW Dimensions

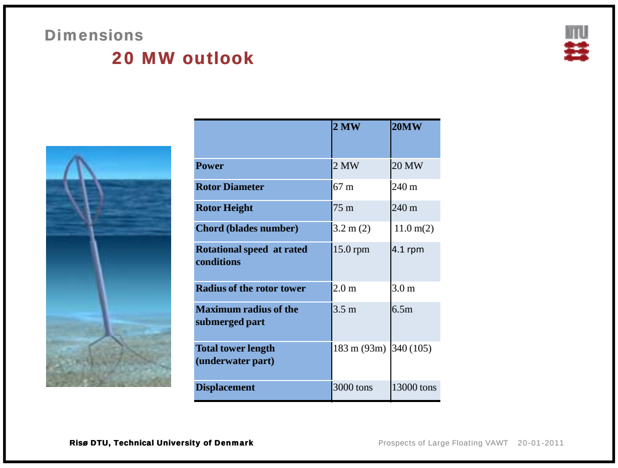
	Deep Wind
Power	2 MW
Rotor Diameter	67 m
Rotor Height	75 m
Chord (blades number)	3.2 m (2)
Rotational speed at rated conditions	15.0 rpm
Radius of the rotor tower	2.0 m
Maximum radius of the submerged part	3.5 m
Total tower length (underwater part)	183 m (93m)
Displacement	3000 tons



Dimensions
2MW VAWT vs HAWT

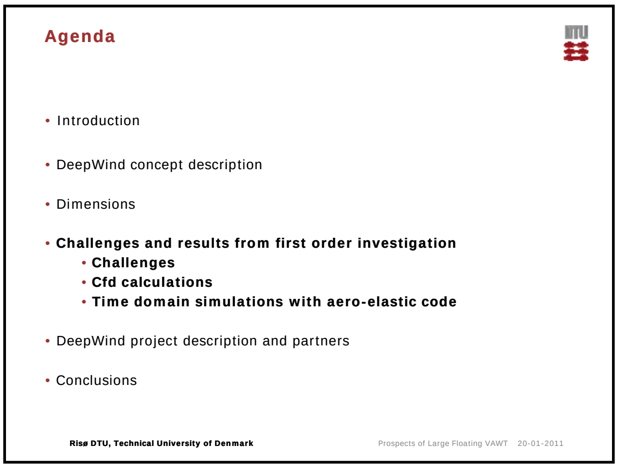
	Deep Wind	HyWind *
Power	2 MW	2.3 MW
Rotor Diameter	67 m	82.4 m
Rotor Height	75 m	65.0 m
Chord (blades number)	3.2 m (2)	(3)
Rotational speed at rated conditions	15.0 rpm	16 .0 rpm
Radius of the rotor tower	2.0 m	3.0 m
Maximum radius of the submerged part	3.5 m	4.15 m
Total tower length (underwater part)	183 m (93m)	165 (100)
Displacement	3000 tons	5300 tons

*“*HYWIND, Concept, challenges and opportunities* “, Statoil



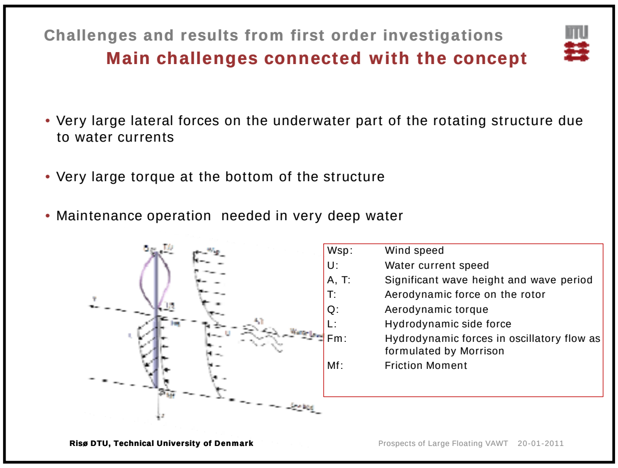
Dimensions
20 MW outlook

	2 MW	20MW
Power	2 MW	20 MW
Rotor Diameter	67 m	240 m
Rotor Height	75 m	240 m
Chord (blades number)	3.2 m (2)	11.0 m(2)
Rotational speed at rated conditions	15.0 rpm	4.1 rpm
Radius of the rotor tower	2.0 m	3.0 m
Maximum radius of the submerged part	3.5 m	6.5m
Total tower length (underwater part)	183 m (93m)	340 (105)
Displacement	3000 tons	13000 tons



Agenda

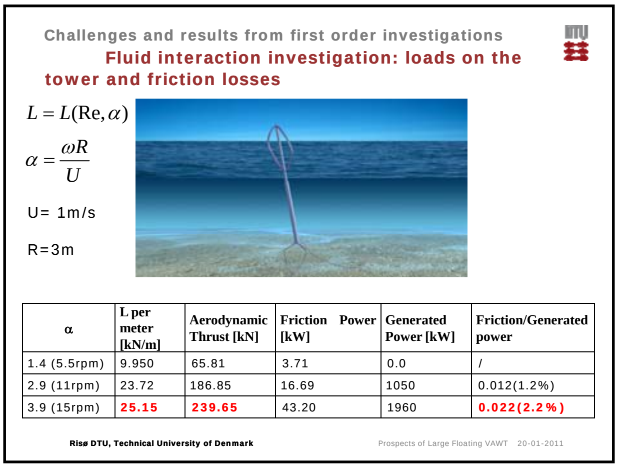
- Introduction
- DeepWind concept description
- Dimensions
- **Challenges and results from first order investigation**
  - **Challenges**
  - **Cfd calculations**
  - **Time domain simulations with aero-elastic code**
- DeepWind project description and partners
- Conclusions



Challenges and results from first order investigations
Main challenges connected with the concept

- Very large lateral forces on the underwater part of the rotating structure due to water currents
- Very large torque at the bottom of the structure
- Maintenance operation needed in very deep water

Wsp: Wind speed
U: Water current speed
A, T: Significant wave height and wave period
T: Aerodynamic force on the rotor
Q: Aerodynamic torque
L: Hydrodynamic side force
Fm: Hydrodynamic forces in oscillatory flow as formulated by Morrison
Mf: Friction Moment



Challenges and results from first order investigations

Fluid interaction investigation: loads on the tower and friction losses

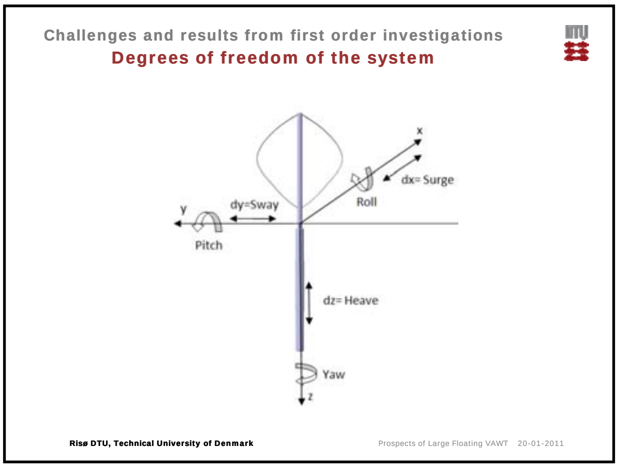
$L = L(\mathrm{Re}, \alpha)$

$\alpha = \frac{\omega R}{U}$

U= 1m/s

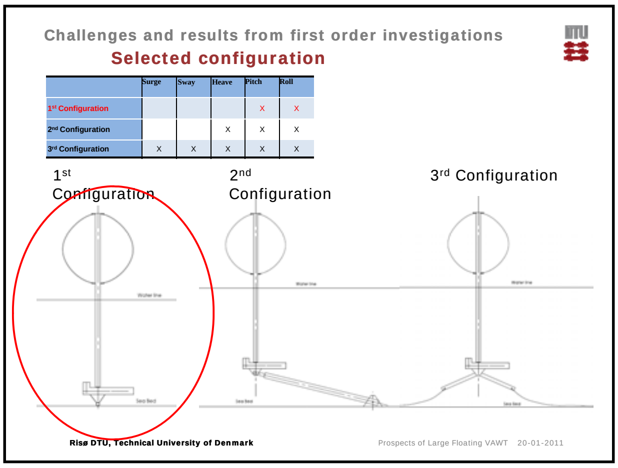
R=3m

α	L per meter [kN/m]	Aerodynamic Thrust [kN]	Friction Power [kW]	Generated Power [kW]	Friction/Generated power
1.4 (5.5rpm)	9.950	65.81	3.71	0.0	/
2.9 (11rpm)	23.72	186.85	16.69	1050	0.012(1.2%)
3.9 (15rpm)	25.15	239.65	43.20	1960	0.022(2.2%)



Challenges and results from first order investigations

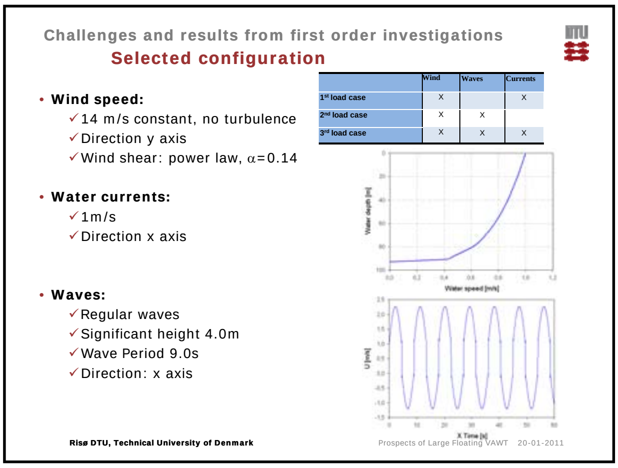
Degrees of freedom of the system



Challenges and results from first order investigations

Selected configuration

	Surge	Sway	Heave	Pitch	Roll
1st Configuration				X	X
2nd Configuration			X	X	X
3rd Configuration	X	X	X	X	X

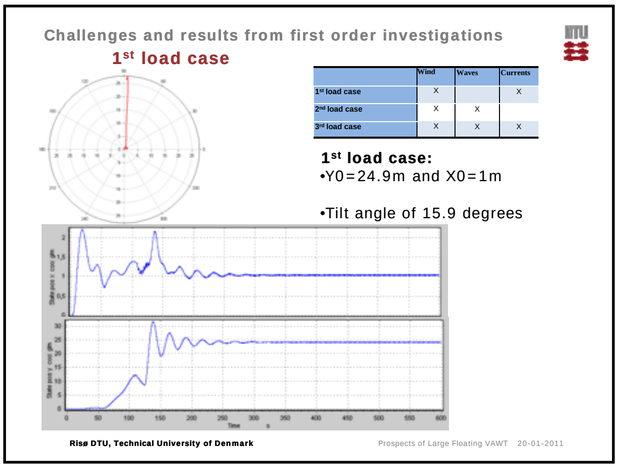


Challenges and results from first order investigations

Selected configuration

	Wind	Waves	Currents
1st load case	X		X
2nd load case	X	X	
3rd load case	X	X	X

- **Wind speed:**
  - ✓14 m/s constant, no turbulence
  - ✓Direction y axis
  - ✓Wind shear: power law, α=0.14
- **Water currents:**
  - ✓1m/s
  - ✓Direction x axis
- **Waves:**
  - ✓Regular waves
  - ✓Significant height 4.0m
  - ✓Wave Period 9.0s
  - ✓Direction: x axis



Challenges and results from first order investigations

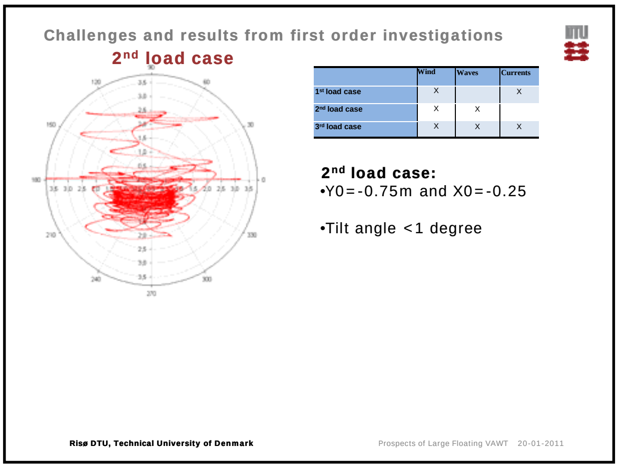
1st load case

	Wind	Waves	Currents
1st load case	X		X
2nd load case	X	X	
3rd load case	X	X	X

1st load case:

•Y0=24.9m and X0=1m

•Tilt angle of 15.9 degrees



Challenges and results from first order investigations

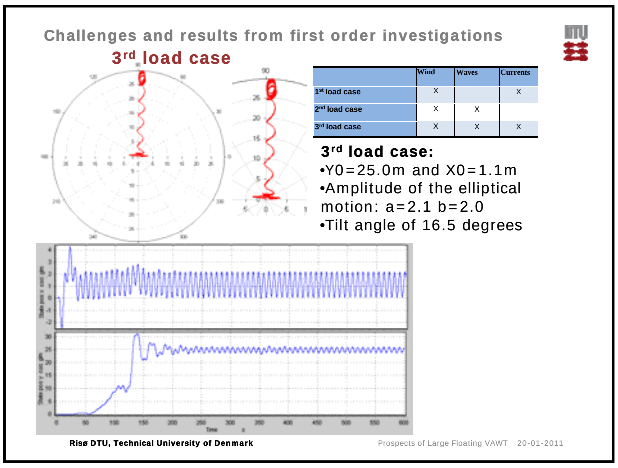
2nd load case

	Wind	Waves	Currents
1st load case	X		X
2nd load case	X	X	
3rd load case	X	X	X

2nd load case:

•Y0=-0.75m and X0=-0.25

•Tilt angle <1 degree



Challenges and results from first order investigations

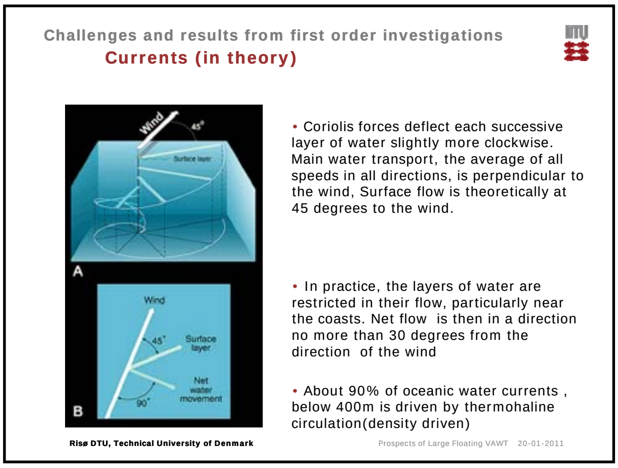
3rd load case

	Wind	Waves	Currents
1st load case	X		X
2nd load case	X	X	
3rd load case	X	X	X

3rd load case:
- Y0=25.0m and X0=1.1m
- Amplitude of the elliptical motion: a=2.1 b=2.0
- Tilt angle of 16.5 degrees

Risø DTU, Technical University of Denmark

Prospects of Large Floating VAWT 20-01-2011



Challenges and results from first order investigations

Currents (in theory)

- Coriolis forces deflect each successive layer of water slightly more clockwise. Main water transport, the average of all speeds in all directions, is perpendicular to the wind, Surface flow is theoretically at 45 degrees to the wind.
- In practice, the layers of water are restricted in their flow, particularly near the coasts. Net flow is then in a direction no more than 30 degrees from the direction of the wind
- About 90% of oceanic water currents , below 400m is driven by thermohaline circulation(density driven)

Risø DTU, Technical University of Denmark

Prospects of Large Floating VAWT 20-01-2011

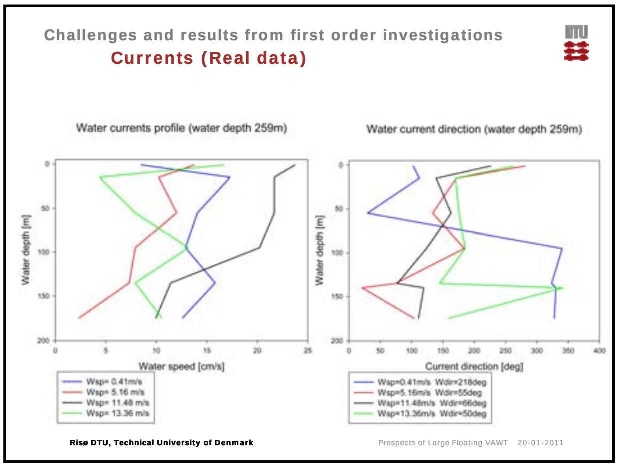
Challenges and results from first order investigations

Currents (Real data)

Sletringen site (Thanks to Joachim Reuder and OCEANOR)

Risø DTU, Technical University of Denmark

Prospects of Large Floating VAWT 20-01-2011

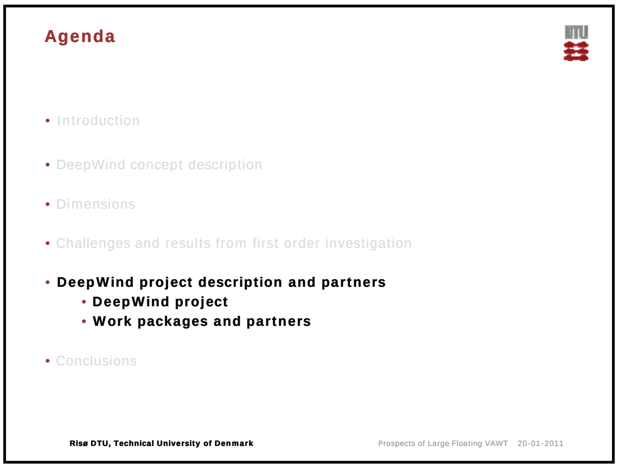


Challenges and results from first order investigations

Currents (Real data)

Risø DTU, Technical University of Denmark

Prospects of Large Floating VAWT 20-01-2011



Agenda

- Introduction
- DeepWind concept description
- Dimensions
- Challenges and results from first order investigation
- **DeepWind project description and partners**
  - **DeepWind project**
  - **Work packages and partners**
- Conclusions

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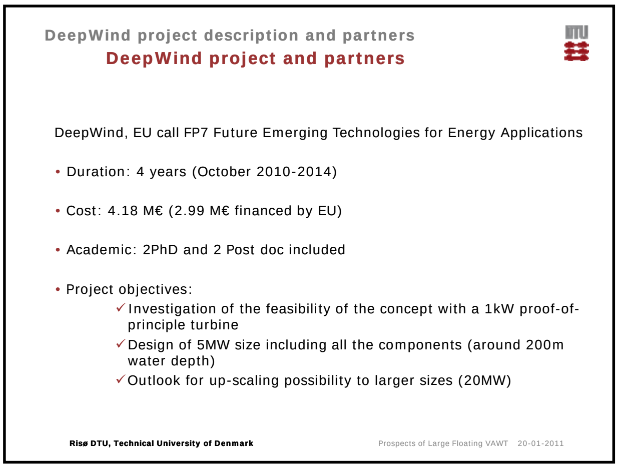
Prospects of Large Floating VAWT 20-01-2011



DeepWind project description and partners

DeepWind project and partners

DeepWind, EU call FP7 Future Emerging Technologies for Energy Applications

- Duration: 4 years (October 2010-2014)
- Cost: 4.18 M€ (2.99 M€ financed by EU)
- Academic: 2PhD and 2 Post doc included
- Project objectives:
  - ✓Investigation of the feasibility of the concept with a 1kW proof-of-principle turbine
  - ✓Design of 5MW size including all the components (around 200m water depth)
  - ✓Outlook for up-scaling possibility to larger sizes (20MW)

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Prospects of Large Floating VAWT 20-01-2011

DeepWind project description and partners

DeepWind project and partners

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

Partners:

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

Advisory board:

- ✓L.O.R.C., DNV, Grontmij CarlBro, DS SM A/S, Vatenfall, Vertax Wind LtD

Agenda

- Introduction
- DeepWind concept desctription
- Dimensions
- Challenges and results from first order investigation
- DeepWind project description and partners
- **Conclusions**

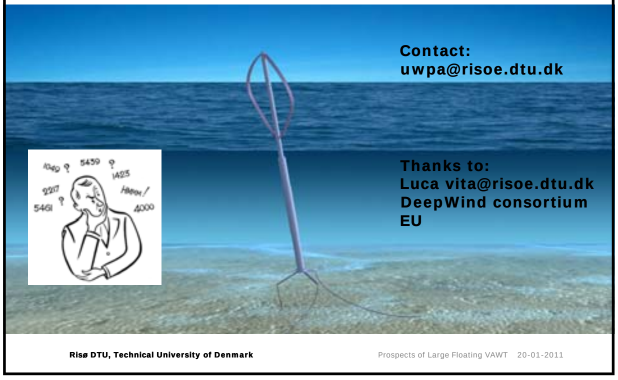
Conclusions

Preliminary conclusions and next steps

- DeepWind aim is to address a solution for offshore wind power at deep sea
- Hydrodynamics forces seem to be dominant in the analysis of the concept
- The choice of the site is crucial for DeepWind concept; a thorough investigation of the met-ocean data at the site is needed
- The simplicity of the design can allow some adaptation strategies to particular sites, if previously investigated
- DeepWind has potential for large up-scaling
- Specific challenges will be investigated in the WPs
- A first experimental study on a small demonstrator will be carried out at Risø fjord at the end of the year

Conclusions

Questions and discussion



Contact:
uwpa@risoe.dtu.dk

Thanks to:
Luca vita@risoe.dtu.dk
DeepWind consortium
EU

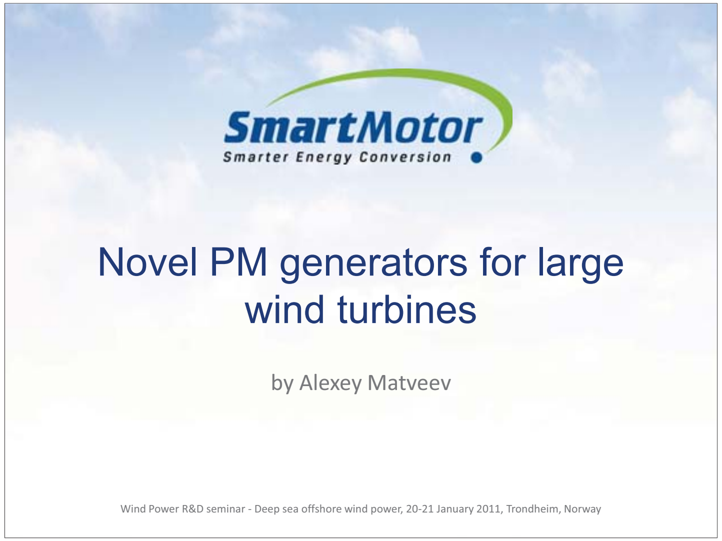
A2) New turbine technology

Novel PM generators for large wind turbines, Alexey Matveev, SmartMotor

Novel methodology for fatigue design of wind turbine components of ductile cast iron, Prof Gunnar Härkegård, NTNU

New power electronic schemes for large wind turbines,
Prof Marta Molinas, NTNU

Standard for floating wind turbine structures,
Johan Sandberg, DNV



SmartMotor
Smarter Energy Conversion

Novel PM generators for large wind turbines

by Alexey Matveev

Wind Power R&D seminar - Deep sea offshore wind power, 20-21 January 2011, Trondheim, Norway

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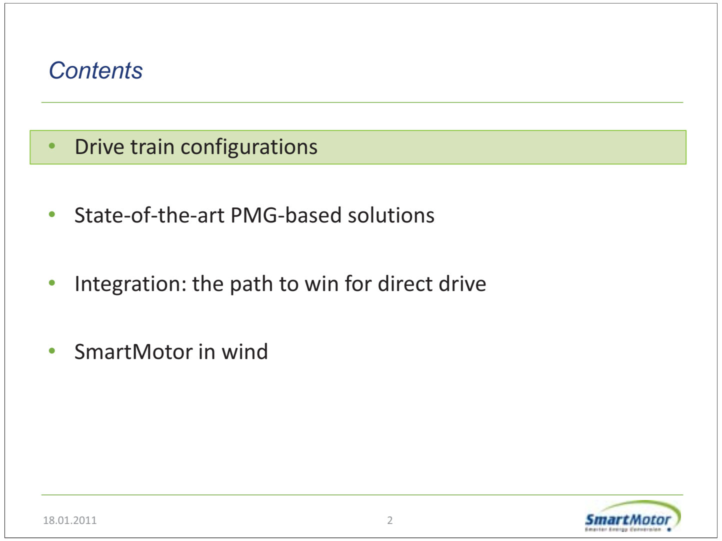
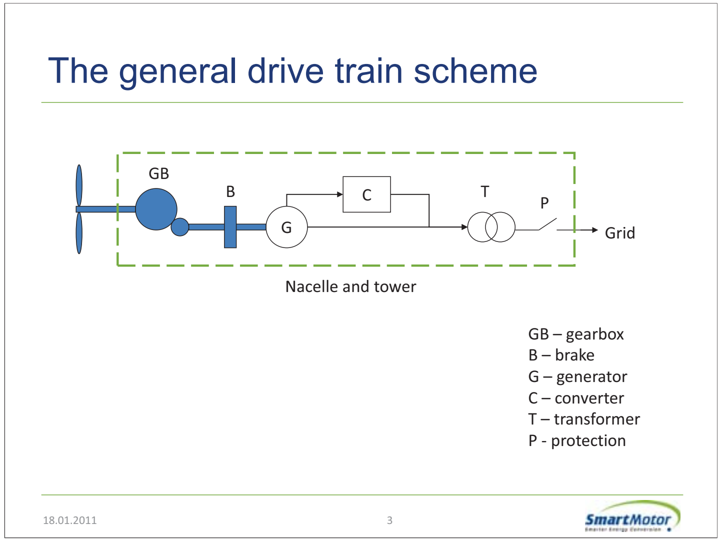


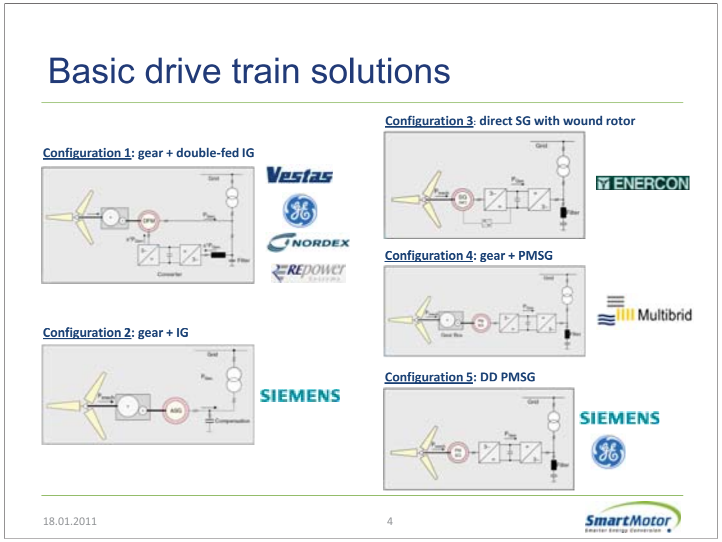
Contents

- Drive train configurations
- State-of-the-art PMG-based solutions
- Integration: the path to win for direct drive
- SmartMotor in wind



The general drive train scheme

GB – gearbox
B – brake
G – generator
C – converter
T – transformer
P - protection



Basic drive train solutions

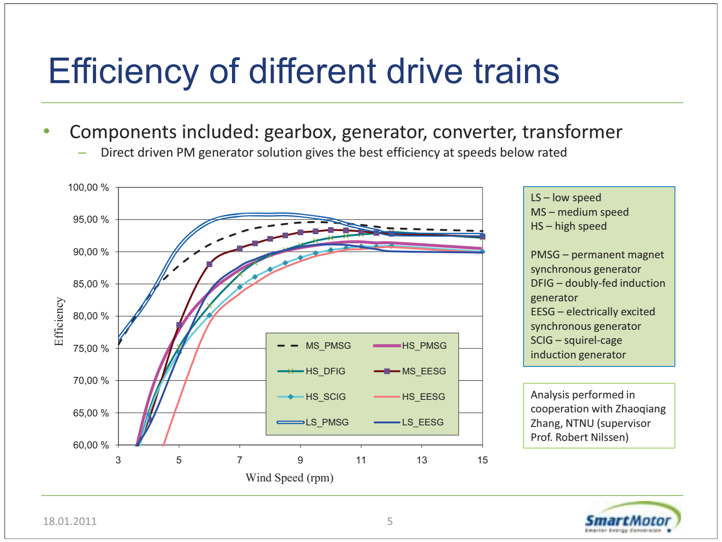
Configuration 1: gear + double-fed IG

Configuration 2: gear + IG

Configuration 3: direct SG with wound rotor

Configuration 4: gear + PMSG

Configuration 5: DD PMSG



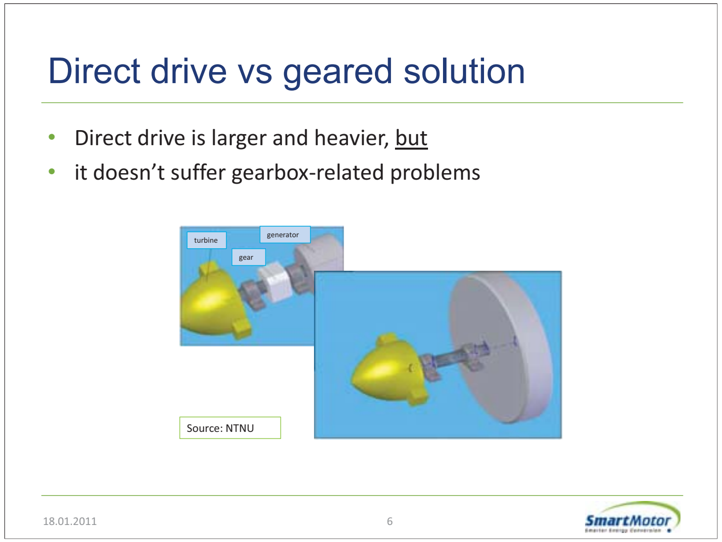
Efficiency of different drive trains

- Components included: gearbox, generator, converter, transformer
  - Direct driven PM generator solution gives the best efficiency at speeds below rated

LS – low speed
MS – medium speed
HS – high speed

PMSG – permanent magnet synchronous generator
DFIG – doubly-fed induction generator
EESG – electrically excited synchronous generator
SCIG – squirel-cage induction generator

Analysis performed in cooperation with Zhaoqiang Zhang, NTNU (supervisor Prof. Robert Nilssen)



Direct drive vs geared solution

- Direct drive is larger and heavier, but
- it doesn't suffer gearbox-related problems

Source: NTNU

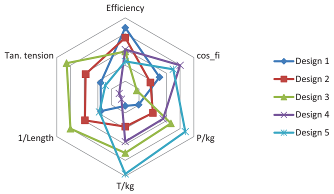
High-torque generator for direct drive

- High-torque generator for direct drive is large. This is basically the only drawback of direct drive solution

PM generator from Siemens. 3 MW, 17 rpm

Some conclusions

- Drive trains with PM generators have the best efficiency
  - Especially without gear (direct drive) and 1-stage gear
- <u>However</u>, there are other characteristics to take into account:
  - Weight
  - Cost
  - Power factor
  - Lifetime
  - Reliability
  - Manufacturability
  - ...

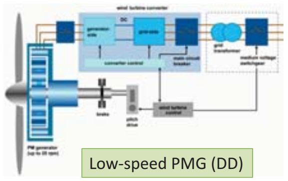


- Design means finding a trade-off between various criteria

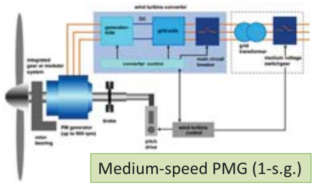
...next part

- Drive train configurations
- State-of-the-art PMG-based solutions
- Integration: the path to win for direct drive
- SmartMotor in wind

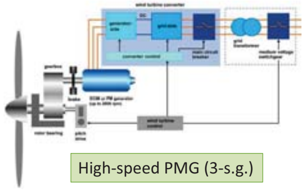
Available solutions with PMG



Low-speed PMG (DD)



Medium-speed PMG (1-s.g.)



High-speed PMG (3-s.g.)

Products of ABB and TheSwitch

- Low-speed, medium-speed and high-speed generators

<1 MW
<2000 rpm

<3.3 MW
<300 rpm

<4.25 MW
<20 rpm

Commercial power electronics

- Examples of medium-voltage (ABB) and low-voltage (TheSwitch) converters

ABB

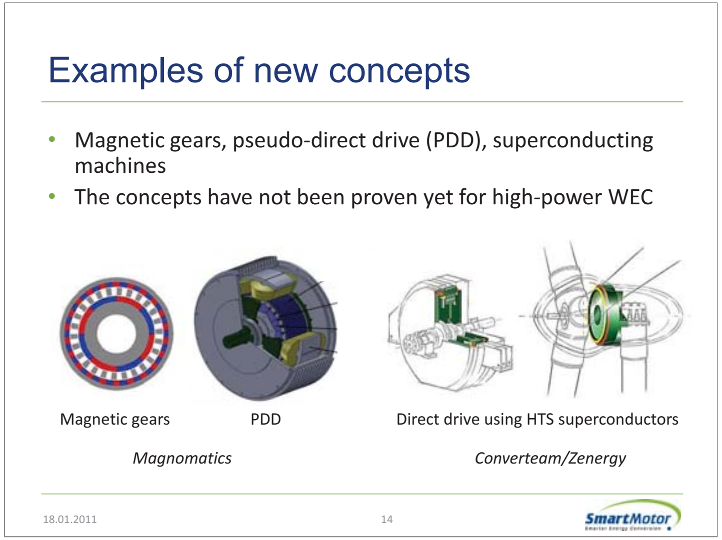
TheSwitch

Is it end of the story?

- Big companies have products and even complete packages up to approximately 5-7 MW. Is it end of the development?

NO!!!

- New concepts under investigation, for example:
  - Magnetic gears and Pseudo-direct drive
  - Superconducting machines
- There are problems when going to powers higher then 5-7 MW. These are to be solved!



Examples of new concepts

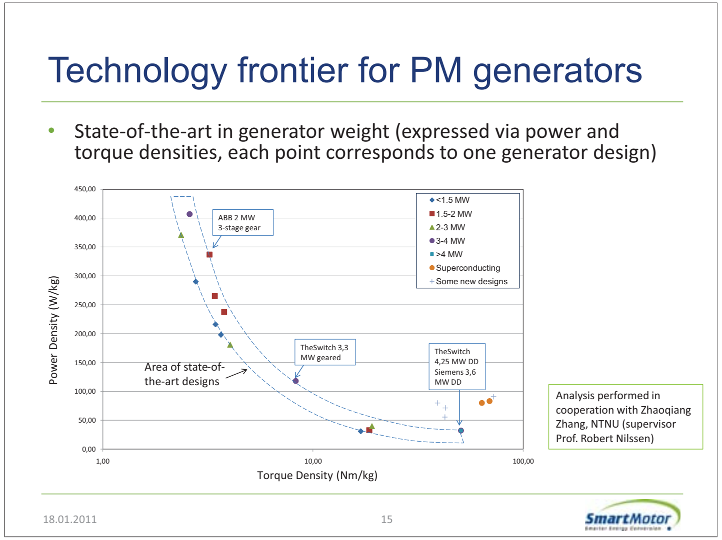
- Magnetic gears, pseudo-direct drive (PDD), superconducting machines
- The concepts have not been proven yet for high-power WEC

Magnetic gears PDD

Magnomatics

Direct drive using HTS superconductors

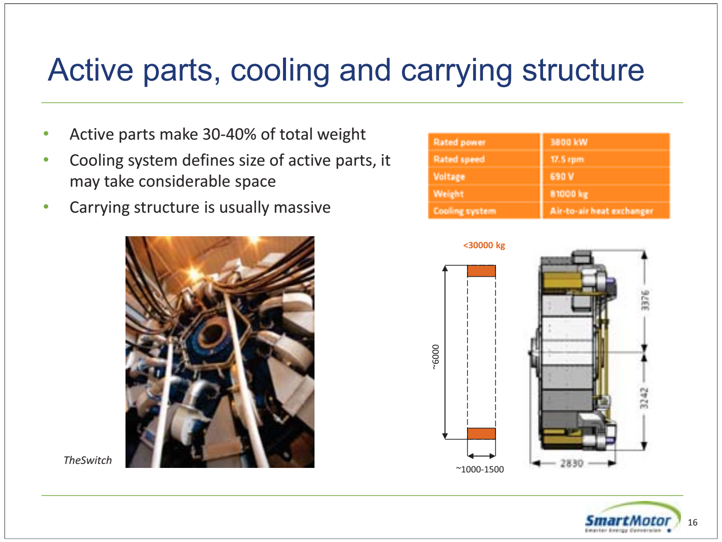
Converteam/Zenergy



Technology frontier for PM generators

- State-of-the-art in generator weight (expressed via power and torque densities, each point corresponds to one generator design)

Analysis performed in cooperation with Zhaoqiang Zhang, NTNU (supervisor Prof. Robert Nilssen)

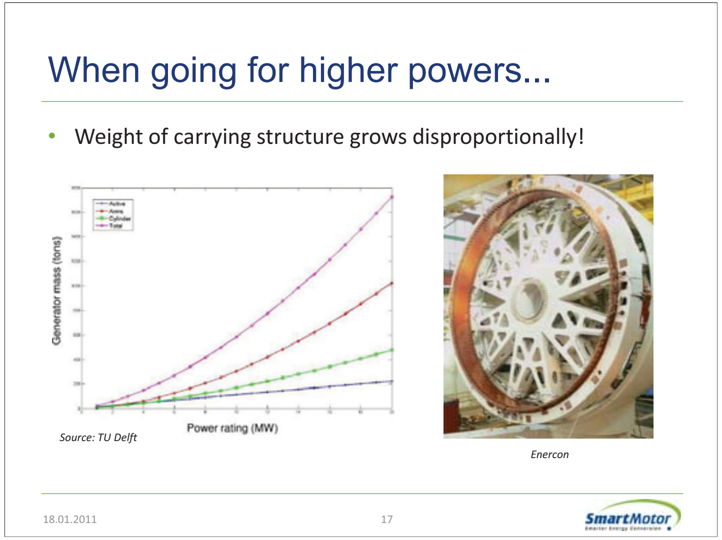


Active parts, cooling and carrying structure

- Active parts make 30-40% of total weight
- Cooling system defines size of active parts, it may take considerable space
- Carrying structure is usually massive

Rated power	3800 kW
Rated speed	17.5 rpm
Voltage	690 V
Weight	81000 kg
Cooling system	Air-to-air heat exchanger

TheSwitch



When going for higher powers...

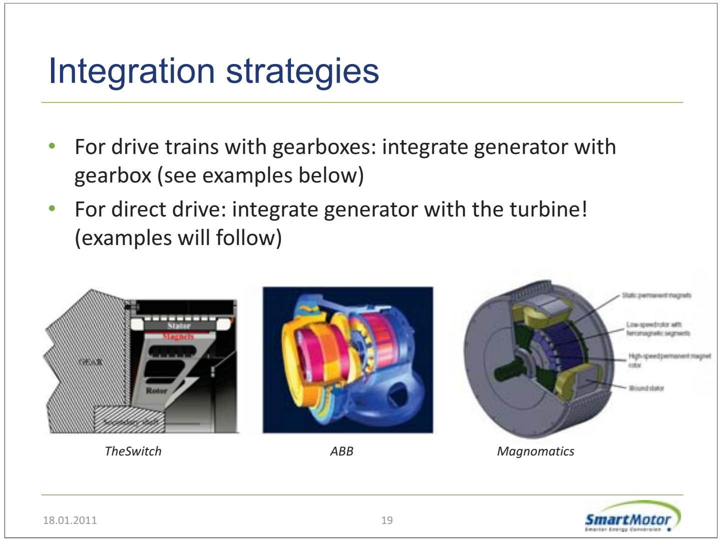
- Weight of carrying structure grows disproportionally!

Source: TU Delft

Enercon

...next part

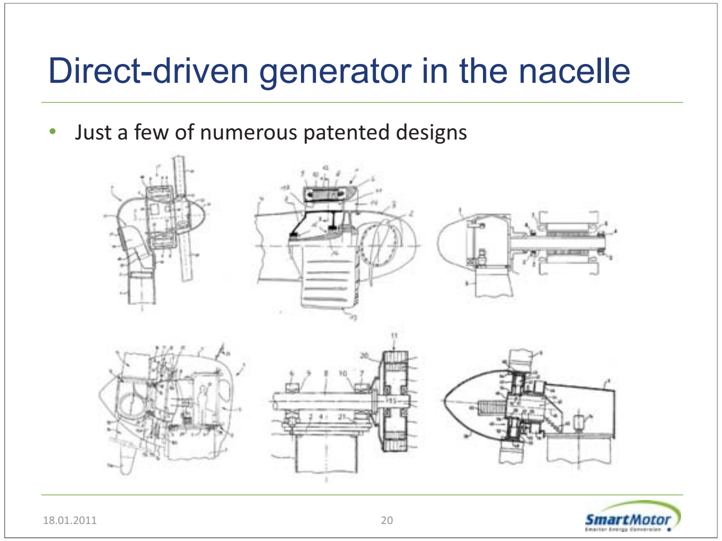
- Drive train configurations
- State of the art PMG-based solutions
- Integration: the path to win for direct drive
- SmartMotor in wind



Integration strategies

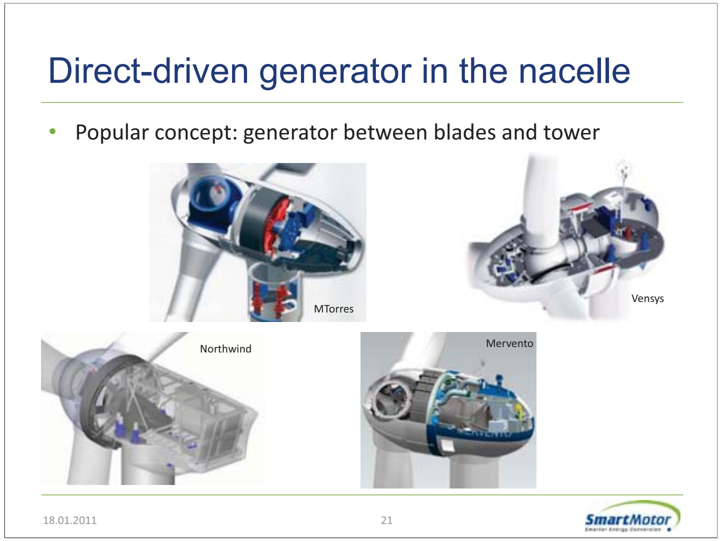
- For drive trains with gearboxes: integrate generator with gearbox (see examples below)
- For direct drive: integrate generator with the turbine! (examples will follow)

TheSwitch *ABB* *Magnomatics*



Direct-driven generator in the nacelle

- Just a few of numerous patented designs



Direct-driven generator in the nacelle

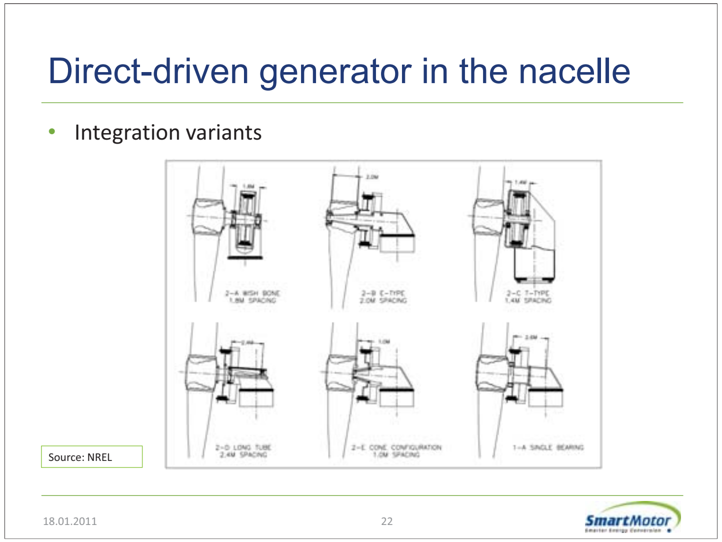
- Popular concept: generator between blades and tower

MTorres

Vensys

Northwind

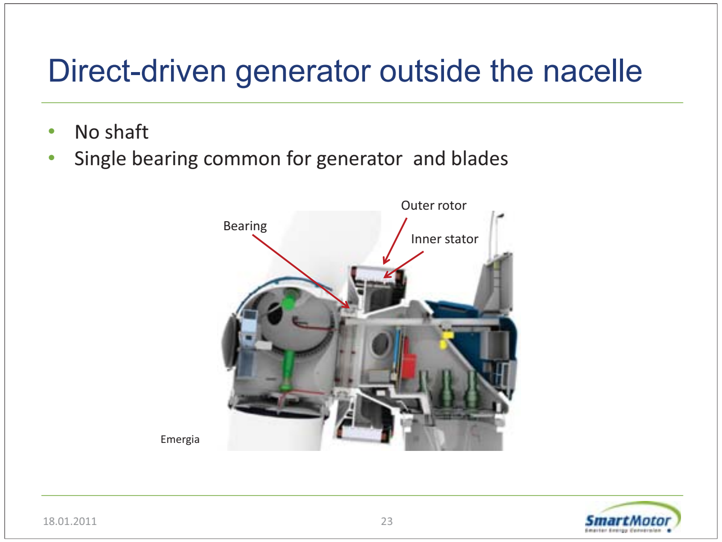
Mervento



Direct-driven generator in the nacelle

- Integration variants

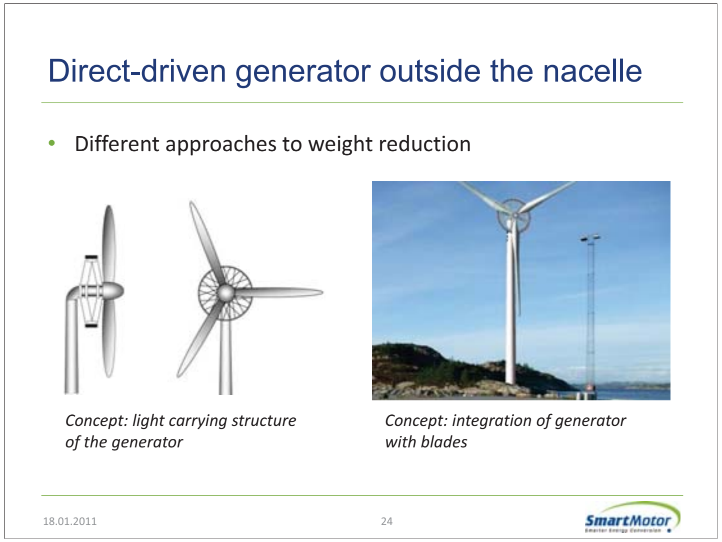
Source: NREL



Direct-driven generator outside the nacelle

- No shaft
- Single bearing common for generator and blades

Emergia

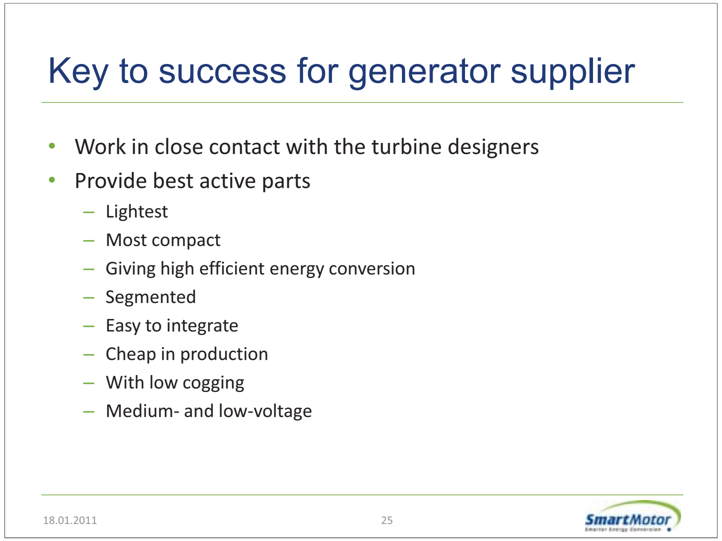


Direct-driven generator outside the nacelle

- Different approaches to weight reduction

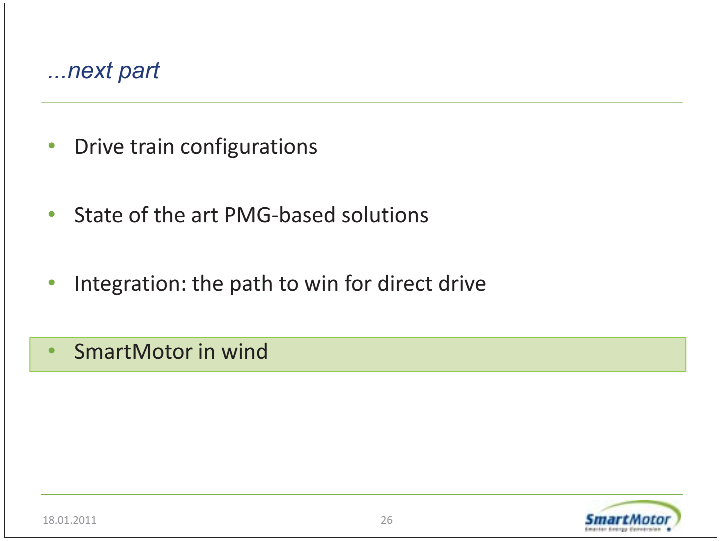
Concept: light carrying structure of the generator

Concept: integration of generator with blades



Key to success for generator supplier

- Work in close contact with the turbine designers
- Provide best active parts
  - Lightest
  - Most compact
  - Giving high efficient energy conversion
  - Segmented
  - Easy to integrate
  - Cheap in production
  - With low cogging
  - Medium- and low-voltage

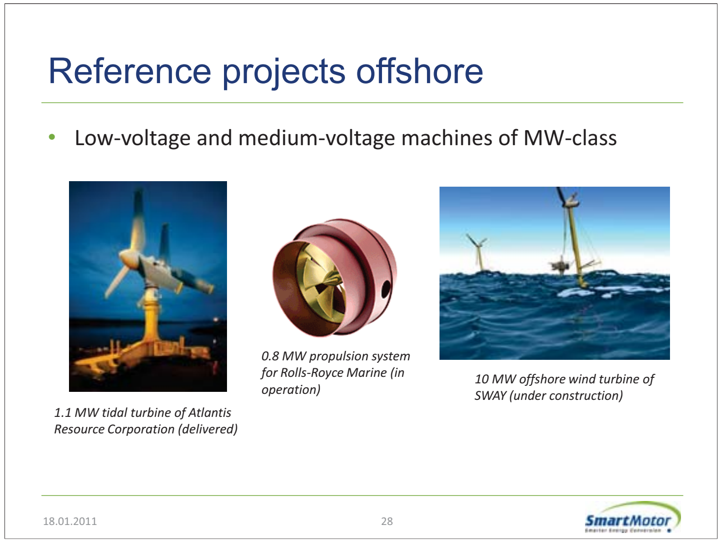


...next part

- Drive train configurations
- State of the art PMG-based solutions
- Integration: the path to win for direct drive
- SmartMotor in wind

What is SmartMotor

- Established in 1996 in Trondheim, Norway
- One of the largest R&D groups in the world with focus on PM technology



Reference projects offshore

- Low-voltage and medium-voltage machines of MW-class

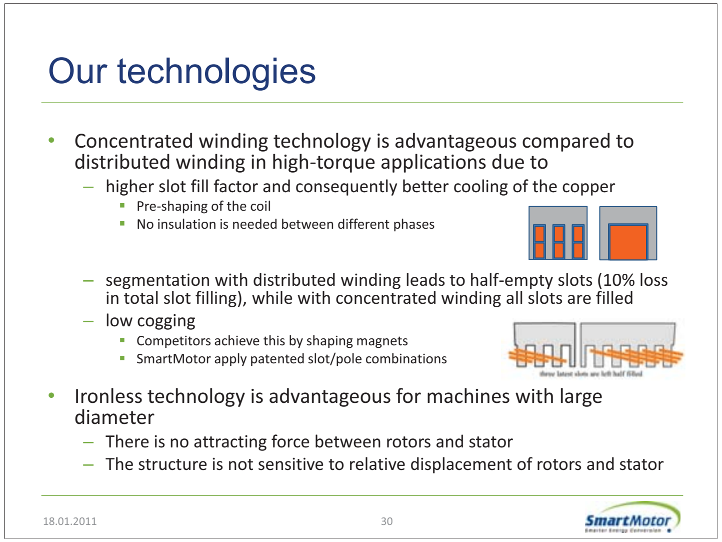
1.1 MW tidal turbine of Atlantis Resource Corporation (delivered)

0.8 MW propulsion system for Rolls-Royce Marine (in operation)

10 MW offshore wind turbine of SWAY (under construction)

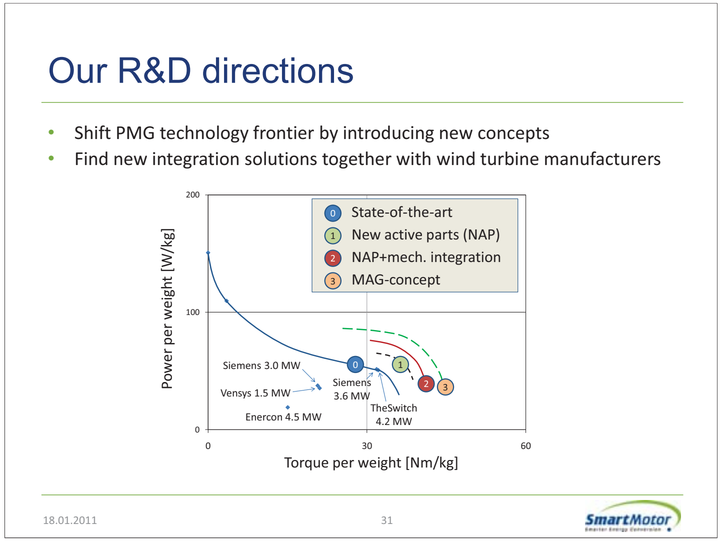
The technologies we believe in

- PM machines with concentrated winding and ironless machines
- Ideal for high-torque applications like wind turbines with direct drive



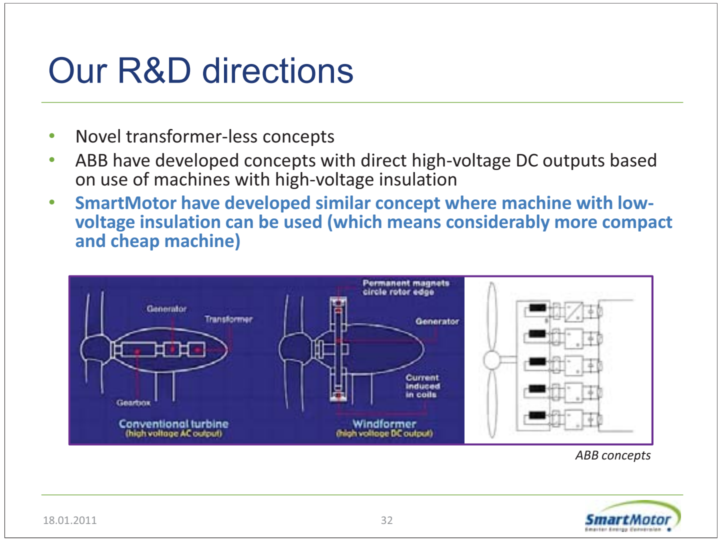
Our technologies

- Concentrated winding technology is advantageous compared to distributed winding in high-torque applications due to
  - higher slot fill factor and consequently better cooling of the copper
    - Pre-shaping of the coil
    - No insulation is needed between different phases
  - segmentation with distributed winding leads to half-empty slots (10% loss in total slot filling), while with concentrated winding all slots are filled
  - low cogging
    - Competitors achieve this by shaping magnets
    - SmartMotor apply patented slot/pole combinations
- Ironless technology is advantageous for machines with large diameter
  - There is no attracting force between rotors and stator
  - The structure is not sensitive to relative displacement of rotors and stator



Our R&D directions

- Shift PMG technology frontier by introducing new concepts
- Find new integration solutions together with wind turbine manufacturers



Our R&D directions

- Novel transformer-less concepts
- ABB have developed concepts with direct high-voltage DC outputs based on use of machines with high-voltage insulation
- **SmartMotor have developed similar concept where machine with low-voltage insulation can be used (which means considerably more compact and cheap machine)**

ABB concepts

...the end)

Thank you!

Contact information: alexey@smartmotor.no, www.smartmotor.no

Wind Power R&D Seminar
Trondheim, 20 January 2011

Novel Methodology for Fatigue Design of Wind Turbine Components of Ductile Cast Iron

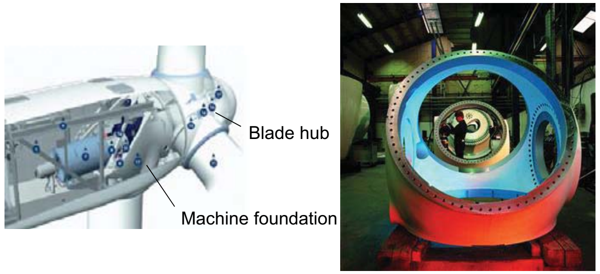
Gunnar Härkegård
Department of Engineering Design and Materials
NTNU, Trondheim

Acknowledgement

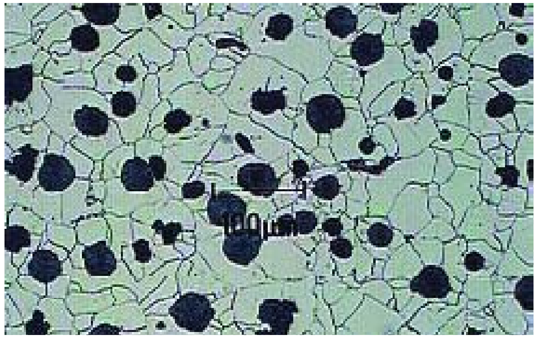
This presentation is based on

- a methodology and its implementation in the FEA based fatigue post-processor P•FAT developed at NTNU/IPM (2003–2007) by Arne Fjeldstad and Anders Wormsen, and
- comprehensive fatigue testing in the SINTEF-led BIA project FeVIND (2007–2010) supported by NRC, Siemens Wind, Vestas, Rolls-Royce, Elkem and Tinfos/Eramet; planning and evaluation are mainly due to Mehdi Shirani.

3 MW wind turbine with components made of ductile cast iron EN-GJS-400-18-LT

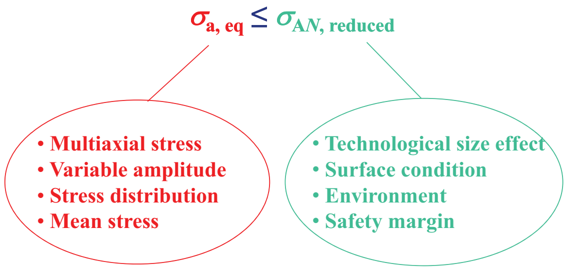


Ductile cast iron GJS-400 with spheroidal graphite nodules in a ferritic matrix



FATIGUE DESIGN

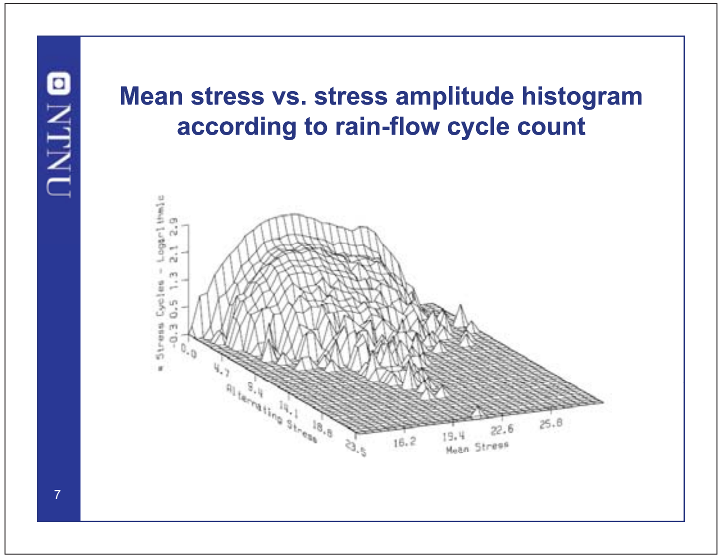
Traditional fatigue design



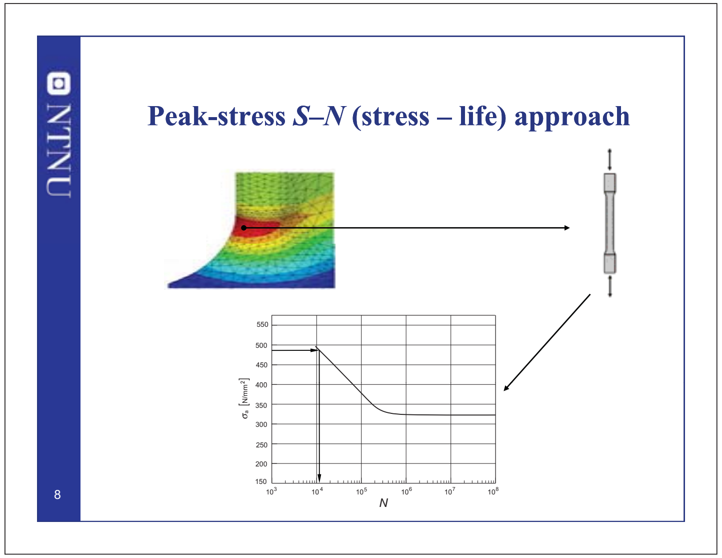
$$\sigma_{\mathbf{a,\,eq}} \leq \sigma_{AN,\ \mathbf{reduced}}$$

- Multiaxial stress
- Variable amplitude
- Stress distribution
- Mean stress

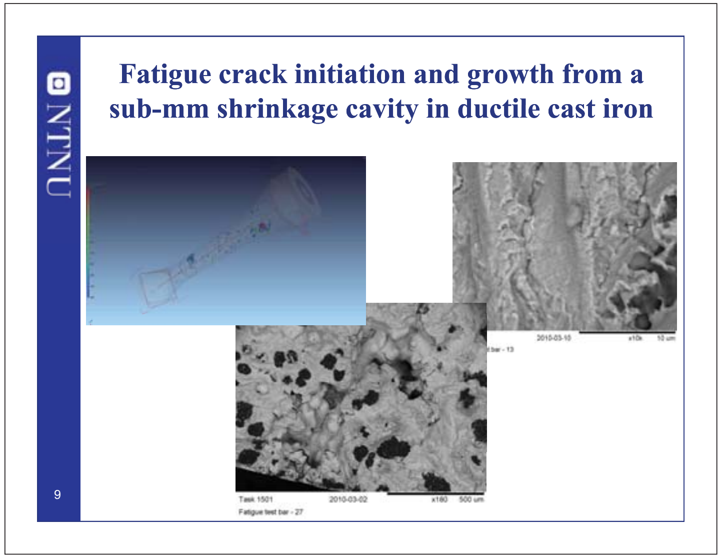
- Technological size effect
- Surface condition
- Environment
- Safety margin



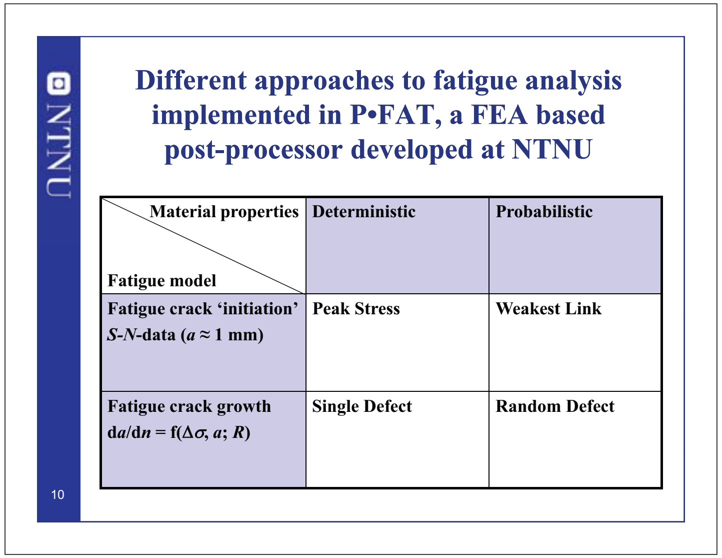
Mean stress vs. stress amplitude histogram according to rain-flow cycle count



Peak-stress *S–N* (stress – life) approach

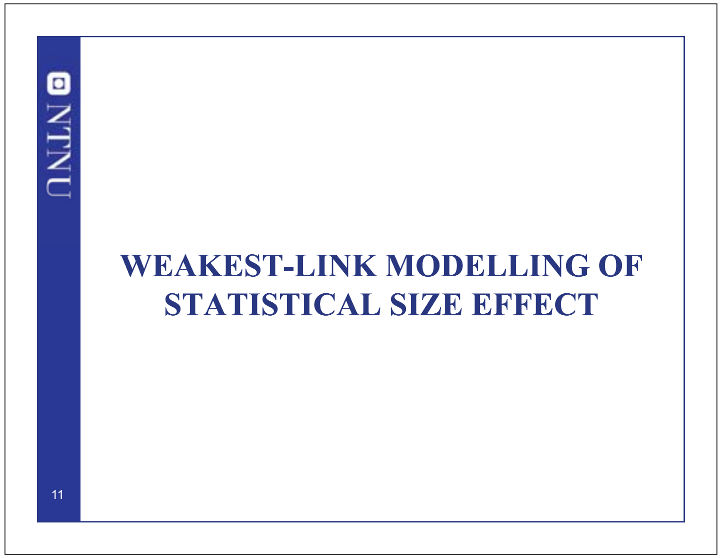


Fatigue crack initiation and growth from a sub-mm shrinkage cavity in ductile cast iron

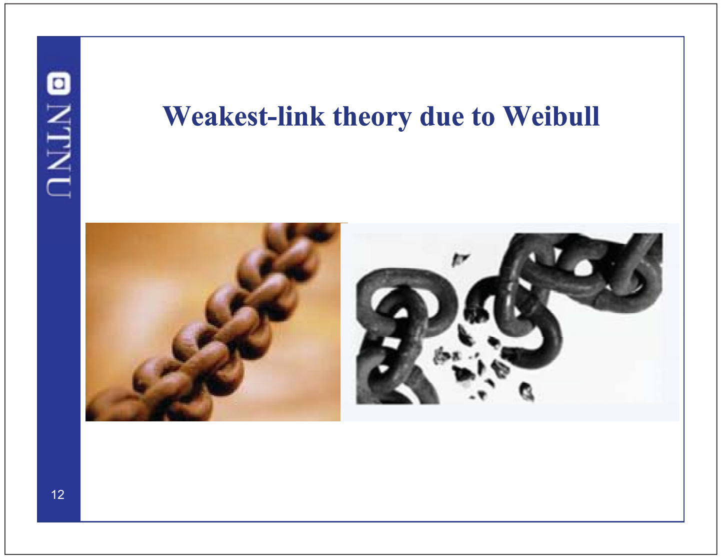


Different approaches to fatigue analysis implemented in P•FAT, a FEA based post-processor developed at NTNU

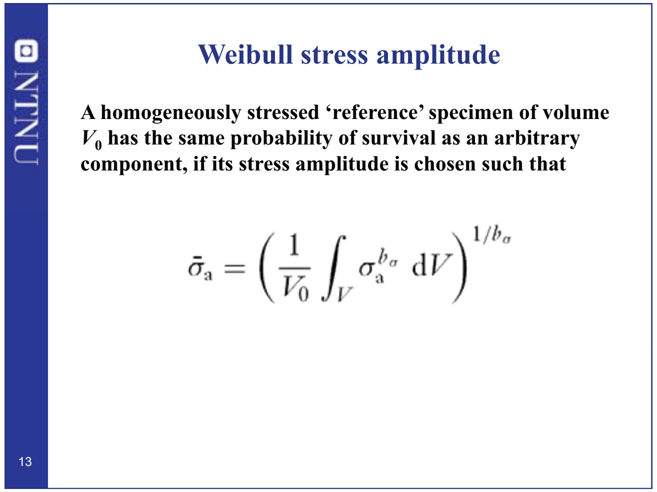
Material properties / Fatigue model	Deterministic	Probabilistic
Fatigue crack 'initiation' *S-N*-data (*a* ≈ 1 mm)	Peak Stress	Weakest Link
Fatigue crack growth d*a*/d*n* = f(Δσ, *a*; *R*)	Single Defect	Random Defect



WEAKEST-LINK MODELLING OF STATISTICAL SIZE EFFECT



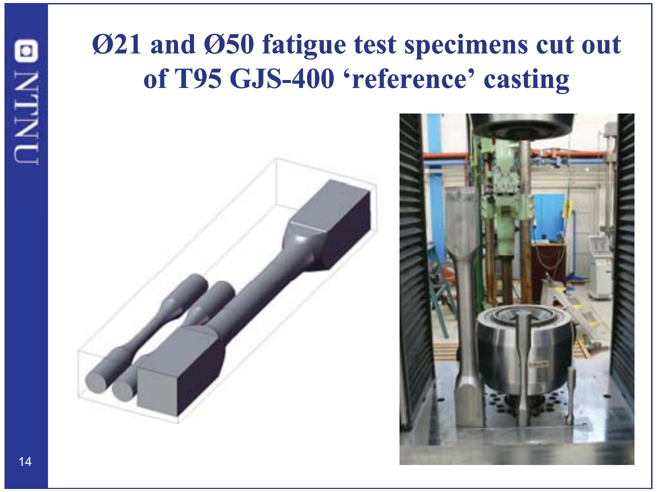
Weakest-link theory due to Weibull



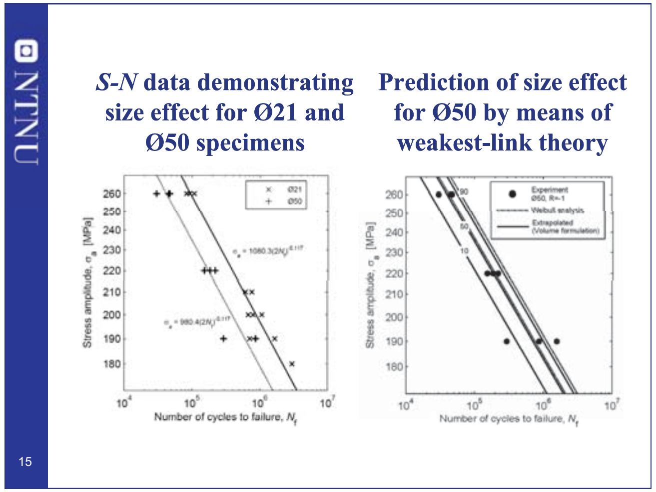
Weibull stress amplitude

A homogeneously stressed 'reference' specimen of volume V_0 has the same probability of survival as an arbitrary component, if its stress amplitude is chosen such that

$$\bar{\sigma}_{\mathrm{a}} = \left(\frac{1}{V_0} \int_V \sigma_{\mathrm{a}}^{b_\sigma} \, \mathrm{d}V \right)^{1/b_\sigma}$$



Ø21 and Ø50 fatigue test specimens cut out of T95 GJS-400 'reference' casting

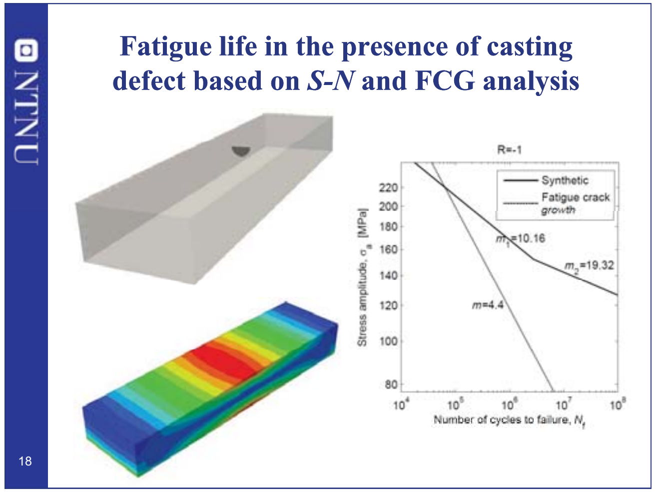


S-N data demonstrating size effect for Ø21 and Ø50 specimens

Prediction of size effect for Ø50 by means of weakest-link theory

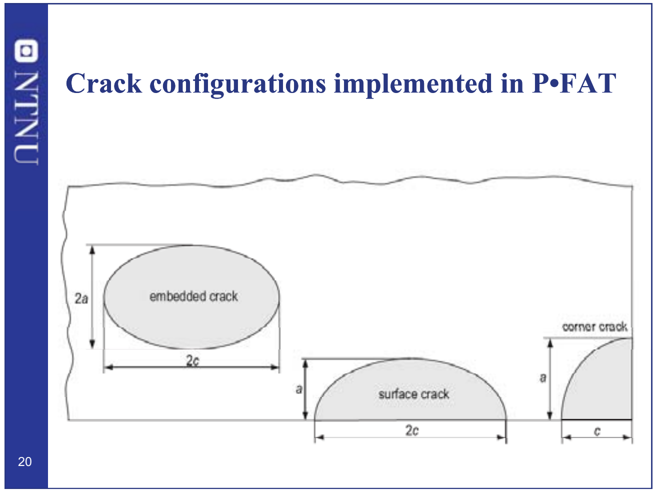
140 x 120 fatigue test specimens cut out of T150 GJS-400 'reference' casting

FATIGUE-CRACK GROWTH

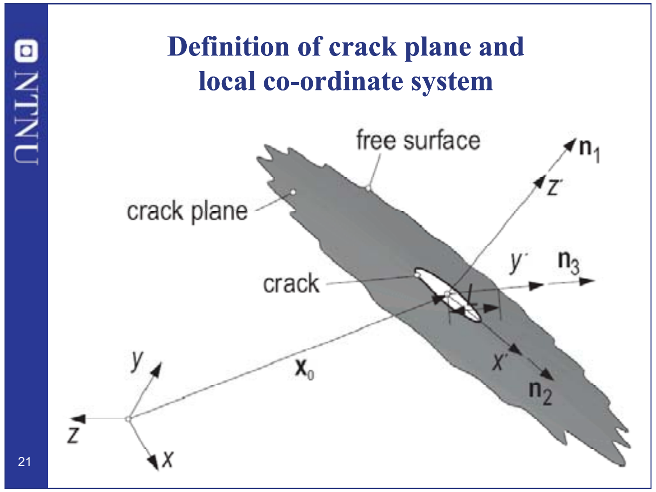


Fatigue life in the presence of casting defect based on *S-N* and FCG analysis

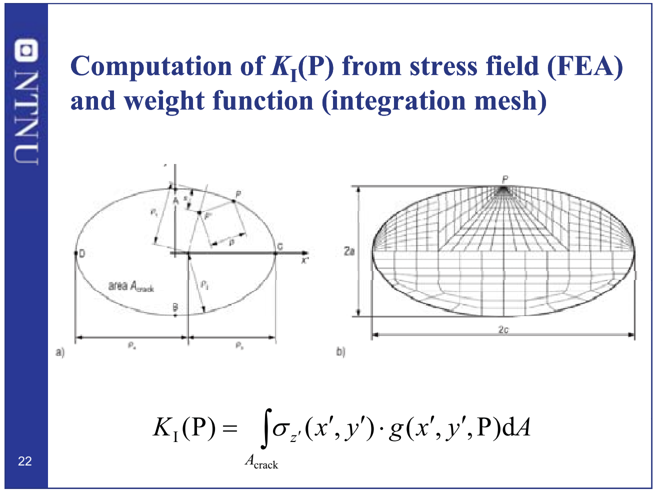
Single Defect



Crack configurations implemented in P•FAT

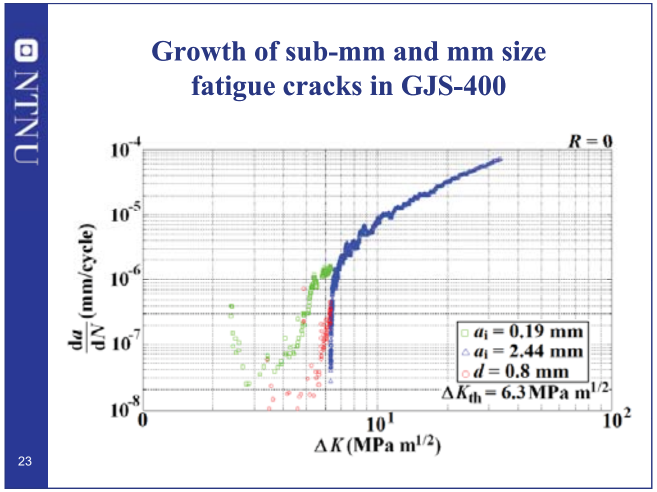


Definition of crack plane and local co-ordinate system



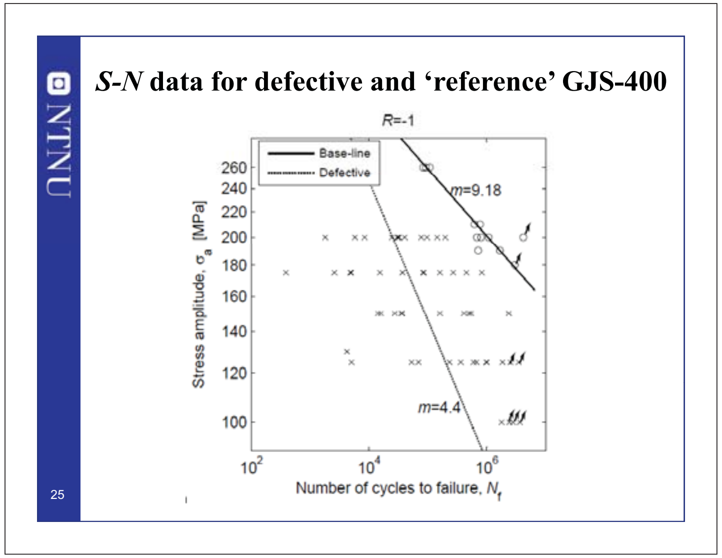
Computation of K_I(P) from stress field (FEA) and weight function (integration mesh)

$$K_I(\mathrm{P}) = \int_{A_{\mathrm{crack}}} \sigma_{z'}(x', y') \cdot g(x', y', \mathrm{P})\mathrm{d}A$$

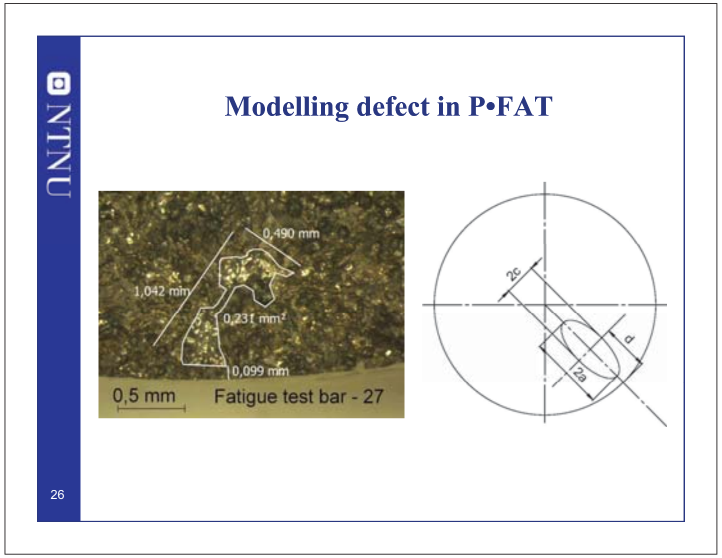


Growth of sub-mm and mm size fatigue cracks in GJS-400

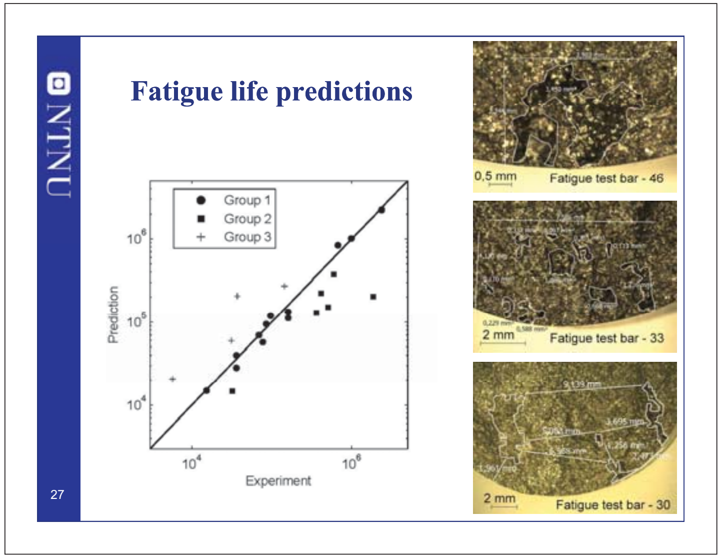
Samples cut out of a rejected hub



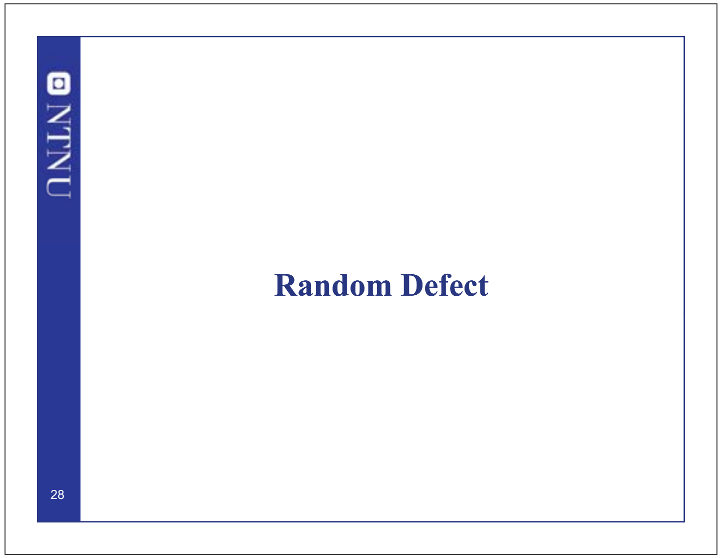
S-N data for defective and 'reference' GJS-400



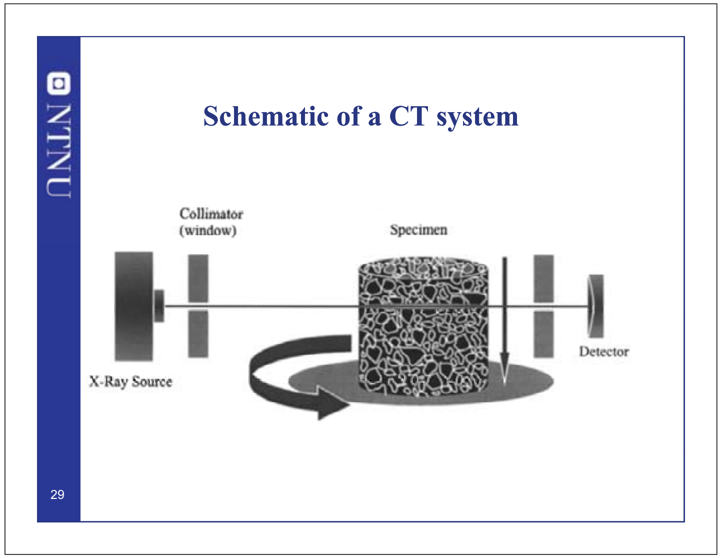
Modelling defect in P•FAT



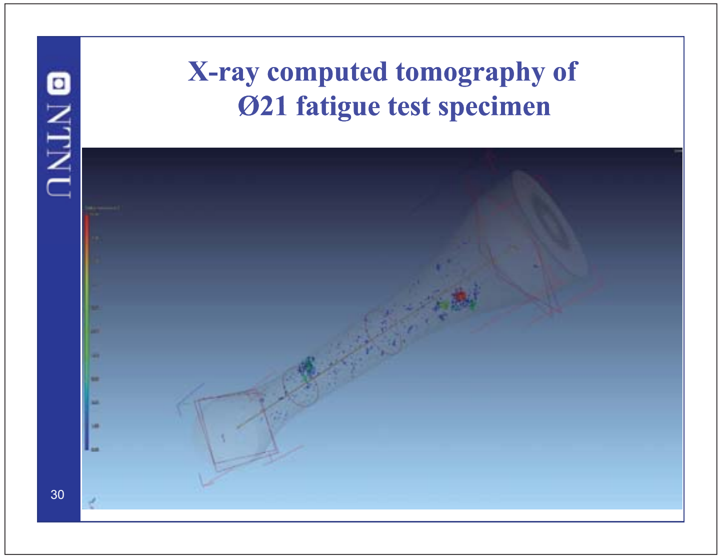
Fatigue life predictions



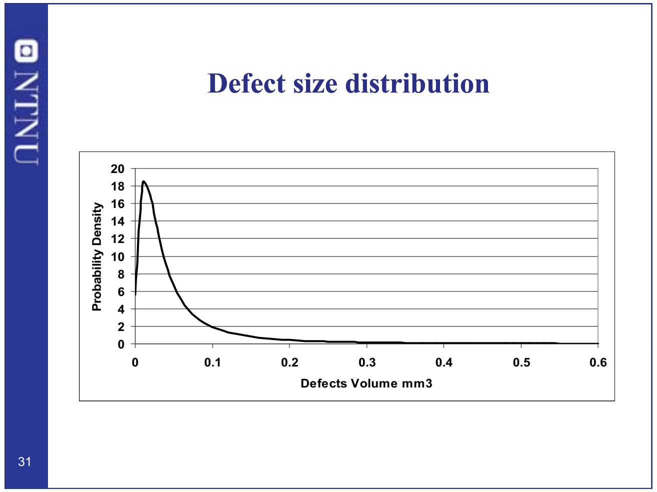
Random Defect



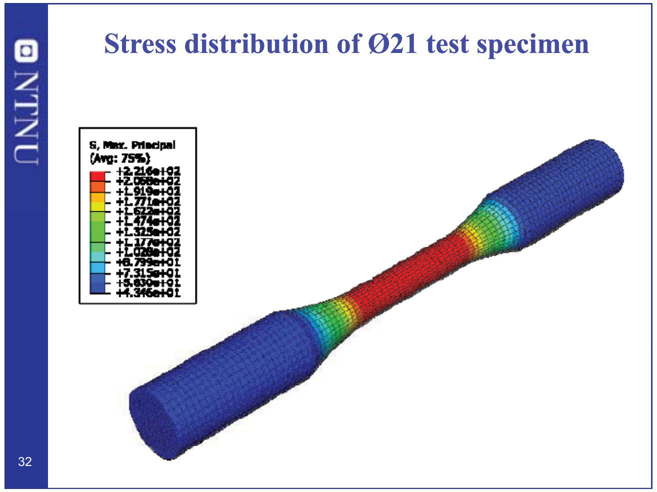
Schematic of a CT system



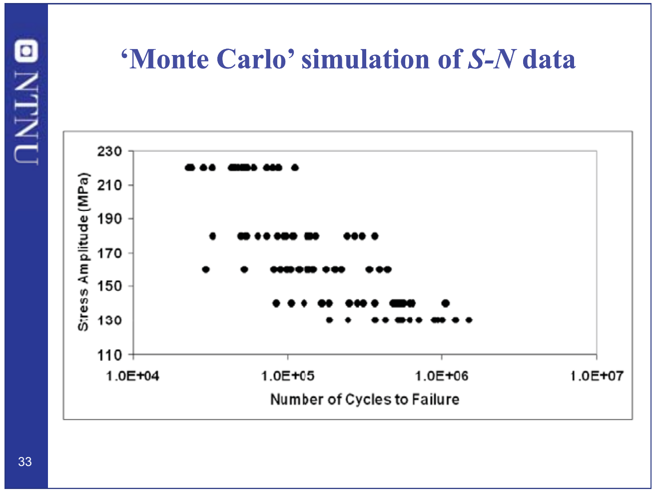
X-ray computed tomography of Ø21 fatigue test specimen



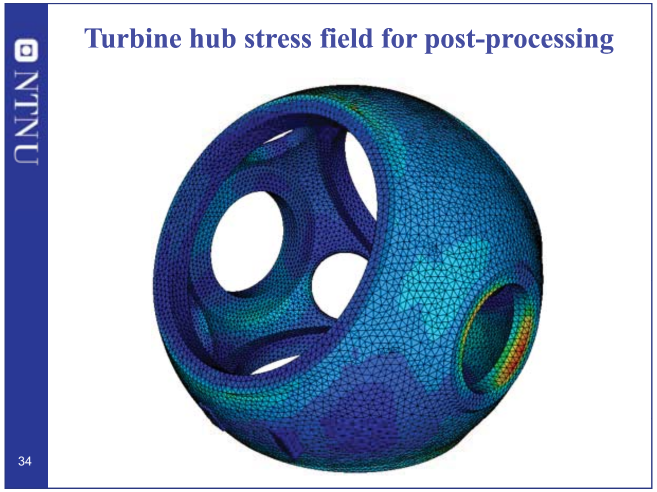
Defect size distribution



Stress distribution of Ø21 test specimen



‘Monte Carlo’ simulation of *S-N* data



Turbine hub stress field for post-processing

Fatigue assessment moving from empirical rules towards mechanism-based analysis

- ☐ Post-processing of the complete FEA stress field as opposed to empirical local-stress concepts
- ☐ Account for crack growth from material defects
  - ✓ NDE findings
  - ✓ statistical distribution
- ☐ Through-process modelling
  - ✓ casting
  - ✓ welding

International Symposium on Fatigue Design & Material Defects

Norwegian University of Science and Technology,
NTNU, Trondheim, Norway, 23–25 May 2011

Co-organised by the Swedish Fatigue Network, UTMIS

Welcome back to Trondheim in May 2011 to learn more about Fatigue & Defects!

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Offshore Wind Farm Research:

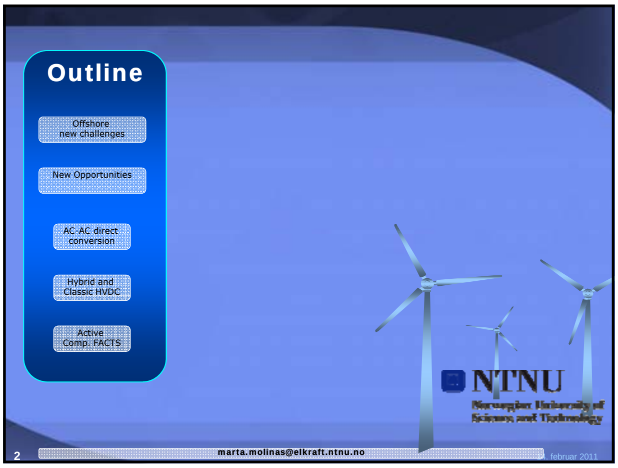
Quo Vadis?

Marta Molinas
Wind Seminar 2011

NTNU
Norwegian University of Science and Technology

1

14. februar 2011



Outline

- Offshore new challenges
- New Opportunities
- AC-AC direct conversion
- Hybrid and Classic HVDC
- Active Comp. FACTS

NTNU
Norwegian University of Science and Technology

2 marta.molinas@elkraft.ntnu.no februar 2011

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Outline

Offshore New Challenges

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Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Offshore new challenges

Investment
- Power density: weight and size
- Platforms

Operation
- Grid integration
- Reliability
- Efficiency

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Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Outline

New Opportunities

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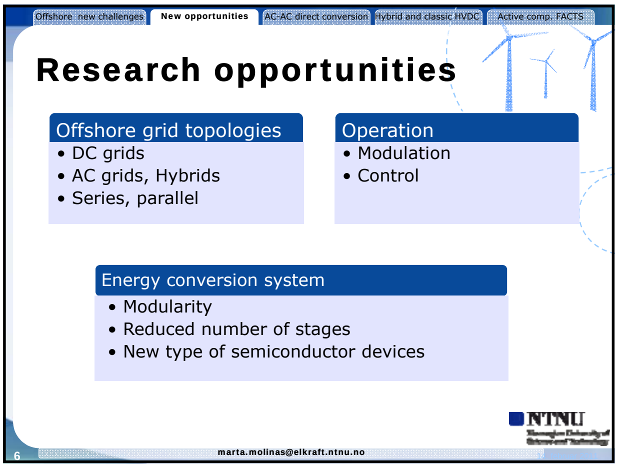

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Research opportunities

Offshore grid topologies
- DC grids
- AC grids, Hybrids
- Series, parallel

Operation
- Modulation
- Control

Energy conversion system
- Modularity
- Reduced number of stages
- New type of semiconductor devices

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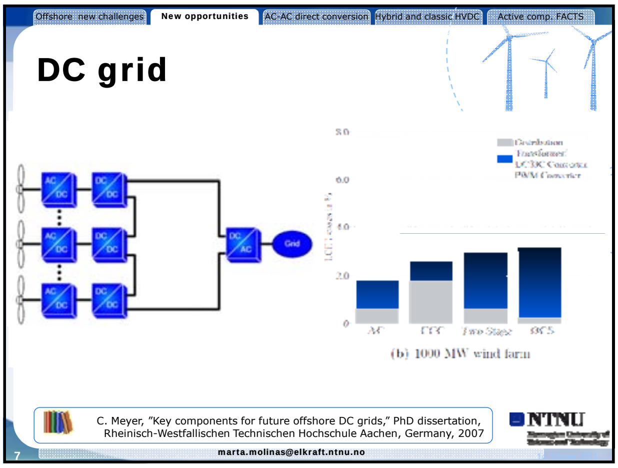
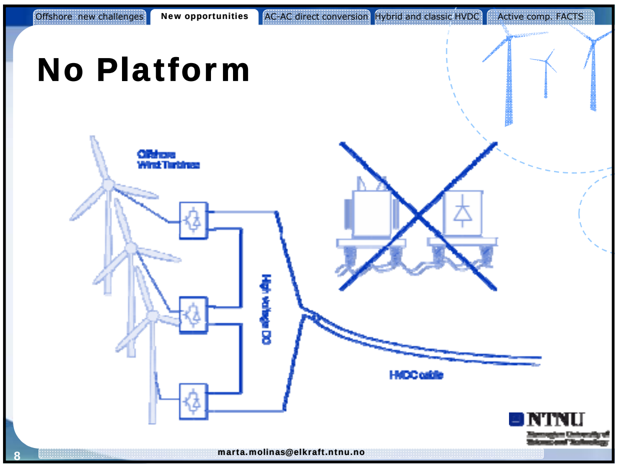


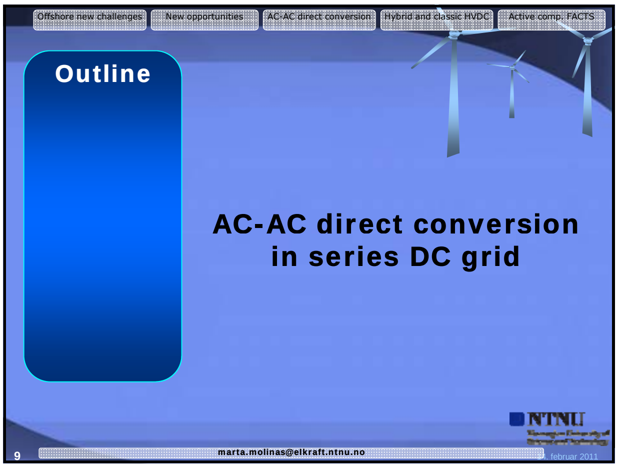
DC grid

(b) 1000 MW wind farm

C. Meyer, "Key components for future offshore DC grids," PhD dissertation, Rheinisch-Westfallischen Technischen Hochschule Aachen, Germany, 2007

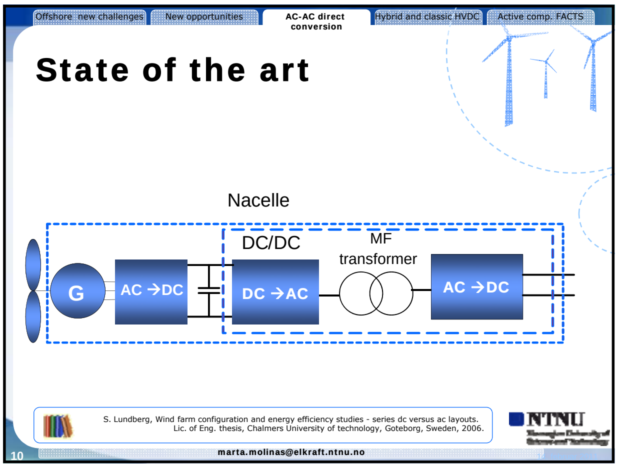


No Platform



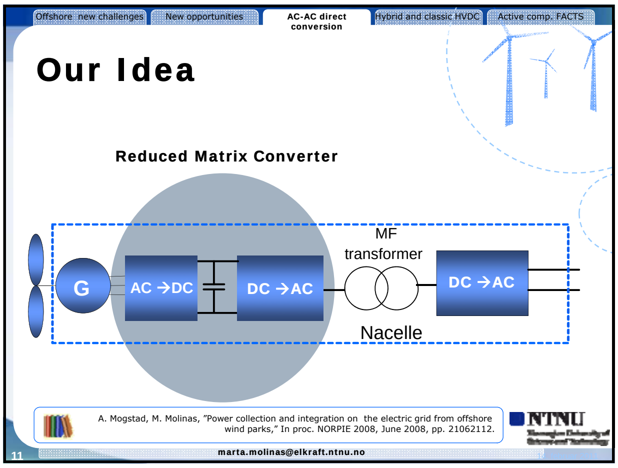
Outline

AC-AC direct conversion in series DC grid



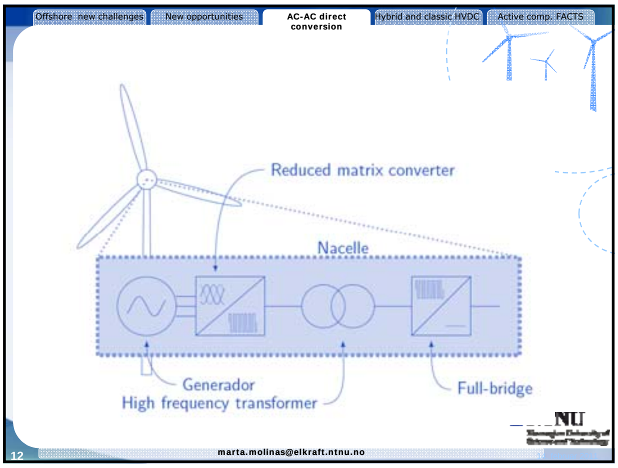
State of the art

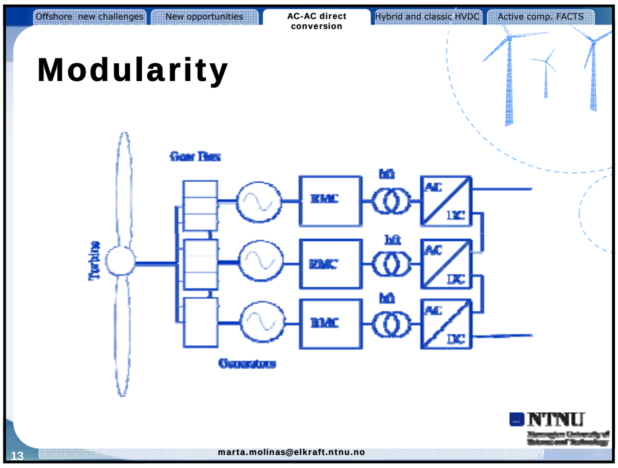
S. Lundberg, Wind farm configuration and energy efficiency studies - series dc versus ac layouts. Lic. of Eng. thesis, Chalmers University of technology, Goteborg, Sweden, 2006.



Our Idea

A. Mogstad, M. Molinas, "Power collection and integration on the electric grid from offshore wind parks," In proc. NORPIE 2008, June 2008, pp. 21062112.





Modularity

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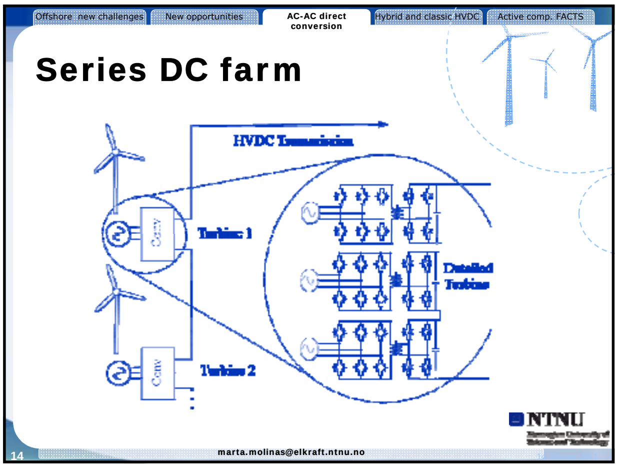

Series DC farm

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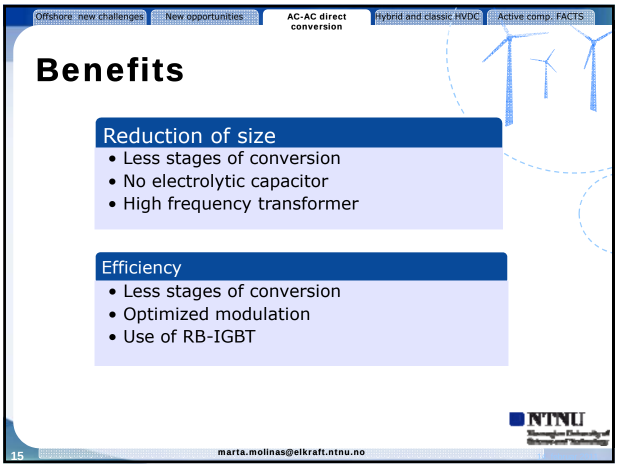

Benefits

Reduction of size

- Less stages of conversion
- No electrolytic capacitor
- High frequency transformer

Efficiency

- Less stages of conversion
- Optimized modulation
- Use of RB-IGBT

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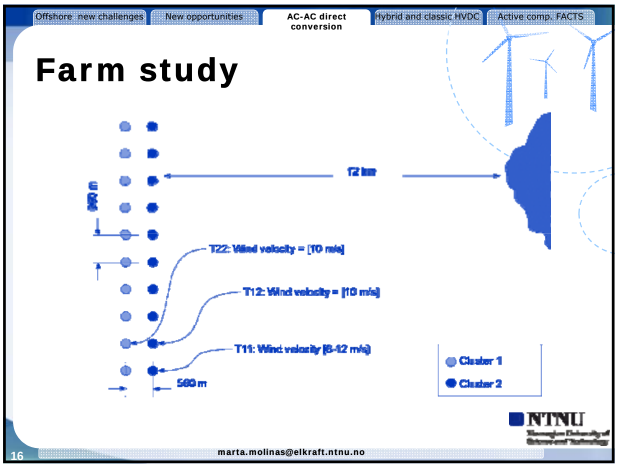

Farm study

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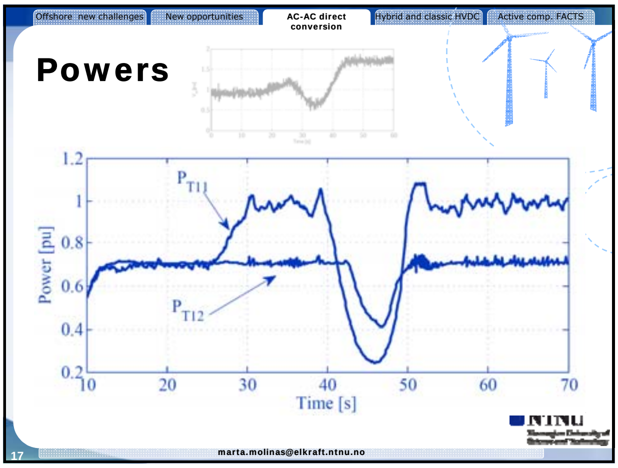

Powers

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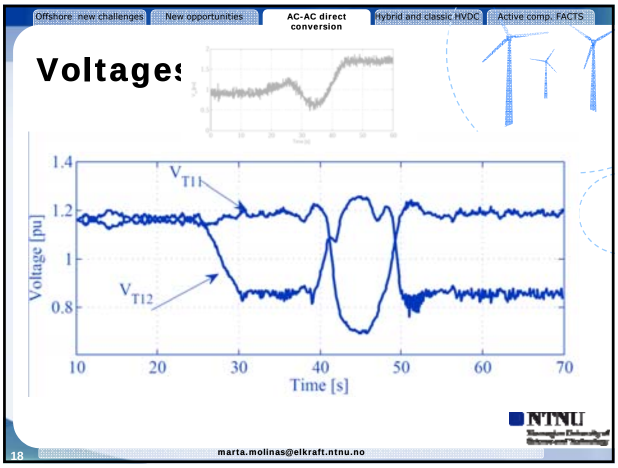

Voltage

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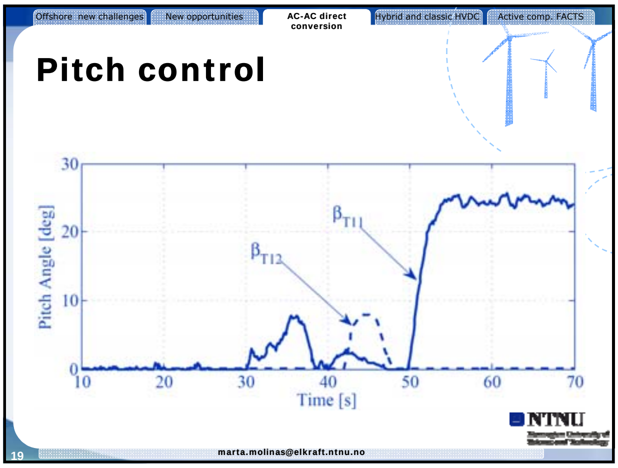
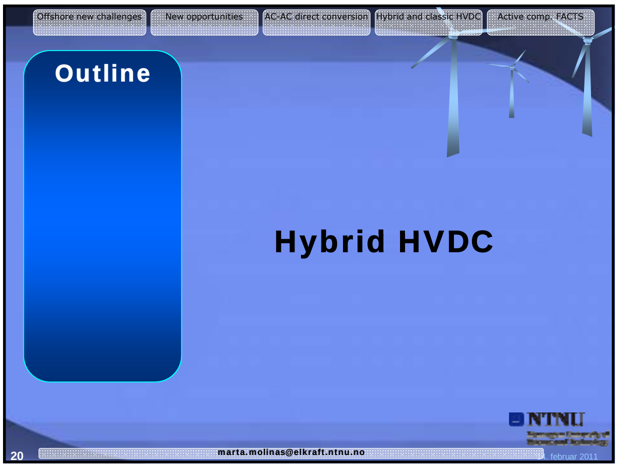
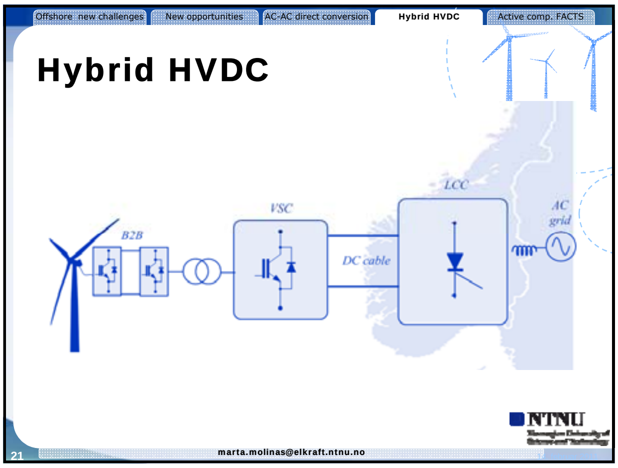


Pitch control

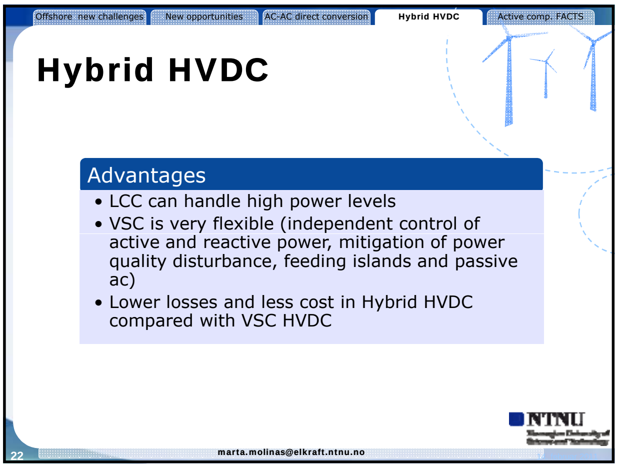


Outline

Hybrid HVDC



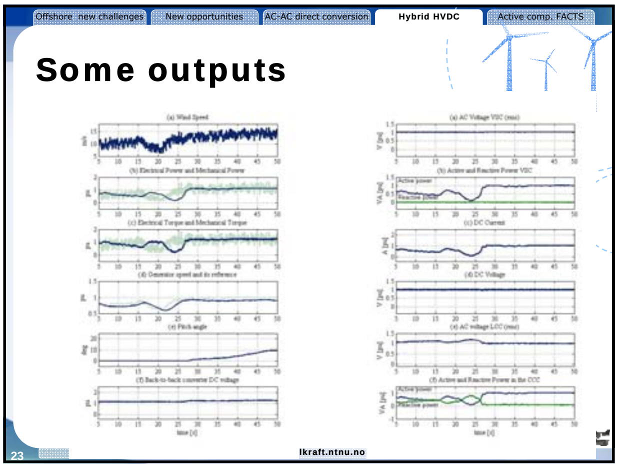
Hybrid HVDC



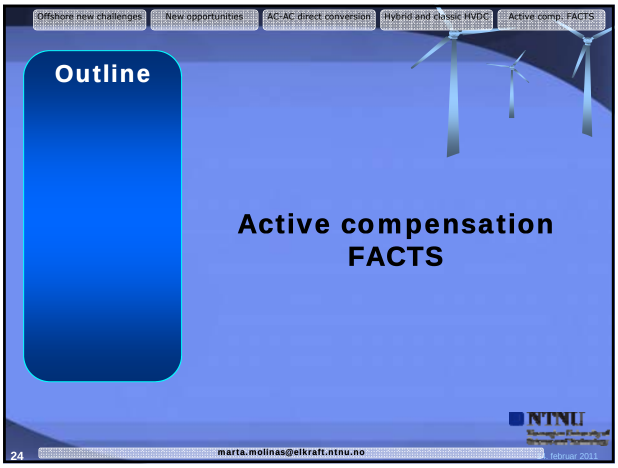
Hybrid HVDC

Advantages

- LCC can handle high power levels
- VSC is very flexible (independent control of active and reactive power, mitigation of power quality disturbance, feeding islands and passive ac)
- Lower losses and less cost in Hybrid HVDC compared with VSC HVDC

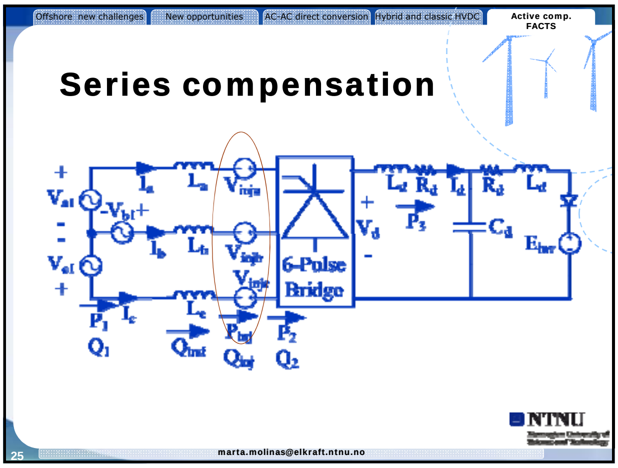


Some outputs



Outline

Active compensation FACTS



Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Series compensation

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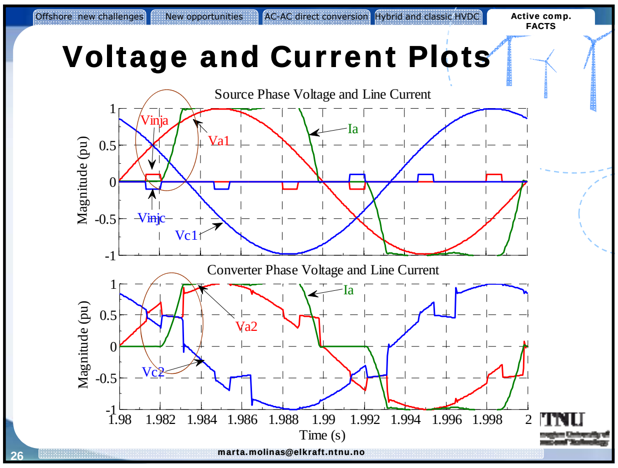

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Voltage and Current Plots

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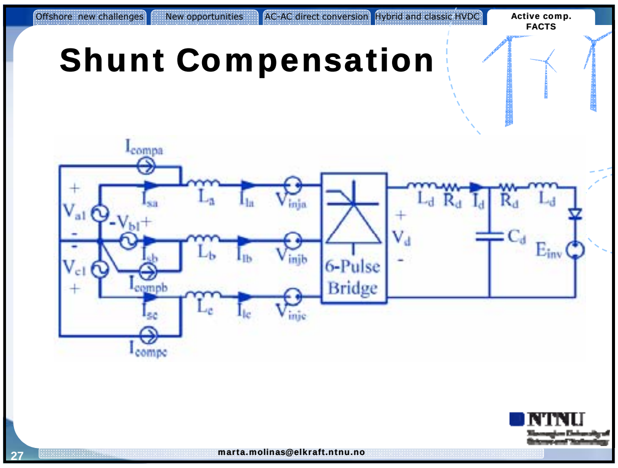

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Shunt Compensation

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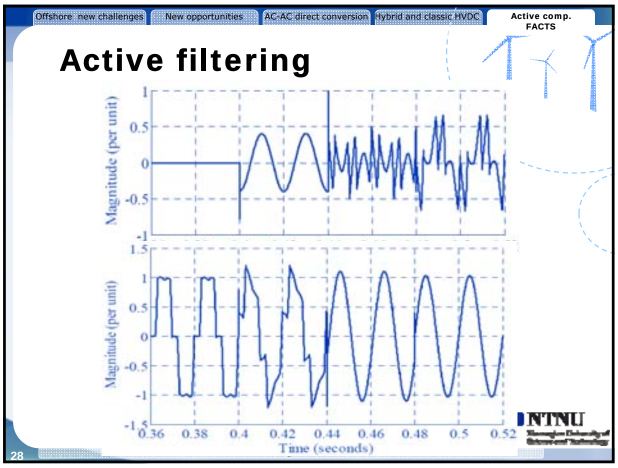

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Active filtering

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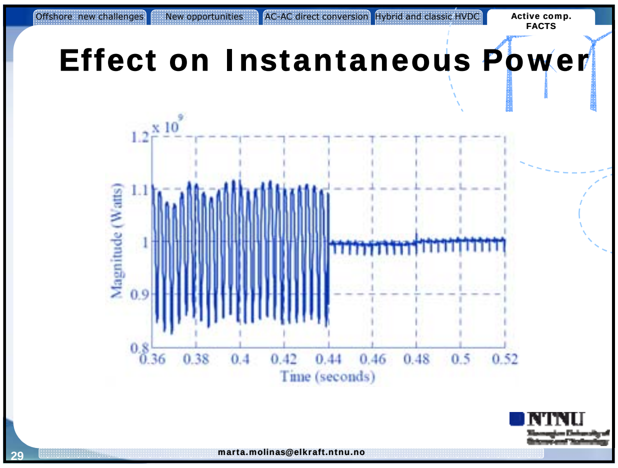

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Effect on Instantaneous Power

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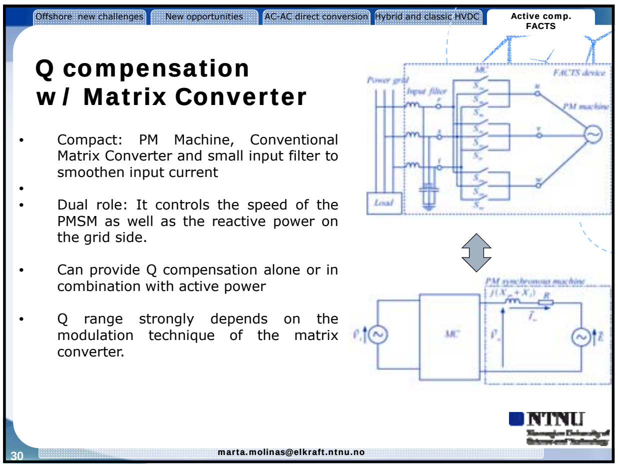

Offshore new challenges | New opportunities | AC-AC direct conversion | Hybrid and classic HVDC | Active comp. FACTS

Q compensation w / Matrix Converter

- Compact: PM Machine, Conventional Matrix Converter and small input filter to smoothen input current
-
- Dual role: It controls the speed of the PMSM as well as the reactive power on the grid side.
- Can provide Q compensation alone or in combination with active power
- Q range strongly depends on the modulation technique of the matrix converter.

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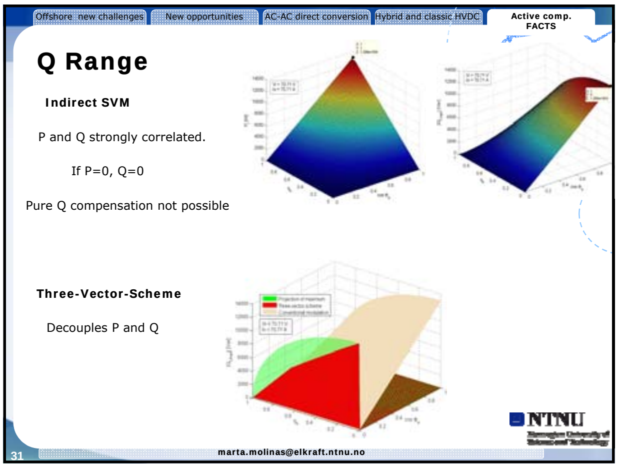

Q Range

Indirect SVM

P and Q strongly correlated.

If P=0, Q=0

Pure Q compensation not possible

Three-Vector-Scheme

Decouples P and Q

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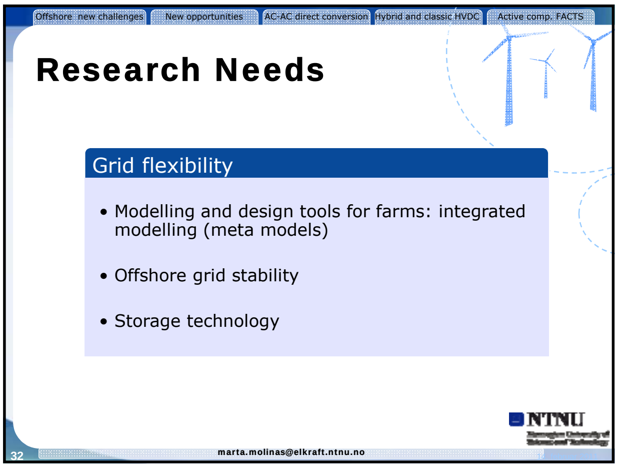

Research Needs

Grid flexibility

- Modelling and design tools for farms: integrated modelling (meta models)
- Offshore grid stability
- Storage technology

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”We’ve passed the point of no return for offshore wind – it is happening on a big scale”

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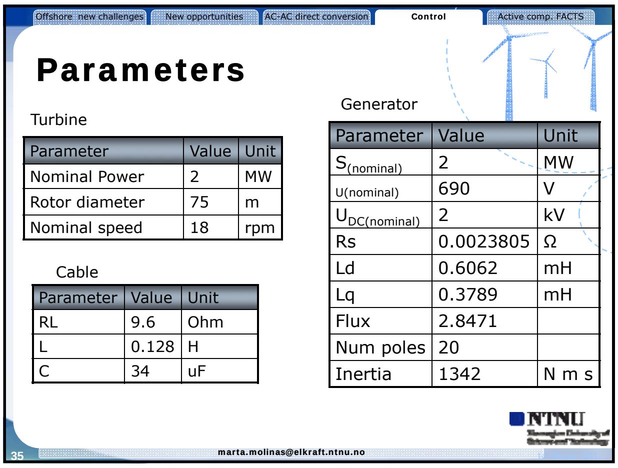
Thanks for your attention



Parameters

Turbine

Parameter	Value	Unit
Nominal Power	2	MW
Rotor diameter	75	m
Nominal speed	18	rpm

Cable

Parameter	Value	Unit
RL	9.6	Ohm
L	0.128	H
C	34	uF

Generator

Parameter	Value	Unit
$S_{(nominal)}$	2	MW
U(nominal)	690	V
$U_{DC(nominal)}$	2	kV
Rs	0.0023805	Ω
Ld	0.6062	mH
Lq	0.3789	mH
Flux	2.8471	
Num poles	20	
Inertia	1342	N m s

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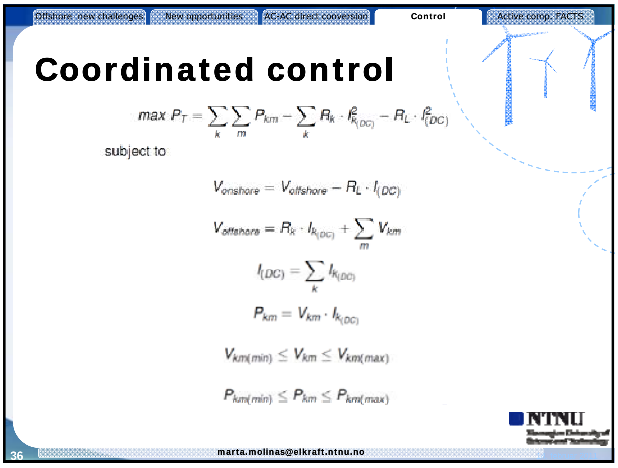

Coordinated control

$$\max P_T = \sum_k \sum_m P_{km} - \sum_k R_k \cdot I^2_{k(DC)} - R_L \cdot I^2_{(DC)}$$

subject to

$$V_{onshore} = V_{offshore} - R_L \cdot I_{(DC)}$$

$$V_{offshore} = R_k \cdot I_{k(DC)} + \sum_m V_{km}$$

$$I_{(DC)} = \sum_k I_{k(DC)}$$

$$P_{km} = V_{km} \cdot I_{k(DC)}$$

$$V_{km(min)} \leq V_{km} \leq V_{km(max)}$$

$$P_{km(min)} \leq P_{km} \leq P_{km(max)}$$

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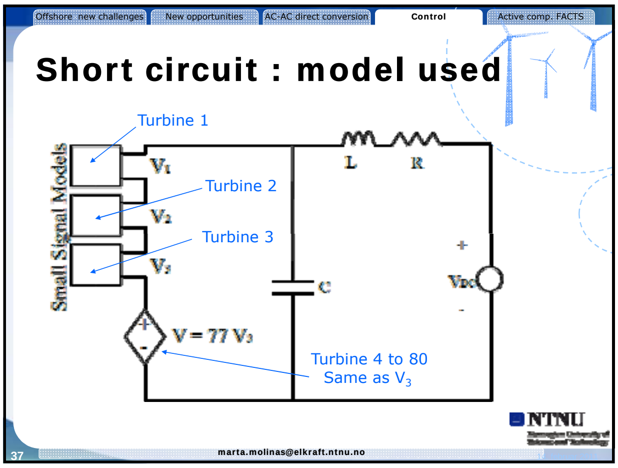


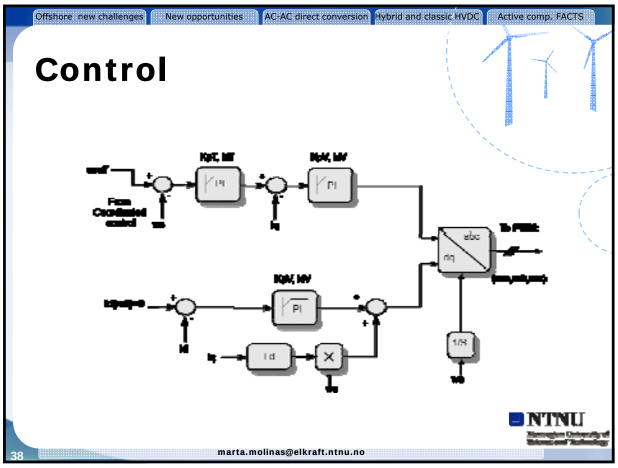
Short circuit : model used

Turbine 1

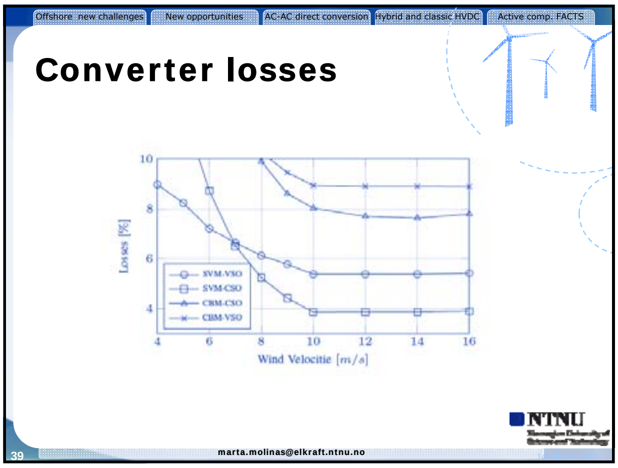
Turbine 2

Turbine 3

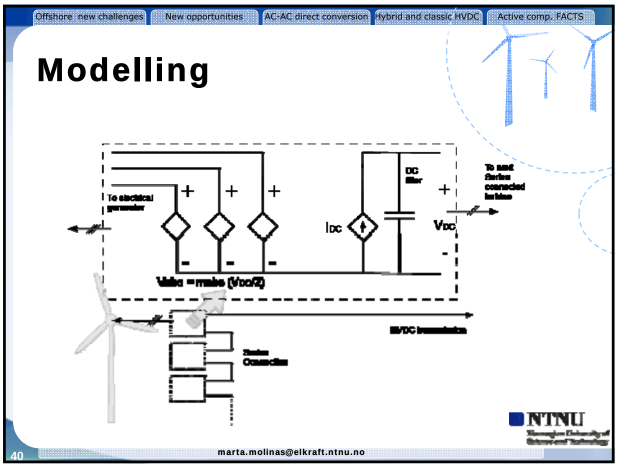
Turbine 4 to 80
Same as V_3



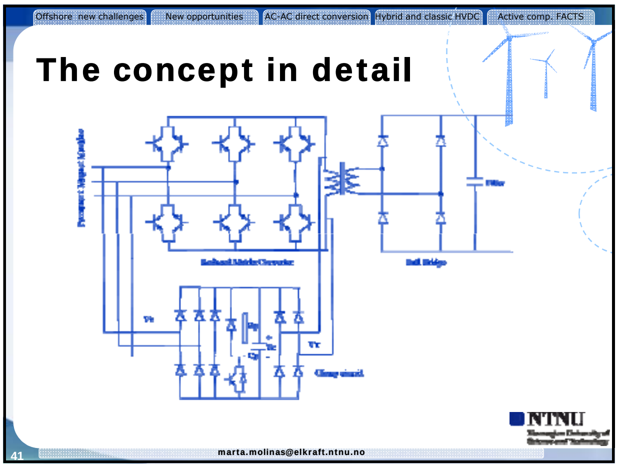
Control



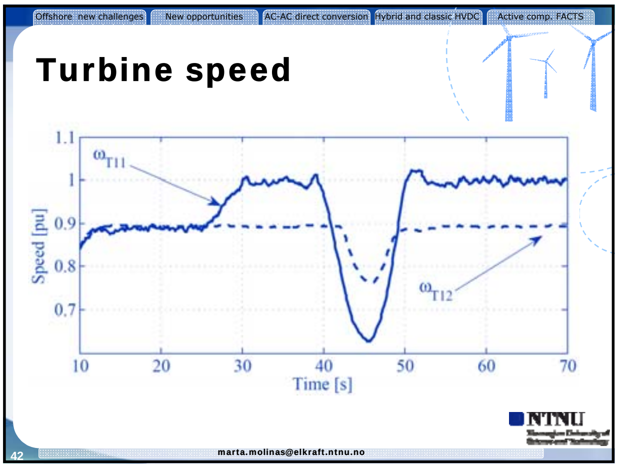
Converter losses



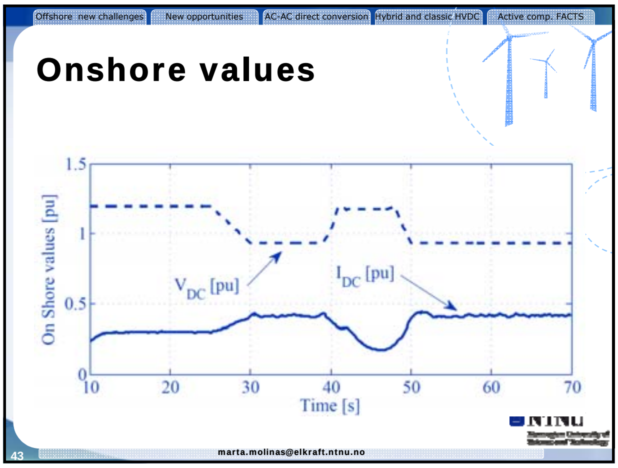
Modelling



The concept in detail

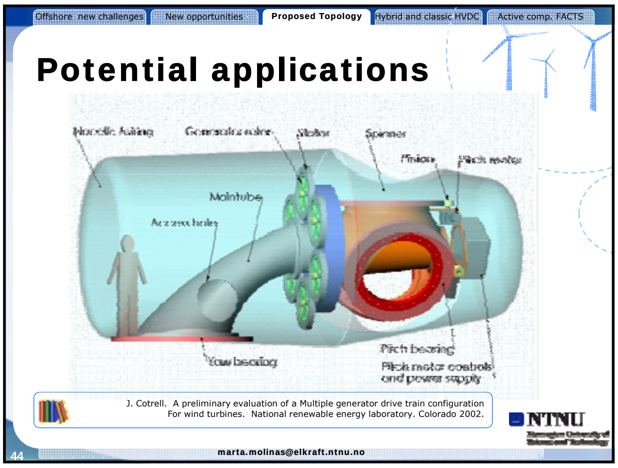


Turbine speed



Onshore values

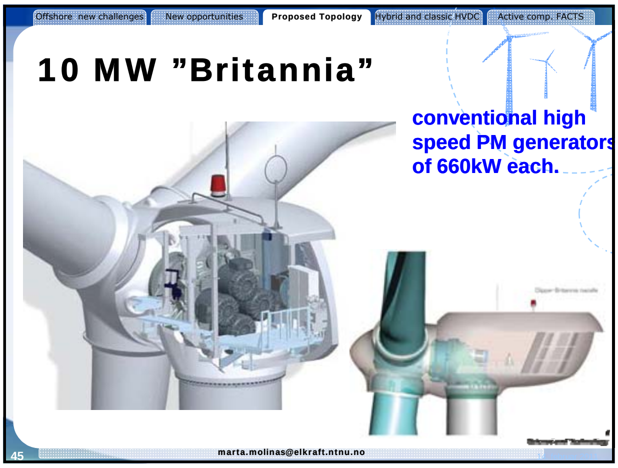
marta.molinas@elkraft.ntnu.no



Potential applications

J. Cotrell. A preliminary evaluation of a Multiple generator drive train configuration
For wind turbines. National renewable energy laboratory. Colorado 2002.

marta.molinas@elkraft.ntnu.no



10 MW ”Britannia”

conventional high speed PM generators of 660kW each.

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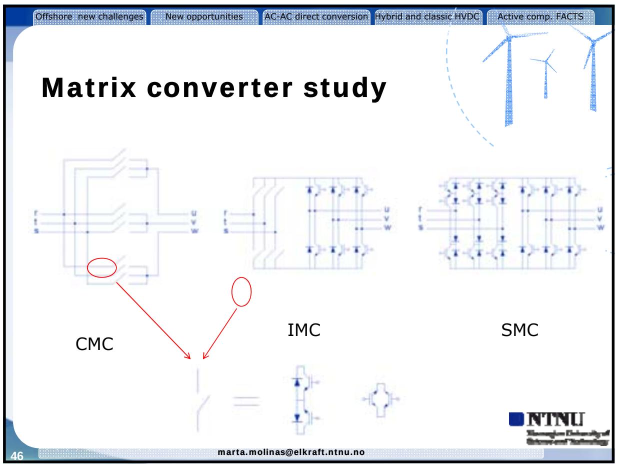
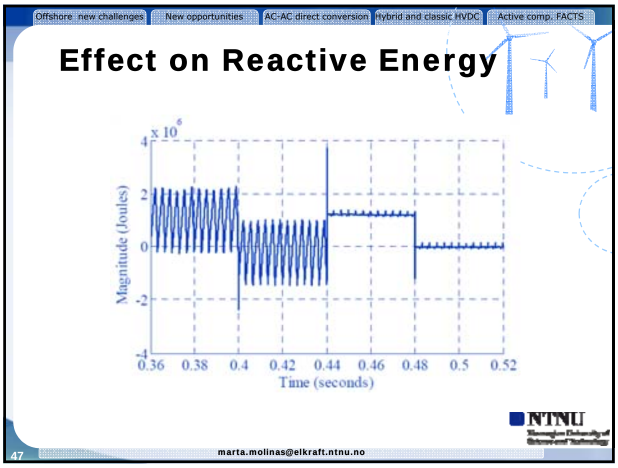


Matrix converter study

marta.molinas@elkraft.ntnu.no



Effect on Reactive Energy

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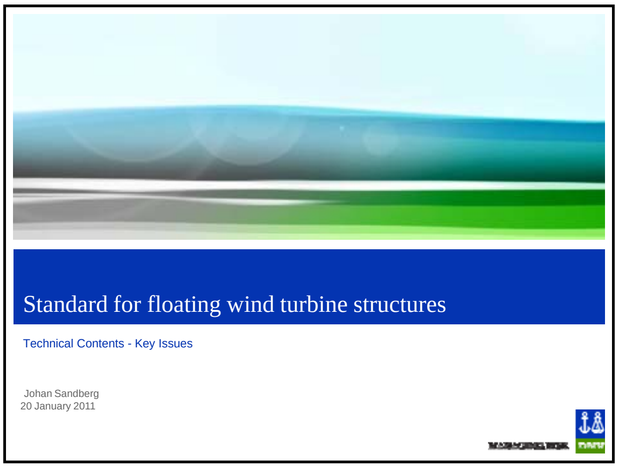
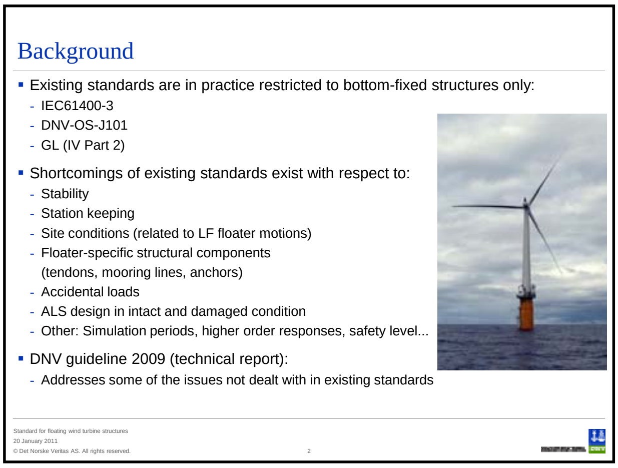


Standard for floating wind turbine structures

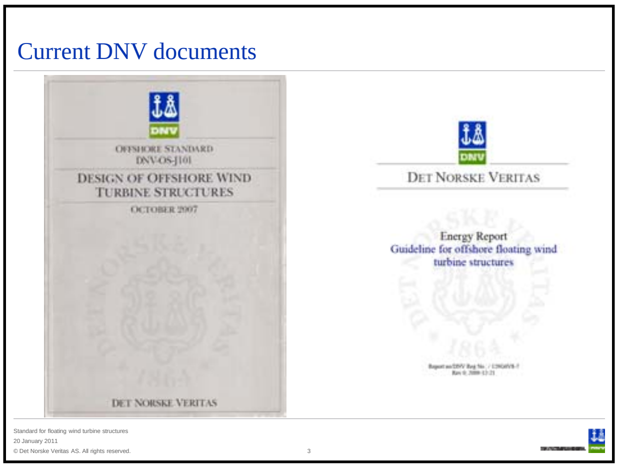
Technical Contents - Key Issues

Johan Sandberg
20 January 2011



Background

- Existing standards are in practice restricted to bottom-fixed structures only:
  - IEC61400-3
  - DNV-OS-J101
  - GL (IV Part 2)
- Shortcomings of existing standards exist with respect to:
  - Stability
  - Station keeping
  - Site conditions (related to LF floater motions)
  - Floater-specific structural components (tendons, mooring lines, anchors)
  - Accidental loads
  - ALS design in intact and damaged condition
  - Other: Simulation periods, higher order responses, safety level...
- DNV guideline 2009 (technical report):
  - Addresses some of the issues not dealt with in existing standards



Current DNV documents

DNV
OFFSHORE STANDARD
DNV-OS-J101
DESIGN OF OFFSHORE WIND TURBINE STRUCTURES
OCTOBER 2007
DET NORSKE VERITAS

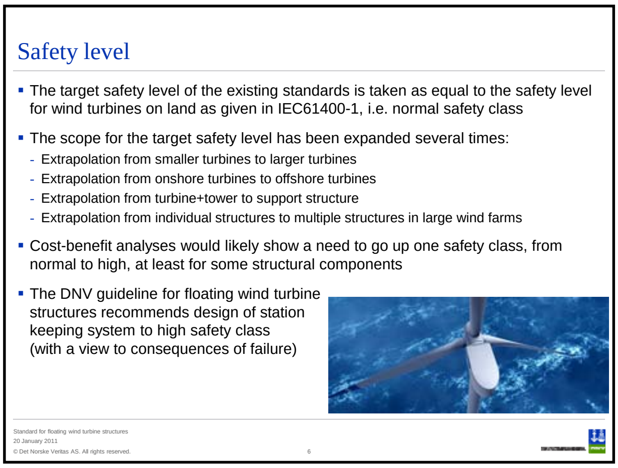
DNV
DET NORSKE VERITAS
Energy Report
Guideline for offshore floating wind turbine structures

Technical tasks

- Safety Philosophy and Design Principles
- Site conditions, loads and response
- Materials and corrosion protection
- Structural design
- Foundation design
- Stability
- Station keeping
- Control and protection system
- Mechanical system and electrical system
- Transport and installation
- In-service inspection, maintenance and monitoring

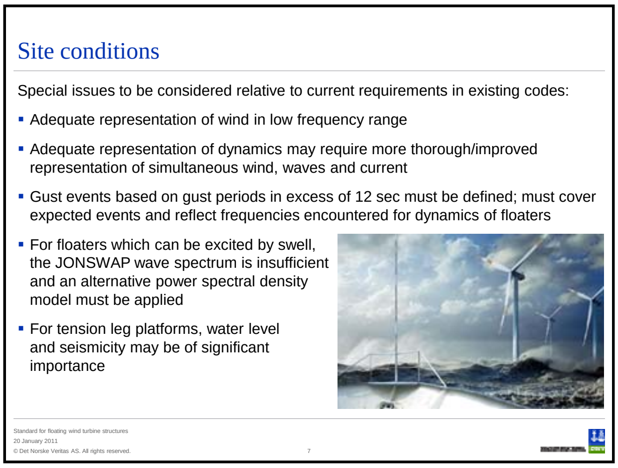
Safety philosophy and design principles; safety level

- Safety philosophy as for fixed wind turbine structures in DNV-OS-J101
  - Safety class methodology; three classes are considered depending on severity of failure consequences:
    - Low
    - Normal
    - High
  - Target failure probability; is set depending on required safety class
- Design principles
  - Partial safety factor method
  - Requirements for partial safety factor; are set depending on required target failure probability
- Safety level
  - It is an important task of the project to determine/decide an adequate safety level for various structural components of floating wind turbine structures



Safety level

- The target safety level of the existing standards is taken as equal to the safety level for wind turbines on land as given in IEC61400-1, i.e. normal safety class
- The scope for the target safety level has been expanded several times:
  - Extrapolation from smaller turbines to larger turbines
  - Extrapolation from onshore turbines to offshore turbines
  - Extrapolation from turbine+tower to support structure
  - Extrapolation from individual structures to multiple structures in large wind farms
- Cost-benefit analyses would likely show a need to go up one safety class, from normal to high, at least for some structural components
- The DNV guideline for floating wind turbine structures recommends design of station keeping system to high safety class (with a view to consequences of failure)

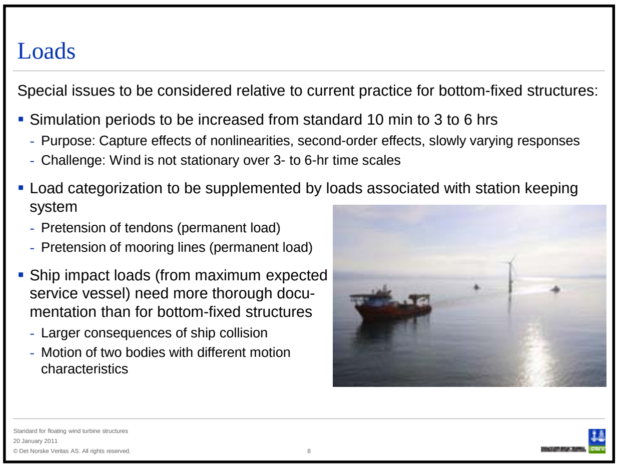


Site conditions

Special issues to be considered relative to current requirements in existing codes:

- Adequate representation of wind in low frequency range
- Adequate representation of dynamics may require more thorough/improved representation of simultaneous wind, waves and current
- Gust events based on gust periods in excess of 12 sec must be defined; must cover expected events and reflect frequencies encountered for dynamics of floaters
- For floaters which can be excited by swell, the JONSWAP wave spectrum is insufficient and an alternative power spectral density model must be applied
- For tension leg platforms, water level and seismicity may be of significant importance

Standard for floating wind turbine structures
20 January 2011

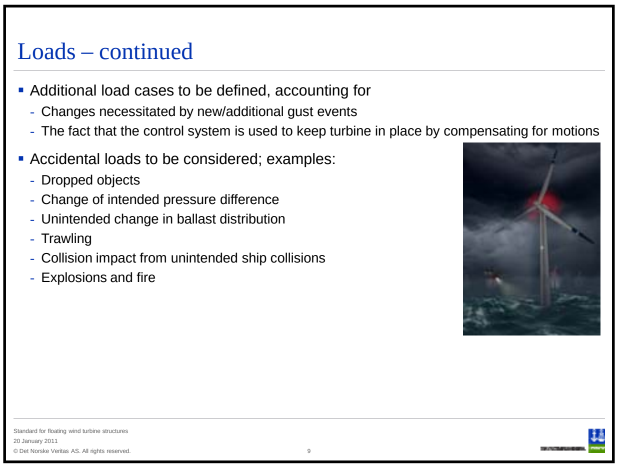


Loads

Special issues to be considered relative to current practice for bottom-fixed structures:

- Simulation periods to be increased from standard 10 min to 3 to 6 hrs
  - Purpose: Capture effects of nonlinearities, second-order effects, slowly varying responses
  - Challenge: Wind is not stationary over 3- to 6-hr time scales
- Load categorization to be supplemented by loads associated with station keeping system
  - Pretension of tendons (permanent load)
  - Pretension of mooring lines (permanent load)
- Ship impact loads (from maximum expected service vessel) need more thorough documentation than for bottom-fixed structures
  - Larger consequences of ship collision
  - Motion of two bodies with different motion characteristics

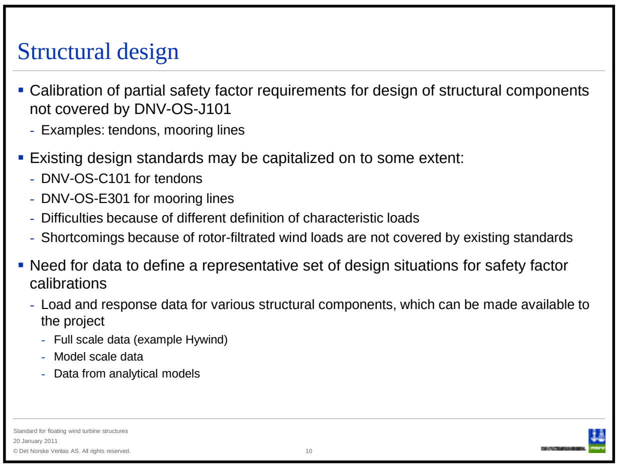
Standard for floating wind turbine structures
20 January 2011



Loads – continued

- Additional load cases to be defined, accounting for
  - Changes necessitated by new/additional gust events
  - The fact that the control system is used to keep turbine in place by compensating for motions
- Accidental loads to be considered; examples:
  - Dropped objects
  - Change of intended pressure difference
  - Unintended change in ballast distribution
  - Trawling
  - Collision impact from unintended ship collisions
  - Explosions and fire

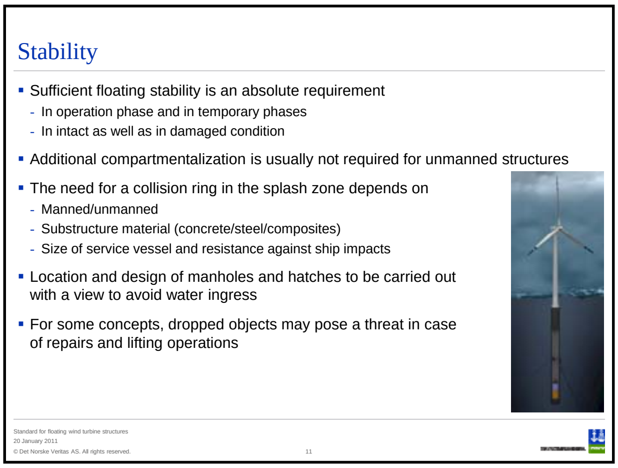
Standard for floating wind turbine structures
20 January 2011



Structural design

- Calibration of partial safety factor requirements for design of structural components not covered by DNV-OS-J101
  - Examples: tendons, mooring lines
- Existing design standards may be capitalized on to some extent:
  - DNV-OS-C101 for tendons
  - DNV-OS-E301 for mooring lines
  - Difficulties because of different definition of characteristic loads
  - Shortcomings because of rotor-filtrated wind loads are not covered by existing standards
- Need for data to define a representative set of design situations for safety factor calibrations
  - Load and response data for various structural components, which can be made available to the project
    - Full scale data (example Hywind)
    - Model scale data
    - Data from analytical models

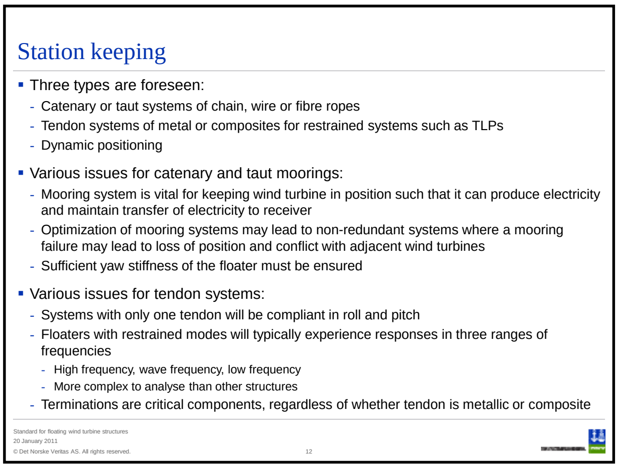
Standard for floating wind turbine structures
20 January 2011



Stability

- Sufficient floating stability is an absolute requirement
  - In operation phase and in temporary phases
  - In intact as well as in damaged condition
- Additional compartmentalization is usually not required for unmanned structures
- The need for a collision ring in the splash zone depends on
  - Manned/unmanned
  - Substructure material (concrete/steel/composites)
  - Size of service vessel and resistance against ship impacts
- Location and design of manholes and hatches to be carried out with a view to avoid water ingress
- For some concepts, dropped objects may pose a threat in case of repairs and lifting operations

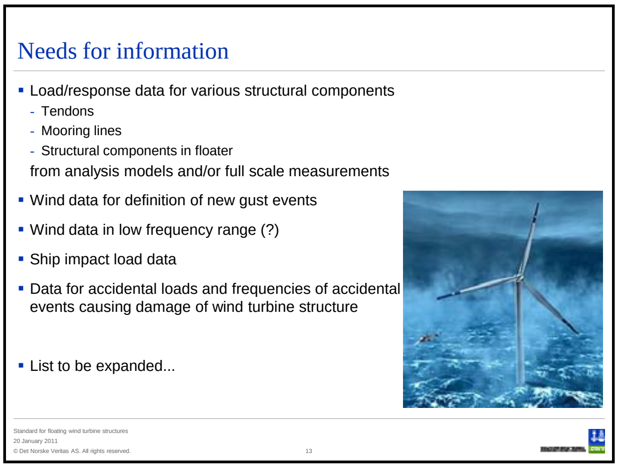
Standard for floating wind turbine structures
20 January 2011



Station keeping

- Three types are foreseen:
  - Catenary or taut systems of chain, wire or fibre ropes
  - Tendon systems of metal or composites for restrained systems such as TLPs
  - Dynamic positioning
- Various issues for catenary and taut moorings:
  - Mooring system is vital for keeping wind turbine in position such that it can produce electricity and maintain transfer of electricity to receiver
  - Optimization of mooring systems may lead to non-redundant systems where a mooring failure may lead to loss of position and conflict with adjacent wind turbines
  - Sufficient yaw stiffness of the floater must be ensured
- Various issues for tendon systems:
  - Systems with only one tendon will be compliant in roll and pitch
  - Floaters with restrained modes will typically experience responses in three ranges of frequencies
    - High frequency, wave frequency, low frequency
    - More complex to analyse than other structures
  - Terminations are critical components, regardless of whether tendon is metallic or composite

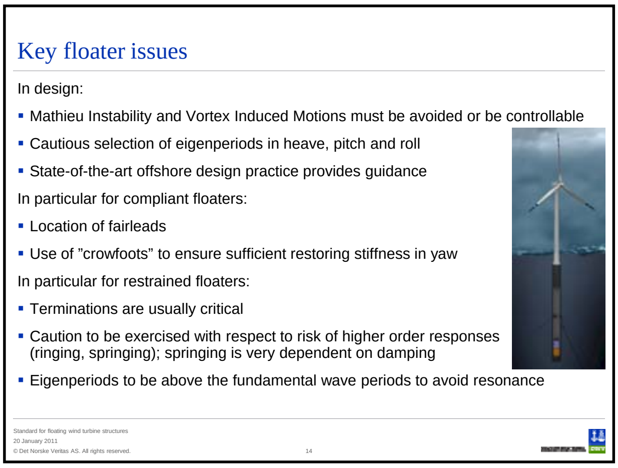
Standard for floating wind turbine structures
20 January 2011



Needs for information

- Load/response data for various structural components
  - Tendons
  - Mooring lines
  - Structural components in floater

  from analysis models and/or full scale measurements
- Wind data for definition of new gust events
- Wind data in low frequency range (?)
- Ship impact load data
- Data for accidental loads and frequencies of accidental events causing damage of wind turbine structure
- List to be expanded...



Key floater issues

In design:

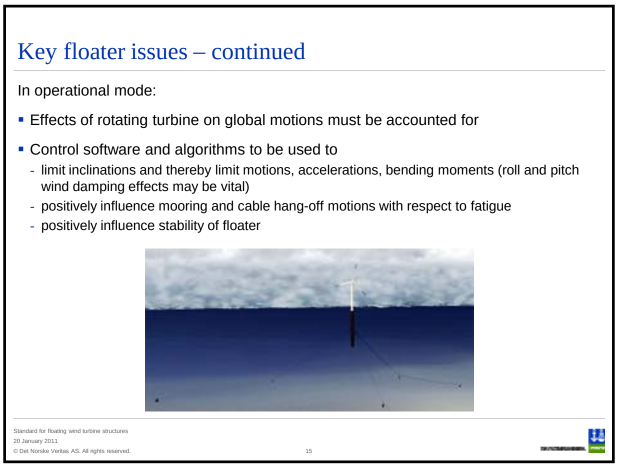
- Mathieu Instability and Vortex Induced Motions must be avoided or be controllable
- Cautious selection of eigenperiods in heave, pitch and roll
- State-of-the-art offshore design practice provides guidance

In particular for compliant floaters:

- Location of fairleads
- Use of ”crowfoots” to ensure sufficient restoring stiffness in yaw

In particular for restrained floaters:

- Terminations are usually critical
- Caution to be exercised with respect to risk of higher order responses (ringing, springing); springing is very dependent on damping
- Eigenperiods to be above the fundamental wave periods to avoid resonance



Key floater issues – continued

In operational mode:

- Effects of rotating turbine on global motions must be accounted for
- Control software and algorithms to be used to
  - limit inclinations and thereby limit motions, accelerations, bending moments (roll and pitch wind damping effects may be vital)
  - positively influence mooring and cable hang-off motions with respect to fatigue
  - positively influence stability of floater

Safeguarding life, property
and the environment

www.dnv.com

B1) Power system integration

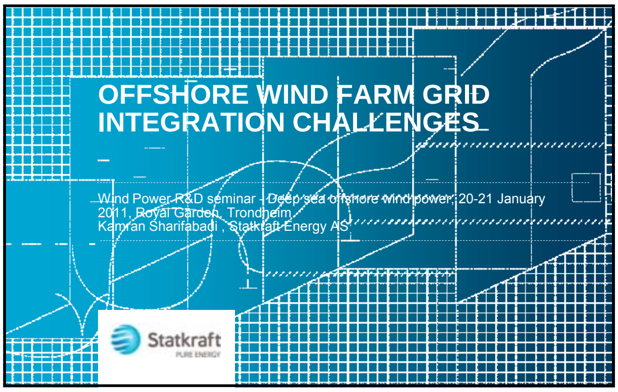
Offshore Wind farm Grid Integration challenges, Sharifabadi Kamran, Statkraft

Offshore grid developments, Kjartan Hauglum, Statnett

Characterization and modelling of the power output variability of wind farms clusters, Prof Hans Georg Beyer, Uni of Agder

Supply of offshore wind energy to oil and gas installations,
Harald Svendsen, SINTEFEnergi AS

Balance management with large scale offshore wind Integration,
Post Doc Steve Völler, NTNU

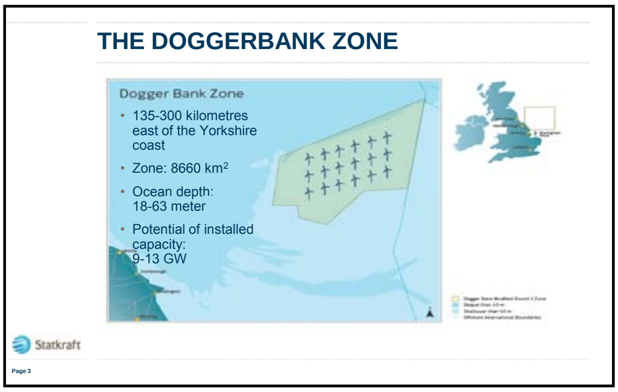


OFFSHORE WIND FARM GRID INTEGRATION CHALLENGES

Wind Power R&D seminar - Deep sea offshore wind power, 20-21 January 2011, Royal Garden, Trondheim
Kamran Sharifabadi , Statkraft Energy AS

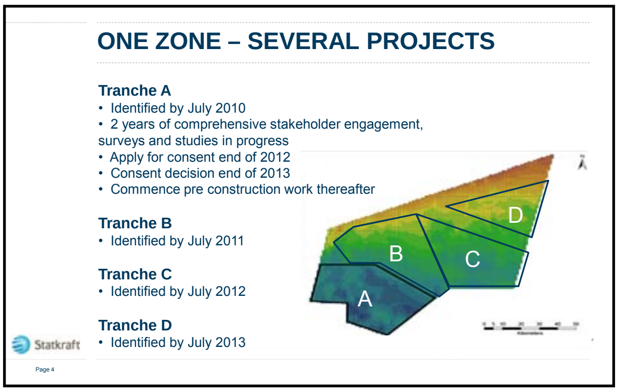
FOREWIND OFFSHORE WIND PROJECTS

Round 3



THE DOGGERBANK ZONE

Dogger Bank Zone
- 135-300 kilometres east of the Yorkshire coast
- Zone: 8660 km^2
- Ocean depth: 18-63 meter
- Potential of installed capacity: 9-13 GW



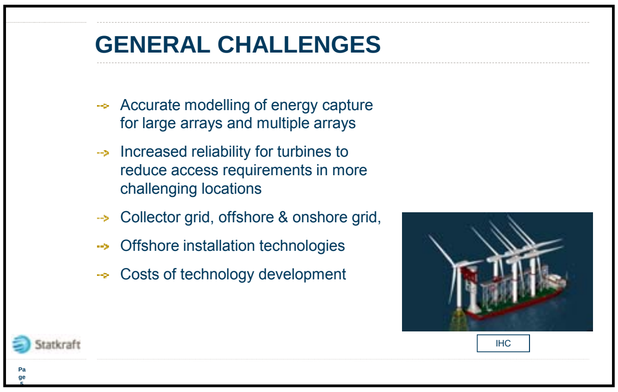
ONE ZONE – SEVERAL PROJECTS

Tranche A
- Identified by July 2010
- 2 years of comprehensive stakeholder engagement, surveys and studies in progress
- Apply for consent end of 2012
- Consent decision end of 2013
- Commence pre construction work thereafter

Tranche B
- Identified by July 2011

Tranche C
- Identified by July 2012

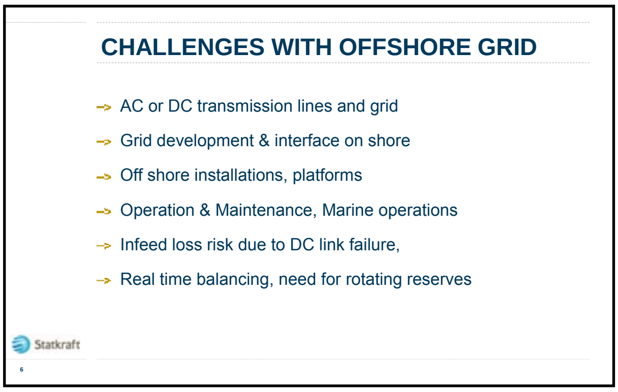
Tranche D
- Identified by July 2013



GENERAL CHALLENGES

- Accurate modelling of energy capture for large arrays and multiple arrays
- Increased reliability for turbines to reduce access requirements in more challenging locations
- Collector grid, offshore & onshore grid,
- Offshore installation technologies
- Costs of technology development

IHC



CHALLENGES WITH OFFSHORE GRID

- AC or DC transmission lines and grid
- Grid development & interface on shore
- Off shore installations, platforms
- Operation & Maintenance, Marine operations
- Infeed loss risk due to DC link failure,
- Real time balancing, need for rotating reserves

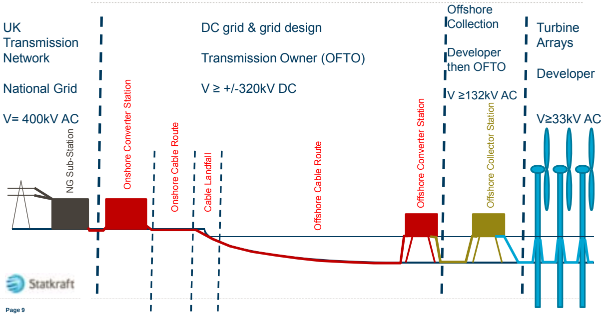
ELECTRICAL SYSTEM DESIGN

- Design & Technical considerations
  - Functionality and reliability
  - How many turbines per string?
  - Distance between turbines?
    - Wake effects vs. available area, CAPEX (cables) and OPEX (O&M, reliability)
  - Voltage level, DC or AC
  - Optimising the cable system (cross-section against losses)
  - Proof of concept

OPTIMISING THE INTER-ARRAY LAYOUT

- Alternative configurations and technologies
  - Meshed or radial network?
  - How many substations? Subsea reactive compensations?
  - How many collector platforms?
  - Distance between turbines?
    - Wake effects vs. available area, CAPEX (cables) and OPEX (O&M, reliability)
  - Wind farm grid voltage?
  - AC or DC collector grid? Advances in converter technology to higher voltages opens more options

OWNERSHIP AND RESPONSIBILITIES



UK Transmission Network

National Grid

V= 400kV AC

DC grid & grid design

Transmission Owner (OFTO)

V ≥ +/-320kV DC

Offshore Collection

Developer then OFTO

V ≥132kV AC

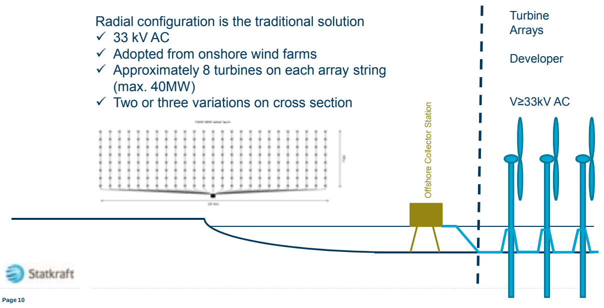
Turbine Arrays

Developer

V≥33kV AC

COLLECTING THE POWER

Radial configuration is the traditional solution
- ✓ 33 kV AC
- ✓ Adopted from onshore wind farms
- ✓ Approximately 8 turbines on each array string (max. 40MW)
- ✓ Two or three variations on cross section

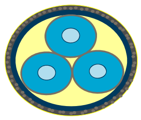


Turbine Arrays

Developer

V≥33kV AC

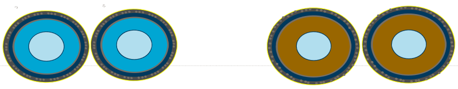
OFFSHORE CABLE TECHNOLOGY



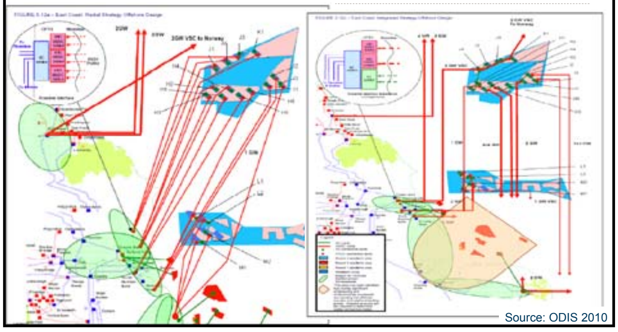
- 275kV 3 core AC cable
- 630mm² copper conductors
- 500MVA capacity
- 5-7 year development timescales
- Not used in studies

- 500kV HVDC XLPE Bipole Pair
- 2500mm² copper conductors
- 2000MW capacity
- 4 year development timescales
- Not used in studies

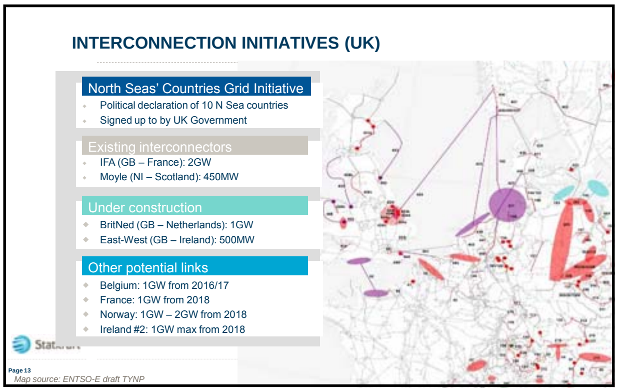
- 650kV MI (PPL) Bipole – laid separately
- 2500mm copper conductors
- 3000MW Capacity
- 2-3 year development timescales
- Not used in studies before 2020



GRID INTERFACE CHALLEMGE



Source: ODIS 2010



INTERCONNECTION INITIATIVES (UK)

North Seas' Countries Grid Initiative
- Political declaration of 10 N Sea countries
- Signed up to by UK Government

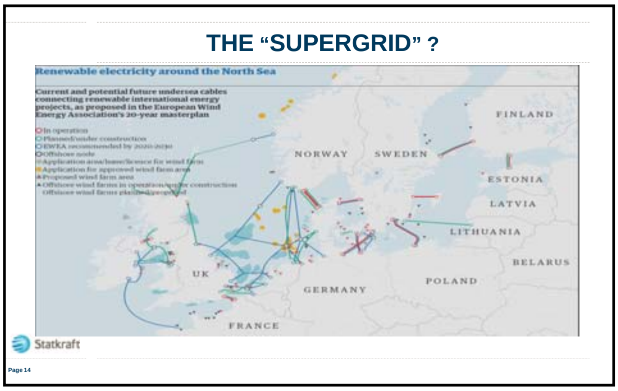
Existing interconnectors
- IFA (GB – France): 2GW
- Moyle (NI – Scotland): 450MW

Under construction
- BritNed (GB – Netherlands): 1GW
- East-West (GB – Ireland): 500MW

Other potential links
- Belgium: 1GW from 2016/17
- France: 1GW from 2018
- Norway: 1GW – 2GW from 2018
- Ireland #2: 1GW max from 2018

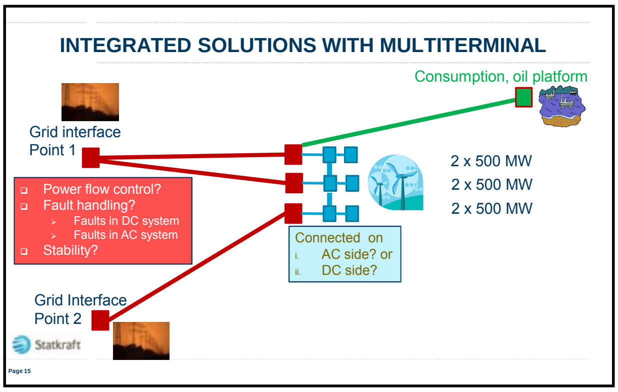
Statkraft

Map source: ENTSO-E draft TYNP



THE "SUPERGRID" ?

Statkraft



INTEGRATED SOLUTIONS WITH MULTITERMINAL

Consumption, oil platform

Grid interface Point 1

- ☐ Power flow control?
- ☐ Fault handling?
  - Faults in DC system
  - Faults in AC system
- ☐ Stability?

2 x 500 MW
2 x 500 MW
2 x 500 MW

Connected on
i. AC side? or
ii. DC side?

Grid Interface Point 2

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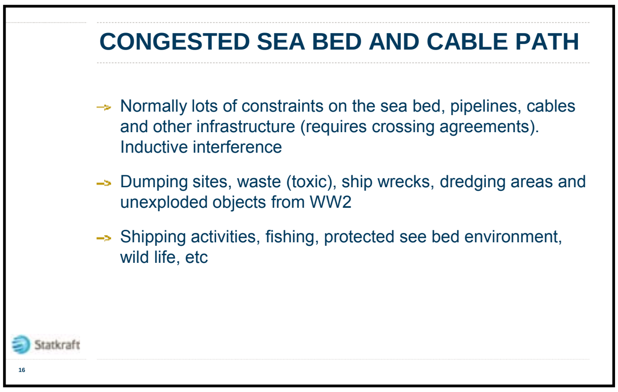

CONGESTED SEA BED AND CABLE PATH

- Normally lots of constraints on the sea bed, pipelines, cables and other infrastructure (requires crossing agreements). Inductive interference
- Dumping sites, waste (toxic), ship wrecks, dredging areas and unexploded objects from WW2
- Shipping activities, fishing, protected see bed environment, wild life, etc

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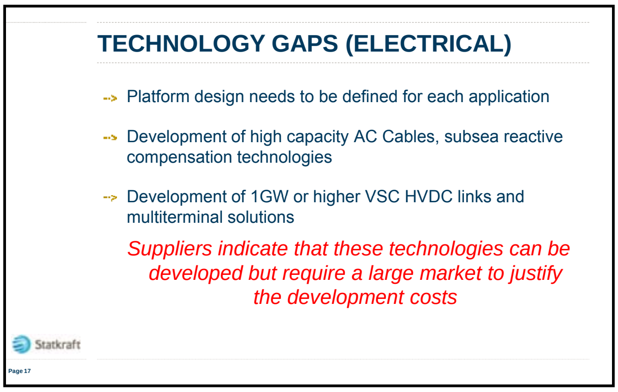

TECHNOLOGY GAPS (ELECTRICAL)

- Platform design needs to be defined for each application
- Development of high capacity AC Cables, subsea reactive compensation technologies
- Development of 1GW or higher VSC HVDC links and multiterminal solutions

Suppliers indicate that these technologies can be developed but require a large market to justify the development costs

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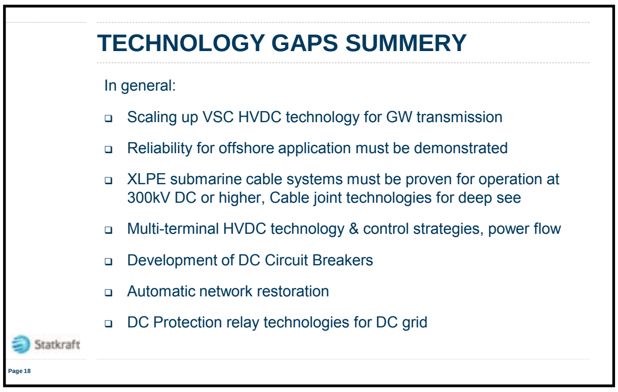

TECHNOLOGY GAPS SUMMERY

In general:

- ☐ Scaling up VSC HVDC technology for GW transmission
- ☐ Reliability for offshore application must be demonstrated
- ☐ XLPE submarine cable systems must be proven for operation at 300kV DC or higher, Cable joint technologies for deep see
- ☐ Multi-terminal HVDC technology & control strategies, power flow
- ☐ Development of DC Circuit Breakers
- ☐ Automatic network restoration
- ☐ DC Protection relay technologies for DC grid

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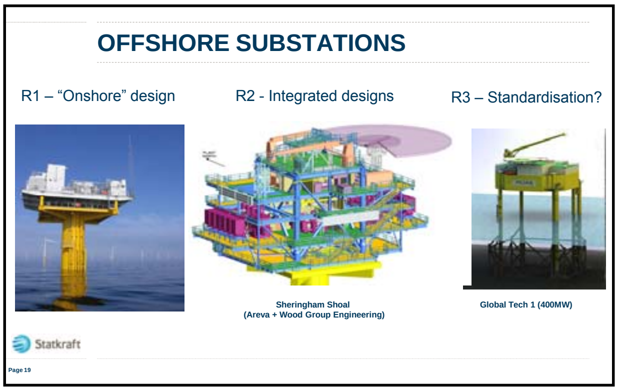


OFFSHORE SUBSTATIONS

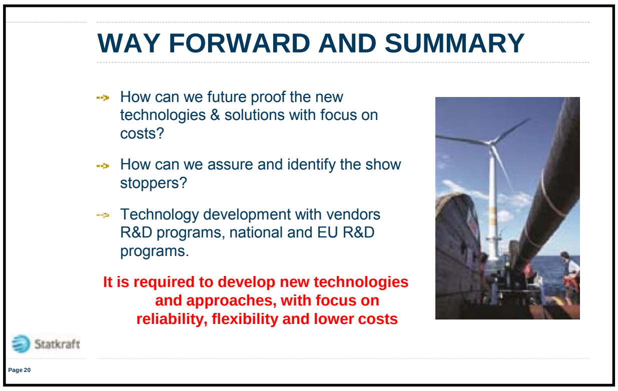
R1 – "Onshore" design

R2 - Integrated designs

R3 – Standardisation?

Sheringham Shoal
(Areva + Wood Group Engineering)

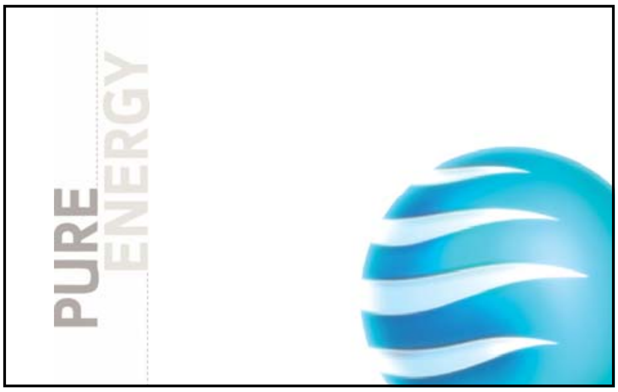
Global Tech 1 (400MW)



WAY FORWARD AND SUMMARY

- How can we future proof the new technologies & solutions with focus on costs?
- How can we assure and identify the show stoppers?
- Technology development with vendors R&D programs, national and EU R&D programs.

It is required to develop new technologies and approaches, with focus on reliability, flexibility and lower costs

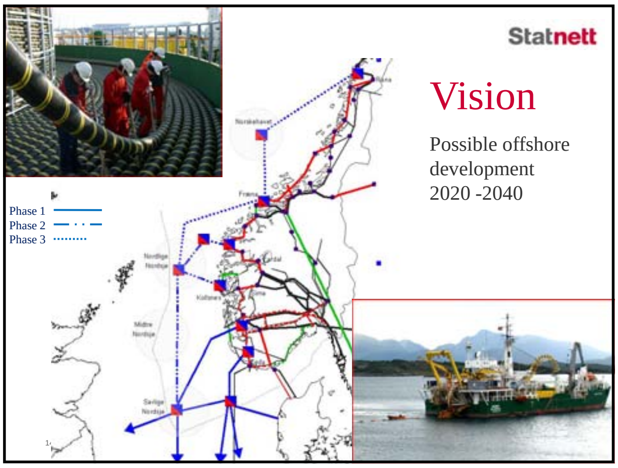


PURE
ENERGY

Statnett

Offshore grid developments

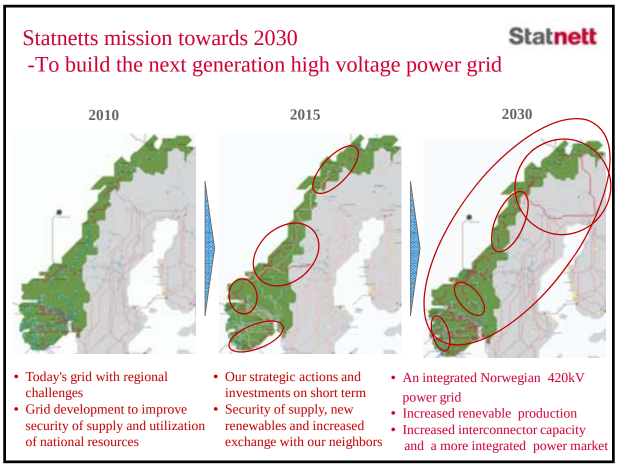
20 jan. 2011 Kjartan Hauglum, Statnett



Statnett

Vision

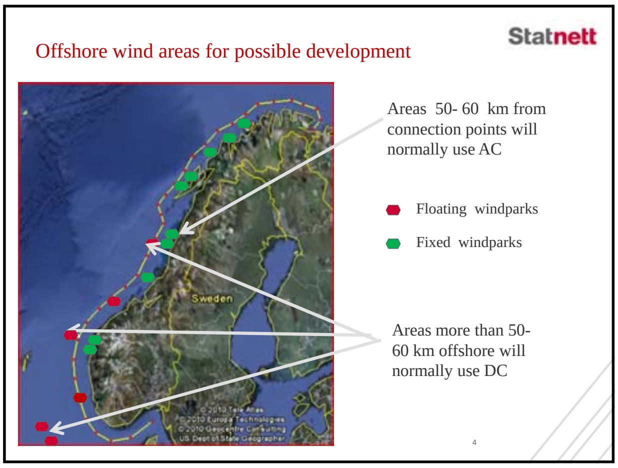
Possible offshore development
2020 -2040



Statnetts mission towards 2030
-To build the next generation high voltage power grid

Statnett

2010	2015	2030
• Today's grid with regional challenges • Grid development to improve security of supply and utilization of national resources	• Our strategic actions and investments on short term • Security of supply, new renewables and increased exchange with our neighbors	• An integrated Norwegian 420kV power grid • Increased renewable production • Increased interconnector capacity and a more integrated power market



Offshore wind areas for possible development

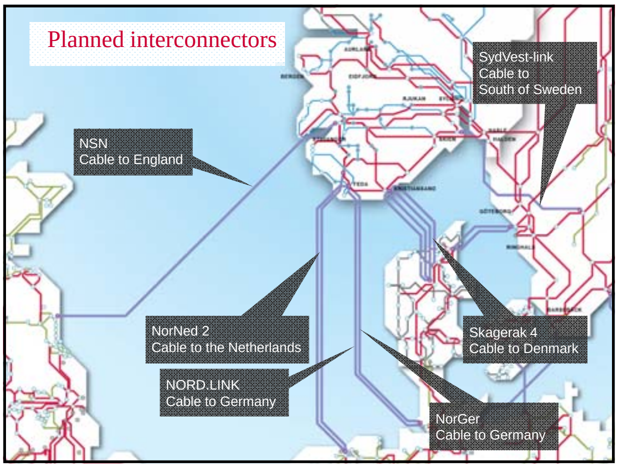
Statnett

Areas 50- 60 km from connection points will normally use AC

🟥 Floating windparks

🟩 Fixed windparks

Areas more than 50-60 km offshore will normally use DC



Planned interconnectors

SydVest-link
Cable to
South of Sweden

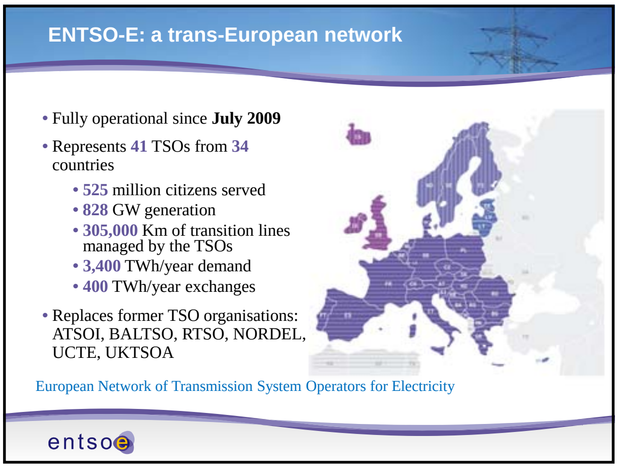
NSN
Cable to England

NorNed 2
Cable to the Netherlands

NORD.LINK
Cable to Germany

Skagerak 4
Cable to Denmark

NorGer
Cable to Germany

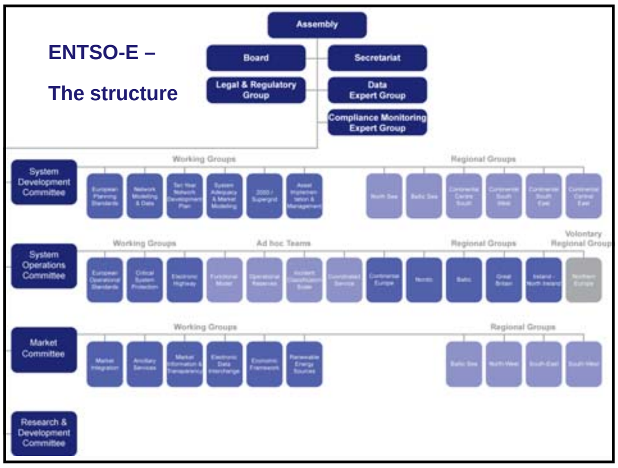


ENTSO-E: a trans-European network

- Fully operational since **July 2009**
- Represents **41** TSOs from **34** countries
  - **525** million citizens served
  - **828** GW generation
  - **305,000** Km of transition lines managed by the TSOs
  - **3,400** TWh/year demand
  - **400** TWh/year exchanges
- Replaces former TSO organisations: ATSOI, BALTSO, RTSO, NORDEL, UCTE, UKTSOA

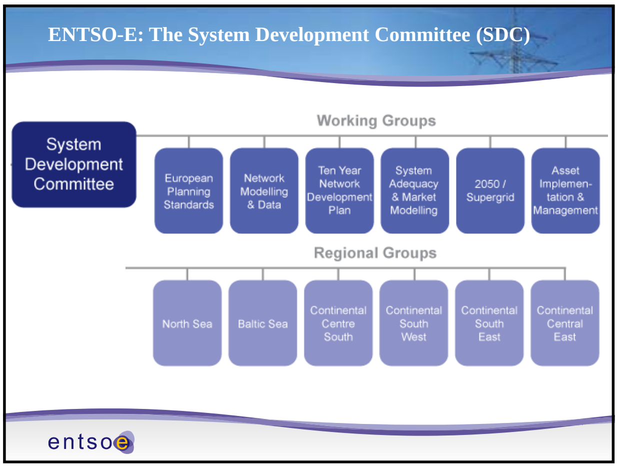
European Network of Transmission System Operators for Electricity

entsoe



ENTSO-E –

The structure



ENTSO-E: The System Development Committee (SDC)

Upcoming ENTSO-E Conference

- **"Towards electricity infrastructure for a carbon neutral Europe"**
- **Brussels, 10-11 February 2011**
- **More information and registration at:**
- **www.entsoe-event.eu**

Confirmed speakers include:

Tamas FELLEGI, Minister for Energy, Hungarian Presidency

Günther OETTINGER, EU Energy Commissioner

Connie HEDEGAARD, EU Climate Action Commissioner

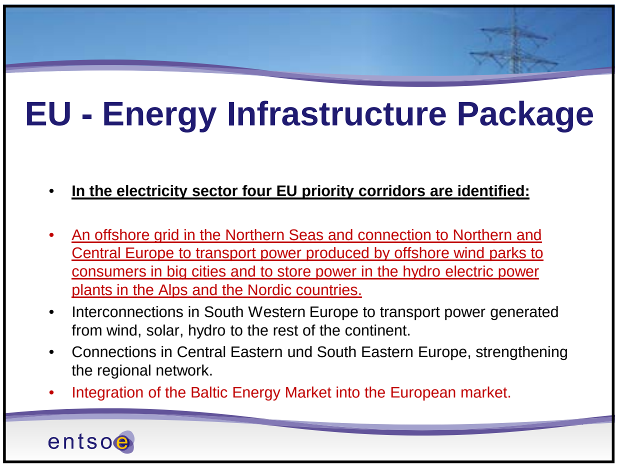
Claude TURMES MEP, MEP, ITRE Member

Arthouros ZERVOS, President, EWEA, EREC and CEO, Public Power Corp

Alberto POTOTSCHNIG, Director, ACER

Heinz HILBRECHT, Director, Security of Supply, Energy Markets & Networks, EC

Daniel DOBBENI, ENTSO-E President and CEO, ELIA



EU - Energy Infrastructure Package

- <u>In the electricity sector four EU priority corridors are identified:</u>
- An offshore grid in the Northern Seas and connection to Northern and Central Europe to transport power produced by offshore wind parks to consumers in big cities and to store power in the hydro electric power plants in the Alps and the Nordic countries.
- Interconnections in South Western Europe to transport power generated from wind, solar, hydro to the rest of the continent.
- Connections in Central Eastern und South Eastern Europe, strengthening the regional network.
- Integration of the Baltic Energy Market into the European market.

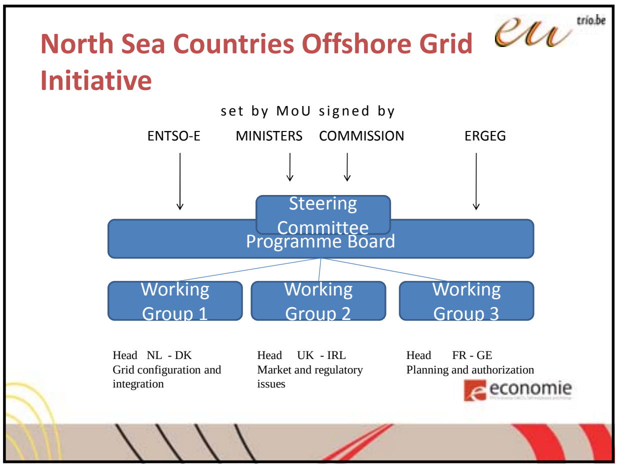
North Seas Countries Offshore Grid Initiative

Olje- og energiminister Terje Riis-Johansen og EU-kommisjonens energikommisær Günther Oettinger.

The North Seas Countries' Offshore Grid Initiative er et ti-lands samarbeid hvor Norge deltar sammen med Belgia, Danmark, Frankrike, Irland, Luxembourg, Nederland, Storbritannia, Sverige og Tyskland. Initiativet er et rammeverk for regionalt samarbeid for å finne felles løsninger for et overføringsnett til havs, i forbindelse med en fremtidig utbygging av havvind i Nordsjøen og andre havområder i Nord-Europa.

- Selv om et fullt integrert kraftoverføringsnett til havs ligger langt frem i tid er det viktig at de ulike landenes myndigheter, regulatorer og systemoperatører har et godt samarbeid, slik at vi får en koordinert og effektiv utvikling av et nett til havs, sier Olje- og energiminister Terje Riis-Johansen.

2011-02-14 11



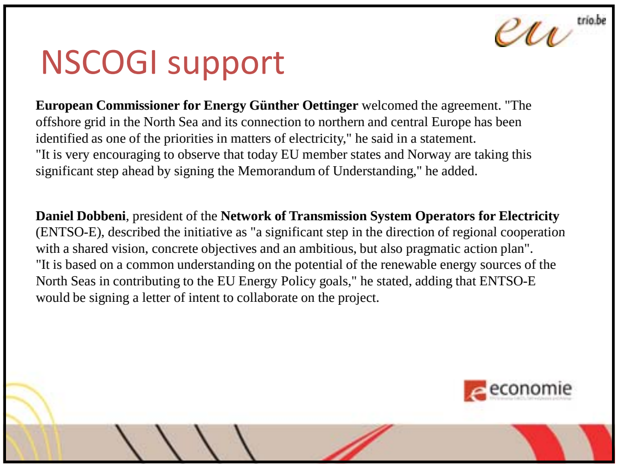
North Sea Countries Offshore Grid Initiative

set by MoU signed by

Head NL - DK
Grid configuration and integration

Head UK - IRL
Market and regulatory issues

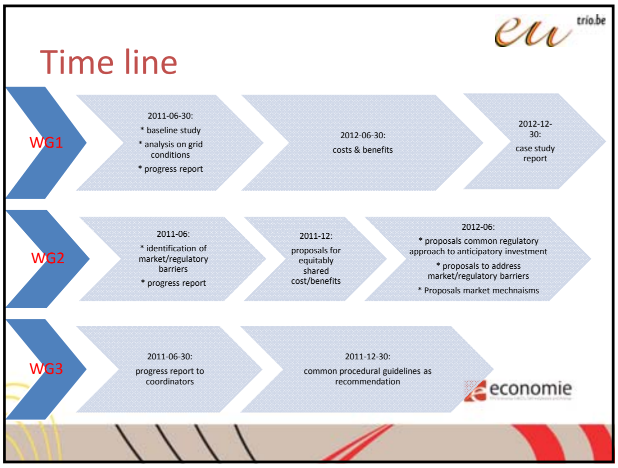
Head FR - GE
Planning and authorization



NSCOGI support

European Commissioner for Energy Günther Oettinger welcomed the agreement. "The offshore grid in the North Sea and its connection to northern and central Europe has been identified as one of the priorities in matters of electricity," he said in a statement.
"It is very encouraging to observe that today EU member states and Norway are taking this significant step ahead by signing the Memorandum of Understanding," he added.

Daniel Dobbeni, president of the **Network of Transmission System Operators for Electricity** (ENTSO-E), described the initiative as "a significant step in the direction of regional cooperation with a shared vision, concrete objectives and an ambitious, but also pragmatic action plan".
"It is based on a common understanding on the potential of the renewable energy sources of the North Seas in contributing to the EU Energy Policy goals," he stated, adding that ENTSO-E would be signing a letter of intent to collaborate on the project.



Time line

WG1

2011-06-30:
* baseline study
* analysis on grid conditions
* progress report

2012-06-30:
costs & benefits

2012-12-30:
case study report

WG2

2011-06:
* identification of market/regulatory barriers
* progress report

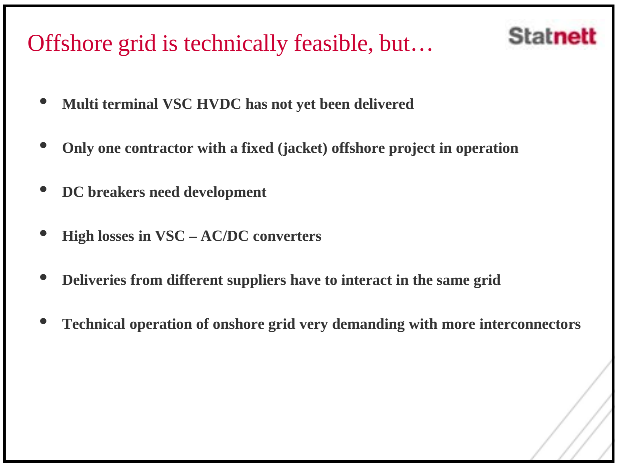
2011-12:
proposals for equitably shared cost/benefits

2012-06:
* proposals common regulatory approach to anticipatory investment
* proposals to address market/regulatory barriers
* Proposals market mechnaisms

WG3

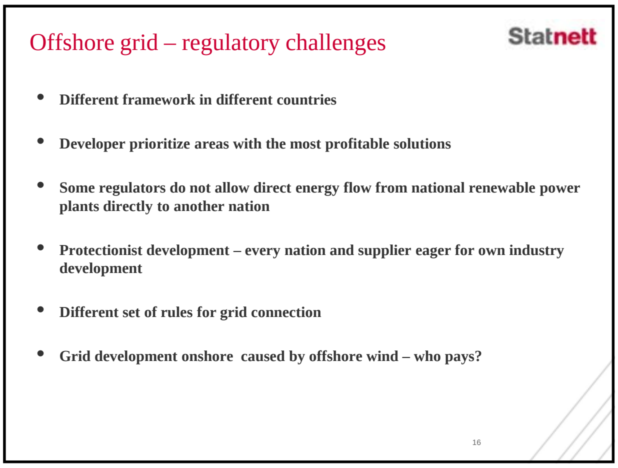
2011-06-30:
progress report to coordinators

2011-12-30:
common procedural guidelines as recommendation



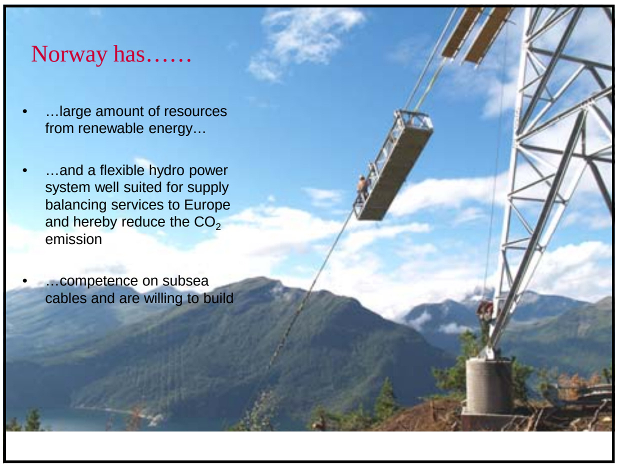
Offshore grid is technically feasible, but…

- **Multi terminal VSC HVDC has not yet been delivered**
- **Only one contractor with a fixed (jacket) offshore project in operation**
- **DC breakers need development**
- **High losses in VSC – AC/DC converters**
- **Deliveries from different suppliers have to interact in the same grid**
- **Technical operation of onshore grid very demanding with more interconnectors**



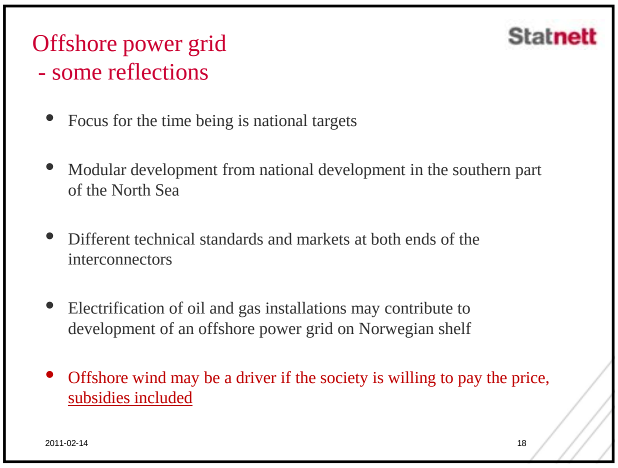
Offshore grid – regulatory challenges

- **Different framework in different countries**
- **Developer prioritize areas with the most profitable solutions**
- **Some regulators do not allow direct energy flow from national renewable power plants directly to another nation**
- **Protectionist development – every nation and supplier eager for own industry development**
- **Different set of rules for grid connection**
- **Grid development onshore caused by offshore wind – who pays?**



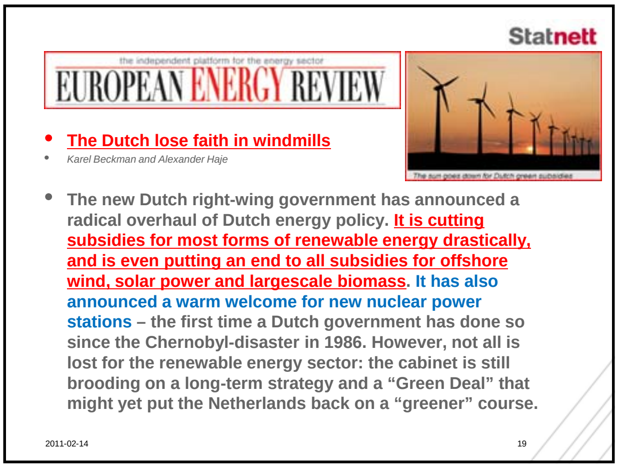
Norway has……

- …large amount of resources from renewable energy…
- …and a flexible hydro power system well suited for supply balancing services to Europe and hereby reduce the CO_2 emission
- …competence on subsea cables and are willing to build



Offshore power grid
- some reflections

- Focus for the time being is national targets
- Modular development from national development in the southern part of the North Sea
- Different technical standards and markets at both ends of the interconnectors
- Electrification of oil and gas installations may contribute to development of an offshore power grid on Norwegian shelf
- Offshore wind may be a driver if the society is willing to pay the price, subsidies included



Statnett

the independent platform for the energy sector

EUROPEAN ENERGY REVIEW

- **The Dutch lose faith in windmills**
- *Karel Beckman and Alexander Haje*

The sun goes down for Dutch green subsidies

- **The new Dutch right-wing government has announced a radical overhaul of Dutch energy policy. It is cutting subsidies for most forms of renewable energy drastically, and is even putting an end to all subsidies for offshore wind, solar power and largescale biomass. It has also announced a warm welcome for new nuclear power stations – the first time a Dutch government has done so since the Chernobyl-disaster in 1986. However, not all is lost for the renewable energy sector: the cabinet is still brooding on a long-term strategy and a "Green Deal" that might yet put the Netherlands back on a "greener" course.**

2011-02-14 19

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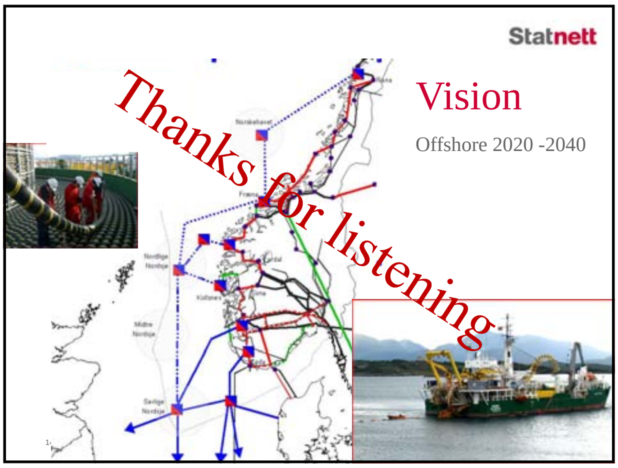
Main message

- Not very likely that we will have an international offshore grid before 2020
  - Will slowly emerge from national development
- Offshore grid are technically feasible but very demanding
  - Complicated structures with many countries involved – standardization and harmonization is needed
- Offshore TSOs not nominated in several countries
- The value of flexible Norwegian hydropower for balancing and storage will increase with more interconnectors
- Statnett works actively through ENTSO-E related to interconnectors, a possible future offshore grid and European market development
- **Offshore grid will become a reality when the drivers are strong enough**

14. februar 2011 20



Statnett

Thanks for listening

Vision

Offshore 2020 -2040

Characterization and modelling of the power output variability of wind farms clusters

Hans Georg Beyer
Department of Engineering
University of Agder, Grimstad

Characterization and modelling of the power output variability of wind farms clusters

- increasing contribution of non-dispatchable (renewable) power calls for new strategies of system operation, unit dispatch and storage management
- for the design of the new strategies, detailed knowledge on the characteristics of the renewable power flows is nececessary

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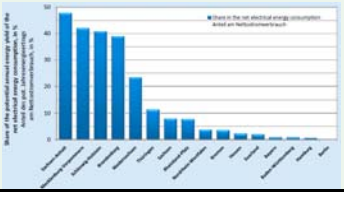
Characterization and modelling of the power output variability of wind farms clusters

- detailed knowledge on the characteristics of the renewable power flows is necessary

  examples are e.g. developed in Germany
  where regional shares of wind energy may amount up to ~50%



Source: DEWI 2010

Characterization and modelling of the power output variability of wind farms clusters

- detailed knowledge on the characteristics of the renewable power flows is necessary

  examples are e.g. developed in Germany

  - for day-to day operation:
    schemes for wind power forecasting are in operational use
  - for planning of capacity extension and grid reinforcement:
    tools for the characterization of the power output variability had bee set up

---

Characterization and modelling of the power output variability of wind farms clusters

- examples are e.g. developed in Germany

  - for planning of capacity extension and grid reinforcement:
    tools for the characterization of the power output variability had been set up

  e.g. Quintero et al. DEWEK 2008
  Knorr et al. EWEC 2009
  coop. with Fraunhofer IWES, Kassel, Germany

  following:

  - approaches used
  - outlook: how to extend to the Norwegian offshore environment

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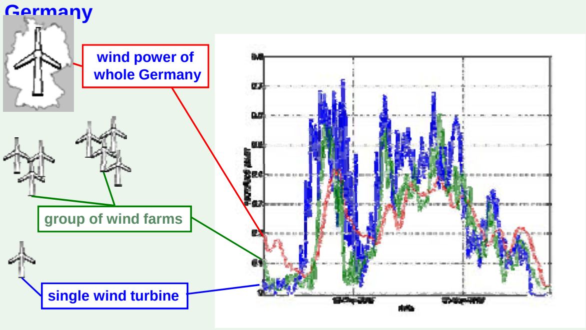
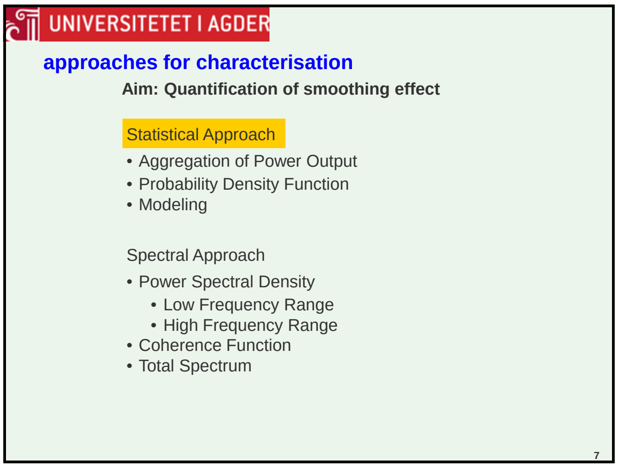
Characterisation output variability / example Germany



Smoothing effect: Increasing size of aggregation ⇨ lower variability



approaches for characterisation

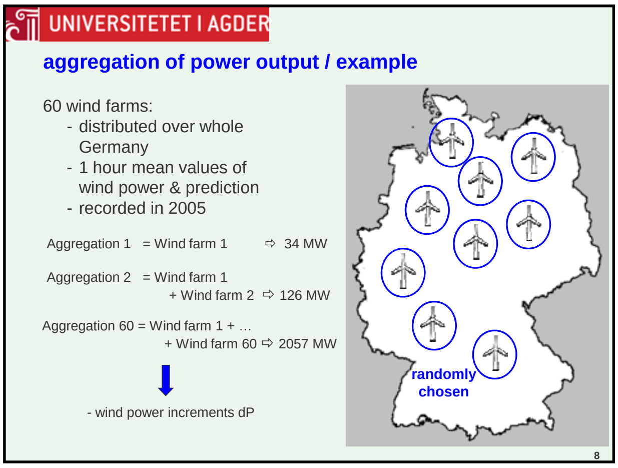
Aim: Quantification of smoothing effect

Statistical Approach

- Aggregation of Power Output
- Probability Density Function
- Modeling

Spectral Approach

- Power Spectral Density
  - Low Frequency Range
  - High Frequency Range
- Coherence Function
- Total Spectrum



aggregation of power output / example

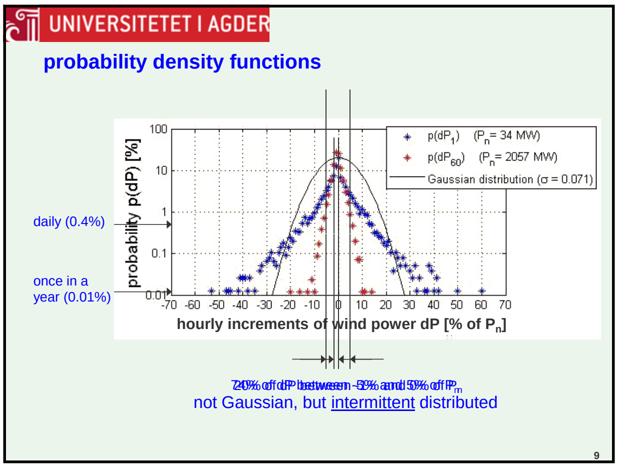
60 wind farms:
- distributed over whole Germany
- 1 hour mean values of wind power & prediction
- recorded in 2005

Aggregation 1 = Wind farm 1 ⇨ 34 MW

Aggregation 2 = Wind farm 1 + Wind farm 2 ⇨ 126 MW

Aggregation 60 = Wind farm 1 + … + Wind farm 60 ⇨ 2057 MW

- wind power increments dP

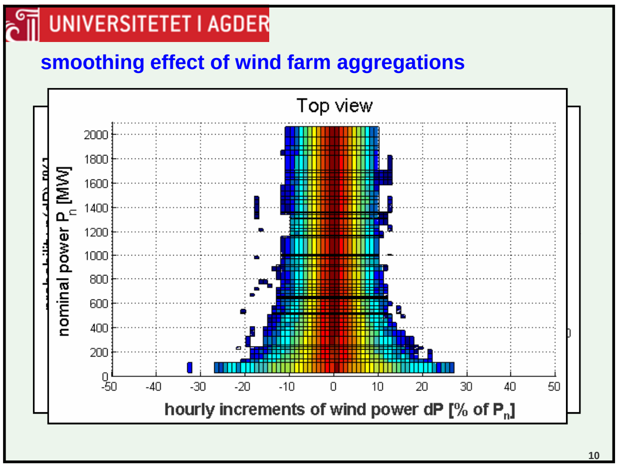


probability density functions

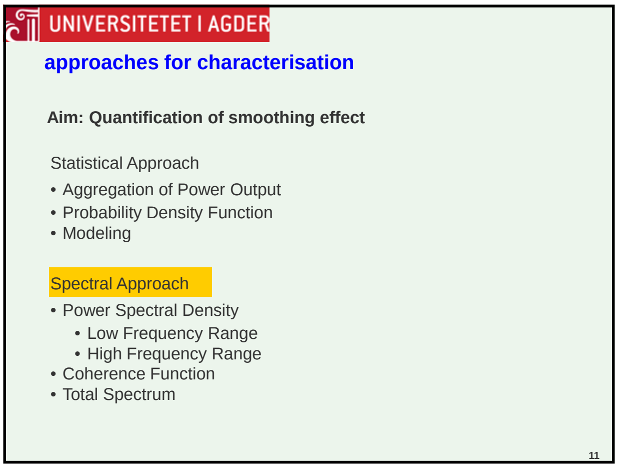
70% of dP between -1% and 1% of P_m

20% of dP between -5% and 5% of P_m

not Gaussian, but intermittent distributed



smoothing effect of wind farm aggregations



approaches for characterisation

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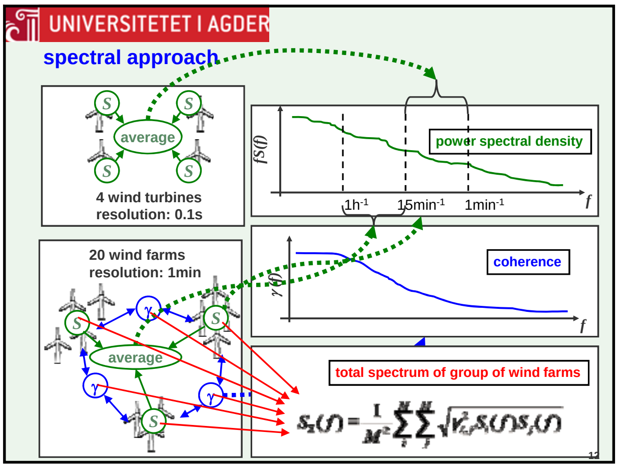
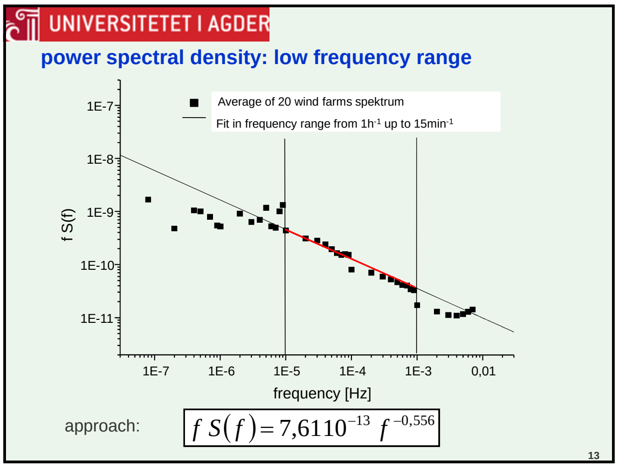


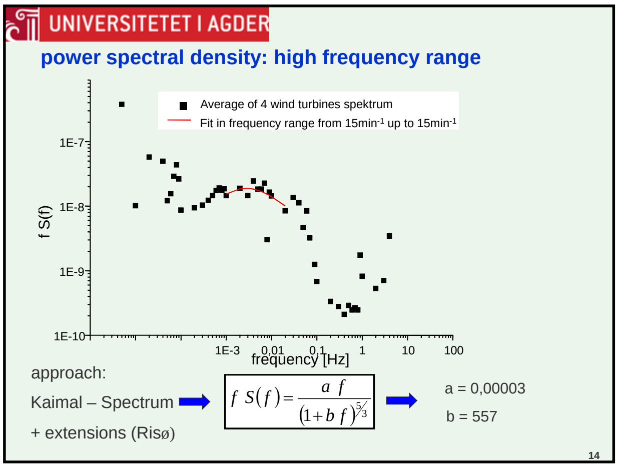
spectral approach

$$S_\Sigma(f)=\frac{1}{M^2}\sum_i^M\sum_j^M\sqrt{\gamma_{i,j}^2 S_i(f) S_j(f)}$$



power spectral density: low frequency range

approach: $$\boxed{f\,S\left(f\right)=7{,}6110^{-13}\;f^{-0{,}556}}$$



power spectral density: high frequency range

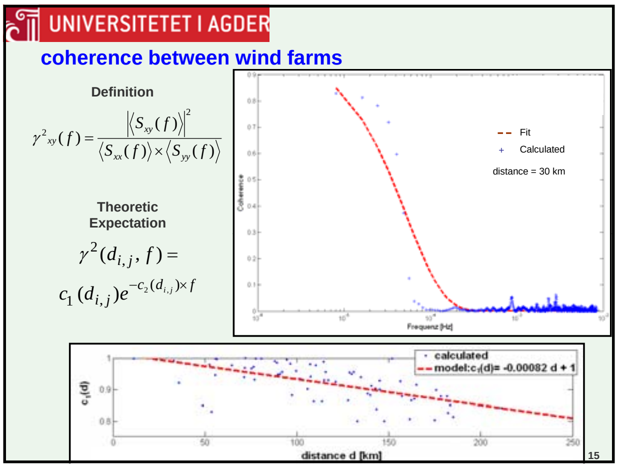
approach:

Kaimal – Spectrum → $$\boxed{f\;S\left(f\right)=\frac{a\;f}{\left(1+b\;f\right)^{5/3}}}$$ →

a = 0,00003

b = 557

+ extensions (Risø)



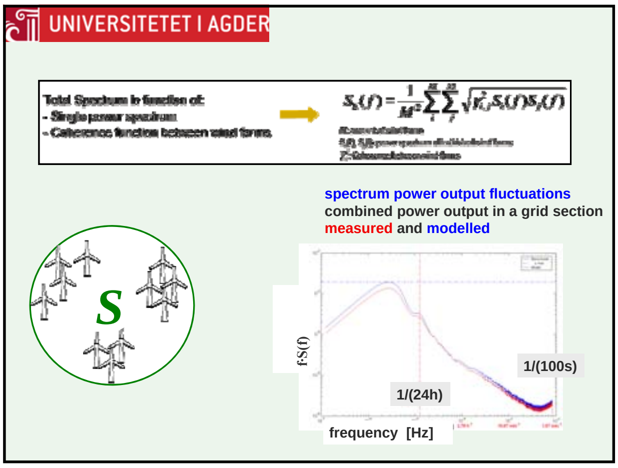
coherence between wind farms

Definition

$$\gamma^2{}_{xy}(f)=\frac{\left|\left\langle S_{xy}(f)\right\rangle\right|^2}{\left\langle S_{xx}(f)\right\rangle\times\left\langle S_{yy}(f)\right\rangle}$$

Theoretic Expectation

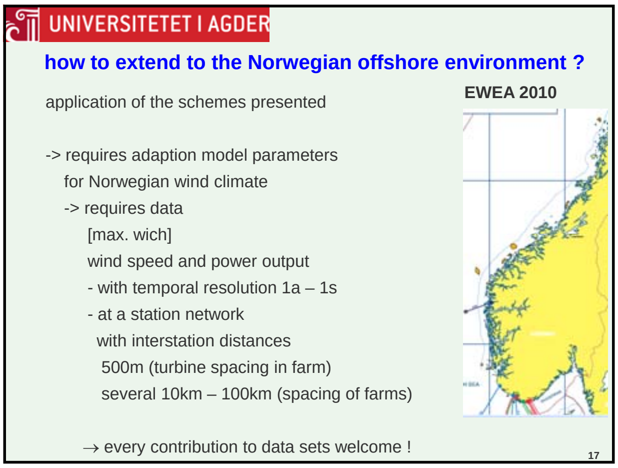
$$\gamma^2(d_{i,j},f)=c_1\,(d_{i,j})e^{-c_2(d_{i,j})\times f}$$



Total Spectrum in function of:
- Single power spectrum
- Coherence function between wind farms

→

spectrum power output fluctuations
combined power output in a grid section
measured and modelled



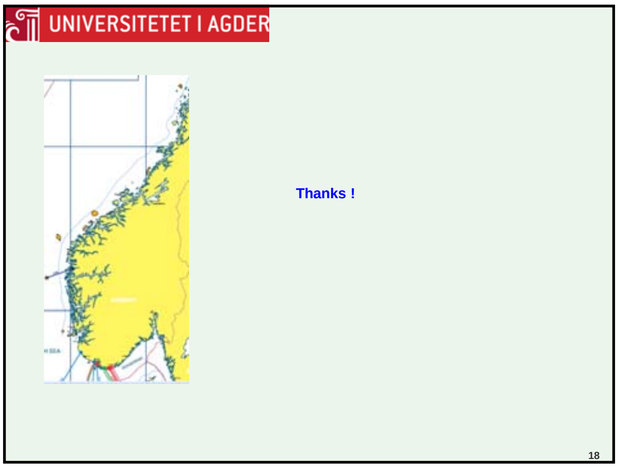
how to extend to the Norwegian offshore environment ?

EWEA 2010

application of the schemes presented

-> requires adaption model parameters
for Norwegian wind climate
-> requires data
[max. wich]
wind speed and power output
- with temporal resolution 1a – 1s
- at a station network
with interstation distances
500m (turbine spacing in farm)
several 10km – 100km (spacing of farms)

→ every contribution to data sets welcome !



Thanks !

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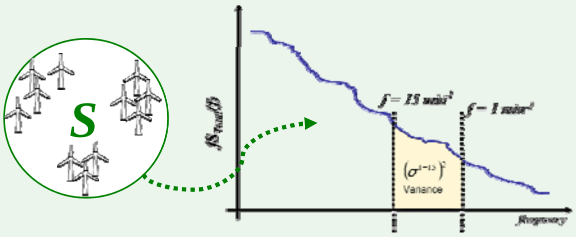
total spectrum from a group of wind farms

Total Spectrum in function of:
- Single power spectrum
- Coherence function between wind farms

$$S_\Sigma(f) = \frac{1}{M^2}\sum_i^M\sum_j^M\sqrt{K_{ij}^2 S_i(f) S_j(f)}$$



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conclusion

- development of model of PDF of wind power gradients → good fit

  depending on installed capacity → spatial distribution should be integrated

- approach to model the PSD of wind farms
  for low frequency range → exponential function
  and high frequency range → Kaimal spektrum

- analysis of coherence → model needs improvements

↓

further development

Modell Building → Simulation

anticipating future scenarios

weather model data ↓ 2004 – 2007, 1h

Preparation of the weather model data
-logarithmical interpolation at hub heights 2020
-insertion of measured 15min-values of wind speed
-across-the-board decrease of wind speed
-smoothing of the time series of wind speed

wind speed ↓ 2004 – 2007, 15min

Park effect

reduced wind speed ↓ 2004 – 2007, 15min

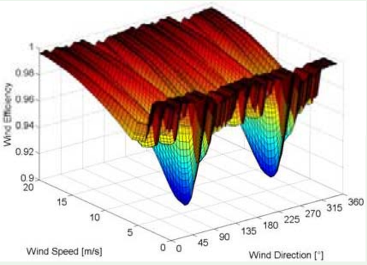
Power curves of wind farms 2020
-determination of nominal power 2020
-deletion and repowering of old wind turbines
-summarizing of remaining and modelled power curves
-spatial smoothing of summarized power curves

wind power ↓ 2020, 4 wind years, 15min

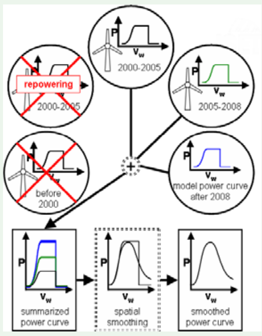
Losses of power output
-availability
-grid losses

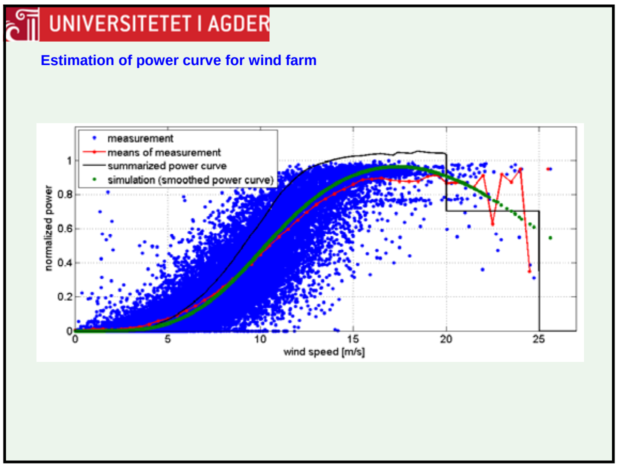
reduced wind power ↓ 2020, 4 wind years, 15min

Park effect::
Wind farm efficiency (average for 12 farms)

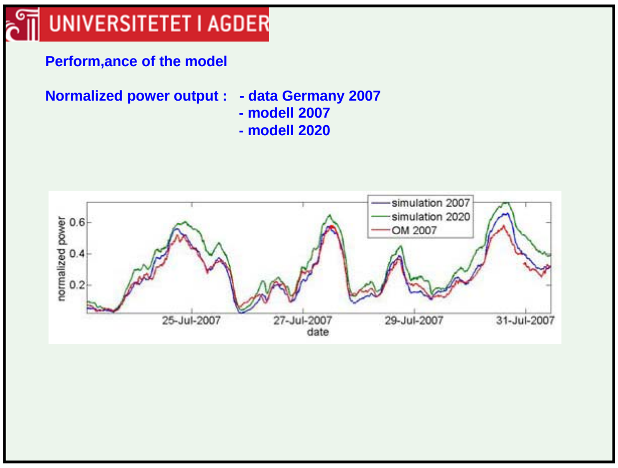


Estimation of power curves for future 'average' turbine



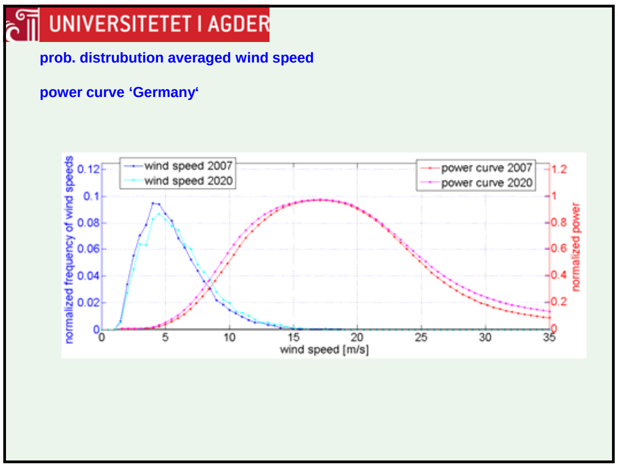


Estimation of power curve for wind farm



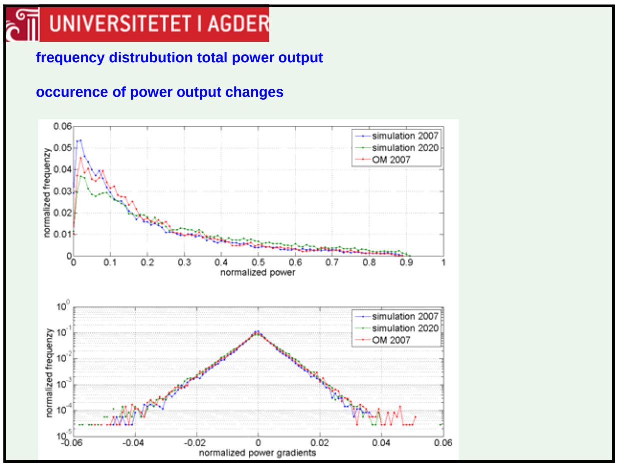
Perform,ance of the model

Normalized power output : - data Germany 2007
- modell 2007
- modell 2020



prob. distrubution averaged wind speed

power curve 'Germany'



frequency distrubution total power output

occurence of power output changes

Characterization and Modeling
of the Variability
of Power Output from Aggregated Wind Farms

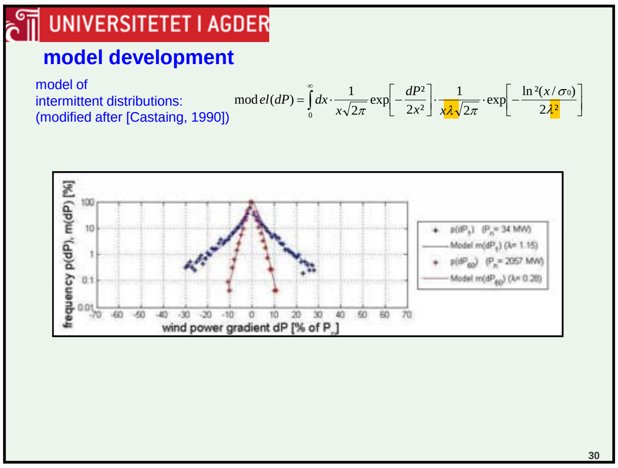
DEWK 2008

C. Quintero, K.Knorr, B. Lange, H.G. Beyer

Simulation and Analysis of Future Wind
Power Scenarios

EWEC 2009

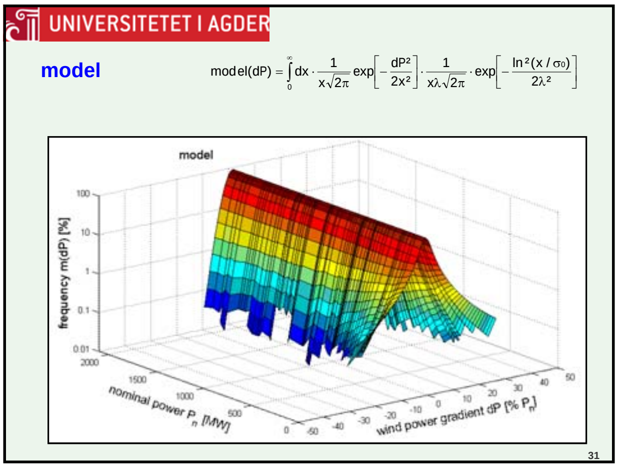
K. Knorr, C.A. Quintero Marrone, D. Callies,
B. Lange, K. Rohrig, H.G. Beyer



model development

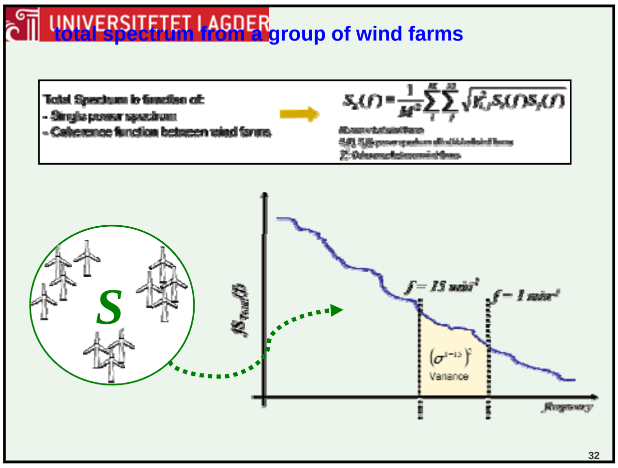
model of
intermittent distributions:
(modified after [Castaing, 1990])

$$\mathrm{mod}\,el(dP)=\int_0^{\infty} dx\cdot\frac{1}{x\sqrt{2\pi}}\exp\left[-\frac{dP^2}{2x^2}\right]\cdot\frac{1}{x\lambda\sqrt{2\pi}}\cdot\exp\left[-\frac{\ln^2(x/\sigma_0)}{2\lambda^2}\right]$$



model

$$\mathrm{model}(dP) = \int_0^\infty dx \cdot \frac{1}{x\sqrt{2\pi}} \exp\left[-\frac{dP^2}{2x^2}\right] \cdot \frac{1}{x\lambda\sqrt{2\pi}} \cdot \exp\left[-\frac{\ln^2(x/\sigma_0)}{2\lambda^2}\right]$$



total spectrum from a group of wind farms

Total Spectrum in function of:
- Single power spectrum
- Coherence function between wind farms

$$S_\Sigma(f) = \frac{1}{M^2}\sum_i^M\sum_j^M \sqrt{K_{ij}^2 S_i(f) S_j(f)}$$

Supply of offshore wind energy to oil and gas installations

Harald G Svendsen[1], Maheshkumar Hadiya[2],
Eirik V Øyslebø[1], Kjetil Uhlen[1,2]
[1] SINTEF Energy Research
[2]NTNU

Outline

- ▶ Background
- ▶ Simulation model
- ▶ Interesting observations / preliminary results
- ▶ Outlook

Background

- ▶ CO_2 emissions
- ▶ Electrification of offshore petroleum installations
  - cables from onshore grid?
  - net CO_2 gain only if new renewable generators are introduced
- ▶ Offshore wind energy
- ▶ Combine them!
  - Electrify offshore platforms with offshore wind
  - How?

Objectives

- ▶ Power system point of view

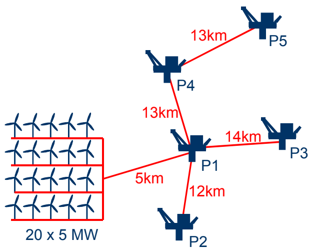
- ▶ Voltage level / power losses
- ▶ Voltage and frequency stability
- ▶ Control strategies
- ▶ Grid topology

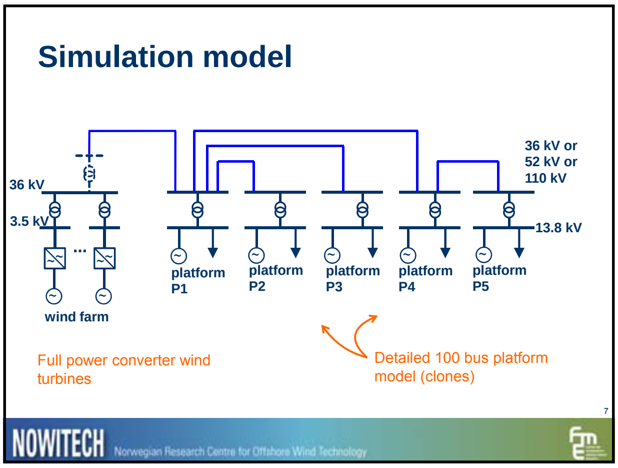
Previous Statoil study

- ▶ 20 MW wind farm / single platform
- ▶ Operational benefits
  - fuel saving
  - emission reduction
- ▶ Power stability
  - Max transient voltage deviation: ΔV = 18% (motor start-up)
  - Max transient frequency deviation: Δf = 7.3% (loss of all wind)
  - Wind fluctuations: Δf = ±1%, ΔV = ±0.05%

W. He et al., *The Potential of Integrating Wind Power with Offshore Oil and Gas Platforms*, Wind Engineering 34 (**2010**) 2, pp 125-137.

Case study model

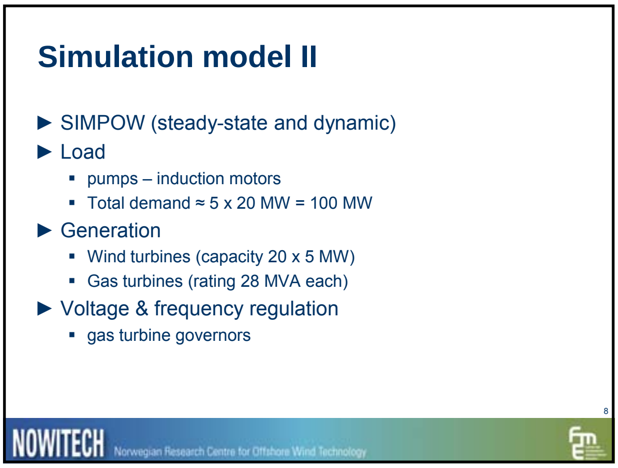




Simulation model

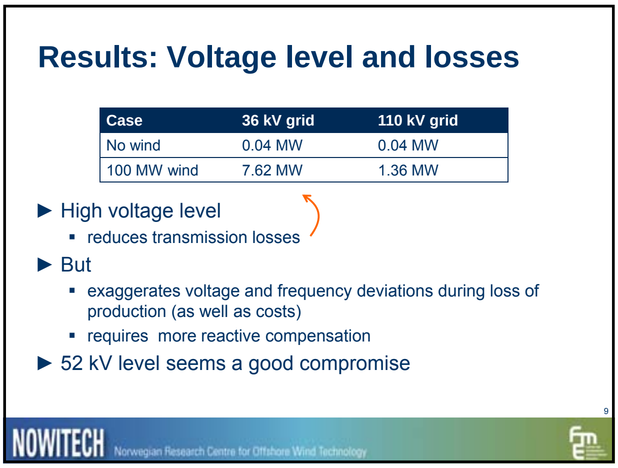
Full power converter wind turbines

Detailed 100 bus platform model (clones)



Simulation model II

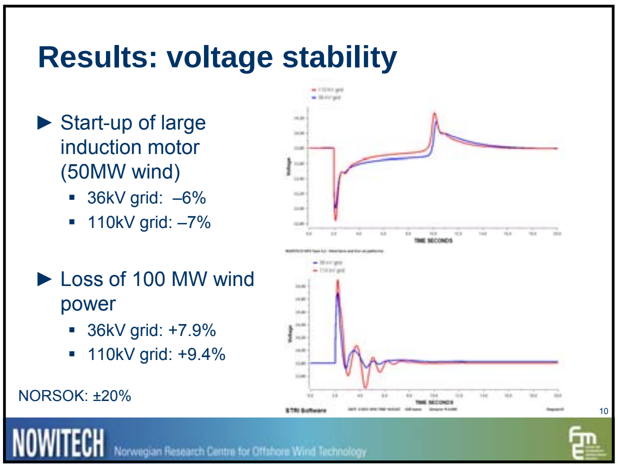
- SIMPOW (steady-state and dynamic)
- Load
  - pumps – induction motors
  - Total demand ≈ 5 x 20 MW = 100 MW
- Generation
  - Wind turbines (capacity 20 x 5 MW)
  - Gas turbines (rating 28 MVA each)
- Voltage & frequency regulation
  - gas turbine governors



Results: Voltage level and losses

Case	36 kV grid	110 kV grid
No wind	0.04 MW	0.04 MW
100 MW wind	7.62 MW	1.36 MW

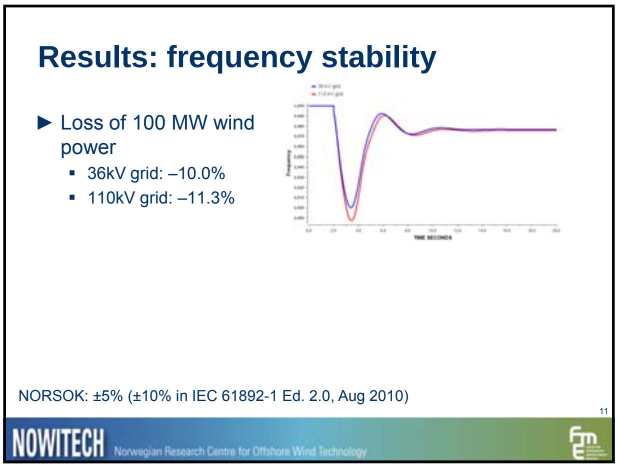
- High voltage level
  - reduces transmission losses
- But
  - exaggerates voltage and frequency deviations during loss of production (as well as costs)
  - requires more reactive compensation
- 52 kV level seems a good compromise



Results: voltage stability

- Start-up of large induction motor (50MW wind)
  - 36kV grid: –6%
  - 110kV grid: –7%
- Loss of 100 MW wind power
  - 36kV grid: +7.9%
  - 110kV grid: +9.4%

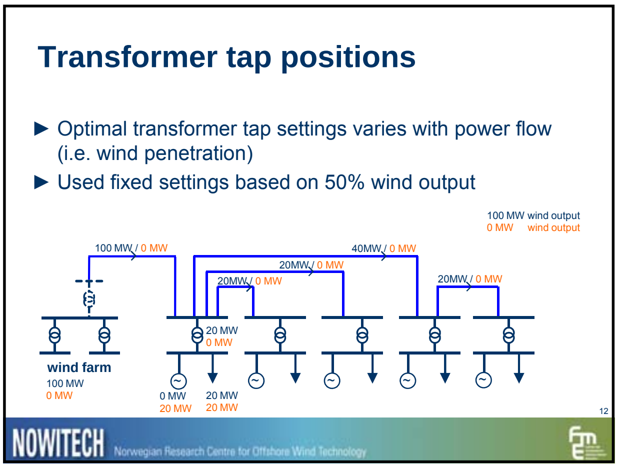
NORSOK: ±20%



Results: frequency stability

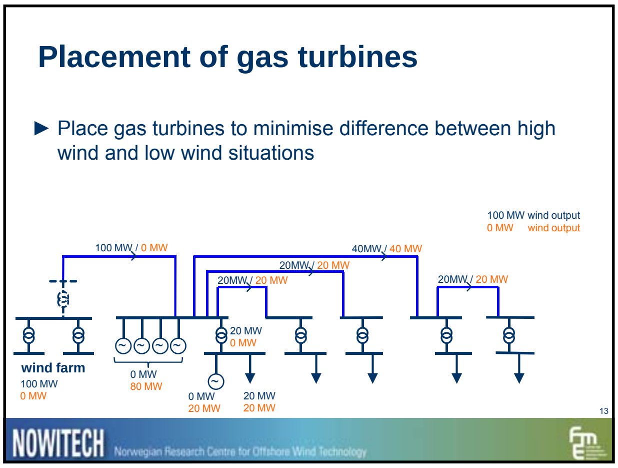
- Loss of 100 MW wind power
  - 36kV grid: –10.0%
  - 110kV grid: –11.3%

NORSOK: ±5% (±10% in IEC 61892-1 Ed. 2.0, Aug 2010)



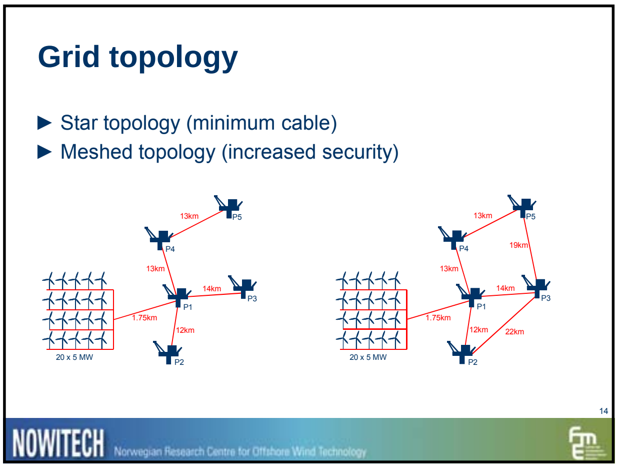
Transformer tap positions

- Optimal transformer tap settings varies with power flow (i.e. wind penetration)
- Used fixed settings based on 50% wind output



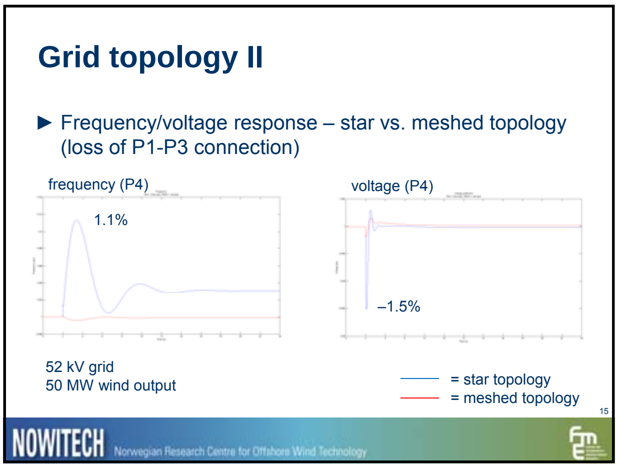
Placement of gas turbines

- ▶ Place gas turbines to minimise difference between high wind and low wind situations



Grid topology

- ▶ Star topology (minimum cable)
- ▶ Meshed topology (increased security)

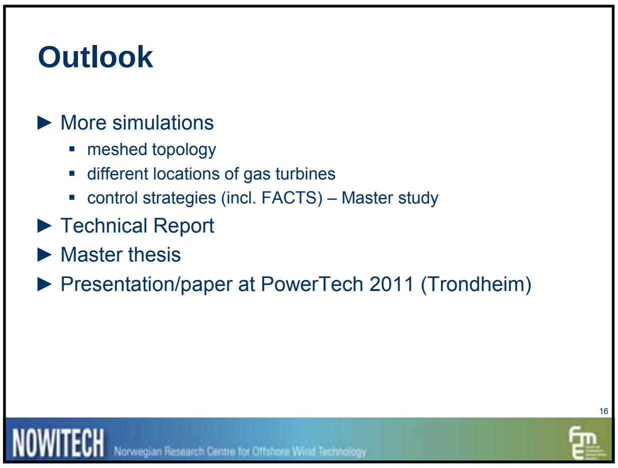


Grid topology II

- ▶ Frequency/voltage response – star vs. meshed topology (loss of P1-P3 connection)

52 kV grid
50 MW wind output

—— = star topology
—— = meshed topology



Outlook

- ▶ More simulations
  - meshed topology
  - different locations of gas turbines
  - control strategies (incl. FACTS) – Master study
- ▶ Technical Report
- ▶ Master thesis
- ▶ Presentation/paper at PowerTech 2011 (Trondheim)

Balance Management with Large Scale Offshore Wind Integration

Steve Völler

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NOWITECH - *Norwegian Research Centre for Offshore Wind Technology*

- Postdoc at NOWITECH / NTNU

  "Balance Management with Large Scale Offshore Wind Integration"

- Research activities

WP1	integrated numerical design tools
WP2	energy conversion systems
WP3	novel substructures
WP4	**grid connection and system integration**
WP5	operation and maintenance
WP6	novel concepts from previous WP

Balance Management with Large Scale Offshore Wind Integration

- Look at the total variability of wind production in the North Sea for different scenarios and time steps
- Influences of futures grids
- Balancing potential of Norway
- Optimal schedule of generation
- Influences of forecasts deviations

- Required: better models, detailed data (generation, load, wind), offshore/onshore grid expansion...

EMPS & PSST

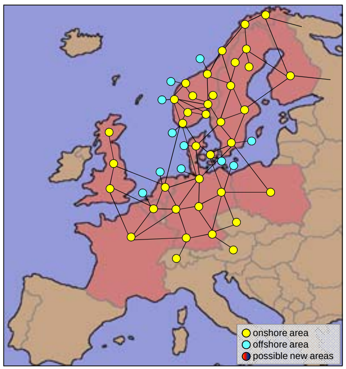
- EMPS (EFI's Multi-area Power-market Simulator) [SUSPLAN]
  - Mid- and long-term optimization of system operation on weekly basis
  - Socio-Economic market simulator assuming a perfect market
  - Hydro & thermal system, transmission lines, wind energy, consumption
  - Optimal unit commitment and generation dispatch
  - Results are area prices and water-values

- PSST (Power System Simulation Tool) [TradeWind]
  - Optimal power flow analysis in hourly time resolution
  - Minimises generation cost
  - Utilization of data & water-values from EMPS as input

EMPS Model

- Current status

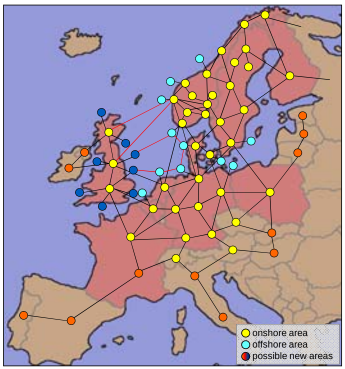
  - Extended Norden-model to countries around North Sea
  - Include some offshore wind areas
  - 700 generation units with start/stop-costs (300 in GB)

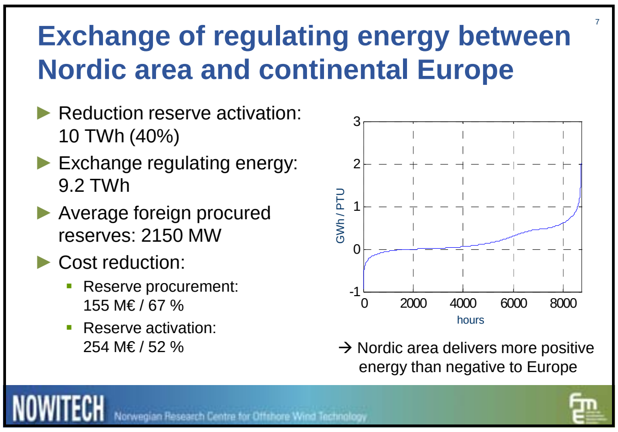


EMPS Model

- Next steps

  - GB offshore wind farms
  - Different variations of offshore grids and interconnections
  - Simplified areas of other countries in Europe

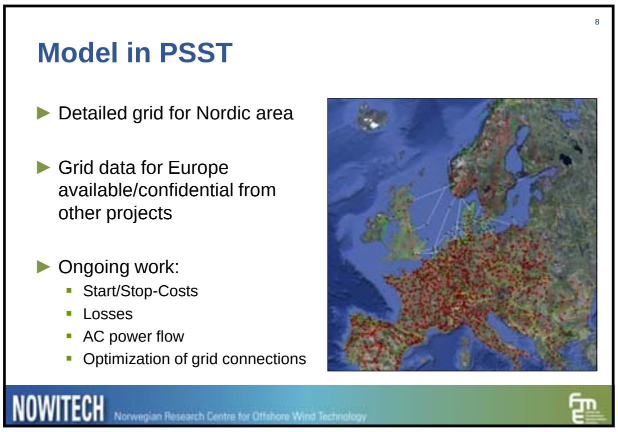




Exchange of regulating energy between Nordic area and continental Europe

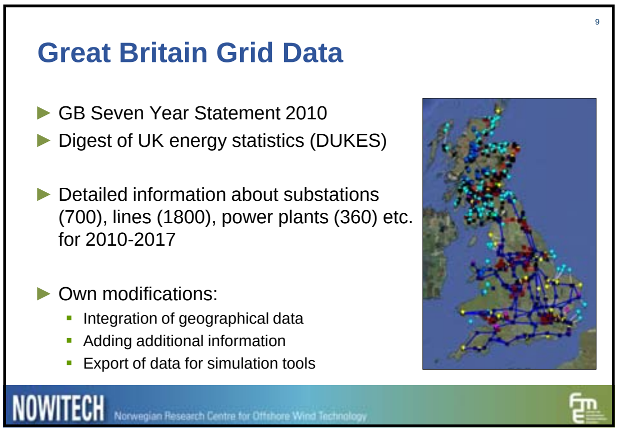
- Reduction reserve activation: 10 TWh (40%)
- Exchange regulating energy: 9.2 TWh
- Average foreign procured reserves: 2150 MW
- Cost reduction:
  - Reserve procurement: 155 M€ / 67 %
  - Reserve activation: 254 M€ / 52 %

→ Nordic area delivers more positive energy than negative to Europe



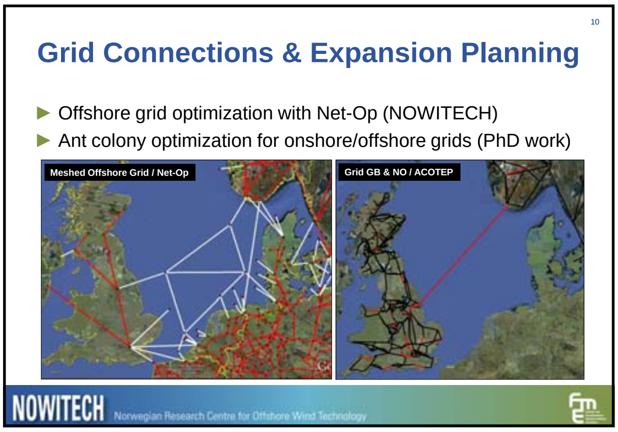
Model in PSST

- Detailed grid for Nordic area
- Grid data for Europe available/confidential from other projects
- Ongoing work:
  - Start/Stop-Costs
  - Losses
  - AC power flow
  - Optimization of grid connections



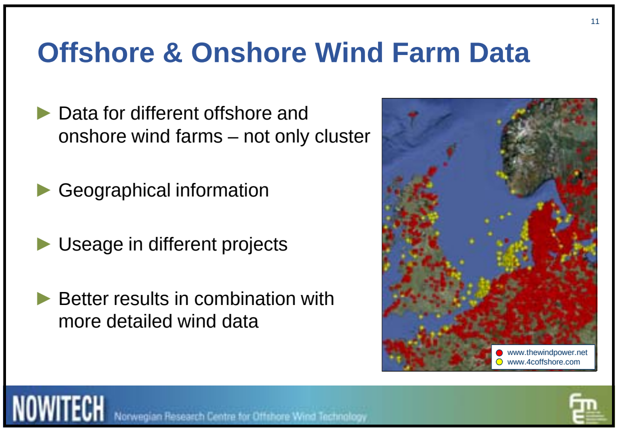
Great Britain Grid Data

- GB Seven Year Statement 2010
- Digest of UK energy statistics (DUKES)
- Detailed information about substations (700), lines (1800), power plants (360) etc. for 2010-2017
- Own modifications:
  - Integration of geographical data
  - Adding additional information
  - Export of data for simulation tools



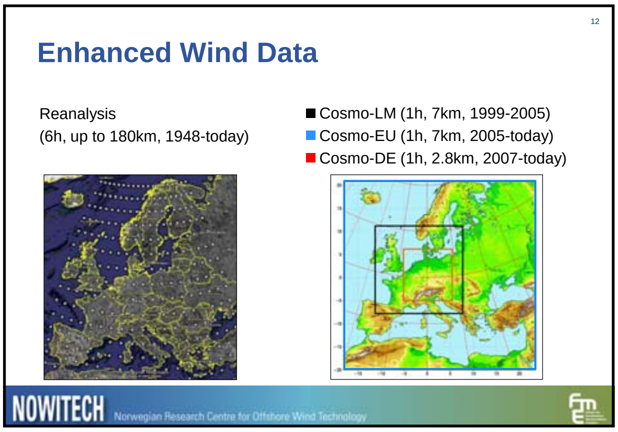
Grid Connections & Expansion Planning

- Offshore grid optimization with Net-Op (NOWITECH)
- Ant colony optimization for onshore/offshore grids (PhD work)



Offshore & Onshore Wind Farm Data

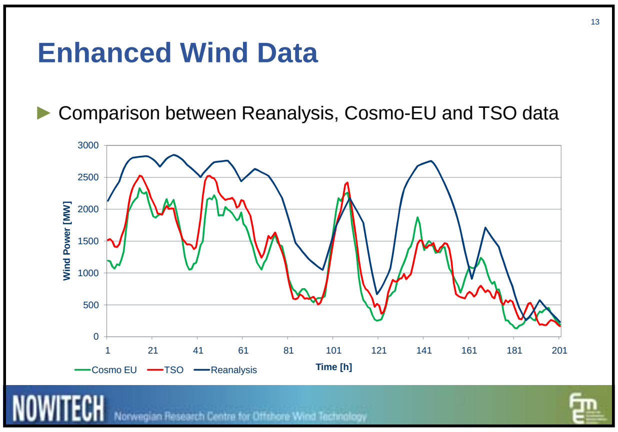
- Data for different offshore and onshore wind farms – not only cluster
- Geographical information
- Useage in different projects
- Better results in combination with more detailed wind data



Enhanced Wind Data

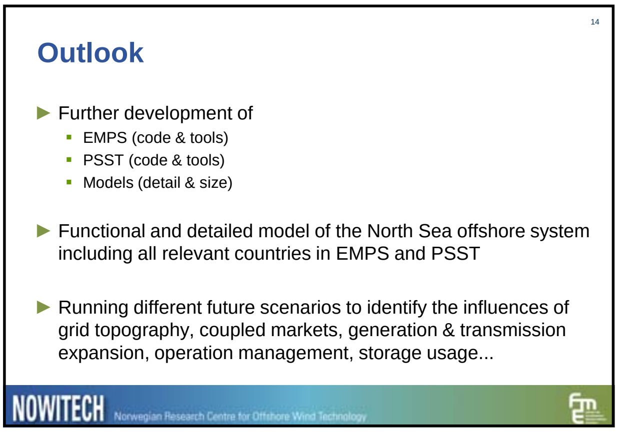
Reanalysis
(6h, up to 180km, 1948-today)

■ Cosmo-LM (1h, 7km, 1999-2005)
🟦 Cosmo-EU (1h, 7km, 2005-today)
🟥 Cosmo-DE (1h, 2.8km, 2007-today)



Enhanced Wind Data

- Comparison between Reanalysis, Cosmo-EU and TSO data



Outlook

- Further development of
  - EMPS (code & tools)
  - PSST (code & tools)
  - Models (detail & size)
- Functional and detailed model of the North Sea offshore system including all relevant countries in EMPS and PSST
- Running different future scenarios to identify the influences of grid topography, coupled markets, generation & transmission expansion, operation management, storage usage...

B2) Grid Connection

Challenges and design of offshore substations, Christer Olerud, Goodtech Projects & Services

Wind farm measurements and model validation, Prof Kjetil Uhlen, NTNU

Transient analysis of transformers and cables for offshore wind connection,
Bjørn Gustavsen, SINTEF Energi AS

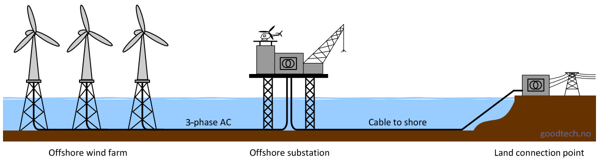
Wind R&D Seminar – Deep Sea Offshore Wind

Challenges and Design of Offshore Substations

Christer Olerud
Trondheim
20.01.2011

New large Nordic company

Offshore wind farm overview



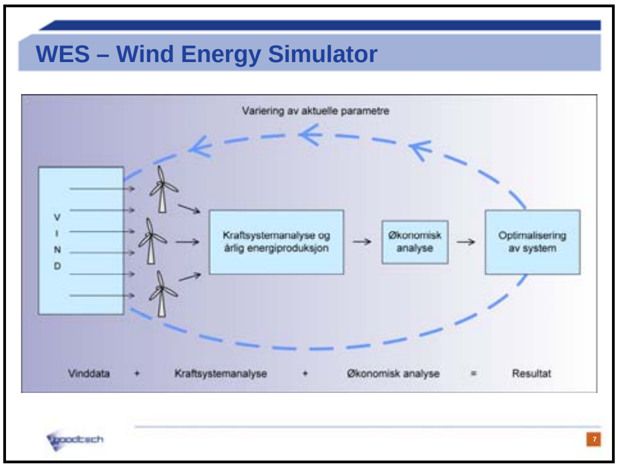
Offshore wind = multidiscipline industry

Main Challenges

- Location of offshore substation
- Number of offshore substations
- Infield cable pattern and choice of cable types
- Offshore substation layout
- Reactive power compensation
- Grid connection
- Total electrical system

Inter array cable network

- Optimizing inter-array cable network
- 1 or 2 substations, inside or outside wind farm area
- Radials or loops
- Cable sizes



WES – Wind Energy Simulator

Variering av aktuelle parametre

V I N D

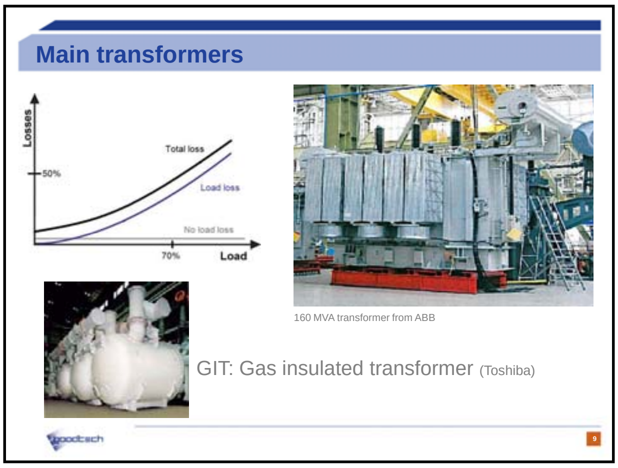
Kraftsystemanalyse og årlig energiproduksjon → Økonomisk analyse → Optimalisering av system

Vinddata + Kraftsystemanalyse + Økonomisk analyse = Resultat

Offshore substation layout and equipment

- Accommodation
- External cladding
- Optimized layout
- Installation *

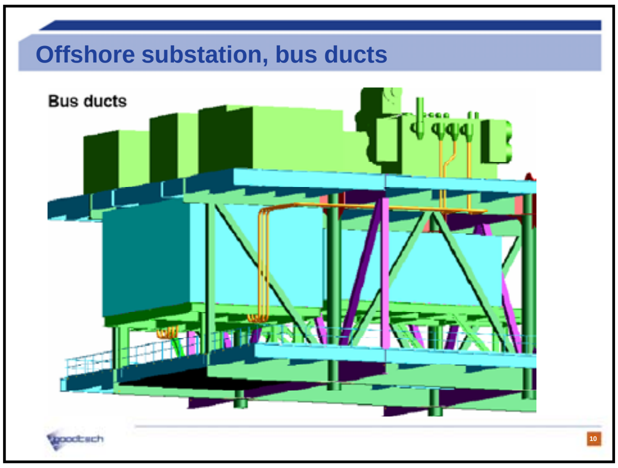
- Cooling of transformers *
- Switchgear
- Cable pull-in
- Bus ducts *



Main transformers

160 MVA transformer from ABB

GIT: Gas insulated transformer (Toshiba)



Offshore substation, bus ducts

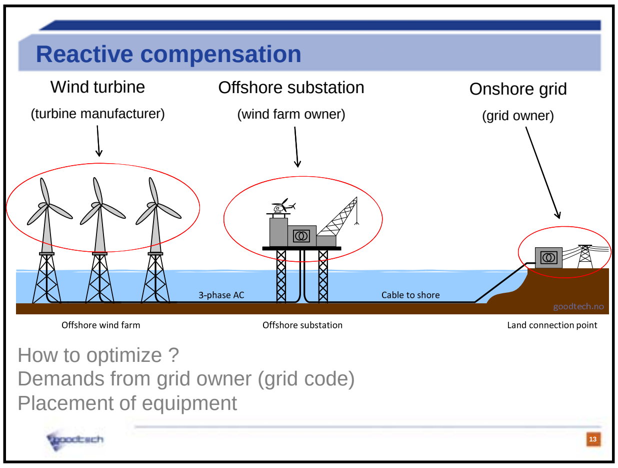
Bus ducts

Offshore substation, installation

http://www.scaldis-smc.com

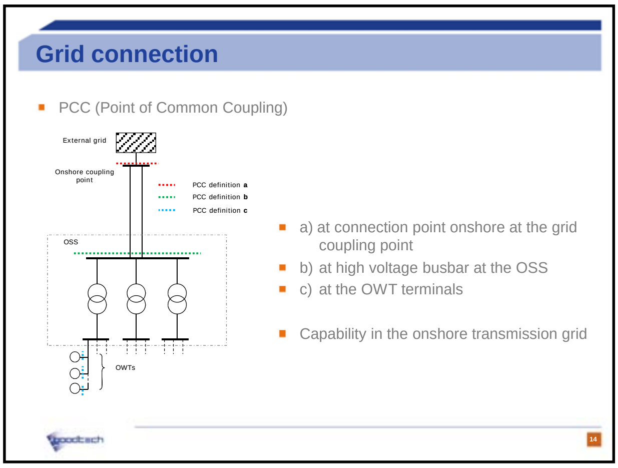
http://www.scaldis-smc.com

Offshore substations



Reactive compensation

How to optimize ?
Demands from grid owner (grid code)
Placement of equipment



Grid connection

- PCC (Point of Common Coupling)

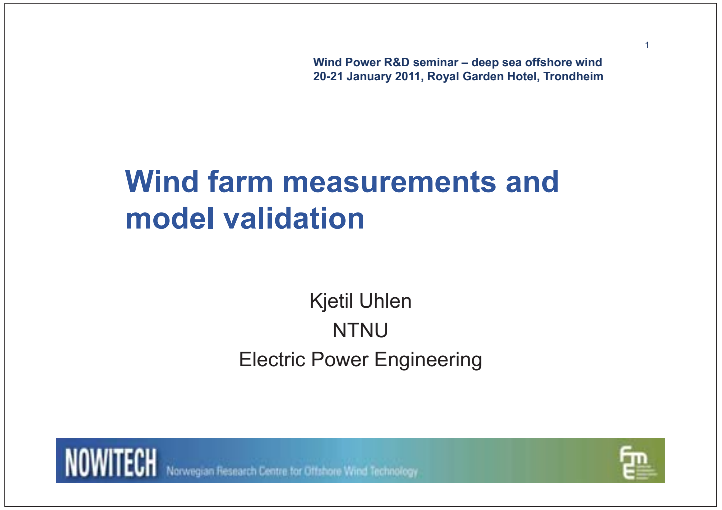
- a) at connection point onshore at the grid coupling point
- b) at high voltage busbar at the OSS
- c) at the OWT terminals

- Capability in the onshore transmission grid

Thank you for your attention!

Thank you for your attention!

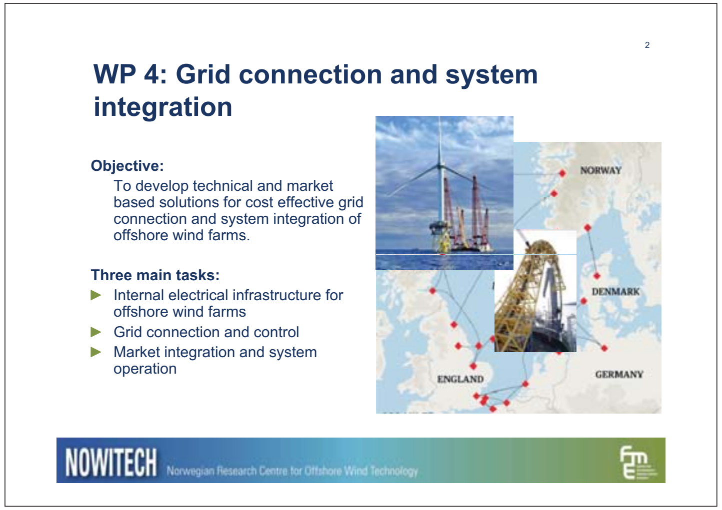
Contact person: christer.olerud@goodtech.no



Wind Power R&D seminar – deep sea offshore wind
20-21 January 2011, Royal Garden Hotel, Trondheim

Wind farm measurements and model validation

Kjetil Uhlen
NTNU
Electric Power Engineering



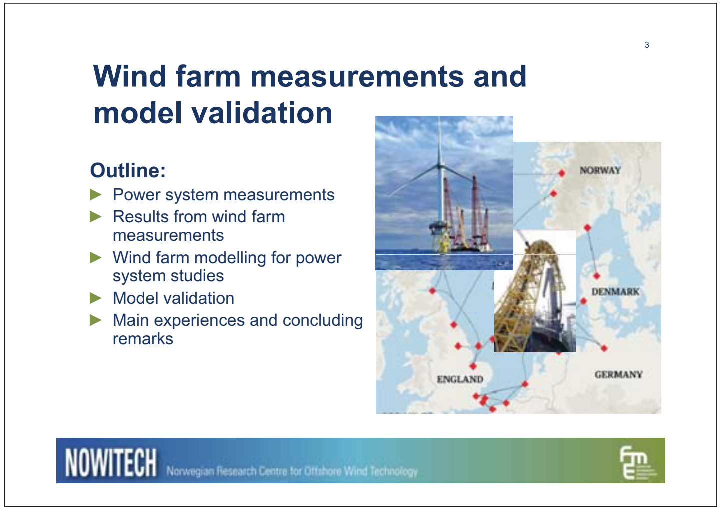
WP 4: Grid connection and system integration

Objective:

To develop technical and market based solutions for cost effective grid connection and system integration of offshore wind farms.

Three main tasks:

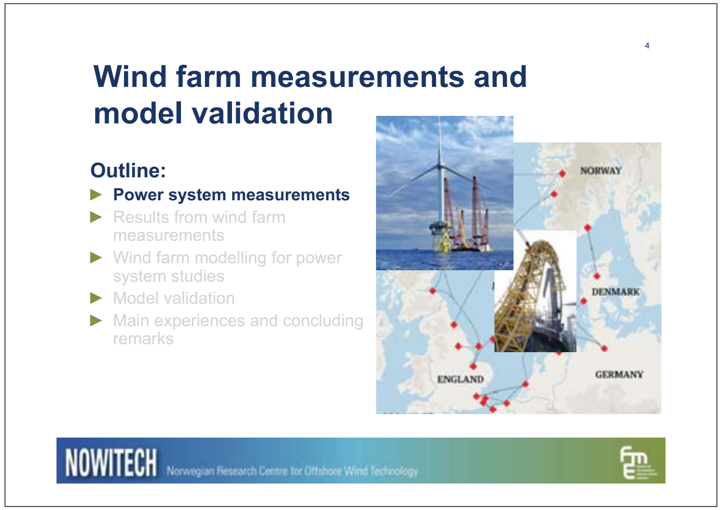
- Internal electrical infrastructure for offshore wind farms
- Grid connection and control
- Market integration and system operation



Wind farm measurements and model validation

Outline:

- Power system measurements
- Results from wind farm measurements
- Wind farm modelling for power system studies
- Model validation
- Main experiences and concluding remarks



Wind farm measurements and model validation

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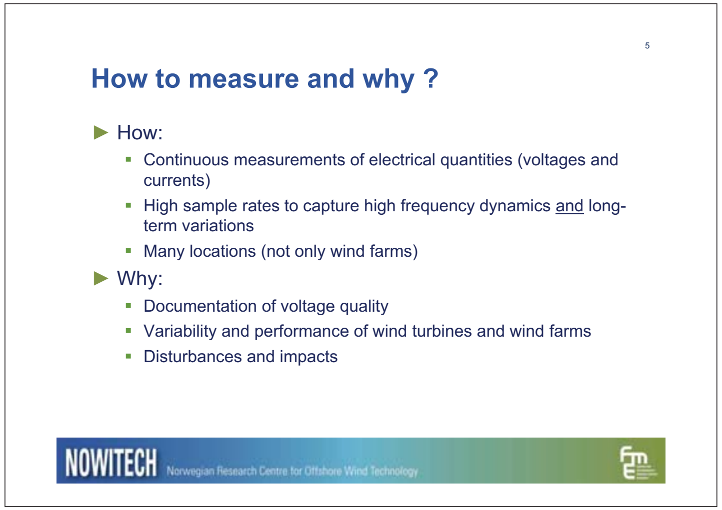
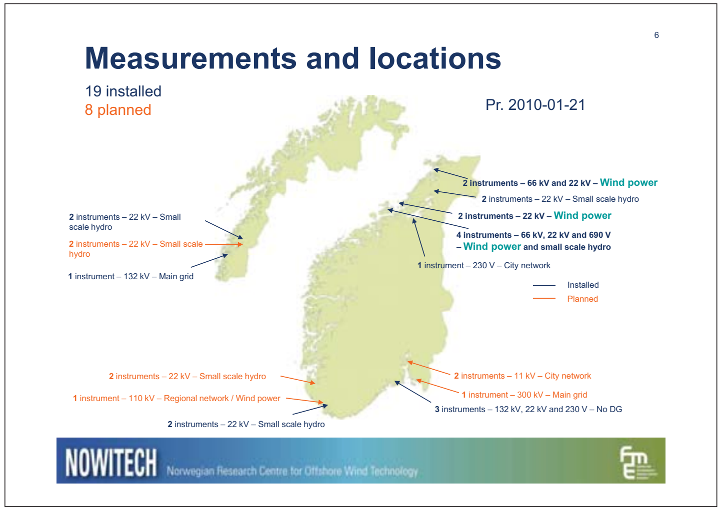


How to measure and why ?

- How:
  - Continuous measurements of electrical quantities (voltages and currents)
  - High sample rates to capture high frequency dynamics and long-term variations
  - Many locations (not only wind farms)
- Why:
  - Documentation of voltage quality
  - Variability and performance of wind turbines and wind farms
  - Disturbances and impacts



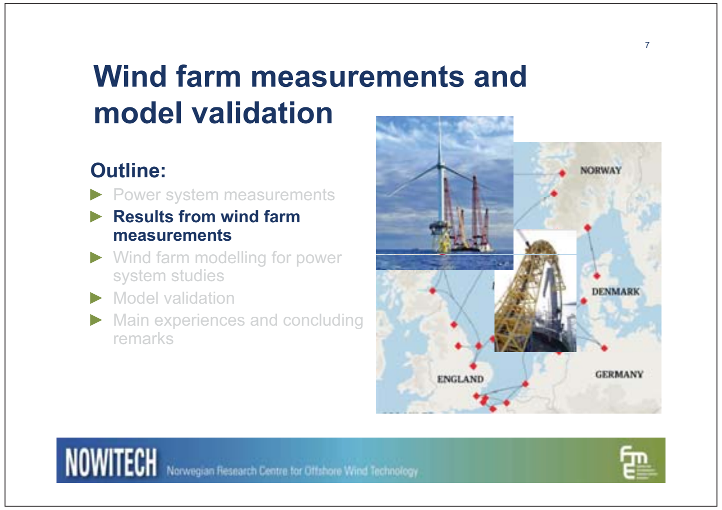
Measurements and locations

19 installed
8 planned

Pr. 2010-01-21

2 instruments – 66 kV and 22 kV – Wind power
2 instruments – 22 kV – Small scale hydro
2 instruments – 22 kV – Wind power
4 instruments – 66 kV, 22 kV and 690 V – Wind power and small scale hydro
1 instrument – 230 V – City network
2 instruments – 22 kV – Small scale hydro
2 instruments – 22 kV – Small scale hydro
1 instrument – 132 kV – Main grid
2 instruments – 22 kV – Small scale hydro
1 instrument – 110 kV – Regional network / Wind power
2 instruments – 22 kV – Small scale hydro
2 instruments – 11 kV – City network
1 instrument – 300 kV – Main grid
3 instruments – 132 kV, 22 kV and 230 V – No DG

Installed
Planned



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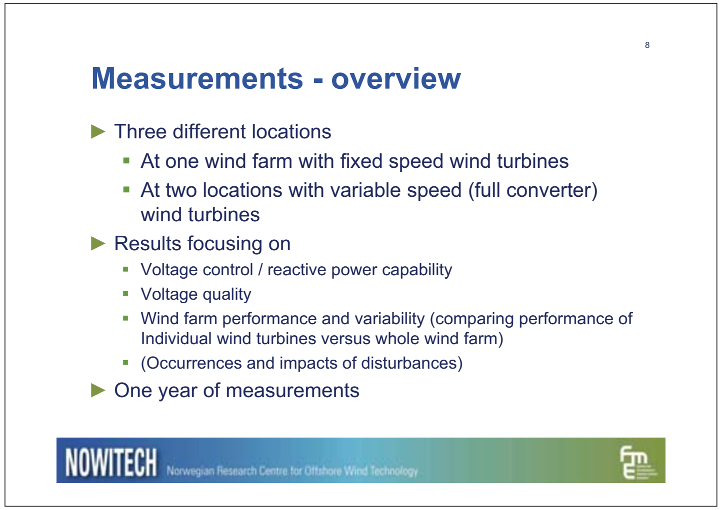
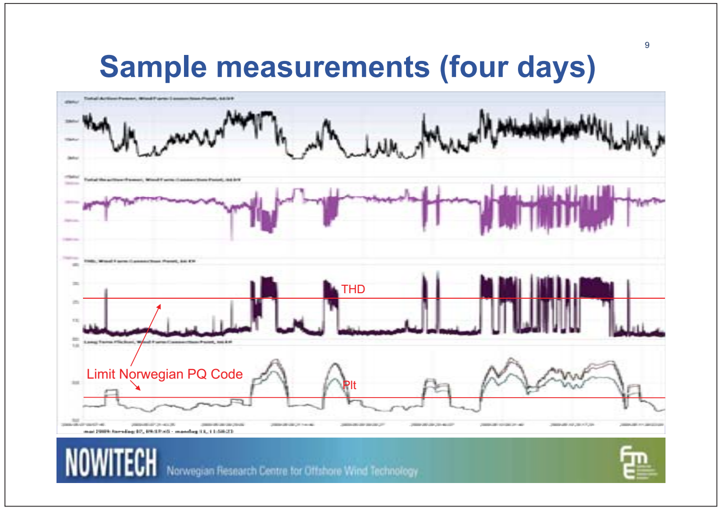
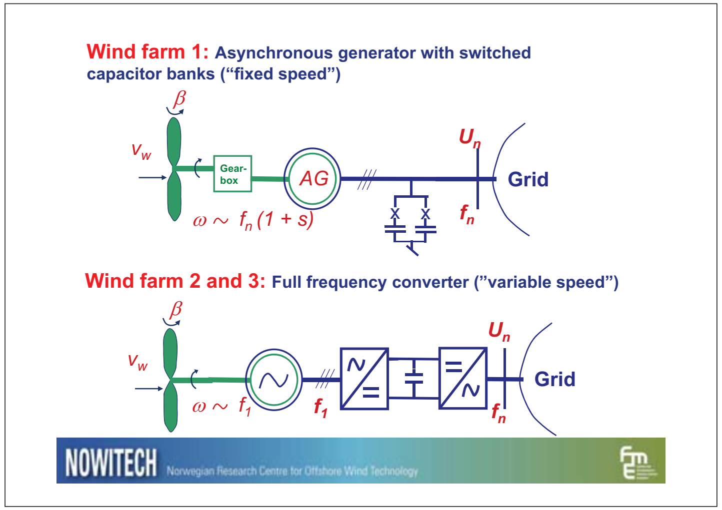


Measurements - overview

- Three different locations
  - At one wind farm with fixed speed wind turbines
  - At two locations with variable speed (full converter) wind turbines
- Results focusing on
  - Voltage control / reactive power capability
  - Voltage quality
  - Wind farm performance and variability (comparing performance of Individual wind turbines versus whole wind farm)
  - (Occurrences and impacts of disturbances)
- One year of measurements

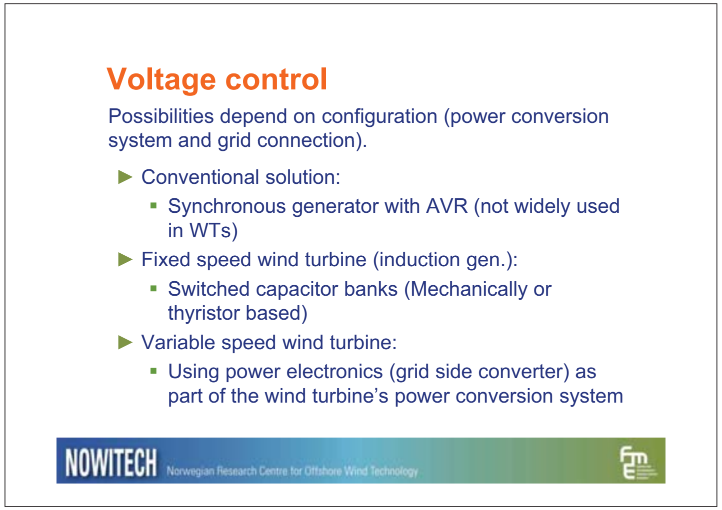


Sample measurements (four days)



Wind farm 1: **Asynchronous generator with switched capacitor banks ("fixed speed")**

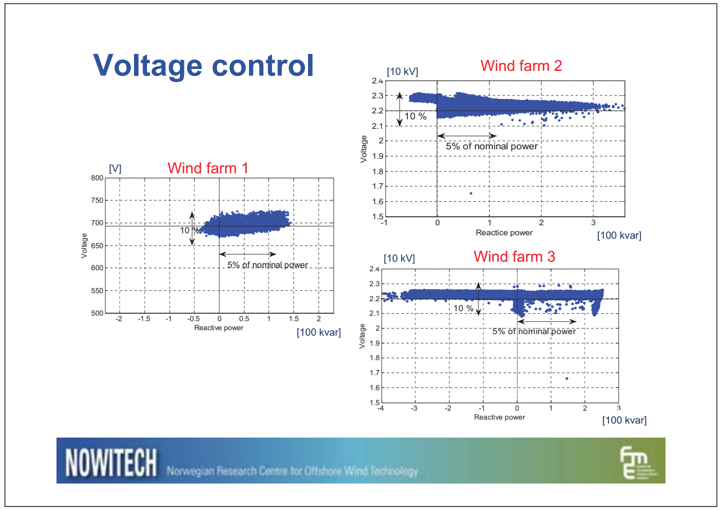
Wind farm 2 and 3: **Full frequency converter ("variable speed")**



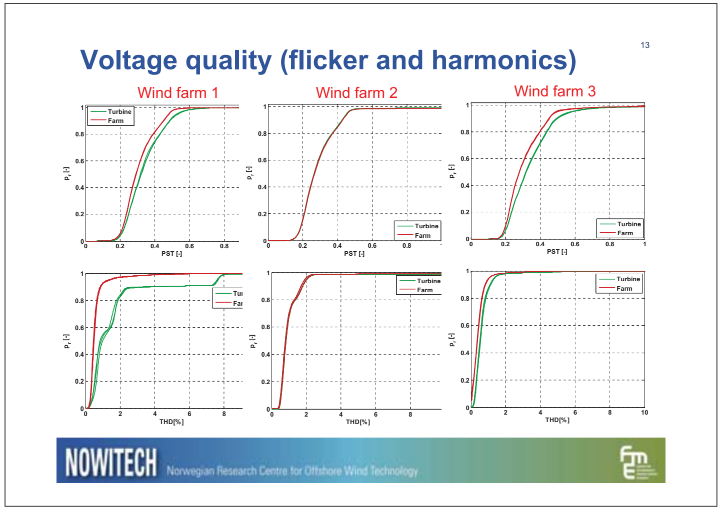
Voltage control

Possibilities depend on configuration (power conversion system and grid connection).

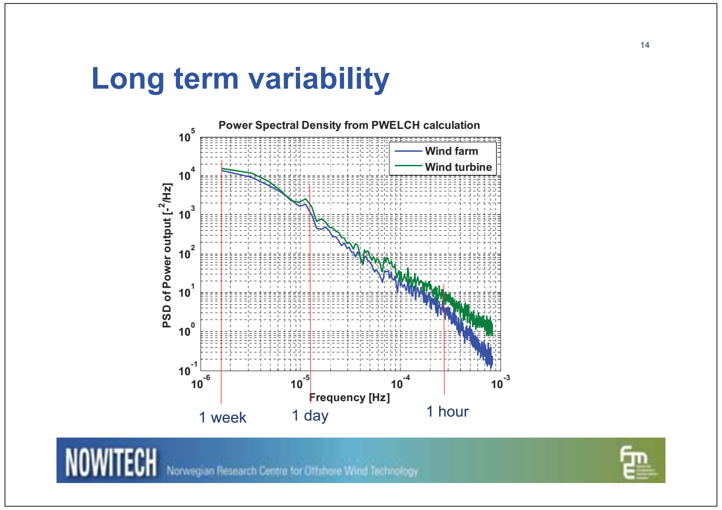
- Conventional solution:
  - Synchronous generator with AVR (not widely used in WTs)
- Fixed speed wind turbine (induction gen.):
  - Switched capacitor banks (Mechanically or thyristor based)
- Variable speed wind turbine:
  - Using power electronics (grid side converter) as part of the wind turbine's power conversion system



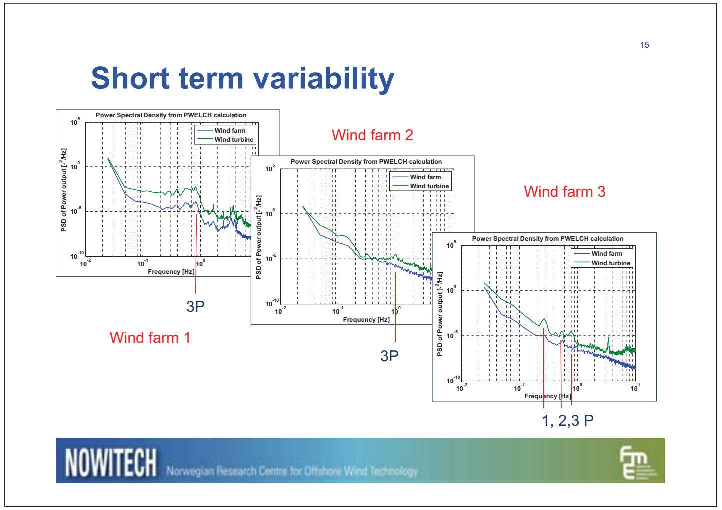
Voltage control



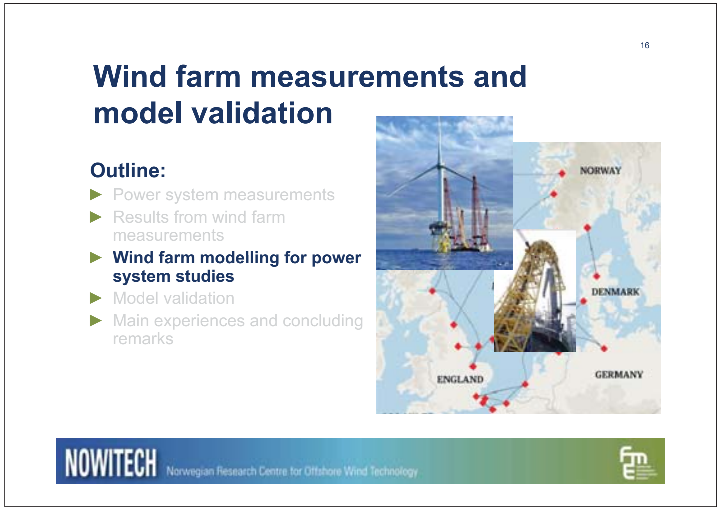
Voltage quality (flicker and harmonics)



Long term variability



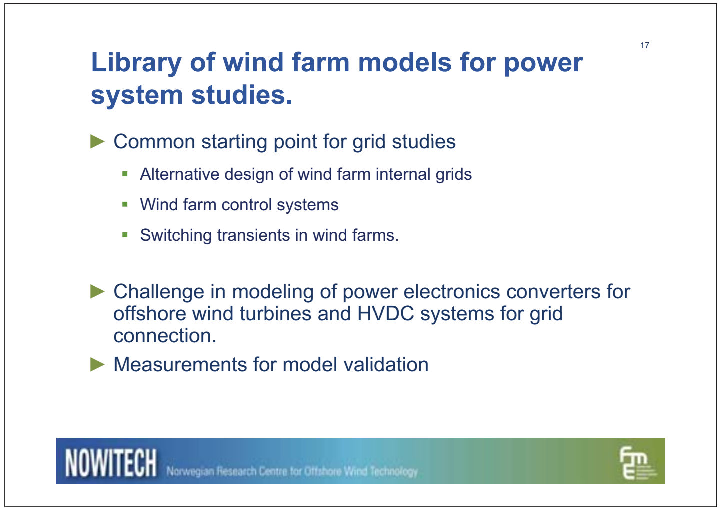
Short term variability



Wind farm measurements and model validation

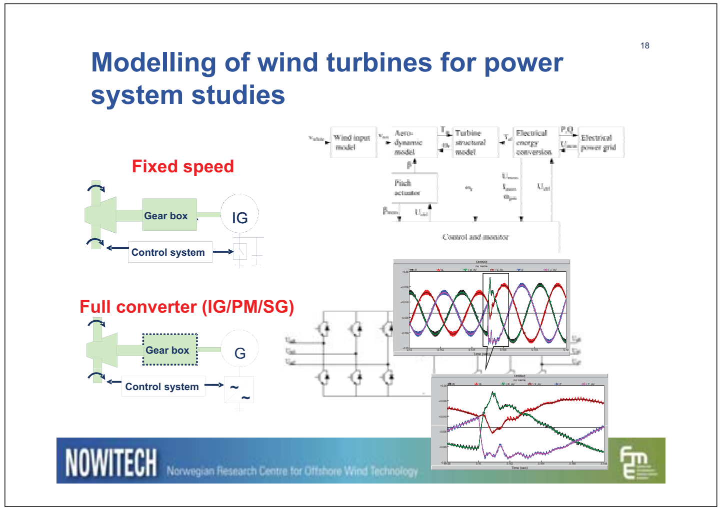
Outline:

- Power system measurements
- Results from wind farm measurements
- **Wind farm modelling for power system studies**
- Model validation
- Main experiences and concluding remarks

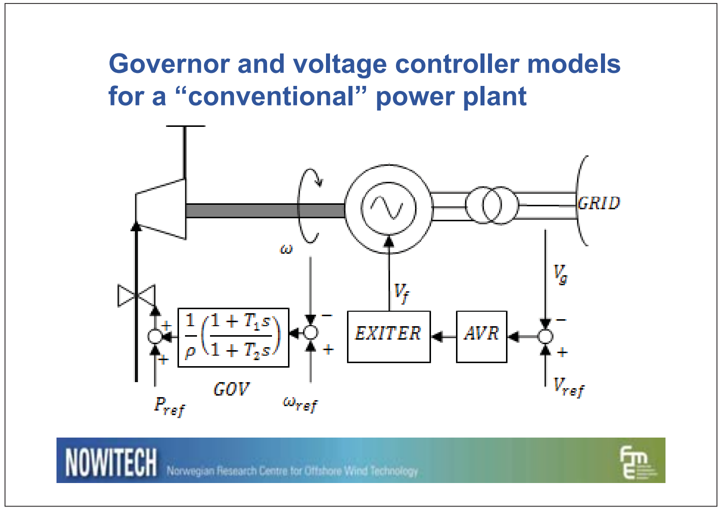


Library of wind farm models for power system studies.

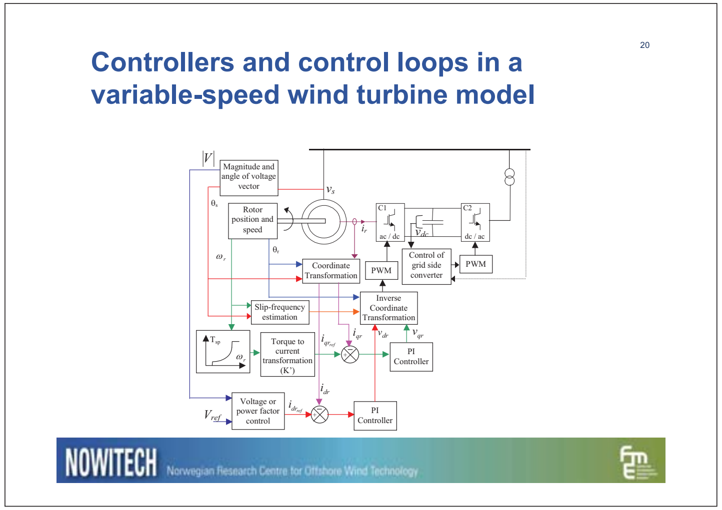
- Common starting point for grid studies
  - Alternative design of wind farm internal grids
  - Wind farm control systems
  - Switching transients in wind farms.
- Challenge in modeling of power electronics converters for offshore wind turbines and HVDC systems for grid connection.
- Measurements for model validation



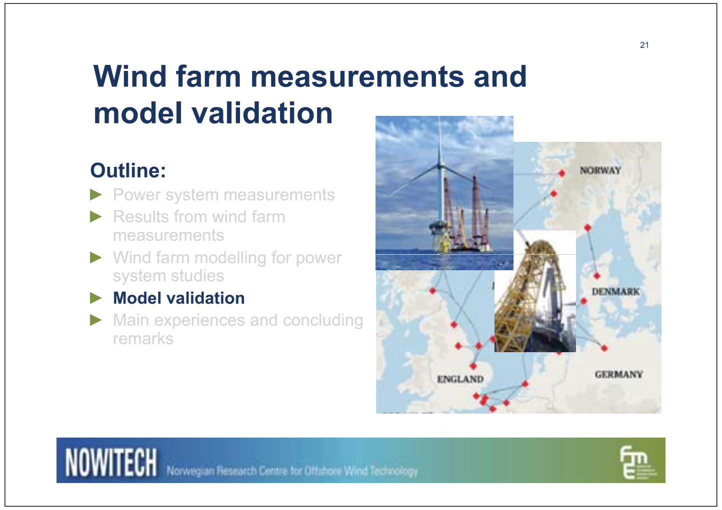
Modelling of wind turbines for power system studies



Governor and voltage controller models for a “conventional” power plant



Controllers and control loops in a variable-speed wind turbine model



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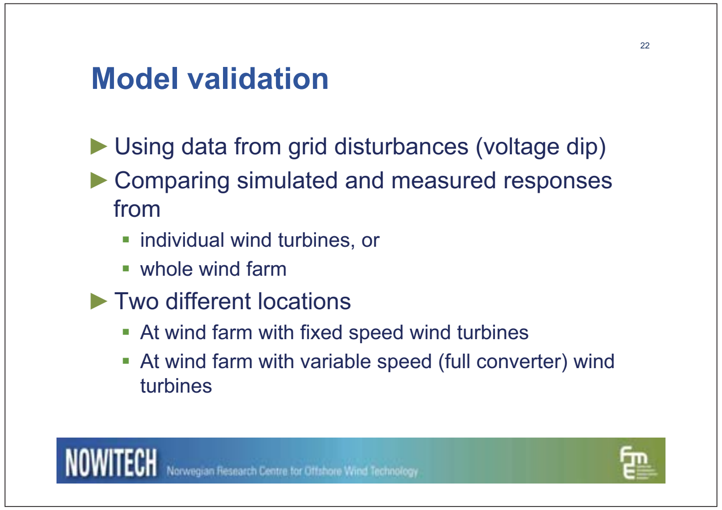
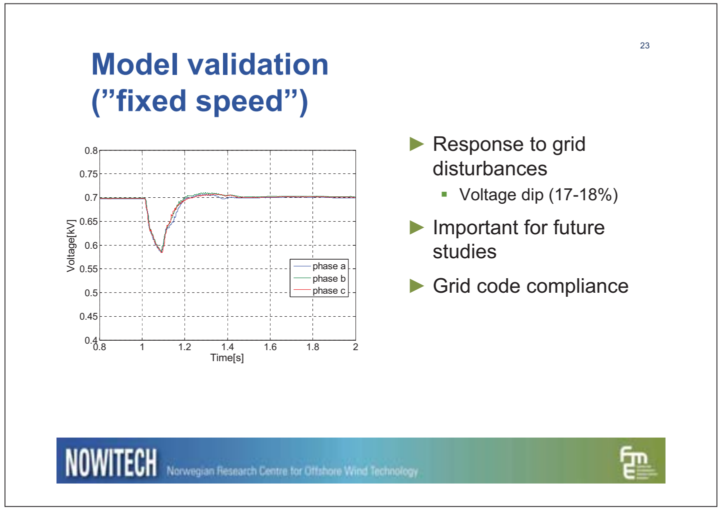


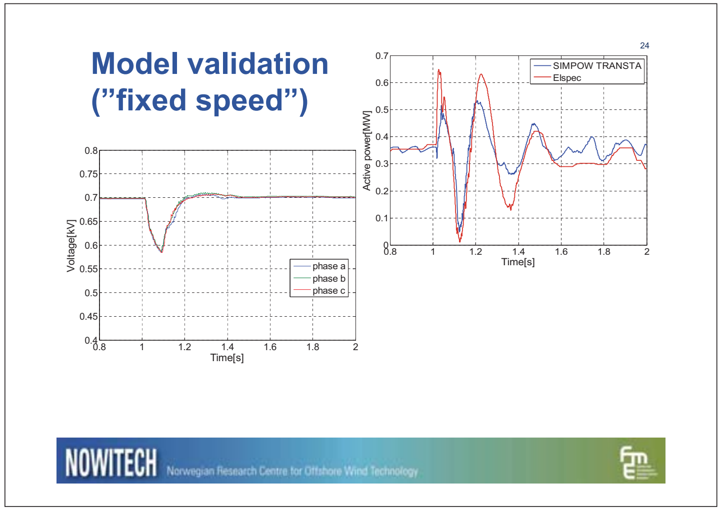
Model validation

- Using data from grid disturbances (voltage dip)
- Comparing simulated and measured responses from
  - individual wind turbines, or
  - whole wind farm
- Two different locations
  - At wind farm with fixed speed wind turbines
  - At wind farm with variable speed (full converter) wind turbines

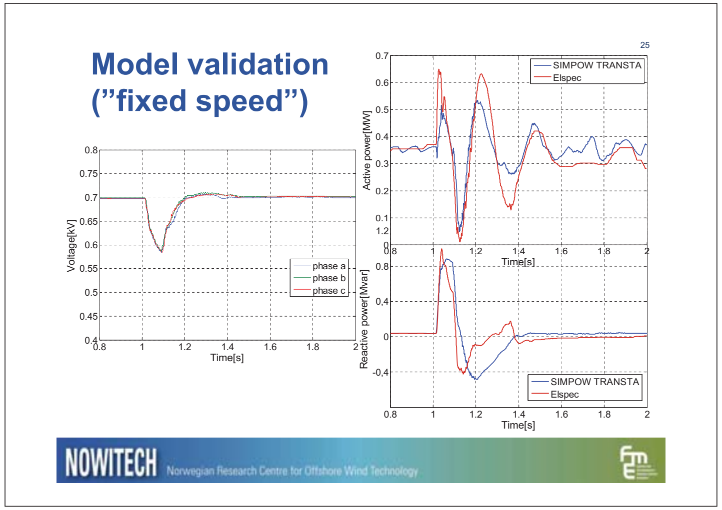


Model validation (”fixed speed”)

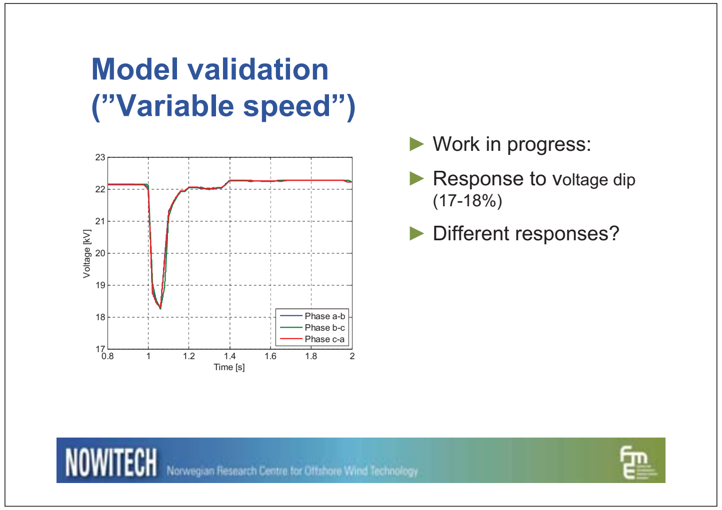
- Response to grid disturbances
  - Voltage dip (17-18%)
- Important for future studies
- Grid code compliance



Model validation (”fixed speed”)

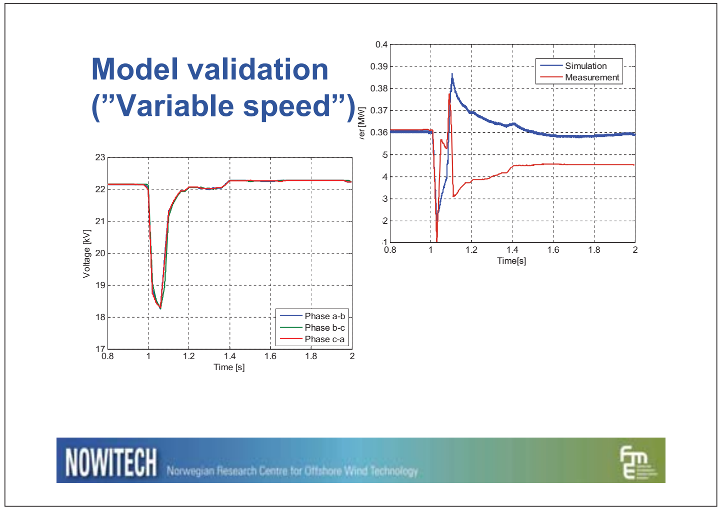


Model validation ("fixed speed")

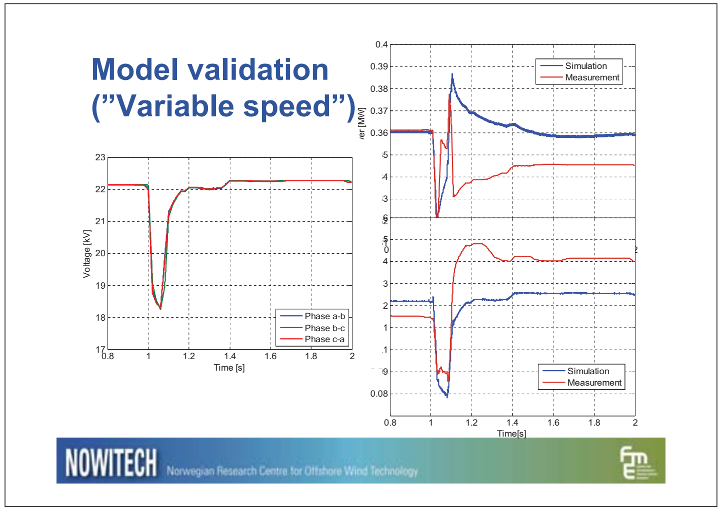


Model validation ("Variable speed")

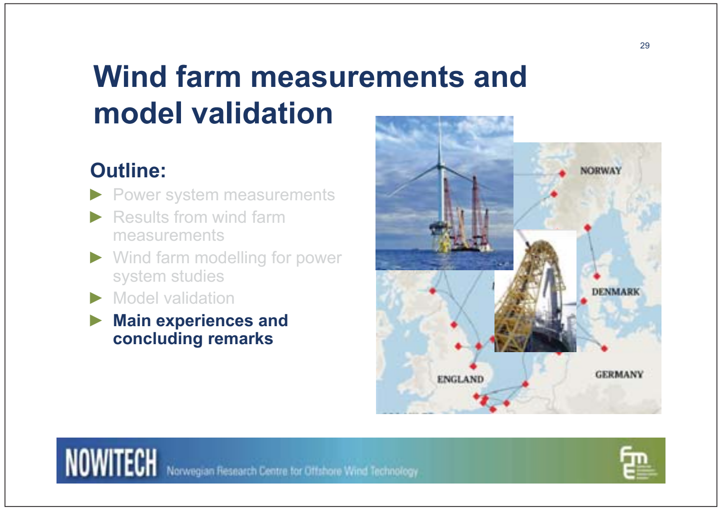
- Work in progress:
- Response to voltage dip (17-18%)
- Different responses?



Model validation ("Variable speed")



Model validation ("Variable speed")



Wind farm measurements and model validation

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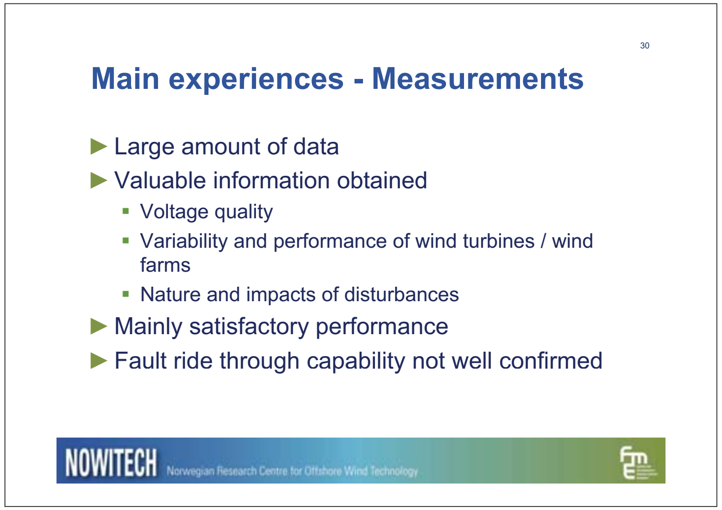
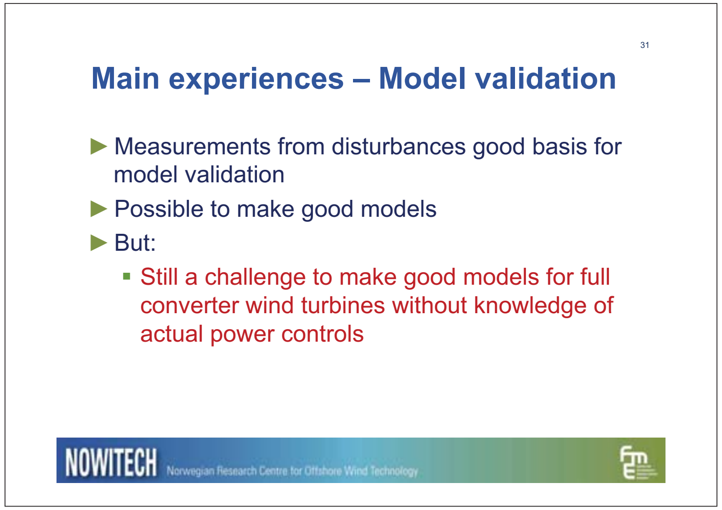
- **Main experiences and concluding remarks**



Main experiences - Measurements

- Large amount of data
- Valuable information obtained
  - Voltage quality
  - Variability and performance of wind turbines / wind farms
  - Nature and impacts of disturbances
- Mainly satisfactory performance
- Fault ride through capability not well confirmed



Main experiences – Model validation

- Measurements from disturbances good basis for model validation
- Possible to make good models
- But:
  - Still a challenge to make good models for full converter wind turbines without knowledge of actual power controls

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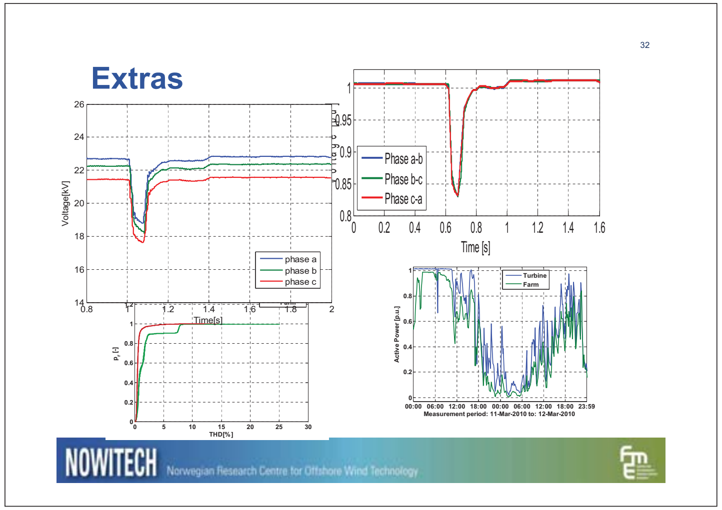
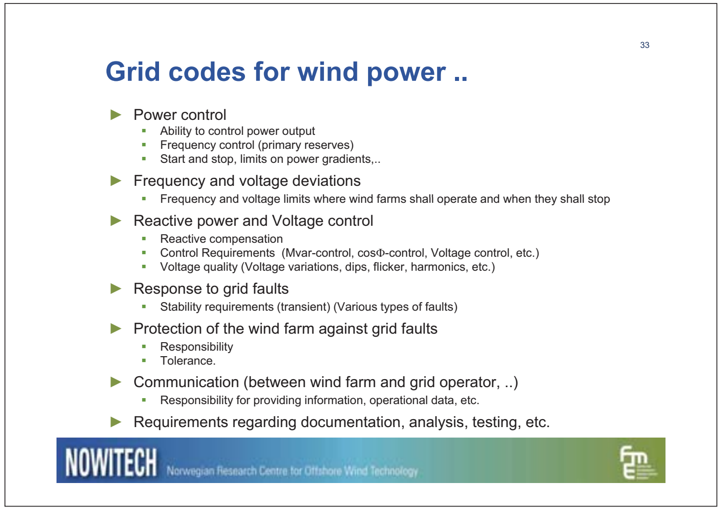
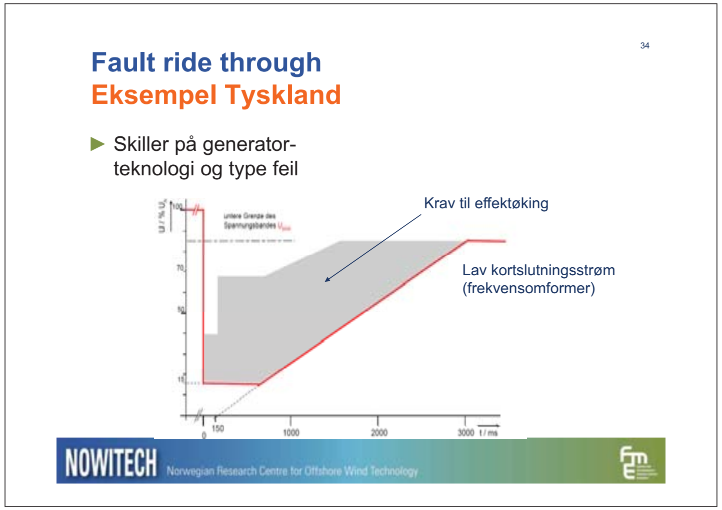


Extras



Grid codes for wind power ..

- Power control
  - Ability to control power output
  - Frequency control (primary reserves)
  - Start and stop, limits on power gradients,..
- Frequency and voltage deviations
  - Frequency and voltage limits where wind farms shall operate and when they shall stop
- Reactive power and Voltage control
  - Reactive compensation
  - Control Requirements (Mvar-control, cosΦ-control, Voltage control, etc.)
  - Voltage quality (Voltage variations, dips, flicker, harmonics, etc.)
- Response to grid faults
  - Stability requirements (transient) (Various types of faults)
- Protection of the wind farm against grid faults
  - Responsibility
  - Tolerance.
- Communication (between wind farm and grid operator, ..)
  - Responsibility for providing information, operational data, etc.
- Requirements regarding documentation, analysis, testing, etc.

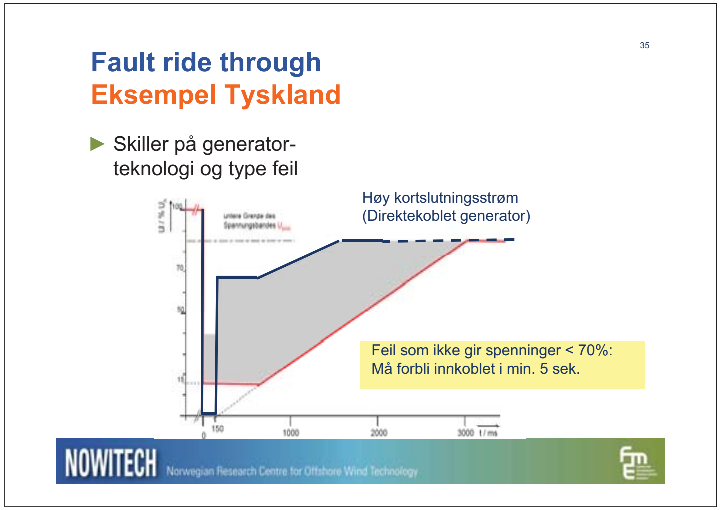


Fault ride through
Eksempel Tyskland

- Skiller på generator-teknologi og type feil

Krav til effektøking

Lav kortslutningsstrøm (frekvensomformer)

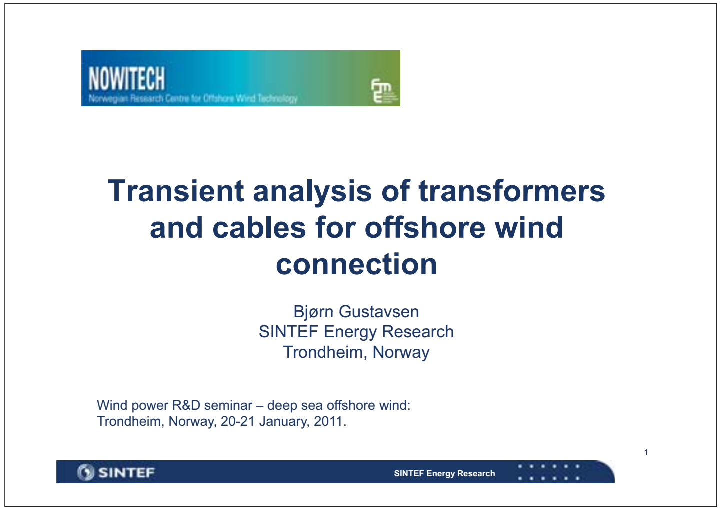


Fault ride through
Eksempel Tyskland

- Skiller på generator-teknologi og type feil

Høy kortslutningsstrøm (Direktekoblet generator)

Feil som ikke gir spenninger < 70%:
Må forbli innkoblet i min. 5 sek.

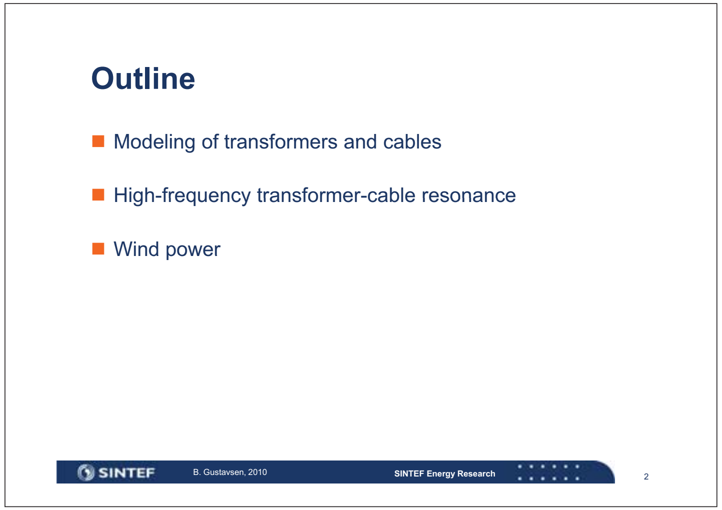


NOWITECH
Norwegian Research Centre for Offshore Wind Technology

Transient analysis of transformers and cables for offshore wind connection

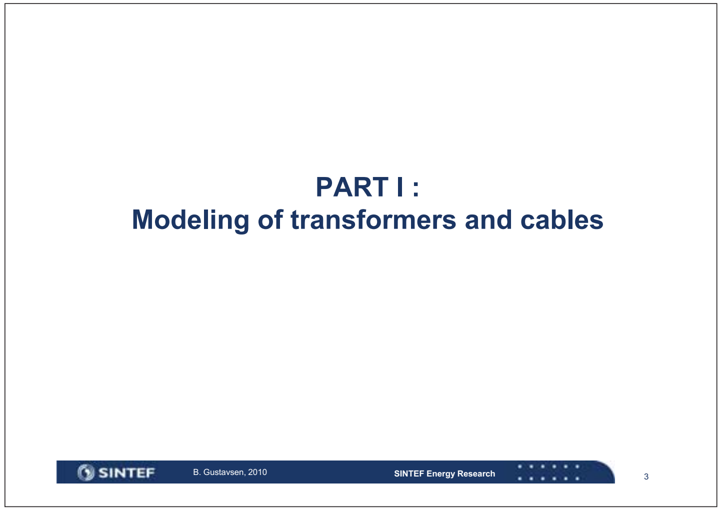
Bjørn Gustavsen
SINTEF Energy Research
Trondheim, Norway

Wind power R&D seminar – deep sea offshore wind:
Trondheim, Norway, 20-21 January, 2011.

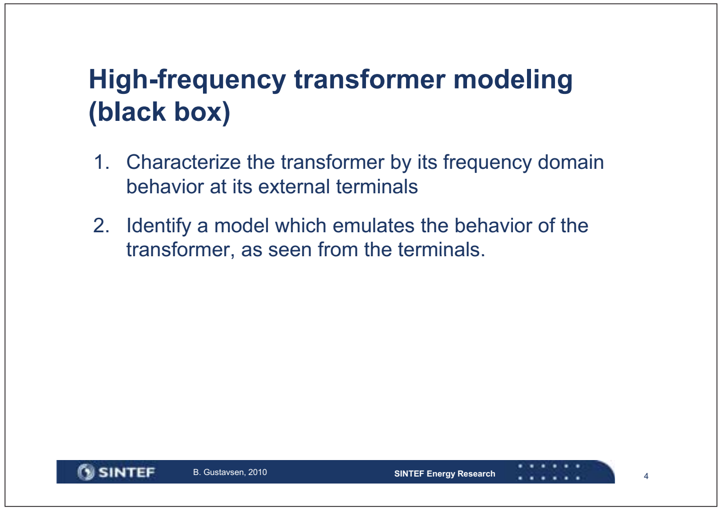


Outline

- Modeling of transformers and cables
- High-frequency transformer-cable resonance
- Wind power

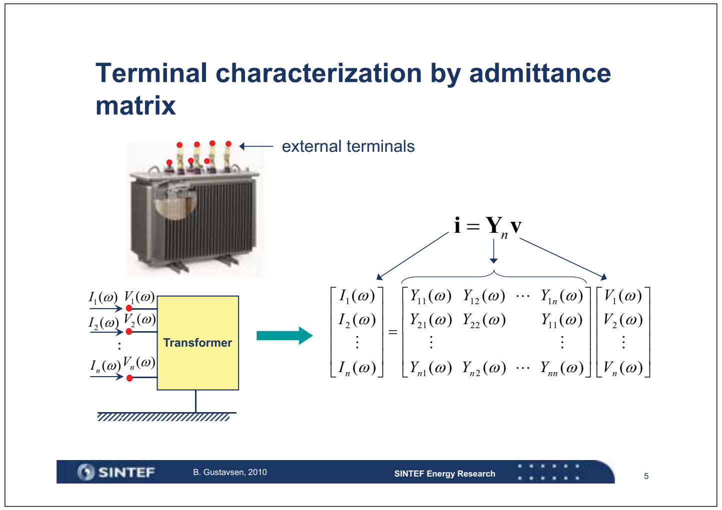


PART I :
Modeling of transformers and cables



High-frequency transformer modeling (black box)

1. Characterize the transformer by its frequency domain behavior at its external terminals
2. Identify a model which emulates the behavior of the transformer, as seen from the terminals.

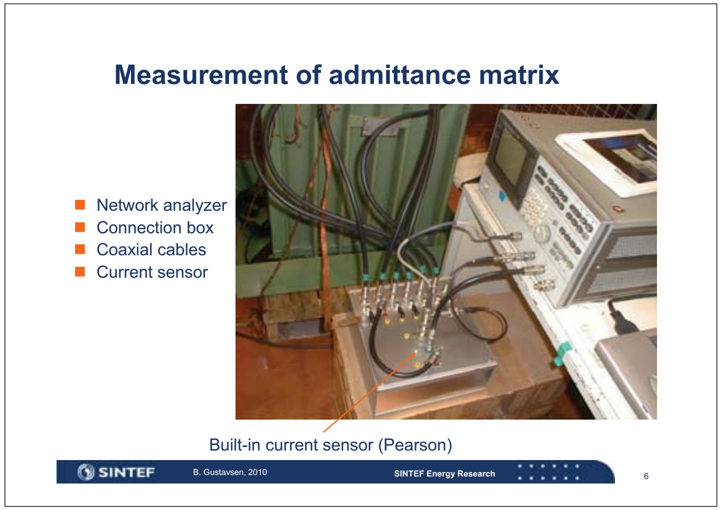


Terminal characterization by admittance matrix

external terminals

$$\mathbf{i} = \mathbf{Y}_n \mathbf{v}$$

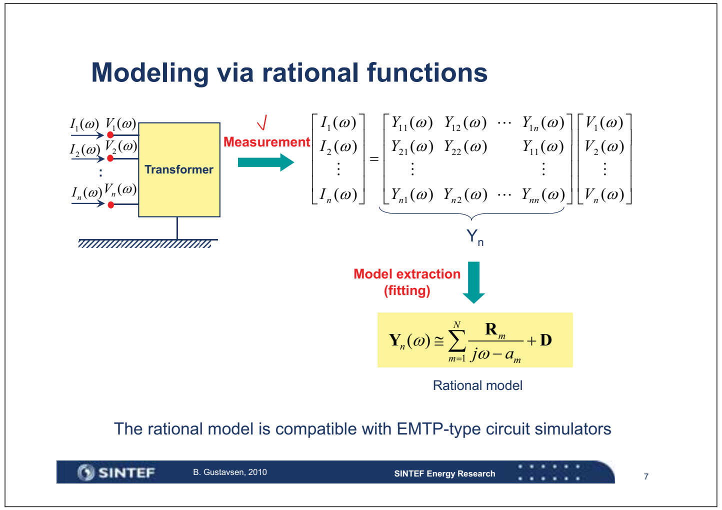
$$\begin{bmatrix} I_1(\omega) \\ I_2(\omega) \\ \vdots \\ I_n(\omega) \end{bmatrix} = \begin{bmatrix} Y_{11}(\omega) & Y_{12}(\omega) & \cdots & Y_{1n}(\omega) \\ Y_{21}(\omega) & Y_{22}(\omega) & & Y_{11}(\omega) \\ \vdots & & & \vdots \\ Y_{n1}(\omega) & Y_{n2}(\omega) & \cdots & Y_{nn}(\omega) \end{bmatrix} \begin{bmatrix} V_1(\omega) \\ V_2(\omega) \\ \vdots \\ V_n(\omega) \end{bmatrix}$$



Measurement of admittance matrix

- Network analyzer
- Connection box
- Coaxial cables
- Current sensor

Built-in current sensor (Pearson)



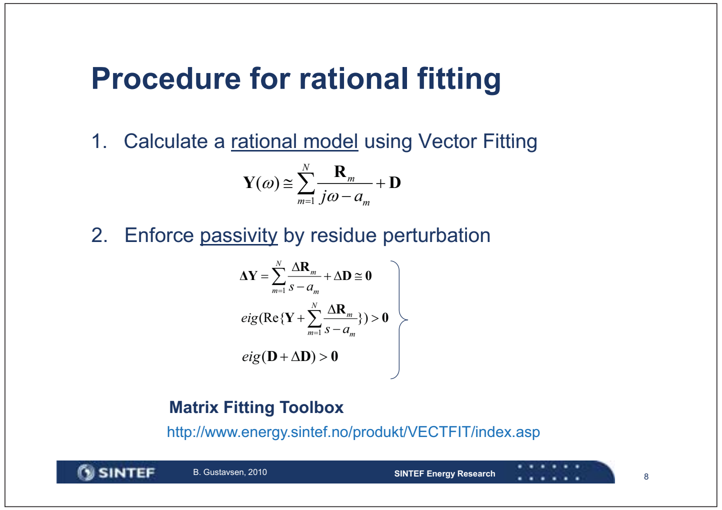
Modeling via rational functions

$$\begin{bmatrix} I_1(\omega) \\ I_2(\omega) \\ \vdots \\ I_n(\omega) \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{11}(\omega) & Y_{12}(\omega) & \cdots & Y_{1n}(\omega) \\ Y_{21}(\omega) & Y_{22}(\omega) & & Y_{11}(\omega) \\ \vdots & & & \vdots \\ Y_{n1}(\omega) & Y_{n2}(\omega) & \cdots & Y_{nn}(\omega) \end{bmatrix}}_{\mathrm{Y_n}} \begin{bmatrix} V_1(\omega) \\ V_2(\omega) \\ \vdots \\ V_n(\omega) \end{bmatrix}$$

$$\mathbf{Y}_n(\omega) \cong \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$

Rational model

The rational model is compatible with EMTP-type circuit simulators



Procedure for rational fitting

1. Calculate a rational model using Vector Fitting

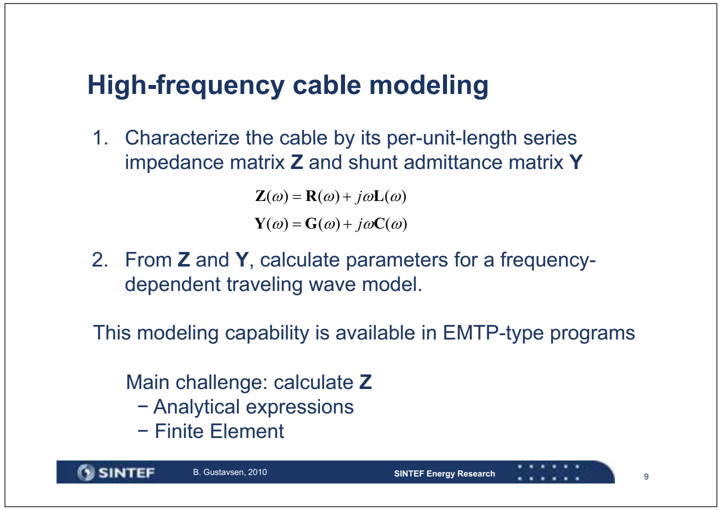
$$\mathbf{Y}(\omega) \cong \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$

2. Enforce passivity by residue perturbation

$$\left.\begin{array}{l} \Delta\mathbf{Y} = \sum_{m=1}^{N} \frac{\Delta\mathbf{R}_m}{s - a_m} + \Delta\mathbf{D} \cong \mathbf{0} \\ eig(\mathrm{Re}\{\mathbf{Y} + \sum_{m=1}^{N} \frac{\Delta\mathbf{R}_m}{s - a_m}\}) > \mathbf{0} \\ eig(\mathbf{D} + \Delta\mathbf{D}) > \mathbf{0} \end{array}\right\}$$

Matrix Fitting Toolbox

http://www.energy.sintef.no/produkt/VECTFIT/index.asp



High-frequency cable modeling

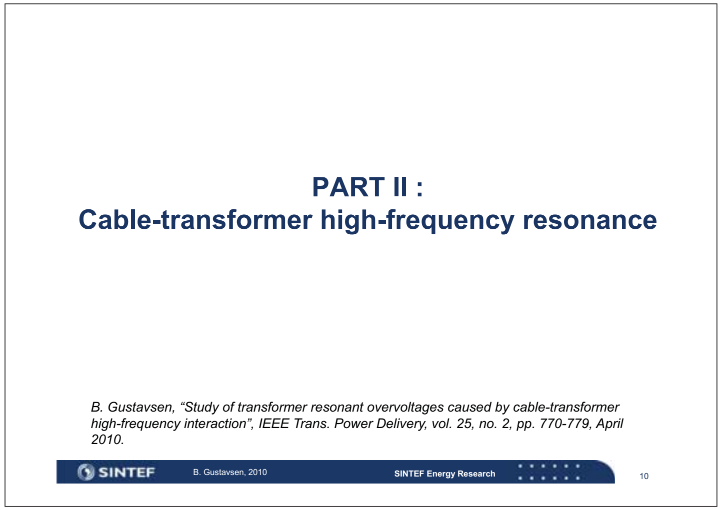
1. Characterize the cable by its per-unit-length series impedance matrix **Z** and shunt admittance matrix **Y**

$$\mathbf{Z}(\omega) = \mathbf{R}(\omega) + j\omega\mathbf{L}(\omega)$$
$$\mathbf{Y}(\omega) = \mathbf{G}(\omega) + j\omega\mathbf{C}(\omega)$$

2. From **Z** and **Y**, calculate parameters for a frequency-dependent traveling wave model.

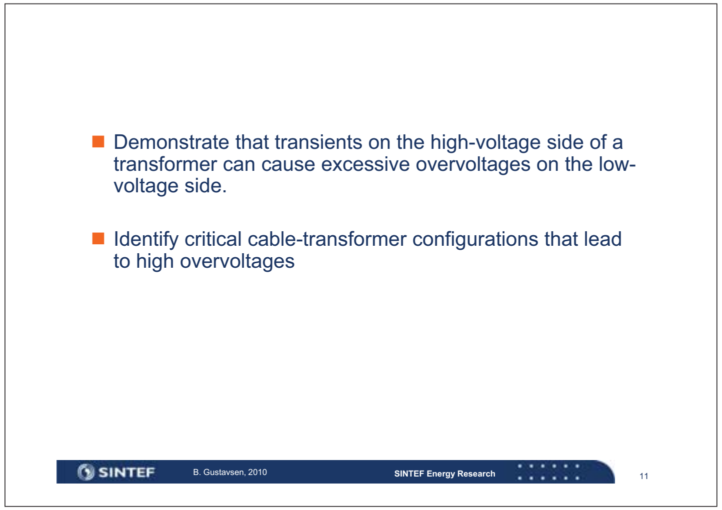
This modeling capability is available in EMTP-type programs

Main challenge: calculate **Z**
- Analytical expressions
- Finite Element

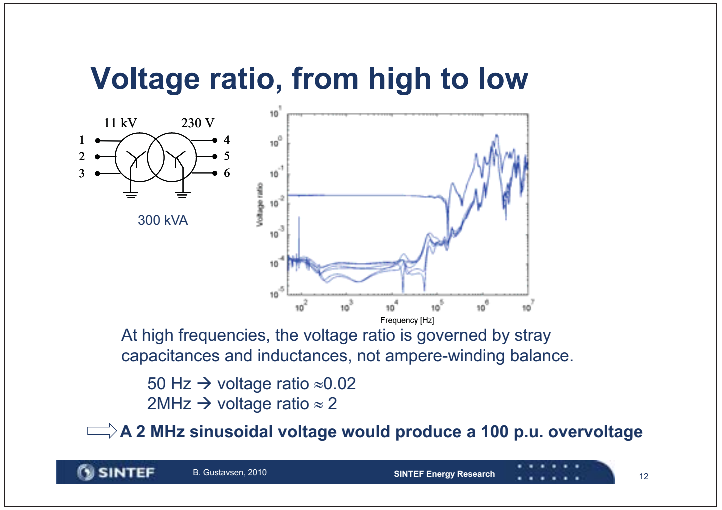


PART II :
Cable-transformer high-frequency resonance

B. Gustavsen, "Study of transformer resonant overvoltages caused by cable-transformer high-frequency interaction", IEEE Trans. Power Delivery, vol. 25, no. 2, pp. 770-779, April 2010.



- Demonstrate that transients on the high-voltage side of a transformer can cause excessive overvoltages on the low-voltage side.
- Identify critical cable-transformer configurations that lead to high overvoltages

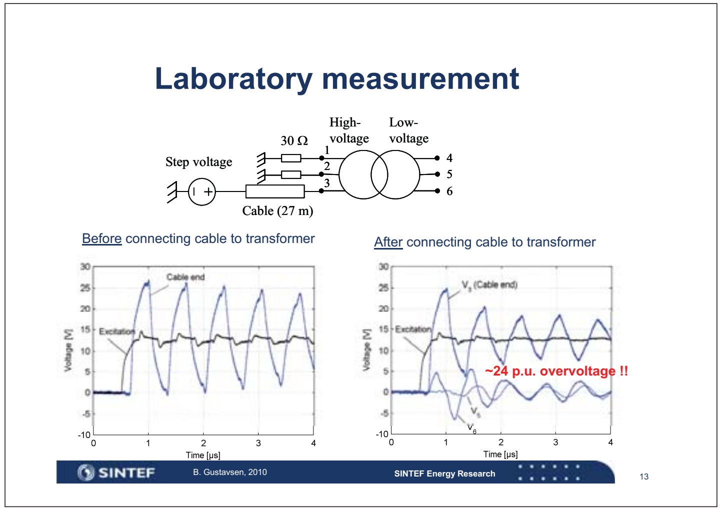


Voltage ratio, from high to low

At high frequencies, the voltage ratio is governed by stray capacitances and inductances, not ampere-winding balance.

50 Hz → voltage ratio ≈0.02
2MHz → voltage ratio ≈ 2

⇨ **A 2 MHz sinusoidal voltage would produce a 100 p.u. overvoltage**

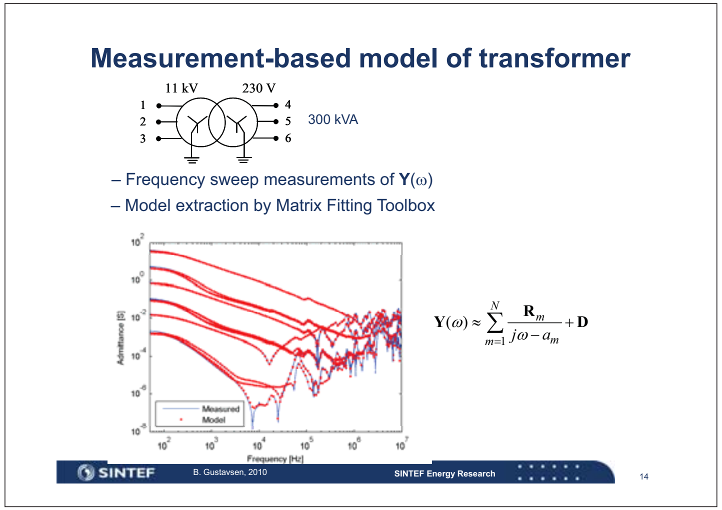


Laboratory measurement

Before connecting cable to transformer

After connecting cable to transformer

~24 p.u. overvoltage !!

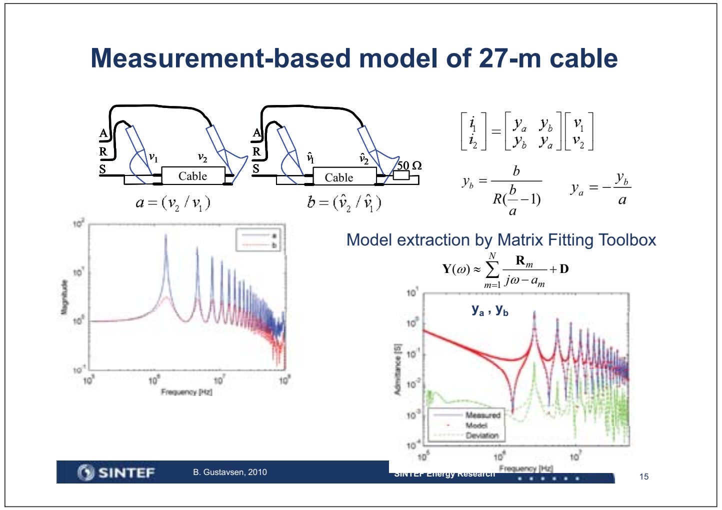


Measurement-based model of transformer

300 kVA

- Frequency sweep measurements of **Y**(ω)
- Model extraction by Matrix Fitting Toolbox

$$\mathbf{Y}(\omega) \approx \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$



Measurement-based model of 27-m cable

$a = (v_2 / v_1)$ $b = (\hat{v}_2 / \hat{v}_1)$

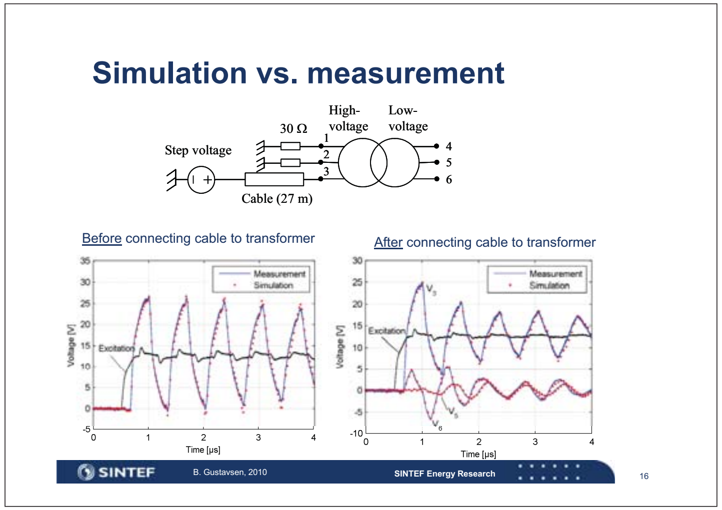
$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} y_a & y_b \\ y_b & y_a \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

$$y_b = \frac{b}{R(\frac{b}{a} - 1)} \qquad y_a = -\frac{y_b}{a}$$

Model extraction by Matrix Fitting Toolbox

$$\mathbf{Y}(\omega) \approx \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$

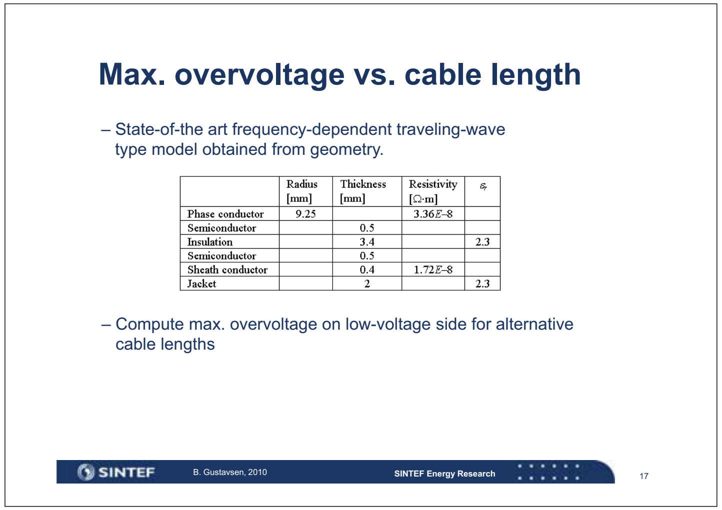
$\mathbf{y_a}$, $\mathbf{y_b}$



Simulation vs. measurement

Before connecting cable to transformer

After connecting cable to transformer

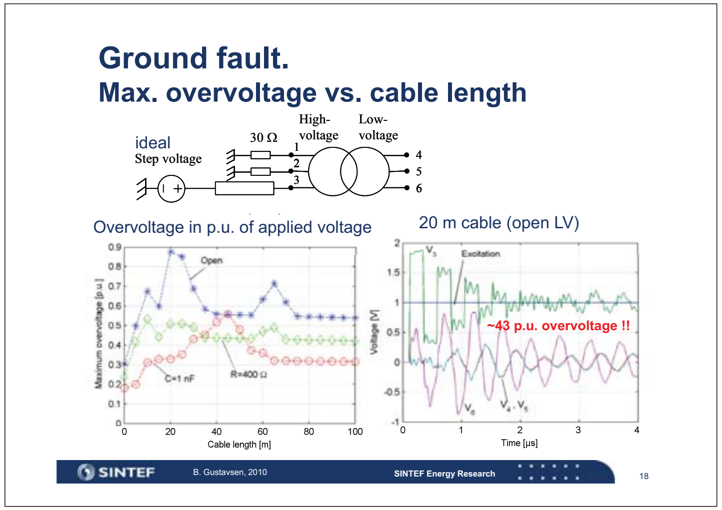


Max. overvoltage vs. cable length

- State-of-the art frequency-dependent traveling-wave type model obtained from geometry.

	Radius [mm]	Thickness [mm]	Resistivity [Ω·m]	ε_r
Phase conductor	9.25		3.36*E*–8	
Semiconductor		0.5		
Insulation		3.4		2.3
Semiconductor		0.5		
Sheath conductor		0.4	1.72*E*–8	
Jacket		2		2.3

- Compute max. overvoltage on low-voltage side for alternative cable lengths

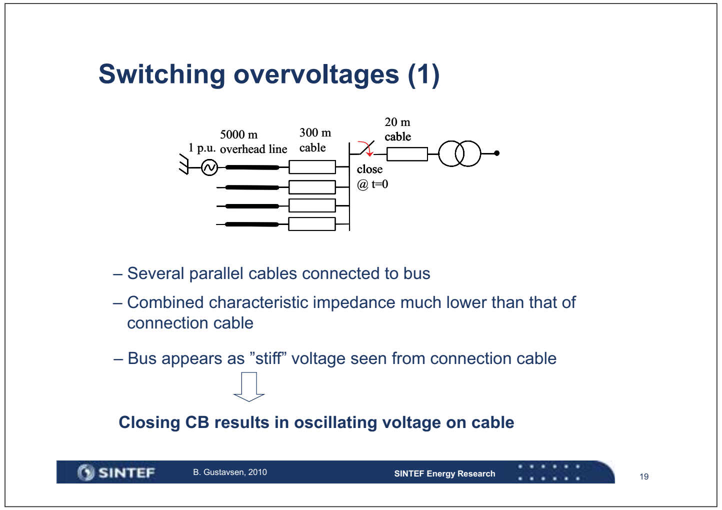


Ground fault.
Max. overvoltage vs. cable length

Overvoltage in p.u. of applied voltage

20 m cable (open LV)

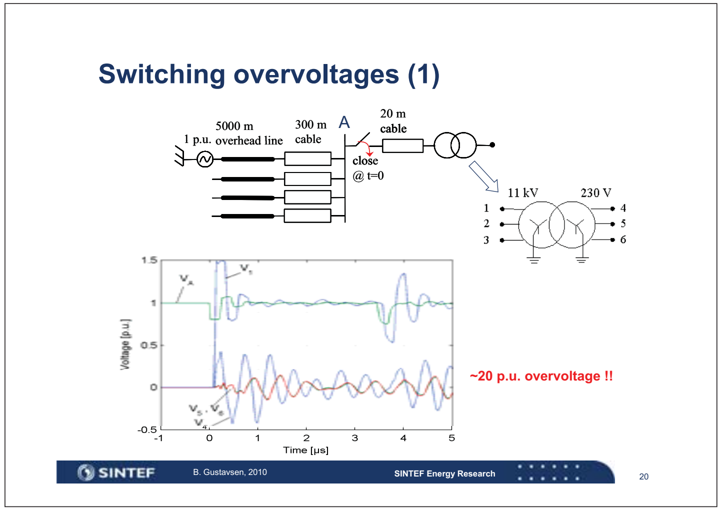
~43 p.u. overvoltage !!



Switching overvoltages (1)

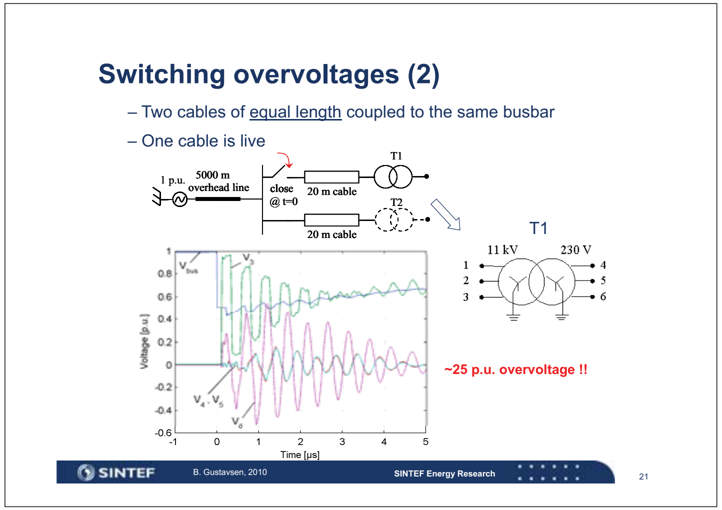
- Several parallel cables connected to bus
- Combined characteristic impedance much lower than that of connection cable
- Bus appears as ”stiff” voltage seen from connection cable

Closing CB results in oscillating voltage on cable



Switching overvoltages (1)

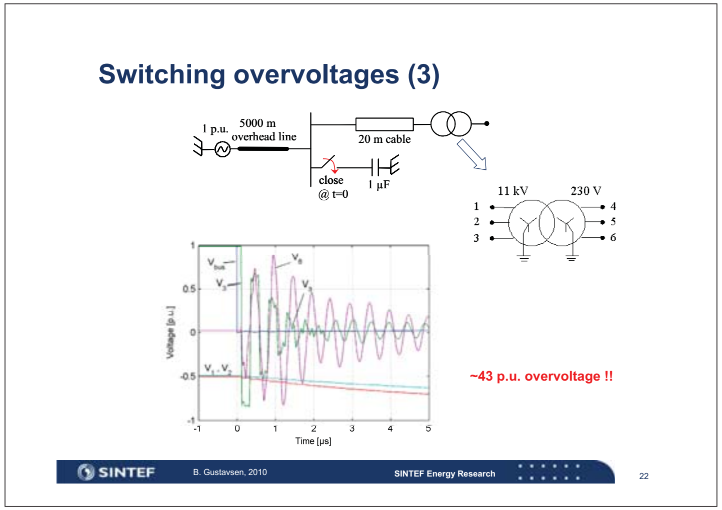
~20 p.u. overvoltage !!



Switching overvoltages (2)

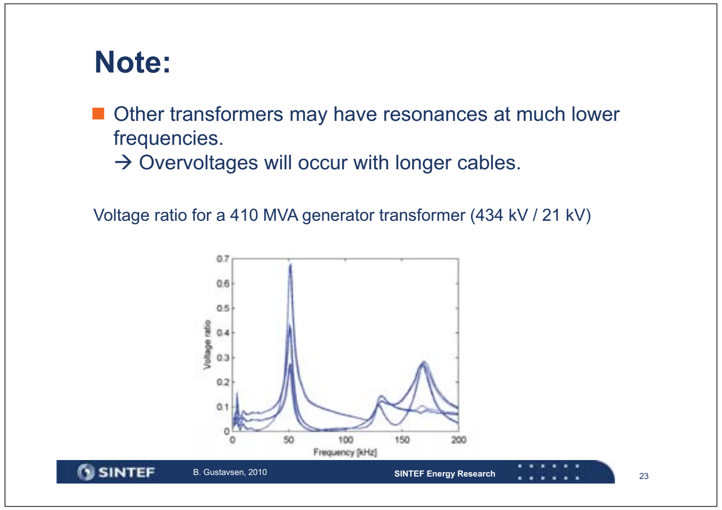
- Two cables of equal length coupled to the same busbar
- One cable is live

~25 p.u. overvoltage !!



Switching overvoltages (3)

~43 p.u. overvoltage !!

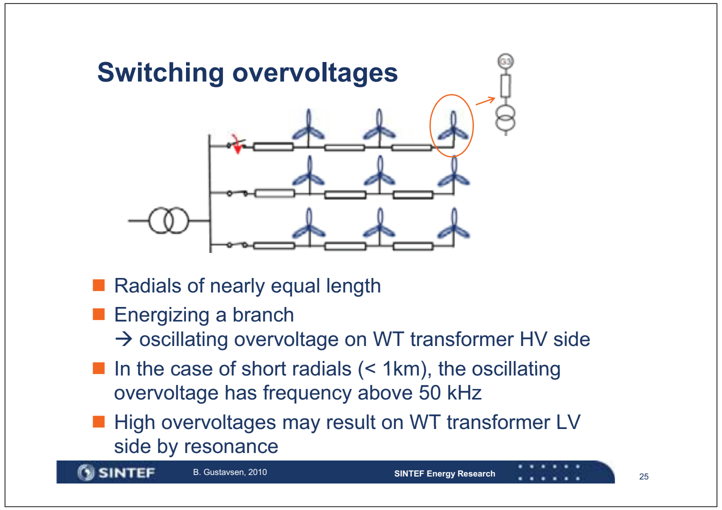


Note:

- Other transformers may have resonances at much lower frequencies.
  → Overvoltages will occur with longer cables.

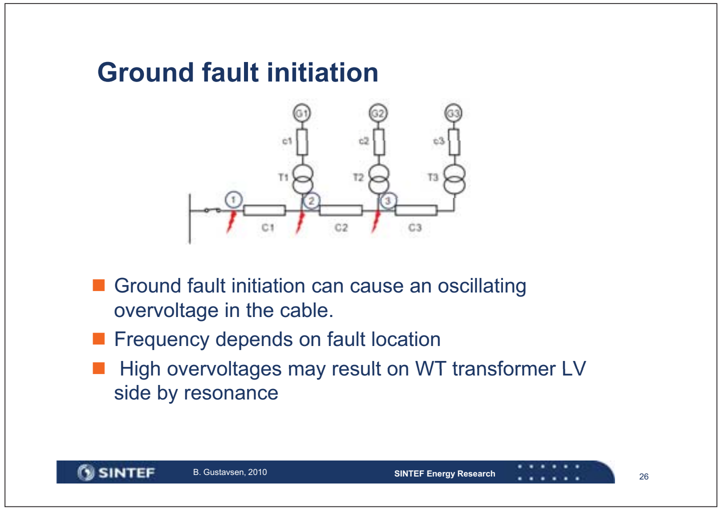
Voltage ratio for a 410 MVA generator transformer (434 kV / 21 kV)

PART III :
Relevance to wind power



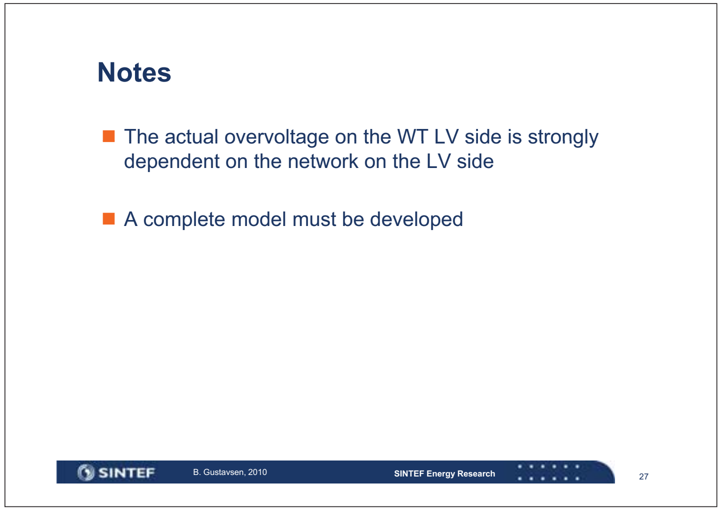
Switching overvoltages

- Radials of nearly equal length
- Energizing a branch
  → oscillating overvoltage on WT transformer HV side
- In the case of short radials (< 1km), the oscillating overvoltage has frequency above 50 kHz
- High overvoltages may result on WT transformer LV side by resonance



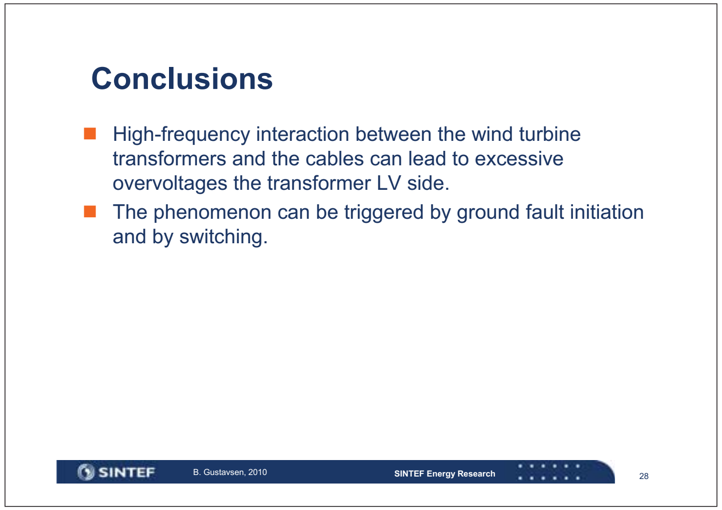
Ground fault initiation

- Ground fault initiation can cause an oscillating overvoltage in the cable.
- Frequency depends on fault location
- High overvoltages may result on WT transformer LV side by resonance



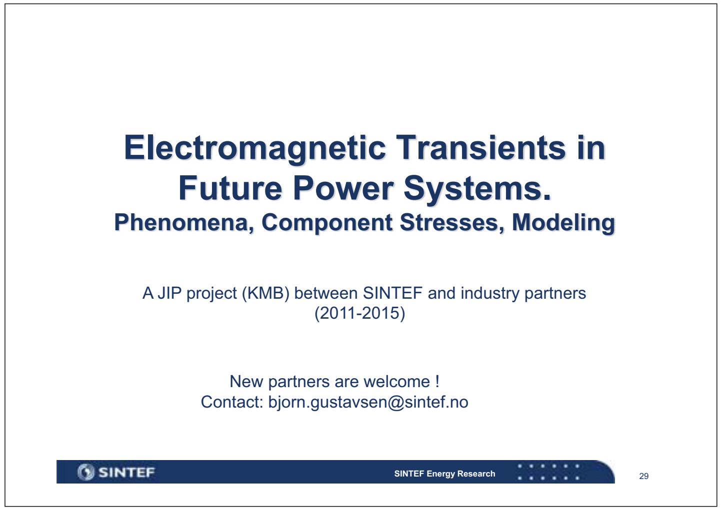
Notes

- The actual overvoltage on the WT LV side is strongly dependent on the network on the LV side
- A complete model must be developed



Conclusions

- High-frequency interaction between the wind turbine transformers and the cables can lead to excessive overvoltages the transformer LV side.
- The phenomenon can be triggered by ground fault initiation and by switching.

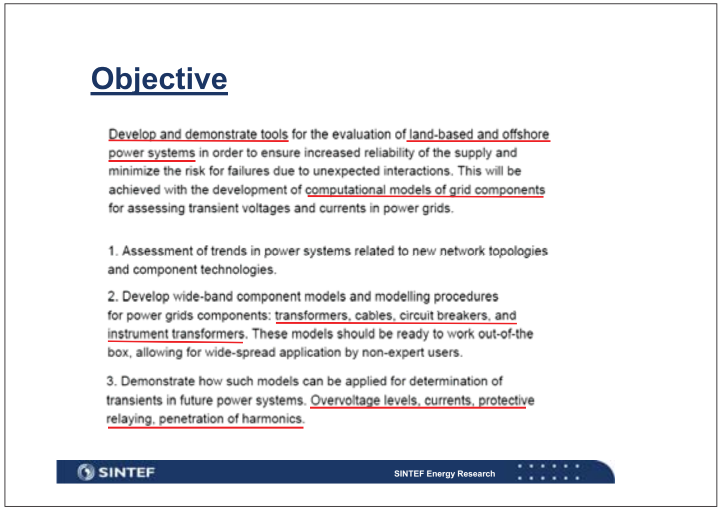


Electromagnetic Transients in Future Power Systems.

Phenomena, Component Stresses, Modeling

A JIP project (KMB) between SINTEF and industry partners
(2011-2015)

New partners are welcome !
Contact: bjorn.gustavsen@sintef.no



Objective

Develop and demonstrate tools for the evaluation of land-based and offshore power systems in order to ensure increased reliability of the supply and minimize the risk for failures due to unexpected interactions. This will be achieved with the development of computational models of grid components for assessing transient voltages and currents in power grids.

1. Assessment of trends in power systems related to new network topologies and component technologies.

2. Develop wide-band component models and modelling procedures for power grids components: transformers, cables, circuit breakers, and instrument transformers. These models should be ready to work out-of-the box, allowing for wide-spread application by non-expert users.

3. Demonstrate how such models can be applied for determination of transients in future power systems. Overvoltage levels, currents, protective relaying, penetration of harmonics.

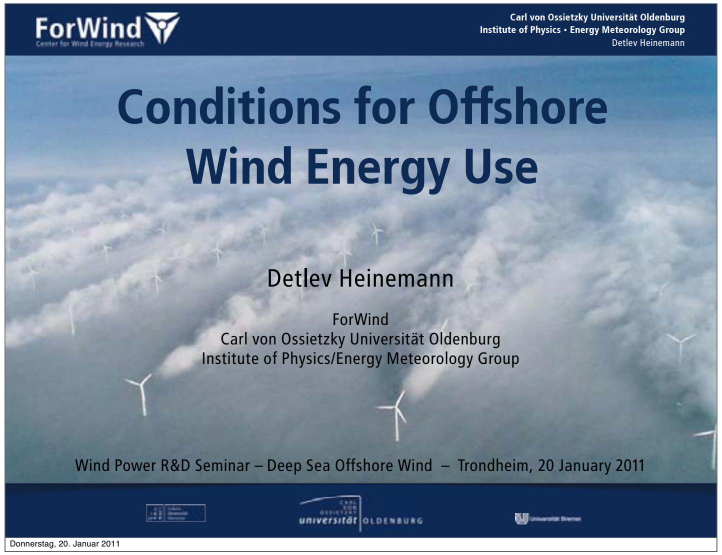
C1) Met-ocean conditions

Conditions for Offshore Wind Energy Use, Prof D Heinemann, Uni. Oldenburg

Atmospheric profiling by lidar for wind energy research, Torben Mikkelsen, DTU Risø

From tower to tower, Svein Erling Hansen, Fugro Oceanor

Effects of ocean waves, Alastair Jenkins, Uni Research



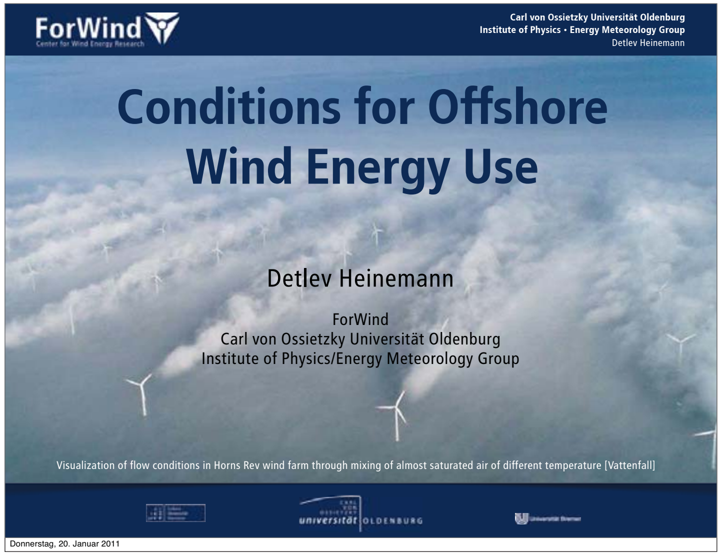
Carl von Ossietzky Universität Oldenburg
Institute of Physics • Energy Meteorology Group
Detlev Heinemann

Conditions for Offshore Wind Energy Use

Detlev Heinemann

ForWind
Carl von Ossietzky Universität Oldenburg
Institute of Physics/Energy Meteorology Group

Wind Power R&D Seminar – Deep Sea Offshore Wind – Trondheim, 20 January 2011



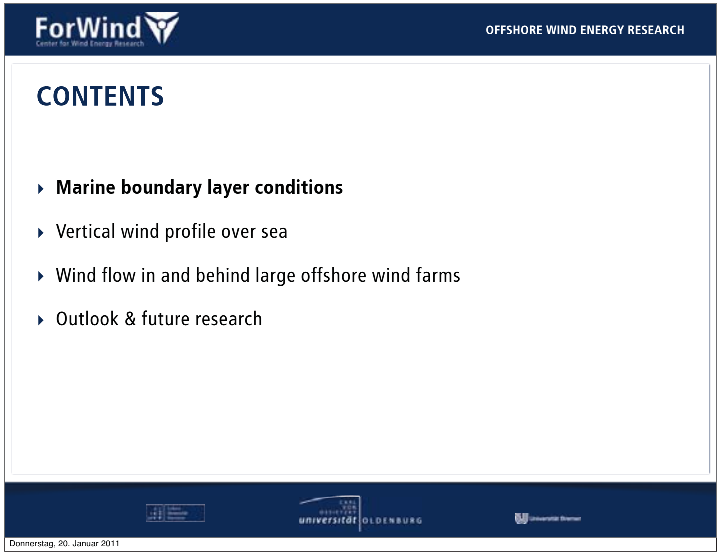
Carl von Ossietzky Universität Oldenburg
Institute of Physics • Energy Meteorology Group
Detlev Heinemann

Conditions for Offshore Wind Energy Use

Detlev Heinemann

ForWind
Carl von Ossietzky Universität Oldenburg
Institute of Physics/Energy Meteorology Group

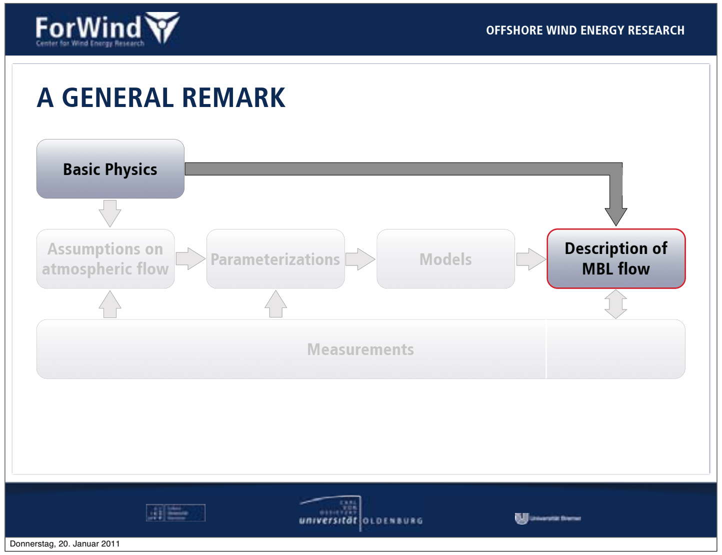
Visualization of flow conditions in Horns Rev wind farm through mixing of almost saturated air of different temperature [Vattenfall]



OFFSHORE WIND ENERGY RESEARCH

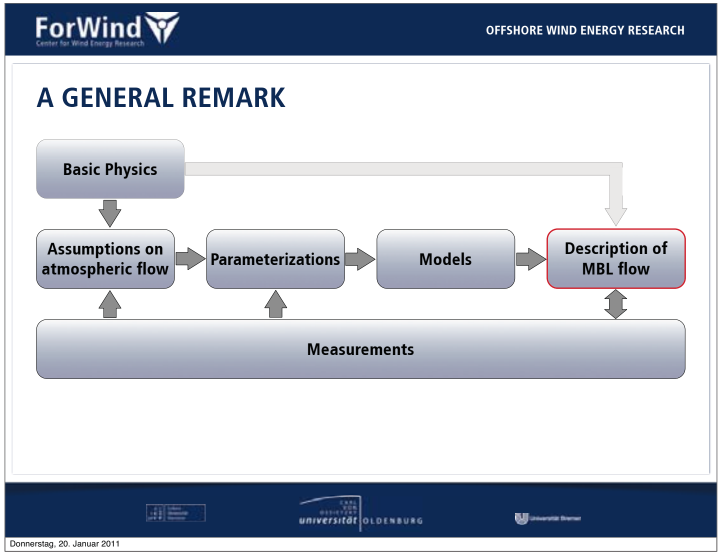
CONTENTS

- **Marine boundary layer conditions**
- Vertical wind profile over sea
- Wind flow in and behind large offshore wind farms
- Outlook & future research



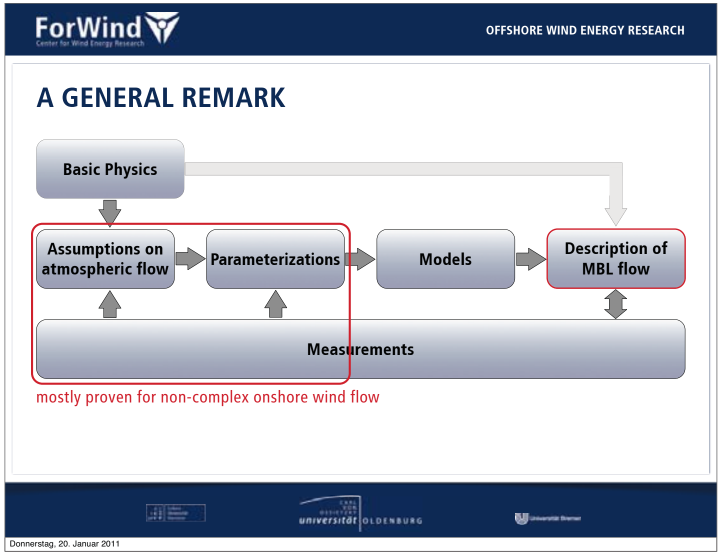
OFFSHORE WIND ENERGY RESEARCH

A GENERAL REMARK



OFFSHORE WIND ENERGY RESEARCH

A GENERAL REMARK

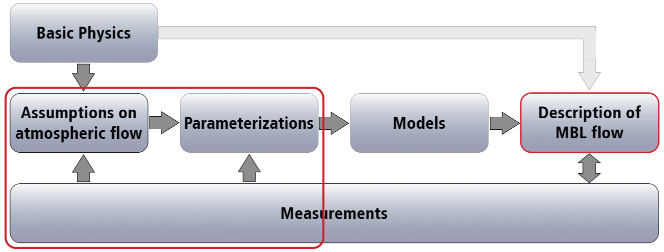


OFFSHORE WIND ENERGY RESEARCH

A GENERAL REMARK

mostly proven for non-complex onshore wind flow

A GENERAL REMARK



mostly proven for non-complex onshore wind flow

Finite knowledge of offshore wind conditions limits our modeling success!

ONSHORE (INLAND) vs. OFFSHORE (MARINE) WINDS

Marine winds are fundamentally different from inland winds in four principal ways:

- **Still vs. Moving Surface**
  - surface moves under the influence of wind forcing
  - momentum from tides, ocean currents, and wind-driven currents
  - wave generation driven by momentum transfer from wind
- **Land-Water Interface**
  - varying coastal wind effects
  - regionally important
- **Atmospheric Stability**
  - poor PBL parameterizations in case of non-stable thermal stratifications
  - highly variable frictional turning over water linked to wave height and stability
- **Isallobaric Winds**
  - local wind effect due to time-varying pressure fields
  - more significant over sea due to decreased friction
  - potential source of large wind forecast errors

MARINE BOUNDARY LAYER CONDITIONS

- MBL is rather shallow compared to continental air masses (higher moisture content ▸lower lifting condensation level)
- Low variability of sea surface temperature (SST), nearly unlimited energy source and sink ▸ smaller diurnal oscillation in air temperature
- MBL flow is more geostrophic in both speed and direction as over land given the same atmospheric conditions
- NWP issues:
  - Errors in model BL profiles of wind, temperature, and dew point due to turbulence and convective parameterizations
  - Simple algorithms for wind-wave coupling
  - Lack of real-time data for model initialization (▸ data assimilation, ▸ remote sensing)
  - Poor resolution of near-surface variables forecast winds (and waves) are often erroneous during both stability extremes in the MBL

MARINE BOUNDARY LAYER CONDITIONS

Turbulence (I)

Mechanical Turbulence

- through interaction of the wind and surface air mass with sea surface waves
- resulting eddies formed by the rising and falling sea surface can extend vertically for tens of meters
- Extent of eddies is based on wave height and vertical near-surface wind shear

---

MARINE BOUNDARY LAYER CONDITIONS

Turbulence (II)

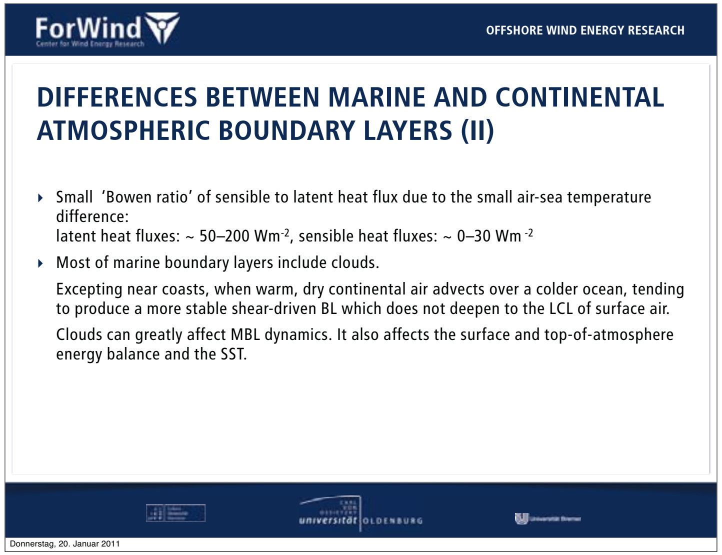
Convective Turbulence

- Due to rising plumes of warm air and compensating downdrafts
- Range from 100 to more than 1000 m height
- Stability is the main factor for the depth of frictional coupling in the MBL due to convective turbulence
- Stratified lower atmosphere: Mixing is minimal and the surface air mass will be decoupled from the winds aloft
- Temperature difference between rather constant SST and temperature of overlying air mass is primary factor impacting stability over water

---

DIFFERENCES BETWEEN MARINE AND CONTINENTAL ATMOSPHERIC BOUNDARY LAYERS (I)

- Near-surface air is always moist, relative humidity typically ~ 75–100%
- Weak diurnal cycle, since surface energy fluxes distribute over a large depth (10–100+ m) of water (large heat capacity!)
- Small air-sea temperature differences, except near coasts. Air is typically 0–2 K cooler than the water due to radiative cooling and advection, except for strong winds or large sea-surface temperature (SST) gradients.
- The MBL air is usually radiatively cooling at 1–2 K/day, and some of this heat is supplied by sensible heat fluxes off the ocean surface. If the air is much colder than the SST, vigorous convection will quickly reduce the temperature difference.



ForWind Center for Wind Energy Research — OFFSHORE WIND ENERGY RESEARCH

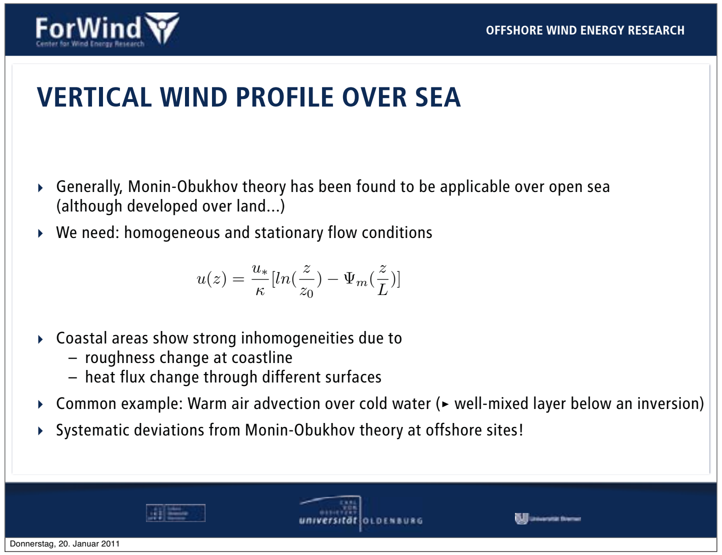
DIFFERENCES BETWEEN MARINE AND CONTINENTAL ATMOSPHERIC BOUNDARY LAYERS (II)

- Small ‘Bowen ratio’ of sensible to latent heat flux due to the small air-sea temperature difference:
  latent heat fluxes: ~ 50–200 Wm^{-2}, sensible heat fluxes: ~ 0–30 Wm^{-2}
- Most of marine boundary layers include clouds.

  Excepting near coasts, when warm, dry continental air advects over a colder ocean, tending to produce a more stable shear-driven BL which does not deepen to the LCL of surface air.

  Clouds can greatly affect MBL dynamics. It also affects the surface and top-of-atmosphere energy balance and the SST.

Donnerstag, 20. Januar 2011



ForWind Center for Wind Energy Research — OFFSHORE WIND ENERGY RESEARCH

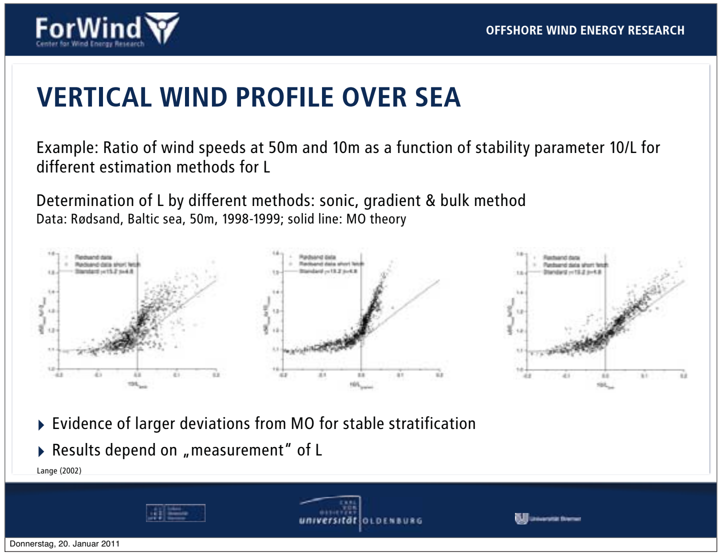
VERTICAL WIND PROFILE OVER SEA

- Generally, Monin-Obukhov theory has been found to be applicable over open sea (although developed over land…)
- We need: homogeneous and stationary flow conditions

$$u(z) = \frac{u_*}{\kappa}[ln(\frac{z}{z_0}) - \Psi_m(\frac{z}{L})]$$

- Coastal areas show strong inhomogeneities due to
  - roughness change at coastline
  - heat flux change through different surfaces
- Common example: Warm air advection over cold water (▸ well-mixed layer below an inversion)
- Systematic deviations from Monin-Obukhov theory at offshore sites!

Donnerstag, 20. Januar 2011



ForWind Center for Wind Energy Research — OFFSHORE WIND ENERGY RESEARCH

VERTICAL WIND PROFILE OVER SEA

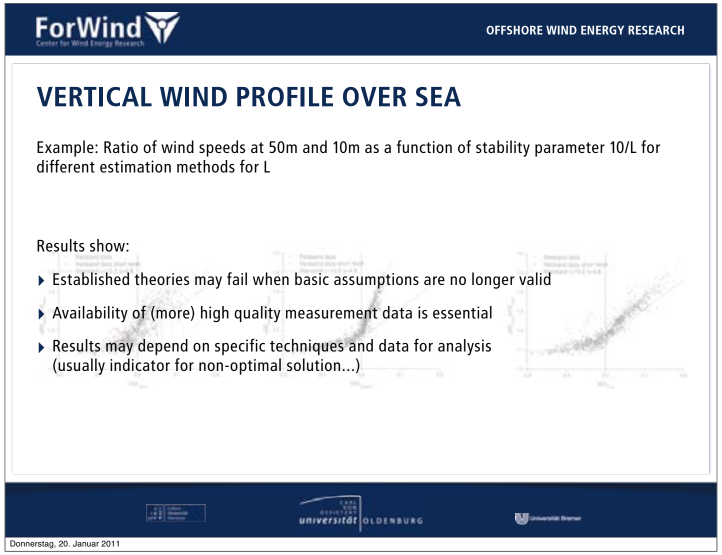
Example: Ratio of wind speeds at 50m and 10m as a function of stability parameter 10/L for different estimation methods for L

Determination of L by different methods: sonic, gradient & bulk method
Data: Rødsand, Baltic sea, 50m, 1998-1999; solid line: MO theory

- Evidence of larger deviations from MO for stable stratification
- Results depend on „measurement“ of L

Lange (2002)

Donnerstag, 20. Januar 2011



ForWind Center for Wind Energy Research — OFFSHORE WIND ENERGY RESEARCH

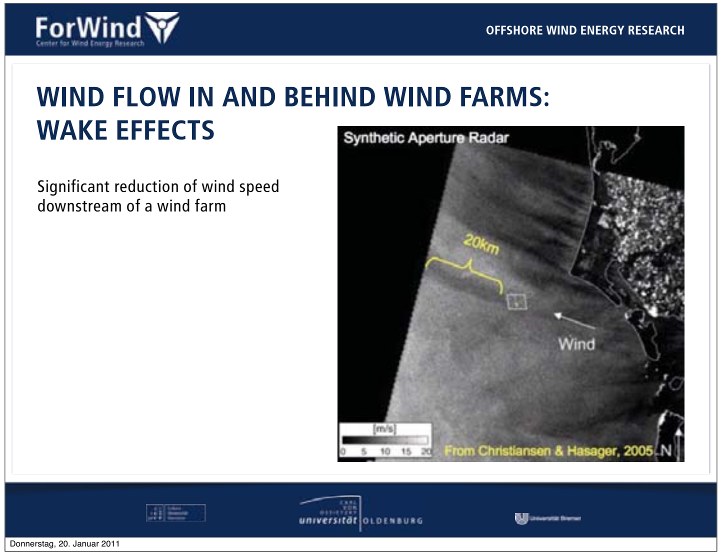
VERTICAL WIND PROFILE OVER SEA

Example: Ratio of wind speeds at 50m and 10m as a function of stability parameter 10/L for different estimation methods for L

Results show:

- Established theories may fail when basic assumptions are no longer valid
- Availability of (more) high quality measurement data is essential
- Results may depend on specific techniques and data for analysis (usually indicator for non-optimal solution…)

Donnerstag, 20. Januar 2011



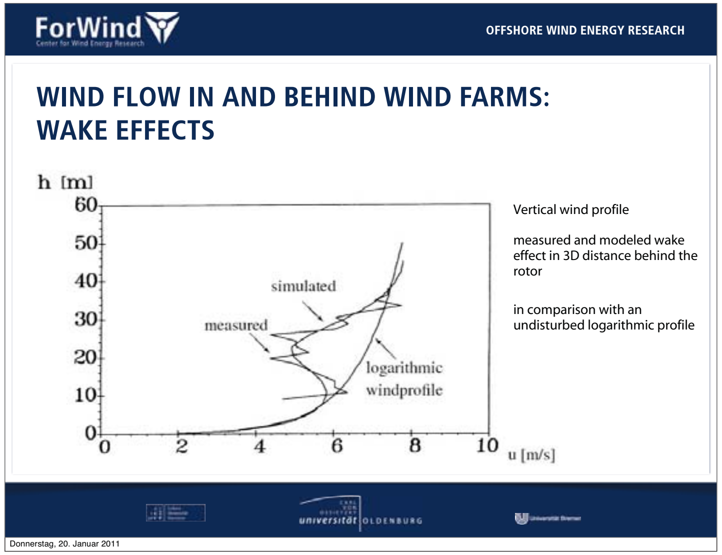
ForWind Center for Wind Energy Research — OFFSHORE WIND ENERGY RESEARCH

WIND FLOW IN AND BEHIND WIND FARMS: WAKE EFFECTS

Significant reduction of wind speed downstream of a wind farm

From Christiansen & Hasager, 2005

Donnerstag, 20. Januar 2011



ForWind Center for Wind Energy Research — OFFSHORE WIND ENERGY RESEARCH

WIND FLOW IN AND BEHIND WIND FARMS: WAKE EFFECTS

Vertical wind profile

measured and modeled wake effect in 3D distance behind the rotor

in comparison with an undisturbed logarithmic profile

Donnerstag, 20. Januar 2011

WIND FLOW IN AND BEHIND WIND FARMS: WAKE EFFECTS

Operation results of Horns Rev offshore wind farm showed 20% less power output than calculated (Barthelmie et al., 2009)

- Fundamental different flow conditions in large wind farms compared to small ones
- Suboptimal consideration of interaction of wind flow in a wind farm and atmospheric boundary layer
- Lack of adequate measurement data
- Larger effects expected for spatially „coupled“ wind farms

WIND FLOW IN AND BEHIND WIND FARMS: WAKE EFFECTS

LES approach

- High-resolution modeling of idealized development of „far wakes“ (10 m)
  - Periodic boundary conditions (non-periodic in development)
  - Development of wakes in the boundary layer
  - Validation with on-site measurements

Coupling of mesoscale model & LES

- Analysis of wake development under real meteorological conditions
  - „nested“ areas
  - WEC model (MYJ-TKE scheme):
    - sink of kinetic energy
    - source of turbulent kinetic energy
  - Analysis of wind farm effects

OUTLOOK & RESEARCH NEEDS (I)

- Measurements for optimization of micro- and meso-scale meteorological models incl. satellite remote sensing (vertical structure?!)
- Improved wake modeling (multiple wakes, wind farm wakes, ► LES)
- Offshore Wind Resource Assessment:
  - Wake Effects and Climate Impacts of Offshore Wind Farms
  - Wakes from large wind farms
  - Impact of wakes on local/regional climate: boundary layer height, boundary layer clouds
  - Future climates and wind resources
  - Validate new mesoscale parameterization for offshore conditions

---

OUTLOOK & RESEARCH NEEDS (II)

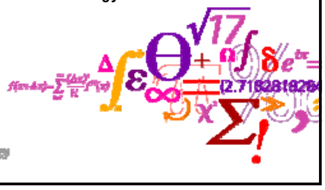
- Surface waves and turbulent boundary layers and their mutual relationships:
  - complex wave surfaces in ABL and OBL LES
  - coupled wind-wave and wave-current models
  - OBL and ABL mixing parameterizations with wave effects;
  - wave and turbulence mechanics in high winds (e.g., hurricanes)
  - wave-breaking structure and statistical distributions
  - disequilibrium, mis-aligned wind-wave conditions

Deep Sea Offshore Wind Power
R&D Seminar Trondheim, 20-21 Jan. 2011

Atmospheric Profiling by Lidar for Wind Energy Research

Torben Mikkelsen

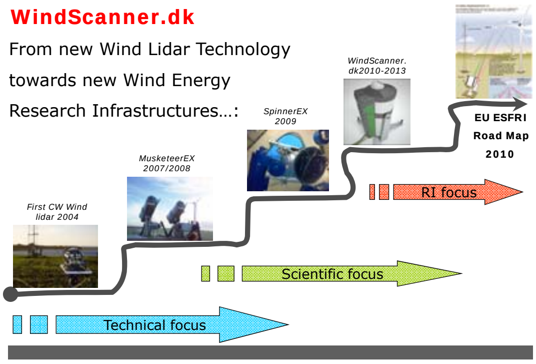
Wind Energy Division
Risø National Laboratory for Sustainable Energy - DTU



Risø DTU
National Laboratory for Sustainable Energy

WindScanner.dk

From new Wind Lidar Technology towards new Wind Energy Research Infrastructures…:



First CW Wind lidar 2004
MusketeerEX 2007/2008
SpinnerEX 2009
WindScanner. dk2010-2013
EU ESFRI Road Map 2010
RI focus
Scientific focus
Technical focus

---

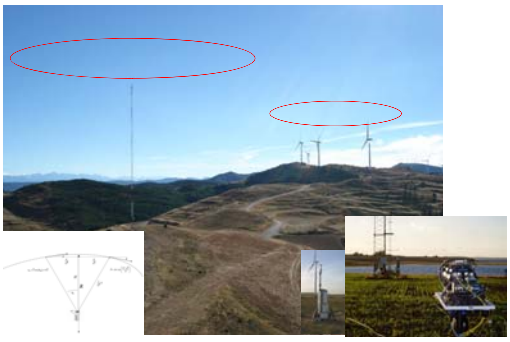
(1)

VISION I:

Full scale off and on shore measurements on WT arrays & wakes
e.g. as here at Horns reef

2

Vision II: RI Windscanner
Secure wind resource estimation in particular in complex terrain



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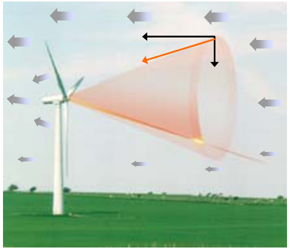
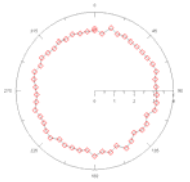
(3)

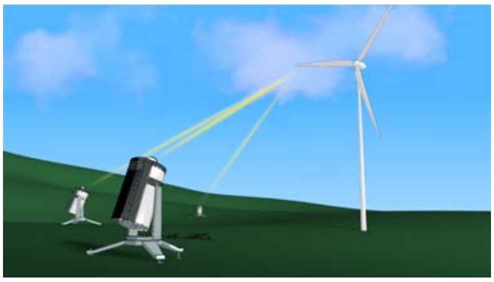
VISION III

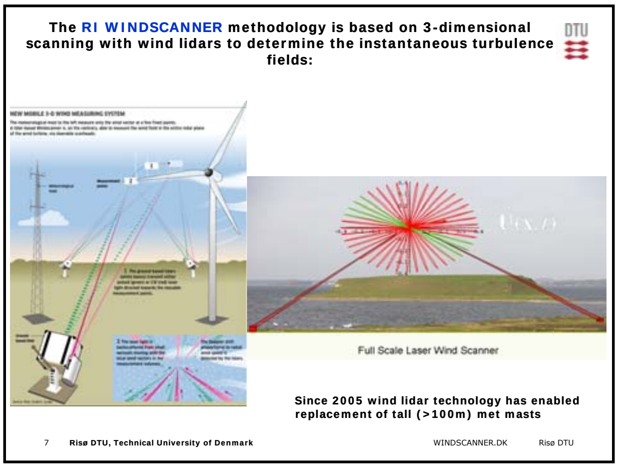
Pro-active wind turbine control from upwind measurements by lidars integrated in the nacelle… :





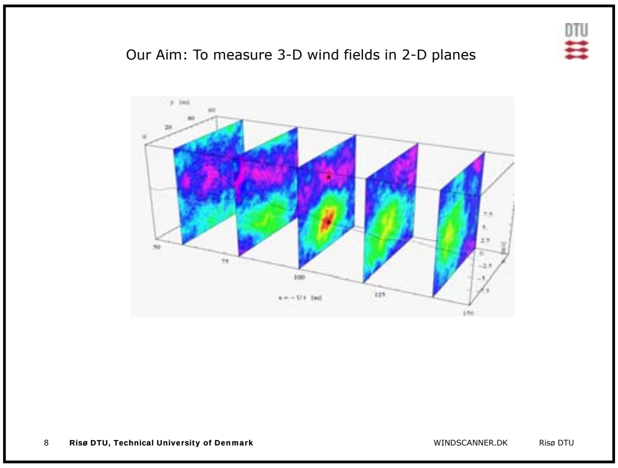
Short-range WindScanners



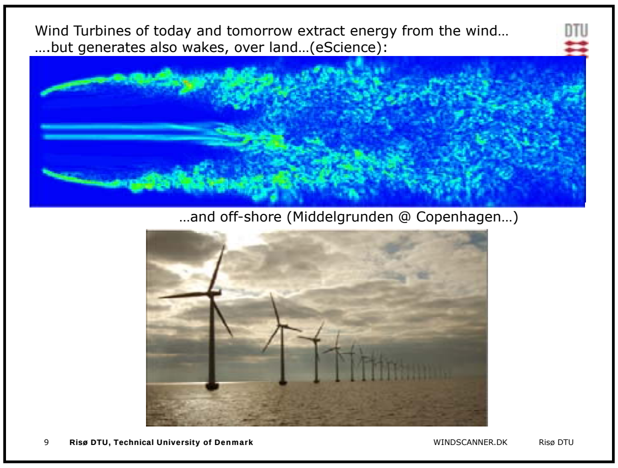


The RI WINDSCANNER methodology is based on 3-dimensional scanning with wind lidars to determine the instantaneous turbulence fields:

Since 2005 wind lidar technology has enabled replacement of tall (>100m) met masts



Our Aim: To measure 3-D wind fields in 2-D planes



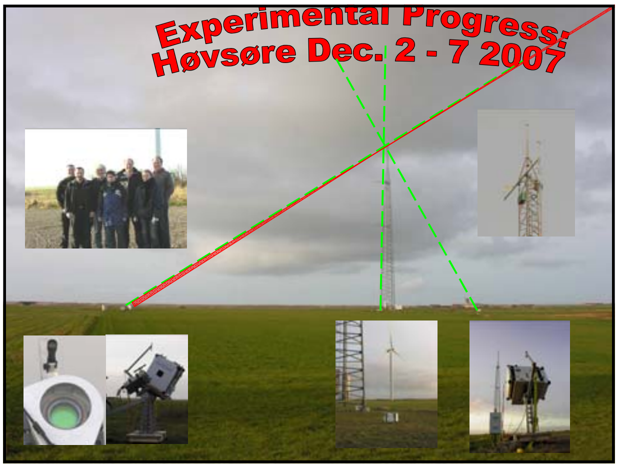
Wind Turbines of today and tomorrow extract energy from the wind…
….but generates also wakes, over land…(eScience):

…and off-shore (Middelgrunden @ Copenhagen…)

MusketeerEx-II:

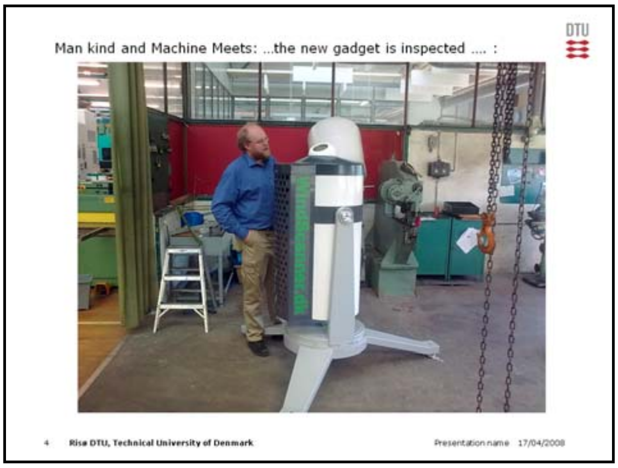
Høvsøre Dec. 2008 Windscanner lidar test

Spatial-resolution improved "Stretch Pod" Unit 107 (left) vs. Windscanner Unit 120 (right)

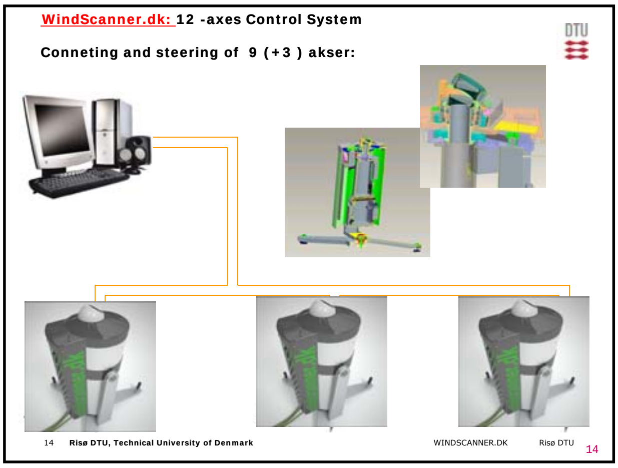


Experimental Progress:
Høvsøre Dec. 2 - 7 2007

.. The first assembled Windscanner (April 2010):

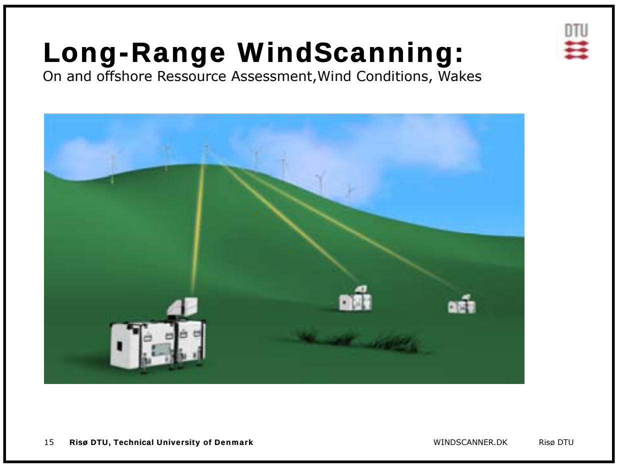


Man kind and Machine Meets: ...the new gadget is inspected .... :



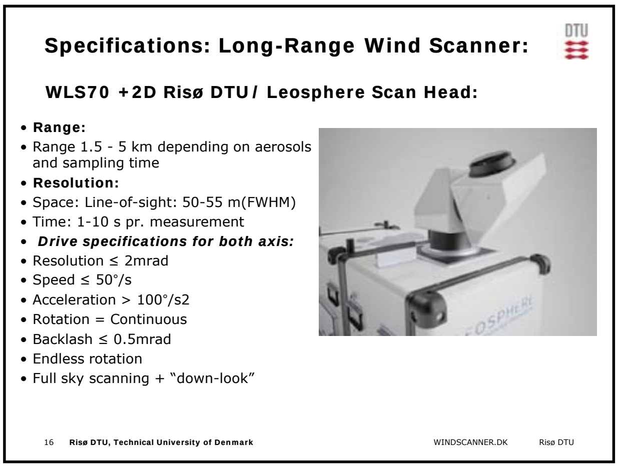
WindScanner.dk: 12 -axes Control System

Conneting and steering of 9 (+3) akser:



Long-Range WindScanning:

On and offshore Ressource Assessment,Wind Conditions, Wakes



Specifications: Long-Range Wind Scanner:

WLS70 +2D Risø DTU / Leosphere Scan Head:

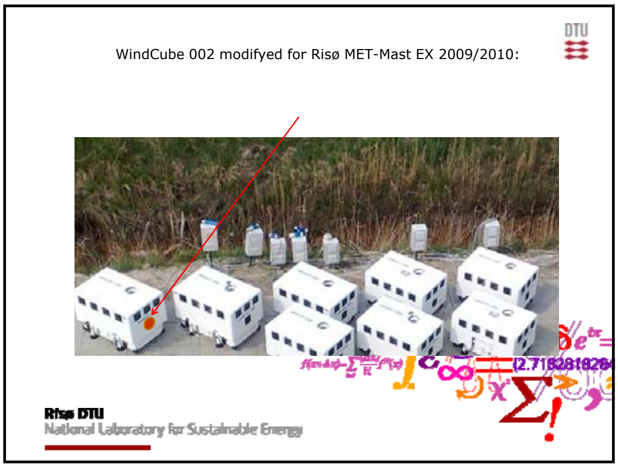
- **Range:**
- Range 1.5 - 5 km depending on aerosols and sampling time
- **Resolution:**
- Space: Line-of-sight: 50-55 m(FWHM)
- Time: 1-10 s pr. measurement
- ***Drive specifications for both axis:***
- Resolution ≤ 2mrad
- Speed ≤ 50°/s
- Acceleration > 100°/s2
- Rotation = Continuous
- Backlash ≤ 0.5mrad
- Endless rotation
- Full sky scanning + “down-look”

First Long-Range Windscanner: Oct.2010

Joint Risø DTU-Leosphere WLS70 (<1.5 km)/200 (<5 km)

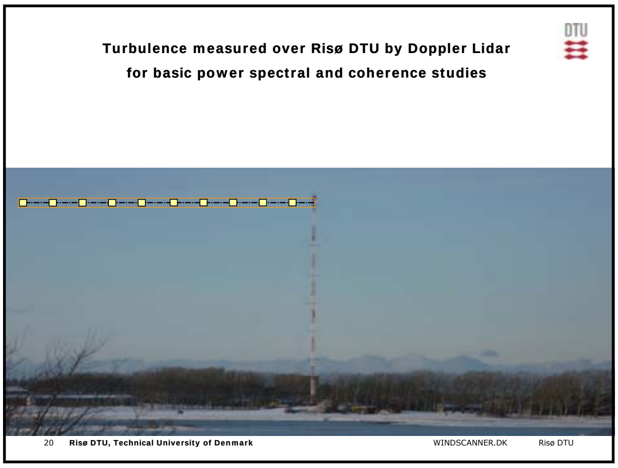
First Long-Range (Max range 5 km) WindScanner

Risø Workshop Risø DTU, Leosphere, Fr. and IPU, DK, Oct. 2010



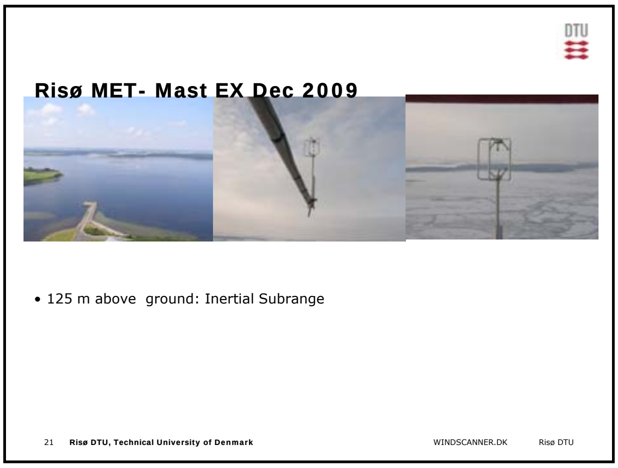
WindCube 002 modifyed for Risø MET-Mast EX 2009/2010:

Risø DTU
National Laboratory for Sustainable Energy



Turbulence measured over Risø DTU by Doppler Lidar for basic power spectral and coherence studies

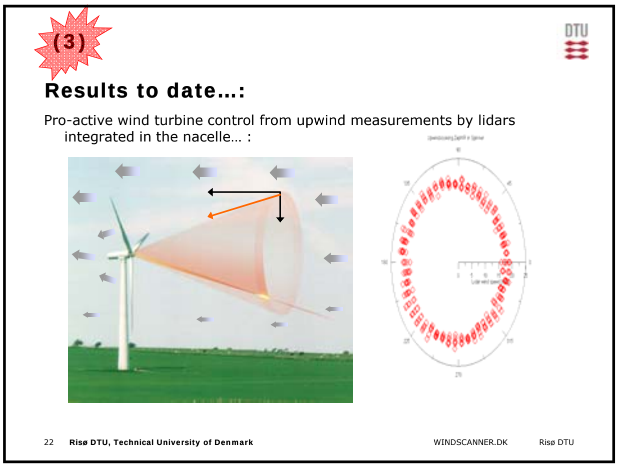
20 Risø DTU, Technical University of Denmark WINDSCANNER.DK Risø DTU



Risø MET- Mast EX Dec 2009

- 125 m above ground: Inertial Subrange

21 Risø DTU, Technical University of Denmark WINDSCANNER.DK Risø DTU



(3)

Results to date…:

Pro-active wind turbine control from upwind measurements by lidars integrated in the nacelle… :

22 Risø DTU, Technical University of Denmark WINDSCANNER.DK Risø DTU

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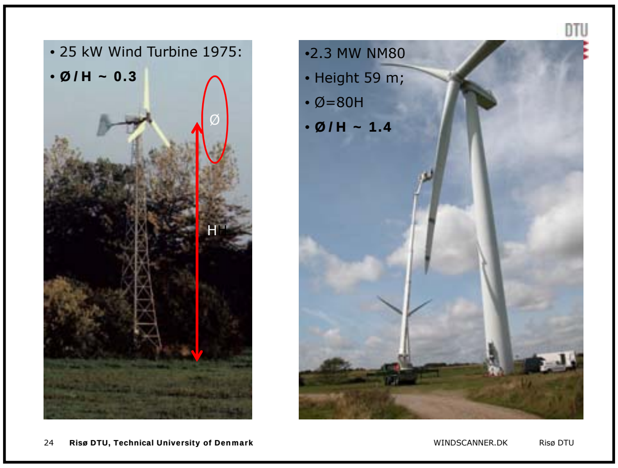

- 25 kW Wind Turbine 1975:
- **Ø / H ~ 0.3**

- 2.3 MW NM80
- Height 59 m;
- Ø=80H
- **Ø / H ~ 1.4**

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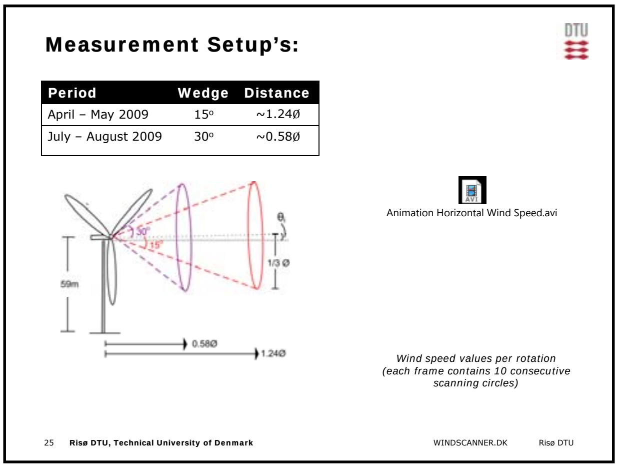
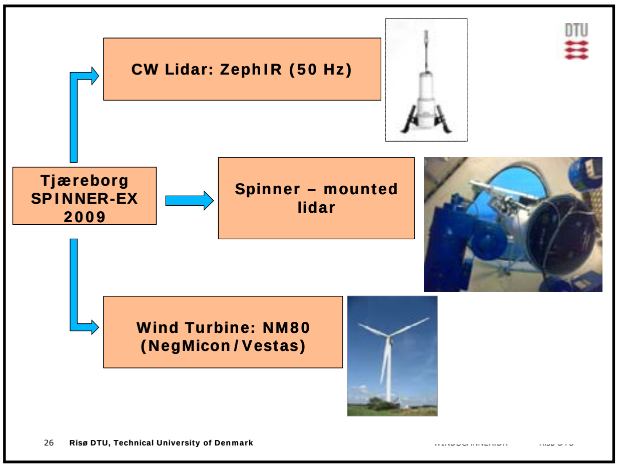


Measurement Setup's:

Period	Wedge	Distance
April – May 2009	15º	~1.24Ø
July – August 2009	30º	~0.58Ø

Animation Horizontal Wind Speed.avi

Wind speed values per rotation (each frame contains 10 consecutive scanning circles)

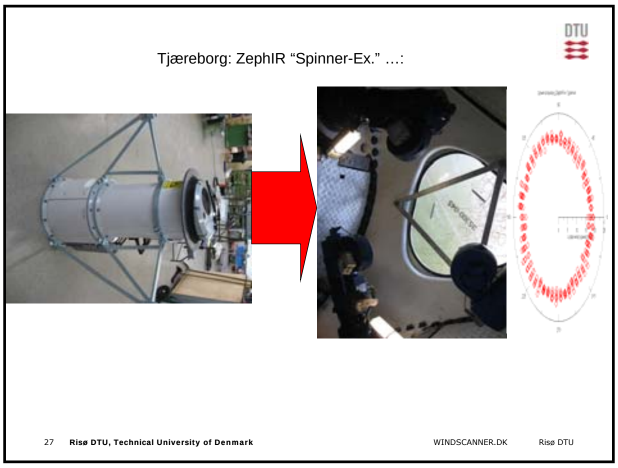


CW Lidar: ZephIR (50 Hz)

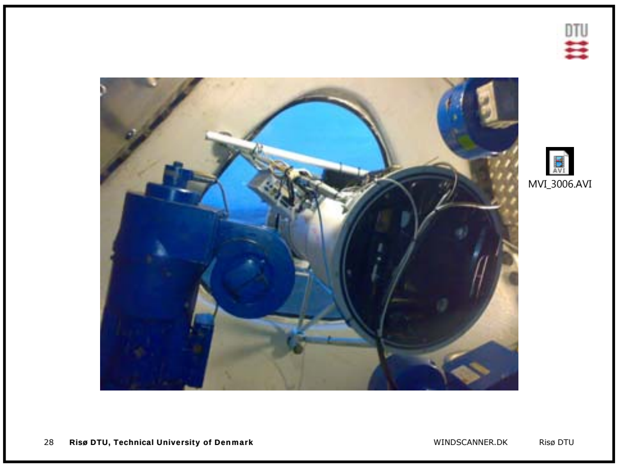
Tjæreborg SPINNER-EX 2009

Spinner – mounted lidar

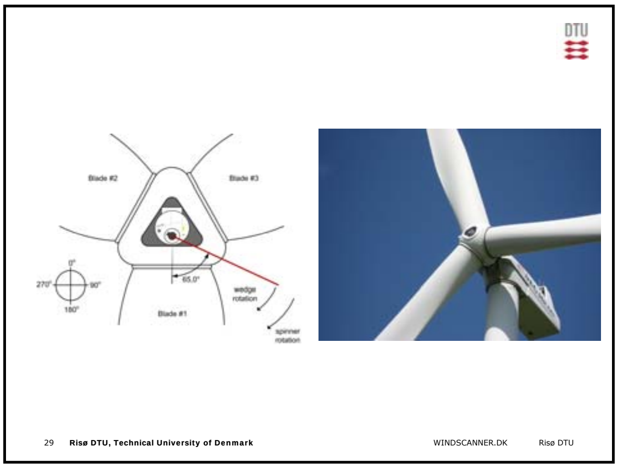
Wind Turbine: NM80 (NegMicon/Vestas)

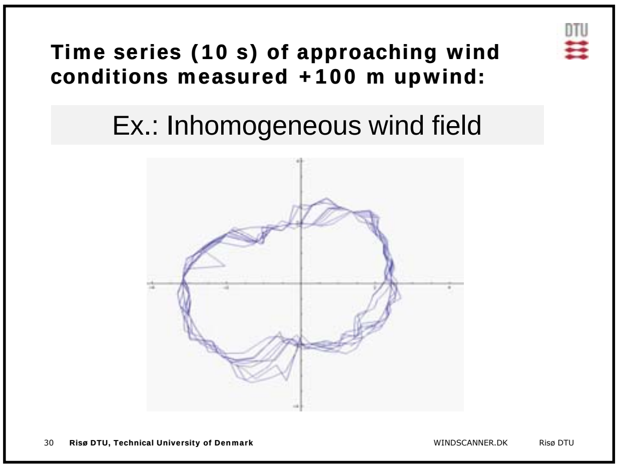


Tjæreborg: ZephIR "Spinner-Ex." …:



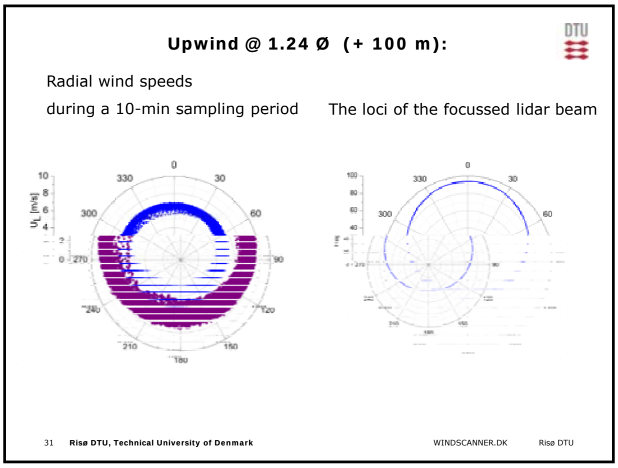
MVI_3006.AVI





Time series (10 s) of approaching wind conditions measured +100 m upwind:

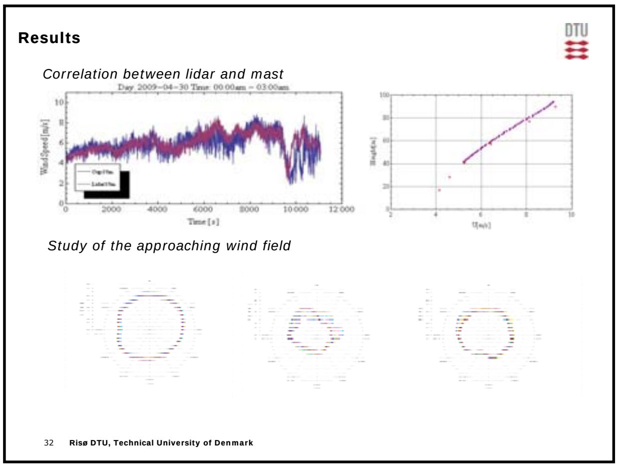
Ex.: Inhomogeneous wind field



Upwind @ 1.24 Ø (+ 100 m):

Radial wind speeds during a 10-min sampling period

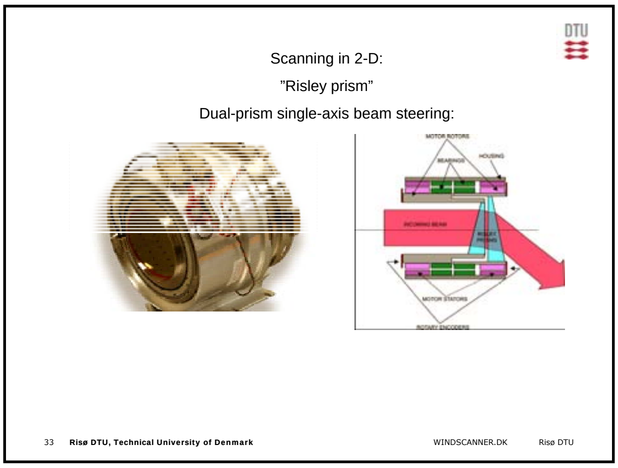
The loci of the focussed lidar beam



Results

Correlation between lidar and mast

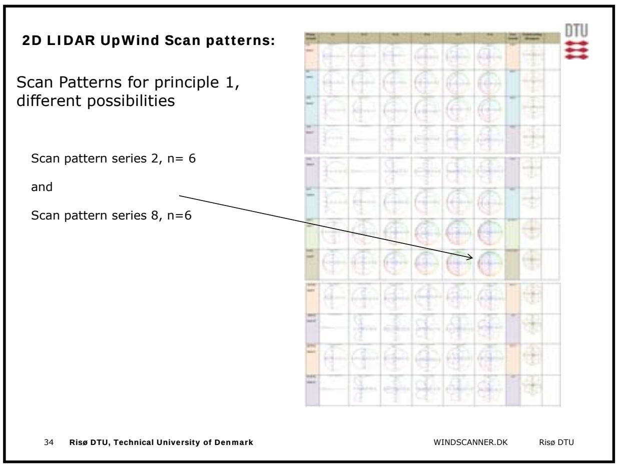
Study of the approaching wind field



Scanning in 2-D:

”Risley prism”

Dual-prism single-axis beam steering:



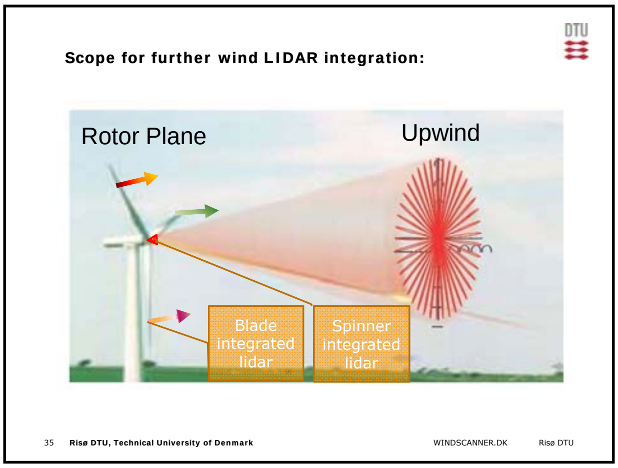
2D LIDAR UpWind Scan patterns:

Scan Patterns for principle 1, different possibilities

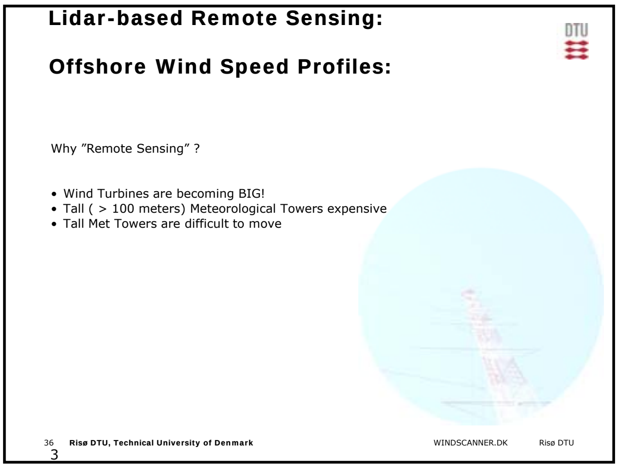
Scan pattern series 2, n= 6

and

Scan pattern series 8, n=6



Scope for further wind LIDAR integration:

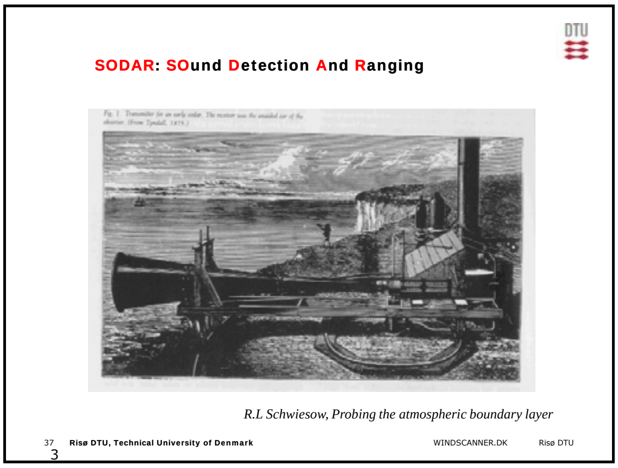


Lidar-based Remote Sensing:

Offshore Wind Speed Profiles:

Why ”Remote Sensing” ?

- Wind Turbines are becoming BIG!
- Tall (> 100 meters) Meteorological Towers expensive
- Tall Met Towers are difficult to move



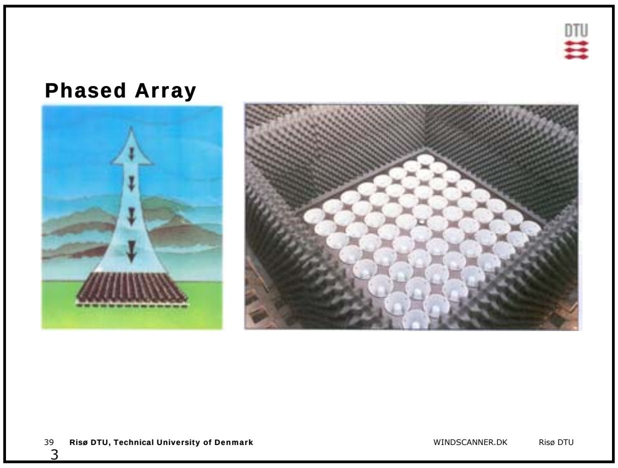
SODAR: SOund Detection And Ranging

Fig. 1 Transmitter for an early sodar. The receiver was the unaided ear of the observer. (From Tyndall, 1875.)

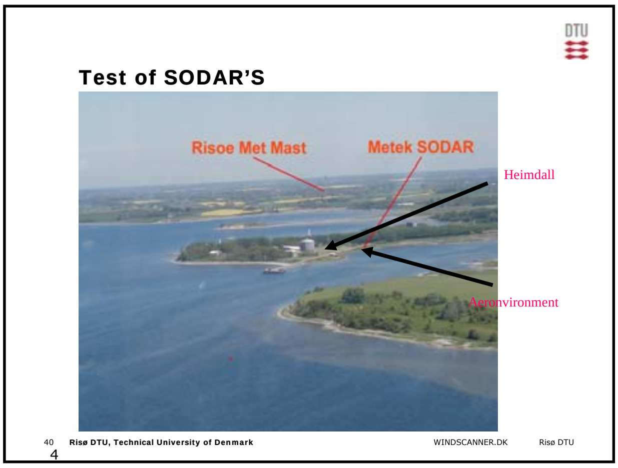
R.L Schwiesow, Probing the atmospheric boundary layer

Monostatic SODAR

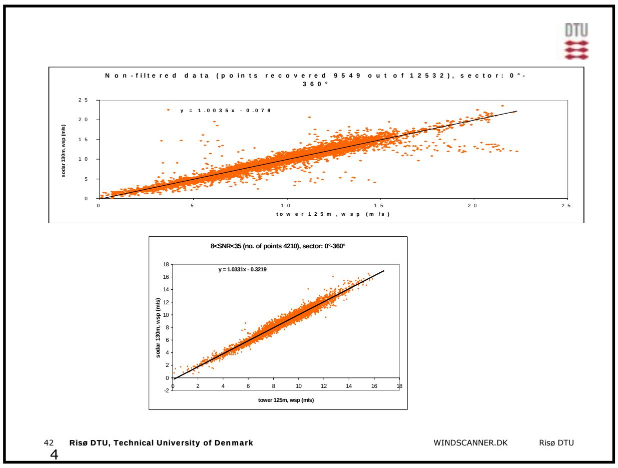
Lidar and sodar

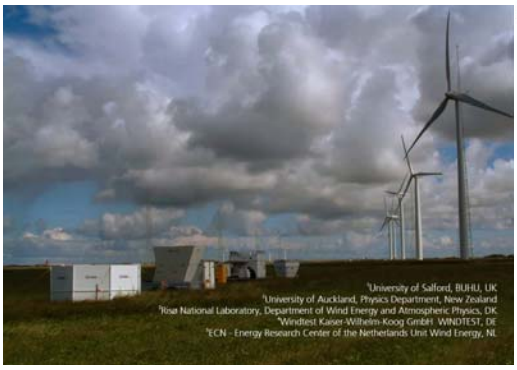


Phased Array



Test of SODAR'S





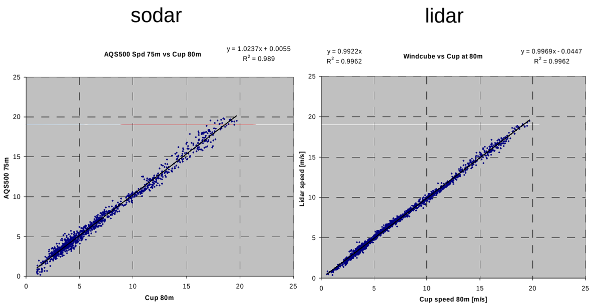
Ground-based RS Wind Sensors @ Høvsøre 2004 - 2009:

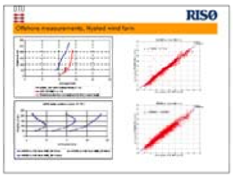

SODARS

CW LIDARS

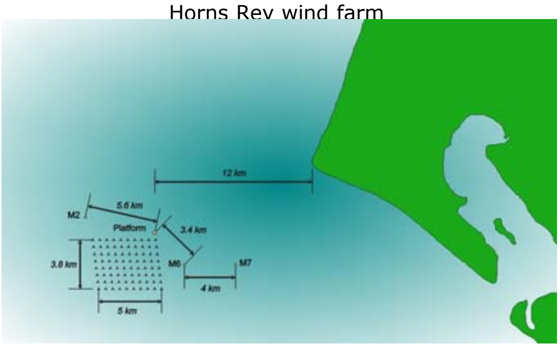
Pulsed LIDARS

Sodar data is inherently noisier than lidar data

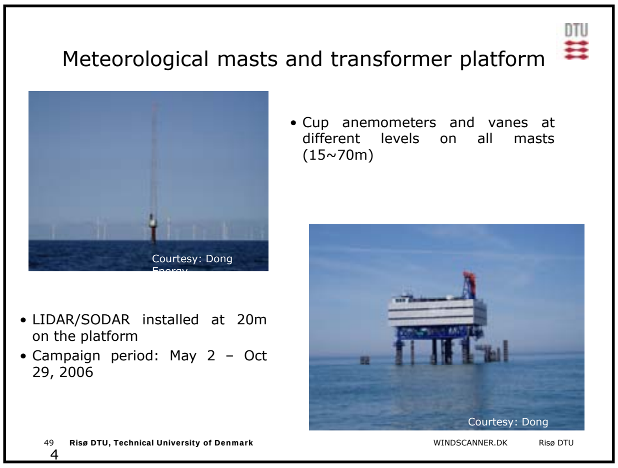




Horns Rev wind farm



Horns Rev-I Wind Farm

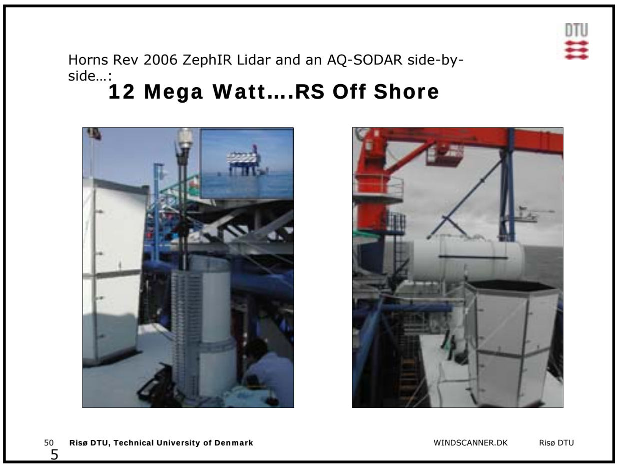


Meteorological masts and transformer platform

- Cup anemometers and vanes at different levels on all masts (15~70m)
- LIDAR/SODAR installed at 20m on the platform
- Campaign period: May 2 – Oct 29, 2006

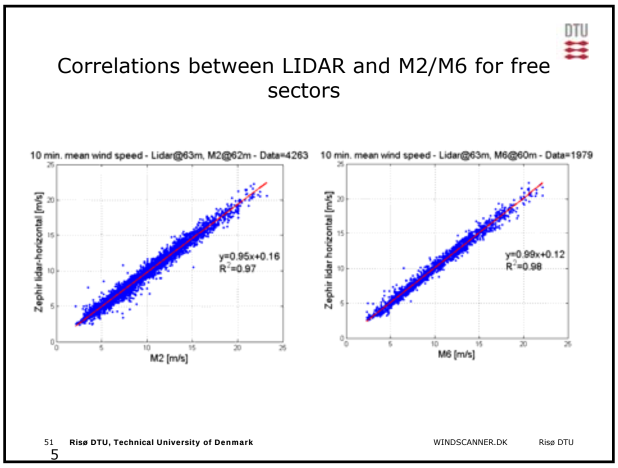
Courtesy: Dong Energy

Courtesy: Dong

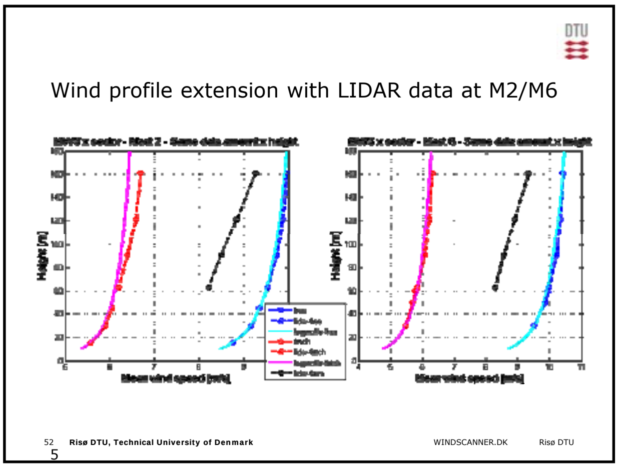


Horns Rev 2006 ZephIR Lidar and an AQ-SODAR side-by-side...:

12 Mega Watt....RS Off Shore



Correlations between LIDAR and M2/M6 for free sectors



Wind profile extension with LIDAR data at M2/M6

Figure: WindCube wind lidar at (~ 25 m) on the platform

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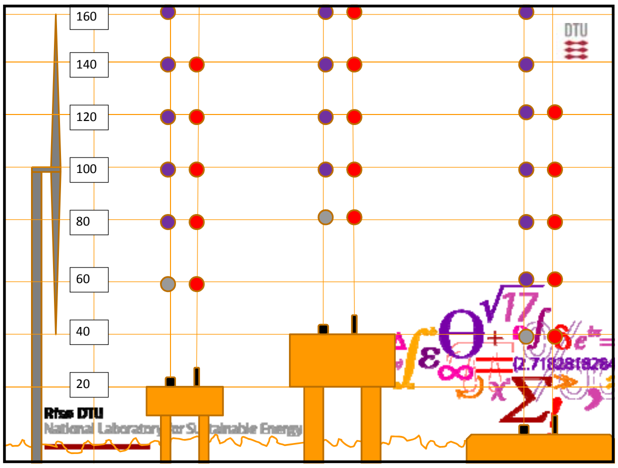
National Laboratory for Sustainable Energy



Overview on wind profiles Horns Rev I Egmond aan Zee Horns Rev II

Contents

- Overview on wind profiles
- Horns Rev I
- Egmond aan Zee
- Horns Rev II

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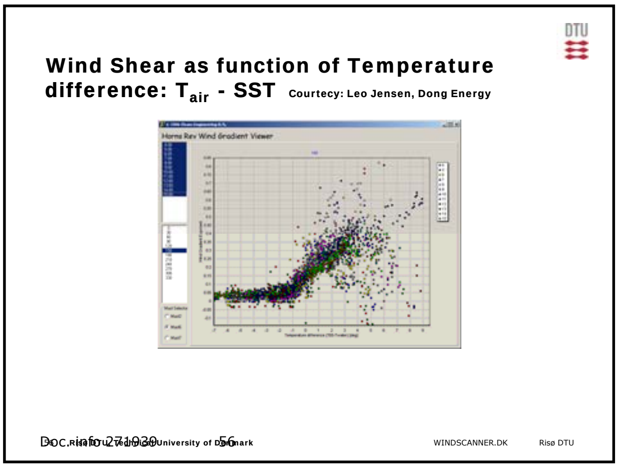

Wind Shear as function of Temperature difference: T_{air} - SST

Courtecy: Leo Jensen, Dong Energy

Doc. info 271939 56
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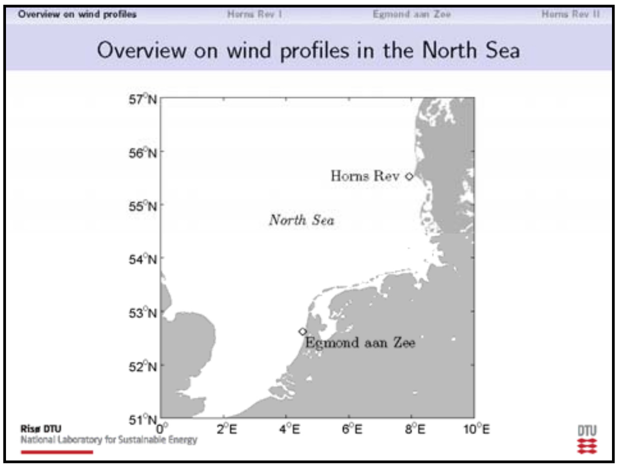

Overview on wind profiles Horns Rev I Egmond aan Zee Horns Rev II

Overview on wind profiles in the North Sea

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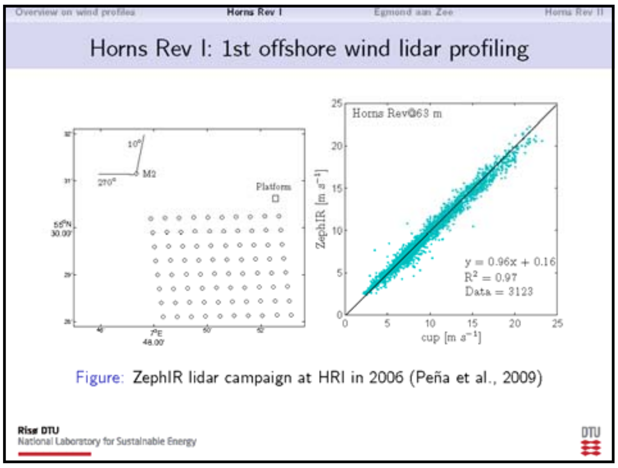

Overview on wind profiles Horns Rev I Egmond aan Zee Horns Rev II

Horns Rev I: 1st offshore wind lidar profiling

Figure: ZephIR lidar campaign at HRI in 2006 (Peña et al., 2009)

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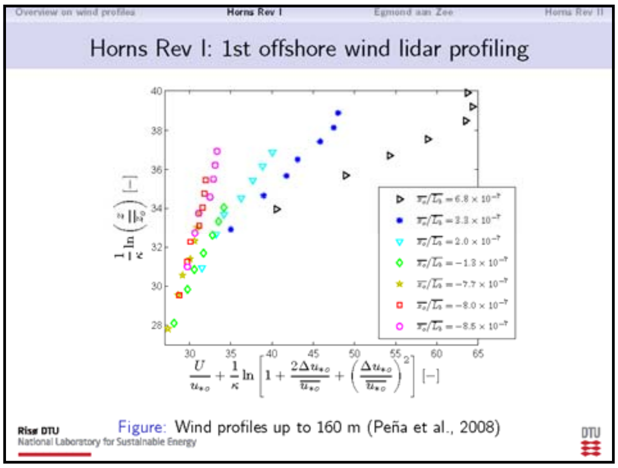

Overview on wind profiles Horns Rev I Egmond aan Zee Horns Rev II

Horns Rev I: 1st offshore wind lidar profiling

Figure: Wind profiles up to 160 m (Peña et al., 2008)

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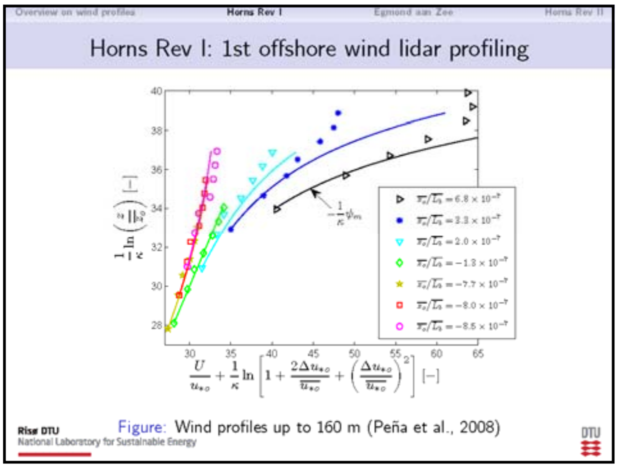

Overview on wind profiles Horns Rev I Egmond aan Zee Horns Rev II

Horns Rev I: 1st offshore wind lidar profiling

Figure: Wind profiles up to 160 m (Peña et al., 2008)

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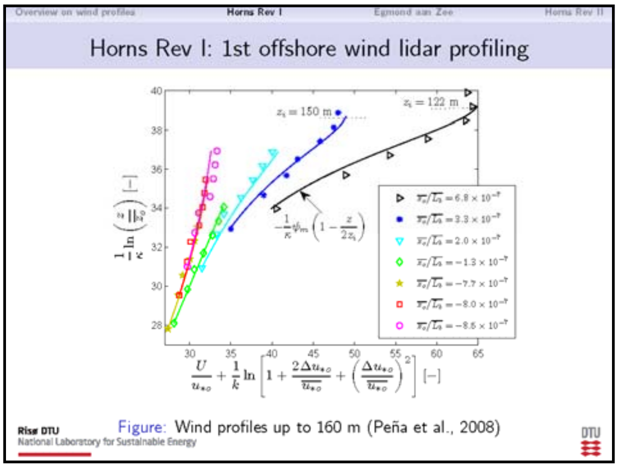
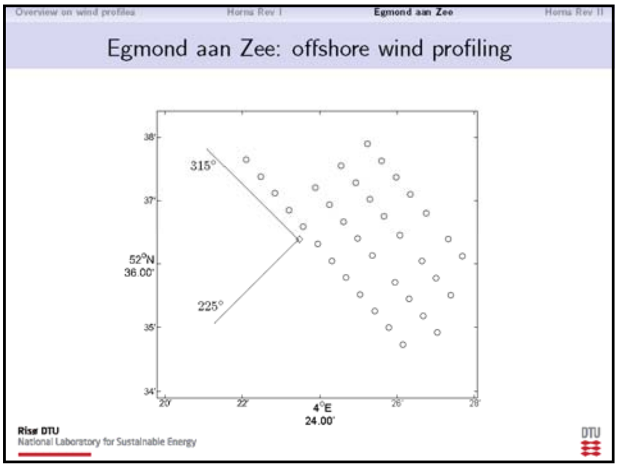

Overview on wind profiles | **Horns Rev I** | Egmond aan Zee | Horns Rev II

Horns Rev I: 1st offshore wind lidar profiling

Figure: Wind profiles up to 160 m (Peña et al., 2008)

Risø DTU
National Laboratory for Sustainable Energy


Overview on wind profiles | Horns Rev I | **Egmond aan Zee** | Horns Rev II

Egmond aan Zee: offshore wind profiling

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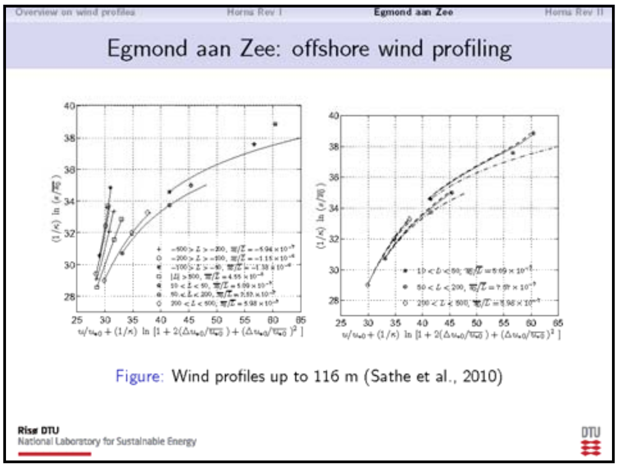
Overview on wind profiles | Horns Rev I | **Egmond aan Zee** | Horns Rev II

Egmond aan Zee: offshore wind profiling

Figure: Wind profiles up to 116 m (Sathe et al., 2010)

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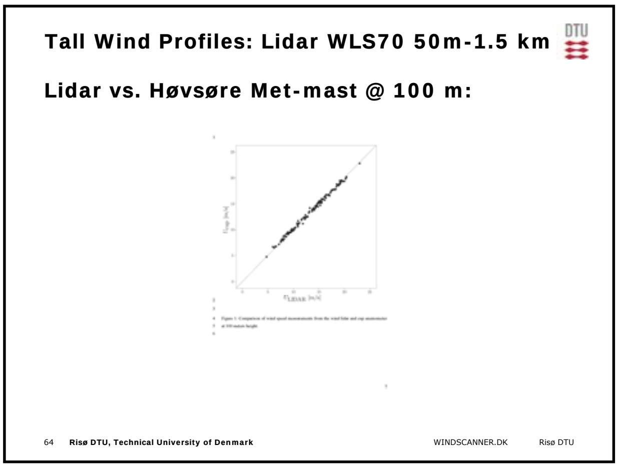

Tall Wind Profiles: Lidar WLS70 50m-1.5 km

Lidar vs. Høvsøre Met-mast @ 100 m:

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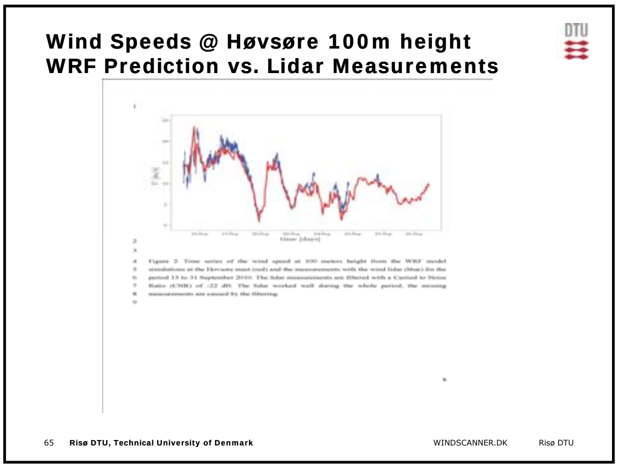

Wind Speeds @ Høvsøre 100m height
WRF Prediction vs. Lidar Measurements

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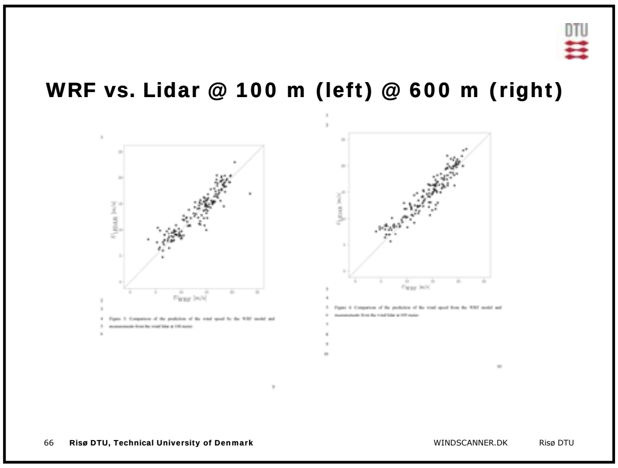

WRF vs. Lidar @ 100 m (left) @ 600 m (right)

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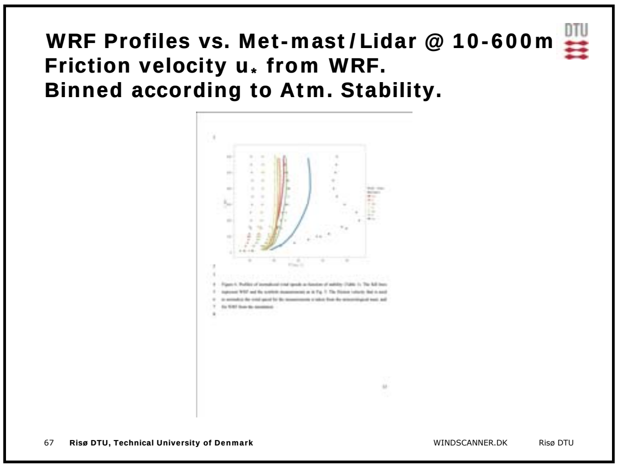


WRF Profiles vs. Met-mast/Lidar @ 10-600m Friction velocity u* from WRF. Binned according to Atm. Stability.

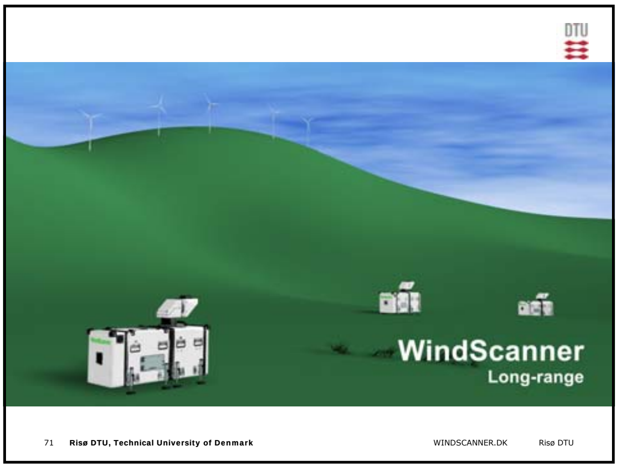
Find more details at: www.risoe.dk www.windscanner.dk

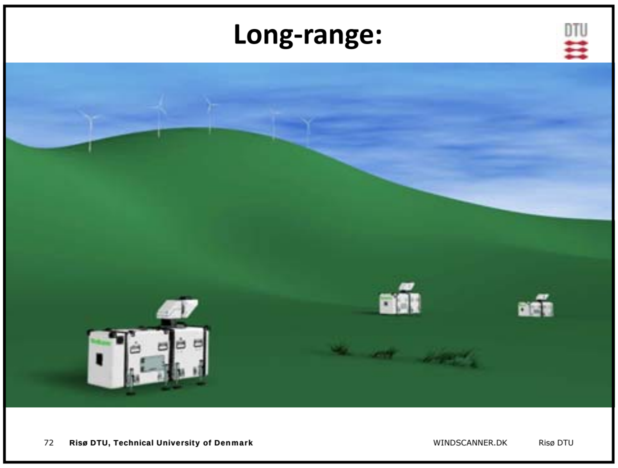
- Acknowledgements to many Risø DTU colleges:

- Charlotte Hasager
- Alfredo Peña
- Roger Floors,
- Ekaterina Batchvarova
- Sven-Erik Gryning
- Andrea Hahmann
- Mikael Sjöholm
- Nikolas Angelou
- Kasper Hansen

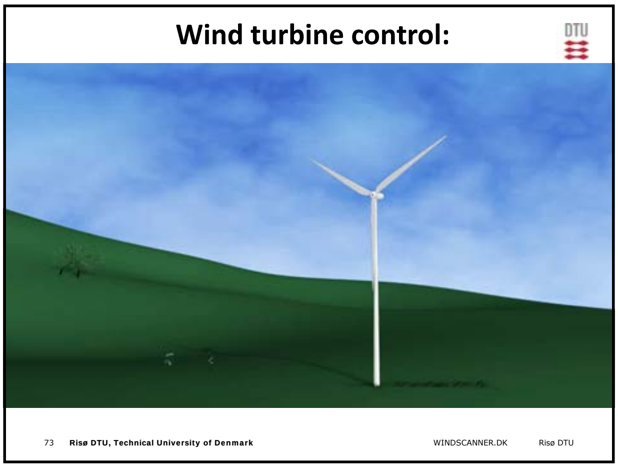
WindScanner

Short-range:

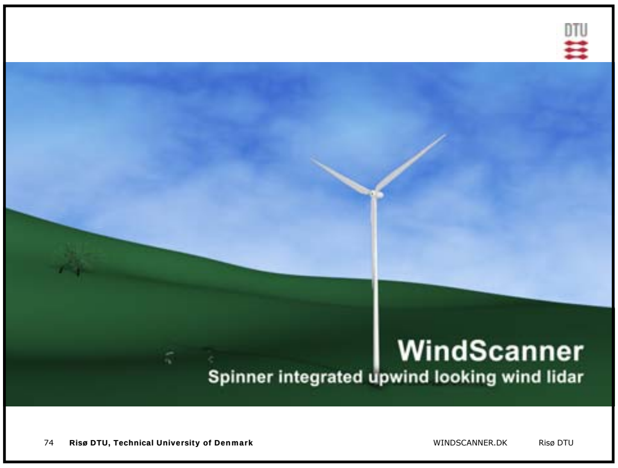




Long-range:



Wind turbine control:



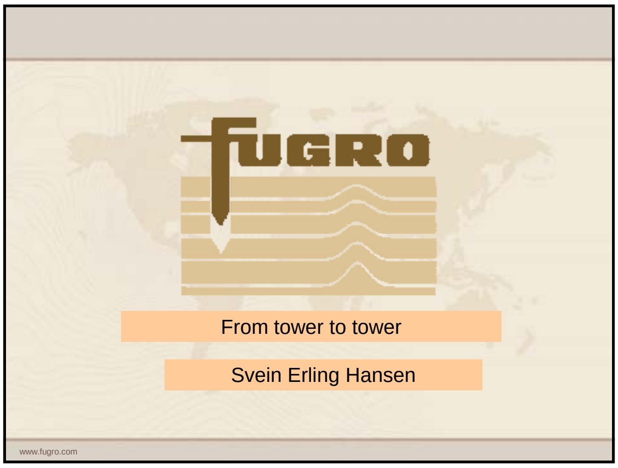
WindScanner

Spinner integrated upwind looking wind lidar

WindScanner

Offshore scanning

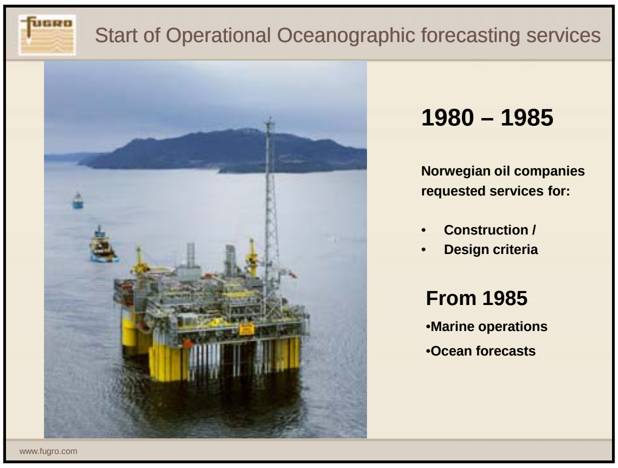
Off shore:



From tower to tower

Svein Erling Hansen

SEAWATCH our system for ocean observations



Start of Operational Oceanographic forecasting services

1980 – 1985

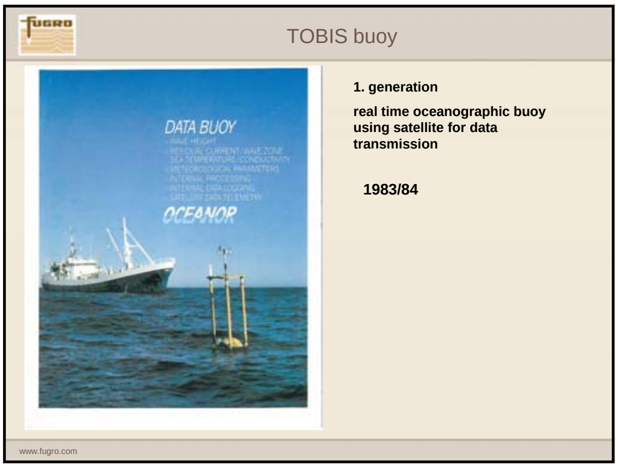
Norwegian oil companies requested services for:

- **Construction /**
- **Design criteria**

From 1985

•Marine operations

•Ocean forecasts



TOBIS buoy

DATA BUOY

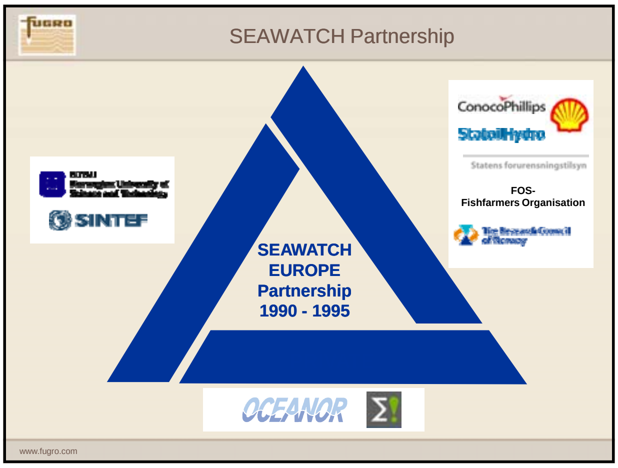
- WAVE HEIGHT
- RESIDUAL CURRENT / WAVE ZONE SEA TEMPERATURE/CONDUCTIVITY
- METEOROLOGICAL PARAMETERS
- INTERNAL PROCESSING
- INTERNAL DATA LOGGING
- SATELLITE DATA TELEMETRY

OCEANOR

1. generation

real time oceanographic buoy using satellite for data transmission

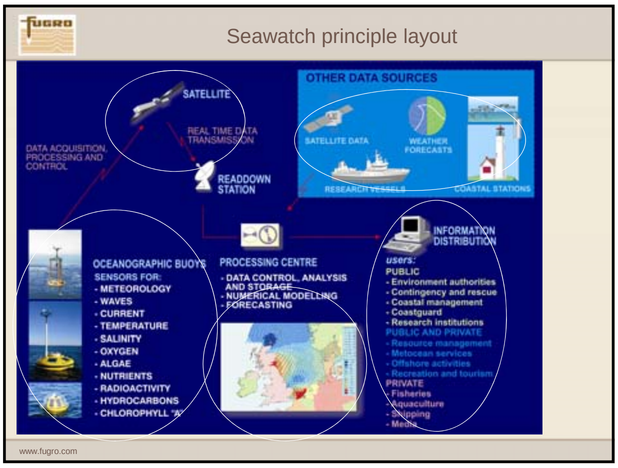
1983/84



SEAWATCH Partnership

FOS-
Fishfarmers Organisation

SEAWATCH EUROPE Partnership 1990 - 1995



Seawatch principle layout

OCEANOGRAPHIC BUOYS
SENSORS FOR:
- METEOROLOGY
- WAVES
- CURRENT
- TEMPERATURE
- SALINITY
- OXYGEN
- ALGAE
- NUTRIENTS
- RADIOACTIVITY
- HYDROCARBONS
- CHLOROPHYLL "A"

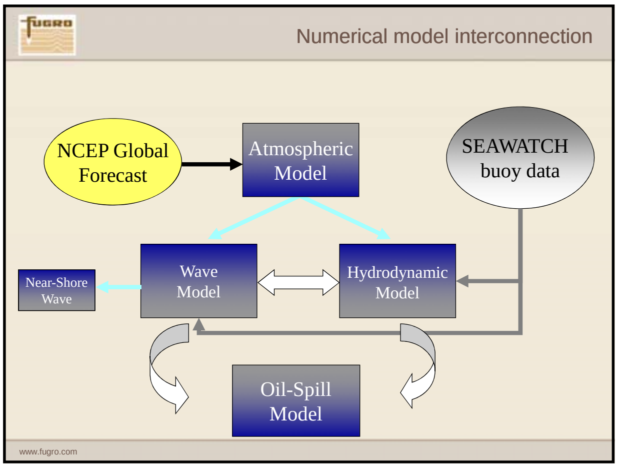
PROCESSING CENTRE
- DATA CONTROL, ANALYSIS AND STORAGE
- NUMERICAL MODELLING
- FORECASTING

users:
PUBLIC
- Environment authorities
- Contingency and rescue
- Coastal management
- Coastguard
- Research institutions

PUBLIC AND PRIVATE
- Resource management
- Metocean services
- Offshore activities
- Recreation and tourism

PRIVATE
- Fisheries
- Aquaculture
- Shipping
- Media

OCEANOR's Metocean buoys



Numerical model interconnection

NCEP Global Forecast

Atmospheric Model

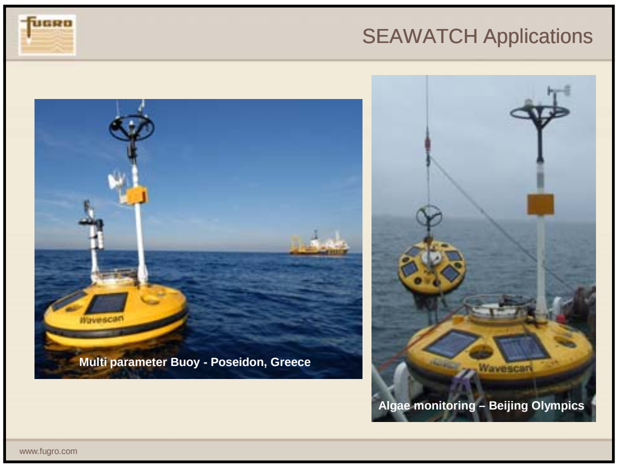
SEAWATCH buoy data

Near-Shore Wave

Wave Model

Hydrodynamic Model

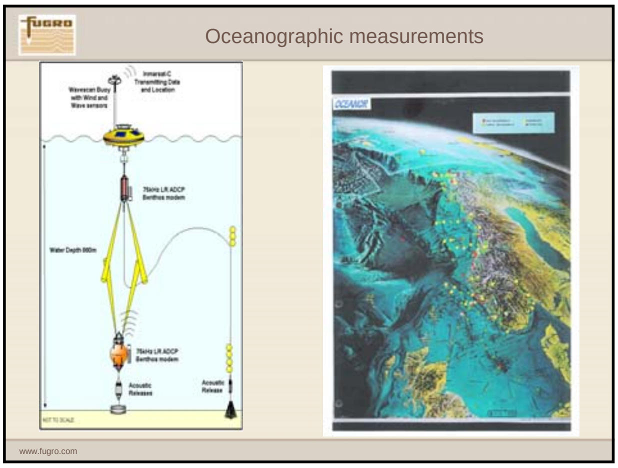
Oil-Spill Model



SEAWATCH Applications

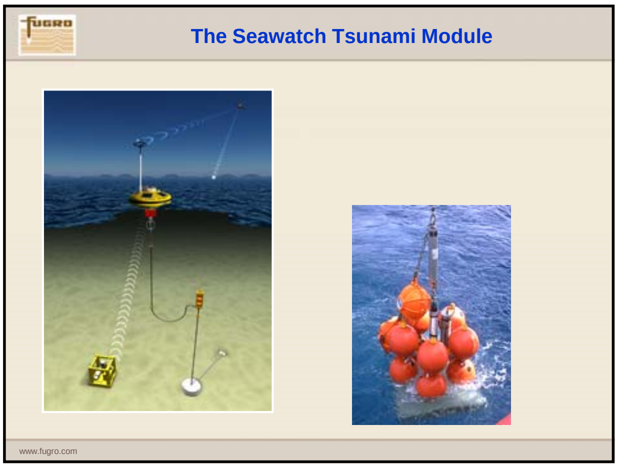
Multi parameter Buoy - Poseidon, Greece

Algae monitoring – Beijing Olympics

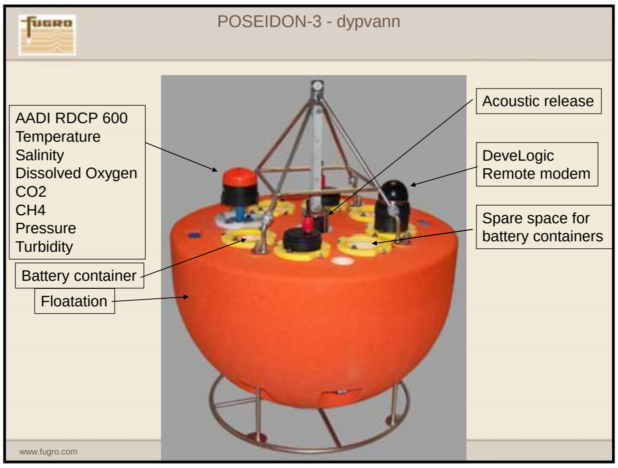


Oceanographic measurements

Operations



The Seawatch Tsunami Module



POSEIDON-3 - dypvann

AADI RDCP 600
Temperature
Salinity
Dissolved Oxygen
CO2
CH4
Pressure
Turbidity

Battery container

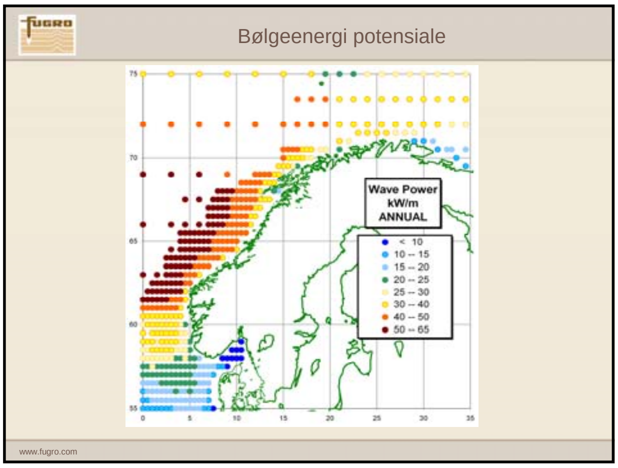
Floatation

Acoustic release

DeveLogic
Remote modem

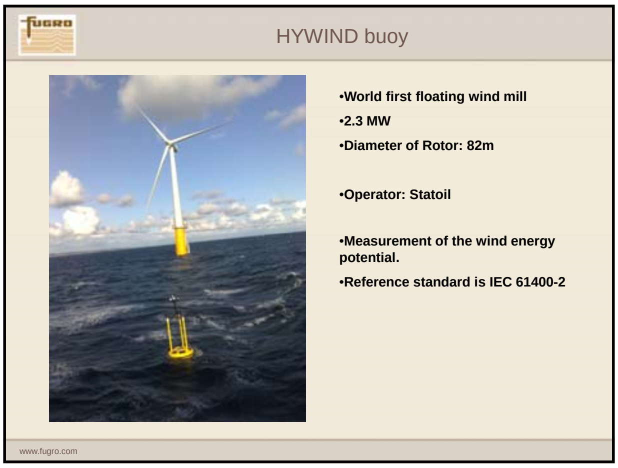
Spare space for
battery containers

www.fugro.com



Bølgeenergi potensiale

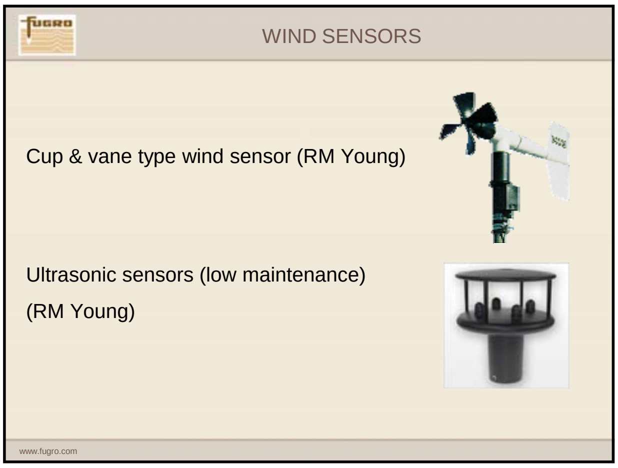
www.fugro.com



HYWIND buoy

- **World first floating wind mill**
- **2.3 MW**
- **Diameter of Rotor: 82m**
- **Operator: Statoil**
- **Measurement of the wind energy potential.**
- **Reference standard is IEC 61400-2**

www.fugro.com



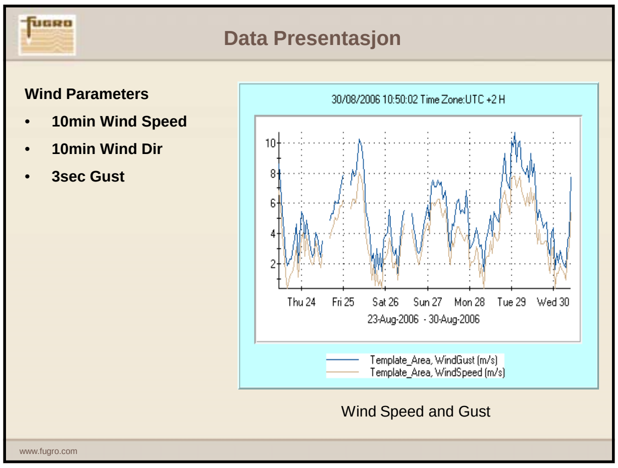
WIND SENSORS

Cup & vane type wind sensor (RM Young)

Ultrasonic sensors (low maintenance)

(RM Young)

www.fugro.com



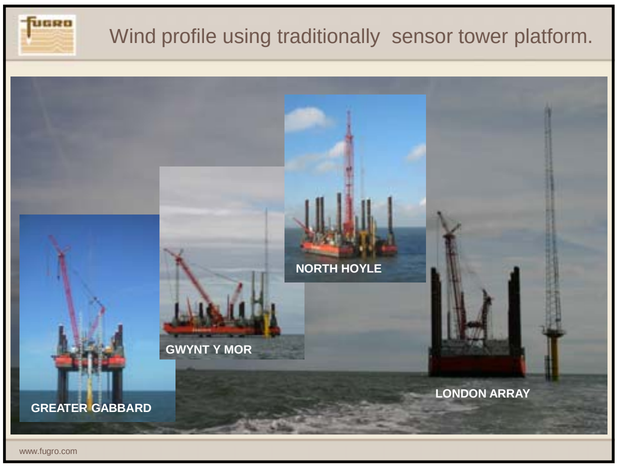
Data Presentasjon

Wind Parameters

- **10min Wind Speed**
- **10min Wind Dir**
- **3sec Gust**

Wind Speed and Gust

www.fugro.com



Wind profile using traditionally sensor tower platform.

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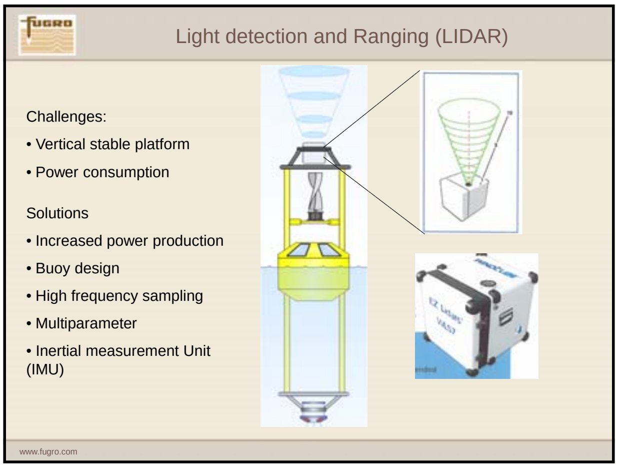

Light detection and Ranging (LIDAR)

Challenges:

- Vertical stable platform
- Power consumption

Solutions

- Increased power production
- Buoy design
- High frequency sampling
- Multiparameter
- Inertial measurement Unit (IMU)

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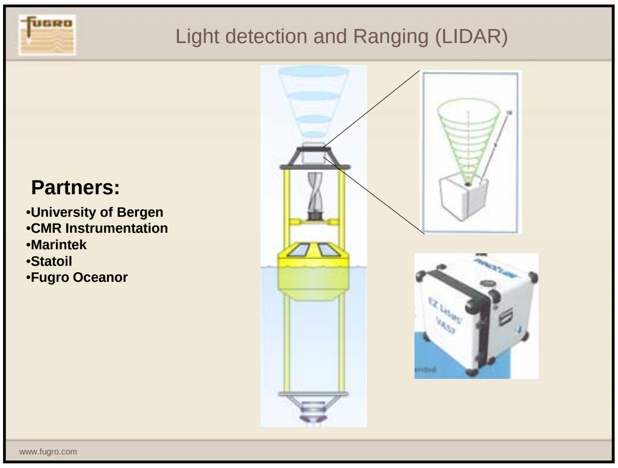

Light detection and Ranging (LIDAR)

Partners:

- **University of Bergen**
- **CMR Instrumentation**
- **Marintek**
- **Statoil**
- **Fugro Oceanor**

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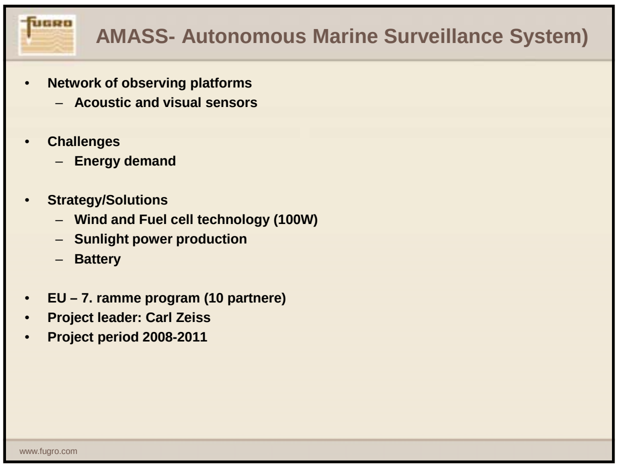

AMASS- Autonomous Marine Surveillance System)

- **Network of observing platforms**
  - **Acoustic and visual sensors**
- **Challenges**
  - **Energy demand**
- **Strategy/Solutions**
  - **Wind and Fuel cell technology (100W)**
  - **Sunlight power production**
  - **Battery**
- **EU – 7. ramme program (10 partnere)**
- **Project leader: Carl Zeiss**
- **Project period 2008-2011**

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THANK YOU

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Effects of ocean waves

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Wind Power R&D Seminar, Trondheim
2011-01-20

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met.no: Lars Robert Hole, Birgitte Furevik, Harald Engedahl, Øyvind Sætra, Øyvind Breivik

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Introduction

Effects of ocean waves on offshore wind power production

- Direct effects:
  - Forces on fixed and floating structures
  - Hydrodynamic forces (drag and inertia)
  - Slamming of free surface (breaking waves)
  - Generation of spray and air bubbles
- Indirect effects:
  - Influence of waves on atmospheric boundary layer
  - Influence of waves on the ocean
- Effect on measurements

Direct effect of waves

- Oscillatory forcing on structure / mooring
- Inertial forces and turbulent drag due to mean current and wave orbital motion (Morison equation etc.)
- Wave breaking / slamming: impulsive loads due to impact of water surface
  - Near-vertical inclination of water surface
  - Breakup of jet ejected from wave crest
  - Sea spray / corrosion, icing
  - Turbulence / air bubbles

Wave effects via atmospheric boundary layer

- Effect on turbulence (drag coefficient, aerodynamic roughness)
- Influence of atmospheric stability
- Oscillatory motions
- Critical layer effect
- Second-order mean flow, wave-induced wind
- Internal waves in boundary layer
- Coupling via dynamics (structural, electrical system)

Wave modelling techniques (examples)

- Direct numerical simulation (DNS); large eddy simulation (LES)
- Boundary integral methods (compute interface only)
- Spectral representation: radiative transfer equations
- Dimensions: 2 spatial, 2 in Fourier space
- Include terms for wave energy input from wind, nonlinear transfer, energy dissipation
- Wave refraction and ray tracing models

Effect on measurements

Waves on the air–sea interface affect the measurement of parameters and flow variables in a numer of ways:

- Via the waves' effect on the turbulent flow, as roughness elements or by extracting momentum from the flow in other ways
- By moving the instrument platform about, so that platform-based fluid velocity and other measurements must be corrected for
- By inducing oscillatory motions in the atmosphere and the ocean, thereby corrupting averaged quantities measured from a moving platform

Turbulent boundary layer

$$U(z) = (u_*/\kappa)\log(z/z_0)$$

- $u_* = (\tau/\rho_a)^{1/2}$ = friction velocity
- Turbulent wind stress $\tau = \rho_a {u_*}^2 = \rho_a C_D(z)[U(z)]^2$
- $C_D(z)$ = drag coefficient referred to height z
- ρ_a = air density
- $\kappa \approx 0.4$ = von Kármán constant
- z_0 = roughness length

Marine boundary layer

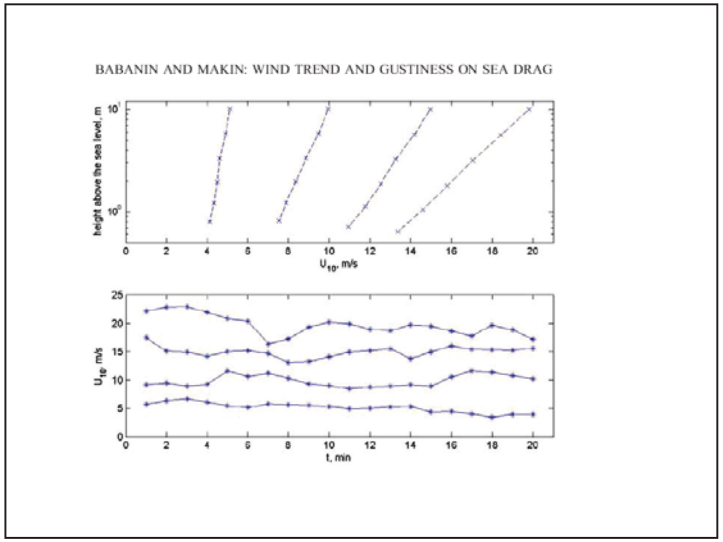
Turbulent drag coefficient / roughness length reduced with respect to land conditions:

- Roughness elements are surface gravity-capillary waves (wind waves)
- The longer/larger wave components travel with the wind, and give a kind of 'slip' boundary condition

Henry Charnock (1955)

- Roughness elements are short gravity waves
- Relevant parameters:
  - friction velocity u_*
  - accel. due to gravity g
- $z_0 = \alpha {u_*}^2/g$
- Charnock coefficient $\alpha \approx 0.014$

Next slide: logarithmic velocity profile and wind gustiness measured by Babanin and Makin (2008)



BABANIN AND MAKIN: WIND TREND AND GUSTINESS ON SEA DRAG

Vertical momentum flux (in air or water)

$$\begin{aligned}\tau &= \rho {u_*}^2 = -\rho\langle u'w'\rangle \quad \text{(Reynolds stress)}\\ &= -\rho\langle(u_t+u_w)(w_t+w_w)\rangle\\ &= \rho C_D(z)[U(z)]^2\end{aligned}$$

$\langle\cdot\rangle$: average

$\langle\cdot\rangle_t$: turbulent, $\langle\cdot\rangle_w$: correlated with wave motions

C_D = drag coefficient

Miles theory for wave generation and wave-induced momentum flux

- J. W. Miles (1957): Wave growth rate determined by curvature of $U(z)$ at the critical level z_c where the wind velocity is equal to the wave phase velocity c
- At z_c the wave-induced Reynolds stress $\tau_w = \rho {u_*}^2 = -\rho\langle u_w w_w\rangle$ has a singularity (for a single wave component)

Next slide: example of modelled wave-induced oscillatory motions in the airflow, showing singular behaviour at $z = z_c$

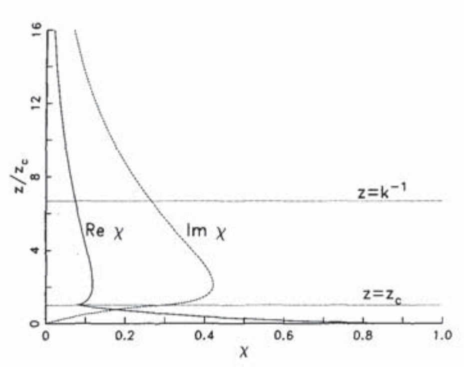
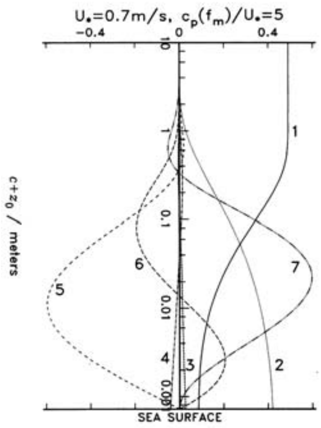


FIG. 4. Example of the solution of the Rayleigh equation for a square root velocity profile, $K = 0.15$.

(Jenkins 1993)



Various contributions to modelled vertical momentum flux (Jenkins 1992). Above the region of wave influence it is turbulent Reynolds stress (1); near the surface is is mostly pressure—surface slope covariance (2)

Wave and turbulent stress computed by Makin (2008)

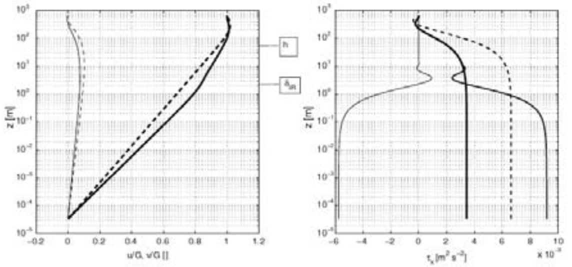
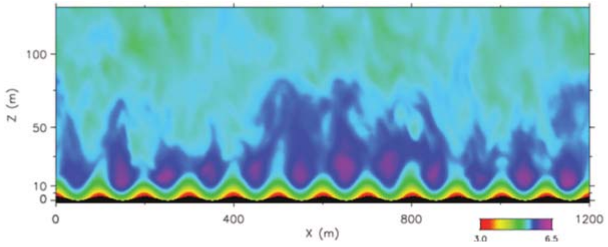
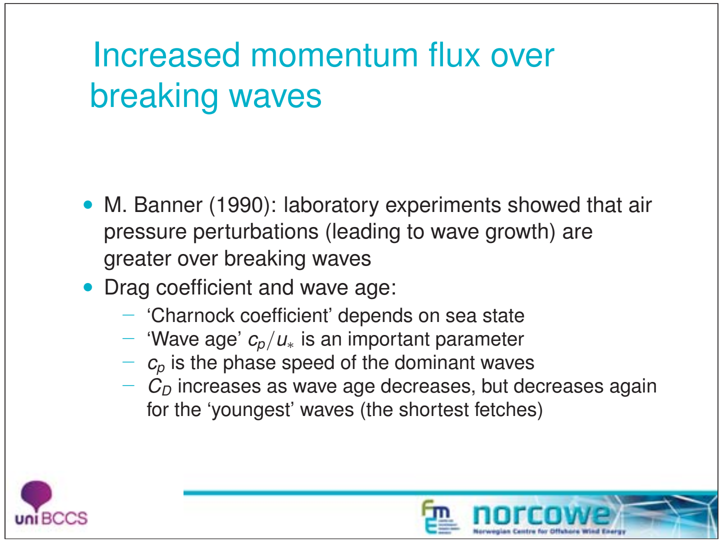


Fig. 1 *Left.* Wind-speed components. *Thick solid line*—*u*-component; *thin solid line*—*v*-component; swell is present, $\alpha_c = -0.62$ ($C_\beta = -500$, $AK = 0.05$). *Thick dashed line*—*u*-component; *thin dashed line*—*v*-component, no swell. *Right.* Stress components (only *x*-axis components are shown). *Thick solid line*—total stress; *medium solid*—turbulent stress; *thin solid*—wave-induced stress, swell is present. *Dashed line*—turbulent stress, no swell. The heights of the inner region δ_{IR} and the atmospheric surface layer h are shown by horizontal lines crossing the vertical axis



Large-eddy simulation modelling above waves (Edson et al. 2007)



Increased momentum flux over breaking waves

- M. Banner (1990): laboratory experiments showed that air pressure perturbations (leading to wave growth) are greater over breaking waves
- Drag coefficient and wave age:
  - 'Charnock coefficient' depends on sea state
  - 'Wave age' c_p/u_* is an important parameter
  - c_p is the phase speed of the dominant waves
  - C_D increases as wave age decreases, but decreases again for the 'youngest' waves (the shortest fetches)

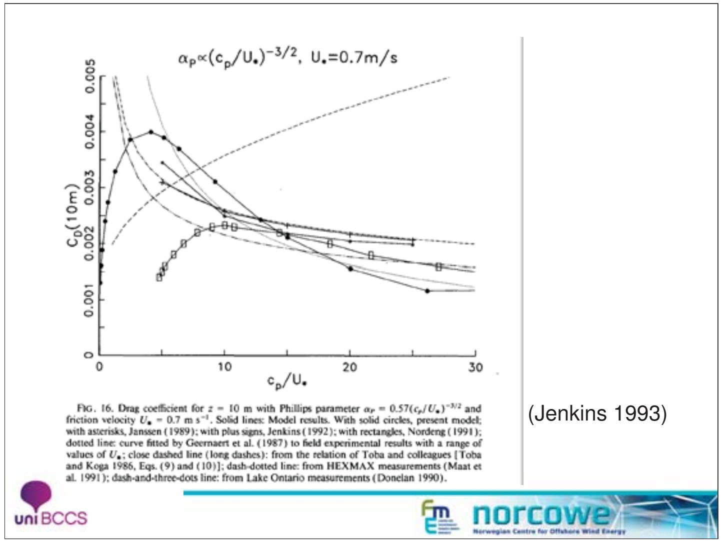


FIG. 16. Drag coefficient for z = 10 m with Phillips parameter $\alpha_P = 0.57(c_p/U_*)^{-3/2}$ and friction velocity U_* = 0.7 m s^{-1}. Solid lines: Model results. With solid circles, present model; with asterisks, Janssen (1989); with plus signs, Jenkins (1992); with rectangles, Nordeng (1991); dotted line: curve fitted by Geernaert et al. (1987) to field experimental results with a range of values of U_*; close dashed line (long dashes): from the relation of Toba and colleagues [Toba and Koga 1986, Eqs. (9) and (10)]; dash-dotted line: from HEXMAX measurements (Maat et al. 1991); dash-and-three-dots line: from Lake Ontario measurements (Donelan 1990).

(Jenkins 1993)

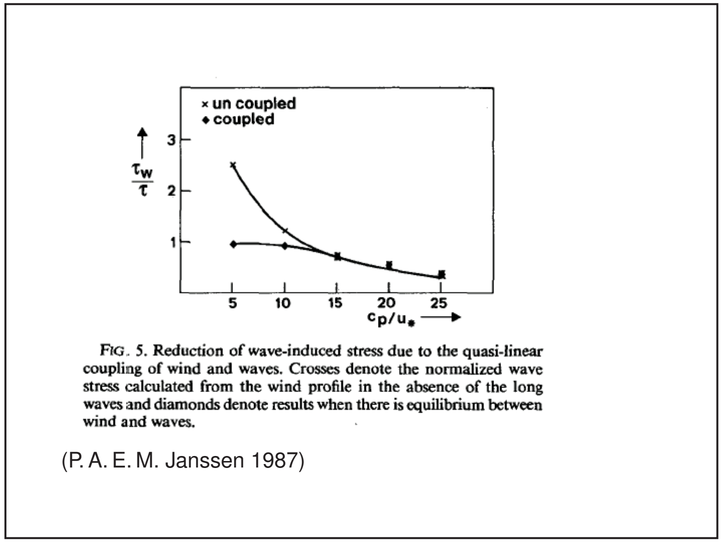
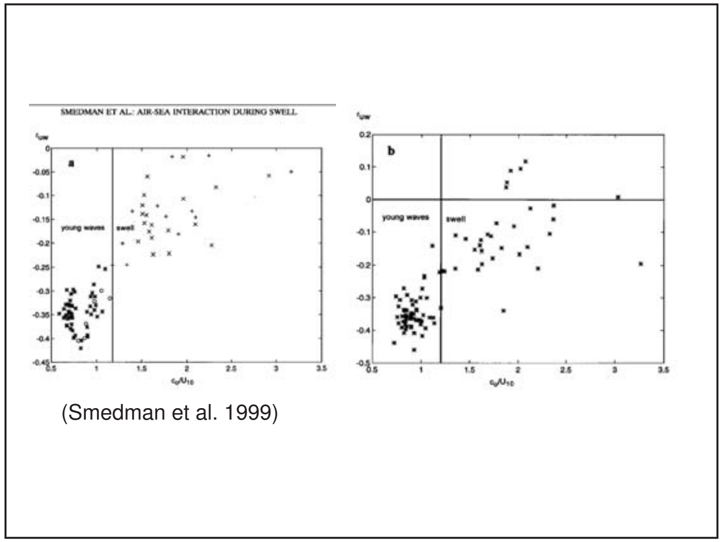
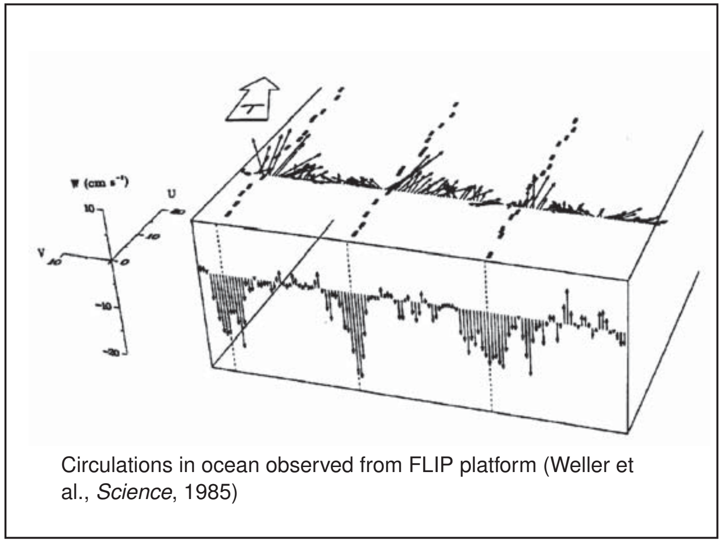


FIG. 5. Reduction of wave-induced stress due to the quasi-linear coupling of wind and waves. Crosses denote the normalized wave stress calculated from the wind profile in the absence of the long waves and diamonds denote results when there is equilibrium between wind and waves.

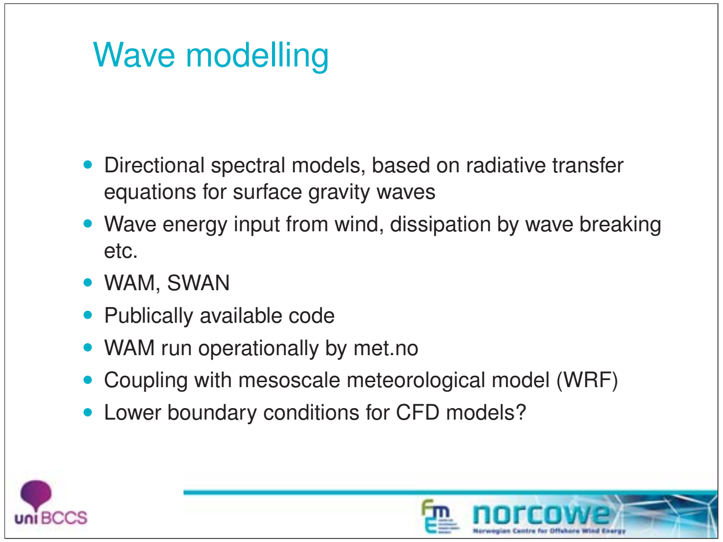
(P. A. E. M. Janssen 1987)



(Smedman et al. 1999)

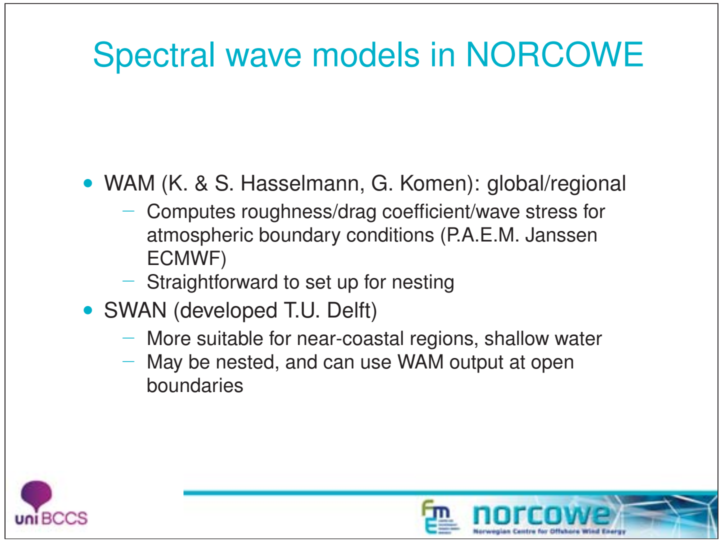


Circulations in ocean observed from FLIP platform (Weller et al., *Science*, 1985)



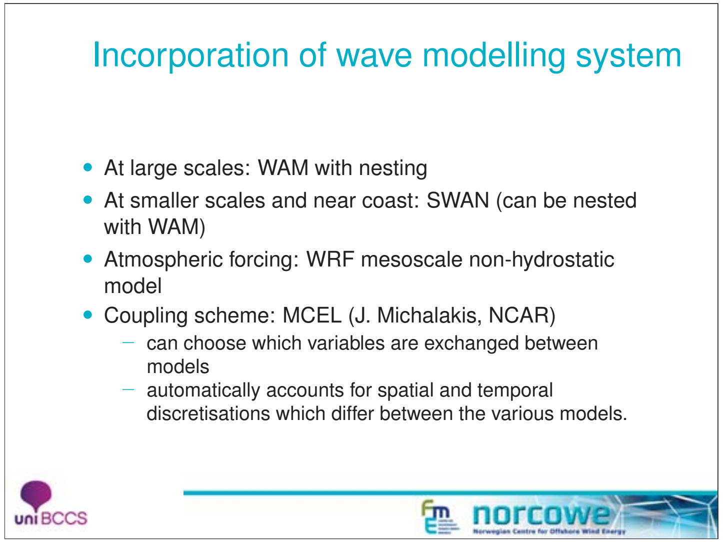
Wave modelling

- Directional spectral models, based on radiative transfer equations for surface gravity waves
- Wave energy input from wind, dissipation by wave breaking etc.
- WAM, SWAN
- Publically available code
- WAM run operationally by met.no
- Coupling with mesoscale meteorological model (WRF)
- Lower boundary conditions for CFD models?



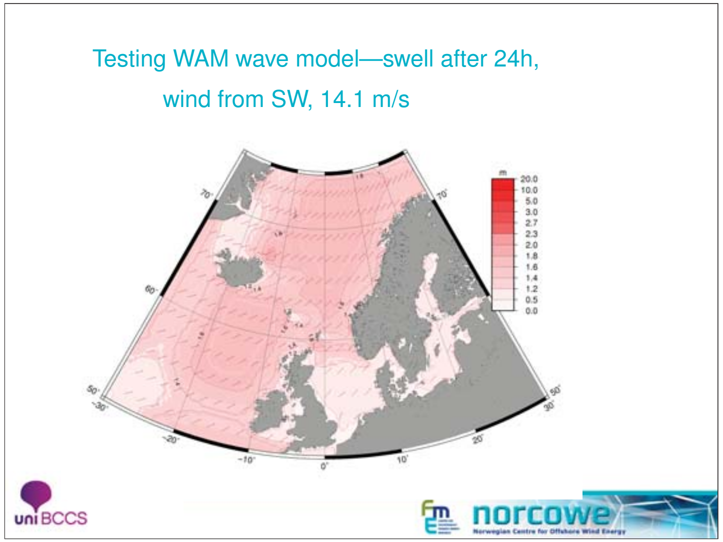
Spectral wave models in NORCOWE

- WAM (K. & S. Hasselmann, G. Komen): global/regional
  - Computes roughness/drag coefficient/wave stress for atmospheric boundary conditions (P.A.E.M. Janssen ECMWF)
  - Straightforward to set up for nesting
- SWAN (developed T.U. Delft)
  - More suitable for near-coastal regions, shallow water
  - May be nested, and can use WAM output at open boundaries

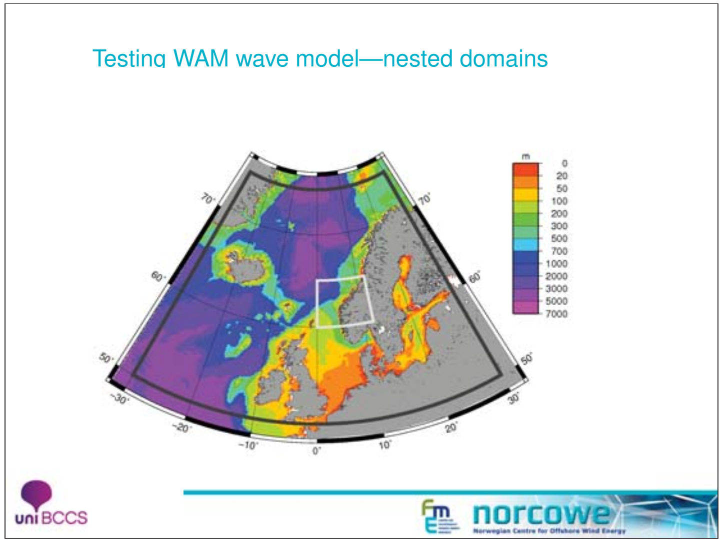


Incorporation of wave modelling system

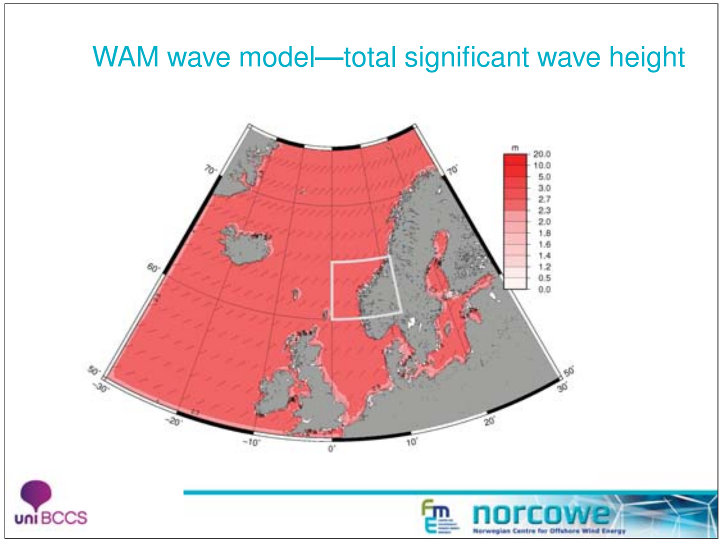
- At large scales: WAM with nesting
- At smaller scales and near coast: SWAN (can be nested with WAM)
- Atmospheric forcing: WRF mesoscale non-hydrostatic model
- Coupling scheme: MCEL (J. Michalakis, NCAR)
  - can choose which variables are exchanged between models
  - automatically accounts for spatial and temporal discretisations which differ between the various models.



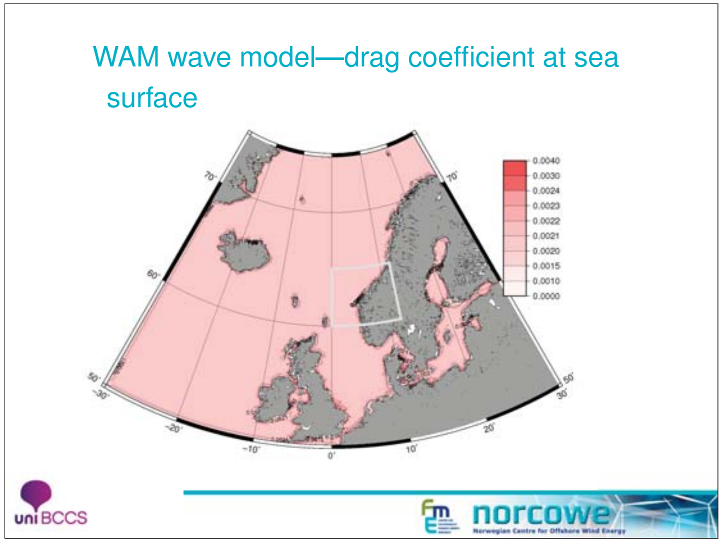
Testing WAM wave model—swell after 24h, wind from SW, 14.1 m/s



Testing WAM wave model—nested domains

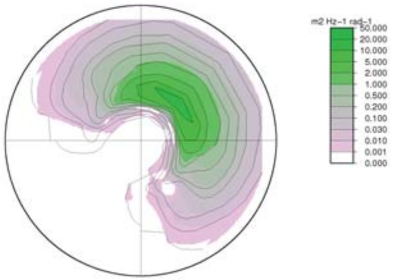


WAM wave model—total significant wave height

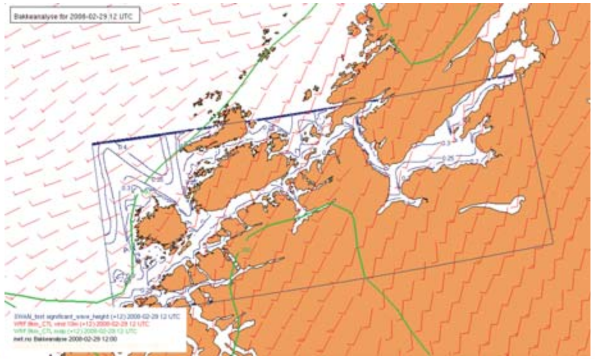


WAM wave model—drag coefficient at sea surface

WAM wave model—spectrum at 65°N, 0°E (log. frequency range, 0.04–0.4 Hz)



Test results, significant wave height from SWAN model, Trondheimsfjorden



Other types of coupling with wave motions

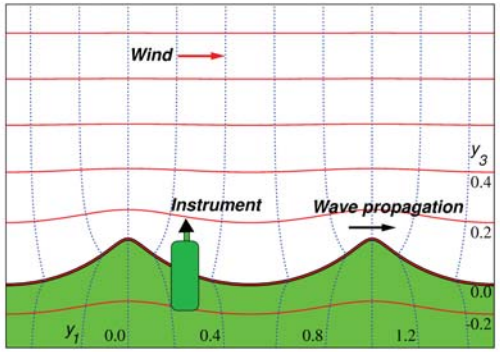
- Coupling to fixed and floating structures:
  - Linear response can use wave spectra directly
  - Nonlinear response may require simulation of time series
  - Slamming from breaking wave crests etc. requires suitable modelling of the behaviour of the free surface
- Sea bottom (oscillatory and mean currents, scour/sediment transport)
  - Calculation of wave orbital velocities and momentum flux / wave-induced mean flow may be required
- For CFD modelling at fine scale:
  - Simulation of wave time series may be required
  - Wave-induced atmospheric oscillations, involving critical-level behaviour
  - How to specify lower boundary in ‘rectangular’ computational domains

Motion corrections I

- Interpretation of observations near the sea surface can be difficult in the presence of surface waves and the associated motions of the air and water
- If measurements are made from a platform which moves with the waves etc. it is necessary to correct velocity observations for the motions of the platform
- Wind lidar instruments will be particularly affected by tilt motions which will significantly alter the position of the target at up to several hundred metres altitude.

Motion corrections II

- Averaged quantities, such as mean current, turbulent fluxes of momentum, heat, and mass, etc., may be systematically affected by correlations between the velocity of the platorm and its position.
- Ocean current observations are particularly subject to contamination from the movement of, for example, a surface-following mooring buoy or ADCP platform (e.g., R. T. Pollard 1982).
- The possible errors in these quantities should be estimated - if they are not too great one may be able to use analytical expressions (perturbation theory) for the corrections



Correction for instrument platform motion I

(Edson et al., J. Atmos. Ocean. Technol., 1998)

$$\mathbf{u} = \mathbf{T}(\mathbf{u}_{\rm obs} + \Omega_{\rm obs} \times \mathbf{R}) + \mathbf{V}_{\rm mot}$$

where

u is the true velocity

$\mathbf{u}_{\rm obs}$ is the observed velocity

$\Omega_{\rm obs} = \begin{pmatrix} \dot{\phi}_{\rm obs} \\ \dot{\theta}_{\rm obs} \\ -\dot{\Psi}_{\rm obs} \end{pmatrix}$ is the angular velocity vector of the motion package

---

Correction for instrument platform motion II

R is the position vector of the sensor with respect to the motion package

$\mathbf{V}_{\rm mot}$ is the velocity of the motion package

T is the transformation matrix between the platform coordinate system and the reference coordinates

---

Correction of fluxes for second-order mean motions I

- (Jenkins 2007, in 'The Air–Sea Interface')
- (Notation employs cofactors K of the Jacobian transformation from curvilinear 'platform-based' coordinates y and rectangular coordinates $x = y + \xi$. Concentration is C and flux is F.)
- We consider fluctuating quantities to first order in the coordinate displacement or wave slope, and mean second-order quantities.
- For a conservative quantity in a quasi-steady state with a basically vertically-directed flux (heat, horizontal momentum, moisture etc.)

Correction of fluxes for second-order mean motions II

$$\begin{aligned} \overline{K_{m3}[C^{\vec{y}}(u_m^{\vec{y}} - x_{m,t}^{\vec{y}}) + F_m^{\vec{y}}]} &= \overline{K_{13}[C(u_1 - x_{1,t}) + F_1]} + \overline{K_{33}[C(u_3 - x_{3,t})]} \\ &= \text{constant,} \end{aligned}$$

Then if we substitute $u_1^{\vec{y}} = \overline{u_1} + u_1{}'$, $u_3^{\vec{y}} = u_3$, $C^{\vec{y}} = \overline{C} + C'$, $F_1^{\vec{y}} = F_1{}'$, and $F_3^{\vec{y}} = \overline{F_3} + F_3{}'$, and neglect averaged products of more than two fluctuating quantities, we obtain:

$$\begin{aligned} \overline{F_3} + \overline{F_3{}'\xi_{3,3}} - \overline{F_1{}'\xi_{3,1}} + \overline{C}[\overline{(u_3{}' - \xi_{3,t})\xi_{3,3}} - \overline{(u_1{}' - \xi_{1,t})\xi_{3,1}}] & \\ + \overline{C'(u_3{}' - \xi_{3,t} - \overline{u_1}\xi_{3,1})} &= \text{constant.} \end{aligned}$$

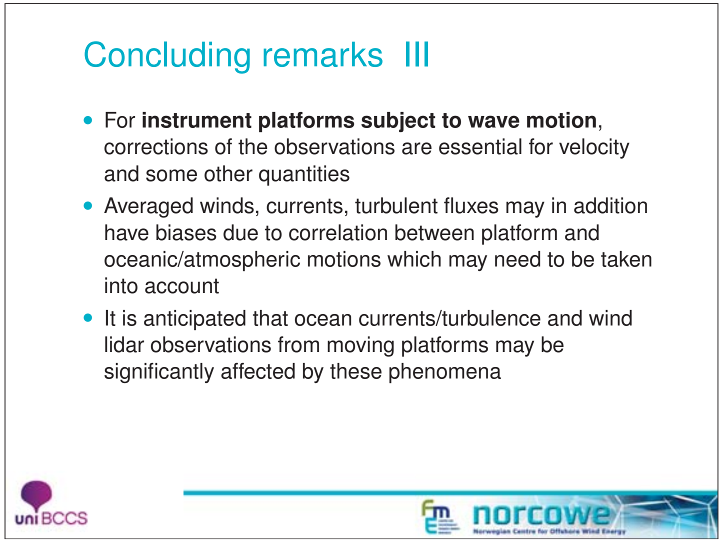
Concluding remarks I

- To constrain offshore wind power development costs, it is important to characterize the marine boundary layer and ocean conditions
- Surface waves affect the physical properties of the ocean and atmosphere: they can act as roughness elements for turbulent flow in the marine atmospheric boundary layer, but the effective roughness length is reduced because the waves propagate with the wind
- The vertical flux of momentum can be determined by the Charnock relation with a friction velocity (or wind speed) dependent roughness length. The parameter in the relation depends on the wave age

---

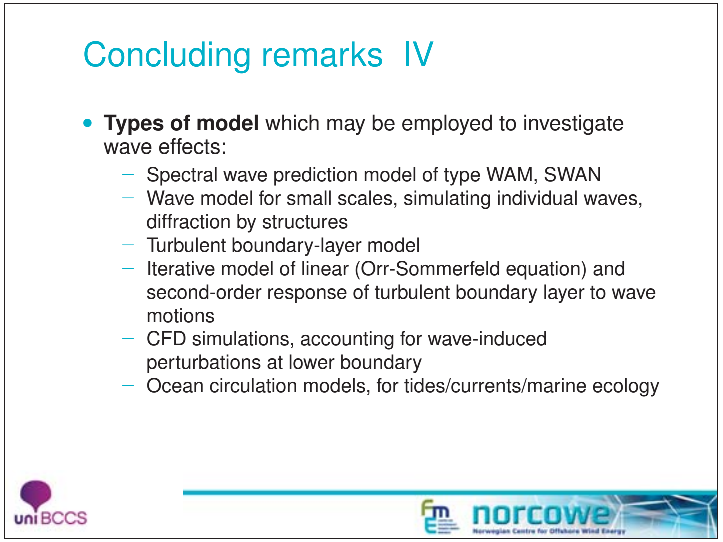
Concluding remarks II

- **Field observations** in the wave-induced boundary layer may be challenging
- It is often necessary to use measurement platforms which move with the sea surface
- Air/water velocities may be corrected for if motion sensors are available
- Other problems: Flow distortion by measurement platform structure (may use e.g. CFD model to evaluate/correct)
- Additional problem: bias in average velocity (wind/current) and fluxes (momentum, heat) due to platform motion - correction of this may require perturbation expansion of flow field to second order in wave slope known problem for current measurements



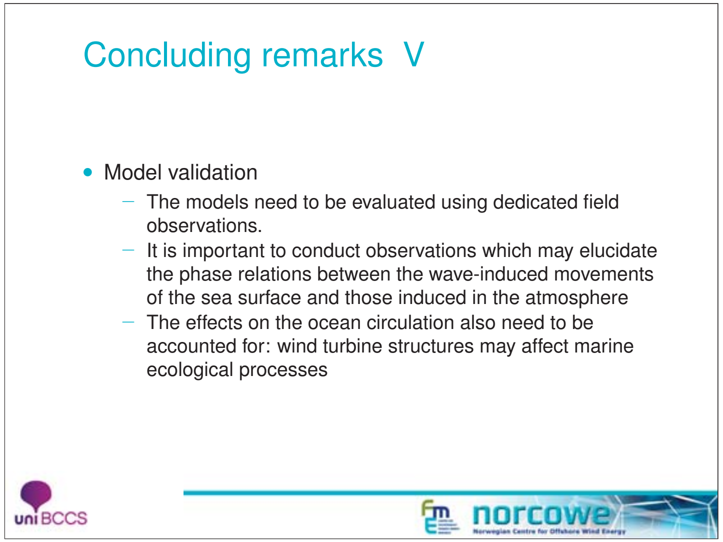
Concluding remarks III

- For **instrument platforms subject to wave motion**, corrections of the observations are essential for velocity and some other quantities
- Averaged winds, currents, turbulent fluxes may in addition have biases due to correlation between platform and oceanic/atmospheric motions which may need to be taken into account
- It is anticipated that ocean currents/turbulence and wind lidar observations from moving platforms may be significantly affected by these phenomena



Concluding remarks IV

- **Types of model** which may be employed to investigate wave effects:
  - Spectral wave prediction model of type WAM, SWAN
  - Wave model for small scales, simulating individual waves, diffraction by structures
  - Turbulent boundary-layer model
  - Iterative model of linear (Orr-Sommerfeld equation) and second-order response of turbulent boundary layer to wave motions
  - CFD simulations, accounting for wave-induced perturbations at lower boundary
  - Ocean circulation models, for tides/currents/marine ecology



Concluding remarks V

- Model validation
  - The models need to be evaluated using dedicated field observations.
  - It is important to conduct observations which may elucidate the phase relations between the wave-induced movements of the sea surface and those induced in the atmosphere
  - The effects on the ocean circulation also need to be accounted for: wind turbine structures may affect marine ecological processes

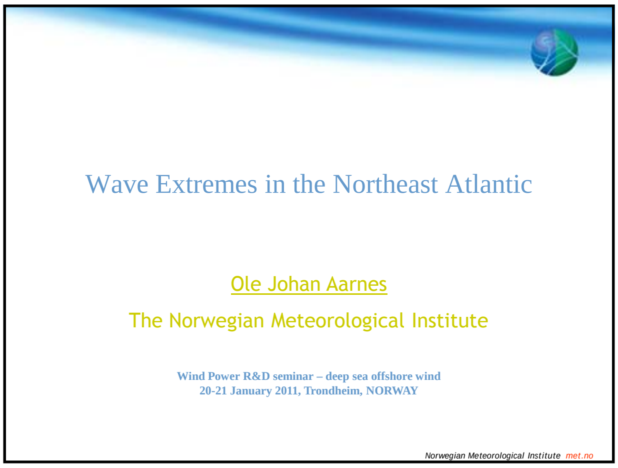
C2) Met-ocean conditions

Wave extremes in the Northeast Atlantic, Ole Johan Aarnes, met.no

The HyWind forecasting project, Birgitte Furevik, met.no

A comparison of Sonic Anemometer- and lidar-sensed wind velocity data at Frøya test site, PhD stud Fabio Pierella, NTNU

Design and operation of floating met-masts, Israel Pinto Grijuela, Grupo APIAXXI



Wave Extremes in the Northeast Atlantic

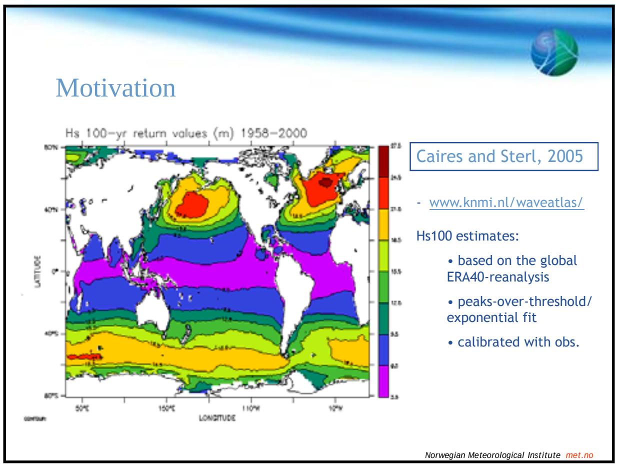
Ole Johan Aarnes

The Norwegian Meteorological Institute

Wind Power R&D seminar – deep sea offshore wind
20-21 January 2011, Trondheim, NORWAY

Outline

- Motivation
- NORA10 – Norwegian Reanalysis 10km
- Extreme Value Theory
  - *Generalized Extreme Value Distribution*
  - *Generalized Pareto Distribution*
- Results - Hs100 estimates from three models
  - Comparison/discrepancy
  - Model diagnostics
  - Is there a local Hs100 minimum in the central Norwegian Sea?
- Conclusions



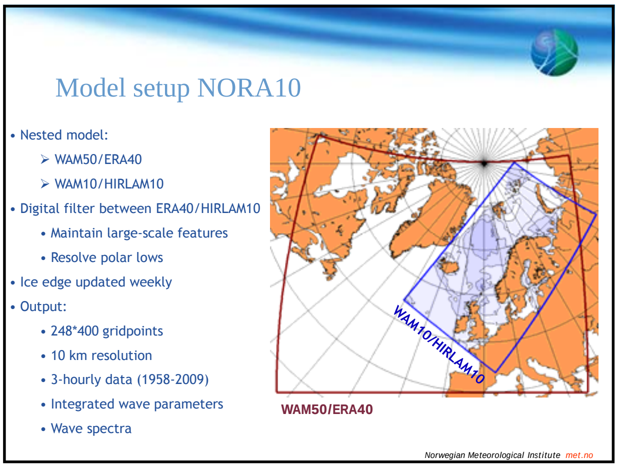
Motivation

Caires and Sterl, 2005

- www.knmi.nl/waveatlas/

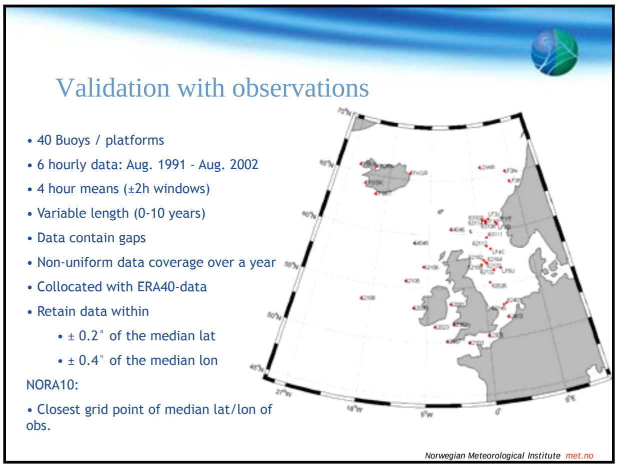
Hs100 estimates:

- based on the global ERA40-reanalysis
- peaks-over-threshold/ exponential fit
- calibrated with obs.



Model setup NORA10

- Nested model:
  - WAM50/ERA40
  - WAM10/HIRLAM10
- Digital filter between ERA40/HIRLAM10
  - Maintain large-scale features
  - Resolve polar lows
- Ice edge updated weekly
- Output:
  - 248*400 gridpoints
  - 10 km resolution
  - 3-hourly data (1958-2009)
  - Integrated wave parameters
  - Wave spectra

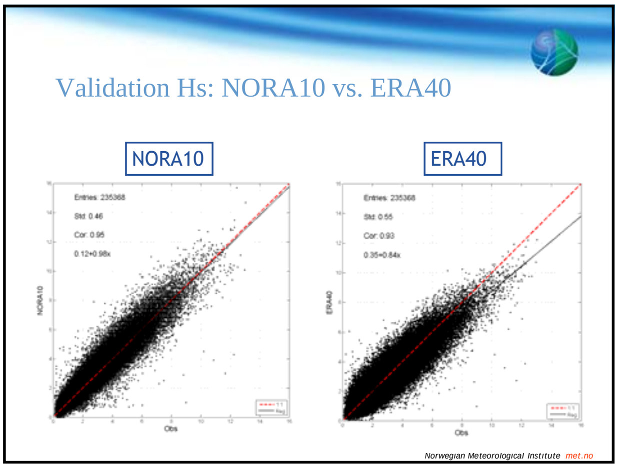


Validation with observations

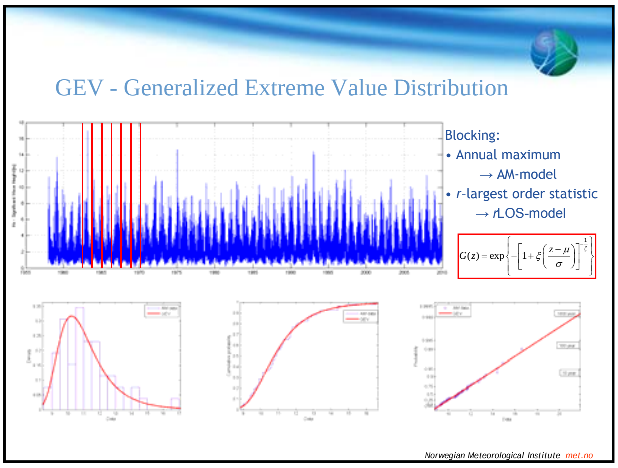
- 40 Buoys / platforms
- 6 hourly data: Aug. 1991 - Aug. 2002
- 4 hour means (±2h windows)
- Variable length (0-10 years)
- Data contain gaps
- Non-uniform data coverage over a year
- Collocated with ERA40-data
- Retain data within
  - ± 0.2° of the median lat
  - ± 0.4° of the median lon

NORA10:

- Closest grid point of median lat/lon of obs.



Validation Hs: NORA10 vs. ERA40



GEV - Generalized Extreme Value Distribution

Blocking:
- Annual maximum
  → AM-model
- *r*-largest order statistic
  → *r*LOS-model

$$G(z)=\exp\left\{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\}$$

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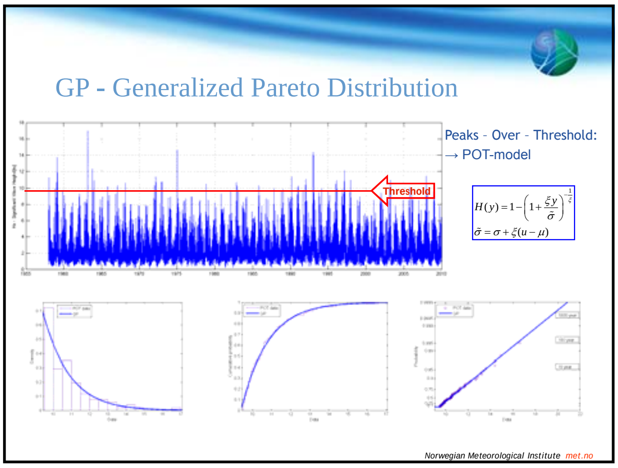

GP - Generalized Pareto Distribution

Peaks - Over - Threshold:
→ POT-model

$$H(y)=1-\left(1+\frac{\xi y}{\tilde{\sigma}}\right)^{-\frac{1}{\xi}}$$

$$\tilde{\sigma}=\sigma+\xi(u-\mu)$$

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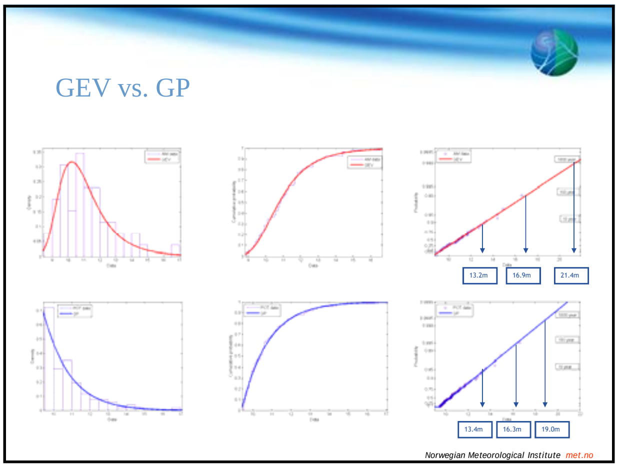

GEV vs. GP

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Fitting procedure – “maximum likelihood”

- likelihood function

$$L(\theta)=\prod_{i=1}^{n} f(x_i;\theta)$$

(f – probability density function of GEV/GP
θ - parameter estimates for GEV/GP*)*

- log-likelihood function

$$\ell(\theta)=\log L(\theta)=\sum_{i=1}^{n}\log f(x_i;\theta)$$

- log-likelihood function is maximized iteratively (Nelder-Mead)

Confidence intervals

- Profile likelihood - approach

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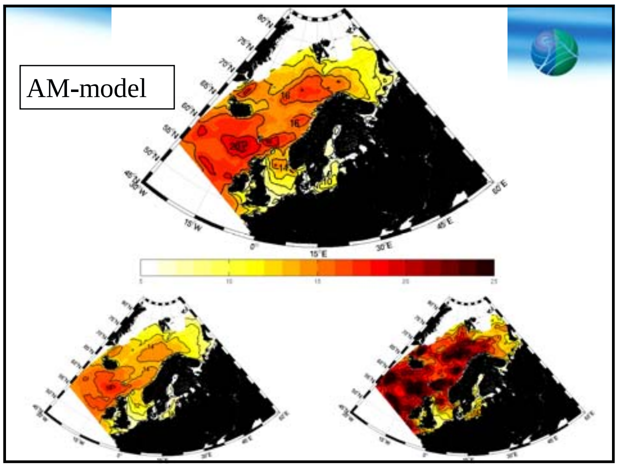
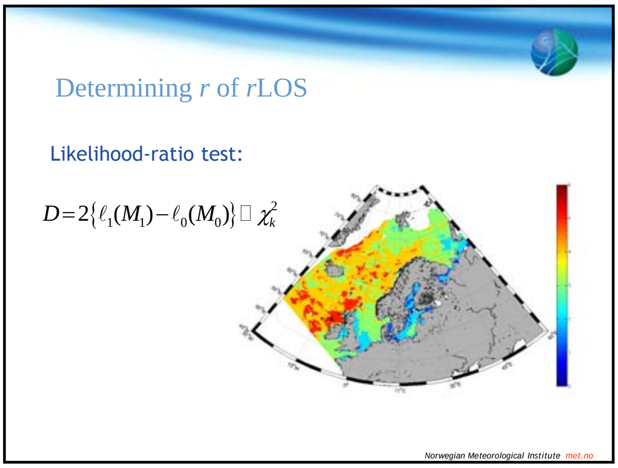


AM-model



Determining *r* of *r*LOS

Likelihood-ratio test:

$$D=2\{\ell_1(M_1)-\ell_0(M_0)\}\square\chi_k^2$$

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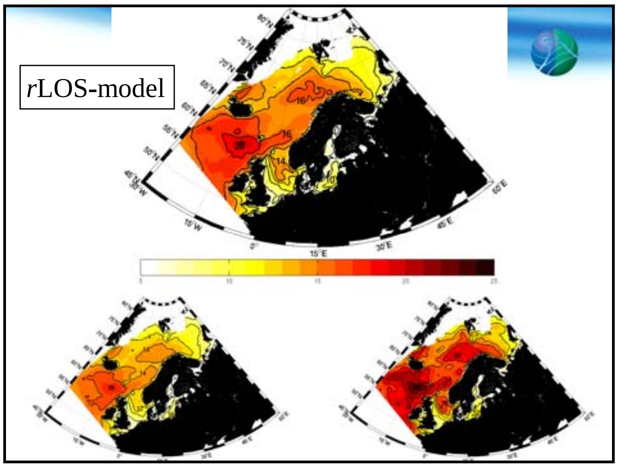
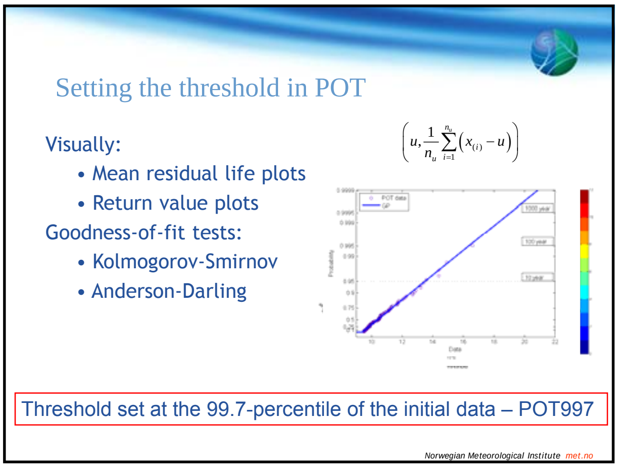


*r*LOS-model



Setting the threshold in POT

$$\left(u, \frac{1}{n_u}\sum_{i=1}^{n_u}\left(x_{(i)} - u\right)\right)$$

Visually:

- Mean residual life plots
- Return value plots

Goodness-of-fit tests:

- Kolmogorov-Smirnov
- Anderson-Darling

Threshold set at the 99.7-percentile of the initial data – POT997

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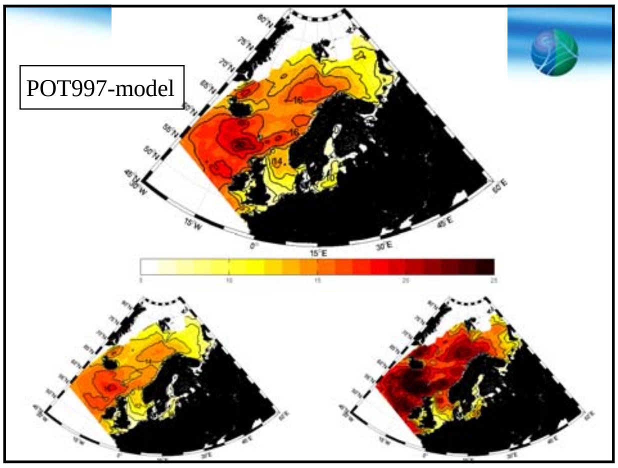
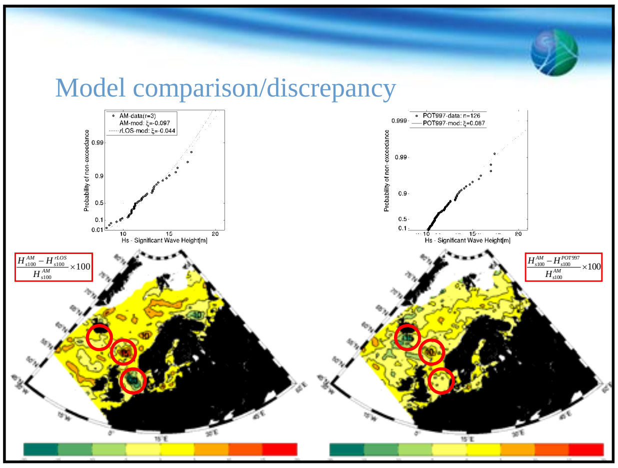


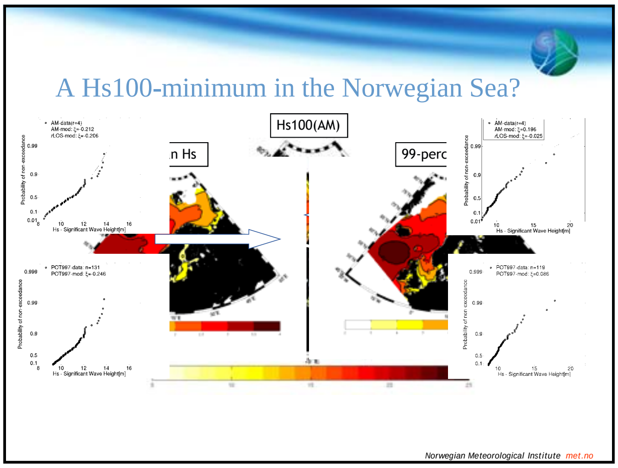
POT997-model



Model comparison/discrepancy

$$\frac{H_{s100}^{AM} - H_{s100}^{rLOS}}{H_{s100}^{AM}} \times 100$$

$$\frac{H_{s100}^{AM} - H_{s100}^{POT997}}{H_{s100}^{AM}} \times 100$$



A Hs100-minimum in the Norwegian Sea?

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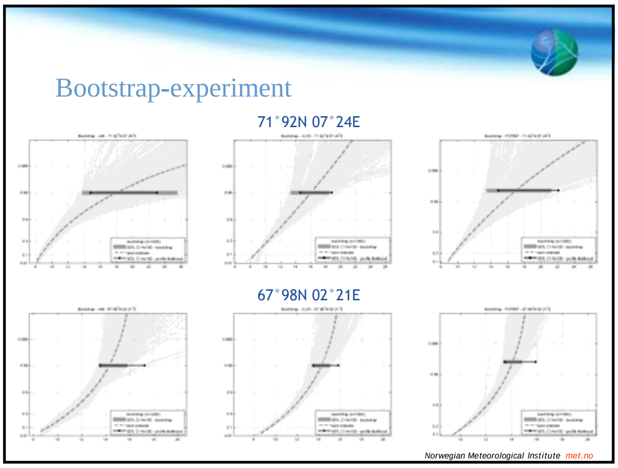

Bootstrap-experiment

71°92N 07°24E

67°98N 02°21E

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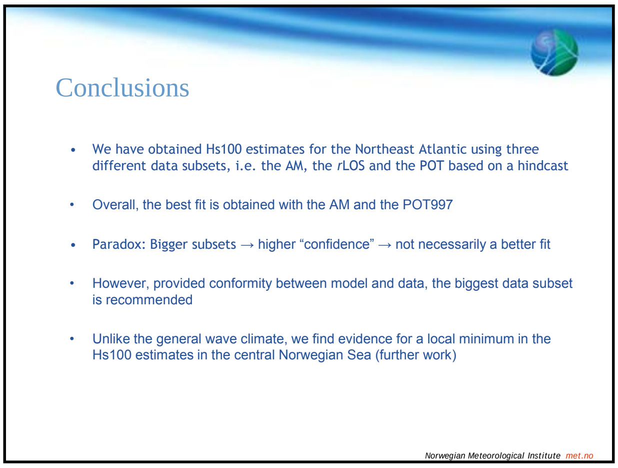

Conclusions

- We have obtained Hs100 estimates for the Northeast Atlantic using three different data subsets, i.e. the AM, the *r*LOS and the POT based on a hindcast
- Overall, the best fit is obtained with the AM and the POT997
- Paradox: Bigger subsets → higher "confidence" → not necessarily a better fit
- However, provided conformity between model and data, the biggest data subset is recommended
- Unlike the general wave climate, we find evidence for a local minimum in the Hs100 estimates in the central Norwegian Sea (further work)

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Hurrican Lili – September 2003

Thank you!

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met.no

The Hywind forecasting project

Birgitte R. Furevik

Wind Power R&D seminar – deep sea offshore wind, 20-21 January 2011, Trondheim

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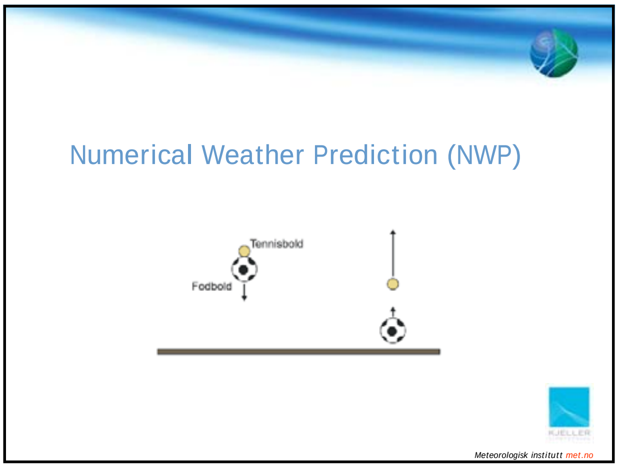
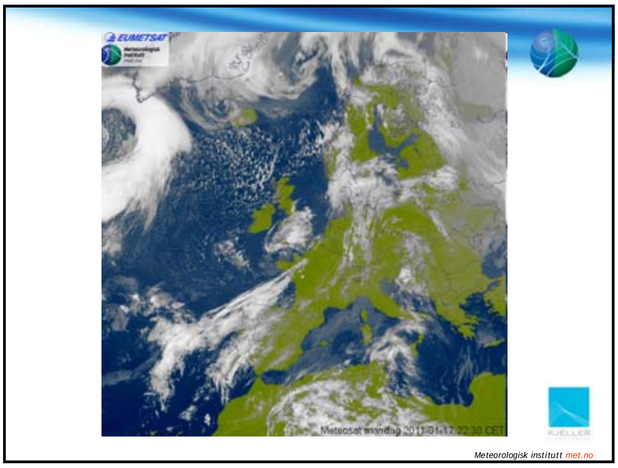
Hywind forecasting project

- Meteorologisk Institutt, Kjeller Vindteknikk and Statoil
- Project start September 1, 2009
- 28 month duration
- Provide reliable forecasts for wind, waves, currents and production during installation and operation of the Hywind turbine
- Validation and development



Numerical Weather Prediction (NWP)



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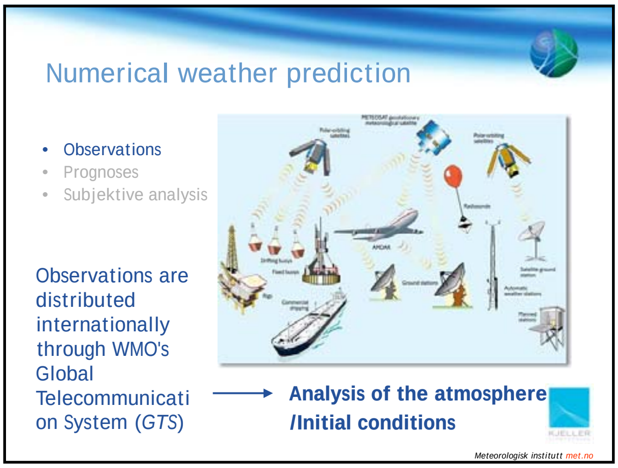
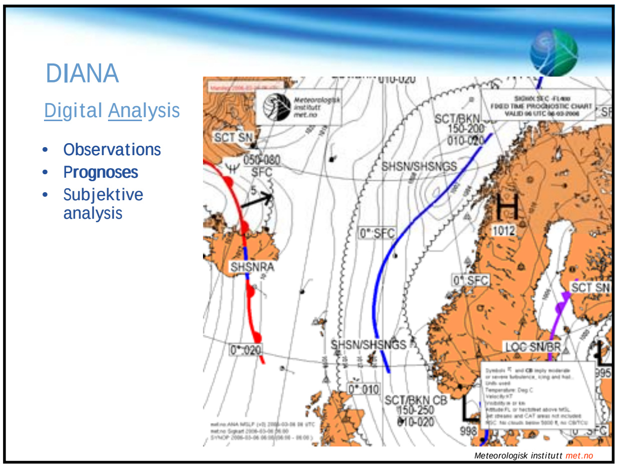


Numerical weather prediction

- Observations
- Prognoses
- Subjektive analysis

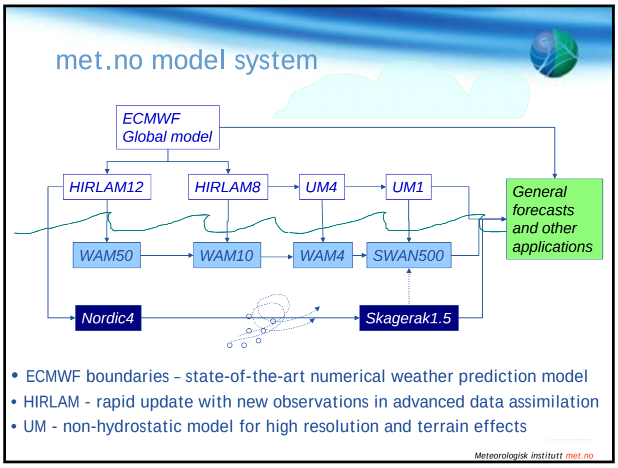
Observations are distributed internationally through WMO's Global Telecommunication System (*GTS*) → **Analysis of the atmosphere /Initial conditions**



DIANA

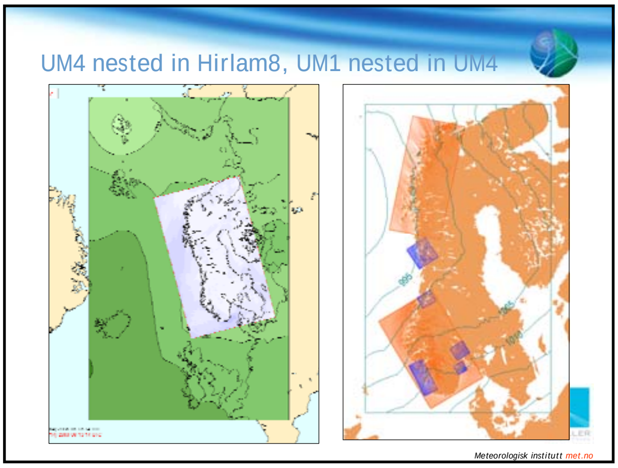
Digital Analysis

- Observations
- Prognoses
- Subjektive analysis

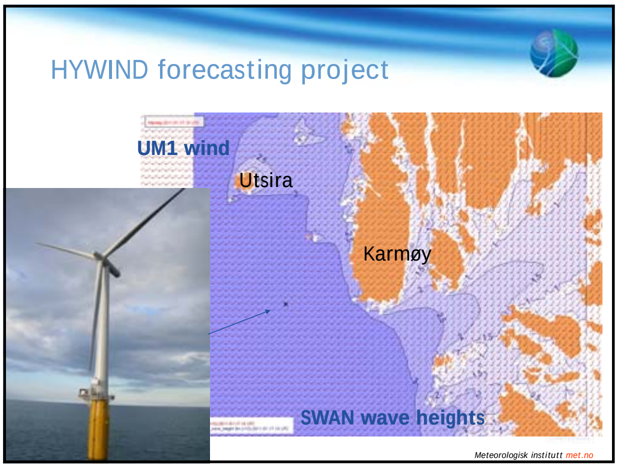


met.no model system

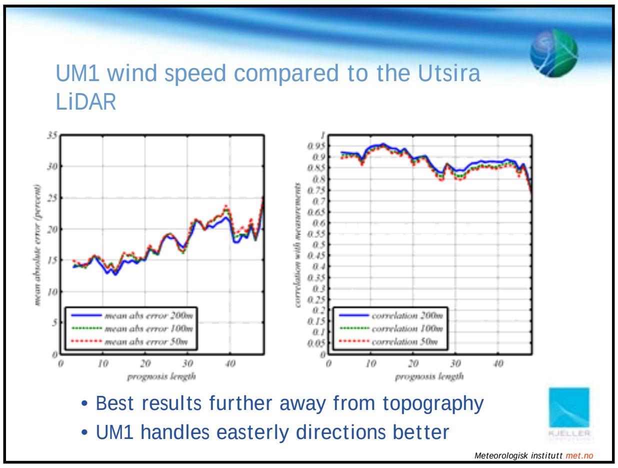
- ECMWF boundaries – state-of-the-art numerical weather prediction model
- HIRLAM - rapid update with new observations in advanced data assimilation
- UM - non-hydrostatic model for high resolution and terrain effects



UM4 nested in Hirlam8, UM1 nested in UM4

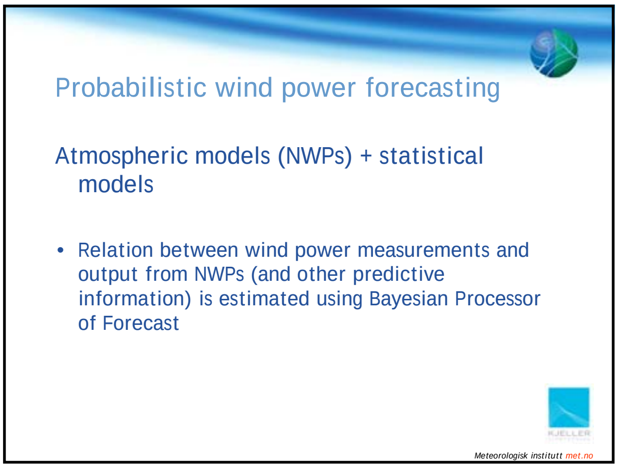


HYWIND forecasting project



UM1 wind speed compared to the Utsira LiDAR

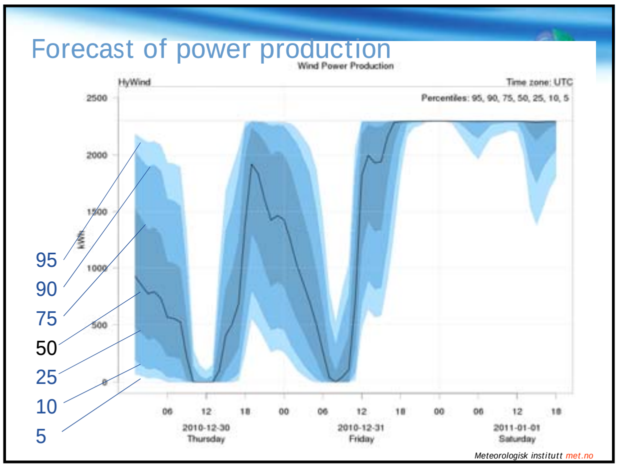
- Best results further away from topography
- UM1 handles easterly directions better



Probabilistic wind power forecasting

Atmospheric models (NWPs) + statistical models

- Relation between wind power measurements and output from NWPs (and other predictive information) is estimated using Bayesian Processor of Forecast



Forecast of power production

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The need for wave forecasts

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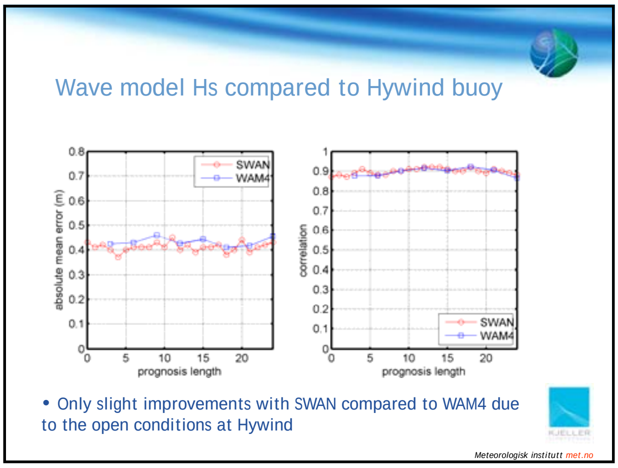

Wave model Hs compared to Hywind buoy

- Only slight improvements with SWAN compared to WAM4 due to the open conditions at Hywind

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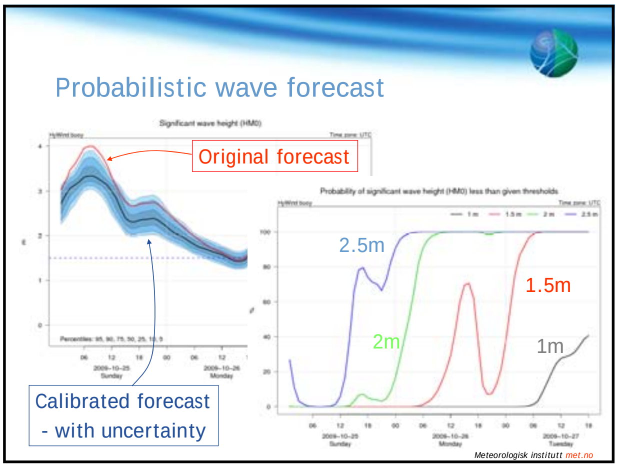

Probabilistic wave forecast

Calibrated forecast
- with uncertainty

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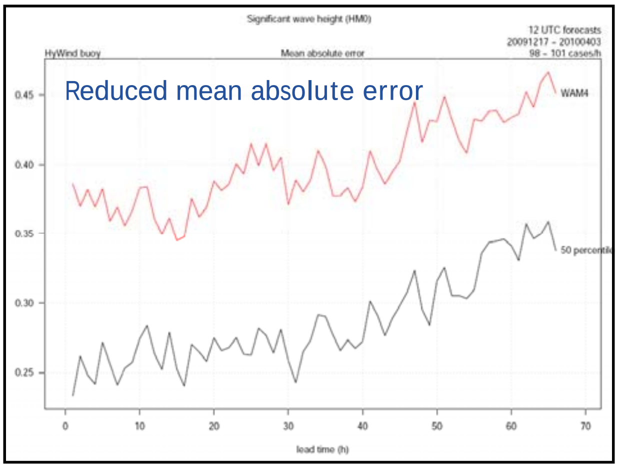

Reduced mean absolute error

New projects

- ”ProVer” – online verification tool

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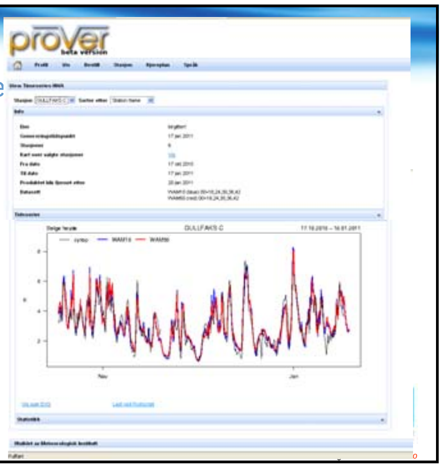
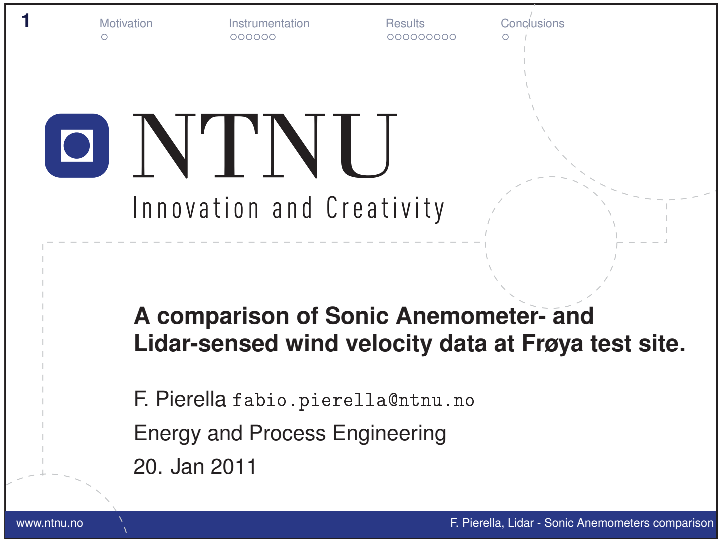
New proje

- ”ProVer”



New projects

- ”ProVer” – online verification tool
- ”Nye Kilden” – online presentation and data access for advanced users
- ICEWIND – improved forecast of wind, waves and icing
  - 4 year project under Nordic Energy Research - Integration of large-scale wind power



NTNU
Innovation and Creativity

A comparison of Sonic Anemometer- and Lidar-sensed wind velocity data at Frøya test site.

F. Pierella `fabio.pierella@ntnu.no`
Energy and Process Engineering
20. Jan 2011

Outline

Motivation

Instrumentation

Results

Conclusions

NTNU
Innovation and Creativity

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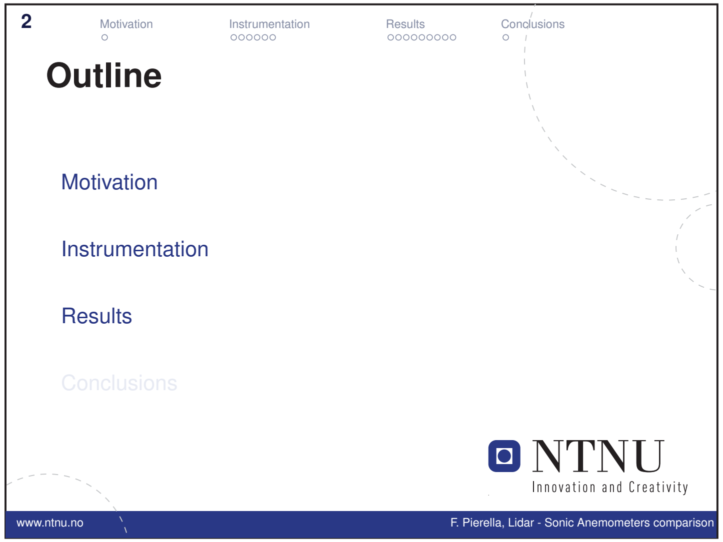

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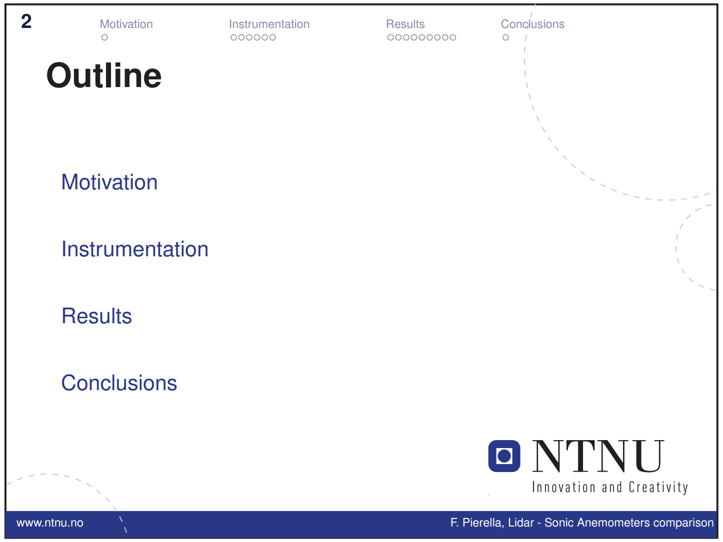

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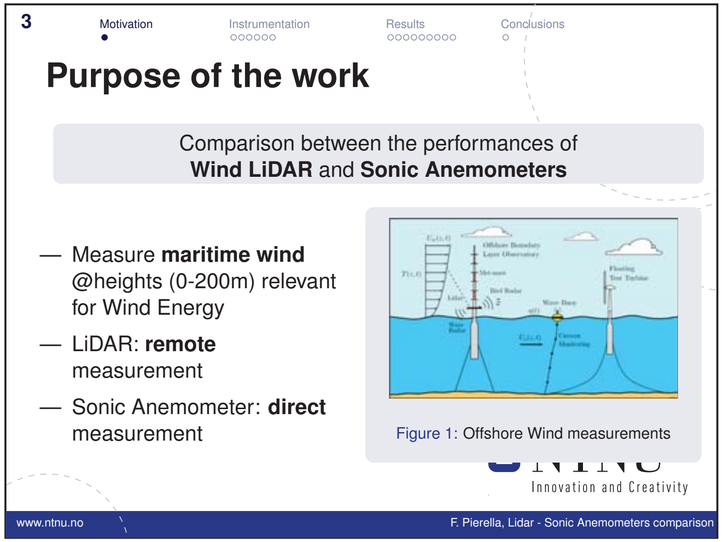


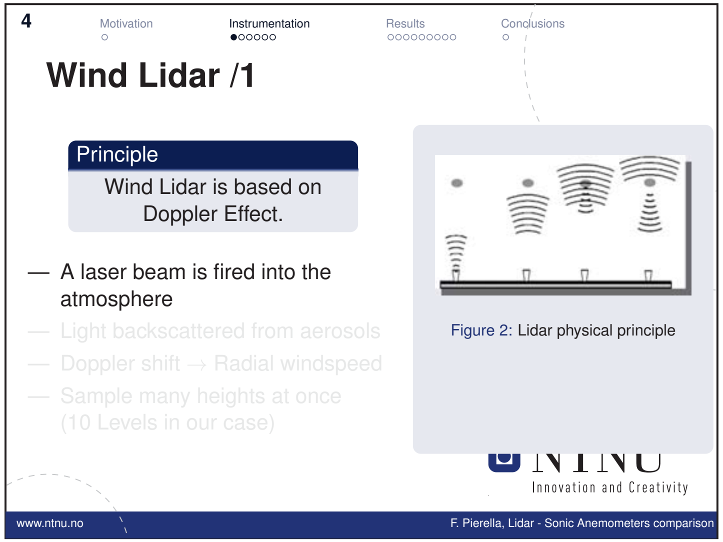
Purpose of the work

Comparison between the performances of
Wind LiDAR and **Sonic Anemometers**

- Measure **maritime wind** @heights (0-200m) relevant for Wind Energy
- LiDAR: **remote** measurement
- Sonic Anemometer: **direct** measurement

Figure 1: Offshore Wind measurements

NTNU
Innovation and Creativity



Wind Lidar /1

Principle

Wind Lidar is based on Doppler Effect.

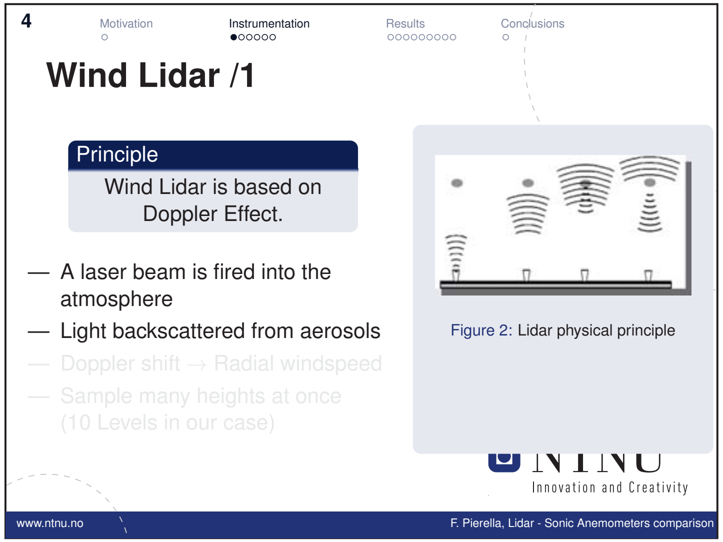
— A laser beam is fired into the atmosphere

— Light backscattered from aerosols

— Doppler shift → Radial windspeed

— Sample many heights at once (10 Levels in our case)

Figure 2: Lidar physical principle



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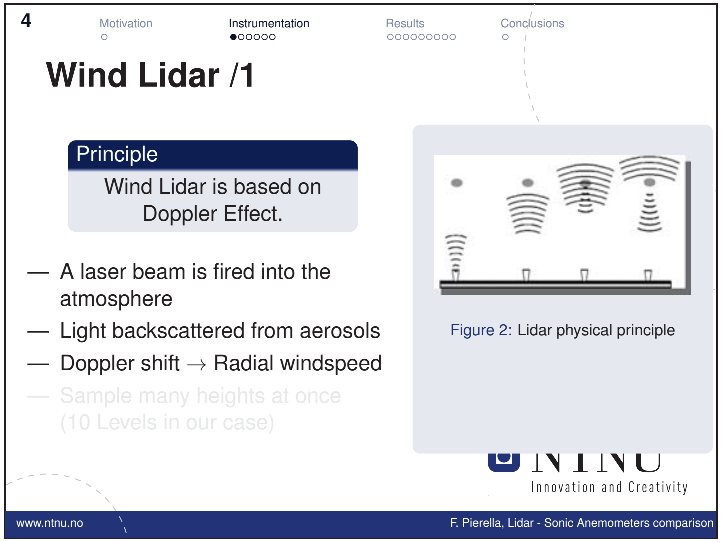

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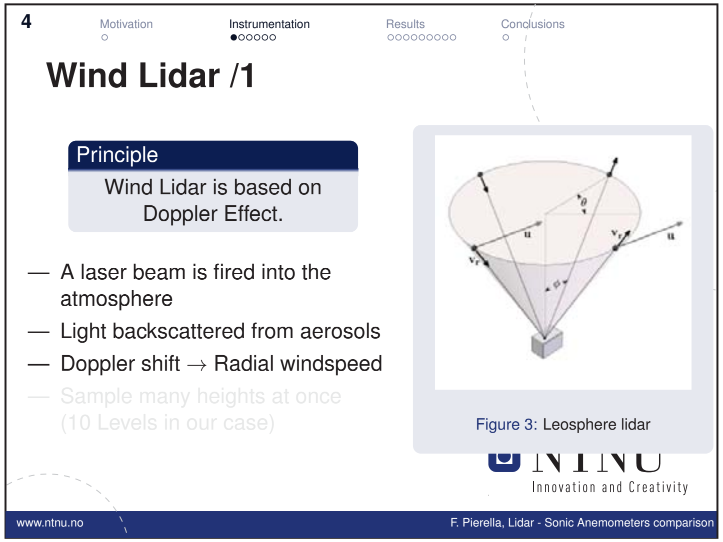

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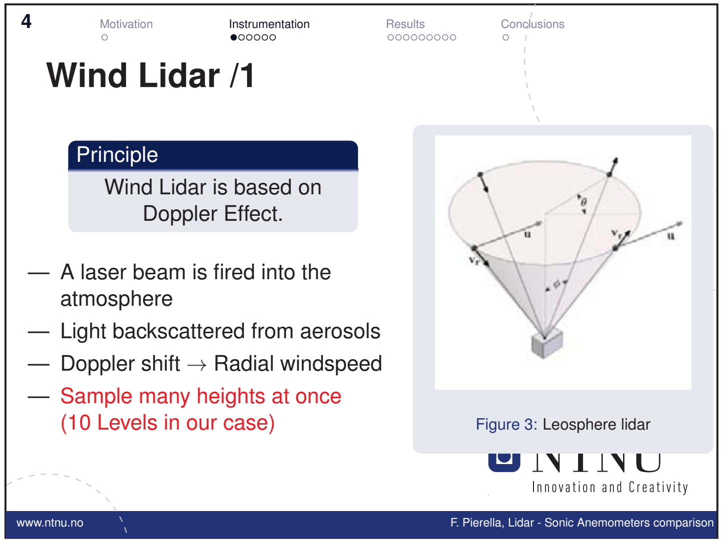
Figure 3: Leosphere lidar



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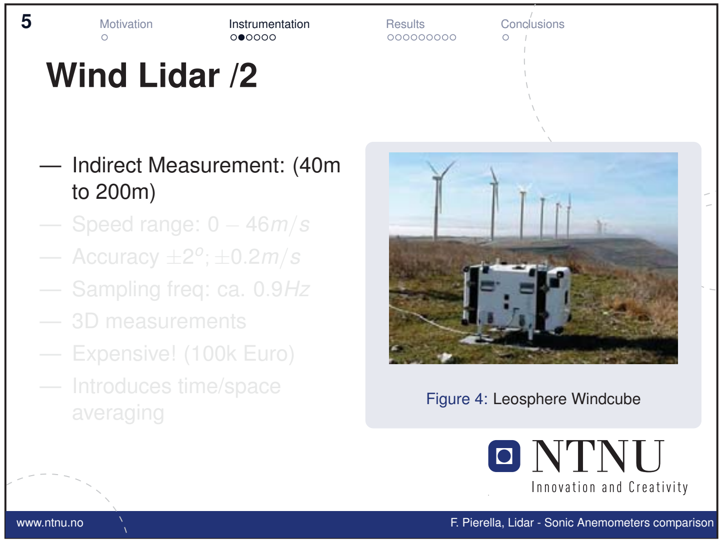


Wind Lidar /2

— Indirect Measurement: (40m to 200m)

— Speed range: 0 – 46m/s

— Accuracy $\pm 2^o, \pm 0.2 m/s$

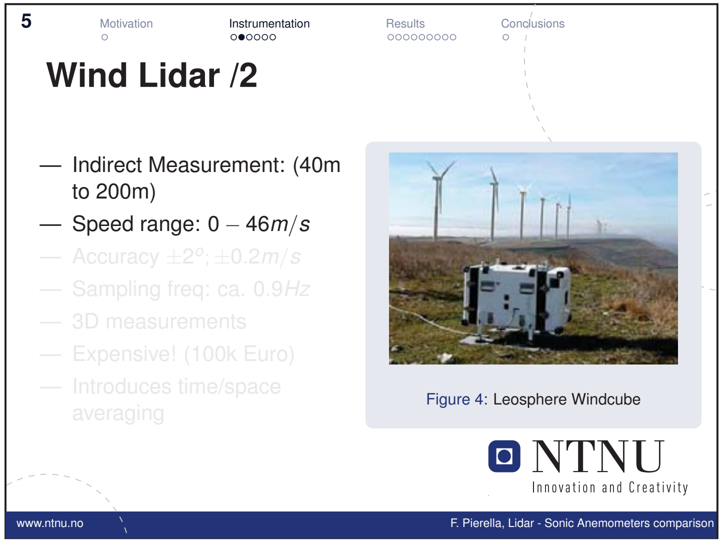
— Sampling freq: ca. 0.9Hz

— 3D measurements

— Expensive! (100k Euro)

— Introduces time/space averaging

Figure 4: Leosphere Windcube



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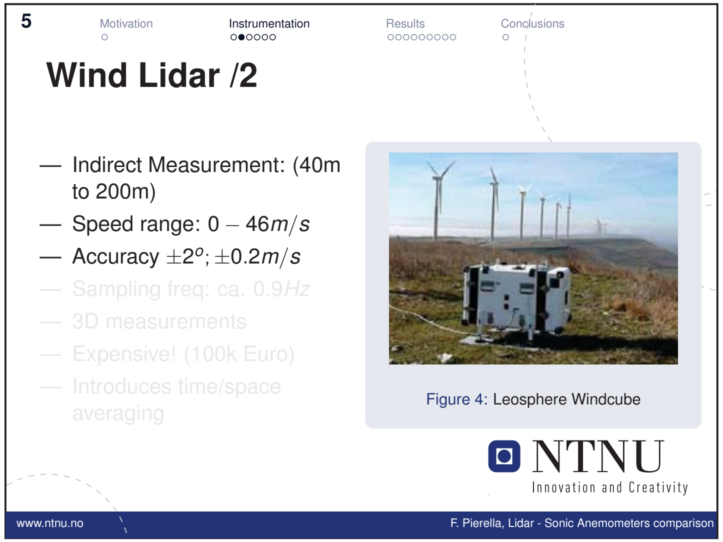

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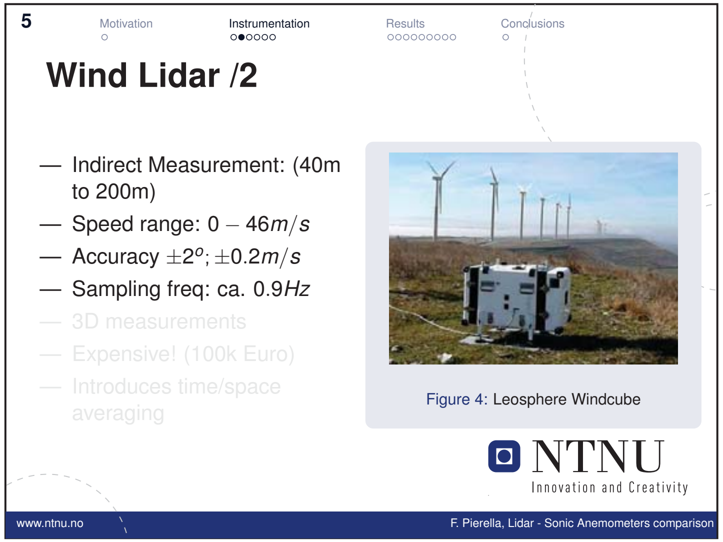

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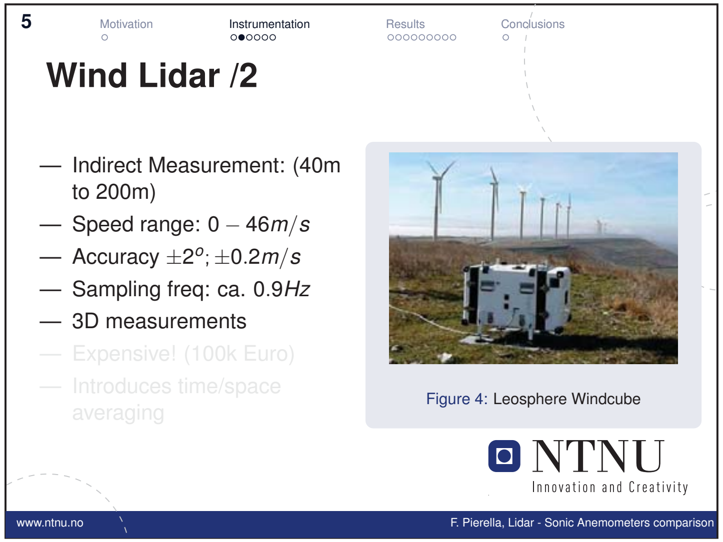

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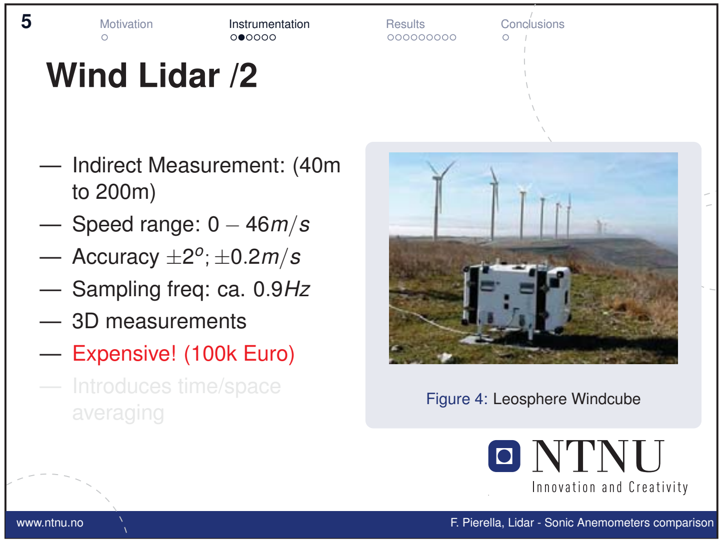

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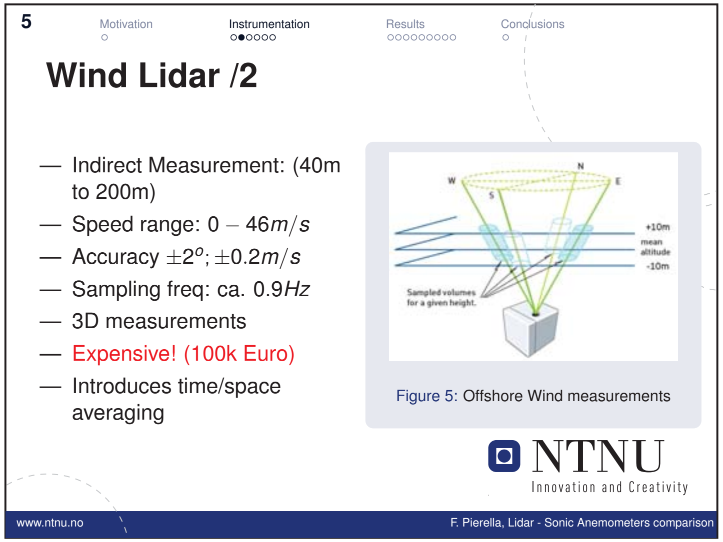

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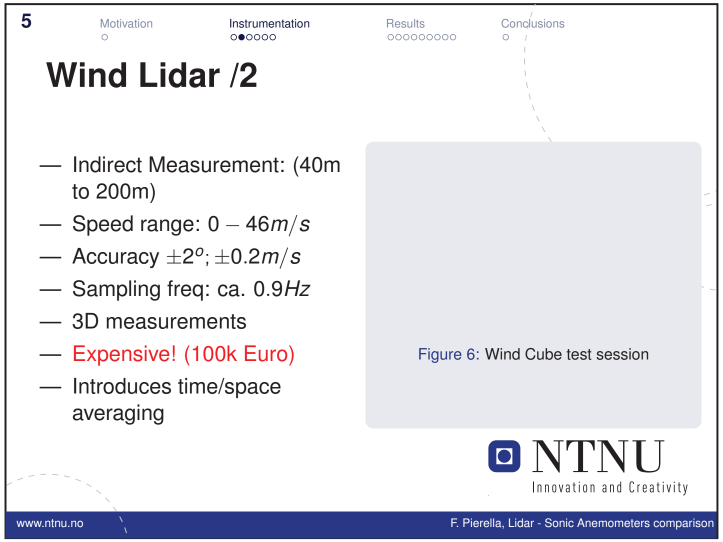
- Introduces time/space averaging

Figure 5: Offshore Wind measurements



Wind Lidar /2

- Indirect Measurement: (40m to 200m)
- Speed range: $0 - 46 m/s$
- Accuracy $\pm 2^o; \pm 0.2 m/s$
- Sampling freq: ca. $0.9 Hz$
- 3D measurements
- Expensive! (100k Euro)
- Introduces time/space averaging

Figure 6: Wind Cube test session

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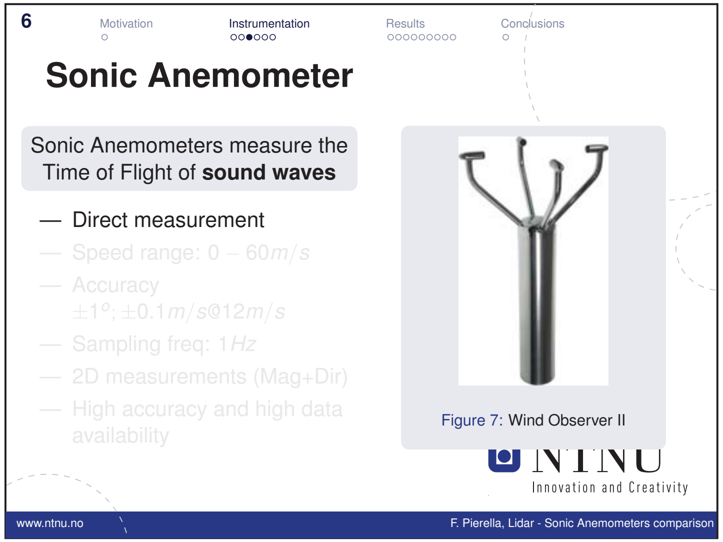

Sonic Anemometer

Sonic Anemometers measure the Time of Flight of **sound waves**

- Direct measurement
- Speed range: $0 - 60 m/s$
- Accuracy $\pm 1^o; \pm 0.1 m/s@12 m/s$
- Sampling freq: $1 Hz$
- 2D measurements (Mag+Dir)
- High accuracy and high data availability

Figure 7: Wind Observer II

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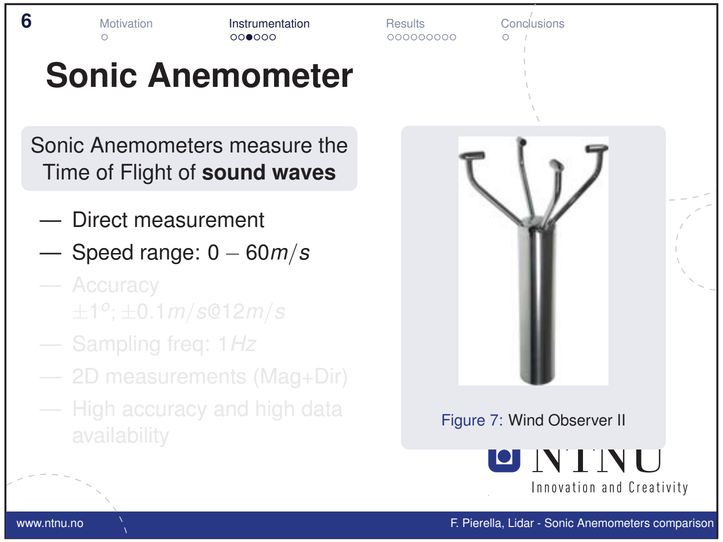
Innovation and Creativity



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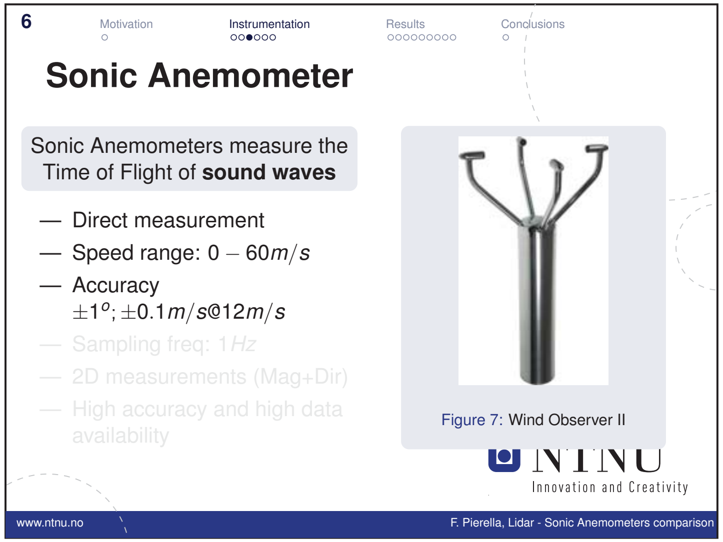

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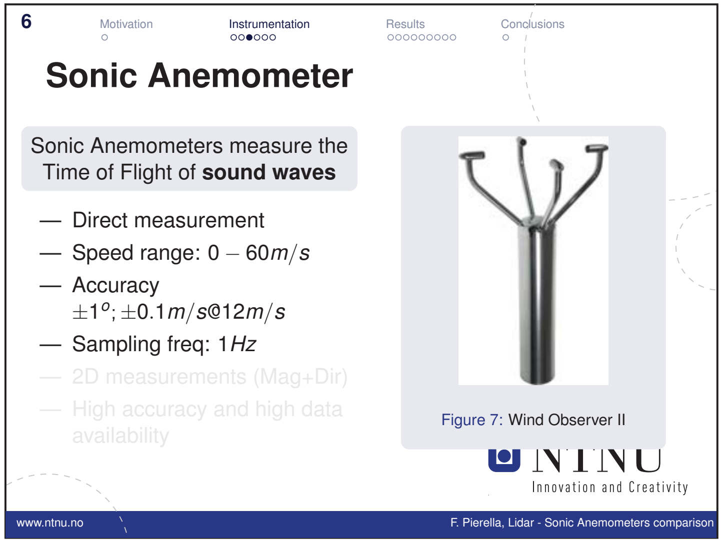

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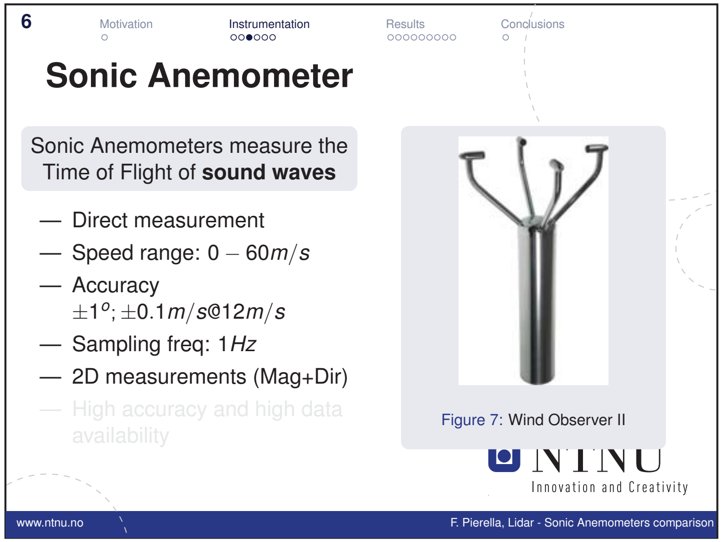

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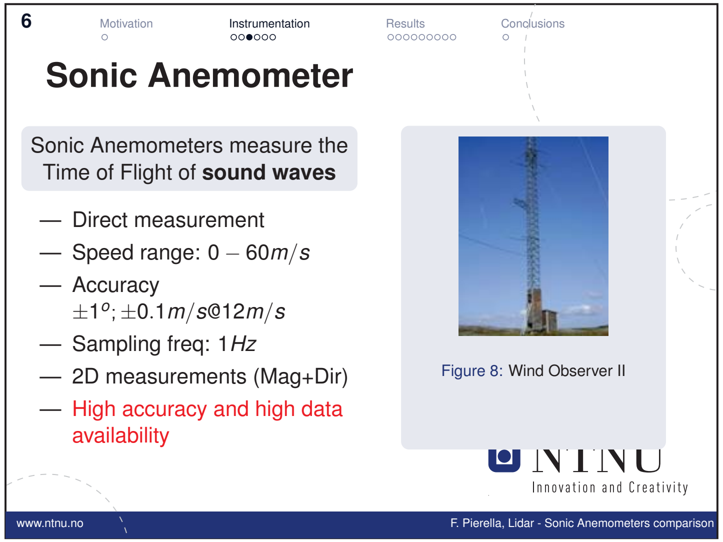

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Figure 8: Wind Observer II

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Innovation and Creativity

Comparison: reasons and challenges

Wind Cube

- Remote measurements (Avg. space/time)
- Quality of signal depends on:
  - Aerosol concentration
  - Rain
  - Wind turbulence

Sonic Anemometers

- Direct measurements, high quality
- Quality of signal depends on:
  - Shading of the Mast
  - Snow/Icing on sensor

Data processing and filtering

- $SNR_{WC} > -10$ and **built-in** WindCube filters
- 10-minutes averages valid if $N_{DataRec} > 50\%$
- Mast Effect on Sonic Anemometer was removed

Innovation and Creativity

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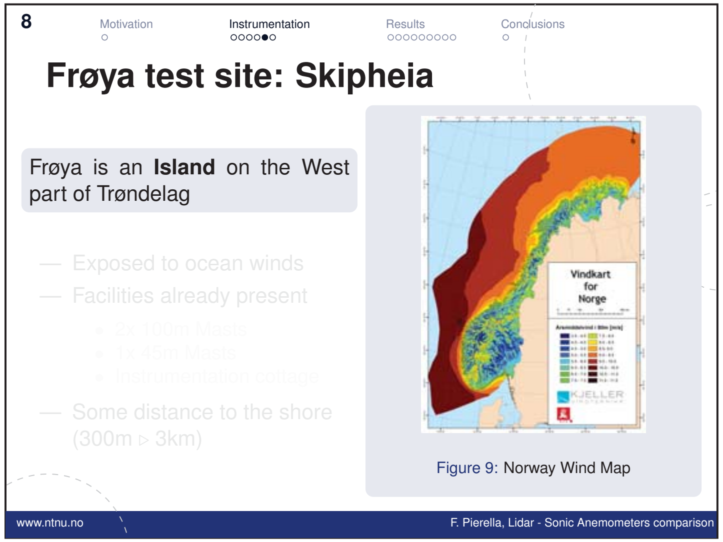

Frøya test site: Skipheia

Frøya is an **Island** on the West part of Trøndelag

- Exposed to ocean winds
- Facilities already present
  - 2x 100m Masts
  - 1x 45m Masts
  - Instrumentation cottage
- Some distance to the shore (300m ▷ 3km)

Figure 9: Norway Wind Map

Frøya test site: Skipheia

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Figure 10: Froya Island

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Figure 11: Skipheia

Frøya test site: Skipheia

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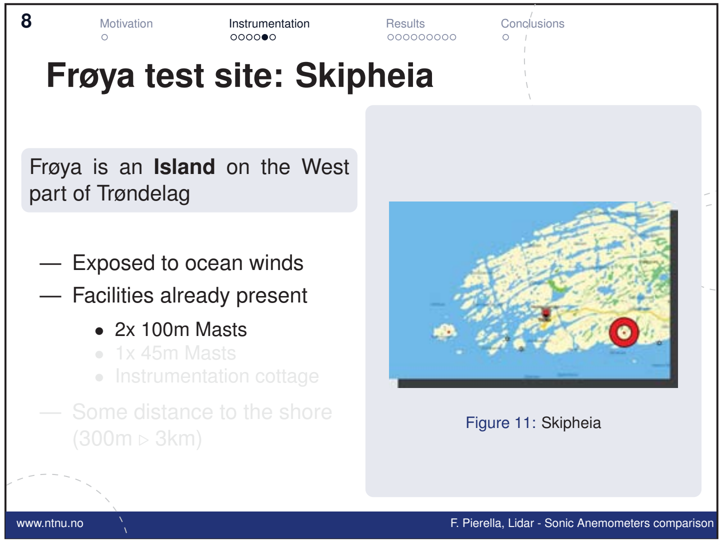

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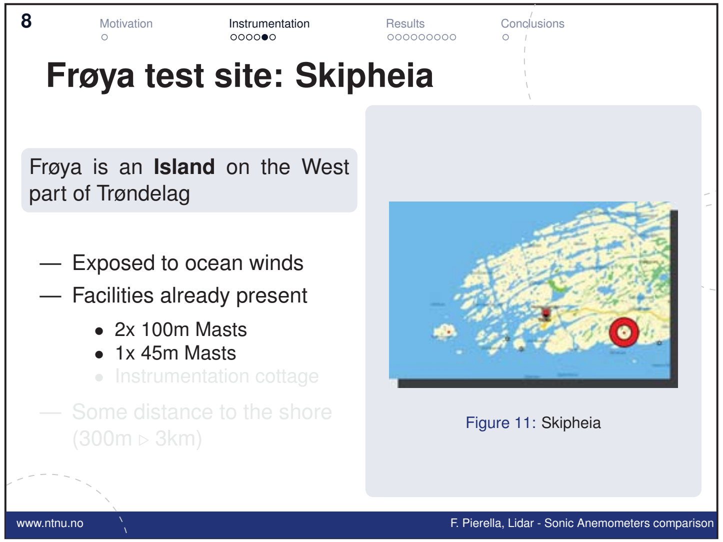

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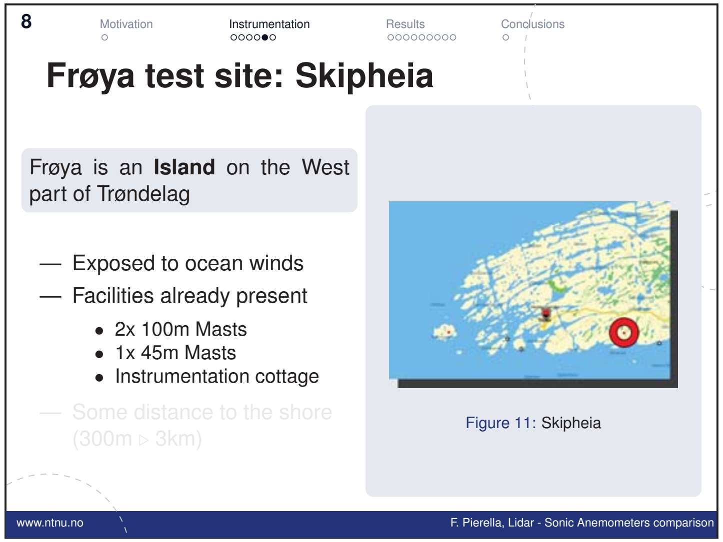

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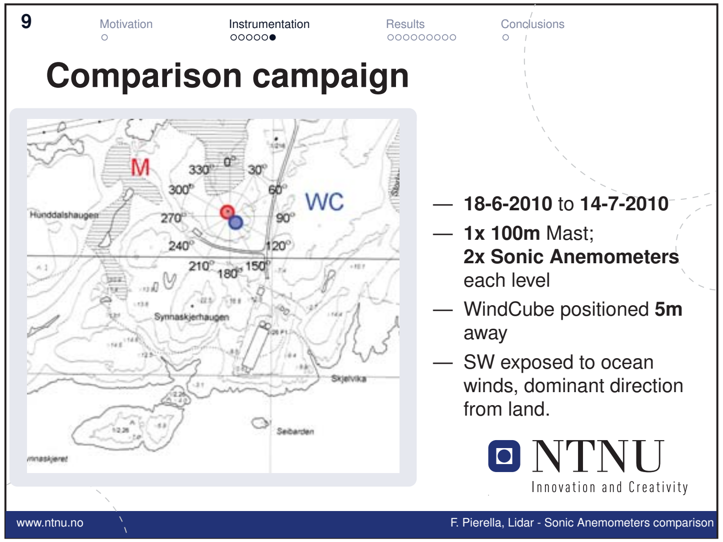
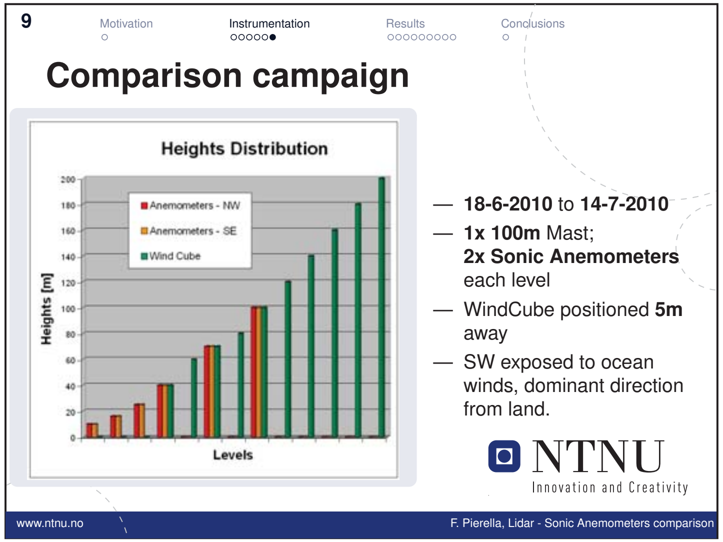
Figure 12: View from the mast



Comparison campaign

- **18-6-2010** to **14-7-2010**
- **1x 100m** Mast; **2x Sonic Anemometers** each level
- WindCube positioned **5m** away
- SW exposed to ocean winds, dominant direction from land.

NTNU Innovation and Creativity



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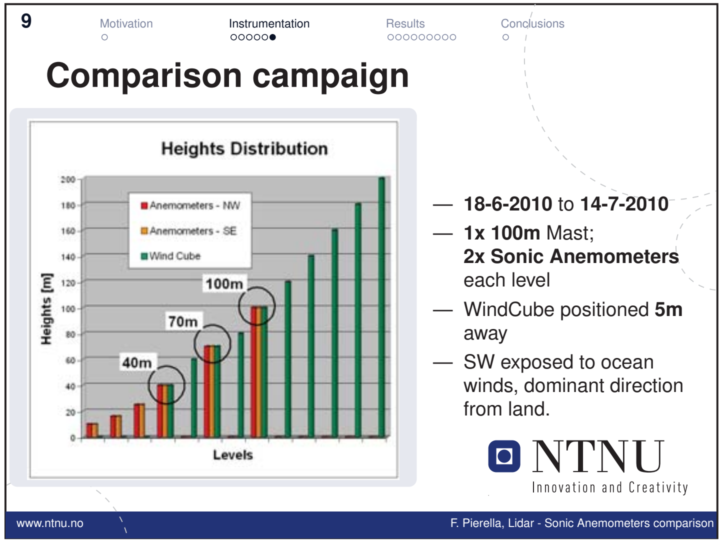

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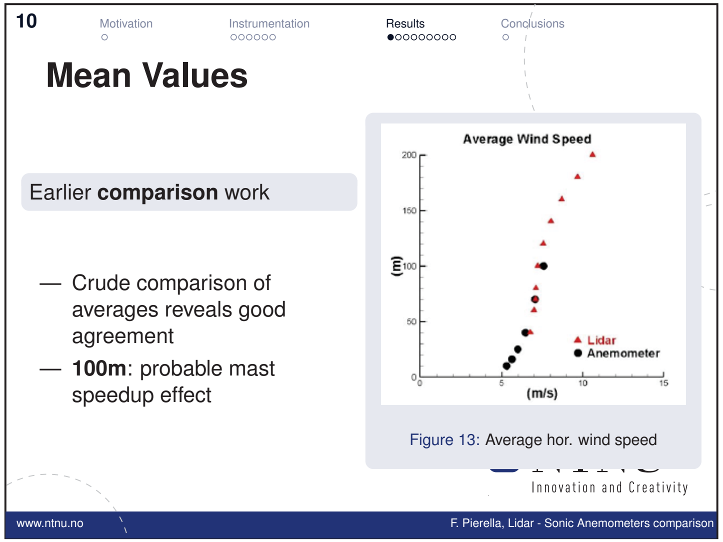


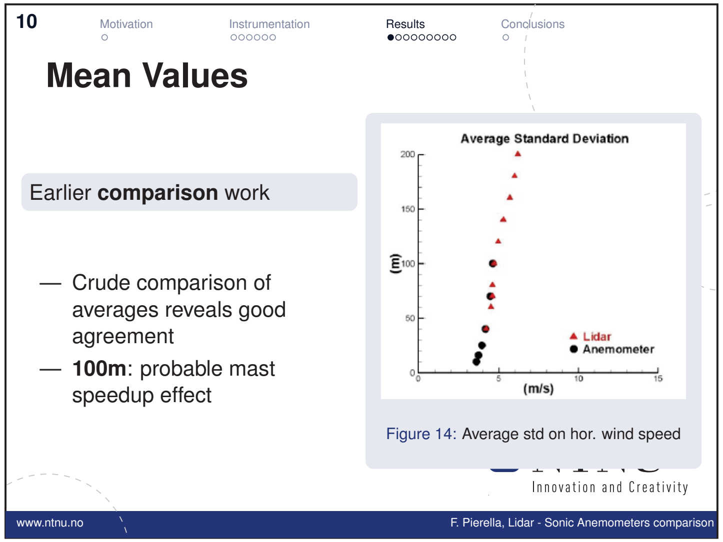
Mean Values

Earlier **comparison** work

- Crude comparison of averages reveals good agreement
- **100m**: probable mast speedup effect

Figure 13: Average hor. wind speed

Innovation and Creativity



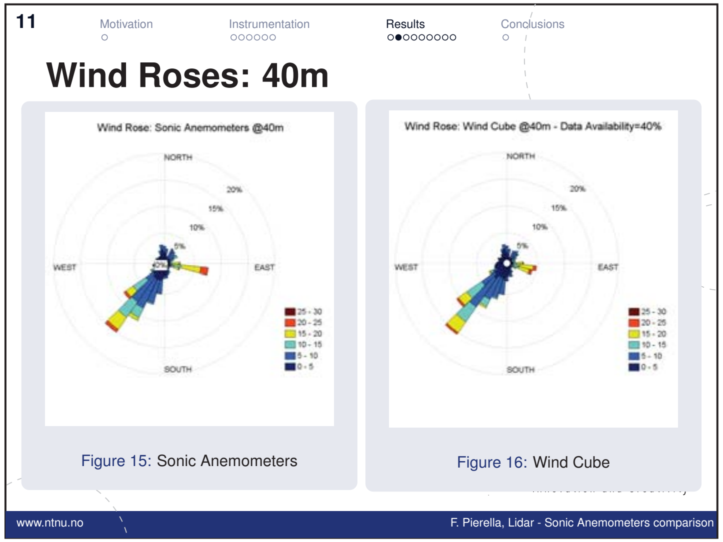
Mean Values

Earlier **comparison** work

- Crude comparison of averages reveals good agreement
- **100m**: probable mast speedup effect

Figure 14: Average std on hor. wind speed

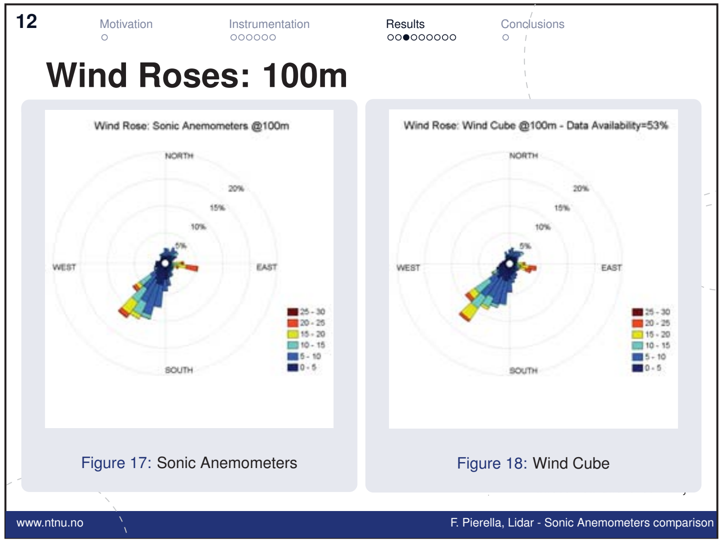
Innovation and Creativity



Wind Roses: 40m

Figure 15: Sonic Anemometers

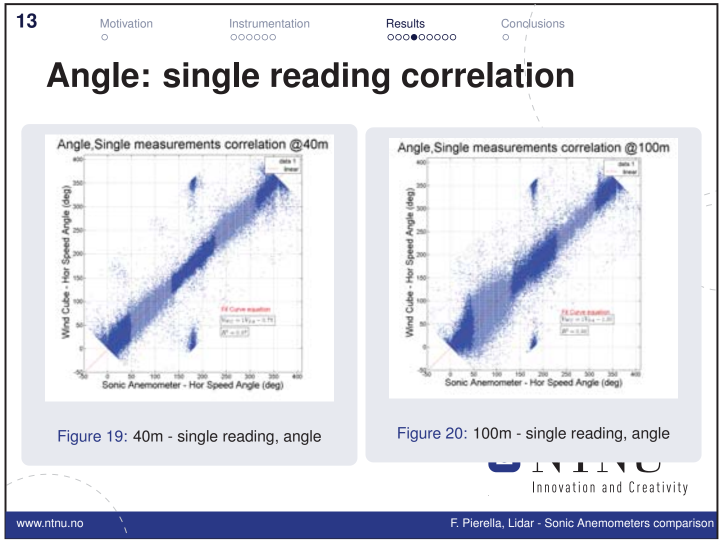
Figure 16: Wind Cube



Wind Roses: 100m

Figure 17: Sonic Anemometers

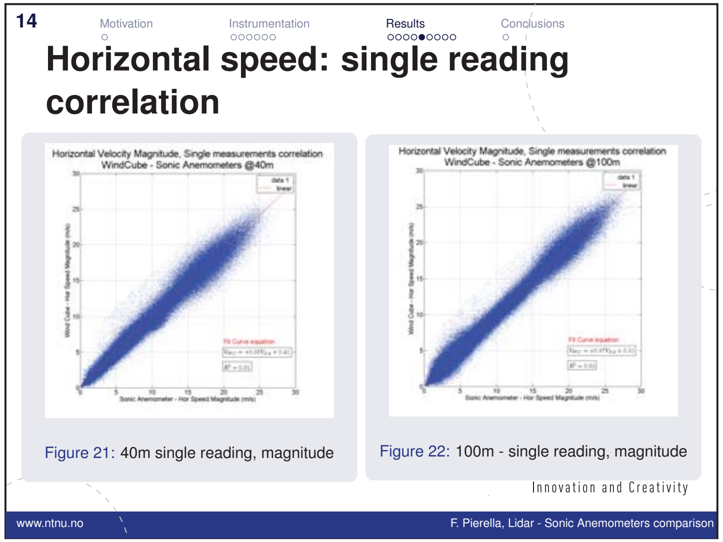
Figure 18: Wind Cube



Angle: single reading correlation

Figure 19: 40m - single reading, angle

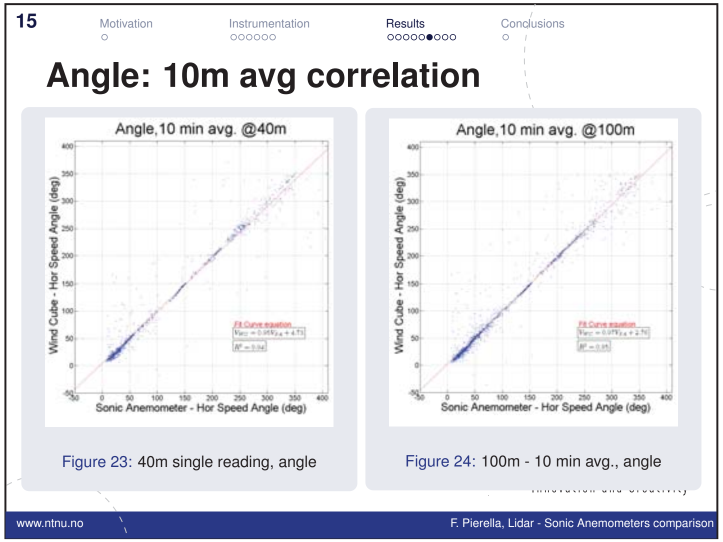
Figure 20: 100m - single reading, angle



Horizontal speed: single reading correlation

Figure 21: 40m single reading, magnitude

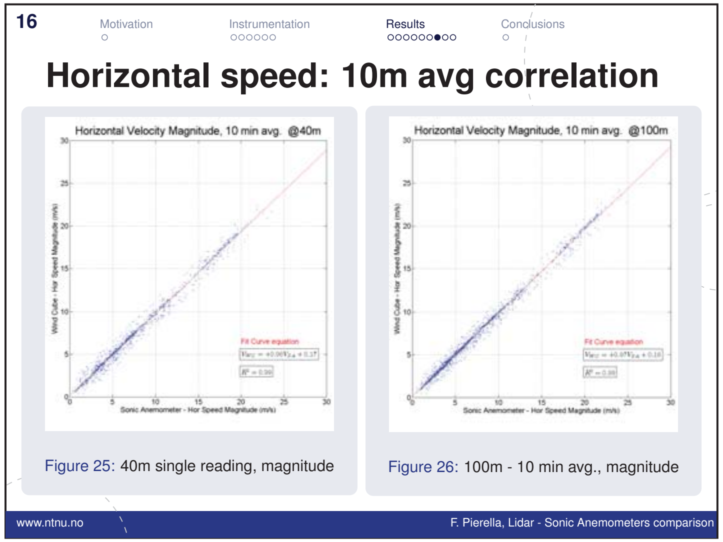
Figure 22: 100m - single reading, magnitude



Angle: 10m avg correlation

Figure 23: 40m single reading, angle

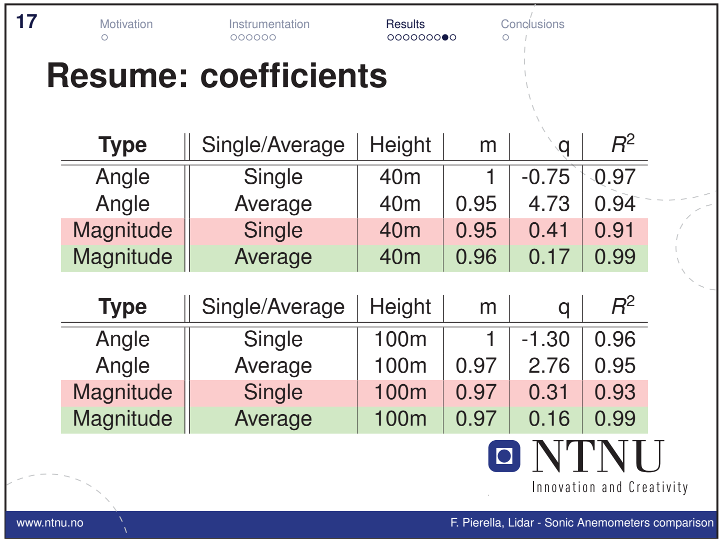
Figure 24: 100m - 10 min avg., angle



Horizontal speed: 10m avg correlation

Figure 25: 40m single reading, magnitude

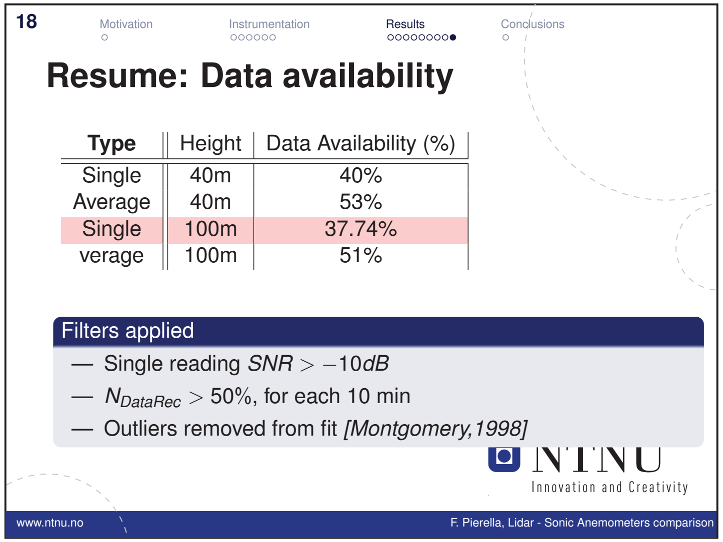
Figure 26: 100m - 10 min avg., magnitude



Resume: coefficients

Type	Single/Average	Height	m	q	R^2
Angle	Single	40m	1	-0.75	0.97
Angle	Average	40m	0.95	4.73	0.94
Magnitude	Single	40m	0.95	0.41	0.91
Magnitude	Average	40m	0.96	0.17	0.99

Type	Single/Average	Height	m	q	R^2
Angle	Single	100m	1	-1.30	0.96
Angle	Average	100m	0.97	2.76	0.95
Magnitude	Single	100m	0.97	0.31	0.93
Magnitude	Average	100m	0.97	0.16	0.99

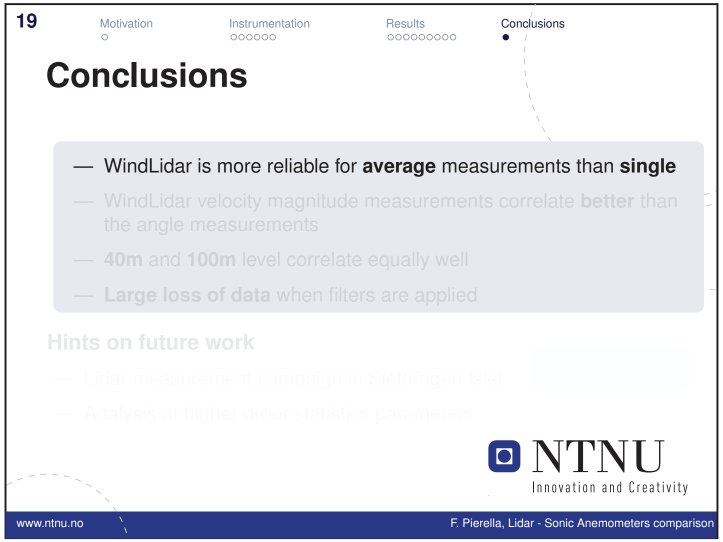


Resume: Data availability

Type	Height	Data Availability (%)
Single	40m	40%
Average	40m	53%
Single	100m	37.74%
verage	100m	51%

Filters applied

- Single reading $SNR > -10dB$
- $N_{DataRec} > 50\%$, for each 10 min
- Outliers removed from fit *[Montgomery,1998]*



Conclusions

- WindLidar is more reliable for **average** measurements than **single**
- WindLidar velocity magnitude measurements correlate **better** than the angle measurements
- **40m** and **100m** level correlate equally well
- **Large loss of data** when filters are applied

Hints on future work

- Lidar measurement campaign in Slettringen Islet
- Analysis of higher order statistics parameters

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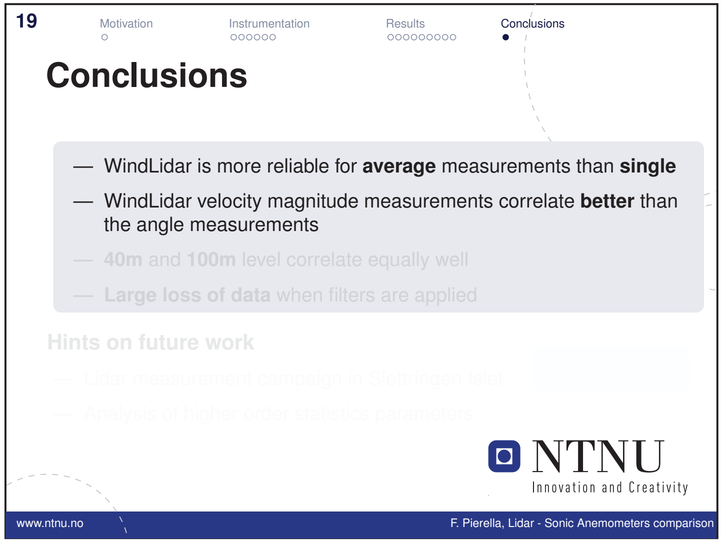
Innovation and Creativity



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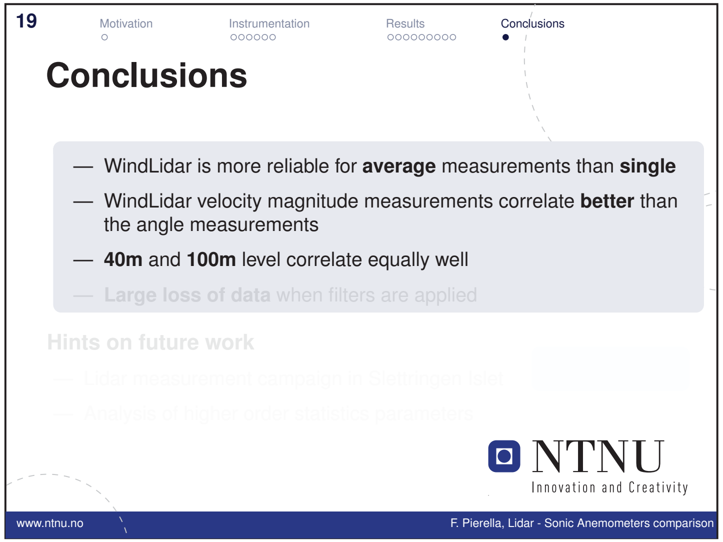

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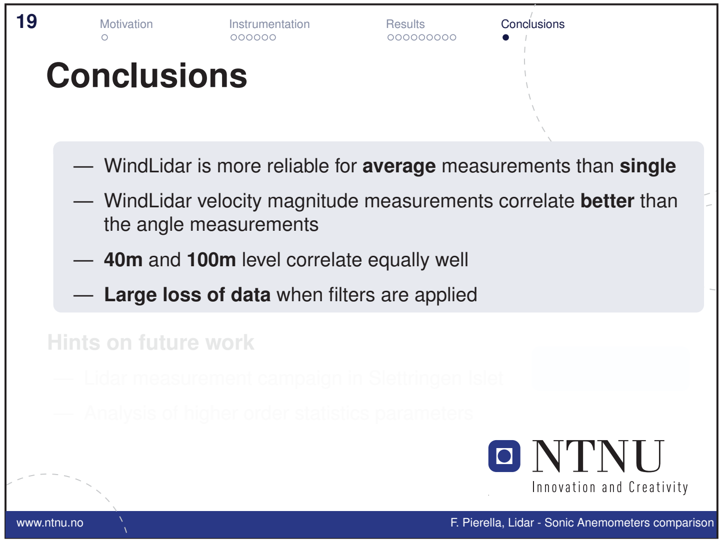

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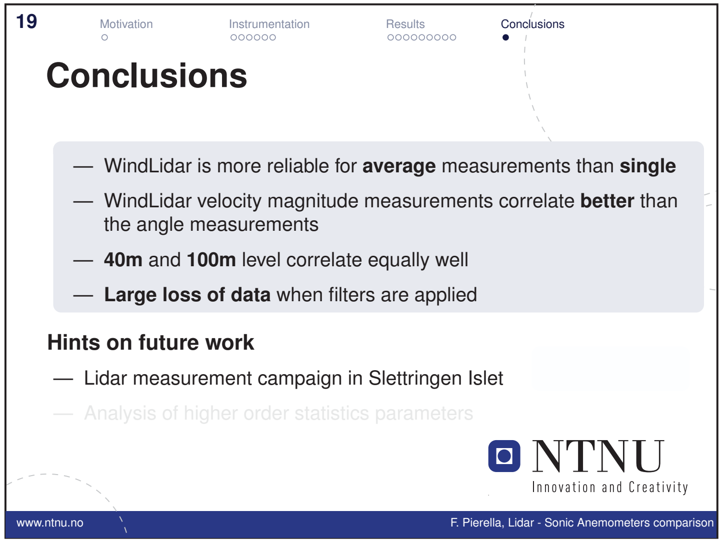

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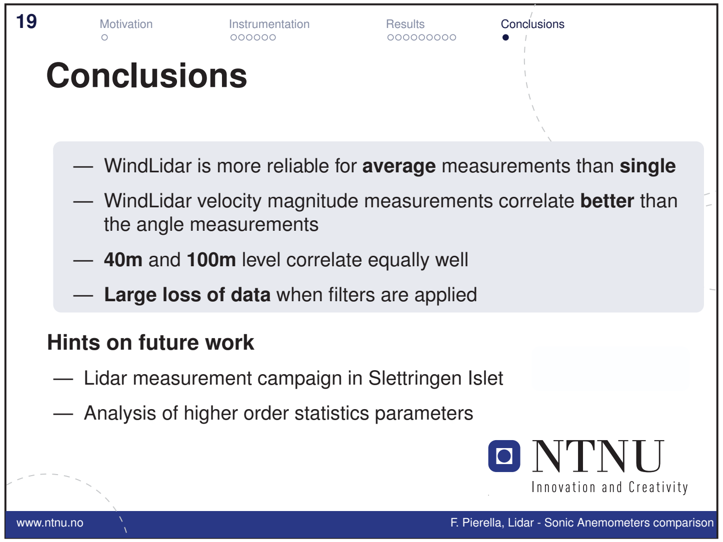

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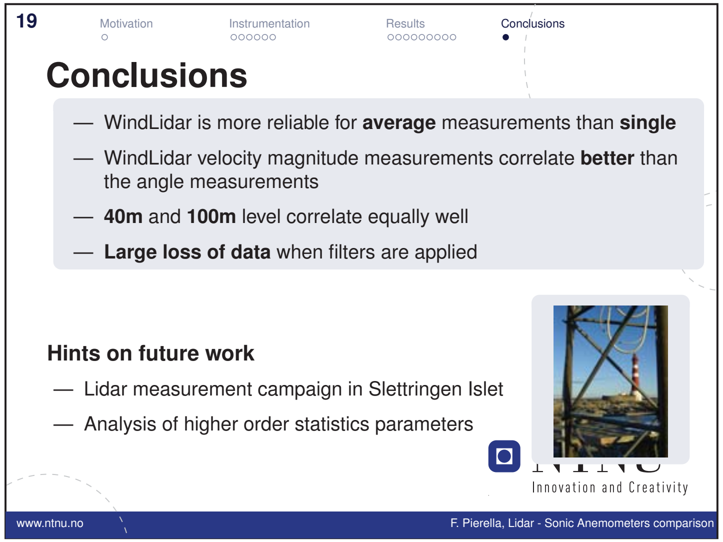

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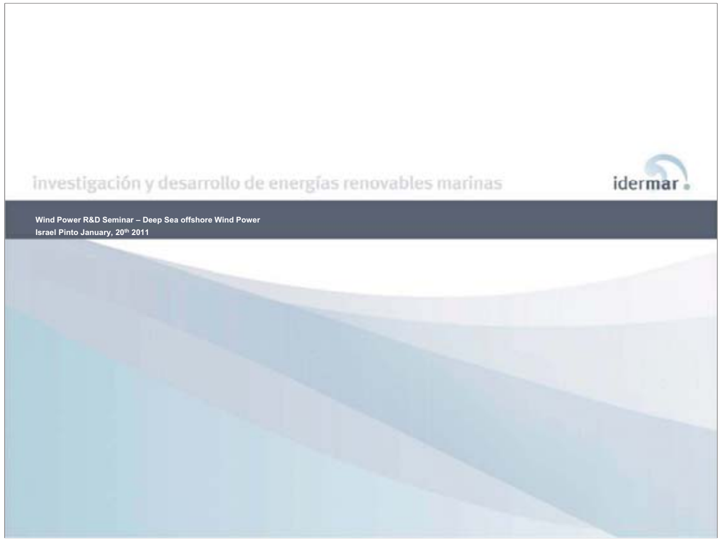

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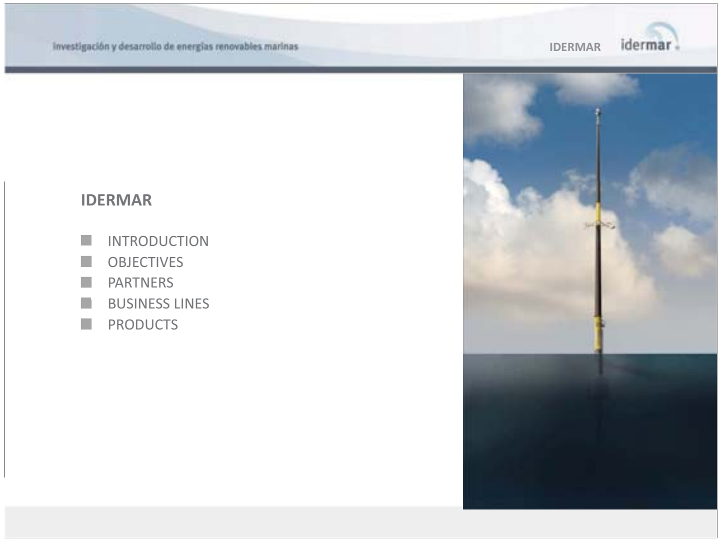
idermar

Wind Power R&D Seminar – Deep Sea offshore Wind Power

Israel Pinto January, 20th 2011



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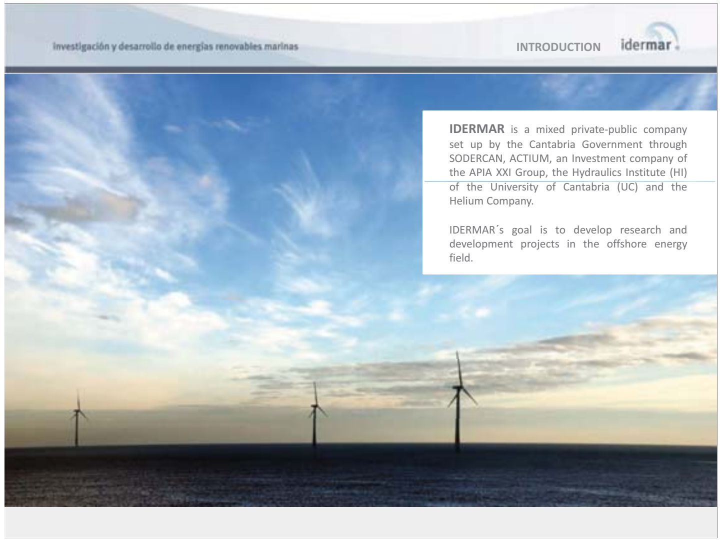
IDERMAR

IDERMAR

- INTRODUCTION
- OBJECTIVES
- PARTNERS
- BUSINESS LINES
- PRODUCTS



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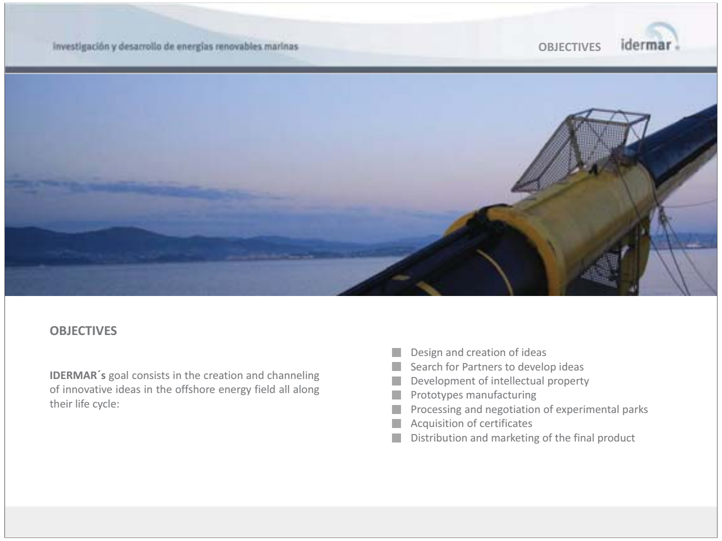
INTRODUCTION

IDERMAR is a mixed private-public company set up by the Cantabria Government through SODERCAN, ACTIUM, an Investment company of the APIA XXI Group, the Hydraulics Institute (HI) of the University of Cantabria (UC) and the Helium Company.

IDERMAR´s goal is to develop research and development projects in the offshore energy field.



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OBJECTIVES

OBJECTIVES

IDERMAR´s goal consists in the creation and channeling of innovative ideas in the offshore energy field all along their life cycle:

- Design and creation of ideas
- Search for Partners to develop ideas
- Development of intellectual property
- Prototypes manufacturing
- Processing and negotiation of experimental parks
- Acquisition of certificates
- Distribution and marketing of the final product

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PARTNERS

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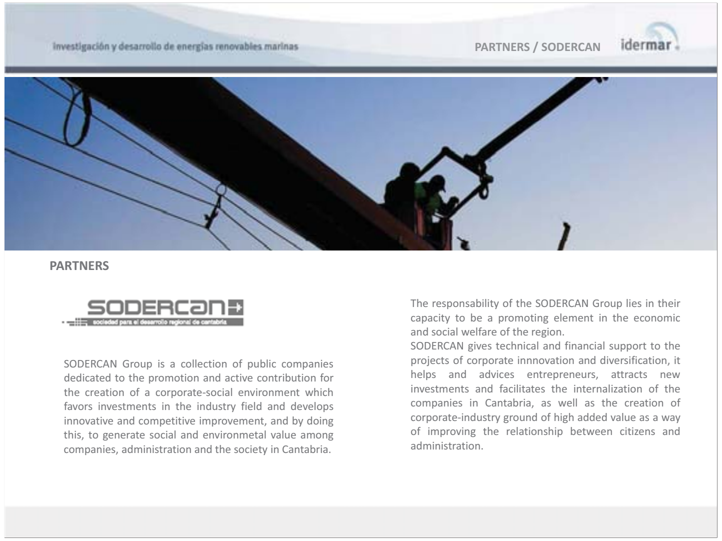

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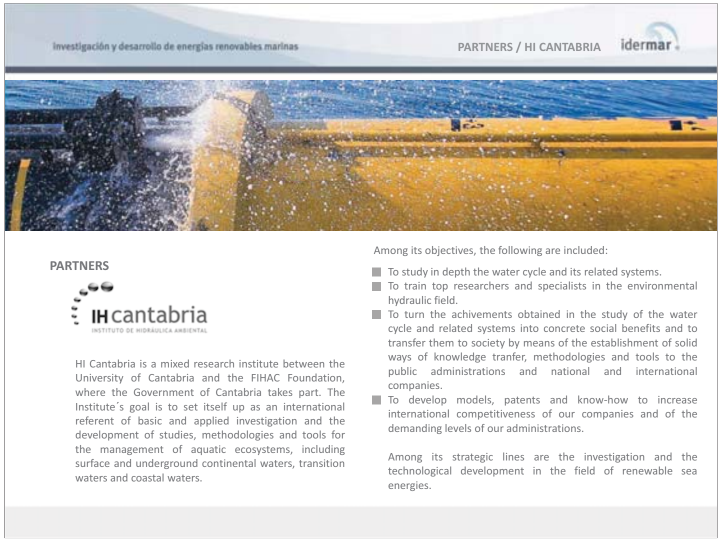
PARTNERS / SODERCAN

PARTNERS

SODERCAN Group is a collection of public companies dedicated to the promotion and active contribution for the creation of a corporate-social environment which favors investments in the industry field and develops innovative and competitive improvement, and by doing this, to generate social and environmetal value among companies, administration and the society in Cantabria.

The responsability of the SODERCAN Group lies in their capacity to be a promoting element in the economic and social welfare of the region.

SODERCAN gives technical and financial support to the projects of corporate innnovation and diversification, it helps and advices entrepreneurs, attracts new investments and facilitates the internalization of the companies in Cantabria, as well as the creation of corporate-industry ground of high added value as a way of improving the relationship between citizens and administration.



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PARTNERS / HI CANTABRIA

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PARTNERS

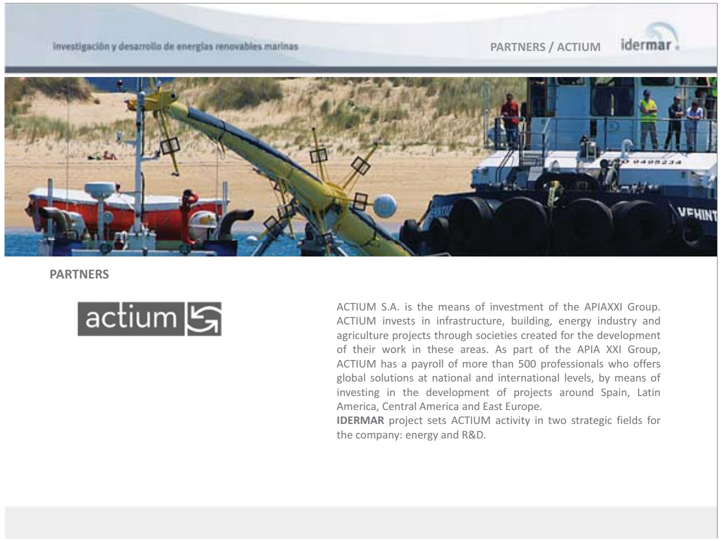
IH cantabria
INSTITUTO DE HIDRÁULICA AMBIENTAL

HI Cantabria is a mixed research institute between the University of Cantabria and the FIHAC Foundation, where the Government of Cantabria takes part. The Institute´s goal is to set itself up as an international referent of basic and applied investigation and the development of studies, methodologies and tools for the management of aquatic ecosystems, including surface and underground continental waters, transition waters and coastal waters.

Among its objectives, the following are included:

- To study in depth the water cycle and its related systems.
- To train top researchers and specialists in the environmental hydraulic field.
- To turn the achivements obtained in the study of the water cycle and related systems into concrete social benefits and to transfer them to society by means of the establishment of solid ways of knowledge tranfer, methodologies and tools to the public administrations and national and international companies.
- To develop models, patents and know-how to increase international competitiveness of our companies and of the demanding levels of our administrations.

Among its strategic lines are the investigation and the technological development in the field of renewable sea energies.



Investigación y desarrollo de energías renovables marinas

PARTNERS / ACTIUM

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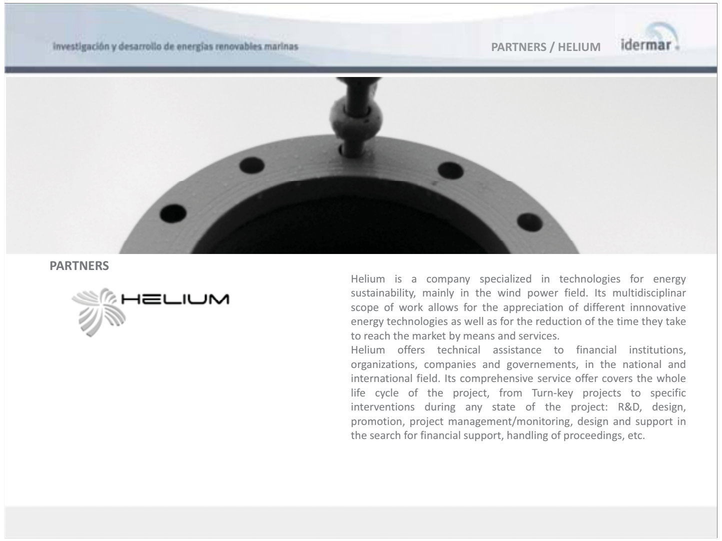
PARTNERS

actium

ACTIUM S.A. is the means of investment of the APIAXXI Group. ACTIUM invests in infrastructure, building, energy industry and agriculture projects through societies created for the development of their work in these areas. As part of the APIA XXI Group, ACTIUM has a payroll of more than 500 professionals who offers global solutions at national and international levels, by means of investing in the development of projects around Spain, Latin America, Central America and East Europe.
IDERMAR project sets ACTIUM activity in two strategic fields for the company: energy and R&D.



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PARTNERS / HELIUM

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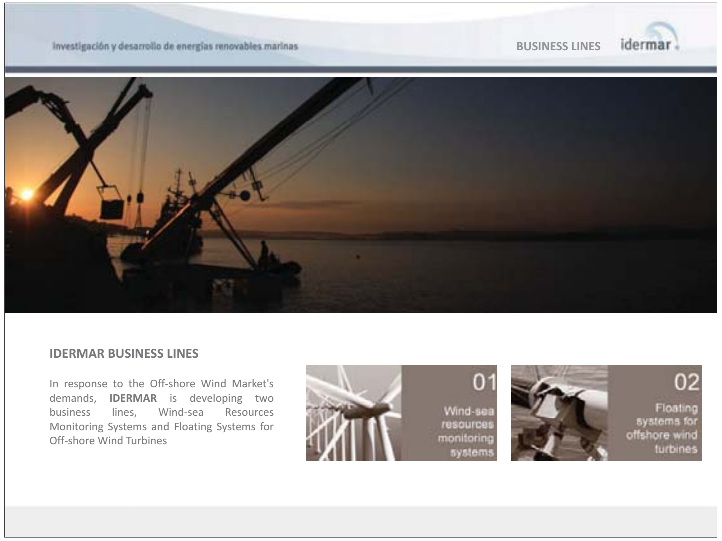
PARTNERS

HELIUM

Helium is a company specialized in technologies for energy sustainability, mainly in the wind power field. Its multidisciplinar scope of work allows for the appreciation of different innnovative energy technologies as well as for the reduction of the time they take to reach the market by means and services.
Helium offers technical assistance to financial institutions, organizations, companies and governements, in the national and international field. Its comprehensive service offer covers the whole life cycle of the project, from Turn-key projects to specific interventions during any state of the project: R&D, design, promotion, project management/monitoring, design and support in the search for financial support, handling of proceedings, etc.



Investigación y desarrollo de energías renovables marinas

BUSINESS LINES

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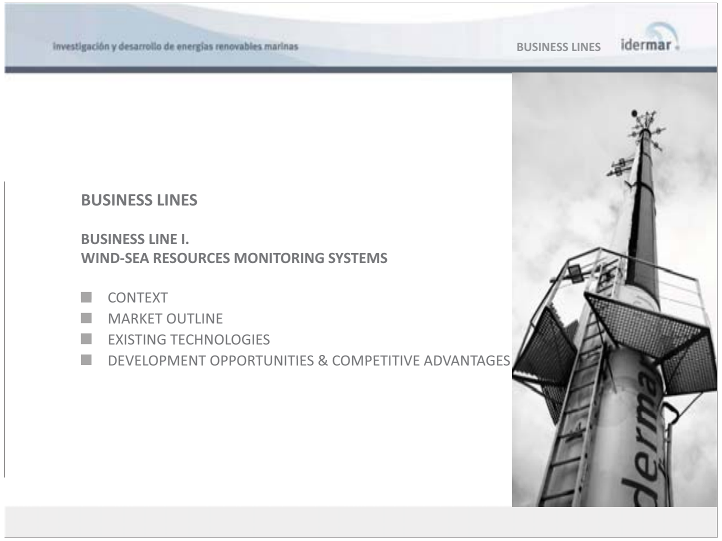
IDERMAR BUSINESS LINES

In response to the Off-shore Wind Market's demands, **IDERMAR** is developing two business lines, Wind-sea Resources Monitoring Systems and Floating Systems for Off-shore Wind Turbines

01
Wind-sea resources monitoring systems

02
Floating systems for offshore wind turbines



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BUSINESS LINES

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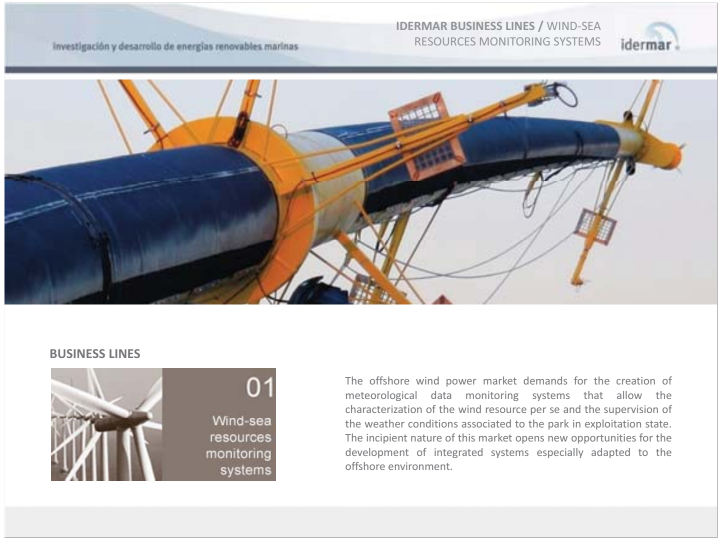
BUSINESS LINES

BUSINESS LINE I.
WIND-SEA RESOURCES MONITORING SYSTEMS

- CONTEXT
- MARKET OUTLINE
- EXISTING TECHNOLOGIES
- DEVELOPMENT OPPORTUNITIES & COMPETITIVE ADVANTAGES



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IDERMAR BUSINESS LINES / WIND-SEA RESOURCES MONITORING SYSTEMS

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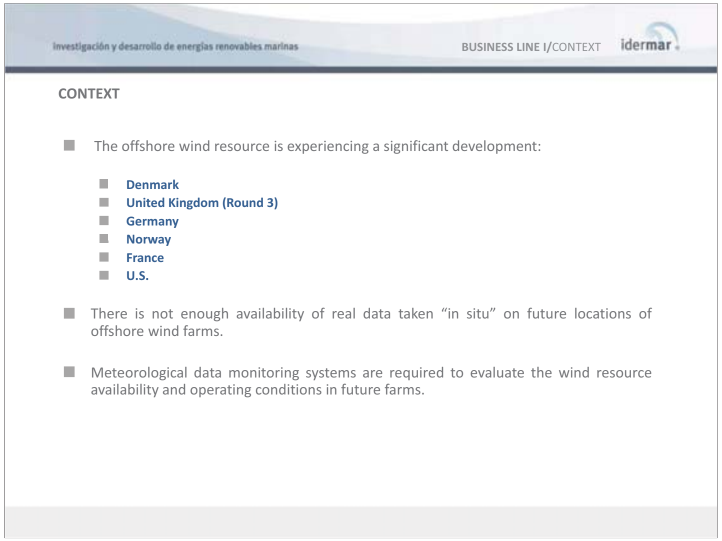
BUSINESS LINES

01
Wind-sea resources monitoring systems

The offshore wind power market demands for the creation of meteorological data monitoring systems that allow the characterization of the wind resource per se and the supervision of the weather conditions associated to the park in exploitation state. The incipient nature of this market opens new opportunities for the development of integrated systems especially adapted to the offshore environment.



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BUSINESS LINE I/CONTEXT

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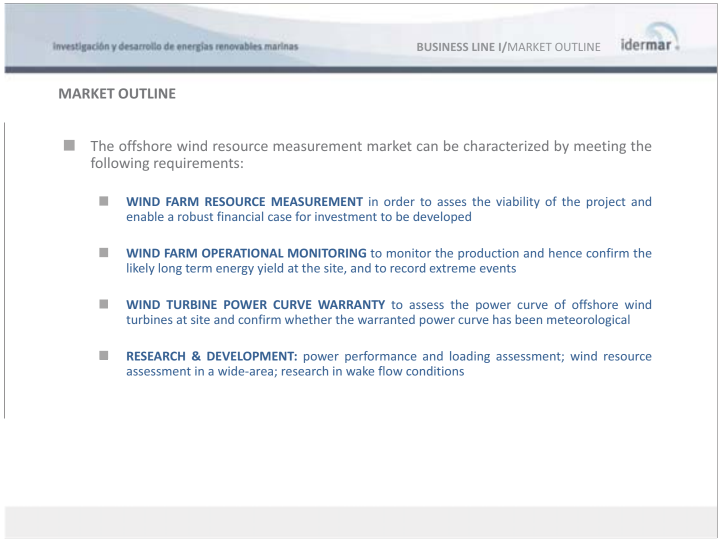
CONTEXT

- The offshore wind resource is experiencing a significant development:
  - **Denmark**
  - **United Kingdom (Round 3)**
  - **Germany**
  - **Norway**
  - **France**
  - **U.S.**
- There is not enough availability of real data taken "in situ" on future locations of offshore wind farms.
- Meteorological data monitoring systems are required to evaluate the wind resource availability and operating conditions in future farms.



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BUSINESS LINE I/MARKET OUTLINE

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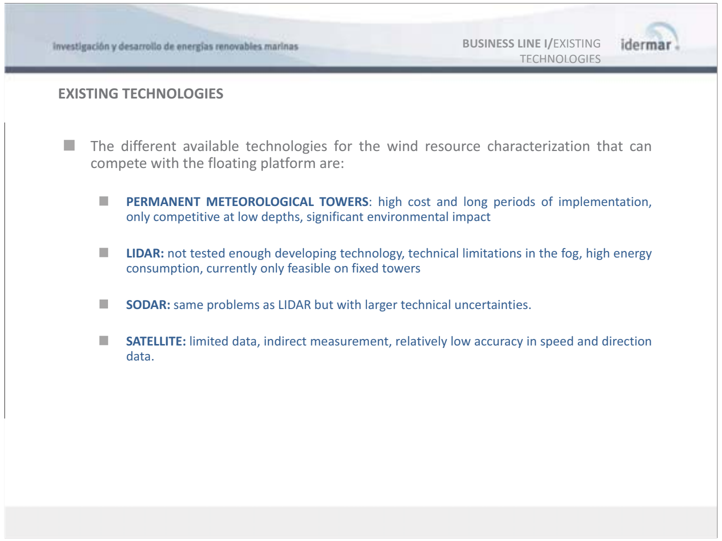
MARKET OUTLINE

- The offshore wind resource measurement market can be characterized by meeting the following requirements:
  - **WIND FARM RESOURCE MEASUREMENT** in order to asses the viability of the project and enable a robust financial case for investment to be developed
  - **WIND FARM OPERATIONAL MONITORING** to monitor the production and hence confirm the likely long term energy yield at the site, and to record extreme events
  - **WIND TURBINE POWER CURVE WARRANTY** to assess the power curve of offshore wind turbines at site and confirm whether the warranted power curve has been meteorological
  - **RESEARCH & DEVELOPMENT:** power performance and loading assessment; wind resource assessment in a wide-area; research in wake flow conditions



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BUSINESS LINE I/EXISTING TECHNOLOGIES

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EXISTING TECHNOLOGIES

- The different available technologies for the wind resource characterization that can compete with the floating platform are:
  - **PERMANENT METEOROLOGICAL TOWERS**: high cost and long periods of implementation, only competitive at low depths, significant environmental impact
  - **LIDAR:** not tested enough developing technology, technical limitations in the fog, high energy consumption, currently only feasible on fixed towers
  - **SODAR:** same problems as LIDAR but with larger technical uncertainties.
  - **SATELLITE:** limited data, indirect measurement, relatively low accuracy in speed and direction data.

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BUSINESS LINE I/DEVELOPMENT OPPORTUNITIES

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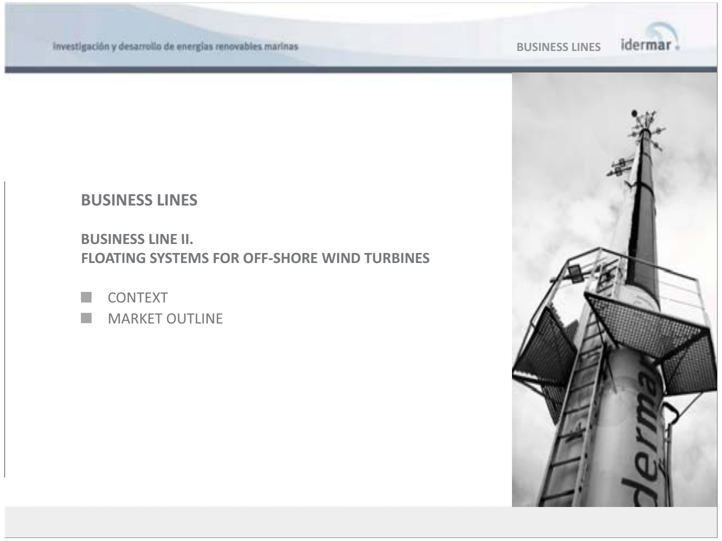
DEVELOPMENT OPPORTUNITIES & COMPETITIVE ADVANTAGES

- In those conditions, the floating meteorological tower concept represents an alternative to conventional solutions that improves its performance and application ranges.
  - **LOWER** installation **COST** than towers fixed to the bottom of the sea
  - Adaptable to **DEPTHS BETWEEN 30 AN 200 METERS** which extends its application field with regard to conventional towers, whether fixed or supported at the bottom
  - **LOWER** manufacturing, installation and handling **LEAD TIMES**
  - **POSSIBILITY OF RELOCATION** and displacement of the tower which extends its spatial coverage
  - **TESTED MEASUREMENT TECHNOLOGY** based on cup anemometers supplemented with ultrasonic anemometers
  - Business model that **MINIMIZES CUSTOMER RISKS**, only data sale, the tower is owned by IDERMAR and, therefore, IDERMAR is responsible for its operation and maintenance



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BUSINESS LINES

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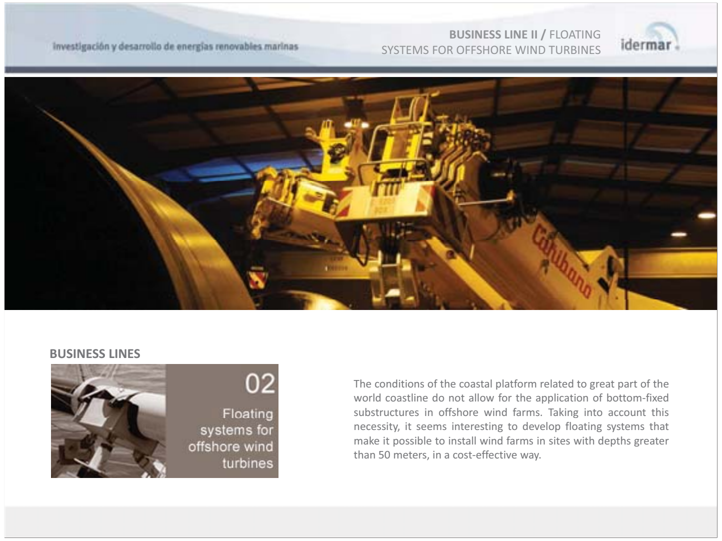
BUSINESS LINES

BUSINESS LINE II.
FLOATING SYSTEMS FOR OFF-SHORE WIND TURBINES

- CONTEXT
- MARKET OUTLINE



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BUSINESS LINE II / FLOATING SYSTEMS FOR OFFSHORE WIND TURBINES

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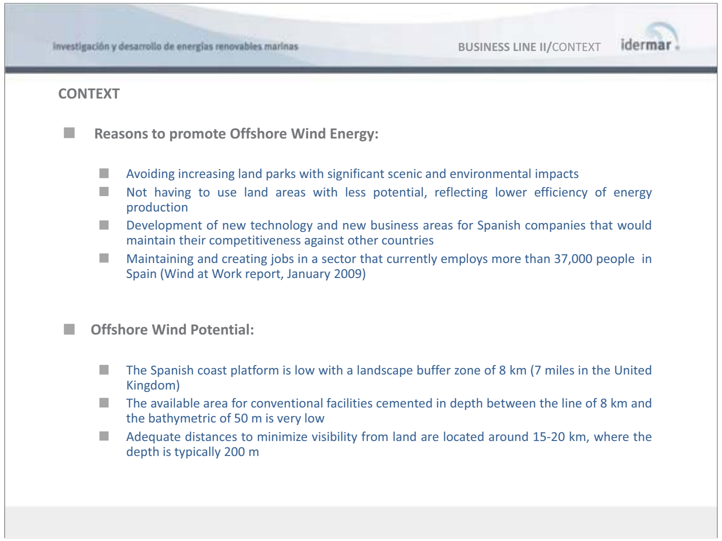
BUSINESS LINES

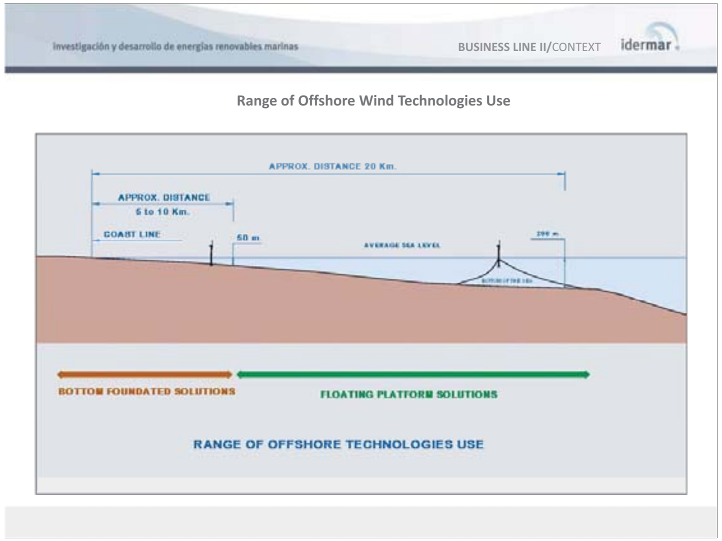
The conditions of the coastal platform related to great part of the world coastline do not allow for the application of bottom-fixed substructures in offshore wind farms. Taking into account this necessity, it seems interesting to develop floating systems that make it possible to install wind farms in sites with depths greater than 50 meters, in a cost-effective way.



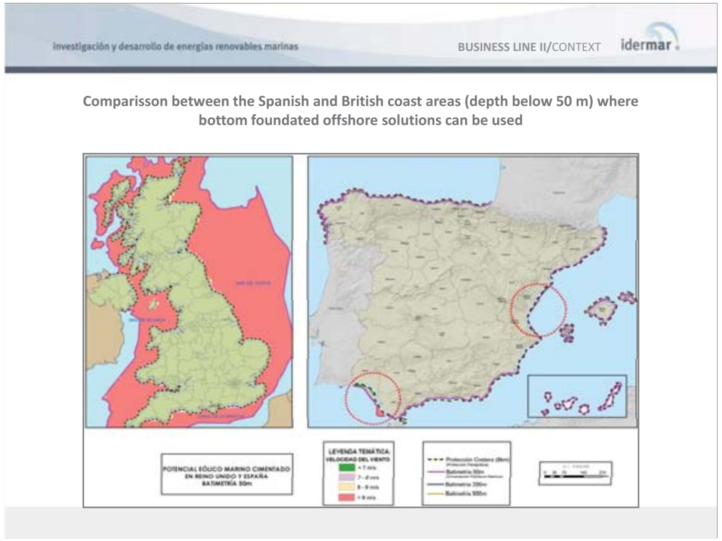
CONTEXT

- **Reasons to promote Offshore Wind Energy:**
  - Avoiding increasing land parks with significant scenic and environmental impacts
  - Not having to use land areas with less potential, reflecting lower efficiency of energy production
  - Development of new technology and new business areas for Spanish companies that would maintain their competitiveness against other countries
  - Maintaining and creating jobs in a sector that currently employs more than 37,000 people in Spain (Wind at Work report, January 2009)

- **Offshore Wind Potential:**
  - The Spanish coast platform is low with a landscape buffer zone of 8 km (7 miles in the United Kingdom)
  - The available area for conventional facilities cemented in depth between the line of 8 km and the bathymetric of 50 m is very low
  - Adequate distances to minimize visibility from land are located around 15-20 km, where the depth is typically 200 m

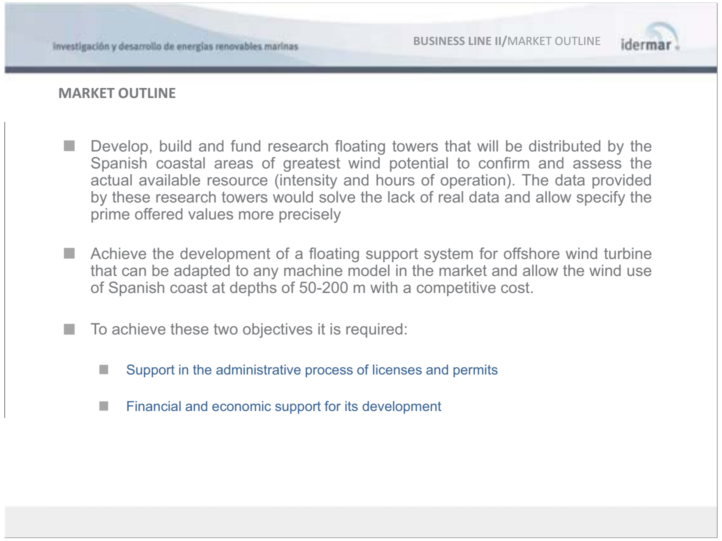


Range of Offshore Wind Technologies Use



Comparisson between the Spanish and British coast areas (depth below 50 m) where bottom foundated offshore solutions can be used

Offshore Wind Potential over Floating Platform in Spain

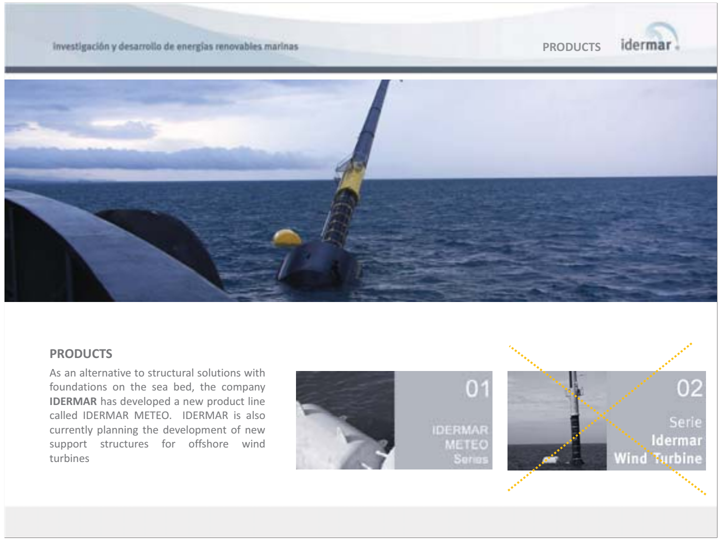


MARKET OUTLINE

- Develop, build and fund research floating towers that will be distributed by the Spanish coastal areas of greatest wind potential to confirm and assess the actual available resource (intensity and hours of operation). The data provided by these research towers would solve the lack of real data and allow specify the prime offered values more precisely

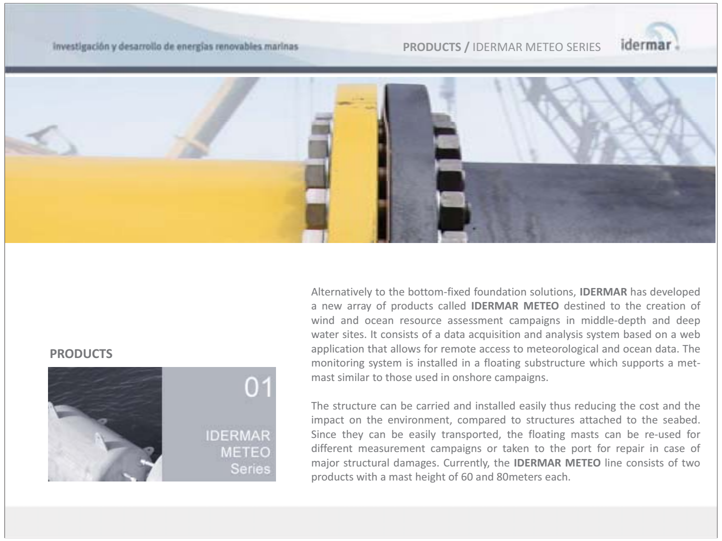
- Achieve the development of a floating support system for offshore wind turbine that can be adapted to any machine model in the market and allow the wind use of Spanish coast at depths of 50-200 m with a competitive cost.

- To achieve these two objectives it is required:
  - Support in the administrative process of licenses and permits
  - Financial and economic support for its development



PRODUCTS

As an alternative to structural solutions with foundations on the sea bed, the company **IDERMAR** has developed a new product line called IDERMAR METEO. IDERMAR is also currently planning the development of new support structures for offshore wind turbines



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PRODUCTS / IDERMAR METEO SERIES

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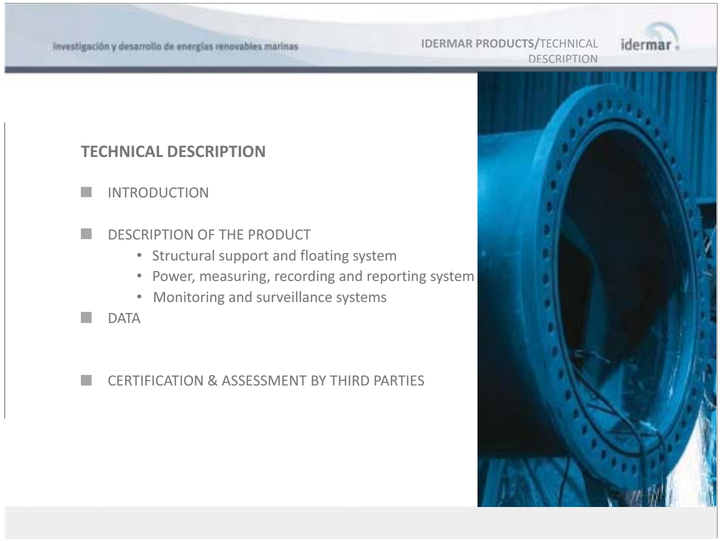
PRODUCTS

01

IDERMAR METEO Series

Alternatively to the bottom-fixed foundation solutions, **IDERMAR** has developed a new array of products called **IDERMAR METEO** destined to the creation of wind and ocean resource assessment campaigns in middle-depth and deep water sites. It consists of a data acquisition and analysis system based on a web application that allows for remote access to meteorological and ocean data. The monitoring system is installed in a floating substructure which supports a met-mast similar to those used in onshore campaigns.

The structure can be carried and installed easily thus reducing the cost and the impact on the environment, compared to structures attached to the seabed. Since they can be easily transported, the floating masts can be re-used for different measurement campaigns or taken to the port for repair in case of major structural damages. Currently, the **IDERMAR METEO** line consists of two products with a mast height of 60 and 80meters each.



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IDERMAR PRODUCTS/TECHNICAL DESCRIPTION

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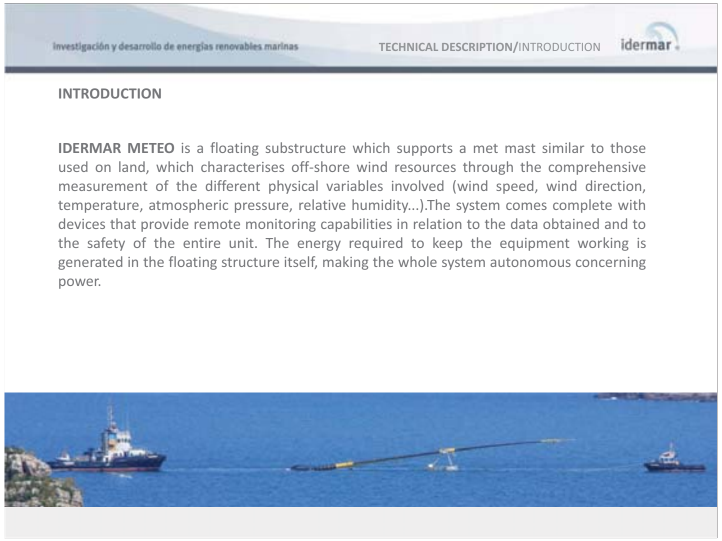
TECHNICAL DESCRIPTION

- INTRODUCTION
- DESCRIPTION OF THE PRODUCT
  - Structural support and floating system
  - Power, measuring, recording and reporting system
  - Monitoring and surveillance systems
- DATA
- CERTIFICATION & ASSESSMENT BY THIRD PARTIES



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TECHNICAL DESCRIPTION/INTRODUCTION

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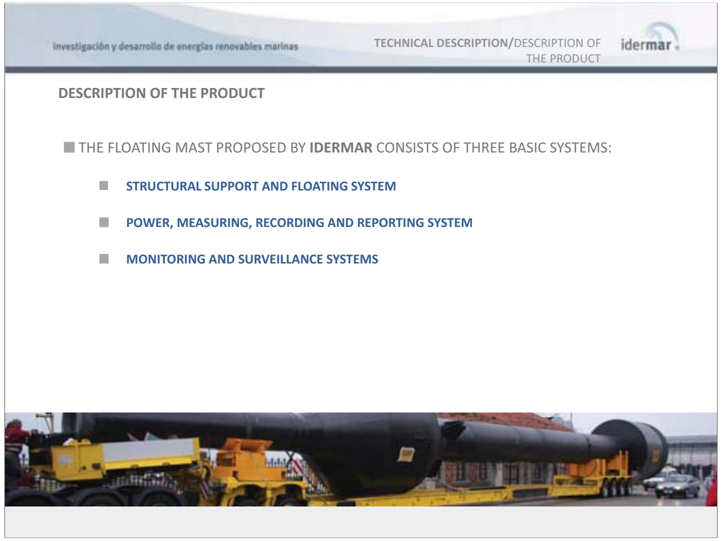
INTRODUCTION

IDERMAR METEO is a floating substructure which supports a met mast similar to those used on land, which characterises off-shore wind resources through the comprehensive measurement of the different physical variables involved (wind speed, wind direction, temperature, atmospheric pressure, relative humidity...).The system comes complete with devices that provide remote monitoring capabilities in relation to the data obtained and to the safety of the entire unit. The energy required to keep the equipment working is generated in the floating structure itself, making the whole system autonomous concerning power.



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TECHNICAL DESCRIPTION/DESCRIPTION OF THE PRODUCT

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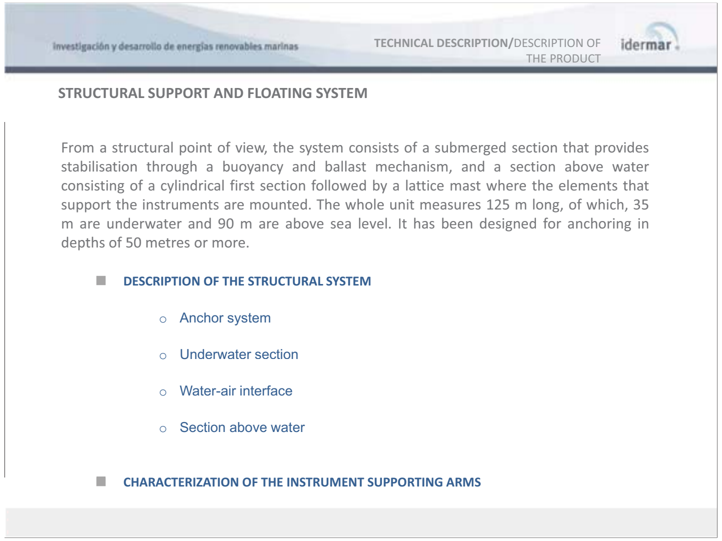
DESCRIPTION OF THE PRODUCT

- THE FLOATING MAST PROPOSED BY **IDERMAR** CONSISTS OF THREE BASIC SYSTEMS:
  - STRUCTURAL SUPPORT AND FLOATING SYSTEM
  - POWER, MEASURING, RECORDING AND REPORTING SYSTEM
  - MONITORING AND SURVEILLANCE SYSTEMS



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TECHNICAL DESCRIPTION/DESCRIPTION OF THE PRODUCT

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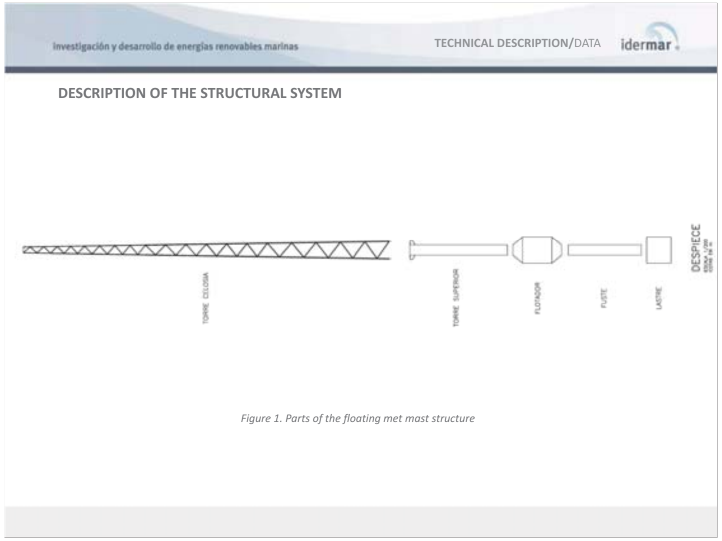
STRUCTURAL SUPPORT AND FLOATING SYSTEM

From a structural point of view, the system consists of a submerged section that provides stabilisation through a buoyancy and ballast mechanism, and a section above water consisting of a cylindrical first section followed by a lattice mast where the elements that support the instruments are mounted. The whole unit measures 125 m long, of which, 35 m are underwater and 90 m are above sea level. It has been designed for anchoring in depths of 50 metres or more.

- DESCRIPTION OF THE STRUCTURAL SYSTEM
  - ○ Anchor system
  - ○ Underwater section
  - ○ Water-air interface
  - ○ Section above water
- CHARACTERIZATION OF THE INSTRUMENT SUPPORTING ARMS



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TECHNICAL DESCRIPTION/DATA

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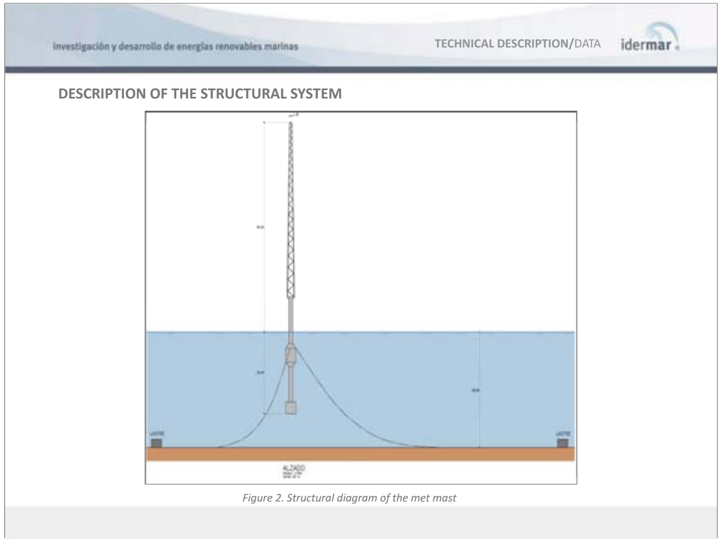
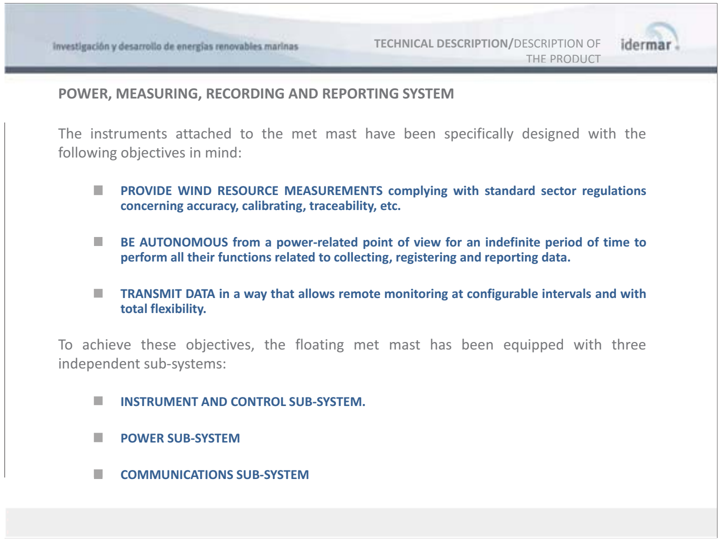
DESCRIPTION OF THE STRUCTURAL SYSTEM

Figure 1. Parts of the floating met mast structure



DESCRIPTION OF THE STRUCTURAL SYSTEM

Figure 2. Structural diagram of the met mast



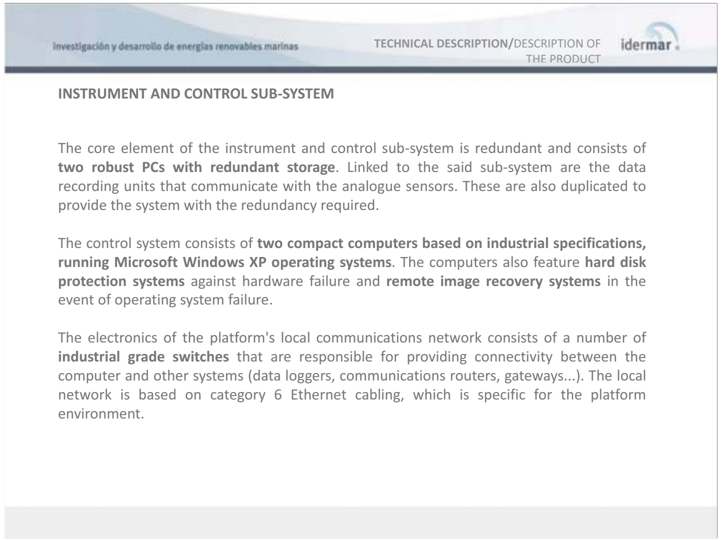
POWER, MEASURING, RECORDING AND REPORTING SYSTEM

The instruments attached to the met mast have been specifically designed with the following objectives in mind:

- **PROVIDE WIND RESOURCE MEASUREMENTS complying with standard sector regulations concerning accuracy, calibrating, traceability, etc.**
- **BE AUTONOMOUS from a power-related point of view for an indefinite period of time to perform all their functions related to collecting, registering and reporting data.**
- **TRANSMIT DATA in a way that allows remote monitoring at configurable intervals and with total flexibility.**

To achieve these objectives, the floating met mast has been equipped with three independent sub-systems:

- **INSTRUMENT AND CONTROL SUB-SYSTEM.**
- **POWER SUB-SYSTEM**
- **COMMUNICATIONS SUB-SYSTEM**

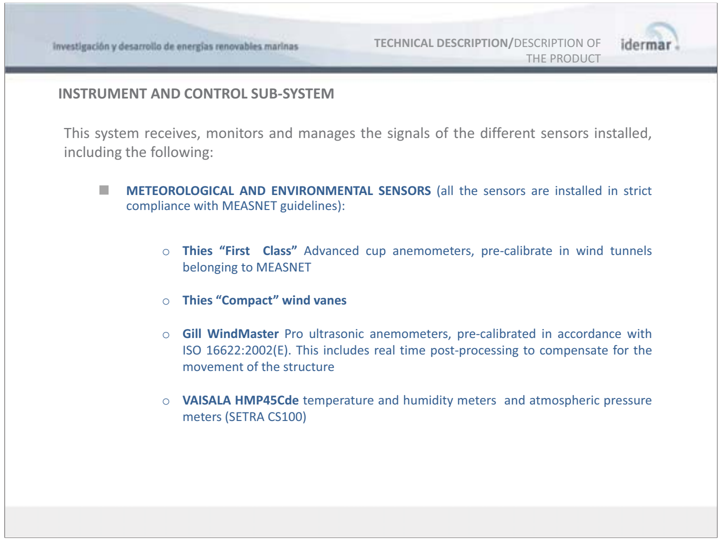


INSTRUMENT AND CONTROL SUB-SYSTEM

The core element of the instrument and control sub-system is redundant and consists of **two robust PCs with redundant storage**. Linked to the said sub-system are the data recording units that communicate with the analogue sensors. These are also duplicated to provide the system with the redundancy required.

The control system consists of **two compact computers based on industrial specifications, running Microsoft Windows XP operating systems**. The computers also feature **hard disk protection systems** against hardware failure and **remote image recovery systems** in the event of operating system failure.

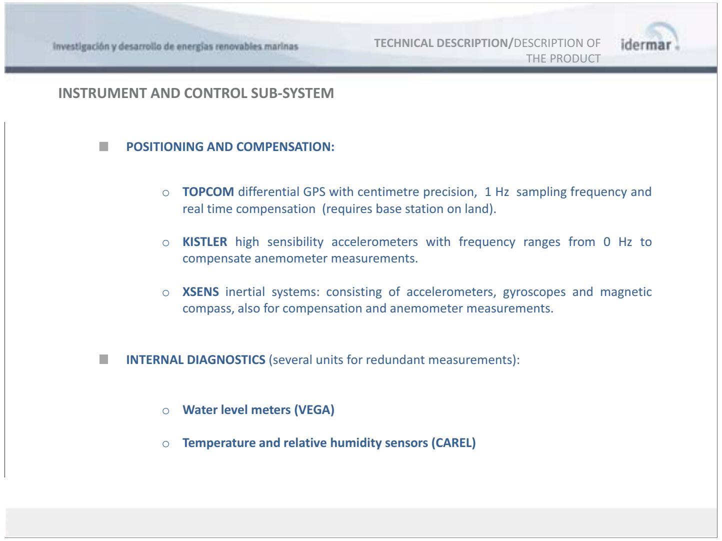
The electronics of the platform's local communications network consists of a number of **industrial grade switches** that are responsible for providing connectivity between the computer and other systems (data loggers, communications routers, gateways...). The local network is based on category 6 Ethernet cabling, which is specific for the platform environment.



INSTRUMENT AND CONTROL SUB-SYSTEM

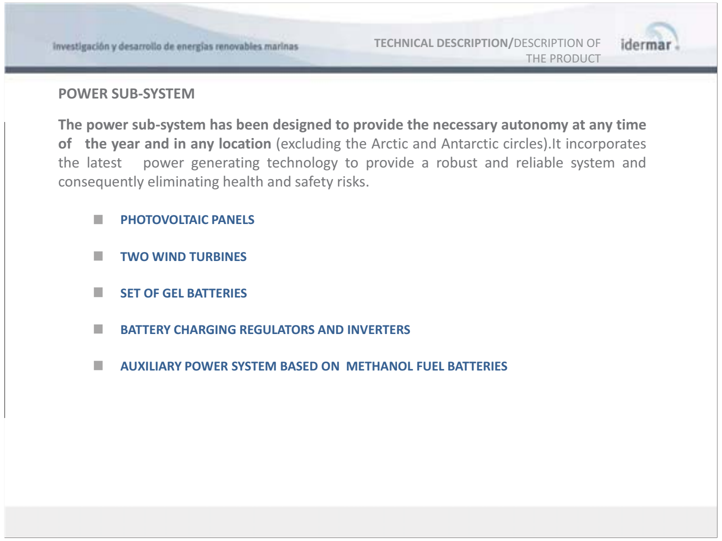
This system receives, monitors and manages the signals of the different sensors installed, including the following:

- **METEOROLOGICAL AND ENVIRONMENTAL SENSORS** (all the sensors are installed in strict compliance with MEASNET guidelines):
  - **Thies "First Class"** Advanced cup anemometers, pre-calibrate in wind tunnels belonging to MEASNET
  - **Thies "Compact" wind vanes**
  - **Gill WindMaster** Pro ultrasonic anemometers, pre-calibrated in accordance with ISO 16622:2002(E). This includes real time post-processing to compensate for the movement of the structure
  - **VAISALA HMP45Cde** temperature and humidity meters and atmospheric pressure meters (SETRA CS100)



INSTRUMENT AND CONTROL SUB-SYSTEM

- **POSITIONING AND COMPENSATION:**
  - **TOPCOM** differential GPS with centimetre precision, 1 Hz sampling frequency and real time compensation (requires base station on land).
  - **KISTLER** high sensibility accelerometers with frequency ranges from 0 Hz to compensate anemometer measurements.
  - **XSENS** inertial systems: consisting of accelerometers, gyroscopes and magnetic compass, also for compensation and anemometer measurements.
- **INTERNAL DIAGNOSTICS** (several units for redundant measurements):
  - **Water level meters (VEGA)**
  - **Temperature and relative humidity sensors (CAREL)**



POWER SUB-SYSTEM

The power sub-system has been designed to provide the necessary autonomy at any time of the year and in any location (excluding the Arctic and Antarctic circles).It incorporates the latest power generating technology to provide a robust and reliable system and consequently eliminating health and safety risks.

- **PHOTOVOLTAIC PANELS**
- **TWO WIND TURBINES**
- **SET OF GEL BATTERIES**
- **BATTERY CHARGING REGULATORS AND INVERTERS**
- **AUXILIARY POWER SYSTEM BASED ON METHANOL FUEL BATTERIES**

COMMUNICATIONS SUB-SYSTEM

Designed for **maximum reliability in any situation and under any conditions**. It consists in a quad communications system that also **minimises the financial cost** of communications.

- **INMARSAT DATA LINK**
- **IRIDIUM DATA LINK**
- **GSM/3G MOBILE/CELL TELEPHONY**
- **PRE-WIMAX RADIO LINK**

COMMUNICATIONS SUB-SYSTEM

All the equipment is managed by **intelligent communications software** that selects the optimum data transmission unit. Communications usually take place once every hour.

However, the system can also provide **continuous and uninterrupted communications when real-time monitoring is required or reduce the frequency of communications when power saving is required**. In summary, the communications management options would be:

- **AUTOMATIC MODE** that selects the ideal unit to transmit communications as programmed.
- **MANUAL MODE** used to select the equipment and communication time.
- **SEMI-AUTOMATIC MODE** used to schedule connections.

MONITORING AND SURVEILLANCE SYSTEMS

IDERMAR METEO incorporates **monitoring and surveillance systems** that allow remote monitoring of the facility, covering two key strategic functions to ensure the success of the data collection campaign:

- **STORAGE OF EXPORTED DATA**, obtained from the met mast's central unit, for statistical processing, distribution and presentation.
- **REAL TIME MONITORING AND SURVEILLANCE** of all operational systems on the mast to ensure the quality of the wind resource data collection campaign and the integrity of the installation.

The monitoring and surveillance systems are based on software developed for the internal management of the floating met mast and its communications with land, as well as software developed for the transmission and use of the said data.

FLOATING MET MAST AND COMMUNICATIONS SOFTWARE

This is the software installed in the floating met mast control computer and its use is restricted to IDERMAR to operate system. It comprises the following components:

- **COMMUNICATIONS MANAGEMENT SYSTEM**
- **SAFE DATA TRANSMISSION SYSTEM**
- **ALARM MANAGEMENT AND ACCUMULATION SYSTEM**
- **LAND BASED DATE RECEPTION AND STORAGE SYSTEMS**
  - An FTP server
  - A service in charge of uploading the data files received to the database
  - SQL Server 2008 database server

DATA PRESENTATION AND DOWNLOADING SOFTWARE

The software used for presenting and downloading data, which is partly accessible to customers, includes a number of **Web-based services** that allow the use of the data stored in the project database.

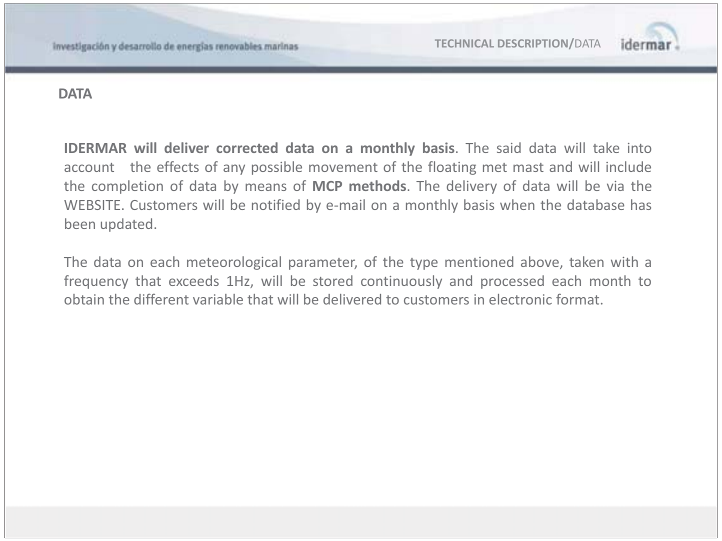
The system also includes a range of services that **trigger alarms** that automatically send e-mails alerts and SMS messages to pre-established recipients for each alert category.

The **WEB services** are based on a complete multi-user and multi-project platform. The system allows each user with access privileges to the consultation system to customize the WEB page based on their needs. This requires a set of controls that take the data stored in the database and presents them to the user in the form of graphs, simulations, lists or other items.

The said set of controls is a permanently growing repository based on the needs and expectations of the different types of system users. Consequently, the view that an operations and maintenance manager has when accessing the system would be a list of alerts and alarms, while the view a met data analyst would get would include reports, graphs, animations, etc. In any case, each user may **customize** the page according to their needs based on a set of controls they will be able to access based on their individual privileges or on the privileges of the access group they belong to.

DATA PRESENTATION AND DOWNLOADING SOFTWARE

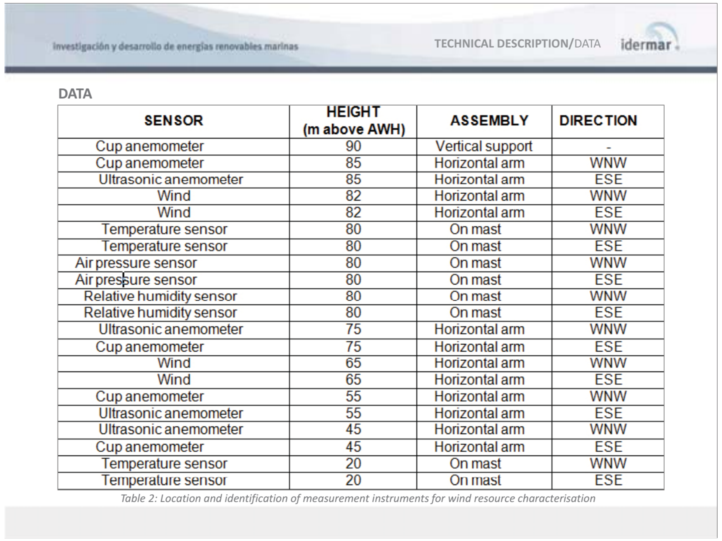
Figure 6: Example of a customized monitoring screen



DATA

IDERMAR will deliver corrected data on a monthly basis. The said data will take into account the effects of any possible movement of the floating met mast and will include the completion of data by means of **MCP methods**. The delivery of data will be via the WEBSITE. Customers will be notified by e-mail on a monthly basis when the database has been updated.

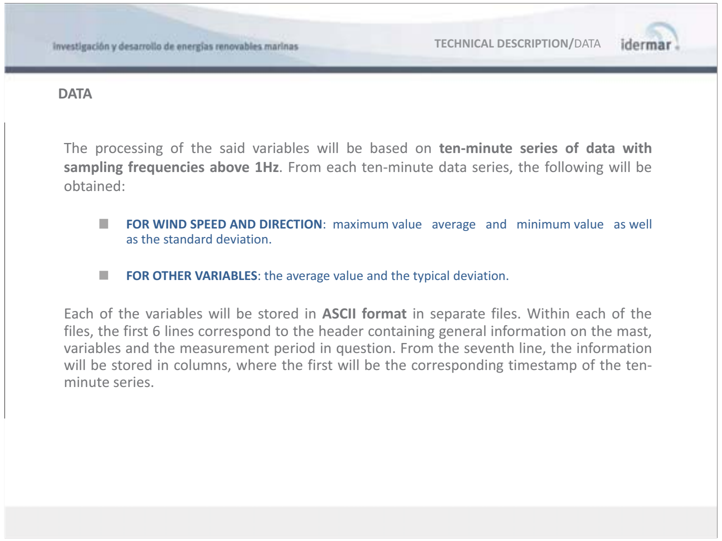
The data on each meteorological parameter, of the type mentioned above, taken with a frequency that exceeds 1Hz, will be stored continuously and processed each month to obtain the different variable that will be delivered to customers in electronic format.



DATA

SENSOR	HEIGHT (m above AWH)	ASSEMBLY	DIRECTION
Cup anemometer	90	Vertical support	-
Cup anemometer	85	Horizontal arm	WNW
Ultrasonic anemometer	85	Horizontal arm	ESE
Wind	82	Horizontal arm	WNW
Wind	82	Horizontal arm	ESE
Temperature sensor	80	On mast	WNW
Temperature sensor	80	On mast	ESE
Air pressure sensor	80	On mast	WNW
Air pressure sensor	80	On mast	ESE
Relative humidity sensor	80	On mast	WNW
Relative humidity sensor	80	On mast	ESE
Ultrasonic anemometer	75	Horizontal arm	WNW
Cup anemometer	75	Horizontal arm	ESE
Wind	65	Horizontal arm	WNW
Wind	65	Horizontal arm	ESE
Cup anemometer	55	Horizontal arm	WNW
Ultrasonic anemometer	55	Horizontal arm	ESE
Ultrasonic anemometer	45	Horizontal arm	WNW
Cup anemometer	45	Horizontal arm	ESE
Temperature sensor	20	On mast	WNW
Temperature sensor	20	On mast	ESE

Table 2: Location and identification of measurement instruments for wind resource characterisation

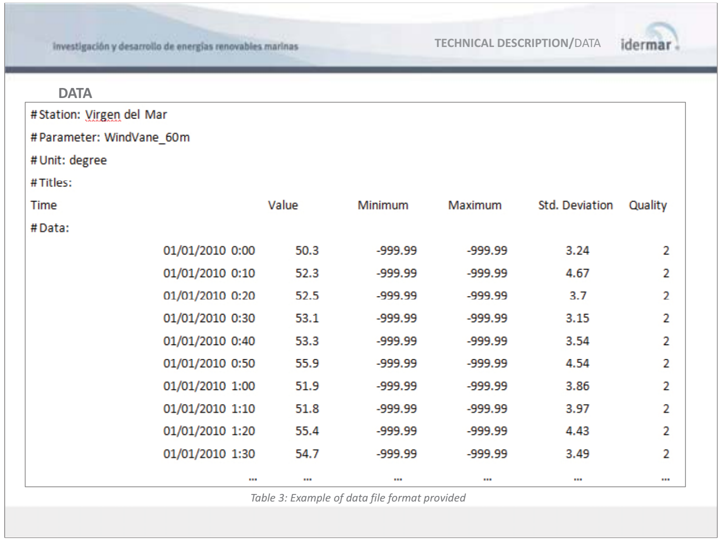


DATA

The processing of the said variables will be based on **ten-minute series of data with sampling frequencies above 1Hz**. From each ten-minute data series, the following will be obtained:

- **FOR WIND SPEED AND DIRECTION**: maximum value average and minimum value as well as the standard deviation.
- **FOR OTHER VARIABLES**: the average value and the typical deviation.

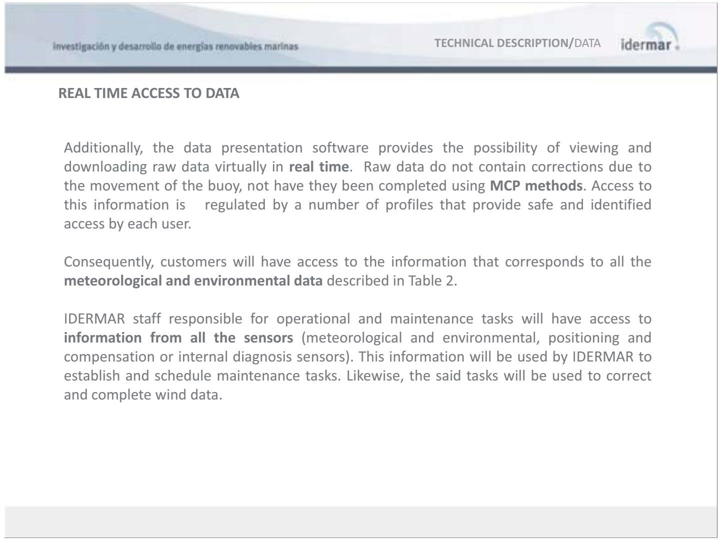
Each of the variables will be stored in **ASCII format** in separate files. Within each of the files, the first 6 lines correspond to the header containing general information on the mast, variables and the measurement period in question. From the seventh line, the information will be stored in columns, where the first will be the corresponding timestamp of the ten-minute series.



DATA

```
#Station: Virgen del Mar
#Parameter: WindVane_60m
#Unit: degree
#Titles:
Time                        Value      Minimum     Maximum    Std. Deviation   Quality
#Data:
          01/01/2010 0:00    50.3      -999.99     -999.99        3.24            2
          01/01/2010 0:10    52.3      -999.99     -999.99        4.67            2
          01/01/2010 0:20    52.5      -999.99     -999.99        3.7             2
          01/01/2010 0:30    53.1      -999.99     -999.99        3.15            2
          01/01/2010 0:40    53.3      -999.99     -999.99        3.54            2
          01/01/2010 0:50    55.9      -999.99     -999.99        4.54            2
          01/01/2010 1:00    51.9      -999.99     -999.99        3.86            2
          01/01/2010 1:10    51.8      -999.99     -999.99        3.97            2
          01/01/2010 1:20    55.4      -999.99     -999.99        4.43            2
          01/01/2010 1:30    54.7      -999.99     -999.99        3.49            2
                 ...          ...        ...         ...          ...             ...
```

Table 3: Example of data file format provided

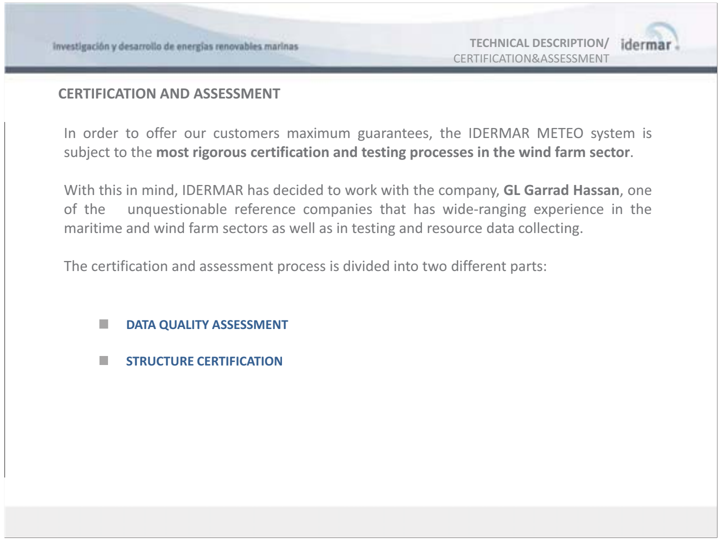


REAL TIME ACCESS TO DATA

Additionally, the data presentation software provides the possibility of viewing and downloading raw data virtually in **real time**. Raw data do not contain corrections due to the movement of the buoy, not have they been completed using **MCP methods**. Access to this information is regulated by a number of profiles that provide safe and identified access by each user.

Consequently, customers will have access to the information that corresponds to all the **meteorological and environmental data** described in Table 2.

IDERMAR staff responsible for operational and maintenance tasks will have access to **information from all the sensors** (meteorological and environmental, positioning and compensation or internal diagnosis sensors). This information will be used by IDERMAR to establish and schedule maintenance tasks. Likewise, the said tasks will be used to correct and complete wind data.



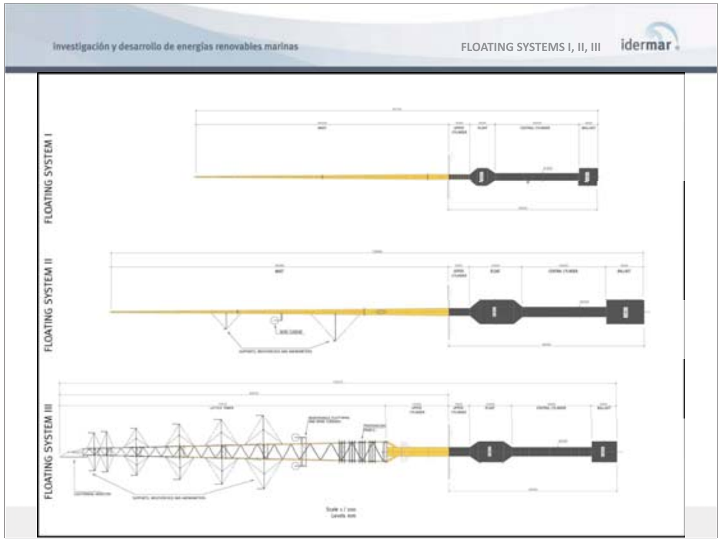
CERTIFICATION AND ASSESSMENT

In order to offer our customers maximum guarantees, the IDERMAR METEO system is subject to the **most rigorous certification and testing processes in the wind farm sector**.

With this in mind, IDERMAR has decided to work with the company, **GL Garrad Hassan**, one of the unquestionable reference companies that has wide-ranging experience in the maritime and wind farm sectors as well as in testing and resource data collecting.

The certification and assessment process is divided into two different parts:

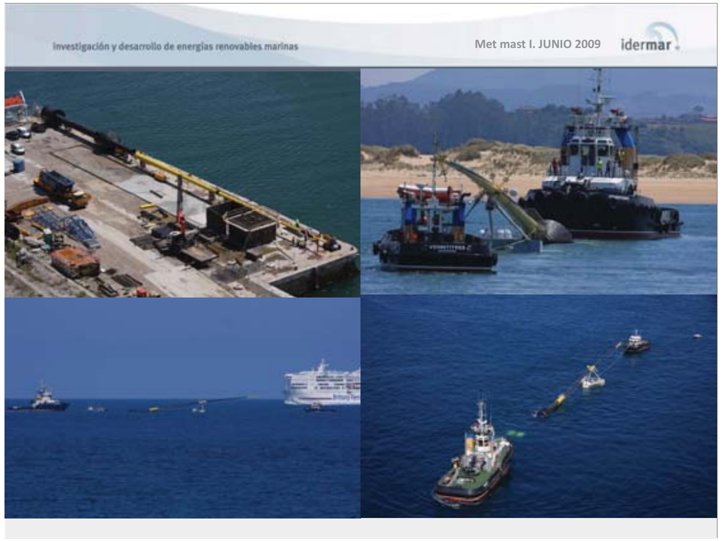
- **DATA QUALITY ASSESSMENT**
- **STRUCTURE CERTIFICATION**



Investigación y desarrollo de energías renovables marinas

FLOATING SYSTEMS I, II, III

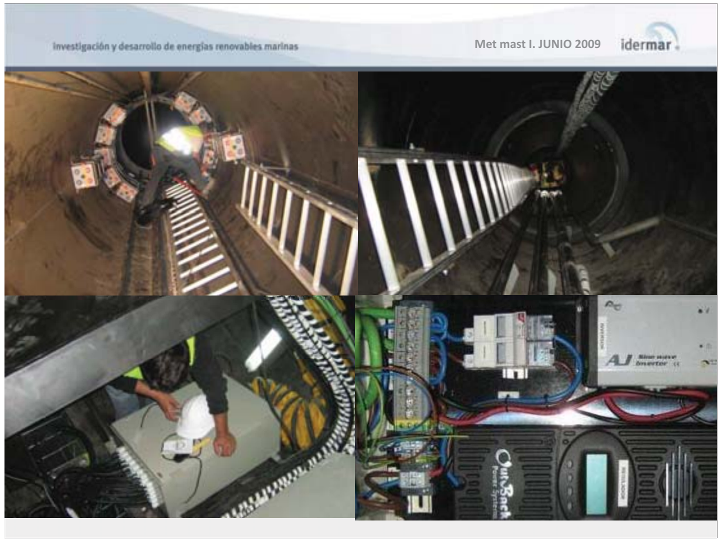
idermar



Investigación y desarrollo de energías renovables marinas

Met mast I. JUNIO 2009

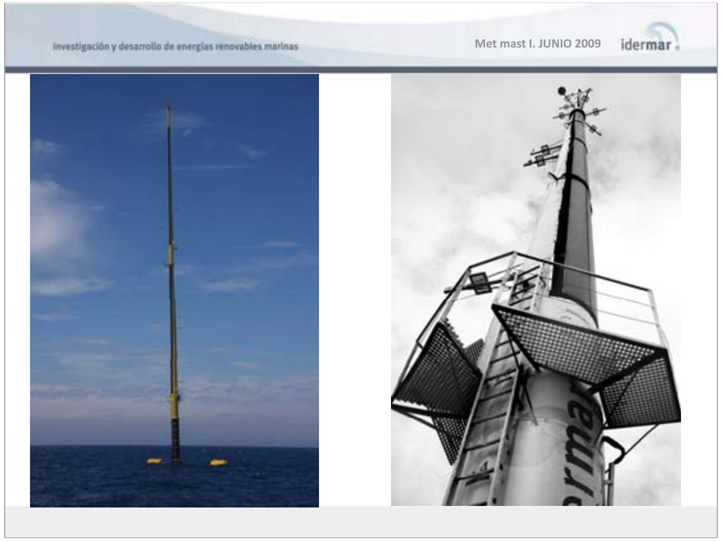
idermar



Investigación y desarrollo de energías renovables marinas

Met mast I. JUNIO 2009

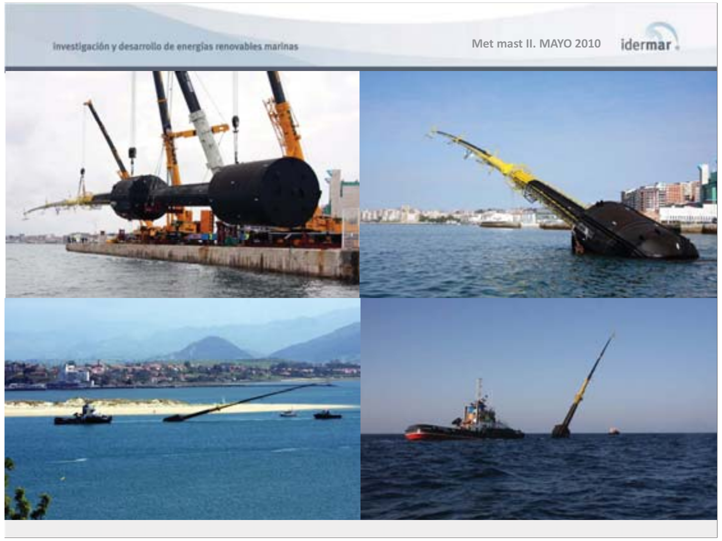
idermar



Investigación y desarrollo de energías renovables marinas

Met mast I. JUNIO 2009

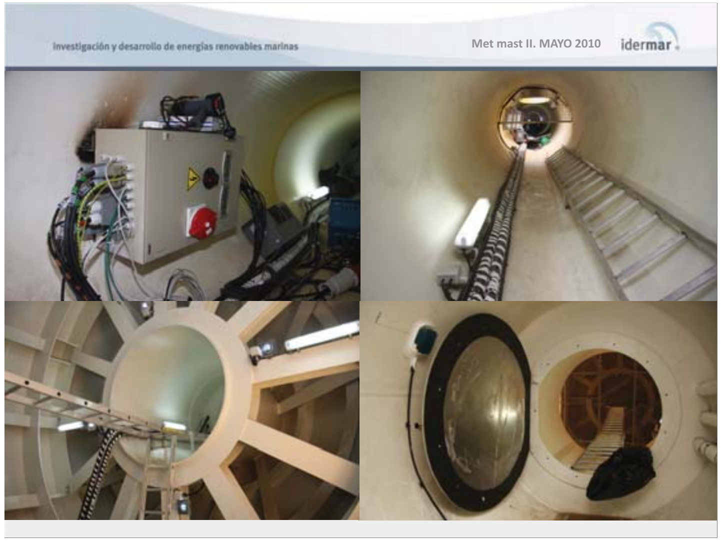
idermar



Investigación y desarrollo de energías renovables marinas

Met mast II. MAYO 2010

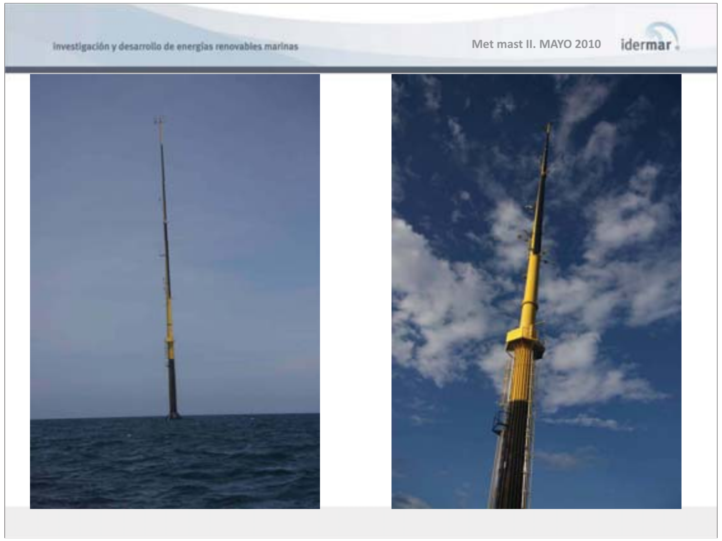
idermar



Investigación y desarrollo de energías renovables marinas

Met mast II. MAYO 2010

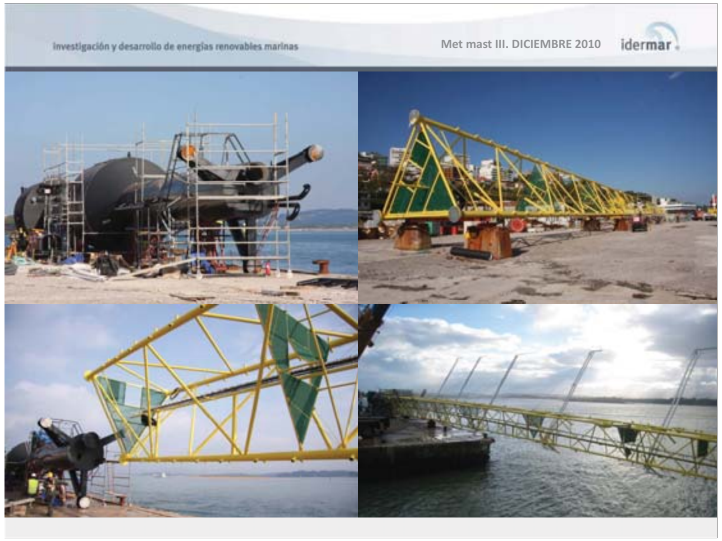
idermar



Investigación y desarrollo de energías renovables marinas

Met mast II. MAYO 2010

idermar



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Met mast III. DICIEMBRE 2010

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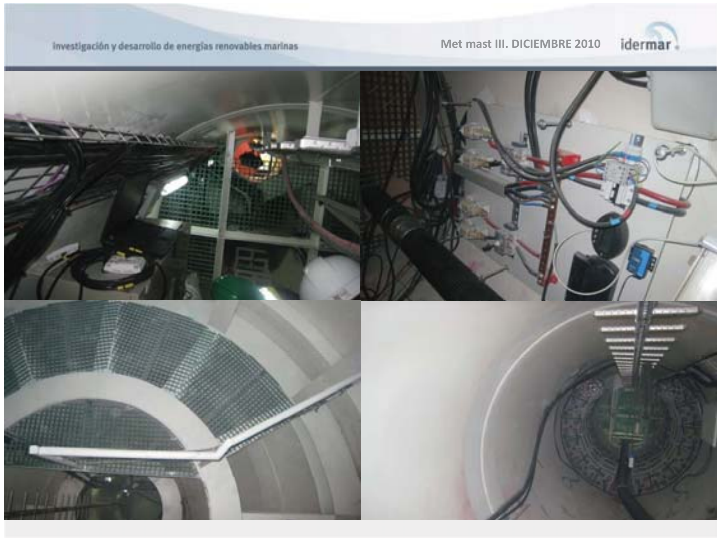

Investigación y desarrollo de energías renovables marinas

Met mast III. DICIEMBRE 2010

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Investigación y desarrollo de energías renovables marinas

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info@idermar.es

Poster presentations of PhD students on offshore wind

Name:	**Title of poster**
Van Buren, Eric, NTNU	Effects of foundation modeling methodology on the dynamic response of offshore wind turbine support structures
Frøyd, Lars, NTNU	Design and analysis of a 10 MW wind turbine
Merz, Karl, NTNU	Blade Design for Offshore Wind Turbines
Karimirad, Madjid, NTNU	Response Instabilities due to Servo-Induced Negative Damping for a Tension Leg Spar Wind Turbine
Zwick, Daniel, NTNU	Loads of Dynamics in Lattice Tower Support Structures for Offshore Wind Turbines
Gjerde, Sverre, NTNU	Integrated converter design with generator for weight reduction of offshore wind turbines
Netland, Øyvind, NTNU	Remote presence, Operation and Maintenance of Offshore Wind Farms without Leaving your Office
Liu, Bing, NTNU	Wind Turbine Power Performance Verification by Anemometer on the Nacelle
	Grid Integration of large Offshore Wind Energy and Oil & Gas Installations using VSC-HVDC
Nguyen, Trinh Hoang, University of Agder	Model-based operations and maintenance for offshore wind
Eliassen, Lene, University of Stavanger	Vortex Methods for Horizontal Axis Wind Turbines
Flügge, Martin, Reuder, Joachim University of Bergen	Atmospheric turbulence measurements close to the ocean surface
Kalvig, Siri, University of Stavanger	Improved energy forecast for offshore wind farms
Garcés Ruiz, Alejandro, NTNU	Series Connection of Offshore Wind Turbines
Aarnes, Ole Johan, University of Bergen:	Wave extremes in the Northeast Atlantic
Ramachandran, G.K.V., DTU:	Response of Tension Leg Configuration subjected to wave & aerodynamic thrust loading
Hameed, Zafar, NTNU:	Challenges in the Reliability and Maintainability Data Collection for Offshore Wind Turbine
Haileselassie, Temesgen, NTNU:	Control and Operation of Multiterminal HVDC for Market Integrated Offshore Wind Farms
Tasar, Gursu, NTNU:	Analysis of Atmospheric Boundary Layer of Frøya Test Site

EFFECT OF FOUNDATION MODELLING METHODOLOGY ON THE DYNAMIC RESPONSE OF OFFSHORE WIND TURBINE SUPPORT STRUCTURES

NTNU
Norwegian University of
Science and Technology
Department of Civil and Transport Engineering

PhD candidate: Eric Van Buren
Supervisor: Geir Moe

BACKGROUND

Offshore wind farms are currently much more costly than their land based counterparts, about 50 per cent more costly according to the EWEA. This cost discrepancy is due in large part to the increased size, complexity, and installation difficulties associated with the support structures at sea; typically costing 2.5 times more than the support structure for a comparable land based turbine. One of the most difficult and most costly aspects in the design and construction of offshore structures is the foundation – specifically the portion of the structure which interacts directly with the seabed.

In addition, because offshore wind turbines are highly dynamic systems, it is important to have a relatively accurate prediction of the dynamic properties of the full wind turbine structure, including the foundation and the interaction between it and the soil. In order to achieve this, the structural model of the system must include provisions for the characteristics of the foundation in some form or fashion.

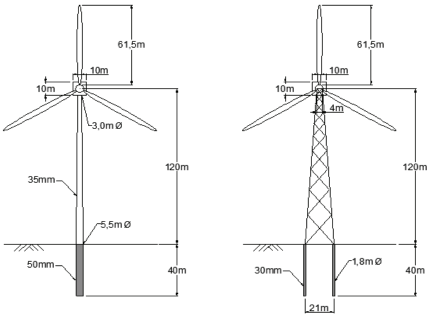
OBJECTIVES

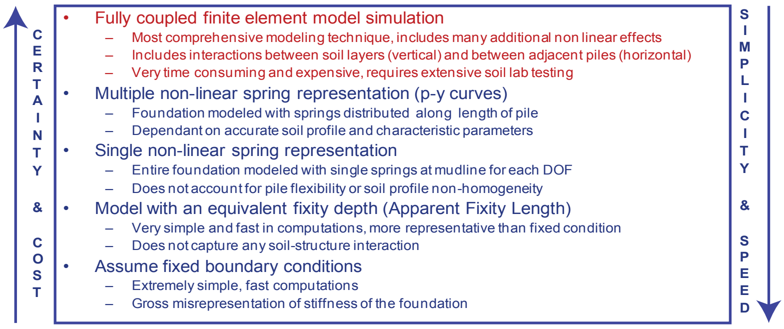
The goal of the current project is to develop improved methods for modeling offshore wind turbine foundations with an aim to decrease the level of uncertainty in foundation design. By improving the level of confidence in pile design, many of the piles may be optimized for the given soil and load conditions, reducing the size and thus leading to shorter installation times and lower costs.

It is believed that current foundation modeling techniques underestimate the amount of damping provided by the foundation. While this was of little importance to the mostly static oil platforms in the past, increased damping in a highly dynamic system such as a wind turbine could greatly influence the overall design of the system, particularly the support structure.

EXPERIMENTAL SETUP

In the current project, piled foundations for both a full-height lattice tower, as well as a monotower, are investigated. These structures can be seen below in Figure 1.
Additionally, several different modeling techniques are used, greatly ranging in complexity and detail, as shown in Figure 2.





- Fully coupled finite element model simulation
  - Most comprehensive modeling technique, includes many additional non linear effects
  - Includes interactions between soil layers (vertical) and between adjacent piles (horizontal)
  - Very time consuming and expensive, requires extensive soil lab testing
- Multiple non-linear spring representation (p-y curves)
  - Foundation modeled with springs distributed along length of pile
  - Dependant on accurate soil profile and characteristic parameters
- Single non-linear spring representation
  - Entire foundation modeled with single springs at mudline for each DOF
  - Does not account for pile flexibility or soil profile non-homogeneity
- Model with an equivalent fixity depth (Apparent Fixity Length)
  - Very simple and fast in computations, more representative than fixed condition
  - Does not capture any soil-structure interaction
- Assume fixed boundary conditions
  - Extremely simple, fast computations
  - Gross misrepresentation of stiffness of the foundation

Figure 2: Foundation Modelling Techniques

Uncoupled Models

- Implemented and Compared using Existing Software (HAWC2, GH Bladed)
- Results compared against field data (RAVE)

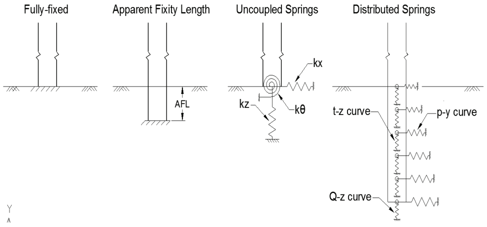


Figure 3: Uncoupled Foundation Models

Coupled FE Model

- Developed using open source FEM foundation code (OpenSees, Code Aster)
- Fully Coupled with Aero-Servo-Hydro-Elastic code (FAST, FLEX5, ADAMS, etc.)

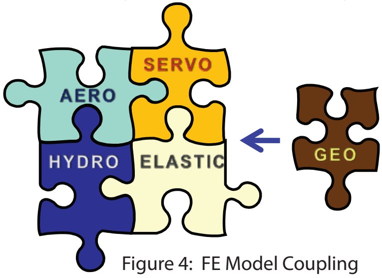


Figure 4: FE Model Coupling

SEQUENTIAL ANALYSIS

As an intermediate step between the uncoupled methods and a fully coupled FE analysis, a so-called sequential analysis can be performed. In this process, the preliminary foundation stiffness is determined with a static FE analysis, and used in a numerical simulation containing multiple non-linear spring representation. This analysis will give time series force data at the pile heads which can then be used in a dynamic finite element analysis. This process can be repeated several times in effort to converge on specific stiffness

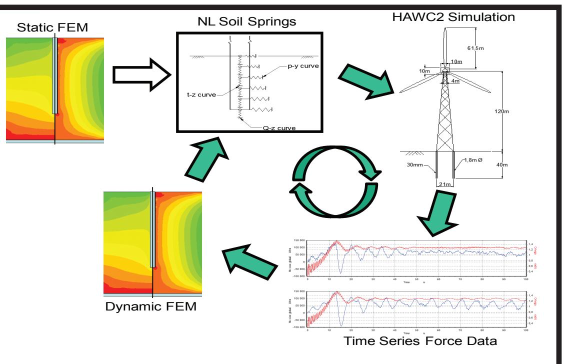


Figure 5: Sequential Analysis Process

CURRENT WORK

Work is currently being done on the sequential analysis in effort to determine proper stiffness and damping parameters for a piled foundation on both a monotwoer and lattice tower structure in layered soil. The NREL 5MW offshore reference turbine is being used to allow for easier comparisons with other works.

Several different soil profiles are being utilized, including profiles from the North-Sea, Gulf of Mexico and the U.S. Atlantic coast. These are all potential future sites for offshore wind turbines.

FUTURE WORK

Following the sequential analysis process, efforts will be made to develop a fully coupled analysis software which contains aero-servo-hydro-elastic and geotechnical processes. This will allow for a much closer look at the dynamic process taking place in the soil and at the soil-pile interface during power production.

This tool will allow a much closer look at the damping provided to the system by the soil-structure interaction, possibly saving material and installation costs.

Design and analysis of a 10 MW wind turbine

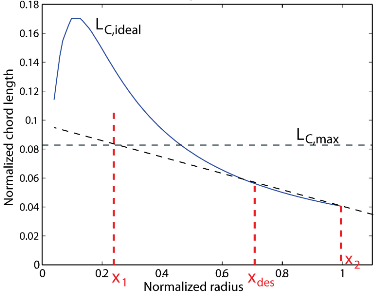
- A brief summary of the status and recent progress

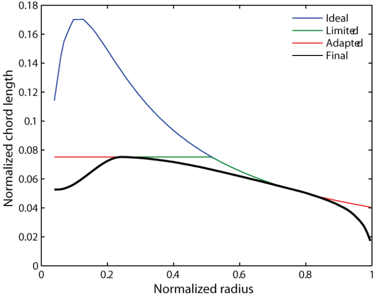
Lars Frøyd, PhD candidate, NTNU

1. Aerodynamic design method

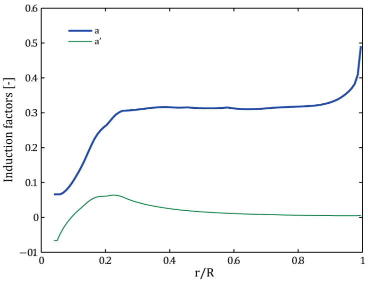
A method for aerodynamic design has been developed based on blade element momentum (BEM) theory such that a realistic wind turbine blade can be designed with a minimum of parameters [1]:

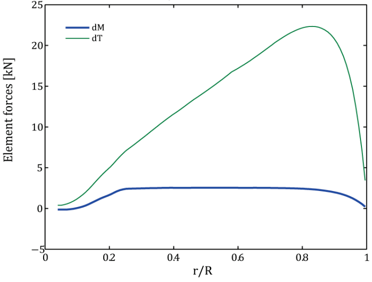
- Thickness to chord ratio along the blade
- A list of airfoils for the range of thicknesses + C_L and C_D data
- The design point x_{des} where the aerodynamics are optimized
- The design point x_1 which is the point of maximum chord length


Chord design definitions


Final chord length of blade

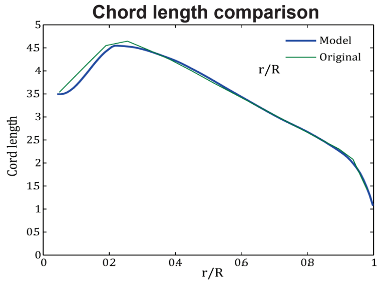
Based on these data a normalized blade geometry is created and scaled to the relevant rated power and rated wind speed. The tip chord length and the twist angle distribution are optimized to yield an ideal distribution of aerodynamic induction and aerodynamic forces:

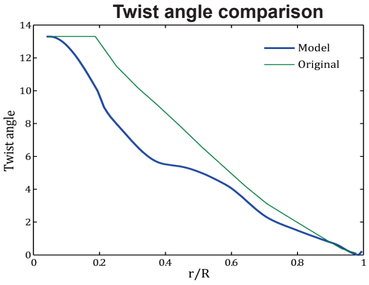

Induction factors


Aerodynamic forces

2. Validation of the design method

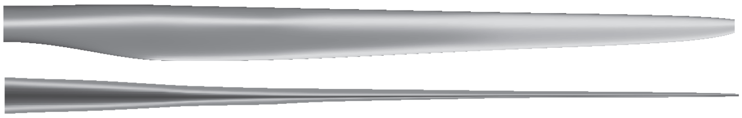
The design is compared to the *NREL 5MW Offshore Baseline* design with the same airfoil distribution. The result shows that the method is suitable for design of large wind turbine blades.


Chord length comparison


Twist angle comparison

3. Aerodynamic design of 10 MW rotor

Using the developed method with a design power of 10 MW, rated wind speed 13 m/s and design tip speed ratio of 7.3, a baseline design is created with a rotor diameter of 144.5 m and C_P = 0.49.

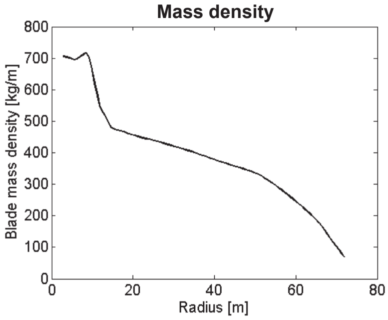


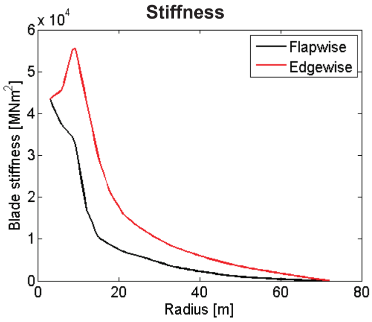
The blade is designed especially for large rotors, with a high aspect ratio to reduce aerodynamic loads at standstill and a long, smoothly changing root section to improve buckling stability.

The design choices made above will later be subject to a parameter study to investigate how the baseline design can be improved.

4. Structural design of the blades

Based on structural design definitions for the blade spar from [2] and [3], and structural definitions of a blade shell from [4], the cross-sectional properties of the blade have been chosen as a first design.

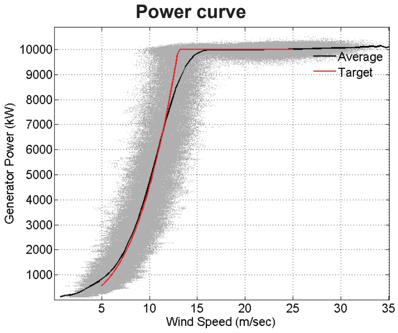

Mass density

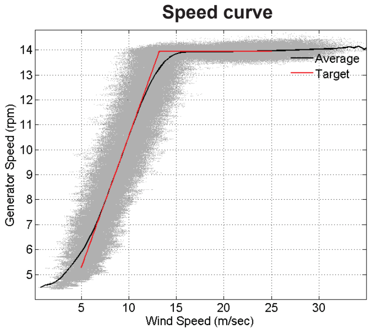

Stiffness

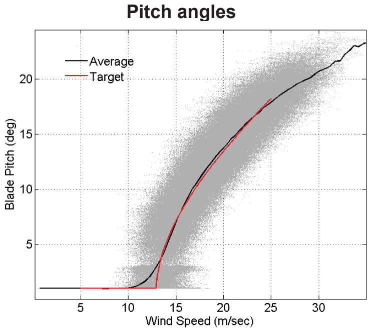
This gives a blade mass of 27 tons, which is comparable to the *LM 61.5* blade of 18 tons.

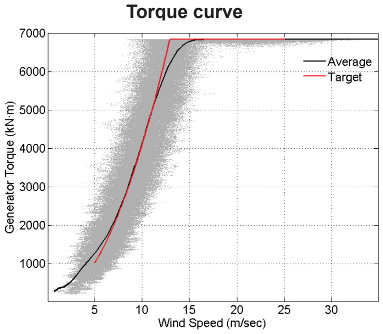
5. Aeroelastic analysis of 10 MW rotor

Based on the method for pitch gain scheduling in [3] a method was created to automatically design a control system for any given turbine design in Simulink. Using the aeroelastic code FAST with Simulink, the 10 MW wind turbine was simulated. The results show that the variable speed, variable pitch control strategy very efficiently limits the loads above rated speed and yields especially good torque response.


Power curve


Speed curve


Pitch angles


Torque curve

6. Further work

- Improved structural design and thorough analyses (buckling/flutter)
- More complete definitions of the baseline 10 MW turbine properties
- Simulation of the 10 MW wind turbine on a floating platform.
- Parametric study of rotor parameters and platform parameters to investigate the design basis for floating wind turbines with respect to fatigue damage.

References

[1] Frøyd, L. & Haugset, S.K., 2010. *Analysis and Design of Wind Turbine Blades for Horizontal Axis Wind Turbines Using Blade Element Momentum Theory*, NTNU.

[2] Höyland, J., 2009. Challenges for large wind turbine blades. Doctoral thesis. NTNU.

[3] Hansen, M.O.L., 2008. Aerodynamics of Wind Turbines, Second Edition, Earthscan Publications.

[4] TPI Composites, 2002. Parametric Study For Large Wind Turbine Blades: WindPACT Blade System Design Studies., Sandia National Laboratories

Statkraft Ocean Energy Research Program

Statkraft

NTNU
Norwegian University of Science and Technology

UPPSALA UNIVERSITET

DTU Mechanical Engineering
Department of Mechanical Engineering

Conceptual Design of Stall-Regulated Rotors for Offshore Wind Turbines

Karl Merz, Department of Civil and Transport Engineering, NTNU; karl.merz@ntnu.no

January 20, 2011

1. Introduction

Deepwater offshore wind turbines are more expensive than their land-based counterparts, for three unavoidable reasons: the support structure is more elaborate; marine operations (including installation and maintenance) are costly and require a favorable weather window; and the electricity must be transmitted over long distances. Minimizing the overall system cost may require configurations that are different from what has become the standard onshore turbine: three-bladed, upwind, pitch-regulated.

It is proposed that passive stall regulation should be revived as a possibility for large offshore wind turbines. The reason is the simplicity of the mechanical systems: the simplest stall-regulated, direct-drive (no gearbox) turbine has only one primary moving part: the aerodynamic rotor / driveshaft / generator rotor. A brake system and yaw drive are also needed, but they are actuated infrequently. Perhaps this simplicity could be leveraged to reduce -- or, optimistically, eliminate -- maintenance requirements and downtime.

The operating characteristics of the rotor influence the design of the support structure to a greater extent than the support structure influences the blade design. Thus it seems that the appropriate place to begin conceptual design is the rotor: what does a stall-regulated rotor look like, which is adapted for operation offshore?

A literature review provided examples of optimization methods that can be employed in blade design: References [1] through [4], for instance. However, there are few examples describing what an optimum stall-regulated blade looks like: how does it behave? Why is it optimal? The work of Fuglsang and colleagues ([5], and related publications) is an exception, although even here the discussion of design principles is brief.

The design of a stall-regulated blade involves a balance between the competing goals of maximizing energy capture, while minimizing loads (including blade weight) on the support structure. The conceptual design process requires fast and simple methods for generating, evaluating, and understanding this tradeoff for various blade designs. Frequency-domain analysis is ideal for this purpose, because it is orders of magnitude faster than time-domain analysis, and it can be understood in terms of superposition.

2. Frequency-Domain Analysis

Frequency-domain analysis methods were developed to predict the dynamic behavior of a stall-regulated blade. Two additions were made to textbook methods [6]: the component of turbulence in the plane of the rotor was included, along with the axial component; and dynamic stall was modelled.

Frequency-domain methods are by nature linear, whereas stalled-flow aerodynamics is nonlinear. Therefore, the aerodynamic equations must be linearized. This involves finding the change in lift coefficient for a given change in angle-of-attack, $\gamma = dC_L/d\alpha$. This lift coefficient slope should be chosen such that it accounts for flow separation. The slope may be a function of frequency, since the total response of the blade is calculated as the sum of the responses at individual frequencies.

Flow separation can be modelled as a first-order time-lag, of the form:

$$\frac{d\alpha_f}{dt} = \frac{\alpha - \alpha_f}{\tau}$$

This time-lag is related to movement of the chordwise position of the separation-point along the low-pressure surface of the airfoil. It is further assumed that a linearized lift coefficient can be calculated as:

$$C_L = \gamma_{\max}\left(\alpha - \alpha_f\right) + \gamma_q\left(\alpha_f - \alpha_0\right)$$

It is proposed that, for calculating blade excitation, it is appropriate to capture the entire range of the lift coefficient, for a given range of angle-of-attack. This is shown in Figure 1. For damping, the energy dissipated over a cycle of oscillation should be matched. This leads to:

$$\gamma_{in} = \gamma_{\max} + \left(\gamma_q - \gamma_{\max}\right)\left(\frac{1}{1+(\tau\omega)^2}\right)$$

and:

$$\gamma_{out} = \left(\gamma_{\max} - \gamma_q\right)\left(\frac{\tau\omega}{1+(\tau\omega)^2}\right)$$

such that for excitation, $\gamma_e = \sqrt{\gamma_{in}^2 + \gamma_{out}^2}$, while for damping, $\gamma_d = \gamma_{in}$.

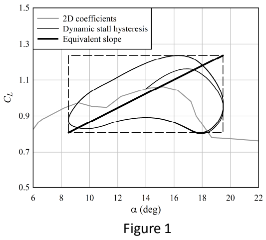


Figure 1

The result is a set of equivalent slopes, an example of which is shown in Figure 2. Figure 3 compares root bending moment spectra obtained using this dynamic stall method against test data and the results of several aeroelastic codes. [7]

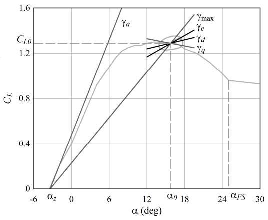


Figure 2

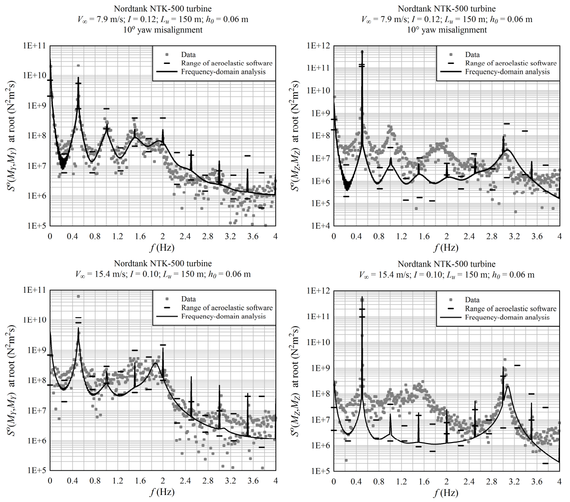


Figure 3

3. Airfoil Model

An airfoil model was developed, based on a survey of published coefficient data, which allows numerically smooth interpolation between a range of airfoil behaviors. Particular attention was paid to the way in which drag increases as the lift coefficient peaks and drops; this drag behavior has an. important influence on the behavior of a stall-regulated turbine. Figure 4 shows an example of the model, in comparison with data.

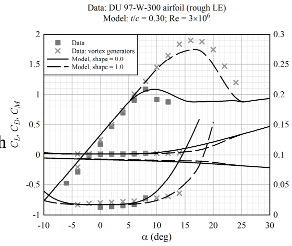


Figure 4

4. Strength Checks

Material stiffness and strength properties, including Goodman diagrams for fatigue, were obtained from Griffin [8]. Fiberglass and carbon-fiber were candidates for the spar material. The outer shell is a fiberglass sandwich construction.

Strength checks were performed in order to size the spar caps. The thickness of the webs was assumed to be proportional to the spar cap thickness.

Local stress spectra were calculated at 12 sections along the length of the blade, at 6 points around each cross-section. From these stress spectra, fatigue cycle counts were obtained by the Dirlik method. In addition, a spectral method (described by Burton et al. [6]) was used to estimate the peak stress.

The fatigue analysis was performed at windspeeds of 5, 7, ..., 23, and 25 m/s. The peak stress analysis was performed using a stochastic dynamic response based upon windspeeds of 25 m/s (operating) and 50 m/s (shut down), with mean stresses calculated using 40 m/s and 70 m/s, respectively, in order to account for the effect of a gust.

Load factors were calculated for tension and compression fracture, buckling, fatigue, maximum tip deflection (limited to 0.1R), and flutter.

5. Optimization

A constrained, gradient-based optimization algorithm, similar to that of Fuglsang and Madsen [9], was used to obtain the optimum blade designs. The method uses sequential linear programming inside the feasible domain, and the method of feasible directions to move away from a constraint boundary.

Constraints are implemented such that the load factors do not exceed 1.0 (indicating failure). Constraints are also implemented to ensure a minimum damping of 0.004 (though preferably much higher) at windspeeds up to 40 m/s; this ensures that blade vibration is stable during gusts, when the turbine is operating in the vicinity of the cut-out windspeed.

Design variables were material thickness, airfoil properties, chord, twist, and t/c ratio at 12 points along the blade.

The cost function is cost-of-energy, not including operation and maintenance, representative of a floating wind turbine. The cost is calculated as the sum of independent component costs, which are assumed to vary with governing loads from the rotor.

6. Results

A unique (to the author's knowledge) type of blade results from the optimization. Figure 5 shows the chord and twist profiles, compared with the NREL 5 MW reference turbine (which is pitch-regulated). First, note that the optimum rated power in the North Sea wind climate (about 9 m/s average windspeed at hub height) is much higher, for a given swept area, than a standard rotor. This follows from the fact that half the total annual energy in the wind is contained at windspeeds over 17 m/s, and it is beneficial to capture some of this "extra" energy.

The discontinuous twist profile near the tip is not an artifact of the optimization; it provides very favorable dynamic properties beyond the rated windspeed, when the blades are in various degrees of stall. Figure 6 shows the mean angle-of-attack, as a ratio to the angle-of-attack at maximum lift; a value of 1 thus represents the point at which stall begins to dominate the airfoil forces. The "back-twist" near the tip, combined with the relatively high-lift airfoil at this location, means that flow stays attached, over a few meters of the blade length, through the cut-out windspeed. Attached flow provides a large amount of damping; thus this blade design has aerodynamic damping that is higher than a typical stall-regulated blade. This region of the blade also produces a large amount of power, which is counteracted by drag over other parts of the blade, such that the total power remains within limits. The stall behavior of the blade is better than normal; the rotational speed needs to vary only a small amount in order to hold power constant at high windspeeds.

The family of blades shown in Figure 5 is recommended for further study, and comparison against pitch-regulated blades. One concern is that the blade element method, used to predict the aerodynamic loads, is not theoretically valid when flow is stalled. It is questionable whether the aerodynamic properties of the attached-flow section of the blade would stay the same when the adjacent sections of the blade stalled. This behavior could be investigated with wind-tunnel measurements or CFD analysis.

Another interesting feature of the blades is that the inner 4/5 of the blade length has t/c ≥ 0.30 (typically right at 0.30). Modern airfoils perform well aerodynamically up to this t/c.

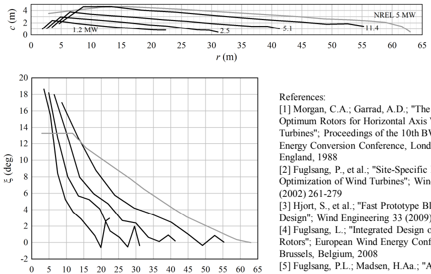


Figure 5

References:
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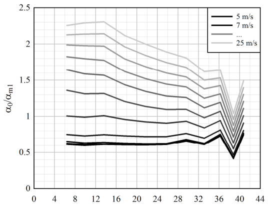


Figure 6

Response Instabilities due to Servo-induced Negative Damping for Floating Wind Turbines

Madjid Karimirad, CeSOS and NOWITECH
Torgeir Moan, CeSOS and NOWITECH

Abstract

The blade pitch control of an operating turbine can introduce negative damping in a floating wind turbine. For example, if the relative wind speed experienced by the blades increases due to the rigid body motion of the system, then, if a conventional controller is used, the blades will feather to maintain the rated electrical power. Thus, the thrust force will decrease, which will introduce negative damping for over-rated wind speed load cases. However, in fixed wind turbines since the frequency of the blade pitch controller is normally less than the frequencies associated with the relative rotor motions induced by the structural responses. In this paper, a tension leg spar (TLS) wind turbine is introduced as a support structure for a wind turbine in deep water with a downwind rotor configuration. A dynamic response analysis of the TLS is performed for simultaneous wave and wind loading. These analyses are based on an integrated time domain aero-hydro-servo-elastic simulations. The wave-induced and wind-wave-induced responses of both parked and operating wind turbines are compared to investigate the control-induced negative damping effect. The correlation of wave and mean wind velocity is considered to define the environmental conditions for below-rated, rated and over-rated wind speeds. The HAWC2 code (version 8.5) with a collective blade pitch controller is used to perform the analysis. It is found that the wave frequency responses of the wave-wind-induced cases are not affected by aerodynamics or the controller actions. In the over-rated wind speed case, the negative damping caused by the controller excites the pitch resonant motion. This extraordinary pitch resonant response governs the power production and other responses, such as the nacelle surge, bending moment and tension responses. It is necessary to avoid the servo-induced negative damping to get an adequate fatigue life. In this paper, the controller gains are modified to reduce the instabilities caused by the servo negative damping. When the tuned controller was applied, the pitch resonant motion was reduced and the power production was improved compared with when the untuned controller was used. The ratio between the standard deviation of the electrical power generated when the untuned and tuned controller is applied for an over-rated wind speed case is 8.1. The similarly defined ratio for the nacelle surge motion, the bending moment at the tower-spar interface and the bending moment at the blade root is 14.5, 4.4 and 2.7, respectively. These results show that negative damping adversely affects the performance and structural integrity of a floating wind turbine. Furthermore, the fatigue limit state is highly influenced by the negative damping.

Model

Tension Leg Spar Floating Wind Turbine

Floating wind turbine properties

Wind turbine	5-MW downwind
No. of blades	3
Blade length	61.5 m
Hub height	90 m
Controller	Collective blade pitch
Rated wind speed	11.2 m/sec
Draft	120 m
Diameter above taper	6.5 m
Diameter below taper	9.4 m
Centre of buoyancy	-62 m
Displacement	8126 m^3
Total mass	7682E+03 kg
Centre of gravity (CG)	-80 m
Pitch/Roll inertia about CG	2.18E+10 $kg.m^2$
Yaw inertia about centreline	1.215E+08 $kg.m^2$
Leg length	Up to 200 m
Leg diameter	1.0 m
Leg thickness	0.036 m
Pretension	7.624 MN

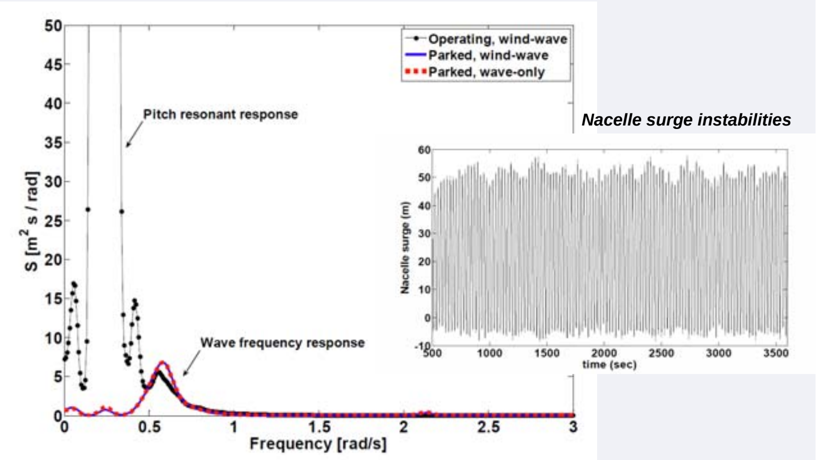
Natural frequencies

Surge/Sway	0.05
Heave	3.69
Pitch/Roll	0.20

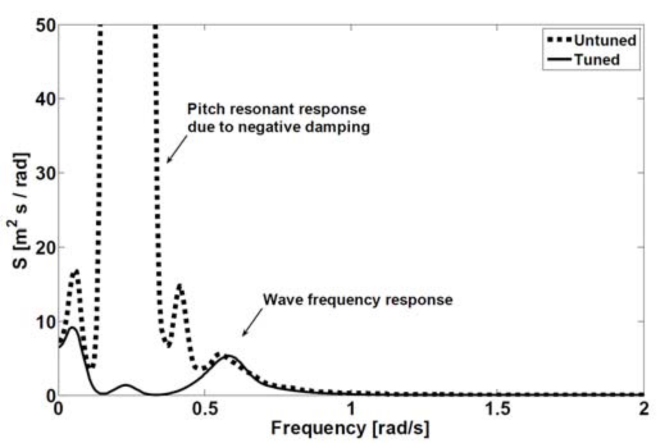
Changes applied to the NREL wind turbine

Parameter	Upwind	Downwind
Rotor position	In front of tower	Behind the tower
Shaft upward tilt	5.0 (deg)	0.0 (deg)
Hub upwind cone	2.5 (deg)	0.0 (deg)

Results



Nacelle surge spectra for responses induced by the wave-only and wind and waves for the operating and parked rotors in the over-rated constant wind condition



Nacelle surge spectra, with the untuned and tuned controller in the over-rated constant wind condition

Conclusions

The blade pitch control of an operating turbine can introduce response instabilities in a floating wind turbine. By tuning the controller gains, negative damping can be eliminated. In this study, the controller is tuned to have a natural frequency less than the TLS pitch natural frequency. The comparison of the tuned and untuned controller showed that using a constant torque algorithm and tuning them controller gains helps to decrease the resonant responses and improves the power production for the over-rated wind speed cases. At the rated wind speed, the response is governed by the surge resonance, and the tuning effect is less effective. However, for the over-rated wind speed region, because the response is governed by the pitch resonance, tuning is effective at eliminating the negative damping. Comparing the statistical characteristics of the responses for the tuned and untuned controller for the wind turbine subjected to the wave and wind loads at the over-rated wind speed case showed that the standard deviation (dynamic part) of the nacelle surge motion, tension, bending moment and electrical generated power decreased due to the removed negative damping. The ratio between the standard deviation of the power for the untuned and tuned controller for the over-rated wind speed case is 8.1. For the nacelle surge motion, the ratio of the standard deviation applying the untuned and tuned controllers reaches 14.5. The ratios between the standard deviation of the bending moment at the tower-spar interface and at the blade root are 4.4 and 2.7, respectively, which means that the negative damping adversely affects the performance and structural integrity of the floating wind turbine. Reducing the standard deviation of the responses will increase the fatigue life of the system. The effect of the turbulence and fatigue life will be discussed in the future research.

Reference

Karimirad M. and Moan T., "**Ameliorating the Negative Damping in the Dynamic Responses of a Tension Leg Spar-Type Support Structure with a Downwind Turbine**", Accepted for publication and oral presentation at the European Wind Energy Conference (EWEC2011), March 2011, Belgium

LOADS AND DYNAMICS IN LATTICE TOWER SUPPORT STRUCTURES FOR OFFSHORE WIND TURBINES

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Supervisor: Geir Moe

Department of Civil and Transport Engineering

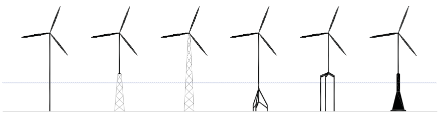
BACKGROUND

The extremely ambitious political goals concerning extensive use of offshore wind energy result in an intense demand of research and development in this field. As an example, round 3 in UK could mean a need to install several thousands of offshore wind turbines within the next ten years. To be able to fulfil this goal, components for offshore wind farms has to be produced by mass production techniques and within reasonably short fabrication time.

New node concepts might be of interest for more automated production of lattice towers. As a basis for such an investigation, loading and dynamic response by focusing on design of the nodes has been analysed with HAWC2 in this study.

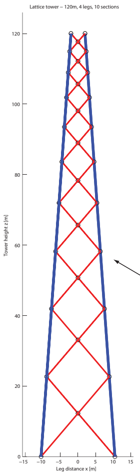
SUPPORT STRUCTURE CONCEPTS

Where offshore wind turbines are planned to be installed in the intermediate water depths of 30-70m, bottom-fixed support structures might be used. One promising concept is the lattice tower type, due to less material use compared to other concepts like monopile or tripod structures. A lattice topology could be used for the entire support structure between sea bottom and turbine nacelle or for the lower part of the tower only.

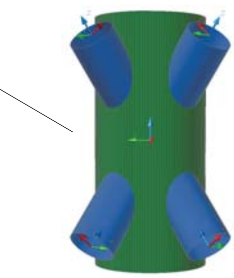


Bottom-fixed support structure concepts for the intermediate water depth of 30-40m

LATTICE TOWERS



Lattice towers are assembled from steel tubes, where legs and bracings are welded together in tubular joints. Legs and bracings are connected in K-joints, while bracings in the planes between the legs are connected in X-joints.

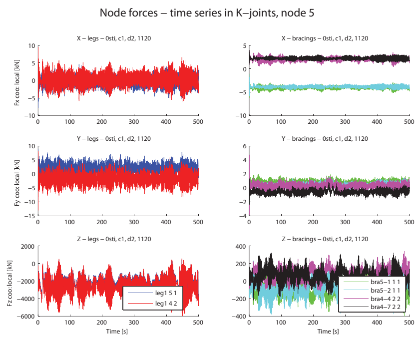


Joint geometry of nodes in lattice towers

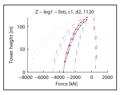
NODE ANALYSIS WITH HAWC2

A lattice tower support structure with 84 beam elements was modelled and analysed with HAWC2. Wind turbine and rotor configuration were taken from the NREL 5MW baseline turbine.

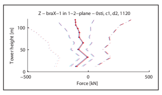
NODE ELEMENT FORCES



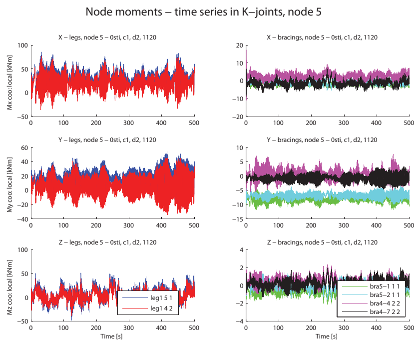
Results from HAWC2 are obtained in time domain. The figure to the left shows an analysis of a complete K-joint in one leg at a specific node. The distribution of mean forces in one leg over the tower height is shown to the right, with standard deviation and min/max range. Absolute forces in z-direction are decreasing towards the tower top.



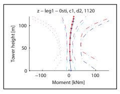
Mean forces in the bracing X-joints are more or less stable over the tower height, but standard deviation and min/max range are increasing towards the tower top.



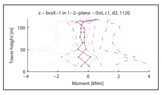
NODE ELEMENT MOMENTS



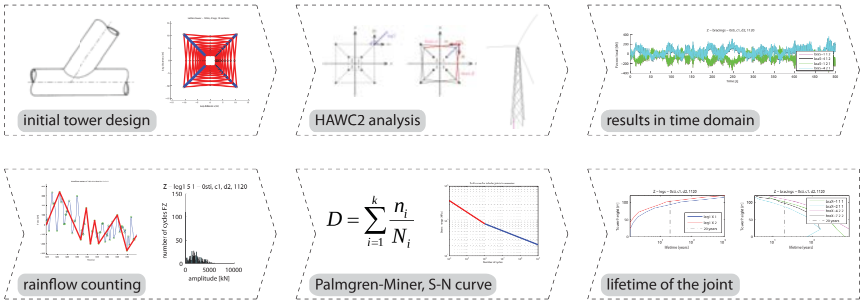
From the same analysis, results for all member moments were extracted. Mean values over the tower height were found to be close to zero in the legs. However, the range of min/max values is increasing strongly towards the tower top. Moments in the highest tower nodes are dependent on the connection design of tower and nacelle.



For the bracing members in X-joints, only small moments were found, varying around a zero mean. Bracing members are mainly loaded by axial forces.



FATIGUE ANALYSIS



$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

MEMBER DIMENSIONS

The initial tower design of this study was analysed with constant leg and bracing dimensions over the tower height. As expected, results from the fatigue analysis show that dimensions for the legs has to be increased towards sea bottom, while bracing dimensions hast to be increased towards tower top. First calculations were based on a traditional node design with circular members intersecting each other. The shown load results will be used for the futher analysis of new node designs, suitable for mass production of lattice towers.

OBJECTIVES

New node concepts for lattice towers will be developed for the following purposes:

- lower total production costs
- faster production, towards mass production
- more automated production
- more reliable welding results
- prefabrication of components

If the complex fabrication of lattice towers can be solved in an effective way, this type might be a preferred solution for support structures in the future.

Integrated Converter Design with Generator for Weight Reduction of Offshore Wind Turbines

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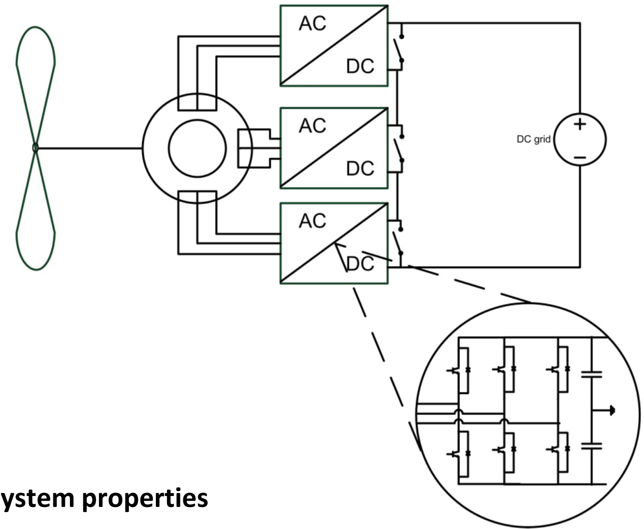
***Motivation:* The expected increase in size of future offshore wind turbines poses new challenges to the electric drive. Due to the increased power, transformation to distribution level voltage (medium voltage) in the nacelle becomes necessary. However, the introduction of a 50 Hz transformer adds significantly to the top weight.**

Therefore, this work aims to propose and investigate a power electronic converter solution which, together with a special generator design, can provide medium voltage without the transformer for large scale (10 MW) wind turbines.

Additionally, the project will follow up recent trends in research, by designing for a DC-collection grid within the offshore wind farm.

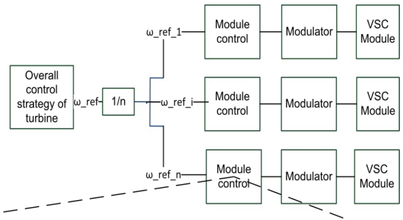


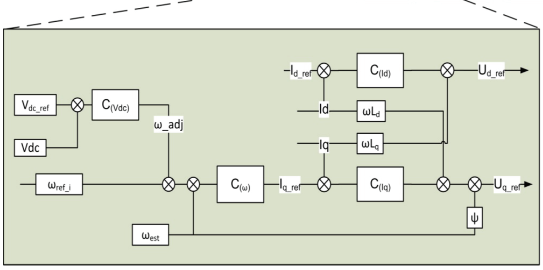
System properties

- Generator with *N* isolated three-phase winding groups
- Each group - connected to AC/DC-converter module
- Converter module - Voltage source converter
- Crowbars for bypassing defect groups
- Weak coupling between phases
- DC-output of modules series connected => Build up output voltage
- Medium voltage DC-collection grid

Proposed control system

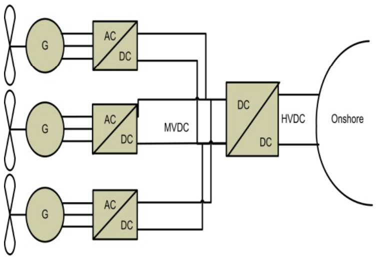
- Each module controlled separately
- Speed reference from overall strategy
- DC-bus balancing in each module





Advantages of converter system

- Modular structure in generator and converter
  ->redundancy
- VSC module can be changed – optimize for voltage levels and harmonic content
- Medium voltage output with no transformer
- Reduced capacitive energy storage



DC-grid

- One conversion step less compared with AC-collection grid
  ⇒Increased efficiency
  ⇒Reduced converter cost

Challenges – focus of work

- Balancing the DC-bus of each converter module
- Control under asymmetric operation
- Operation in a DC-grid – overall control strategy
- Impact of short circuit on the DC-side

Remote presence, Operation and Maintenance of Offshore Wind Farms Without Leaving Your Office

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Introduction

There are large areas with good wind conditions available for offshore wind farms, but they are unfortunately more expensive than wind farms on land. Operation and maintenance is one of the reasons for this, and it is estimated that O&M will contribute to 25%-30% of the total energy cost of offshore wind energy.

Reasons for the high costs are:

- Transporting personnel is expensive and time consuming, contributing to offshore operations costing 5-10 times more than operations on land.
- Equipment for heavy lifting is at least 10 times as expensive as on land.
- Offshore wind turbines are inaccessible in harsh weather.

To make offshore wind energy economically viable, technology to make it less expensive is required. The focus of our work is how **`Remote Presence`** can be used to reduce the number of expensive and time consuming maintenance visits, reducing the O&M cost.

Remote Presence

Remote presence lets a user feel he is present at a remote location, meaning he can sense, move around in and interact with the environment there. This makes working there possible, even without travelling.

For sensing the remote location, sensors that mimic the user's senses is used:

- Camera for vision.
- Microphones for hearing.
- Gas/smoke detectors for smell.
- Temperature sensor for feeling heat.
- Vibration sensor.

Sensors can be placed on a mobile robot that acts on the behalf of the user at the remote location. The user can interact with the remote environment by controlling tools on the robot.

A completely realistic feeling of being at a remote location will be impossible to create without technology from science fiction movies like "Avatar "(as illustrated in figure 1).

A completely realistic experience is however not necessary, a limited system that are tailored to its specific task can be more effective and easier to use. Such systems could be beneficial in many applications where work has to be done at a location that is difficult to access or dangerous. On this poster the application in offshore wind energy is discussed.

Remote Presence for Offshore Wind

The purpose of remote presence for offshore wind farms is to make it possible to do work onboard a wind turbine from land, reducing the need for expensive and time consuming transportation.

Examples of O&M tasks possible with remote presence are:

- Routine inspections.
- Planning maintenance operations.
- Confirming diagnosis from condition monitoring systems.
- Capture images for visual diagnostic
- Cleaning and lubrication.
- Preventive maintenance operations.

Figure 1: Illustration of remote presence inspired by Avatar

System Design

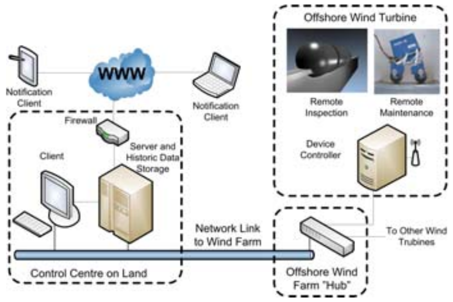

Figure 2: System design

In our design of a remote presence system there are two devices inside the nacelle of a wind turbine:

- **`Remote Inspection Device`** is a semi-mobile sensor platform moving on a rail installed in the roof and walls of the nacelle.
- **`Remote Maintenance Robot`** is fully mobile robot equipped with tools for doing maintenance tasks.

These devices are controlled by a **`Device Controller`**, either autonomously or based on commands from a technician on land using a **`Client`**. The different parts of the system and their interactions are described in figure 2.

Future Plans for Remote Maintenance

For the future we plan to extend the system to also be able to do maintenance tasks remotely. For such tasks, proximity to the part being maintained is important, which is not possible with the limited mobility of the remote inspection device.

The following abilities will be necessary for a remote maintenance robot:

- Able to move freely.
- Ability to climb over obstacles and on walls.
- Be equipped with tools to do maintenance tasks.
- Local intelligence to avoid situations that are potentially dangerous for the robot or the wind turbine.
- Local intelligence to react to unforeseen events.

Prototype

Figure 3: Remote inspection device

We have created a prototype of the remote inspection device, as seen in figure 3, to be used for further developments and to test the capabilities of such a system. A short demonstration rail have also be created for the device to move on. Figure 4 shows the prototype and the rail.

Some properties of the prototype:

- Able to know its position on the rail.
- Rack and pinion movement to avoid "spin"and make it easier to move vertically.
- Modular design, making it possible to give the device different abilities.
- Dual-rail solution for a stable platform able to carry heavy loads and operating robotic arms.
- Power supply through the rail, avoiding heavy and expensive batteries.

Figure 4: Prototype on rail

Conclusions

Advantages using a remote presence system for O&M of offshore wind turbines:

- Preparing a remote operation takes seconds, while it can take days or even weeks to prepare an offshore operation.
- Experienced technicians can use their skills effectively, instead of wasting it in transit.
- Possible to do frequent routine inspection and maintenance, since remote operations are quick and inexpensive.
- Co-operation with condition monitoring system to increase its accuracy.
- Remote operations are possible even in harsh weather.
- Planning of larger operations that are not possible to do remotely.

Acknowledgements

This work has been funded by Norwegian Research Centre for Offshore Wind Technology (NOWITECH).

I would also like to thank Norsk Automatisering AS for funding of prototype building, Viktor Fidje for having the main responsibility for building the prototype, and the master student Tor Mæhlum Karlsen for helping with research and software development.

Wind Turbine Power Performance Verification by Anemometer on the Nacelle

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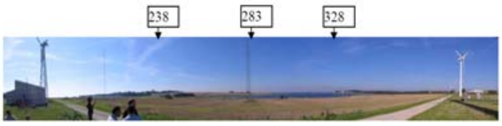
Introduction:

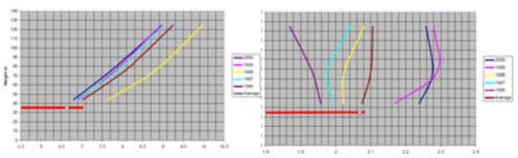
The power curve verification is important for both power output optimization and contractual promising check for wind energy producers. However, the traditional power curve verification by IEC61400-12A is costly and time consuming due to the meteorological metmast tower installation on test sites. The newly published IEC61400-12**B** gives the possibility of verifying the power curve and AEP (Annual Energy Production) by the existing anemometers on the wind turbine nacelle. The purpose of this project is to investigate how is the validation of power performance method by IEC61400-12B under different weather conditions (wind shear / temperature / Turbulence intensity / wind direction variation) and different types of terrain (Complex or flat terrain at site).

The 5 cup anemometer types for performance evaluation.

Test Turbine and Test Site :

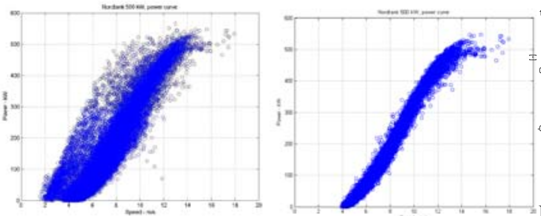


Determine free, undisturbed sectors. Surrounding landscape, terrain, obstacles influence power production.

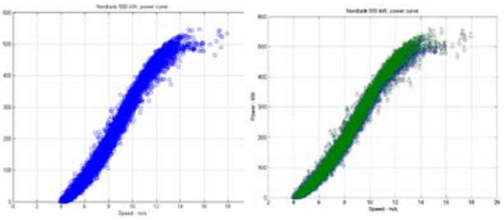


A=6.7 K =2.07

Unvalid Wind Direction Data Elimination.



Discard data where anemometer is within WT downstream sector. Discard data affected by obstacles. Manually discard wrong data due to abnormal WT operation or measurement system errors.



$$t2 = t + 273.15$$

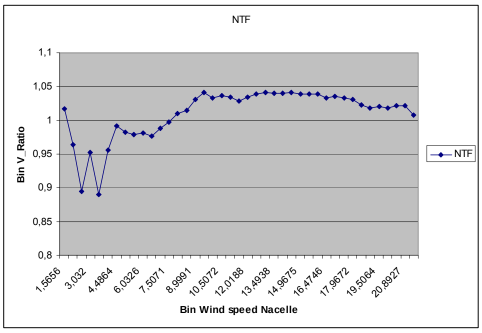
$$\rho = 1.225\left(\frac{288.5}{t2}\right)\left(\frac{p}{1013.3}\right)$$

$$P2 = P\left(\frac{1.225}{\rho}\right)$$

P2 = Power corrected to standard conditions (15°C, 1013 mBar)
P = Uncorrected (measured) power
ρ = Test air density
t2 = Air temperature, degrees Kelvin
t2 = t + 273.15, where
t = air temperature (measured) in degrees C
p = Barometric pressure (measured), mbar

Nacelle Transfer Function (NTF)

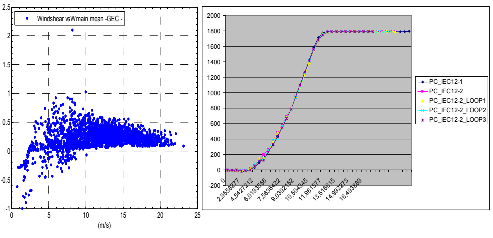
The NTF is the relationship between the measured wind speed on nacelle and the actual wind speed when it is free stream.



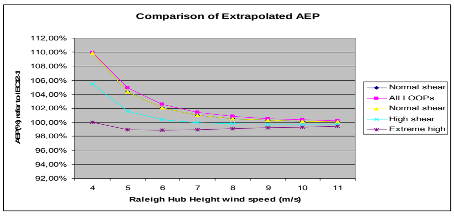
Wind Shear's Influence to Power Curve & AEP

Wind shear is the change in wind speed or direction with height in the atmosphere. The data was divided into 3 groups, representing the different wind shear scope to compare the power curves.

Extreme high	≥0,4 (LOOP 3)
High	0.4≥ Wind Shear ≥0.3 (LOOP 2)
Normal	0.3> Wind Shear ≥0.1 (LOOP 1)
Low	0.1> Wind Shear

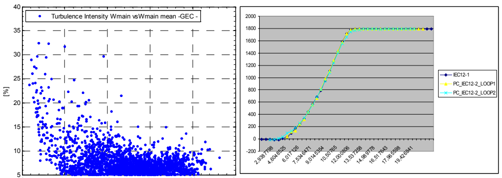


In the higher wind speed sections, different wind shear did not bring significant impact to the NTF based Power Curve. In lower wind speed, different wind shear brings slight deviation to power curve & AEP.



Turbulence Intensity (TI) Influence to Power Curve

Low TI: (0, 8), Normal TI: (8, 15), High TI: (15, :)



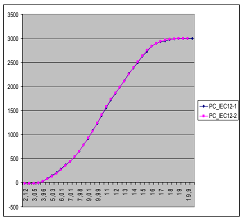
Turbulence Intensity distribution Power Curve comparison

Extrapolated AEP							
		All LOOPs		**Low TI 0-8**		**Normal TI 8-15**	
	IEC 12-1	IEC 12-2		IEC 12-2		IEC 12-2	
4	1030,48	1133,21	109,97%	1027,41	99,70%	1113,8	**108,09%**
5	2244,56	2355,23	104,93%	2235,01	99,57%	2312,77	**103,04%**
6	3698,97	3794,96	102,60%	3690,62	99,77%	3741,37	**101,15%**
7	5180,37	5255,64	101,45%	5174,99	99,90%	5198,32	**100,35%**
8	6549,01	6605,45	100,86%	6546,26	99,96%	6548,36	**99,99%**
9	7731,73	7773,37	100,54%	7730,88	99,99%	7718,58	**99,83%**
10	8692,33	8723,03	100,35%	8692,76	100,00%	8671,54	**99,76%**
11	9417,43	9440,22	100,24%	9418,66	100,01%	9392,43	**99,73%**

Different TI did not bring significant impact to the NTF based Power Curve by IEC61400-12B.

Complex Terrain NTF Analysis

Hilly test site presents obstacles and neighbouring WT. Site calibration was executed according IEC61400-12-1 due to topographical variations of complex terrain.



	Extrapolated AEP		
	IEC 12-1	IEC 12-2	
4	1162,182	1122,475	**103,54%**
5	2400,455	2363,007	**101,58%**
6	3975,519	3948,763	**100,68%**
7	5752,792	5738,731	**100,25%**
8	7586,19	7583,771	**100,03%**
9	9339,064	9346,15	**99,92%**
10	10896,26	10910,56	**99,87%**
11	12177,95	12197,39	**99,84%**

In complex terrain, different wind shear brings slight deviation to power curve & AEP.

Conclusions:

- The IEC61400-12B power performance evaluation method has acceptable variation with IEC61400-12A.
- Different wind shear / temperature / Turbulence intensity / wind direction variation and different types of terrain (complex or flat) will NOT bring significant deviation to power curve & AEP. (less than 3.54% at wind speed 4m/s @ complex terrain.)

Bing Liu, PhD-Stipendiat på Institutt for elkraftteknikk, NTNU, Apr. 2008 to **Mar. 2012**
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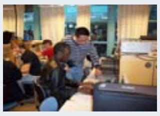
Wind Energy Master Program @DTU Denmark



PhD-Stipendiat på Institutt for elkraftteknikk, Research focus: Offshore Wind Farm Electrical System & Transmission.

Grid Integration of Large Offshore Wind Energy and Oil& Gas Installations Using VSC-HVDC

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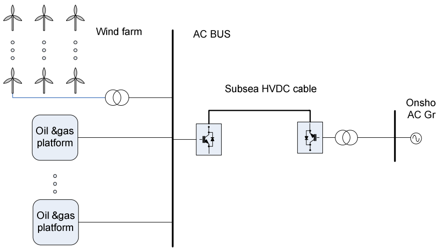
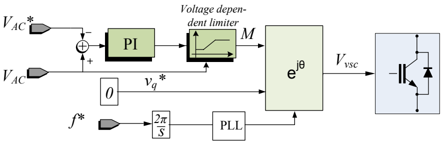
Introduction:

Offshore wind energy will become an important energy source in the near future. On the other hand, the low efficiency of gas turbines or diesel engines at offshore oil & gas installations calls for alternative power supplies. Therefore it is necessary and possible to integrate oil installations and offshore wind farms to the onshore grid by single transmission link. This poster presents an analysis and fault mitigation methods of grid integration of offshore wind farms and oil & gas installations using Voltage Source Converter (VSC) HVDC.

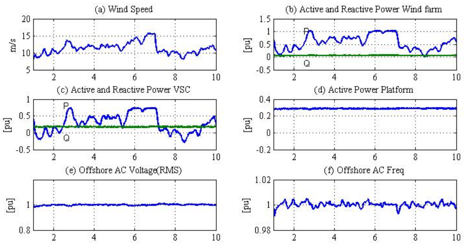
VSC HVDC offshore transmission



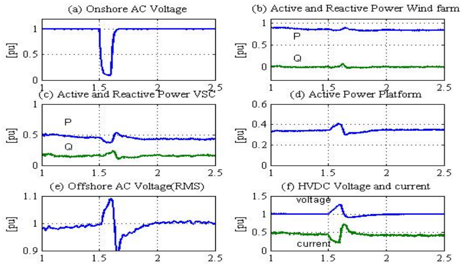
Offshore AC Frequency Control



The fixed frequency control strategy is used. First, it enable the VSC to absorb the fast changing wind power generation and achieve bi-direction power transmission. Second, the extra power control loop is not needed, therefore, fast offshore communication systems are not necessary.



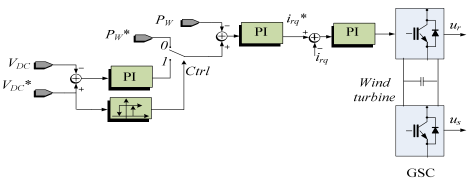
Onshore grid fault:



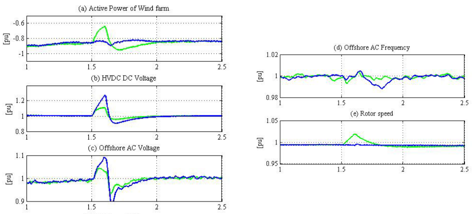
DC link over voltage and offshore AC voltage variation during onshore fault.

DC link voltage control (DLVC):

An offshore AC grid voltage independent limiter is implemented in the ac voltage control loop via the modulation index (M) of the VSC:

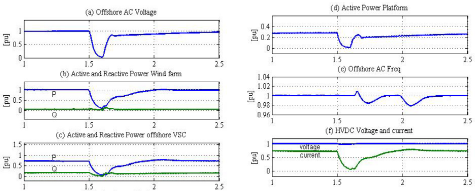


Proposed DC Link Voltage Controller

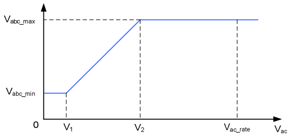


With DLVC controller presence, the HVDC DC voltage, offshore AC voltage and offshore AC frequency (green solid curves in upper figure a and b) peak values are smaller than the configuration without DLVC controller.

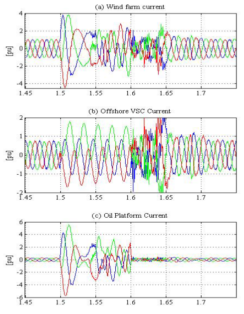
Offshore AC Grid Fault Mitigation:



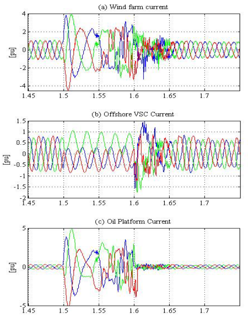
The exact design of the Vac versus Vvsc curve in below figure is depends on the detailed VSC design and how fast the wind generation recovers from faults, in order to reach the active power balance in the offshore AC grid.



Vac vs Vvsc relationship in voltage dependent limiter.



Currents of wind farm, offshore VSC and oil platform (with ac voltage limitation 1.5 p.u. at offshore VSC)



Currents of wind farm, offshore VSC and oil platform (with ac voltage limitation 1.1 p.u. at offshore VSC)

Conclusions:

Several faults mitigation control strategies for the offshore VSC HVDC grid integrating offshore wind farm and oil & gas installations has been proposed in this project stage, for example, the DC link voltage controller for onshore grid faults and the voltage dependent limiter for offshore AC grid faults. Simulation results in PSCAD show the satisfied performance.

Acknowledgements:

This research was presented under assistance of Statkraft Ocean Energy Research Program.

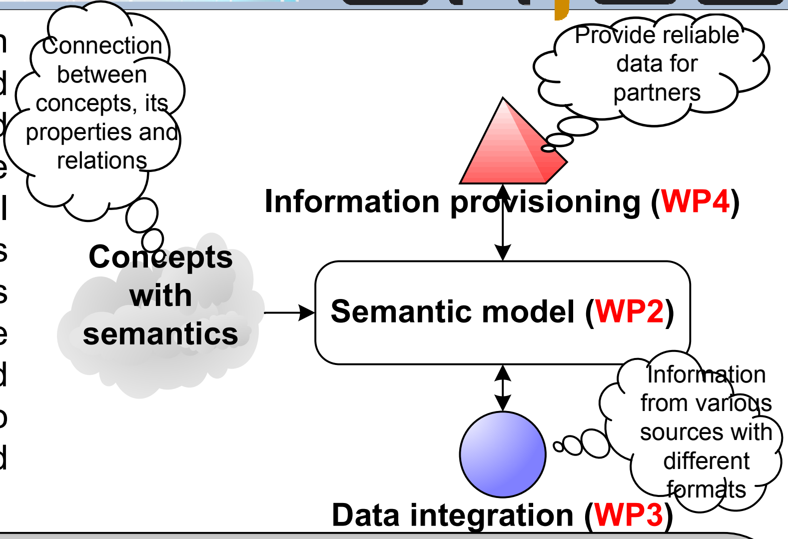
References :

[1] Bing Liu; Jia Xu; Torres-Olguin, R.E.; Undeland, T.; “ Faults mitigation control design for grid integration of offshore wind farms and oil & gas installations using VSC HVDC”, SPEEDAM, PP. 792 – 797, June 2010

Model-based operations and maintenance for offshore wind

Trinh Hoang Nguyen, Andreas Prinz, Trond Friisø
trinh.h.nguyen@uia.no

Abstract: There is a huge potential in producing electrical energy with offshore wind turbines. To fully release this economical and environmental potential, a significant decrease in initial investments as well as operational expenses must be realized. This work focuses on a foundation for efficient remote operations of offshore wind farms.The research challenge addressed in this work is to architect and develop an IT system for data integration to optimize remote operations of offshore wind farms.



Provide reliable data for partners

Connection between concepts, its properties and relations

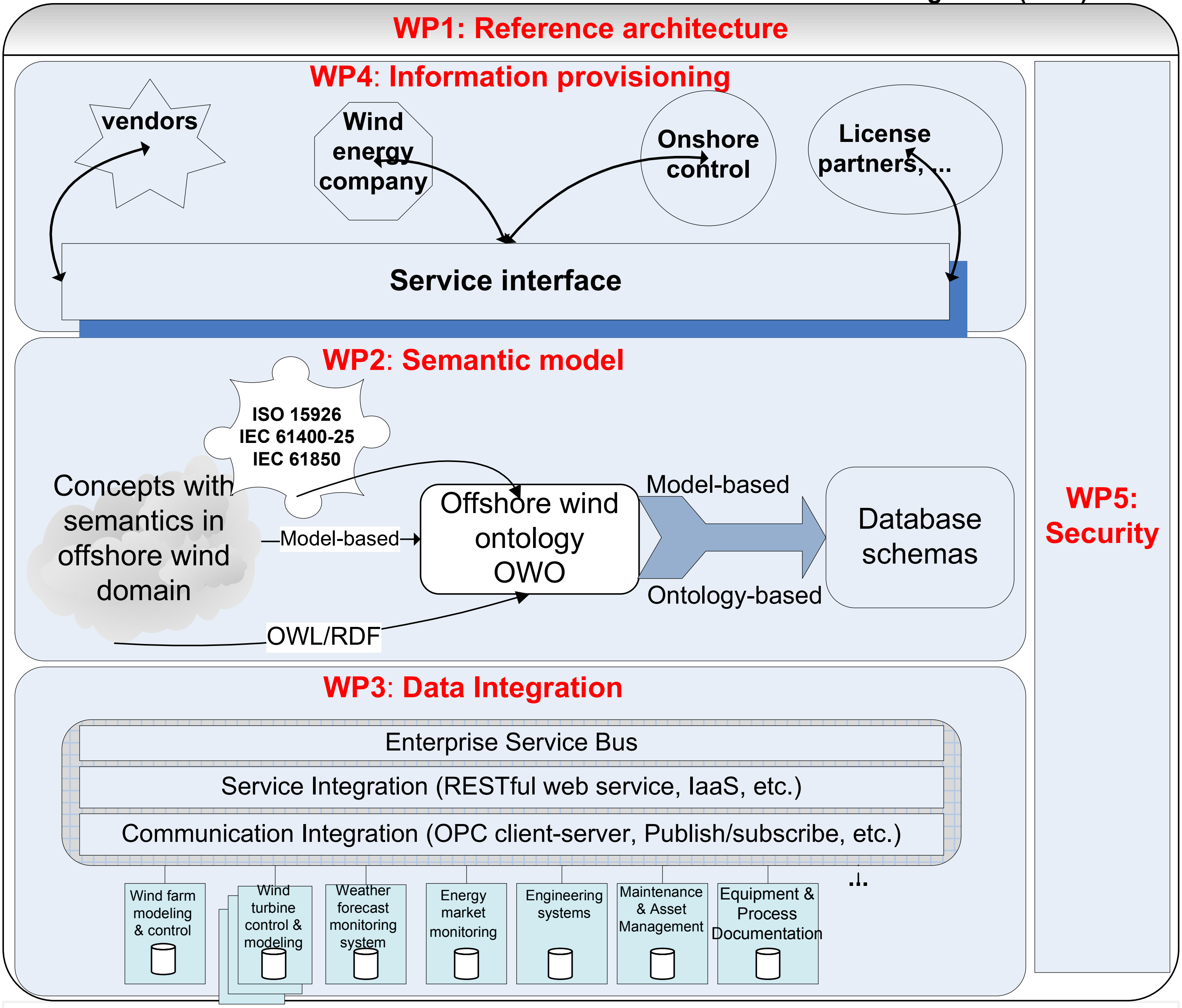
Information provisioning (WP4)

Concepts with semantics

Semantic model (WP2)

Information from various sources with different formats

Data integration (WP3)



WP1: Reference architecture

WP4: Information provisioning

vendors

Wind energy company

Onshore control

License partners, ...

Service interface

WP2: Semantic model

ISO 15926
IEC 61400-25
IEC 61850

Concepts with semantics in offshore wind domain

Model-based

Offshore wind ontology OWO

Model-based

Ontology-based

Database schemas

OWL/RDF

WP3: Data Integration

Enterprise Service Bus

Service Integration (RESTful web service, IaaS, etc.)

Communication Integration (OPC client-server, Publish/subscribe, etc.)

Wind farm modeling & control

Wind turbine control & modeling

Weather forecast monitoring system

Energy market monitoring

Engineering systems

Maintenance & Asset Management

Equipment & Process Documentation

...

WP5: Security

Conclusion: As the outcomes of PhD project, we expect to get a working system that is able to secure cost-efficient operation of offshore wind turbines. In addition to that an offshore wind ontology (OWO) will be ready to use and opened for the future extension.

norcowe
Norwegian Centre for Offshore Wind Energy

University of Stavanger

Vortex Methods for Integrated Dynamic Analysis of Offshore Wind Turbines

Lene Eliassen, University of Stavanger
Supervisors: Jasna Bogunovic Jakobsen (UiS), Jonas Thor Snæbjørnsson (UiS)

✓What advantages does the vortex method provide compared to the Beam Element Momentum (BEM) Method?
✓ Which method is the best tool to be used on the next generation wind turbines?
✓ Can we develop a state-of-art vortex method for Horizontal Axis Wind Turbines (HAWT) and apply it in an integrated dynamic analysis of an offshore wind turbine?

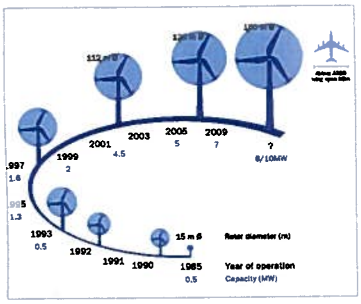


Figure 1: An illustration of the growth of wind turbines from 1985 to 2009, [1].

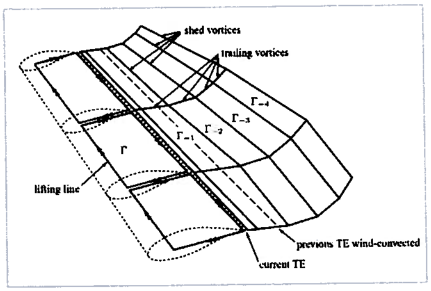


Figure 2: The wake geometry in AWSM [2].

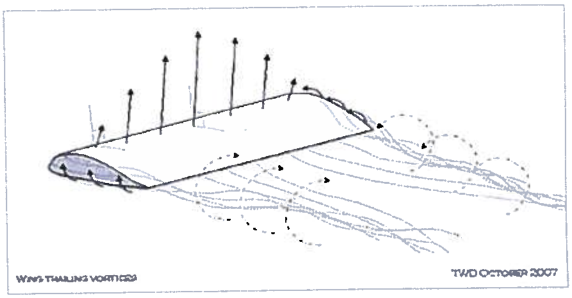


Figure 3: An illustration of wing trailing vortices. [5]

Introduction and motivation

The size of wind turbines have increased significantly over the last years, see fig 1. This development has required more advanced design tools. Instead of simple static calculations (assuming a constant wind) advanced dynamic simulations are used.

Most codes that are used to perform such dynamic simulations rely on the Beam Element Momentum (BEM) method. The BEM method is very efficient, and provided that reliable airfoil data exist, yields fairly accurate results.

However, more advanced numerical models based on the Euler and Navier-Stokes equations are becoming so efficient that they have begun to replace the BEM method in some situations. In these approaches the flow field is modelled more directly, and less empirical input is required compared to the BEM method.

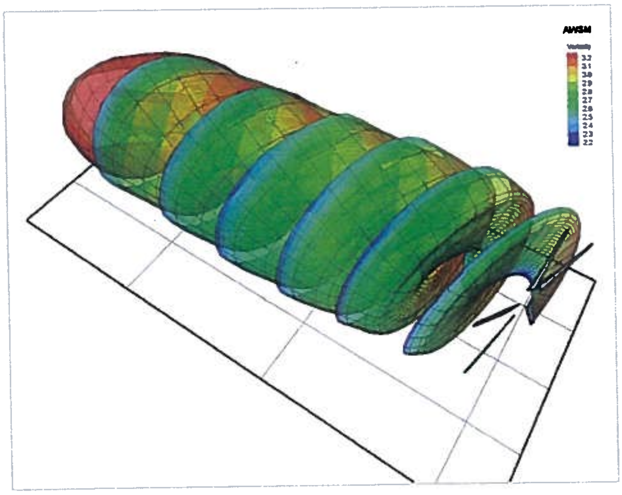


Figure 4: Wake modelling of a 5-bladed turbine in yawed flow by the vortex code AWSM. [4]

Further work

A state-of-the-art review of the aeroelastic modelling of wind turbines using the vortex methods will be made. This includes evaluating existing vortex codes for aeroelastic modelling of wind turbines, such as AWSM, GENUVP and HAWTDAWG.

The aim of the study is to implement a vortex model based code in an integrated dynamic analysis of an offshore wind turbine.

A short description of the vortex model

Wind turbines are subjected to atmospheric turbulence, wind shear from the ground effect, wind directions that change both in time and in space, and effects from the wake of neighbouring wind turbines. These operating conditions experienced by the blades are an important part of the aerodynamic analysis, and can be implemented by using the vortex model.

In the vortex models the rotor blades and the wake are represented by lifting lines or surfaces. There are several methods to model the blade and the wake. In figure 2, blade is represented as a lifting line on which a grid of horseshoe vortices are superimposed. The velocities at an arbitrary point can be calculated using the law of Biot-Savart. [7]

The vorticity in the vortex models is usually limited to the modelled blades and the wake, the remaining flow is assumed inviscid. The fact that viscous forces are neglected has restricted the usage of such models on wind turbines. There are however full 3D models of viscous-inviscid interaction techniques that can be used in aeroelastic analysis. [8]

Vortex codes and Horizontal Axis Wind Turbines

At the moment there exist some codes (based on vortex models) that are aimed at aeroelastic modelling of wind turbines. The most known codes are:
-AWSM (Energy Research Centre of the Netherlands), [2]
-GENUVP (NTUA,CRES)
-HAWTDAWG (University of Glasgow), [6]

An extended version of the vortex wake code HAWTDAWG, called Dynamic Prescribed Wake (DPW), has been built in to the aerodynamic code AERODYN and linked to the structural code FAST. Comparisons have been made with the DPW , the BEM and the Generalized Dynamic Wake (GDW) models built into AERODYN and to experimental results. The vortex wake model gives a better physical representation of a turbine wake than BEM and GDW, however the code needs further validation [6].

References:

[1] European Wind Energy Association, ewea.org, last visited 17.01.2011
[2] van Garrel, A. "Developement of a Wind Turbine Aerodynamics Simulation Module",ECN—03-079, August 2003
[4] AWSM, http://www.ecn.nl/fileadmin/ecn/units/wind/docs/Aerodynamics/AWSM_B-09-013.pdf, downloaded 18.01.2011
[5] Ground Effect, www.ground-effect.com, downloaded 18.01.2011
[6] Currinm, H. , Coton, F. N. and Wood, B. "Dynamic Prescribed Vortex Weka Model for AERODYN/FAST", ASME J. Sol. Energy Eng., vol 130, August 2008
[7] Bertin, J. B., Michael, L. S., "Aerodynamics for Engineers", Prentice Hall, USA, 2nd Ed, 1989
[8] Hansen, M. O. L, Sørensen, J. N., Voutsinas, S., Madsen, H. Aa. " State of the art in wind turbine aerodynamics and aeroelasticity" Aerospace Science, 42 (2006), pp 285-330

Atmospheric turbulence measurements close to the ocean surface

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BACKGROUND

In the last decade offshore wind parks have been placed close to the shoreline. Due to the increased demand of renewable energy the development of wind parks far offshore and for larger water depth has started. The main challenge is that up to now only very few and sporadic meteorological measurements are available for the highly required characterization of the marine atmospheric boundary layer (MABL) under real offshore conditions, e.g. from the German FINO platforms for shallow water and results from various campaigns using the U.S. research vessel FLIP.

Model results from Sullivan et al, 2008 indicate that ocean surface waves influence the lower part of the marine atmospheric boundary layer (MABL) in horizontal and vertical directions. Direct turbulence measurements of MABL turbulence will distinctly improve the understanding of the turbulent momentum transfer in the lower atmosphere and the corresponding exchange processes with the sea surface. For offshore conditions, this involves measurements from floating platforms, e.g. buoys or ships. Platform motions results in an extra peak in the power spectra that is usually approximated by a straight line (figure 2). This procedure can also remove real atmospheric motions induced by the wave field in the same frequency range. To overcome this issue we use a mathematical algorithm that transforms wind speed from a moving (floating) coordinate system to "actual" measured wind speeds in a fast reference system. In our approach, the collected data will be corrected for platform motion and orientation before the data analysis.

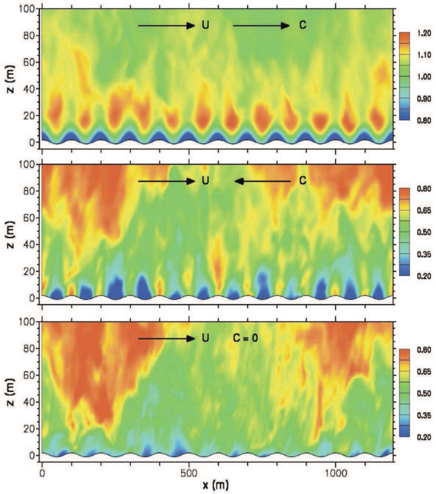


FIG. 5. Contours of the u component of the horizontal wind field for cases with moving and stationary surface waves. The nondimensional field shown is $\overline{u}/U_g$. (top) Wind following waves; (middle) wind opposing waves; and (bottom) stationary bumps. For each case the geostrophic wind $(U_g, V_g) = (5, 0)$ m s^{-1} and the wave slope $ak = 0.1$ where the wave amplitude $a = 1.6$ m. In the top and middle panels the wave phase speed $c = 12.5$ m s^{-1}. The color bar changes between the top and middle panels. Note the supergeostrophic winds near the surface in the top panel.

Figure 1: Model results from figure 5 of Sullivan et al, 2008 suggesting an impact of ocean surface waves on the MABL in both horizontal and vertical directions.

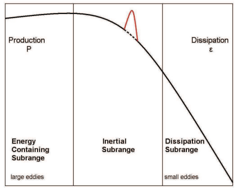


Figure 2: Sketch of the turbulence power spectra with (red) extra peak do to platform motion and its (dashed) straight line approximation.

References:

Edson et al, 1998: Direct covariance flux estimates from mobile platforms at sea. *J. Atmos. Oceanic Technol.*, **15**(2), 547-562.

Sullivan et al, 2008: Large-eddy simulations and observations of atmospheric marine boundary layers above nonequilibrium surface waves. *J. Atmos. Sci.*, **65**(4), 1225-1245.

Türk and Emeis, 2010: The dependence of offshore turbulence intensity on wind speed. *J. Wind Eng. Ind. Aerodyn.*, **98**, 466-471.

THE SYSTEM

Two identical eddy correlation systems have been purchased via NORCOWE. At the moment the systems are assembled at the University of Ireland in Galway. Software adaption and the first test of the components have been performed in December 2010. The planned take over and the first tests of the complete system is planned for the beginning of 2011.

System components

The Sonic anemometer is a Gill R3A-100

- Sampling rate up to 100Hz
- Both binary and ASCII output available
- Can provide an average of a fixed number of readings

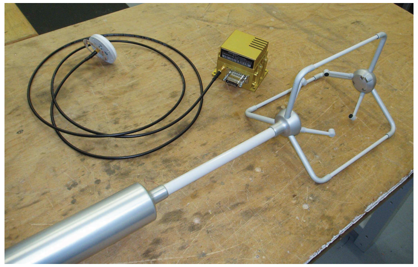
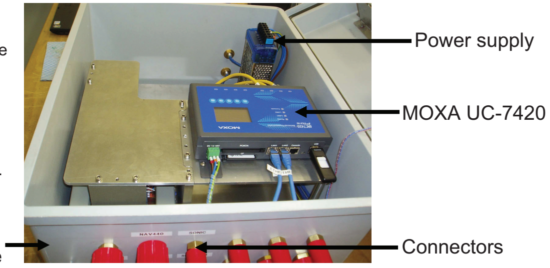


Figure 3: The systems Gill R3A-100 and the Crossbow NAV440 with GPS antenna.

The attitude information is provided by the Crossbow NAV440

- Integrated GPS and Attitude & Heading Reference system (AHRS)
- Utilizes low drift based MEMS-based inertial sensors with GPS
- Data output provided at rates of >100Hz

Figure 4:The Campbell enclosure with MOXA, Power Supply and Connectors.



The industrial computer MOXA UC-7420 acts as data logging and control unit for the system:

- RISC based ready-to-run LINUX computer
- 8 RS-232/422/485 serial ports
- PCMCIA interface for WLAN communication
- CompactFlash and USB-port for adding external memory
- Using WLAN all recorded data is send to an external PC and saved on its hard disk

The UC-7420 and the power supply (+15V) for all sensors will be housed in an Campbell ENC 16/18 enclosure. The NAV440 will be housed inside a watertight box at the sensor head. Cables will run between the Campbell enclosure and the sensor head.

Outlook

The system will first be used in short test campaigns, first in the laboratory, than on land and finally close to the shore at sea. Later on it is planned to mount the system on a moored buoy a few kilometers off the Norwegian coast. A third similar system is operated aboard the Irish research vessel R/V Celtic Explorer. A mathematical algorithm that transforms wind speed from a moving (floating) coordinate system to "actual" measured wind speeds in a fast reference system has been provided by James Edson, University of Connecticut, for adaption to the project. In addition, a data set from the Air Sea Interaction Tower (ASIT) and a nearby meteorological buoy off the coast of Martha's Vineyard, Massachusetts, are also available for the advancement of the motion correction code. Collaborations with the turbulence groups of Brain Ward from the National University of Ireland and James Edson from the University of Connecticut have been established. This enables us to have joint field campaigns in both Norway, Ireland and the USA.

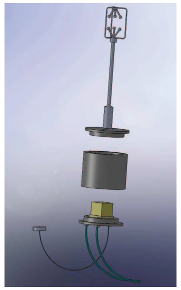


Figure 5: Overview of the systems sensor head.

Improved energy forecast for Offshore Wind farms

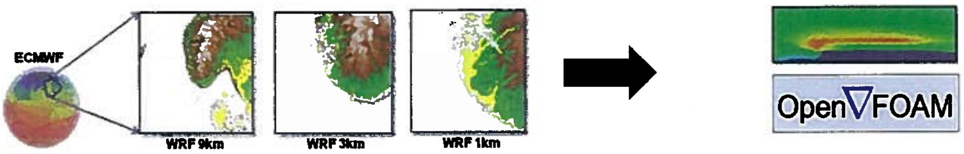
Siri Kalvig, University of Stavanger and StormGeo
Supervisors; Jafar Mahmoudi (IRIS/UiS), Ivar Langen (UiS), Nina Winther (StormGeo)

✓ What environmental input data do the engineers needs for operations and maintenances and in order to ensure reliable design? How can meteorologist and oceanographers best forecast these input data?

✓ Ensure improved energy forecast by combining the meteorological and oceanographic 'macro and meso scale world' with the structural engineering and material sciences 'micro scale world'.

Meso Scale
Operational, ECMWF, WRF

Micro scale
Project based, CFD codes



Motivations;

✓ The air and sea interact and exchange momentum, heat and gases in the Marine Boundary Layer (MBL) in a complex way. This air-sea interaction depends in a sensitive way on the sea state.

✓ Accurate wind estimations requires high quality offshore wind forecast and this will depend on a fine scale coupled model system that incorporates the air-sea interaction.

✓ MetOcen modeling is essential for both assessment (hindcast) and for operation and maintenance. Do we need to account for stability and changing sea surface roughness in design calculations and for energy forecasts?

✓ Idealized studies of air-sea interaction gives guidelines on how to set up an operational fine scale coupled model system. With such a system it will be possible to minimize power loss and perform correct load calculations.

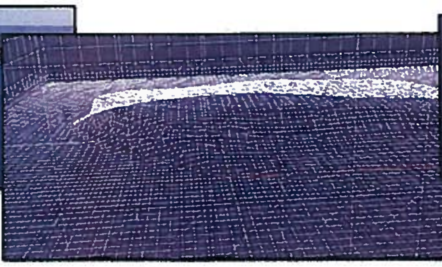
✓With a new and better understanding of the air-sea interactions it is important that the most representative input parameters to various dynamical response tools and the most representative boundary condition for the CFD simulations is used.

✓ There is a limit for when it is cost efficient and useful to use dynamical and coupled MetOcean models at very fine resolution.

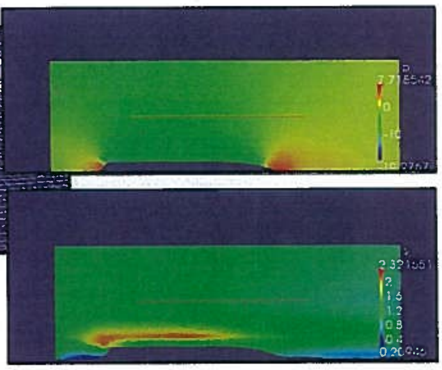
Tasks;

- Review of relevant literature
- Investigate who roughness and stability is interpreted in the standards for Offshore Wind turbines (IEC 61400-3). Identify gaps between "best knowledge" (science) and "best practice" (codes, standards)
- Simulate possible increased loads/fatigue due to changing roughness and stability over sea surface.
- Simulate wind effects in OpenFoam over different surface (set up from Bolund Experiment) and with moving grid (wave - set up from Sullivan et al.)
- Suggest the optimal configuration of an operational model set up in order to maximize quality forecast for both forecasting and nowcasting and within feasible computational time.

Terrain data from the Bolund experiment, Risø DTU

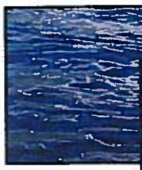


Bolund mesh created by the use of openFoam's snappyHexMesh

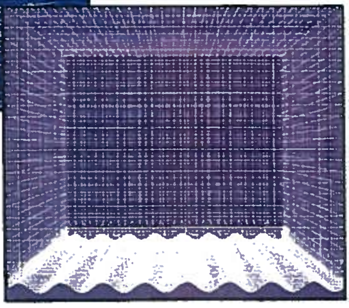


OpenFOAM is a open source Computational Fluid Dynamic (CFD) software package. It uses finite volume numerics and is based on a flexible set of C++ modules.

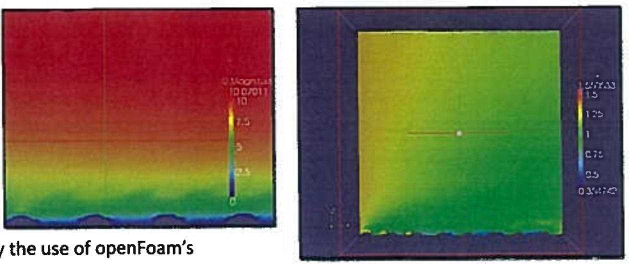
Preliminary wind flow simulations over Bolund hill. Turbulent kinetic energy and pressure are calculated by the use of openFoam (simpleWindFoam and kEpsilon turbulence model)



Wave surface generation code from AconaWellPro



Idealized sinusoidal wave, mesh created by the use of openFoam's snappyHexMesh. It creates unstructured mesh of polyhedral cells.



Preliminary openFoam simulation. Wind flow over wave surface. Wind speed, and turbulent kinetic energy.

Series Connection of Offshore Wind Turbines

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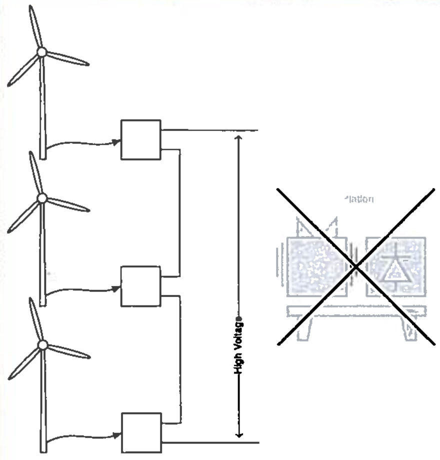
NTNU
Det skapande universitetet

Introduction

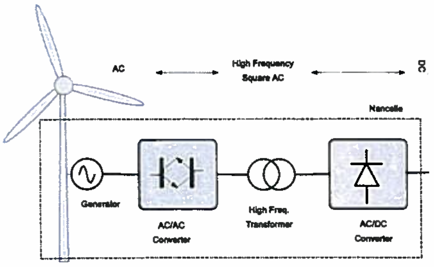
SERIES connection of wind turbines is a promising topology for offshore grids. However, it carries with technological challenges which needs to be further studied: variation in the wind velocity causes variations in the output power and therefore in the output voltage. As a result of that, a wide variation capability of output voltage is required in each turbine and a coordinated control must be developed. The objectives of this research include to develop an optimal power flow for series connection of offshore wind farms in order to extract maximum power.

Why Series Connection ?



- Losses in the offshore grid are as low as the losses in the transmission stage since the current is the same.
- The investment could be reduced since the length of cable is shorter than in parallel connection and the offshore platform might not be required.
- Potential to improve the efficiency and overall weight.

Converter Technology



Objectives:

- Size and weight reduction
- Increase efficiency
- Increase reliability

Model

A simple way to control the entire system, is to guarantee equal power generated by each turbine. However, imposing proper constrains, it is also possible to use an optimal load flow algorithm to maximize the power on shore and minimize losses as follow:

$$max\ P_T = \sum_k \sum_m P_{km} - \sum_k R_k \cdot I_k^2 - R_L \cdot I_L^2 \quad (1)$$

subject to

$$U_{onshore} = U_{offshore} - R_L \cdot I_L \quad (2)$$

$$U_{offshore} = \sum_m U_{km} - R_k \cdot I_k \quad (3)$$

$$I_L = \sum_k I_k \quad (4)$$

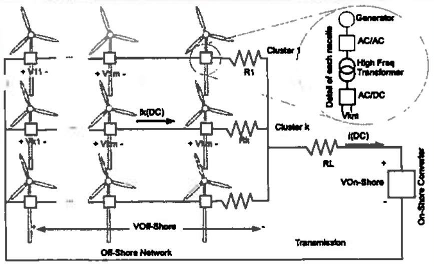
$$P_{km} = V_{km} \cdot I_k \quad (5)$$

$$U_{km(min)} \leq U_{km} \leq U_{km(max)} \quad (6)$$

$$P_{km(min)} \leq P_{km} \leq P_{km(max)} \quad (7)$$

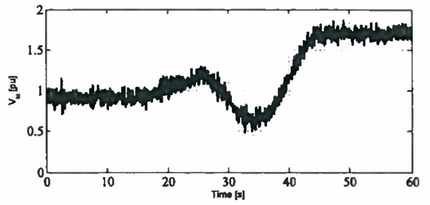
$$P_{km(max)} = \left\{ \begin{array}{ll} \left(\frac{V_w}{V_{w(nom)}}\right)^3 & V_w \leq V_{w(nom)} \\ 1\ pu & V_w > V_{w(nom)} \end{array} \right\} \quad (8)$$

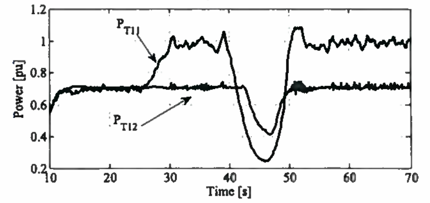
Cluster

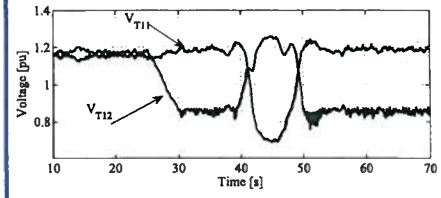


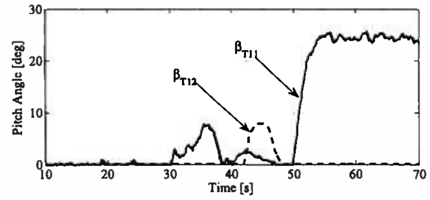
Cluster topology could increase the reliability of the system holding the advantages of both series and parallel connections.

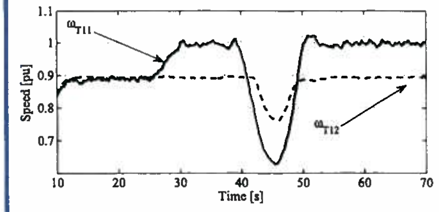
Results

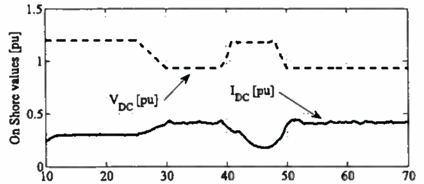












Conclusions

A coordinated control is required for series connected wind turbines which takes into account the electrical constrains of this type of connection. Conventional maximum tracking point needs to be replaced by an optimal power flow, which takes into account not only the maximum transfered power but also the electrical constraints.

The most clear advantage of series connection is the reduction of the off shore grid losses and the substation platform avoidance. Furthermore, in the present concept no platform will be required offshore and less cable is used. The voltage limits in one turbine could impose power limits in the other turbines when the wind velocity is different between them. Therefore, series connection is a promising alternative if the covariance in the wind velocities are close to zero.

WAVE EXTREMES IN THE NORTHEAST ATLANTIC

O.J. Aarnes[1,2], Ø. Breivik[1] and M. Reistad[1]
[1]Meteorological Institute of Bergen, Norway
[2]University of Bergen, Norway

Objective

The main objective of this study is to compute 100-year return values of significant wave height (H_s) using a new hindcast developed by the Norwegian Meteorological Institute. This regional hindcast covers the Northeast-Atlantic and spans the period 1958-2009.

The return value estimates are based upon three different approaches within classical extreme value theory, i.e. the Generalized Extreme Value(GEV) distribution, the r-largest order statistics and the Generalized Pareto(GP) distribution. Here, we investigate the qualitative difference between the estimates and their corresponding confidence intervals.

Norwegian Reanalysis - NORA10

NORA10 (NOrwegian ReAnalysis 10 km) is the latest contribution to the series of wave hindcasts developed by the Norwegian Meteorological Institute, see Reistad et al. (2007, 2010). This regional hindcast utilizes boundary conditions obtained with the ERA-40 reanalysis(Uppala and et al., 2005)(1958 - August 2002) and is extended using EC-analysis (September 2002 -2009), producing three hourly wave fields at 10 km grid spacing for the period 1958-2009. For wave simulations a modified version of the WAM cycle 4 (Komen et al., 1996) is run on the same grid as 10km HIRLAM model, nested inside a larger 50 km WAM-model, see Figure 1. No wave energy is advected into the model domain of the WAM50, only wind dependent wave spectra are set at the boundaries.

Figure 1: Outer domain: WAM50. Inner domain: WAM10/Hirlam10 - hindcast area.

Preliminary conclusions and further work

We obtain fairly similar 100-year return value estimates of H_s using three different statistical approaches, however, we see a few local exceptions we want to investigate further. Primarily, we see an increased precision in the confidence intervals when utilizing methods of increased data subsets, like the POT approach and the r-largest order statistics.

Future emphasis will be made on the POT approach and ways to optimize the threshold selection. Finally, a qualitative comparison of the three methods will be made using different goodness-of-fit tests.

References

S. Coles. *An introduction to Statistical Modelling of Extreme Values.* Springer-Verlag, 2001

G. J. Komen, M. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann, and P. A. E. M. Janssen. *Dynamics and Modelling of Ocean Waves.* Cambridge University Press, 1996.

M. Reistad, O. Breivik, and H. Haakenstad. A high-resolution hindcast study for the north sea, the norwegian sea and the barents sea. In *Proceedings of the 10th International Workshop on Wave Hindcast and Forecasting and Coastal Hazard Symposium.*, 2007

M. Reistad, O. Breivik, H. Haakenstad, O. J. Aarnes, and B. R. Furevik. A high-resolution hindcast of wind and waves for the north sea, the norwegian sea and the barents sea. *Journal of Geophysical Research, Oceans.(revision)*, 2010.

S. M. Uppala and et al. The era-40 re-analysis. *Q. J. R. Meteorol. Soc.*, 131:2961–3012, 2005.

Method

The following analysis is based on the extreme value theory presented in Coles (2001). We are using two different but closely related families of distributions, determined by the selection of data subset, i.e.:

- The Generalized Extreme Value(GEV) distribution:

$$G(z) = exp\left\{-\left[1+\alpha\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \tag{1}$$

, where z represents the wave height and ξ , σ , and μ are the shape, scale and location parameters of the distribution function, respectively.

- The Generalized Pareto(GP) distribution:

$$H(z_u) = 1 - \left(1+\frac{\xi z_u}{\tilde{\sigma}}\right)^{-1/\xi} \tag{2}$$

$$\tilde{\sigma} = \sigma + \xi(u-\mu) \tag{3}$$

, where $z_u = z - u > 0$ and u represents a relative large threshold.

Return value plots:

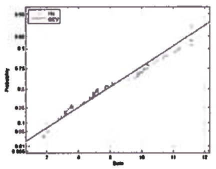


Figure 2: Annual maximum/GEV

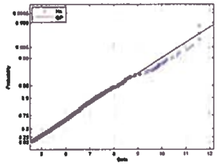


Figure 3: POT/GP

Distribution fitting

We utilize the *maximum likelihood* in our parameter estimation, i.e. maximizing the likelihood function L iteratively, or preferably minimizing the negative log-likelihood equation l

$$L(\theta) = \prod_{i=1}^{n} f_i(z_i;\theta) \Longrightarrow -l(\theta) = -logL(\theta) = \sum_{i=1}^{n} f_i(z_i;\theta) \tag{4}$$

, where f_i represents the probability density for each $z_i, i = 1....,n$, defined by the distribution parameters $\theta(\xi,\sigma,\mu)$.

Data subsets

- Annual maximum → GEV
  1 entry per year
- r-largest order statistics → GEV (modified likelihood function L)
  2-7 entries per year (based on the likelihood ratio test)
- Peaks-over-threshold(POT)→ GP
  ~ 6-60 entries per year (based on the mean residual life plot)

100-year return value estimates of significant wave height

Annual maximum/GEV

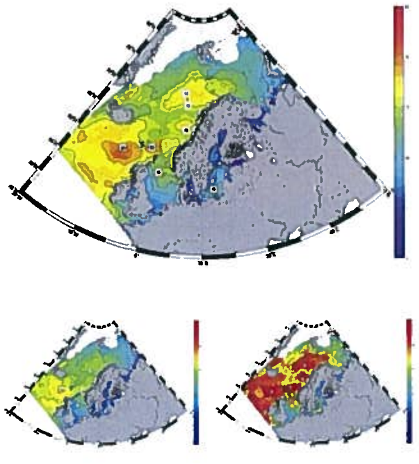


Figure 4: Top: best estimate.
Bottom: 5% and 95% confidence limits.

r-largest order statistics/GEV

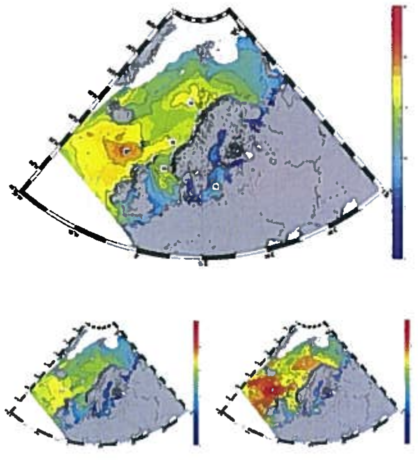


Figure 5: Top: best estimate.
Bottom: 5% and 95% confidence limits.

POT/GP

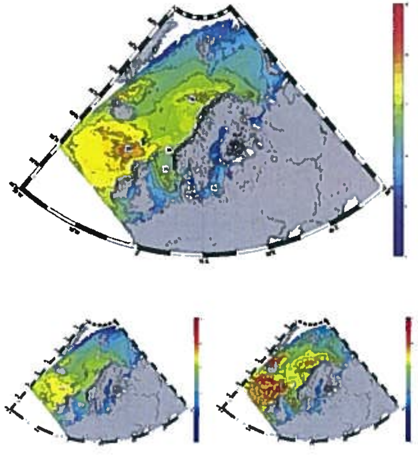


Figure 6: Top: best estimate.
Bottom: 5% and 95% confidence limits.

DTU Mechanical Engineering
Department of Mechanical Engineering

Response of Tension Leg Configuration subjected to wave & aerodynamic thrust loading

G. K. V. Ramachandran, J. N. Sørensen, J. J. Jensen and H. Bredmose

Introduction

In order to tap the wind potential available in the deep sea, floating offshore wind turbine configurations have been proposed, which needs mathematical tools to accurately predict the hydro-aero-servo-elastic loads on wind turbine and platform.

For the initial computations, a Tension Leg Platform (TLP) configuration has been chosen.

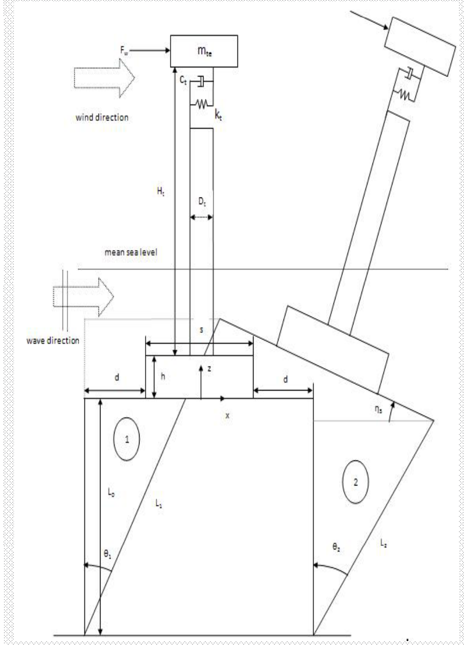
Proposed Location – wave & wind climate

Parameter	Value
Significant wave height	7 m
Peak period	10 s
Water depth	200 m
Annual avg. wind speed	8-10 m/s
Predominant wind direction	W, SW

Assumptions

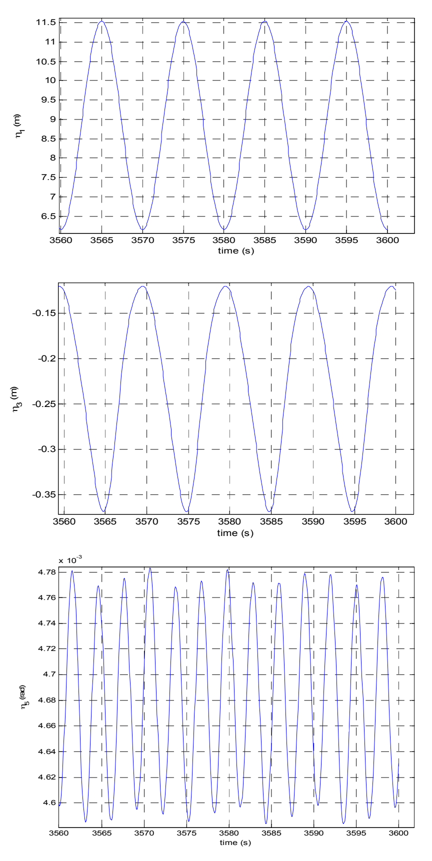
- Platform is rigid, having 6 DOF. In 2D, these reduce to *surge*, *heave* and *pitch*.
- Tendons are *extensible*.
- Tower bending *flexibility* considered.
- Airy wave theory for *irregular* waves.
- Wave loads – Morison’s equation.

Initial Configuration



Results

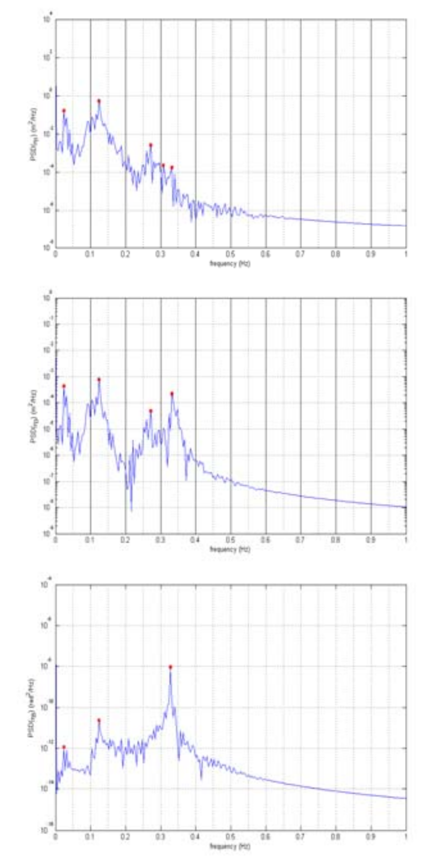
Regular wave + ramped thrust – time domain response



Comparison of Results – Ramped thrust case

		Regular H = $H_s/2$	Irregular H = H_s
η_1 (m)	Mean	8.875	9.0
	Max.	11.5	11.25
	SD	1.91	0.74
η_3 (m)	Mean	-0.25	-0.23
	Max.	-0.375	-0.35
	SD	0.09	0.04
η_5 (rad/˚)	Mean	0.005/0.27	0.005/0.27
	Max.	0.005/0.27	0.005/0.28
	SD	6.6E-5/ 0.004	6.2E-5/ 0.004

Irregular wave + ramped thrust – frequency domain response



Conclusions

- The coupled dynamic model has been implemented.
- Results verified under static conditions.
- The dynamic responses are complying with that in the literature.

References

1. Joensen, S, Jensen, J.J and Mansour, A.E (2007), Extreme value predictions for wave and wind-induced loads on floating offshore wind turbines using FORM, *10th Int. Symposium PRADS’2007*, Pennsylvania, USA.
2. Zhen-Zhe Chen, Deepwater Floater for Wind Turbines (2005), M.Sc Thesis, DTU.

Acknowledgements

This research was carried out as part of the Statkraft Ocean Energy Research Programme, sponsored by Statkraft (www.statkraft.no). This support is gratefully acknowledged.

Statkraft Ocean Energy Research Program

Challenges in the Reliability and Maintainability Data Collection for Offshore Wind Turbine

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Introduction

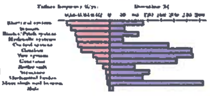
- More Wind available offshore
- Complex Operation & Maintenance
- Social reasons

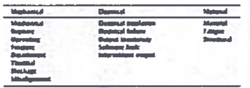
Year	Offshore wind GW	Yearly growth offshore wind /%	Offshore of total wind power / %	Production from offshore wind/ TWh/y	Expected global electricity consumption /TWh/y	Penetration of offshore wind, %
2006	0.9		1.2	3	15500	0.0
2015	12.8	34	2.6	42	21300	0.2
2020	42.4	27	4.0	140	23800	0.6
2030	251.1	19.5	9.5	829	29750	2.8
2050	773.8	5.5	18.4	2559	40100	6.4

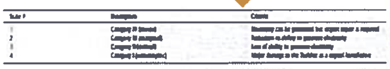
(J.Twidell, et al, "Offshore wind turbines)

Failures in Wind Turbine

- Failures occurs in Wind Turbine
  - Higher failures
    - Electrical system
    - Sensors
    - Blades/Pitch
  - Higher downtime
    - Gearbox
    - Main shaft and bearin
    - Yaw system
- Failure Mechanism
- Effects







(Hoseynabadi et al, 2010)

Need for database

- Failure behavior of offshore wind turbines is still under investigation!
- Logistics, Accessibility weather dependent
- Expensive and complex maintenance in offshore
  - Higher lifting costs in offshore (at least 5 times more)

Objectives of database

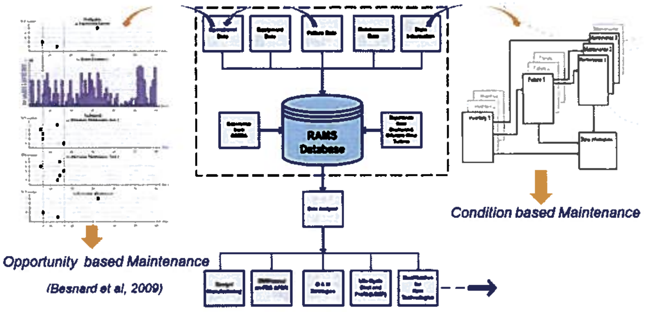
- Collect and exchange operating experience
- Promote reliability engineering
- Develop a reference for the collection and analysis of reliability data
- Develop cost-efficient data collection methods and tools
- Feedback of operating experience to the equipment manufacturers
- Co-operate with other organizations and research

Existing database

- **WindStats Newsletter** – Denmark & Germany (quarterly, 7000 WT)
  - Failure data are specified per component (e.g. yaw system, gearbox, brake), but not per wind turbine size or type
  - Every month failures, but not always failure causes, of about 7000 turbines are reported
- **LWK** – Germany (yearly, >650 WT, closed 2006)
  - Contains output data and number of failures per system of all WTs
- **WMEP** – Germany (yearly, >1500 WT, closed 2006)
  - Detailed information about reliability and availability of WTs
  - The most reliable characteristic values regarding reliability (MTBF, MTTR)
- **Vindstat** (VPC) – Sweden (yearly, 723 WT before 2005)
  - Production and downtime, provides information for wind power
  - Incomplete reporting which made the statistical processing invalid
- **VTT** – Finland (yearly, 105 WT)
  - Contains data of performance, failures, and downtimes for wind power plants
  - Quality of the data might be insufficient for making conclusions
  - Failure reporting is mandatory
- **OWMEP** for Offshore Wind Turbines
  - Concept stage
  - Partly included O & M aspects
  - Aiming at implementing reliability techniques

Proposed database

- **RAMS Database** (Reliability, Maintainability, Availability, and Safety)



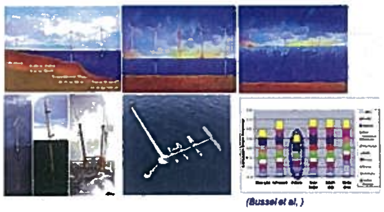
Opportunity based Maintenance

(Besnard et al, 2009)

Condition based Maintenance

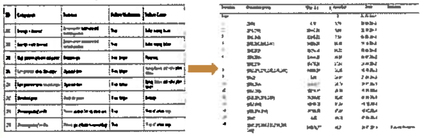
Challenges

- Adaptability with novel concepts



(Bussel et al,)

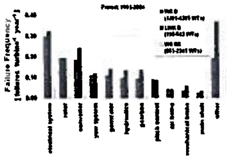
- Maintenance Optimization
  - Dynamic grouping
    - Preventive and corrective maintenance costs are required



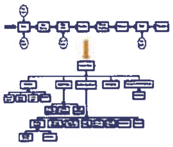
Total Saving till Planned Shutdown 21%
(Hameed et al, 2010)

- Cost effective
- Self Maintenance Machine
- Efficiency tool enhancement
- Failure rate estimation
  - Quality and accuracy
  - Measuring and predicting the reliability
- Clear definition of data boundaries
- Anonymity of data suppliers
- Competitor rivalries
  - Don't want to work together
- Comparability
- Wake effect on failure rates
- Mistakes and startup problems
- Experiences from other relevant industries

(Echavarria, et al)



(Spinato et al, 2008)



Conclusions

- RAMS database will act as reliability enhancement tool
- Design improvement
- Access, logistics and transportation issues could be planned in an accurate way in offshore environment

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Control and Operation of Multiterminal HVDC for Market Integrated Offshore Wind Farms

TEMESGEN M. HAILESELASSIE, KJETIL UHLEN, TORE UNDELAND

***Abstract*—The North Sea area has a great potential for exploiting vast amount of offshore wind energy. A multiterminal HVDC (MTDC) connection can provide a suitable grid integration solution for the offshore wind farms and at the same time can create electricity market opportunities between all onshore and offshore MTDC connected points.**

Figure 1: Early stage scenario of multiterminal HVDC in the North Sea

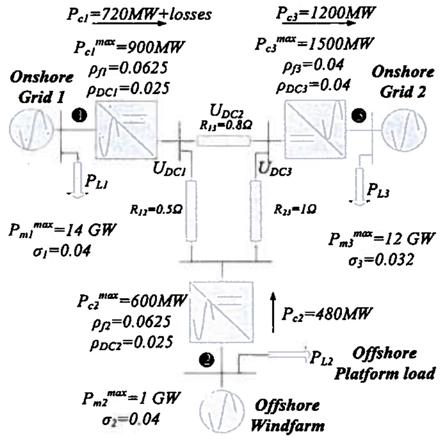


Figure 2: A three terminal HVDC model used for simulation

Salient Features of the Employed MTDC Grid Control Scheme

- Dc voltage droop control for instantaneous balancing power inside the MTDC
- Frequency droop control employed for the converter terminals
- No need for communication between terminals

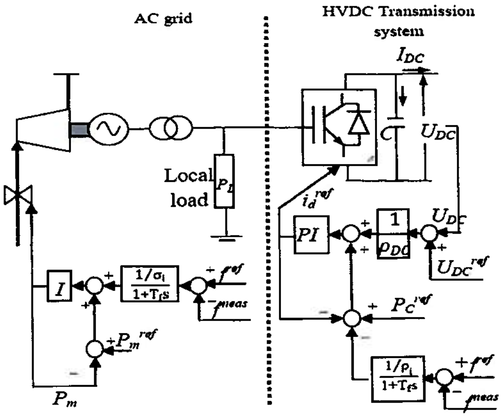


Figure 3: Complete schematic of the VSC-HVDC terminal controller

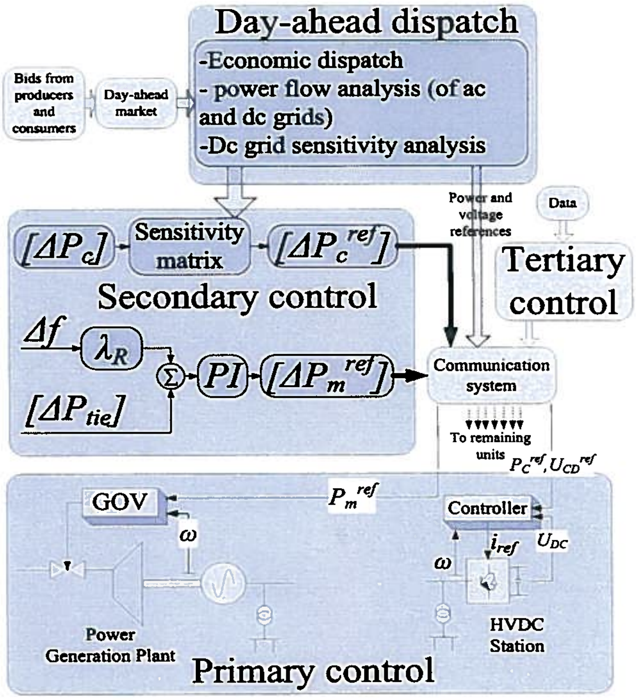


Figure 4: Flow chart showing operation of MTDC in a market integrated system

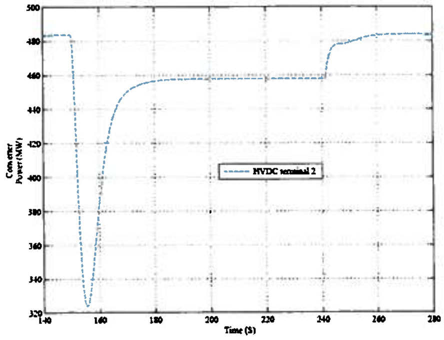


Figure 5: Time response of HVDC terminal power for load changes and the effect of secondary control

Conclusions

- Robust control of MTDC has been achieved by dc voltage droop control.
- No need of fast communication between terminals for instantaneous power balancing under normal operations.
- Primary and secondary control of MTDC integrated has been system demonstrated.
- MTDC can be readily operated based upon the electricity market.

NTNU

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Analysis of Atmospheric Boundary Layer of Frøya Test Site

G. Tasar, F. Pierella, L. Sætran.
Department of Energy and Process Engineering, Norwegian University of Science and Technology,
7491 Trondheim, Norway

1. LOCATION

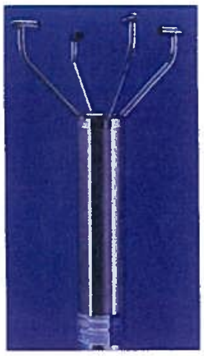
Skipheia **is wind measuring station** in Titran, Frøya, run by **NTNU** which is located on the south west tip of **Frøya** (Sør Trøndelag). The station is 200 km away from Trondheim and NTNU. It is highly exposed to ocean winds.

2. FACILITIES

- Three masts: 2 x **100m** , 1 x **45m**
- Additional Mast (45m) in nearby island
- Twelve anemometers, two at each level
- Temperature sensor at each level
- Lidar (Light Detection and Ranging)
- Measurement cottage

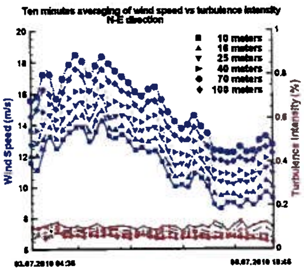
- **Lidar**
  - *Frequency* : one 3D velocity vector every 1.1s
  - *Vertical resolution*: max 10 altitudes (40 ~200m)
  - *Probed length*: 20m
  - *Reported accuracy*: 0.2 m/s
  - *Range*: 46 m/s

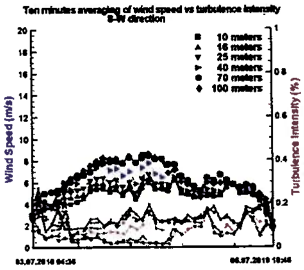
- **Ultrasonic Gill Anemometers**
  - *Range:*0 – 65 m/s
  - *Accuracy:* ±2 % @ 12 m/s
  - *Resolution:*0.01 m/s
  - *Offset:* ±0.01 m/s

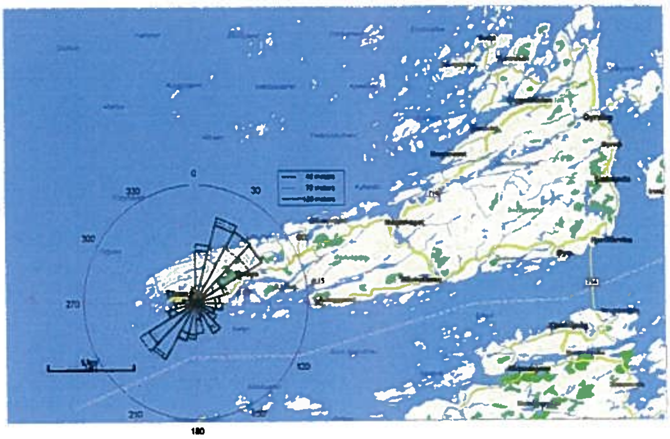


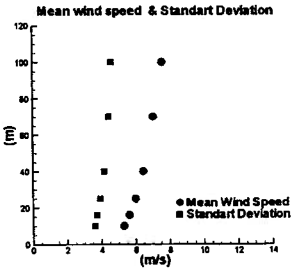
3. RESULTS

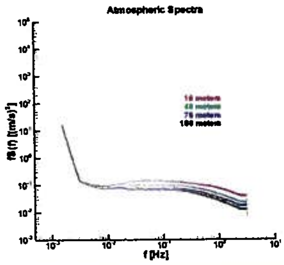
- **Directional distribution**
- **Ten minutes averaging:** Influence of wind direction on stability.
- **Ten minutes averaging:** Velocity components and turbulence intensity patterns.
- **Turbulence:** Turbulence intensity and standard deviation variation at different levels.
- **Atmospheric Spectra:** Comparison of different levels.

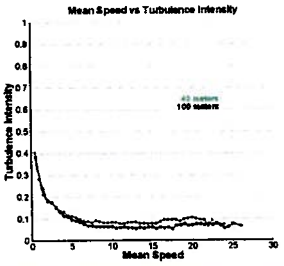












References:

1. Tore Heggem; *Measurements of Coastal Wind and Temperature*; PhD Thesis, NTNU; ISBN 82-7861-056-8.
2. R. B. Stull; *An Introduction to Boundary Layer Meteorology; Kluwer Academic Publishers.*

D) Operations & maintenance

The German wind turbine reliability database (WMEP),
Jochen Bard, Fraunhofer IWES

Framework for risk-based O&M planning for offshore wind turbines,
Prof John D Sørensen, Uni. of Aalborg

Cooperation on O&M and LCC analysis with Vattenfall,
F. Besnard, Chalmers Uni. Technology

HSE challenges related to offshore renewable energy,
Camilla Tveiten, SINTEF

THE GERMAN WIND TURBINE RELIABILITY DATABASE

WMEP

Wind Power R&D seminar – Deep sea offshore wind power
20-21 January 2011, Trondheim, Norway

J. Bard, S. Faulstich, P. Lyding
Fraunhofer Institute for Wind Energy and Energy System Technology (IWES)

THE GERMAN WIND TURBINE RELIABILITY DATABASE

- Introduction
- WMEP
- Reliability of wind turbines
- Offshore~WMEP
- Conclusions

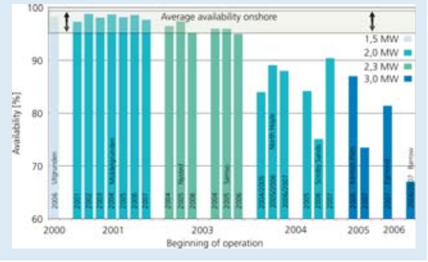
Introduction

Starting Point:

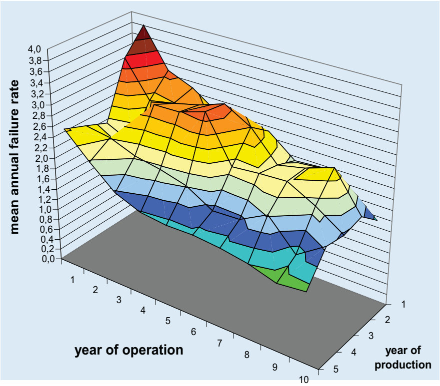
Modern wind turbines achieve high availability

Number of faults cause unplanned downtimes
➔ high maintenance efforts and costs

Offshore: drop of availability expected



Introduction



WMEP

Scientific Measurement and Evaluation programme WMEP

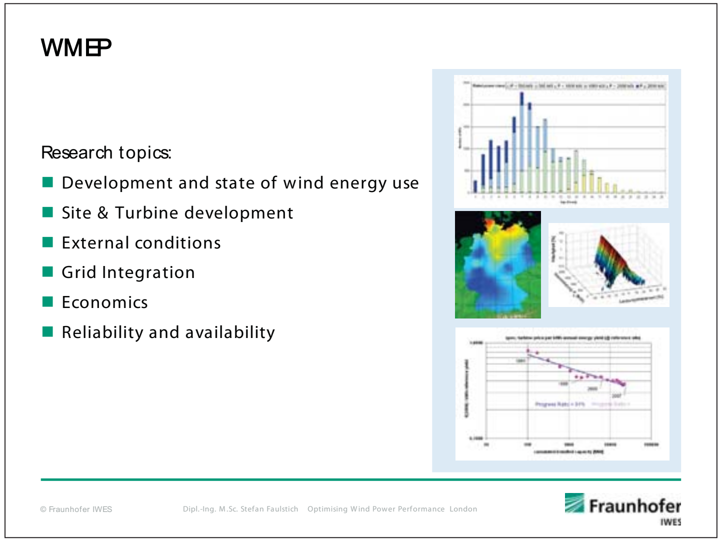
„ 250 MW Wind“ (1989-2006)

	193.000	monthly operation reports
and	64.000	Incident reports
from	1.500	wind turbines

WMEP

Dissemination:

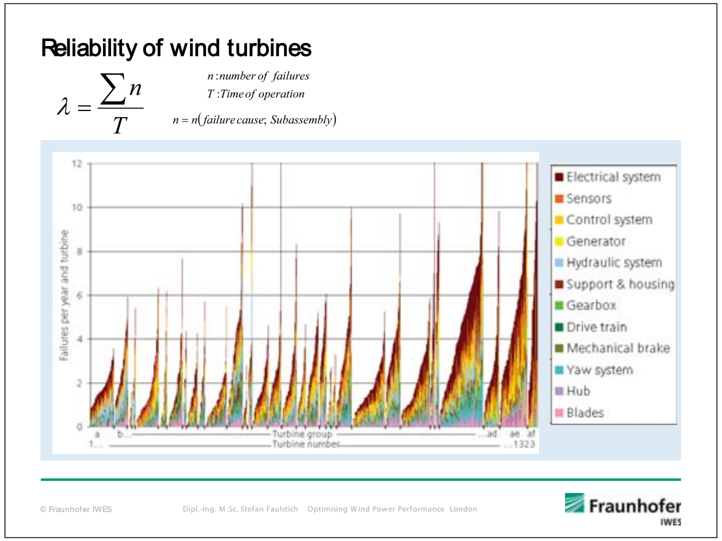
- Wind Energy Report (yearly published, 2010 coming soon)
- Internetportal
  www.windmonitor.de
- Project Homepage
  www.offshore-wmep.de



WMEP

Research topics:

- Development and state of wind energy use
- Site & Turbine development
- External conditions
- Grid Integration
- Economics
- Reliability and availability



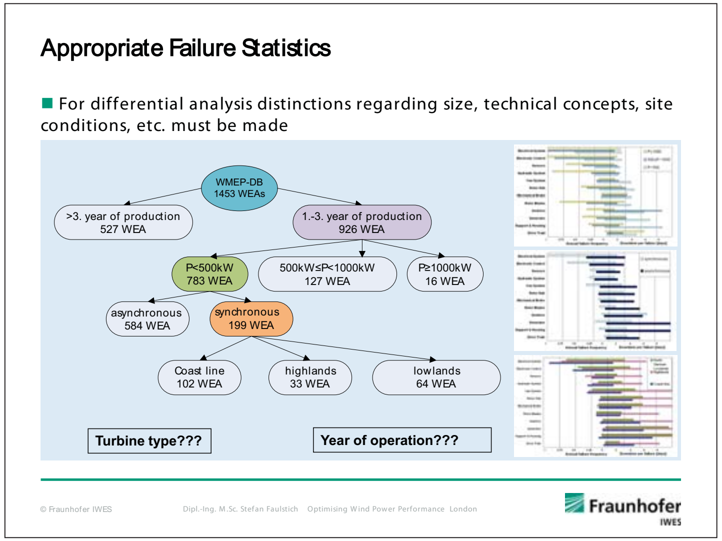
Reliability of wind turbines

$$\lambda = \frac{\sum n}{T}$$

n : number of failures

T : Time of operation

$n = n(\text{failure cause; Subassembly})$



Appropriate Failure Statistics

- For differential analysis distinctions regarding size, technical concepts, site conditions, etc. must be made

Turbine type???

Year of operation???

Reliability based maintenance

Increasing availability:

➔ extending uptime

→ *increasing reliability of turbine and sub-assemblies*

➔ reducing downtime

→ *qualified maintenance*

→ *efficient strategies for spar parts*

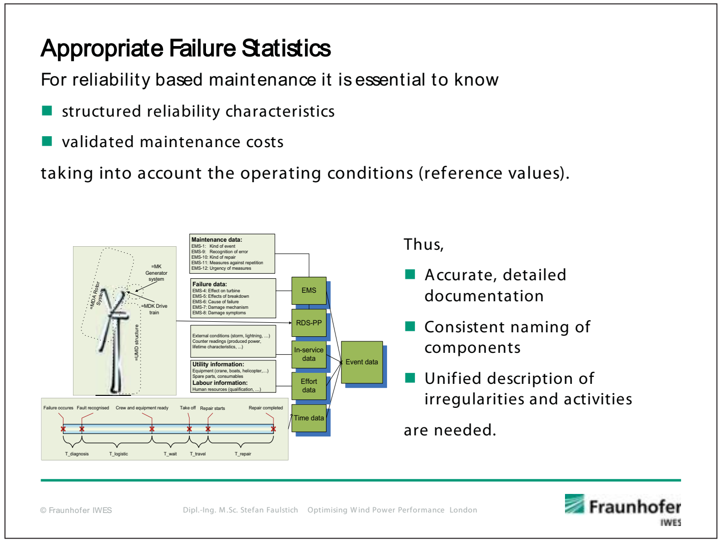
→ *additional preventive measures*

Basis for reliability based maintenance is

- structured reliability characteristics
- validated maintenance costs

in consideration of operating conditions (reference values)

➔ Accurate and detailed documentation, consistent labelling of sub-assemblies, and unified description of events are needed



Appropriate Failure Statistics

For reliability based maintenance it is essential to know

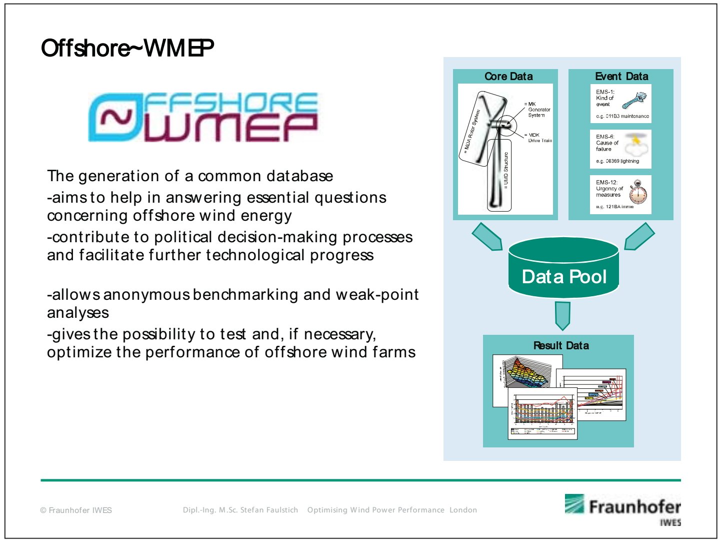
- structured reliability characteristics
- validated maintenance costs

taking into account the operating conditions (reference values).

Thus,

- Accurate, detailed documentation
- Consistent naming of components
- Unified description of irregularities and activities

are needed.



Offshore~WMEP

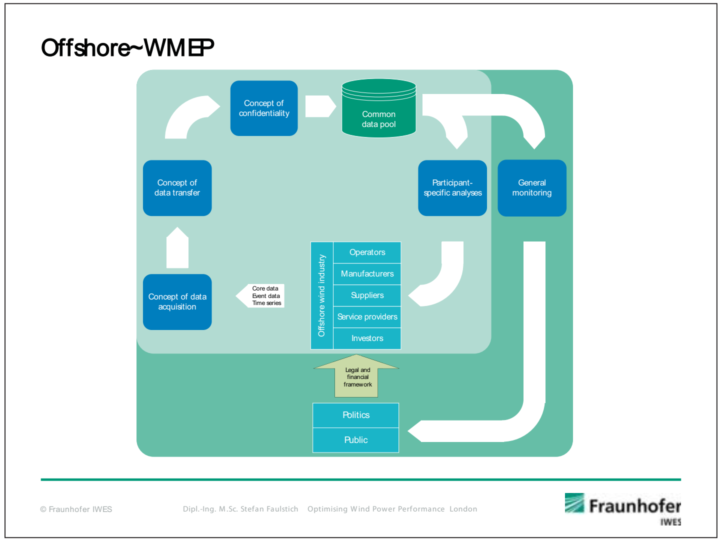
The generation of a common database

-aims to help in answering essential questions concerning offshore wind energy

-contribute to political decision-making processes and facilitate further technological progress

-allows anonymous benchmarking and weak-point analyses

-gives the possibility to test and, if necessary, optimize the performance of offshore wind farms



Offshore~WMEP

Concept of confidentiality

Common data pool

Concept of data transfer

Participant-specific analyses

General monitoring

Offshore wind industry

Operators

Manufacturers

Suppliers

Service providers

Investors

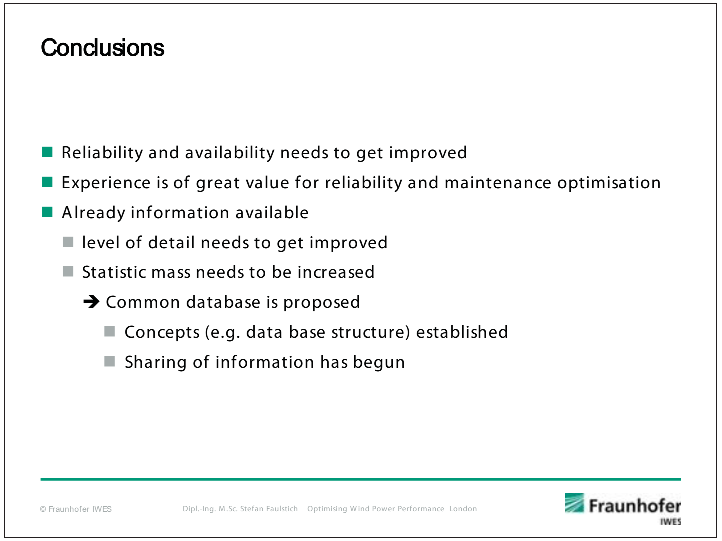
Core data
Event data
Time series

Concept of data acquisition

Legal and financial framework

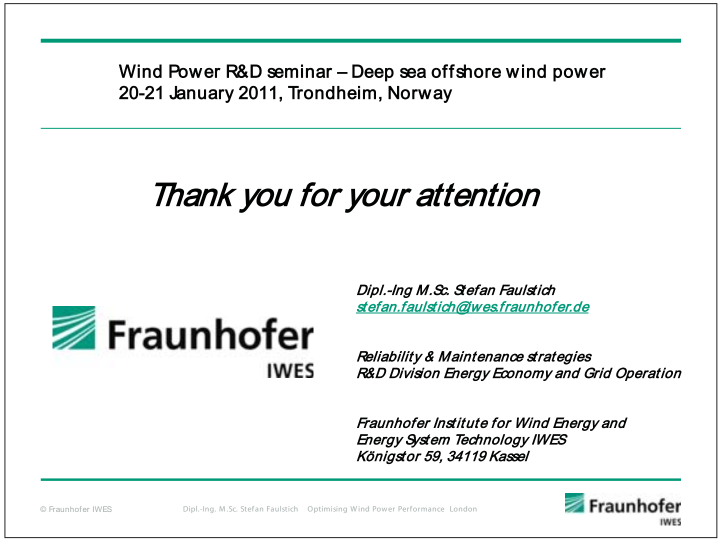
Politics

Public



Conclusions

- Reliability and availability needs to get improved
- Experience is of great value for reliability and maintenance optimisation
- Already information available
  - level of detail needs to get improved
  - Statistic mass needs to be increased
    - ➔ Common database is proposed
      - Concepts (e.g. data base structure) established
      - Sharing of information has begun



Wind Power R&D seminar – Deep sea offshore wind power
20-21 January 2011, Trondheim, Norway

Thank you for your attention

Dipl.-Ing M.Sc. Stefan Faulstich
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Reliability & Maintenance strategies
R&D Division Energy Economy and Grid Operation

Fraunhofer Institute for Wind Energy and
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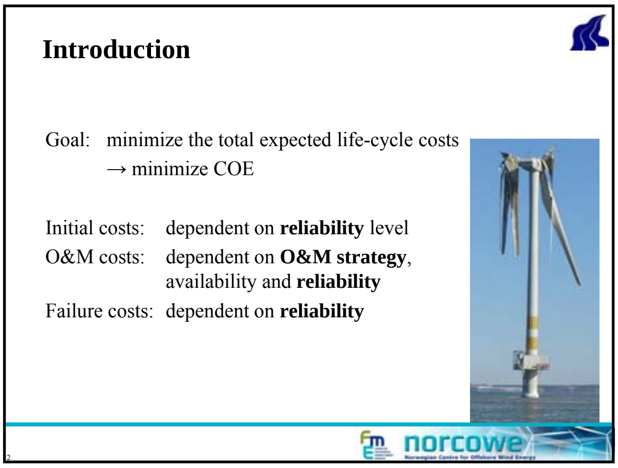
Framework for risk-based O&M planning for offshore wind turbines

John Dalsgaard Sørensen
Aalborg University, Denmark

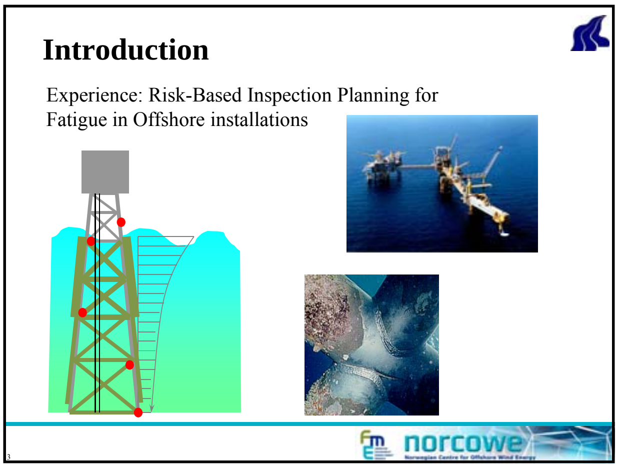
- Introduction
- Reliability
- Operation & Maintenance
- Bayesian Networks
- Examples
- Summary-Conclusions



Introduction

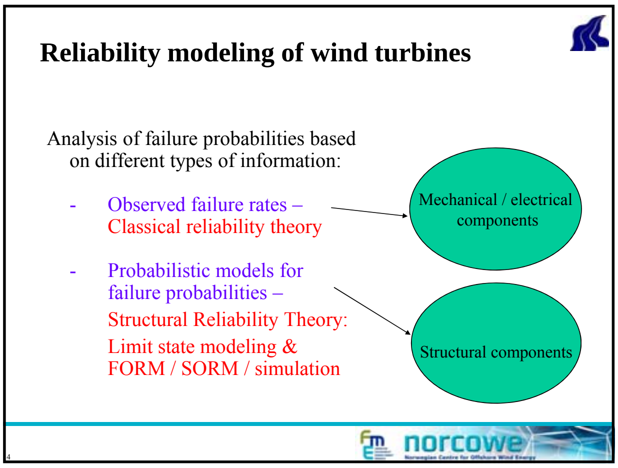
Goal: minimize the total expected life-cycle costs
→ minimize COE

Initial costs: dependent on **reliability** level
O&M costs: dependent on **O&M strategy**, availability and **reliability**
Failure costs: dependent on **reliability**



Introduction

Experience: Risk-Based Inspection Planning for Fatigue in Offshore installations



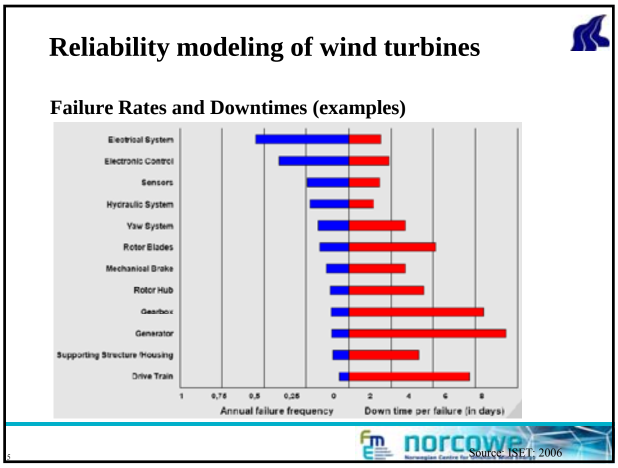
Reliability modeling of wind turbines

Analysis of failure probabilities based on different types of information:

- Observed failure rates – Classical reliability theory
- Probabilistic models for failure probabilities – Structural Reliability Theory: Limit state modeling & FORM / SORM / simulation

Mechanical / electrical components

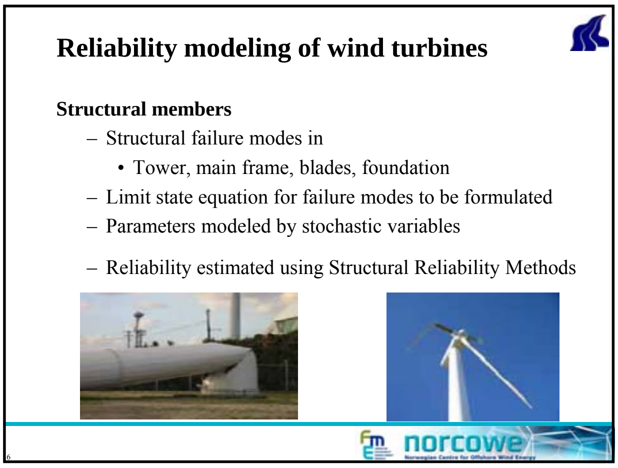
Structural components



Reliability modeling of wind turbines

Failure Rates and Downtimes (examples)

Source: ISET; 2006



Reliability modeling of wind turbines

Structural members

- Structural failure modes in
  - Tower, main frame, blades, foundation
- Limit state equation for failure modes to be formulated
- Parameters modeled by stochastic variables
- Reliability estimated using Structural Reliability Methods

Reliability modeling

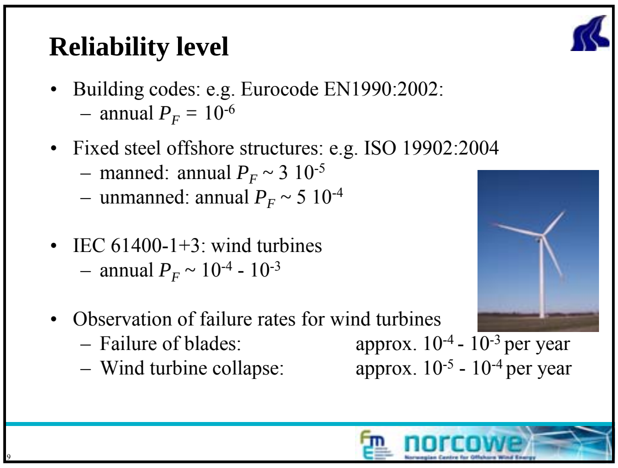
- **Physical uncertainty** Aleatory uncertainty
  - Strength parameters: Yield strength of steel
  - Annual maximum wind speed
  - Turbulence intensity
- **Measurement uncertainty** Epistemic uncertainty
  - Wind measurement
  - Strain gauge
- **Statistical uncertainty** Epistemic uncertainty
  - Limited number of data
- **Model uncertainty** Epistemic uncertainty
  - Mathematical model as an approximation of failure mode

Reliability - System aspects

- Series / parallel system?
- Damage tolerant design
- Robustness

Robustness (system reliability) can be increased by

- increased redundancy
  - mechanical load sharing
  - statistical parallel system effects
- increased ductility
- protecting the wind turbine to (unforeseen) incidents and defects
- good quality control in all phases



Reliability level

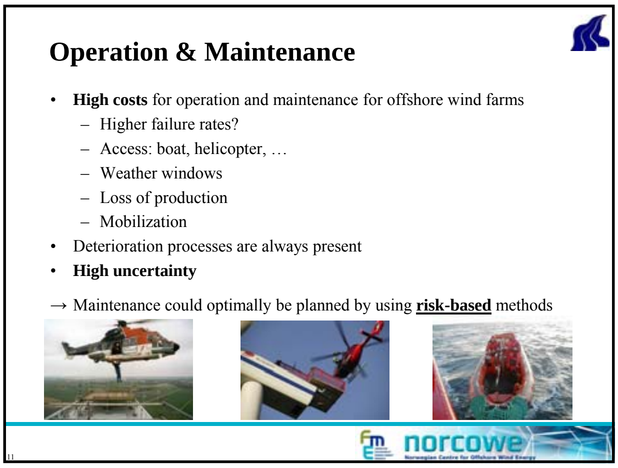
- Building codes: e.g. Eurocode EN1990:2002:
  - annual P_F = 10^{-6}
- Fixed steel offshore structures: e.g. ISO 19902:2004
  - manned: annual $P_F \sim 3\ 10^{-5}$
  - unmanned: annual $P_F \sim 5\ 10^{-4}$
- IEC 61400-1+3: wind turbines
  - annual $P_F \sim 10^{-4}$ - 10^{-3}
- Observation of failure rates for wind turbines
  - Failure of blades: approx. 10^{-4} - 10^{-3} per year
  - Wind turbine collapse: approx. 10^{-5} - 10^{-4} per year

Operation & Maintenance

How can risk-based methods be used to optimal planning of

- future inspections / monitoring (time / type)
- decisions on maintenance/repair on basis of (unknown) observations from future inspections / monitoring

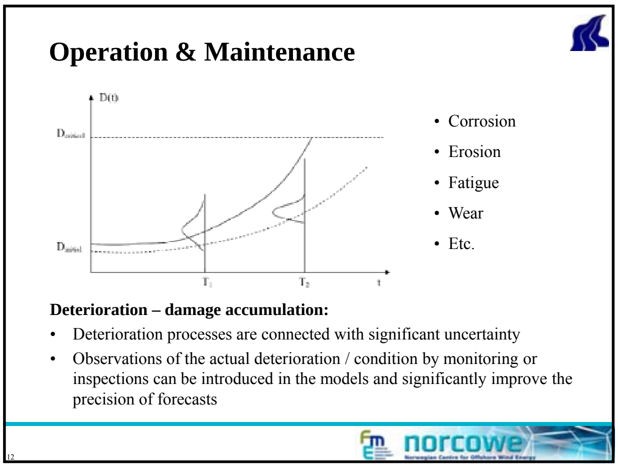
taking into account uncertainty and costs?



Operation & Maintenance

- **High costs** for operation and maintenance for offshore wind farms
  - Higher failure rates?
  - Access: boat, helicopter, …
  - Weather windows
  - Loss of production
  - Mobilization
- Deterioration processes are always present
- **High uncertainty**

→ Maintenance could optimally be planned by using **risk-based** methods



Operation & Maintenance

- Corrosion
- Erosion
- Fatigue
- Wear
- Etc.

Deterioration – damage accumulation:

- Deterioration processes are connected with significant uncertainty
- Observations of the actual deterioration / condition by monitoring or inspections can be introduced in the models and significantly improve the precision of forecasts

Operation & Maintenance

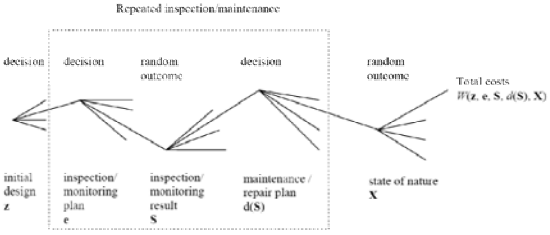
- Corrective (unplanned):
  - exchange / repair of failed components
- Preventive (planned):
  - Timetabled: inspections / service after predefined scheme
  - Conditioned: monitor condition of system and decide next on inspection based on degree of deterioration

→ based on **pre-posterior Bayesian decision model**

Operation & Maintenance

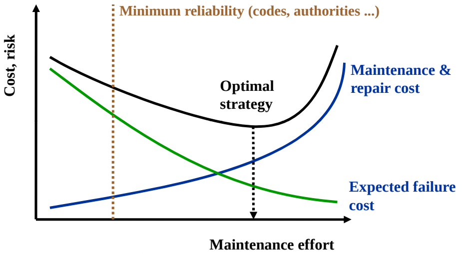
Theoretical basis – life-cycle approach:

Bayesian decision theory – pre-posterior formulation



Optimal decision: Minimum total expected costs in lifetime

Operation & Maintenance



Increasing maintenance efforts

→ Decreasing risk (expected failure cost)

Operation & Maintenance

$$\max_{\mathbf{z},\mathbf{e},d} \quad W(\mathbf{z},\mathbf{e},d) = B(\mathbf{z},\mathbf{e},d) - C_I(\mathbf{z},\mathbf{e},d) - C_{IN}(\mathbf{z},\mathbf{e},d) - C_{REP}(\mathbf{z},\mathbf{e},d) - C_F(\mathbf{z},\mathbf{e},d)$$

$$\text{s.t.} \quad z_i^l \le z_i \le z_i^u \qquad ,i = 1,\ldots,N$$

$$\Delta P_t\ (t,\mathbf{z},\mathbf{e},d) \le \Delta P_F^{\max} \qquad ,t = 1,2,\ldots,T_L$$

Expected benefits: $B(\mathbf{z},\mathbf{e},d) = \sum_{i=1}^{N} B_i \left(1 - P_F(T_i)\right) \frac{1}{(1+r)^{T_i}}$

Expected inspection costs: $C_{IN}(\mathbf{z},\mathbf{e},d) = \sum_{i=1}^{N} C_{IN,i} \left(1 - P_F(T_i)\right) \frac{1}{(1+r)^{T_i}}$

Expected repair costs: $C_{REP}(\mathbf{z},\mathbf{e},d) = \sum_{i=1}^{N} C_{R,i} P_{R_i} \frac{1}{(1+r)^{T_i}}$

Expected failure costs: $C_F(\mathbf{z},\mathbf{e},d) = \sum_{t=1}^{T_L} C_F(t) \Delta P_{F,t} P_{COL|FAT} \frac{1}{(1+r)^{t}}$

Operation & Maintenance

Failure / error types:

- Gearbox
- Generator
- Rotor blades
- Blade pitch mechanism
- Yaw mechanism
- Main shaft
- …
- Tower / support structure (jacket): cracks, corrosion, …

Operation & Maintenance

Time scale for decisions:

- Short: minutes
  - Operation: ex: Stop wind turbines if price too low - Include uncertainty on wind forecasts and price development
- Medium: days
  - Maintenance: ex: Start maintenance / repair operation on offshore wind turbine – Include uncertainty on weather windows
- Long: months / years
  - Preventive maintenance:
    - Inspection- and monitoring planning
      - Gearboxes, generators, fatigue cracks, …

Operation & Maintenance

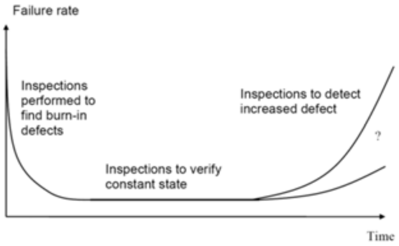
Information collection:

- Condition Monitoring System (CMS)
- SCADA data

- Inspections (direct information on defect / damage rate)
  - Example: measurement of crack size in fatigue

- Indicators (indirect information on defect / damage rate)
  - Example: gearbox metallic particle monitoring

Operation & Maintenance



Example – gearbox

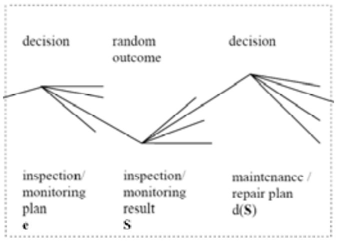
Examples of inspection methods and inspection results:

- **Visual inspection** though inspection covers → indication of extent of wear
- **Oil analysis** (time interval) → sample taken indicating extent of wear
- **Magnet** (time interval) → representative sample taken indicating extent of wear material
- **Investigation of oil filters** (time interval) → representative sample is taken indicating extent of wear material
- **Particle counting** (online) → continuously representative samples are taken indicating extent of wear material
- **Condition monitoring** (continuously) → vibration response is monitored and used to indicate mechanical changes

→ Indirect information (indicators)

Example – gearbox

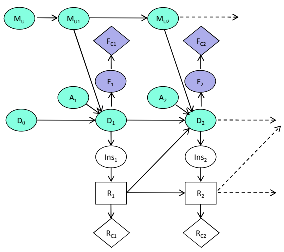
Repeated inspection/maintenance



Inspection plan	Observation(s) - indicators on damage	Decision on maintenance based on observation ex: repair now / wait to next inspection

Operation & Maintenance

Application of Bayesian Networks



Summary - Conclusions

- Risk-based methods can be used to optimal planning of
  - future inspections / monitoring (time / type)
  - decisions on maintenance/repair on basis of (unknown) observations from future inspections / monitoring

  taking into account uncertainty and costs

- Risk-based operation & maintenance
  - theoretical basis: pre-posterior decision theory

- Optimal decisions: maximize total expected benefits-costs

- Examples:
  - Inspection planning for fatigue cracks, corrosion,…
  - O&M for gearbox exposed to deterioration

Framework for risk-based O&M planning for offshore wind turbines

Thank You For Your Attention

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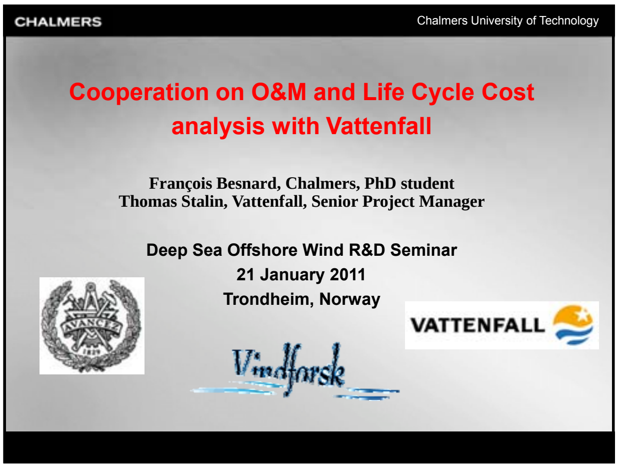
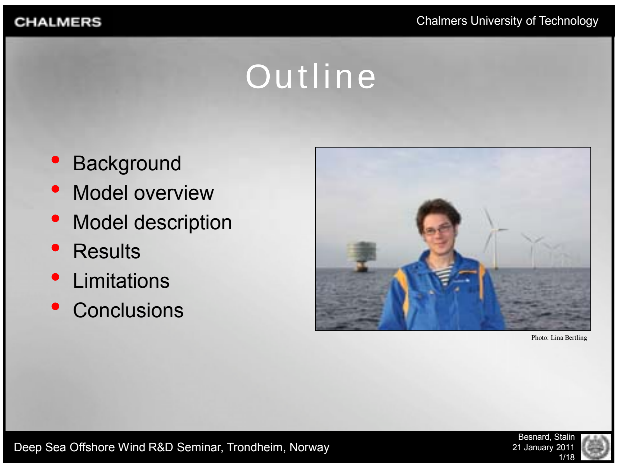


Cooperation on O&M and Life Cycle Cost analysis with Vattenfall

François Besnard, Chalmers, PhD student
Thomas Stalin, Vattenfall, Senior Project Manager

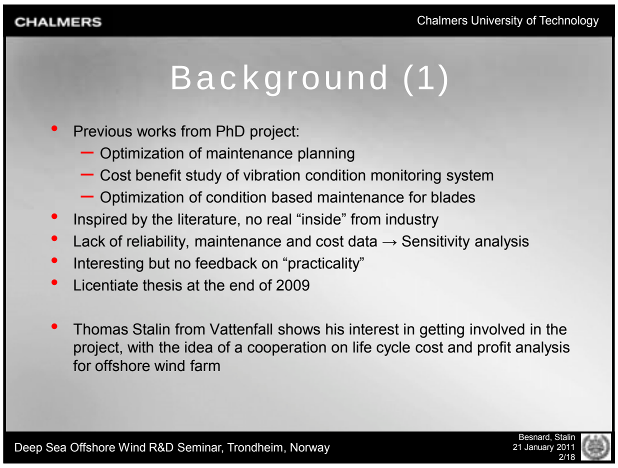
Deep Sea Offshore Wind R&D Seminar
21 January 2011
Trondheim, Norway



Outline

- Background
- Model overview
- Model description
- Results
- Limitations
- Conclusions

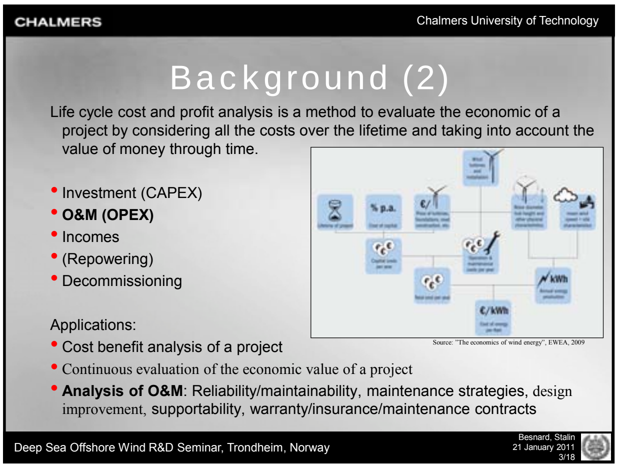
Photo: Lina Bertling



Background (1)

- Previous works from PhD project:
  - Optimization of maintenance planning
  - Cost benefit study of vibration condition monitoring system
  - Optimization of condition based maintenance for blades
- Inspired by the literature, no real “inside” from industry
- Lack of reliability, maintenance and cost data → Sensitivity analysis
- Interesting but no feedback on “practicality”
- Licentiate thesis at the end of 2009

- Thomas Stalin from Vattenfall shows his interest in getting involved in the project, with the idea of a cooperation on life cycle cost and profit analysis for offshore wind farm



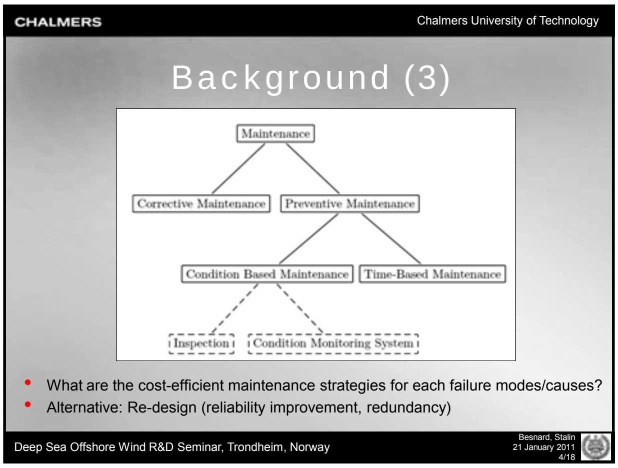
Background (2)

Life cycle cost and profit analysis is a method to evaluate the economic of a project by considering all the costs over the lifetime and taking into account the value of money through time.

- Investment (CAPEX)
- **O&M (OPEX)**
- Incomes
- (Repowering)
- Decommissioning

Source: "The economics of wind energy", EWEA, 2009

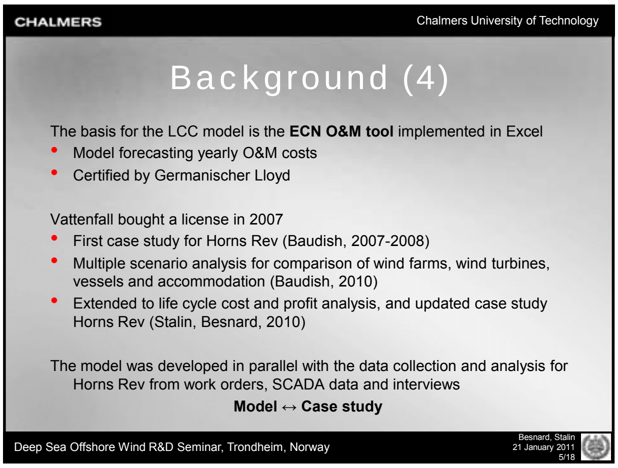
Applications:
- Cost benefit analysis of a project
- Continuous evaluation of the economic value of a project
- **Analysis of O&M**: Reliability/maintainability, maintenance strategies, design improvement, supportability, warranty/insurance/maintenance contracts



Background (3)

Maintenance
Corrective Maintenance
Preventive Maintenance
Condition Based Maintenance
Time-Based Maintenance
Inspection
Condition Monitoring System

- What are the cost-efficient maintenance strategies for each failure modes/causes?
- Alternative: Re-design (reliability improvement, redundancy)



Background (4)

The basis for the LCC model is the **ECN O&M tool** implemented in Excel
- Model forecasting yearly O&M costs
- Certified by Germanischer Lloyd

Vattenfall bought a license in 2007
- First case study for Horns Rev (Baudish, 2007-2008)
- Multiple scenario analysis for comparison of wind farms, wind turbines, vessels and accommodation (Baudish, 2010)
- Extended to life cycle cost and profit analysis, and updated case study Horns Rev (Stalin, Besnard, 2010)

The model was developed in parallel with the data collection and analysis for Horns Rev from work orders, SCADA data and interviews

Model ↔ Case study

Model Overview

The model focuses especially on the O&M phase:

- Simple investment and decommissioning model
- Simple energy yield model (based on capacity factor + availability)
- Simple electricity price scenarios (incentive system + prognosis)

O&M cost structure:

- Corrective maintenance
- Service/Preventive maintenance
- Retrofits
- Catastrophic/serial failures

Direct costs: Staff, material, vessel/equipment

Indirect costs: Revenue losses

- **Fixed costs** (administration, transportation, logistic, O&M facilities, insurance, maintenance contracts…)

Insurance/Warranty/Maintenance contracts cover part of the costs

Model Description (1)

Corrective maintenance:

- Frequency maintenance events (repair, replacement, preparation)
- Seasonal distribution (i.e. planning with condition based maintenance)
- Maintenance procedure:
  - Spare part logistic time
  - Vessels and equipment, and duration of use during repair
  - Number of technicians
  - Repair times
  - Splitting activity
- Cost for the material and spare part
- Applicable retrofit (defined in a similar way in a separate worksheet)
- Applicable Warranty/Insurance (spare part, vessels, production losses)

Data structured according to RDS-PP, VGB, 2007

Model Description (2)

Vessel characteristics and costs:

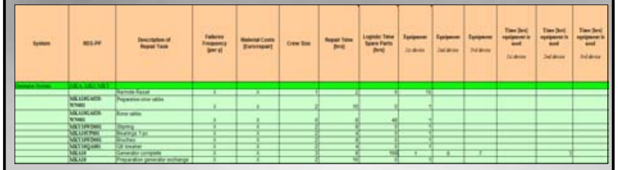
- Weather constraints (wind and waves)
- Logistic and travelling times
- MOB/DEMOB costs and daily rate
- Clustering

The accessibility is modeled as a **waiting time** depending on the weather constraints. It is calculated based on wind and wave statistics

Preventive maintenance activities:

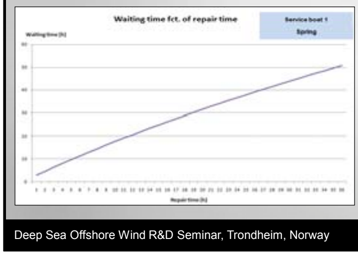
- Seasonal distribution
- Duration
- Staff, equipment,

General wind farm data (capacity factors/seasons, staff costs and working hours, number of wind turbines) and **overhead costs**



	Maintenance type 1		Minor service maintenance		
Number of occurances during lifetime of 20 years		20	year		
Duration of maintenance		24	hrs		
Crew size		2,4	-		
Mat. Costs		X	Euro		
Type of equipment		2	service boat 2		
Travel time to or from the wind farm (one-way) [hr]		1	hrs		
Distribution over seasons		winter	spring	summer	autumn
		5%	20%	65%	10%
Length of working day [hr]	8.00	8.00	8.00	8.00	8.00
Working period	3.00	0.15	0.60	1.95	0.30

- Examples of some input data for corrective and preventive maintenance



- Examples of data for vessels and waiting time defined by a polynomial function

Model Description (3)

The life cycle cost scenario:

- Investment costs (development, installation, WTs, foundations, grid), decommissioning costs, WF lifetime
- Real discount rate
- Electricity price scenarios
- Failure distribution for each corrective maintenance activity:
  - Constant failure rate (cf. "failure description")
  - Continuous improvement

  + Retrofits

  - Renewal process with Weibull distribution
  - Alternative for flexibility: Defined for each year
- Service/preventive maintenance activities defined for each year
- Service and corrective maintenance, contracted availability during warranty
- Possibility to use historical costs (overwrite calculated costs)

Results

- Cost distributions with/without warranty and insurances
- Cumulative income and cost

Project performance indicators:

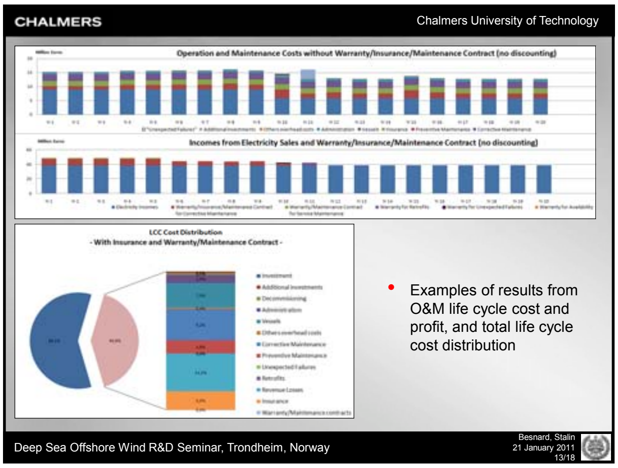
- Net Present Value (NPV)
- Internal Rate of Return (IRR)
- Profitability Index (PI)
- Break-even year
- Levelized Cost of Energy (CoE)

$$NPV = \sum_{t=0}^{20} \frac{I_t}{(1+r)^t} - C_{Inv} - \sum_{t=0}^{20} \frac{C_{t,O\&M}}{(1+r)^t} - \frac{C_{Dec}}{(1+r)^{20}}$$

$$PI = \frac{C_{Inv} + \sum_{t=0}^{N} \frac{I_t - C_t}{(1+r)^t}}{C_{Inv}}$$

$$CoE = \frac{NPV\ of\ Costs}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}}$$

- Remaining economic value
- Possibility to focus on a specific year



- Examples of results from O&M life cycle cost and profit, and total life cycle cost distribution

Limitations

Basis model:

- Production losses during waiting time are underestimated (ECN OMCE*)
- Only fixed transportation strategies (i.e. not depending on wind/wave condition at failure) → Complex, need time-series and simulation tool to consider number of failures and weather prognosis *
- No constraints on availability of staff, vessel, spare part, equipment
  → Limited evaluation of supportability *

For LCC:

- Detailed investment costs and driving factors (depends on application)
- Scenarios for material, staff and vessel costs
- Risk analysis *
- Impact of condition based maintenance assessed subjectively, or estimated in a separated model *

Conclusions

- A tool for life cycle cost and profit analysis with special focus on O&M
- A successful project thanks to a close cooperation between Vattenfall and Chalmers:
  - Mutual interests
  - Weekly meetings
  - Access to reliability and cost data (NDA)
  - Hard work on data analysis

→ Need for structured and automatized reliability and maintenance data collection (implementation in SAP system at Vattenfall) and training maintenance personnel

- Future case studies: Continuation Horns Rev, Lillgrund, Kentish Flats, Egmond aan Zee

Thank you for your attention!

Questions?

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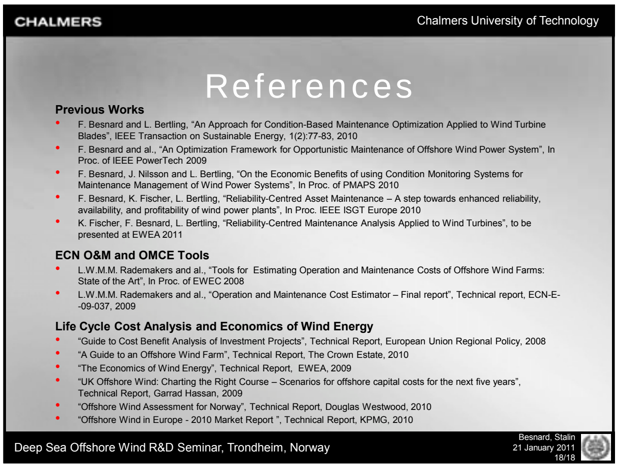

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- “Offshore Wind Assessment for Norway”, Technical Report, Douglas Westwood, 2010
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HSE challenges related to offshore renewable energy

- A study of HSE issues related to current and future offshore wind power concepts

Presentation for the deep sea offshore wind power R&D seminar 2011-01-21
Camilla K Tveiten
Eirik Albrechtsen
Jørn Heggset
Matthias Hofmann
Per Kristian Norddal
Erik Jersin

HSE challenges related to offshore renewable energy

- Object for the study: to identify the HSE factors related to offshore renewable energy production (with focus on offshore wind energy).
- Our report:
  - Lists different offshore wind developing concepts that exist today as well developments that may result in future concepts.
    - Technical solutions and operation philosophy (both fixed and floating concepts)
    - A brief summary of actors and plans for development in Norway
    - Regulations and standards for offshore renewable energy are briefly listed
  - A qualitative analysis of the hazards that exist for different stages for offshore wind turbine farms.
    - Several possible accident scenarios
      - possible consequences for humans, environment and material issues.
    - A qualitative prioritization of the scenarios.
    - Issues related to risk mitigation and regulations

Potential areas of development

- Offshore wind farms are planned along the whole coast of Norway
  - bottom fixed or floating wind turbines.
  - distances from shore vary mainly from 1 to 60 km
  - the Southern North Sea has a distance of around 150 km to the shore.
  - many offshore wind farms are in the concept stadium

Source: NVE (2010): Havvind – Forslag til utredningsområder.

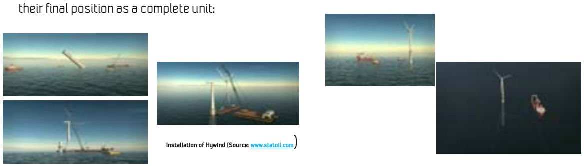
Installation

Bottom fixed substructures has to be transported to the offshore wind farm with transport vessels before fixed to the seabed:

Lowering of the jacket or tripod onto the pin piles (source www.alpha-ventus.de)

Transport and erection of a fully onshore constructed wind turbine at Beatrice (Source: www.scaldis-smc.com)

Floating structures and the turbine are preassembled close to the construction port and then towed out to their final position as a complete unit:



Installation of Hywind (Source: www.statoil.com)

Access methods

- Access not always possible because of weather conditions
- Three main alternatives for access:
  - Direct landing by use of vessel
  - Use of equipment to compensate for motion
  - Helicopter

Source: www.southboatssp.co.uk

Source: www.ampelmann.nl

Source: Repower

- Possible to have living quarters near the offshore wind farm to shorten travel time
  - Access to turbine still involves the same challenges

Overview of access types and (dis-) advantages

Type	Signicant wave height in metres	Average wind speed in m/s (1hr at 10 m height)	Example of application	Advantages	Disadvantages
Direct boat landing	0.5 - 1.5 (rubber boats) 2.5 (SWATH)	10	Nysted (rubber boats) Bard 1 (SWATH)	Simple	Sensitive to marine growth and icing
Boat landing with motion compensating	2 - 2.5 (OAS) 2 - 3 (Ampelmann)	11.5 (OAS) 14 (Ampelmann)	Tested	Not sensitive to marine growth	Installation of additonal equipment on the vessel required
Hoisting by crane	2.5	?	None	Not sensitive to marine growth	Remote control of crane Maintenance offshore required
Helicopter	-	15 - 20	Horns Rev, alpha ventus	Not sensitive to waves Fast transport	Expensive

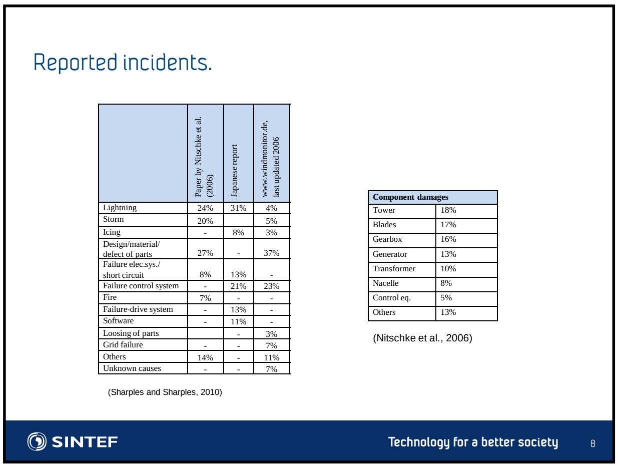
HSE – more frequent incidents and accidents?

- Damage to construction (rotor blades fall loose, the construction collapses)
- Fire
- Crane- and lift related incidents (Loss of -/damage to equipment)
- Diving accidents
- Occupational accidents (crush/squeeze injuries, fractures, head injuries, drowning etc.)
  - "Just bare luck that more serious accidents do not happen"
- Corrosion
- Cable rupture/cable displacement

Source : http://www.telegraph.co.uk/

Source: http://wind-energy.gemzies.com/

Source: outside-blog.away.com



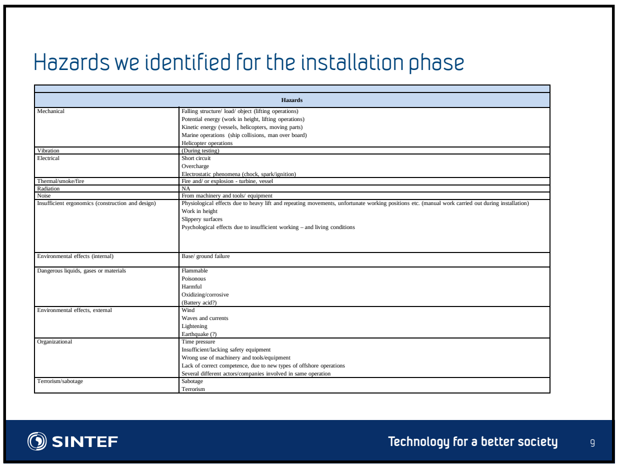
Reported incidents.

	Paper by Nitschke et al. (2006)	Japanese report	www.windmonitor.de, last updated 2006
Lightning	24%	31%	4%
Storm	20%		5%
Icing	-	8%	3%
Design/material/ defect of parts	27%	-	37%
Failure elec.sys./ short circuit	8%	13%	-
Failure control system	-	21%	23%
Fire	7%	-	-
Failure-drive system	-	13%	-
Software	-	11%	-
Loosing of parts		-	3%
Grid failure	-	-	7%
Others	14%	-	11%
Unknown causes	-	-	7%

(Sharples and Sharples, 2010)

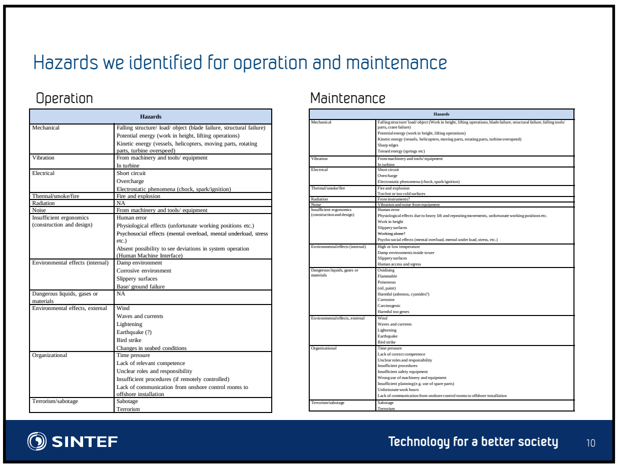
Component damages	
Tower	18%
Blades	17%
Gearbox	16%
Generator	13%
Transformer	10%
Nacelle	8%
Control eq.	5%
Others	13%

(Nitschke et al., 2006)



Hazards we identified for the installation phase

Hazards	
Mechanical	Falling structure/ load/ object (lifting operations) Potential energy (work in height, lifting operations) Kinetic energy (vessels, helicopters, moving parts) Marine operations (ship collisions, man over board) Helicopter operations
Vibration	(During testing)
Electrical	Short circuit Overcharge Electrostatic phenomena (chock, spark/ignition)
Thermal/smoke/fire	Fire and/ or explosion - turbine, vessel
Radiation	NA
Noise	From machinery and tools/ equipment
Insufficient ergonomics (construction and design)	Physiological effects due to heavy lift and repeating movements, unfortunate working positions etc. (manual work carried out during installation) Work in height Slippery surfaces Psychological effects due to insufficient working – and living conditions
Environmental effects (internal)	Base/ ground failure
Dangerous liquids, gases or materials	Flammable Poisonous Harmful Oxidizing/corrosive (Battery acid?)
Environmental effects, external	Wind Waves and currents Lightening Earthquake (?)
Organizational	Time pressure Insufficient/lacking safety equipment Wrong use of machinery and tools/equipment Lack of correct competence, due to new types of offshore operations Several different actors/companies involved in same operation
Terrorism/sabotage	Sabotage Terrorism



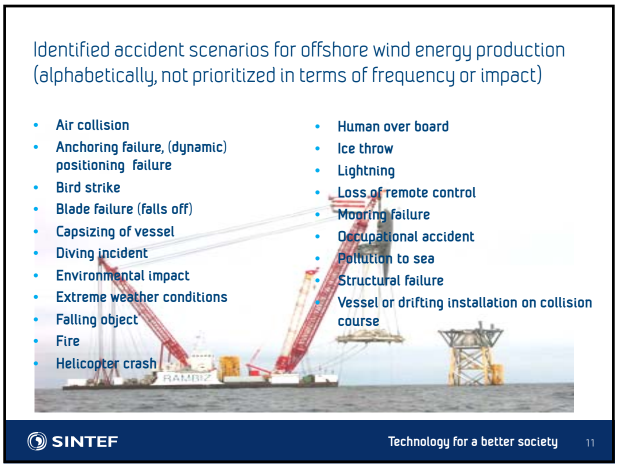
Hazards we identified for operation and maintenance

Operation

Hazards	
Mechanical	Falling structure/ load/ object (blade failure, structural failure) Potential energy (work in height, lifting operations) Kinetic energy (vessels, helicopters, moving parts, rotating parts, turbine overspeed)
Vibration	From machinery and tools/ equipment In turbine
Electrical	Short circuit Overcharge Electrostatic phenomena (chock, spark/ignition)
Thermal/smoke/fire	Fire and explosion
Radiation	NA
Noise	From machinery and tools/ equipment
Insufficient ergonomics (construction and design)	Human error Physiological effects (unfortunate working positions etc.) Psychosocial effects (mental overload, mental underload, stress etc.) Absent possibility to see deviations in system operation (Human Machine Interface)
Environmental effects (internal)	Damp environment Corrosive environment Slippery surfaces Base/ ground failure
Dangerous liquids, gases or materials	NA
Environmental effects, external	Wind Waves and currents Lightening Earthquake (?) Bird strike Changes in seabed conditions
Organizational	Time pressure Lack of relevant competence Unclear roles and responsibility Insufficient procedures (if remotely controlled) Lack of communication from onshore control rooms to offshore installation
Terrorism/sabotage	Sabotage Terrorism

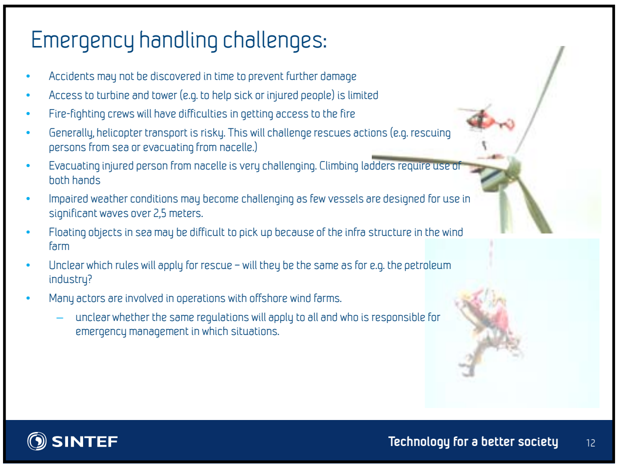
Maintenance

Hazards	
Mechanical	Falling structure/ load/ object (Work in height, lifting operations, blade failure, structural failure, falling tools/ parts, crane failure) Potential energy (work in height, lifting operations) Kinetic energy (vessels, helicopters, moving parts, rotating parts, turbine overspeed) Sharp edges Tensed energy (springs etc)
Vibration	From machinery and tools/ equipment In turbine
Electrical	Short circuit Overcharge Electrostatic phenomena (chock, spark/ignition)
Thermal/smoke/fire	Fire and explosion Too hot or too cold surfaces
Radiation	From instruments?
Noise	Vibration and noise from equipment
Insufficient ergonomics (construction and design)	Human error Physiological effects due to heavy lift and repeating movements, unfortunate working positions etc. Work in height Slippery surfaces Working alone? Psycho social effects (mental overload, mental under load, stress, etc.)
Environmental effects (internal)	High or low temperature Damp environments inside tower Slippery surfaces Human access and egress
Dangerous liquids, gases or materials	Oxidising Flammable Poisonous (oil, paint) Harmful (asbestos, cyanides?) Corrosive Carcinogenic Harmful too genes
Environmental effects, external	Wind Waves and currents Lightening Earthquake Bird strike
Organizational	Time pressure Lack of correct competence Unclear roles and responsibility Insufficient procedures Insufficient safety equipment Wrong use of machinery and equipment Insufficient planning(e.g. use of spare parts) Unfortunate work hours Lack of communication from onshore control rooms to offshore installation
Terrorism/sabotage	Sabotage Terrorism



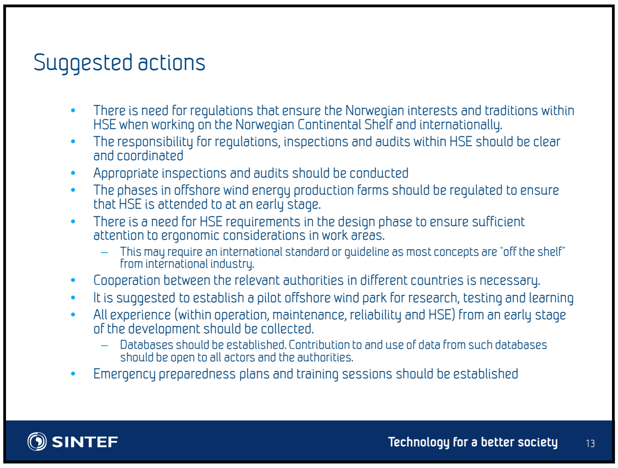
Identified accident scenarios for offshore wind energy production (alphabetically, not prioritized in terms of frequency or impact)

- **Air collision**
- **Anchoring failure, (dynamic) positioning failure**
- **Bird strike**
- **Blade failure (falls off)**
- **Capsizing of vessel**
- **Diving incident**
- **Environmental impact**
- **Extreme weather conditions**
- **Falling object**
- **Fire**
- **Helicopter crash**
- **Human over board**
- **Ice throw**
- **Lightning**
- **Loss of remote control**
- **Mooring failure**
- **Occupational accident**
- **Pollution to sea**
- **Structural failure**
- **Vessel or drifting installation on collision course**



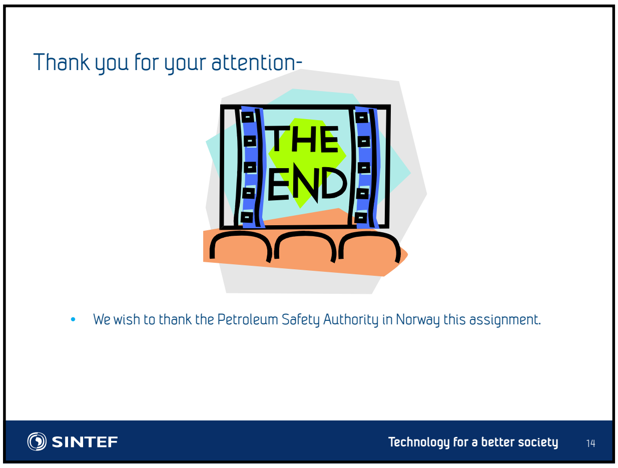
Emergency handling challenges:

- Accidents may not be discovered in time to prevent further damage
- Access to turbine and tower (e.g. to help sick or injured people) is limited
- Fire-fighting crews will have difficulties in getting access to the fire
- Generally, helicopter transport is risky. This will challenge rescues actions (e.g. rescuing persons from sea or evacuating from nacelle.)
- Evacuating injured person from nacelle is very challenging. Climbing ladders require use of both hands
- Impaired weather conditions may become challenging as few vessels are designed for use in significant waves over 2,5 meters.
- Floating objects in sea may be difficult to pick up because of the infra structure in the wind farm
- Unclear which rules will apply for rescue – will they be the same as for e.g. the petroleum industry?
- Many actors are involved in operations with offshore wind farms.
  - unclear whether the same regulations will apply to all and who is responsible for emergency management in which situations.



Suggested actions

- There is need for regulations that ensure the Norwegian interests and traditions within HSE when working on the Norwegian Continental Shelf and internationally.
- The responsibility for regulations, inspections and audits within HSE should be clear and coordinated
- Appropriate inspections and audits should be conducted
- The phases in offshore wind energy production farms should be regulated to ensure that HSE is attended to at an early stage.
- There is a need for HSE requirements in the design phase to ensure sufficient attention to ergonomic considerations in work areas.
  - This may require an international standard or guideline as most concepts are "off the shelf" from international industry.
- Cooperation between the relevant authorities in different countries is necessary.
- It is suggested to establish a pilot offshore wind park for research, testing and learning
- All experience (within operation, maintenance, reliability and HSE) from an early stage of the development should be collected.
  - Databases should be established. Contribution to and use of data from such databases should be open to all actors and the authorities.
- Emergency preparedness plans and training sessions should be established



Thank you for your attention-

- We wish to thank the Petroleum Safety Authority in Norway this assignment.

E) Installation & sub-structures

Coupled analysis of floating wind turbines, Elizabeth Passano, MARINTEK

The effects of breaking wave-induced currents, PhD stud Sung-Jin Choi,
Uni of Stavanger

Effects of Foundation Modeling Methodology on the Dynamic Response of
Offshore Wind Turbine Support, PhD stud Eric van Buren, NTNU

Wind Power R&D seminar – deep sea offshore wind, Trondheim 20-21 January 2011

Coupled Analysis
of
Floating Wind Turbines

Harald Ormberg and Elizabeth Passano
MARINTEK

Background

- Need for integrated analysis of floating wind turbines
- Difficult to couple existing programs
- Decision to add functionality to our existing tool for floating offshore structures (SIMO and RIFLEX)

Floating wind turbine system

Main components:

Rotor
Nacelle

Tower

Support structure
(SPAR buoy)

Mooring lines
Power cables

Floating wind turbine system

Aerodynamic loads on blades, tower and floater

Interaction between blade motions and aerodynamic loads

Control of blade pitch and applied electrical torque

Hydrodynamic loads on floater, mooring lines and power cable

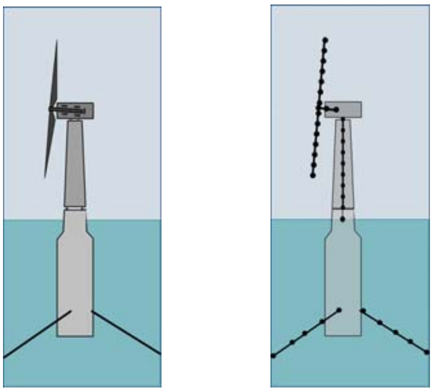
Interaction between mooring line dynamics and floater motions.

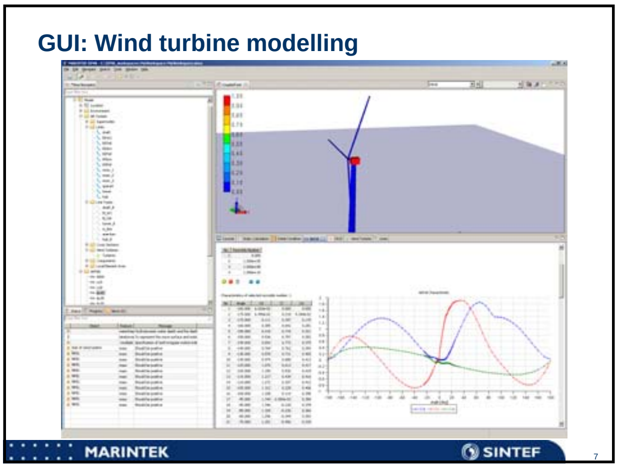
Seafloor contact

RIFLEX: New Functionality

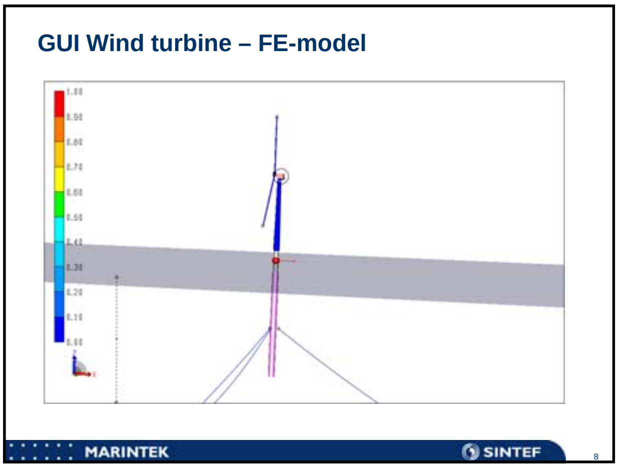
- Wind loads on blade elements based on foil formulation
- Aerodynamic interaction based on Blade Element Momentum method (BEM-method)
- Control systems for blade pitch and electrical torque
- Apply blade pitch as prescribed relative rotation

Finite element model of a floating wind turbine

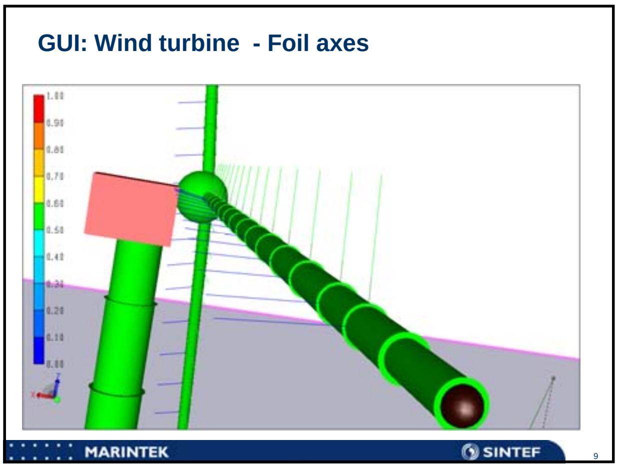




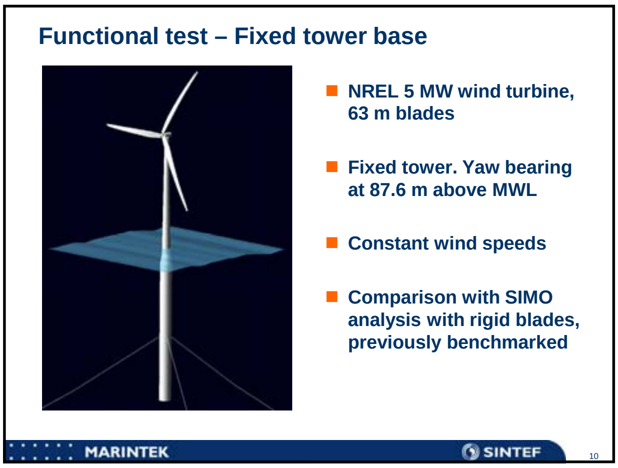
GUI: Wind turbine modelling



GUI Wind turbine – FE-model

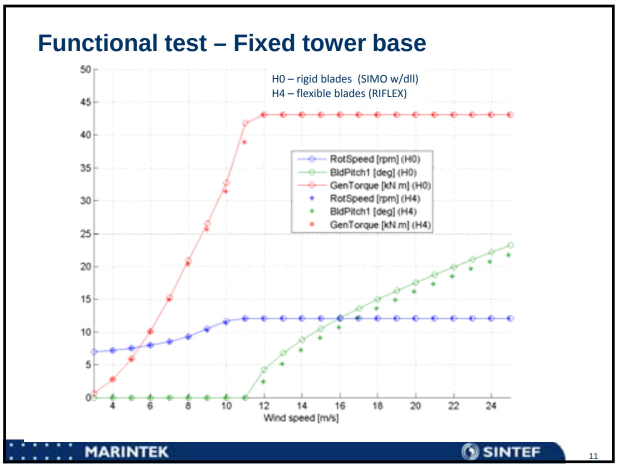


GUI: Wind turbine - Foil axes



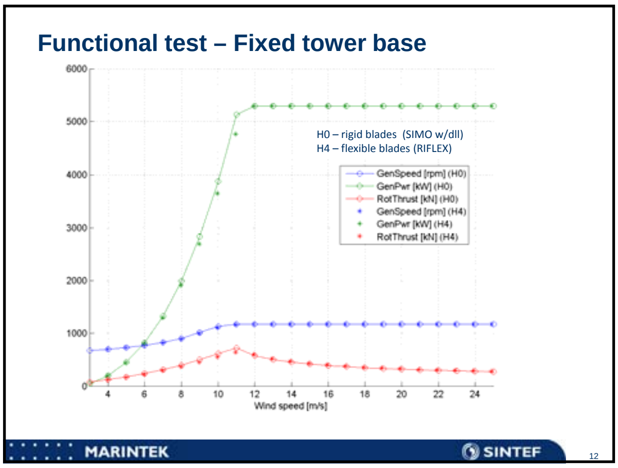
Functional test – Fixed tower base

- **NREL 5 MW wind turbine, 63 m blades**
- **Fixed tower. Yaw bearing at 87.6 m above MWL**
- **Constant wind speeds**
- **Comparison with SIMO analysis with rigid blades, previously benchmarked**



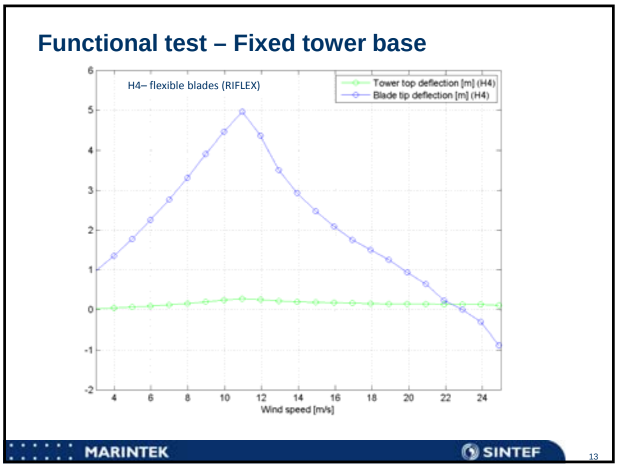
Functional test – Fixed tower base

H0 – rigid blades (SIMO w/dll)
H4 – flexible blades (RIFLEX)



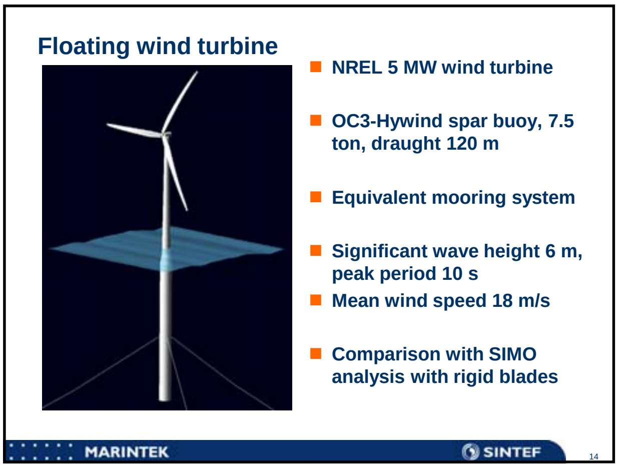
Functional test – Fixed tower base

H0 – rigid blades (SIMO w/dll)
H4 – flexible blades (RIFLEX)



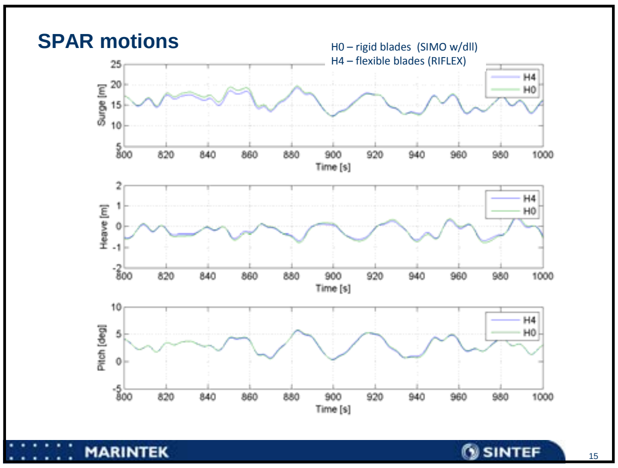
Functional test – Fixed tower base

H4– flexible blades (RIFLEX)



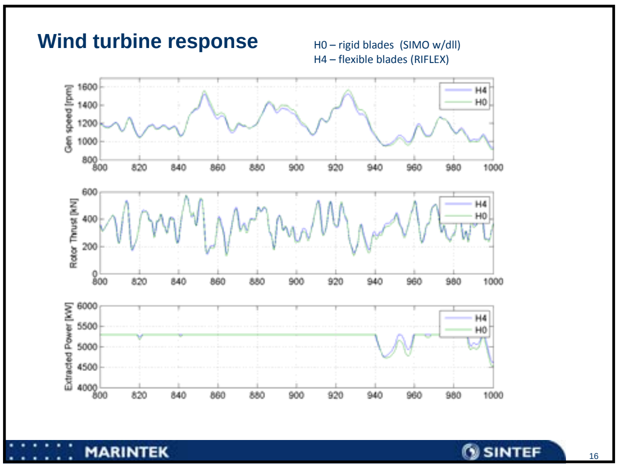
Floating wind turbine

- NREL 5 MW wind turbine
- OC3-Hywind spar buoy, 7.5 ton, draught 120 m
- Equivalent mooring system
- Significant wave height 6 m, peak period 10 s
- Mean wind speed 18 m/s
- Comparison with SIMO analysis with rigid blades



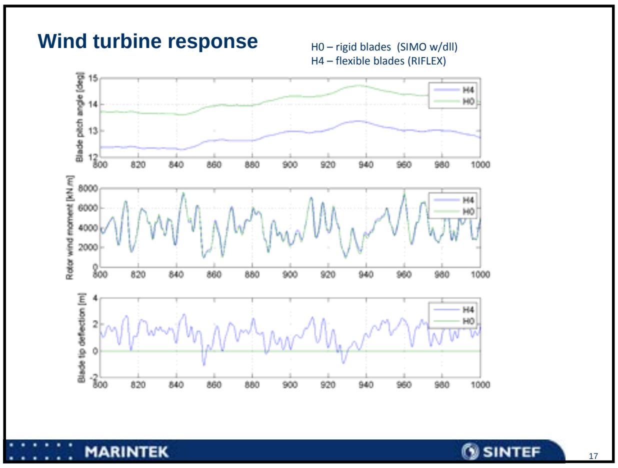
SPAR motions

H0 – rigid blades (SIMO w/dll)
H4 – flexible blades (RIFLEX)



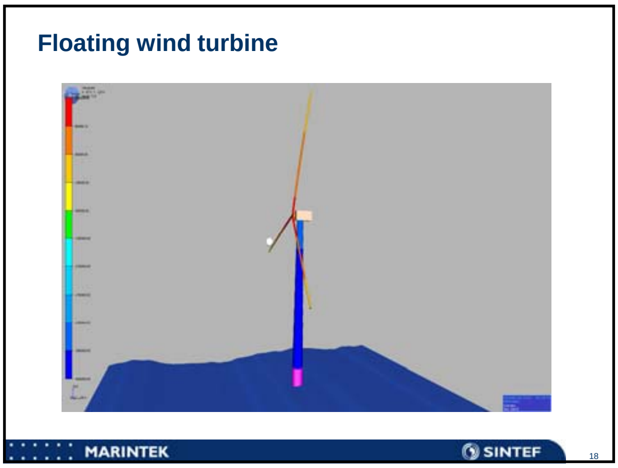
Wind turbine response

H0 – rigid blades (SIMO w/dll)
H4 – flexible blades (RIFLEX)



Wind turbine response

H0 – rigid blades (SIMO w/dll)
H4 – flexible blades (RIFLEX)



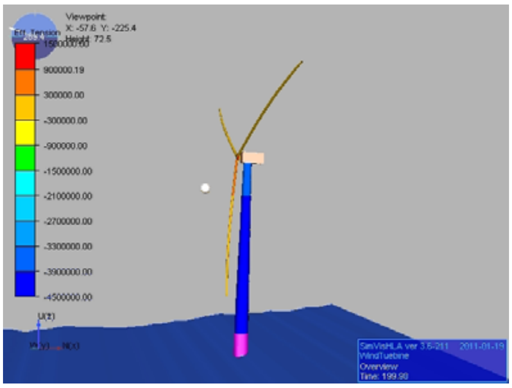
Floating wind turbine

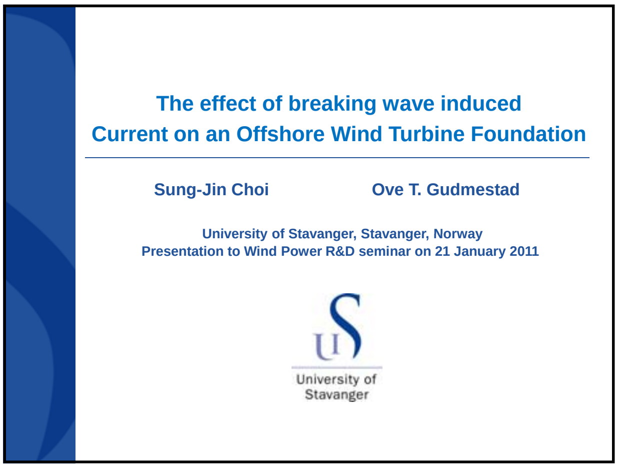
Conclusions

- A tool for coupled analysis of floating wind turbines has been developed
  - Nonlinear finite element method
  - Stochastic waves and wind
  - Interaction between mooring dynamics and tower motions
  - Interaction between blade dynamics and aerodynamic loads
  - Aerodynamic loads based on the blade element momentum method
- Graphical User Interface to aid modeling and analysis

Planned work

- Publish benchmarking of analysis tool and case study
- Ease modeling of blade twist
- 3D wind field
- Comparison with full scale measurements (Hywind)
- Continued development of GUI



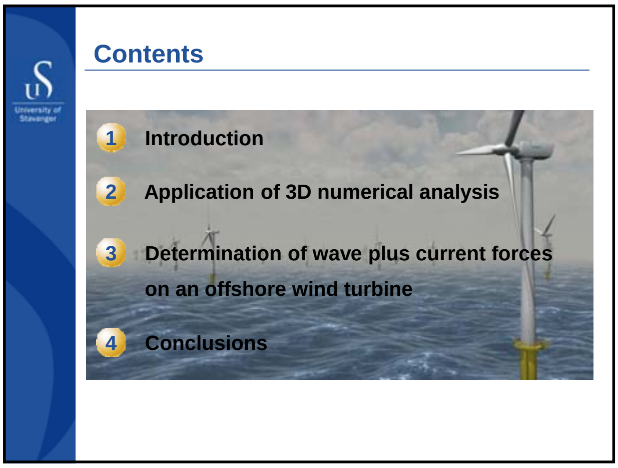


The effect of breaking wave induced Current on an Offshore Wind Turbine Foundation

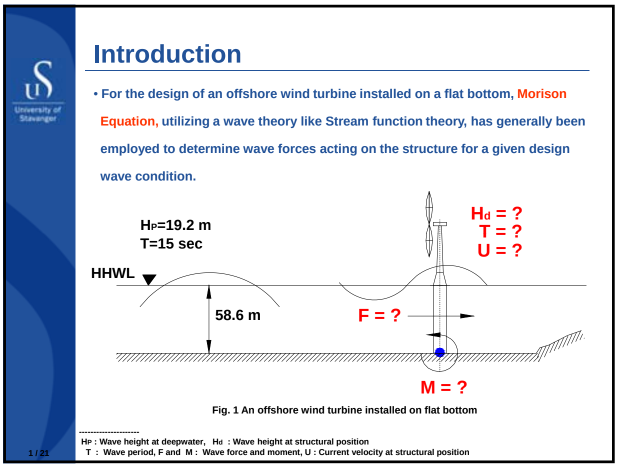
Sung-Jin Choi **Ove T. Gudmestad**

University of Stavanger, Stavanger, Norway

Presentation to Wind Power R&D seminar on 21 January 2011



Contents

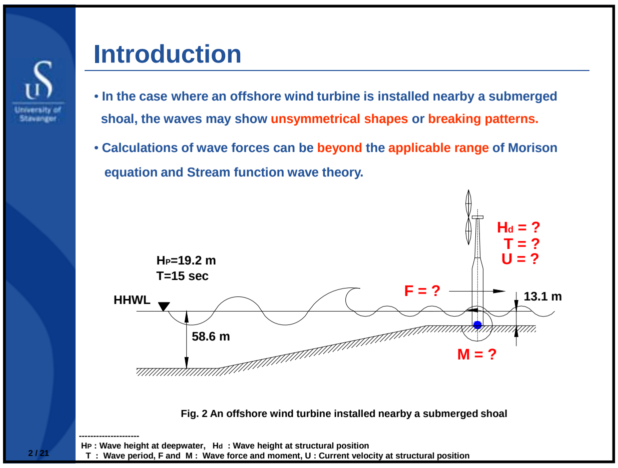


Introduction

- For the design of an offshore wind turbine installed on a flat bottom, Morison Equation, utilizing a wave theory like Stream function theory, has generally been employed to determine wave forces acting on the structure for a given design wave condition.

Fig. 1 An offshore wind turbine installed on flat bottom

H_P : Wave height at deepwater, H_d : Wave height at structural position
T : Wave period, F and M : Wave force and moment, U : Current velocity at structural position



Introduction

- In the case where an offshore wind turbine is installed nearby a submerged shoal, the waves may show unsymmetrical shapes or breaking patterns.
- Calculations of wave forces can be beyond the applicable range of Morison equation and Stream function wave theory.

Fig. 2 An offshore wind turbine installed nearby a submerged shoal

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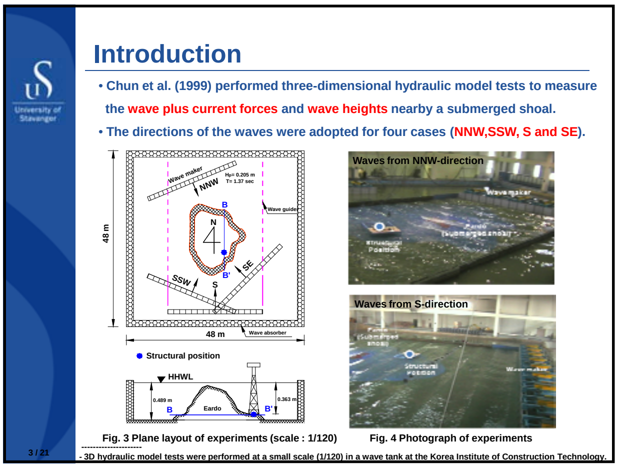
H_P : Wave height at deepwater, H_d : Wave height at structural position
T : Wave period, F and M : Wave force and moment, U : Current velocity at structural position



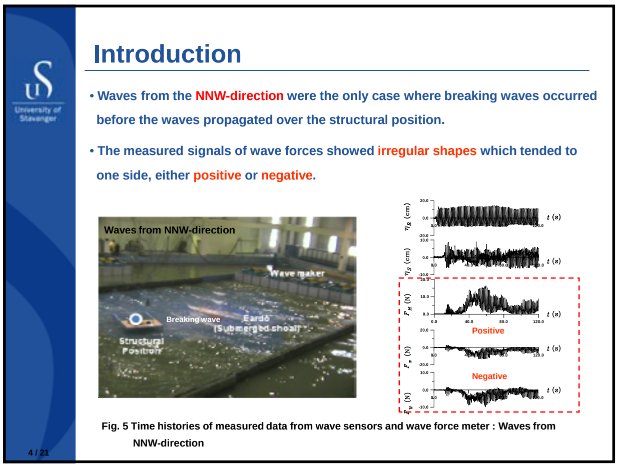
Introduction

- Chun et al. (1999) performed three-dimensional hydraulic model tests to measure the wave plus current forces and wave heights nearby a submerged shoal.
- The directions of the waves were adopted for four cases (NNW,SSW, S and SE).

Fig. 3 Plane layout of experiments (scale : 1/120)

Fig. 4 Photograph of experiments

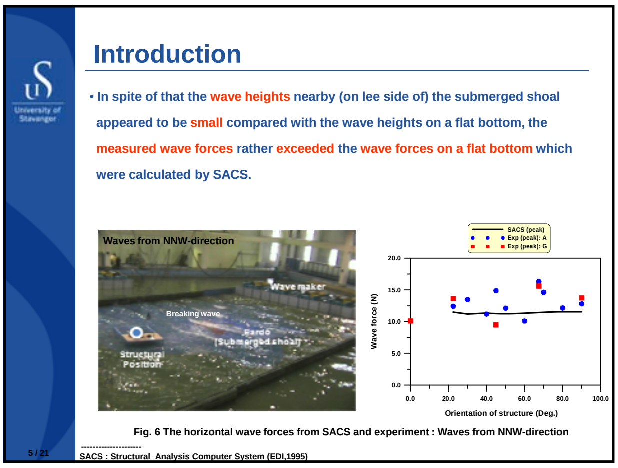
- 3D hydraulic model tests were performed at a small scale (1/120) in a wave tank at the Korea Institute of Construction Technology.



Introduction

- Waves from the NNW-direction were the only case where breaking waves occurred before the waves propagated over the structural position.
- The measured signals of wave forces showed irregular shapes which tended to one side, either positive or negative.

Fig. 5 Time histories of measured data from wave sensors and wave force meter : Waves from NNW-direction



Introduction

- In spite of that the wave heights nearby (on lee side of) the submerged shoal appeared to be small compared with the wave heights on a flat bottom, the measured wave forces rather exceeded the wave forces on a flat bottom which were calculated by SACS.

Fig. 6 The horizontal wave forces from SACS and experiment : Waves from NNW-direction

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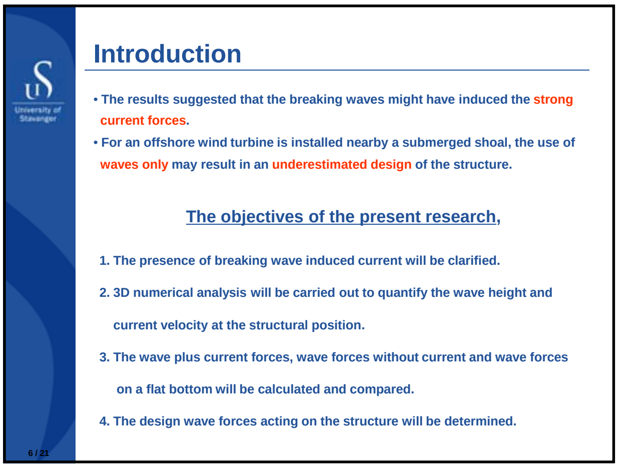
SACS : Structural Analysis Computer System (EDI,1995)

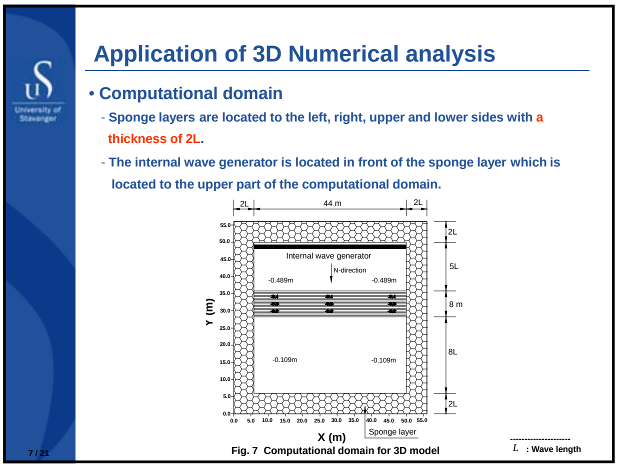


Introduction

- The results suggested that the breaking waves might have induced the strong current forces.
- For an offshore wind turbine is installed nearby a submerged shoal, the use of waves only may result in an underestimated design of the structure.

The objectives of the present research,

1. The presence of breaking wave induced current will be clarified.
2. 3D numerical analysis will be carried out to quantify the wave height and current velocity at the structural position.
3. The wave plus current forces, wave forces without current and wave forces on a flat bottom will be calculated and compared.
4. The design wave forces acting on the structure will be determined.

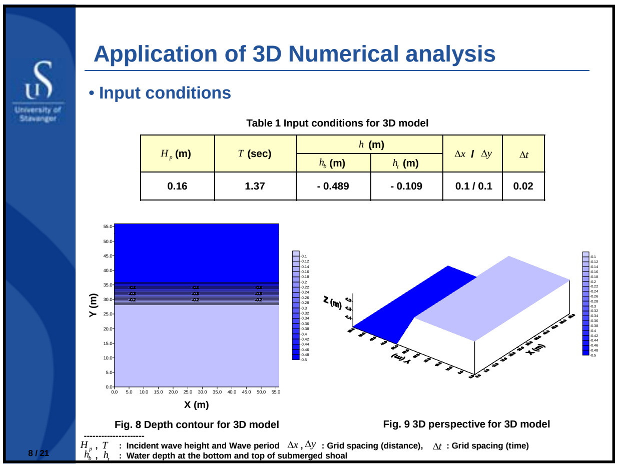


Application of 3D Numerical analysis

- Computational domain
  - Sponge layers are located to the left, right, upper and lower sides with a thickness of 2L.
  - The internal wave generator is located in front of the sponge layer which is located to the upper part of the computational domain.

Fig. 7 Computational domain for 3D model

L : Wave length



Application of 3D Numerical analysis

- Input conditions

Table 1 Input conditions for 3D model

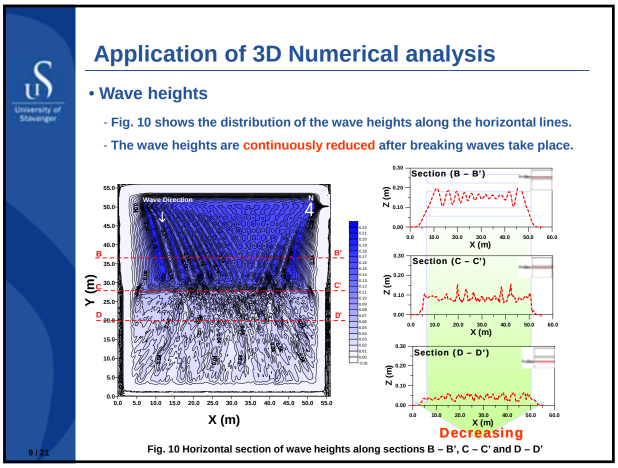
H_p (m)	T (sec)	h (m)		Δx / Δy	Δt
		h_b (m)	h_t (m)		
0.16	1.37	- 0.489	- 0.109	0.1 / 0.1	0.02

Fig. 8 Depth contour for 3D model

Fig. 9 3D perspective for 3D model

H_p , T : Incident wave height and Wave period Δx , Δy : Grid spacing (distance), Δt : Grid spacing (time)

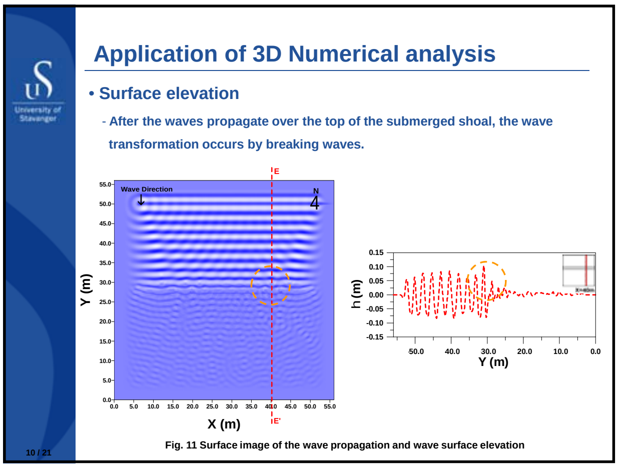
h_b , h_t : Water depth at the bottom and top of submerged shoal



Application of 3D Numerical analysis

- Wave heights
  - Fig. 10 shows the distribution of the wave heights along the horizontal lines.
  - The wave heights are continuously reduced after breaking waves take place.

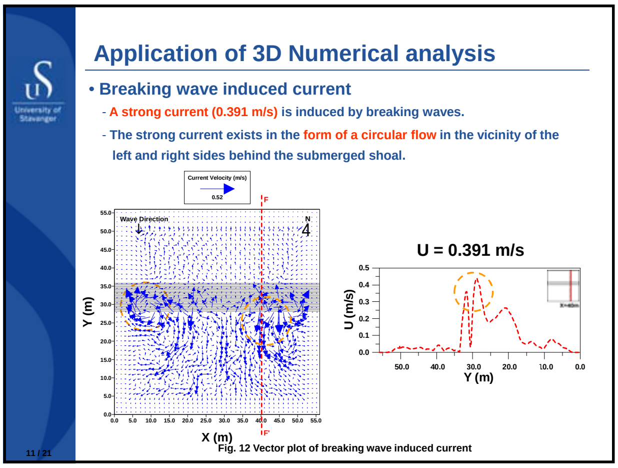
Fig. 10 Horizontal section of wave heights along sections B – B', C – C' and D – D'



Application of 3D Numerical analysis

- Surface elevation
  - After the waves propagate over the top of the submerged shoal, the wave transformation occurs by breaking waves.

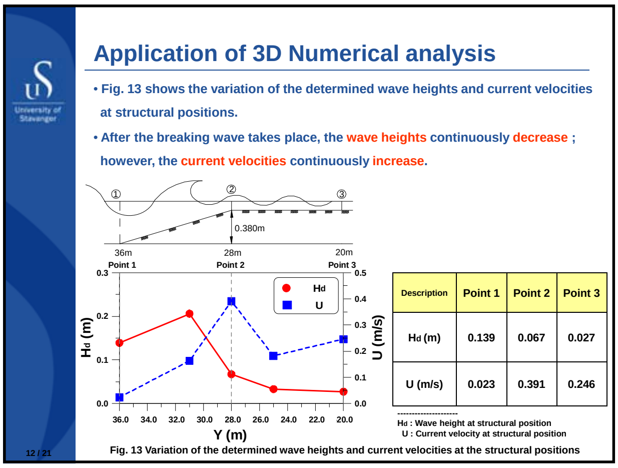
Fig. 11 Surface image of the wave propagation and wave surface elevation



Application of 3D Numerical analysis

- Breaking wave induced current
  - A strong current (0.391 m/s) is induced by breaking waves.
  - The strong current exists in the form of a circular flow in the vicinity of the left and right sides behind the submerged shoal.

Fig. 12 Vector plot of breaking wave induced current



Application of 3D Numerical analysis

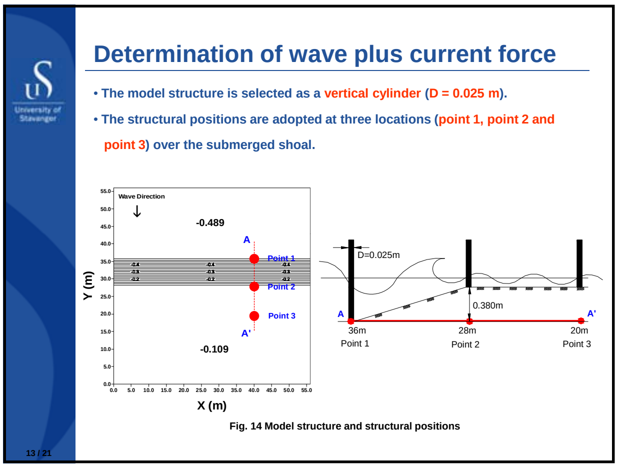
- Fig. 13 shows the variation of the determined wave heights and current velocities at structural positions.
- After the breaking wave takes place, the wave heights continuously decrease ; however, the current velocities continuously increase.

Description	Point 1	Point 2	Point 3
H_d (m)	0.139	0.067	0.027
U (m/s)	0.023	0.391	0.246

H_d : Wave height at structural position

U : Current velocity at structural position

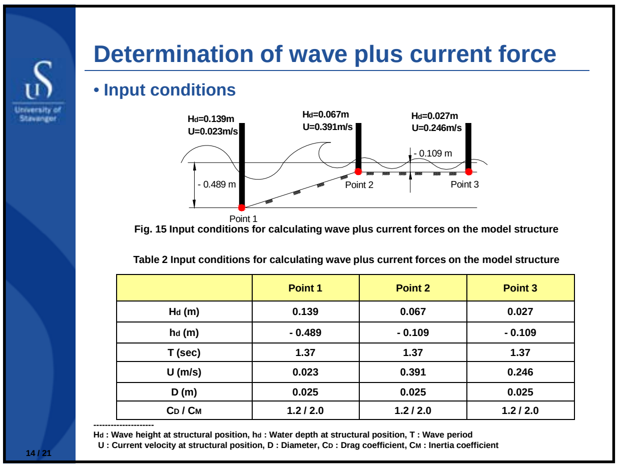
Fig. 13 Variation of the determined wave heights and current velocities at the structural positions



Determination of wave plus current force

- The model structure is selected as a vertical cylinder (D = 0.025 m).
- The structural positions are adopted at three locations (point 1, point 2 and point 3) over the submerged shoal.

Fig. 14 Model structure and structural positions



Determination of wave plus current force

- Input conditions

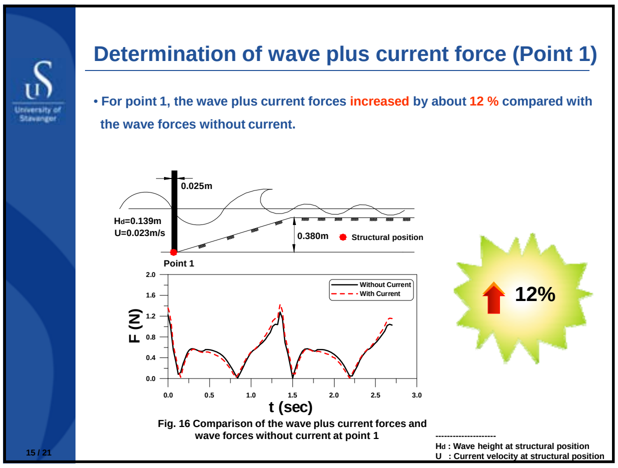
Fig. 15 Input conditions for calculating wave plus current forces on the model structure

Table 2 Input conditions for calculating wave plus current forces on the model structure

	Point 1	Point 2	Point 3
H_d (m)	0.139	0.067	0.027
h_d (m)	- 0.489	- 0.109	- 0.109
T (sec)	1.37	1.37	1.37
U (m/s)	0.023	0.391	0.246
D (m)	0.025	0.025	0.025
C_D / C_M	1.2 / 2.0	1.2 / 2.0	1.2 / 2.0

H_d : Wave height at structural position, h_d : Water depth at structural position, T : Wave period

U : Current velocity at structural position, D : Diameter, C_D : Drag coefficient, C_M : Inertia coefficient



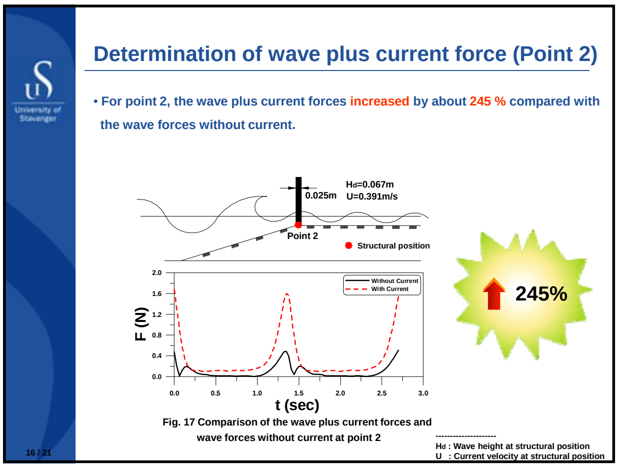
Determination of wave plus current force (Point 1)

- For point 1, the wave plus current forces increased by about 12 % compared with the wave forces without current.

Fig. 16 Comparison of the wave plus current forces and wave forces without current at point 1

H_d : Wave height at structural position

U : Current velocity at structural position



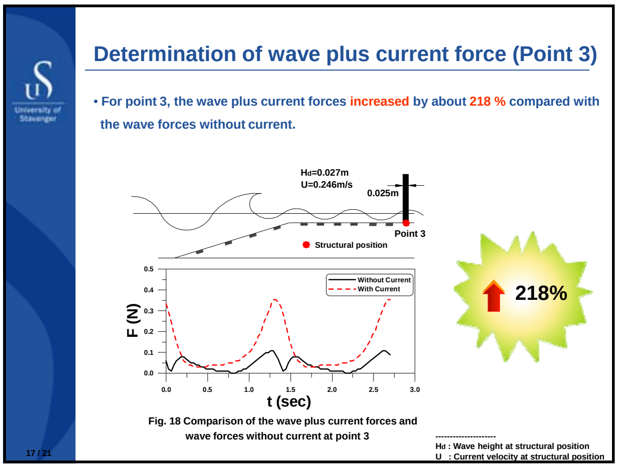
Determination of wave plus current force (Point 2)

- For point 2, the wave plus current forces increased by about 245 % compared with the wave forces without current.

Fig. 17 Comparison of the wave plus current forces and wave forces without current at point 2

H_d : Wave height at structural position

U : Current velocity at structural position

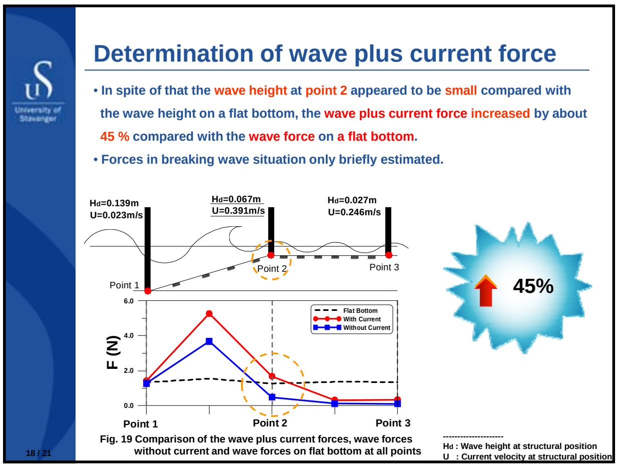


Determination of wave plus current force (Point 3)

- For point 3, the wave plus current forces increased by about 218 % compared with the wave forces without current.

Fig. 18 Comparison of the wave plus current forces and wave forces without current at point 3

Hd : Wave height at structural position
U : Current velocity at structural position

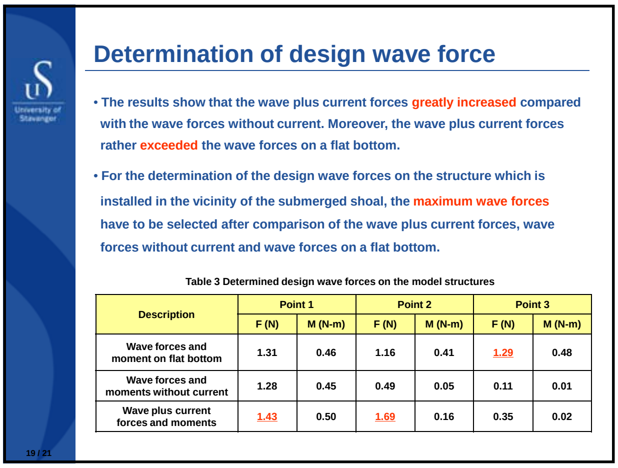


Determination of wave plus current force

- In spite of that the wave height at point 2 appeared to be small compared with the wave height on a flat bottom, the wave plus current force increased by about 45 % compared with the wave force on a flat bottom.
- Forces in breaking wave situation only briefly estimated.

Fig. 19 Comparison of the wave plus current forces, wave forces without current and wave forces on flat bottom at all points

----
Hd : Wave height at structural position
U : Current velocity at structural position

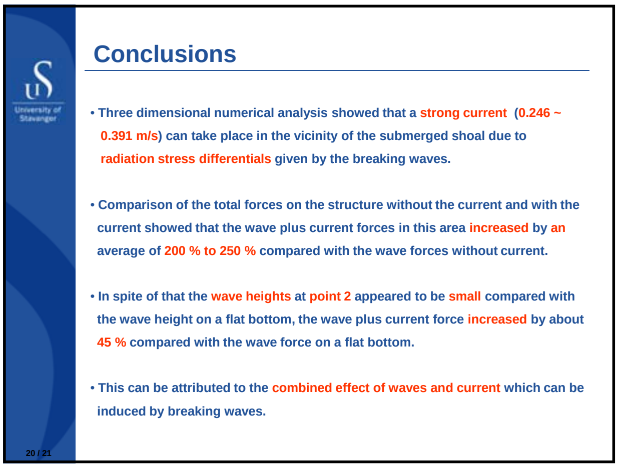


Determination of design wave force

- The results show that the wave plus current forces greatly increased compared with the wave forces without current. Moreover, the wave plus current forces rather exceeded the wave forces on a flat bottom.
- For the determination of the design wave forces on the structure which is installed in the vicinity of the submerged shoal, the maximum wave forces have to be selected after comparison of the wave plus current forces, wave forces without current and wave forces on a flat bottom.

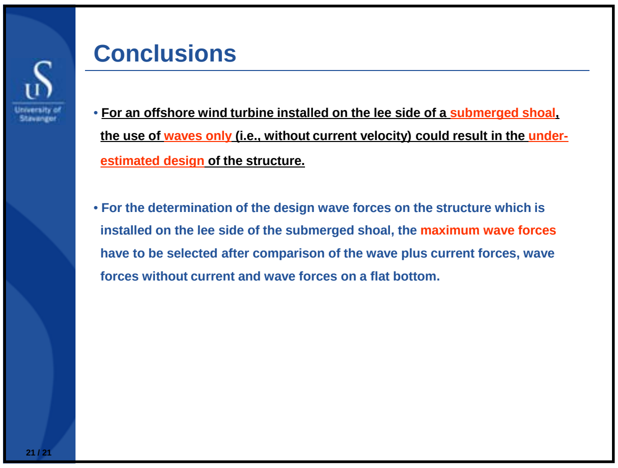
Table 3 Determined design wave forces on the model structures

Description	Point 1		Point 2		Point 3	
	F (N)	M (N-m)	F (N)	M (N-m)	F (N)	M (N-m)
Wave forces and moment on flat bottom	1.31	0.46	1.16	0.41	1.29	0.48
Wave forces and moments without current	1.28	0.45	0.49	0.05	0.11	0.01
Wave plus current forces and moments	1.43	0.50	1.69	0.16	0.35	0.02



Conclusions

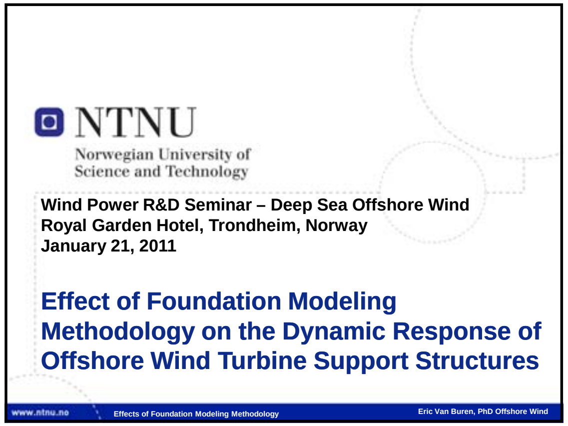
- Three dimensional numerical analysis showed that a strong current (0.246 ~ 0.391 m/s) can take place in the vicinity of the submerged shoal due to radiation stress differentials given by the breaking waves.
- Comparison of the total forces on the structure without the current and with the current showed that the wave plus current forces in this area increased by an average of 200 % to 250 % compared with the wave forces without current.
- In spite of that the wave heights at point 2 appeared to be small compared with the wave height on a flat bottom, the wave plus current force increased by about 45 % compared with the wave force on a flat bottom.
- This can be attributed to the combined effect of waves and current which can be induced by breaking waves.



Conclusions

- For an offshore wind turbine installed on the lee side of a submerged shoal, the use of waves only (i.e., without current velocity) could result in the under-estimated design of the structure.
- For the determination of the design wave forces on the structure which is installed on the lee side of the submerged shoal, the maximum wave forces have to be selected after comparison of the wave plus current forces, wave forces without current and wave forces on a flat bottom.

Thank you



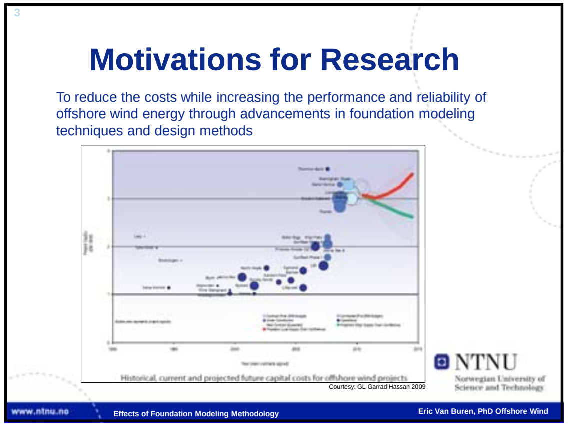
NTNU
Norwegian University of Science and Technology

Wind Power R&D Seminar – Deep Sea Offshore Wind
Royal Garden Hotel, Trondheim, Norway
January 21, 2011

Effect of Foundation Modeling Methodology on the Dynamic Response of Offshore Wind Turbine Support Structures

Agenda

- Motivations for research
- Research Questions
- Project details and methods
- Results
- Conclusions
- Further work

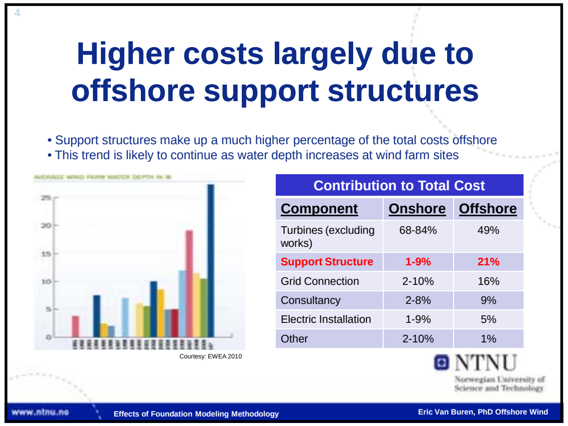


Motivations for Research

To reduce the costs while increasing the performance and reliability of offshore wind energy through advancements in foundation modeling techniques and design methods

Historical, current and projected future capital costs for offshore wind projects

Courtesy: GL-Garrad Hassan 2009



Higher costs largely due to offshore support structures

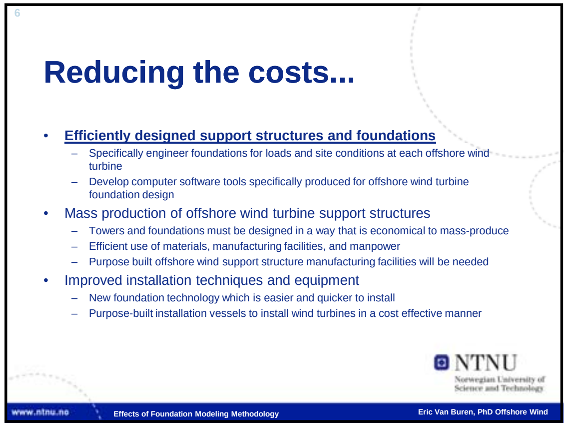
- Support structures make up a much higher percentage of the total costs offshore
- This trend is likely to continue as water depth increases at wind farm sites

Courtesy: EWEA 2010

Contribution to Total Cost		
Component	**Onshore**	**Offshore**
Turbines (excluding works)	68-84%	49%
Support Structure	**1-9%**	**21%**
Grid Connection	2-10%	16%
Consultancy	2-8%	9%
Electric Installation	1-9%	5%
Other	2-10%	1%

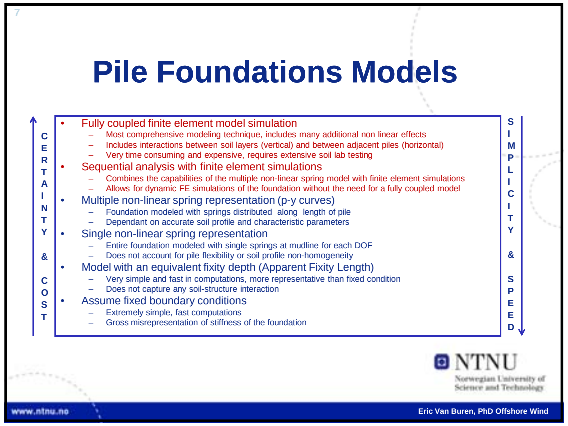
Installation Difficulties

- Very large and expensive installation vessels are required
- Foundations and tower must be installed to very precise tolerances
- Many components must be installed in calm weather to avoid damage
  - Bad weather can lead to large amounts of downtime , running up costs
- Foundation installation is the most time consuming part of the process
  - Extremely large diameter piles or immensely heavy gravity based must be installed
  - Preparation of the seabed and scour protection may be required
  - **Offshore foundations cost 2.5x more than for a similar land-based wind turbine**



Reducing the costs...

- **Efficiently designed support structures and foundations**
  - Specifically engineer foundations for loads and site conditions at each offshore wind turbine
  - Develop computer software tools specifically produced for offshore wind turbine foundation design
- Mass production of offshore wind turbine support structures
  - Towers and foundations must be designed in a way that is economical to mass-produce
  - Efficient use of materials, manufacturing facilities, and manpower
  - Purpose built offshore wind support structure manufacturing facilities will be needed
- Improved installation techniques and equipment
  - New foundation technology which is easier and quicker to install
  - Purpose-built installation vessels to install wind turbines in a cost effective manner

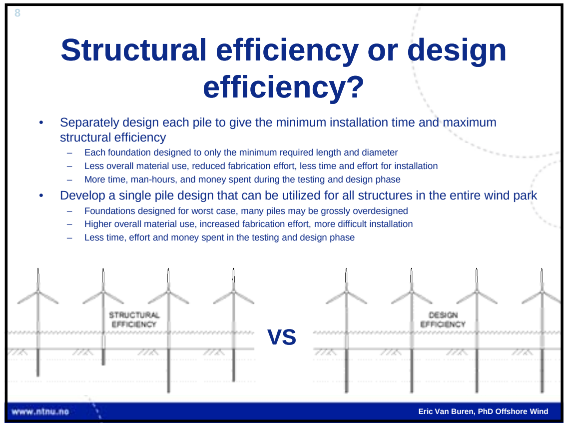


Pile Foundations Models

- Fully coupled finite element model simulation
  - Most comprehensive modeling technique, includes many additional non linear effects
  - Includes interactions between soil layers (vertical) and between adjacent piles (horizontal)
  - Very time consuming and expensive, requires extensive soil lab testing
- Sequential analysis with finite element simulations
  - Combines the capabilities of the multiple non-linear spring model with finite element simulations
  - Allows for dynamic FE simulations of the foundation without the need for a fully coupled model
- Multiple non-linear spring representation (p-y curves)
  - Foundation modeled with springs distributed along length of pile
  - Dependant on accurate soil profile and characteristic parameters
- Single non-linear spring representation
  - Entire foundation modeled with single springs at mudline for each DOF
  - Does not account for pile flexibility or soil profile non-homogeneity
- Model with an equivalent fixity depth (Apparent Fixity Length)
  - Very simple and fast in computations, more representative than fixed condition
  - Does not capture any soil-structure interaction
- Assume fixed boundary conditions
  - Extremely simple, fast computations
  - Gross misrepresentation of stiffness of the foundation

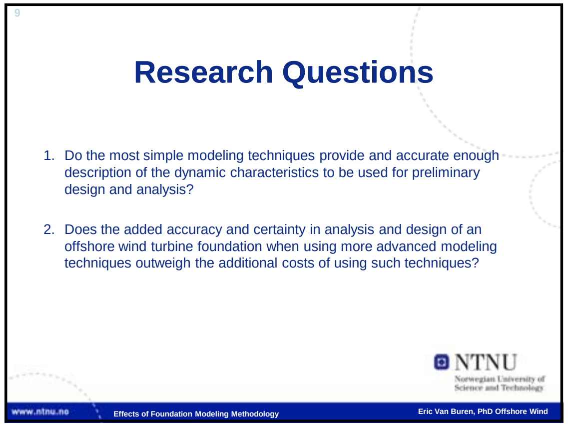
CERTAINTY & COST

SIMPLICITY & SPEED



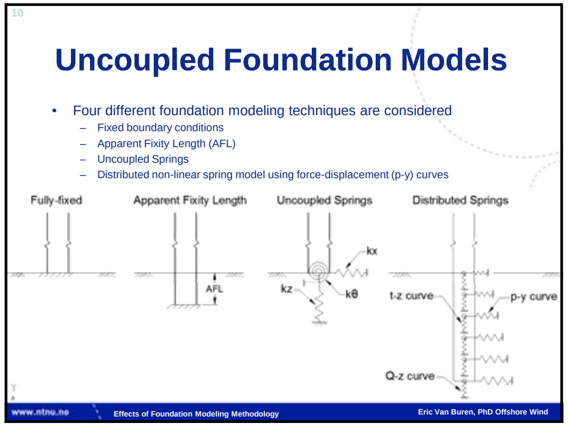
Structural efficiency or design efficiency?

- Separately design each pile to give the minimum installation time and maximum structural efficiency
  - Each foundation designed to only the minimum required length and diameter
  - Less overall material use, reduced fabrication effort, less time and effort for installation
  - More time, man-hours, and money spent during the testing and design phase
- Develop a single pile design that can be utilized for all structures in the entire wind park
  - Foundations designed for worst case, many piles may be grossly overdesigned
  - Higher overall material use, increased fabrication effort, more difficult installation
  - Less time, effort and money spent in the testing and design phase



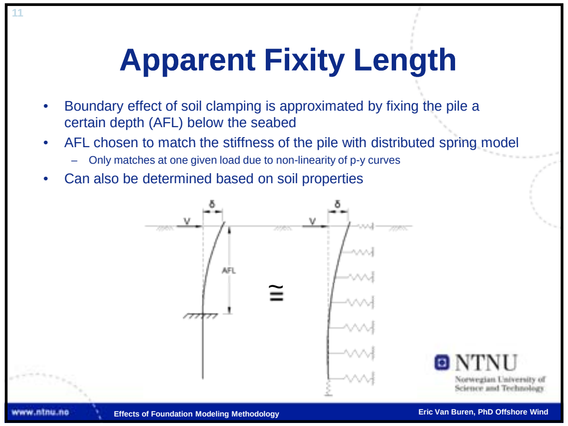
Research Questions

1. Do the most simple modeling techniques provide and accurate enough description of the dynamic characteristics to be used for preliminary design and analysis?
2. Does the added accuracy and certainty in analysis and design of an offshore wind turbine foundation when using more advanced modeling techniques outweigh the additional costs of using such techniques?



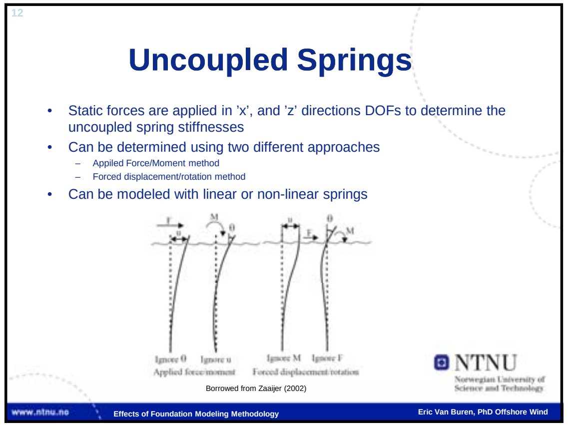
Uncoupled Foundation Models

- Four different foundation modeling techniques are considered
  - Fixed boundary conditions
  - Apparent Fixity Length (AFL)
  - Uncoupled Springs
  - Distributed non-linear spring model using force-displacement (p-y) curves



Apparent Fixity Length

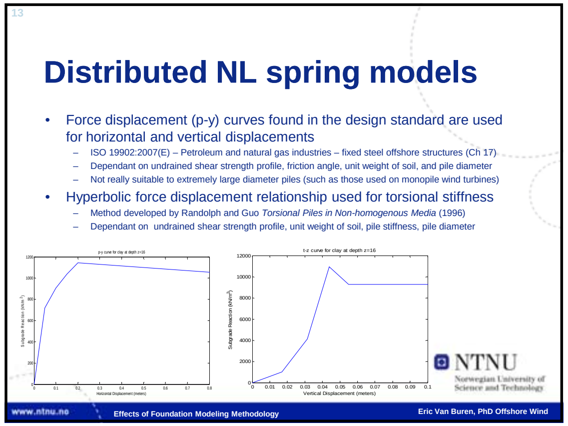
- Boundary effect of soil clamping is approximated by fixing the pile a certain depth (AFL) below the seabed
- AFL chosen to match the stiffness of the pile with distributed spring model
  - Only matches at one given load due to non-linearity of p-y curves
- Can also be determined based on soil properties



Uncoupled Springs

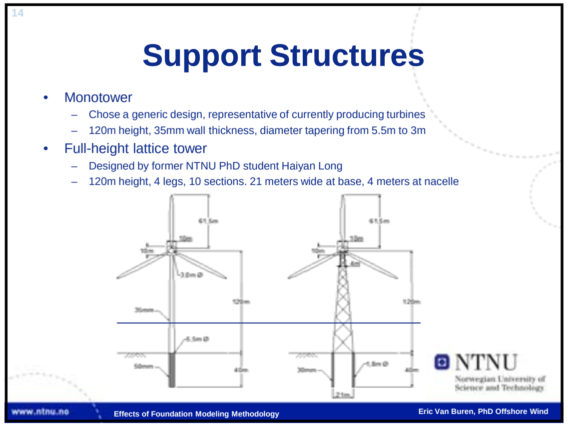
- Static forces are applied in 'x', and 'z' directions DOFs to determine the uncoupled spring stiffnesses
- Can be determined using two different approaches
  - Appiled Force/Moment method
  - Forced displacement/rotation method
- Can be modeled with linear or non-linear springs

Borrowed from Zaaijer (2002)



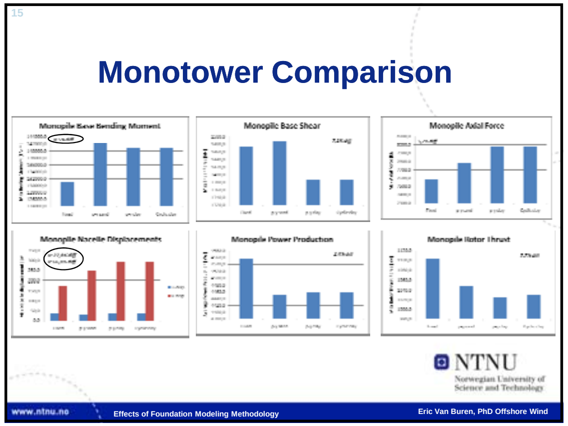
Distributed NL spring models

- Force displacement (p-y) curves found in the design standard are used for horizontal and vertical displacements
  - ISO 19902:2007(E) – Petroleum and natural gas industries – fixed steel offshore structures (Ch 17)
  - Dependant on undrained shear strength profile, friction angle, unit weight of soil, and pile diameter
  - Not really suitable to extremely large diameter piles (such as those used on monopile wind turbines)
- Hyperbolic force displacement relationship used for torsional stiffness
  - Method developed by Randolph and Guo *Torsional Piles in Non-homogenous Media* (1996)
  - Dependant on undrained shear strength profile, unit weight of soil, pile stiffness, pile diameter

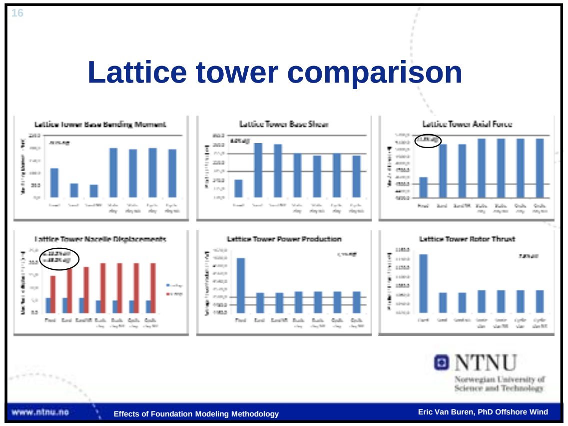


Support Structures

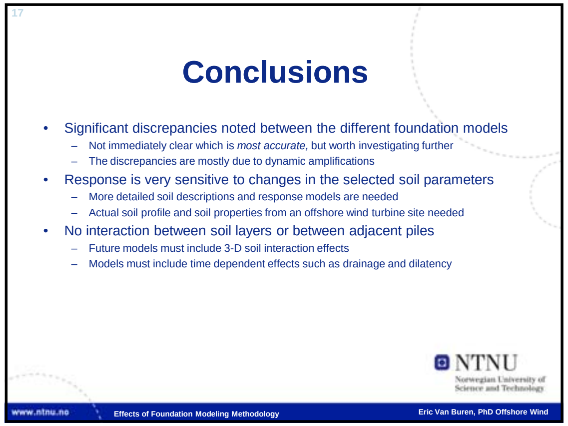
- Monotower
  - Chose a generic design, representative of currently producing turbines
  - 120m height, 35mm wall thickness, diameter tapering from 5.5m to 3m
- Full-height lattice tower
  - Designed by former NTNU PhD student Haiyan Long
  - 120m height, 4 legs, 10 sections. 21 meters wide at base, 4 meters at nacelle



Monotower Comparison

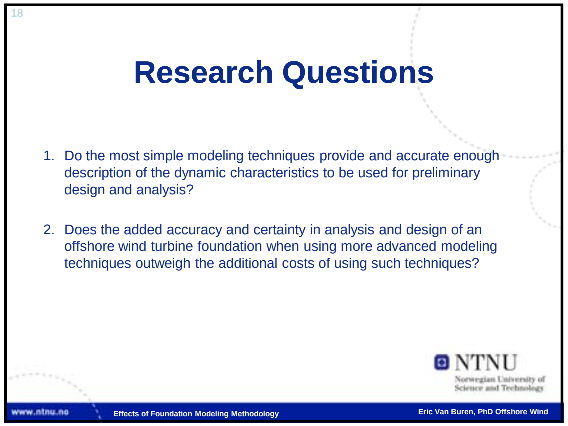


Lattice tower comparison



Conclusions

- Significant discrepancies noted between the different foundation models
  - Not immediately clear which is *most accurate*, but worth investigating further
  - The discrepancies are mostly due to dynamic amplifications
- Response is very sensitive to changes in the selected soil parameters
  - More detailed soil descriptions and response models are needed
  - Actual soil profile and soil properties from an offshore wind turbine site needed
- No interaction between soil layers or between adjacent piles
  - Future models must include 3-D soil interaction effects
  - Models must include time dependent effects such as drainage and dilatency



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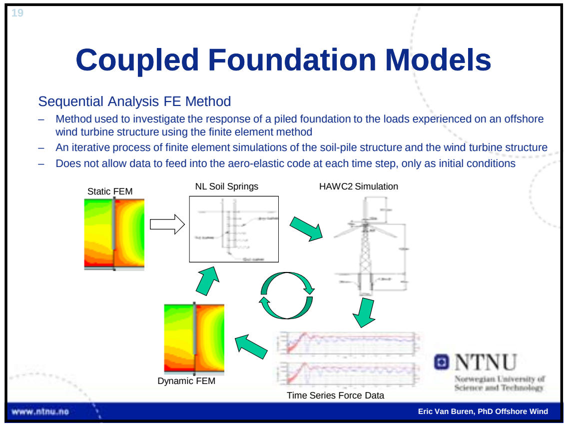

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Coupled Foundation Models

Sequential Analysis FE Method

- Method used to investigate the response of a piled foundation to the loads experienced on an offshore wind turbine structure using the finite element method
- An iterative process of finite element simulations of the soil-pile structure and the wind turbine structure
- Does not allow data to feed into the aero-elastic code at each time step, only as initial conditions

Static FEM

NL Soil Springs

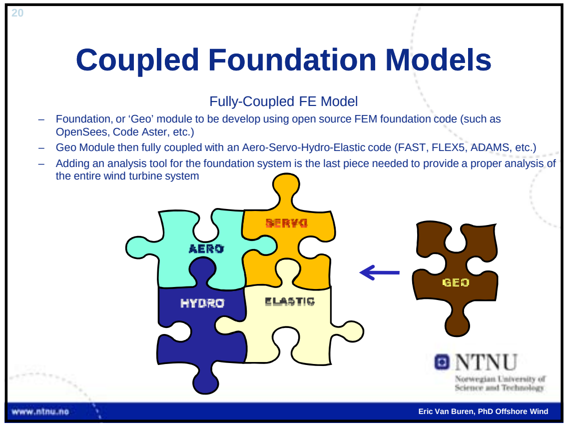
HAWC2 Simulation

Dynamic FEM

Time Series Force Data

NTNU
Norwegian University of Science and Technology

www.ntnu.no Eric Van Buren, PhD Offshore Wind



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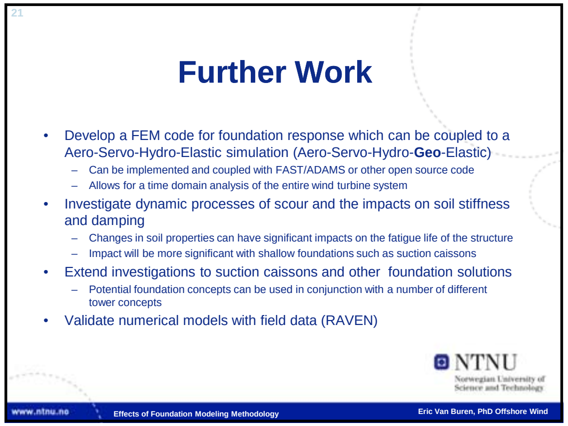
Coupled Foundation Models

Fully-Coupled FE Model

- Foundation, or 'Geo' module to be develop using open source FEM foundation code (such as OpenSees, Code Aster, etc.)
- Geo Module then fully coupled with an Aero-Servo-Hydro-Elastic code (FAST, FLEX5, ADAMS, etc.)
- Adding an analysis tool for the foundation system is the last piece needed to provide a proper analysis of the entire wind turbine system

NTNU
Norwegian University of Science and Technology

www.ntnu.no Eric Van Buren, PhD Offshore Wind



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Further Work

- Develop a FEM code for foundation response which can be coupled to a Aero-Servo-Hydro-Elastic simulation (Aero-Servo-Hydro-**Geo**-Elastic)
  - Can be implemented and coupled with FAST/ADAMS or other open source code
  - Allows for a time domain analysis of the entire wind turbine system
- Investigate dynamic processes of scour and the impacts on soil stiffness and damping
  - Changes in soil properties can have significant impacts on the fatigue life of the structure
  - Impact will be more significant with shallow foundations such as suction caissons
- Extend investigations to suction caissons and other foundation solutions
  - Potential foundation concepts can be used in conjunction with a number of different tower concepts
- Validate numerical models with field data (RAVEN)

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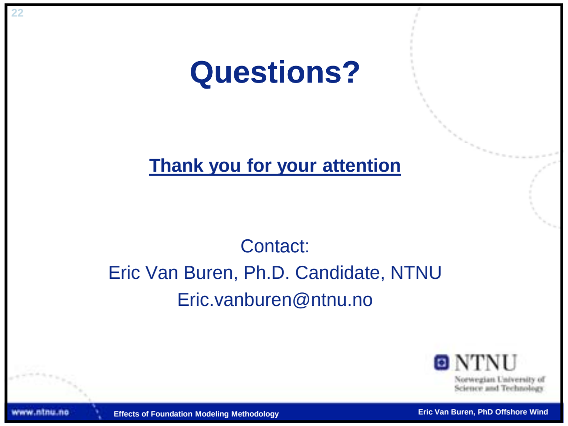
www.ntnu.no Effects of Foundation Modeling Methodology Eric Van Buren, PhD Offshore Wind



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Questions?

Thank you for your attention

Contact:
Eric Van Buren, Ph.D. Candidate, NTNU
Eric.vanburen@ntnu.no

NTNU
Norwegian University of Science and Technology

www.ntnu.no Effects of Foundation Modeling Methodology Eric Van Buren, PhD Offshore Wind

F) Wind farm modelling

Wakes in between wind parks, Idar Barstad, Uni Research

Wake models compared with measurements, Jennifer van Rij, IFE

Wind and wake modelling using CFD, Jens A Melheim, CMR GexCon

A model study of wind turbine interference, Prof Per Åge Krogstad, NTNU

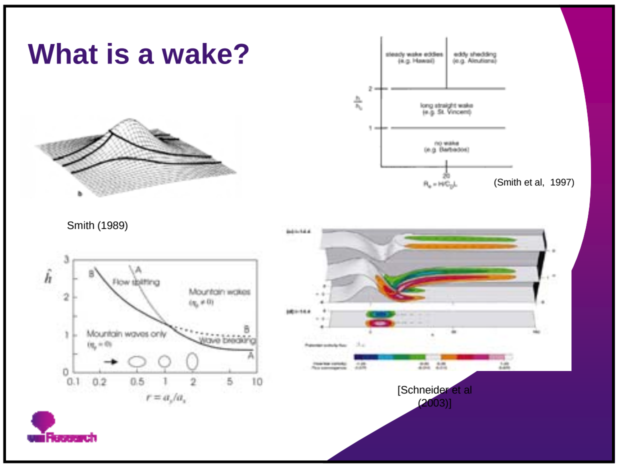
Wakes in between wind parks

- and what we can learn from mountain meteorology

Idar Barstad
(A Fitch, A Sapronova, A Gupta)
idar.barstad@uni.no

What is a wake?

Ile Amsterdam , Indian sea (hm=800m)

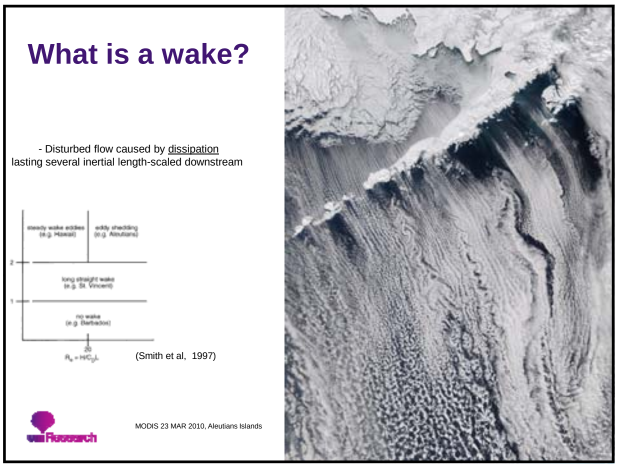


What is a wake?

(Smith et al, 1997)

Smith (1989)

[Schneider et al (2003)]

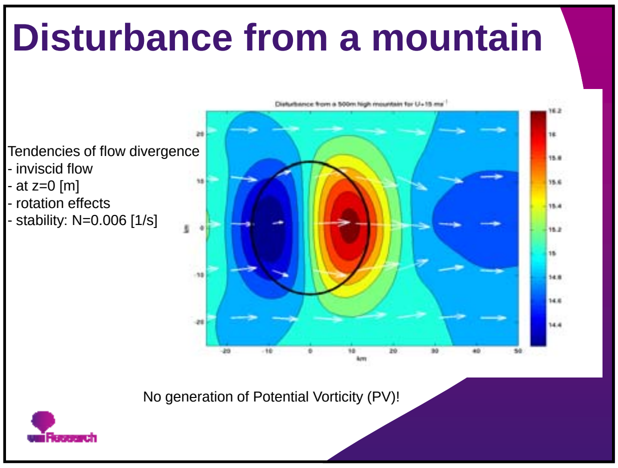


What is a wake?

- Disturbed flow caused by <u>dissipation</u> lasting several inertial length-scaled downstream

(Smith et al, 1997)

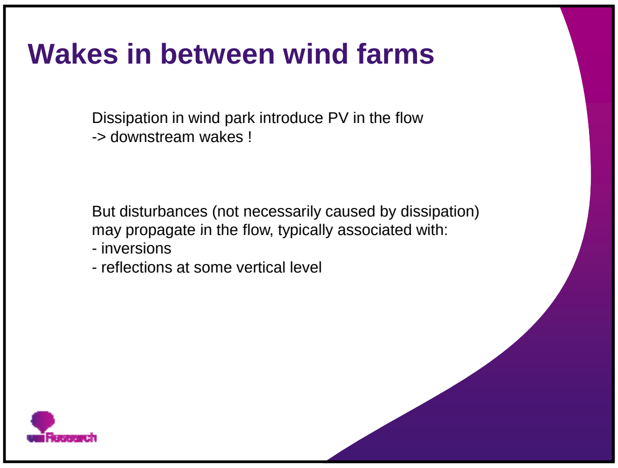
MODIS 23 MAR 2010, Aleutians Islands



Disturbance from a mountain

Tendencies of flow divergence
- inviscid flow
- at z=0 [m]
- rotation effects
- stability: N=0.006 [1/s]

No generation of Potential Vorticity (PV)!



Wakes in between wind farms

Dissipation in wind park introduce PV in the flow
-> downstream wakes !

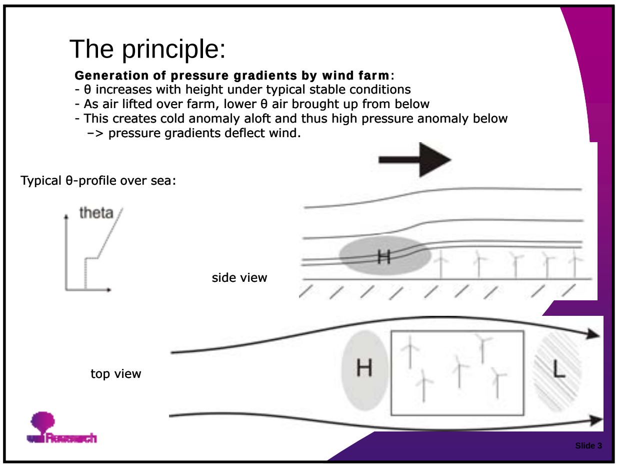
But disturbances (not necessarily caused by dissipation) may propagate in the flow, typically associated with:
- inversions
- reflections at some vertical level

Test for a single wind farm

Two sophistication levels:

1) reduced and simplified model (LM;Smith 2009)

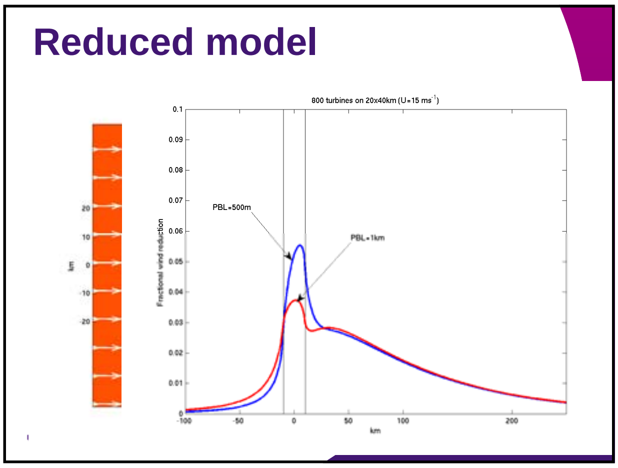
2) full mesoscale model with turbine drag (WRF)



The principle:

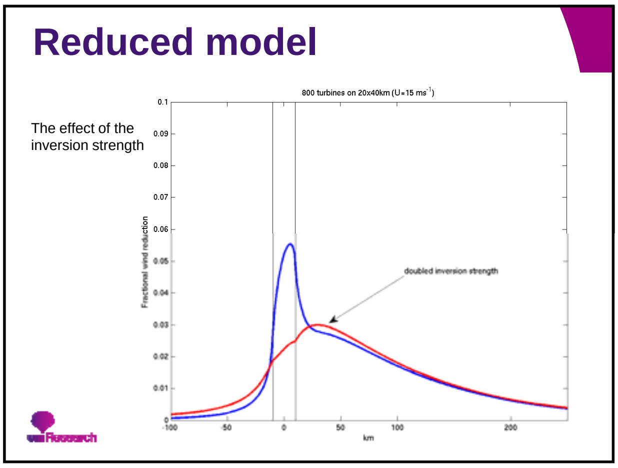
Generation of pressure gradients by wind farm:
- θ increases with height under typical stable conditions
- As air lifted over farm, lower θ air brought up from below
- This creates cold anomaly aloft and thus high pressure anomaly below
  –> pressure gradients deflect wind.

Typical θ-profile over sea:



Reduced model

800 turbines on 20x40km (U=15 ms^{-1})

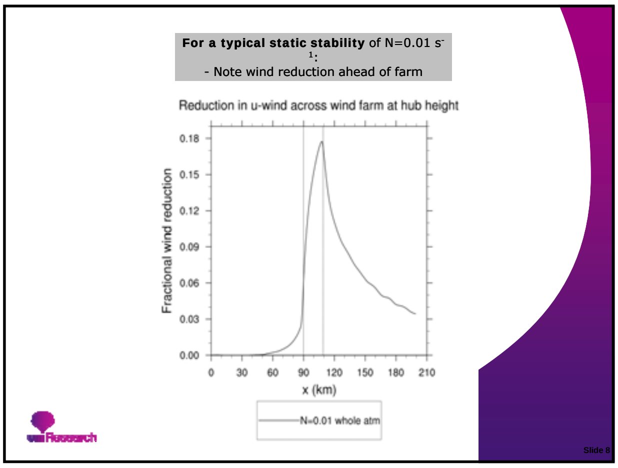


Reduced model

The effect of the inversion strength

800 turbines on 20x40km (U=15 ms^{-1})

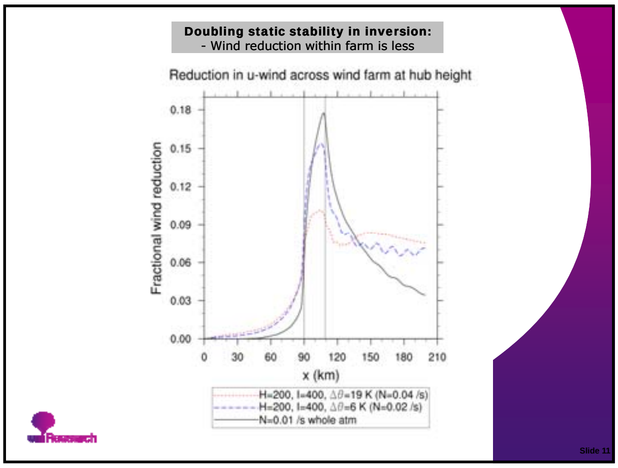
Full model



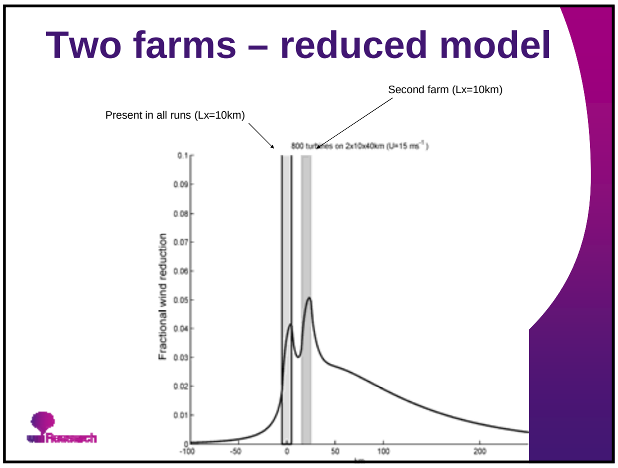
For a typical static stability of N=0.01 s^{-1}:

- Note wind reduction ahead of farm

Reduction in u-wind across wind farm at hub height



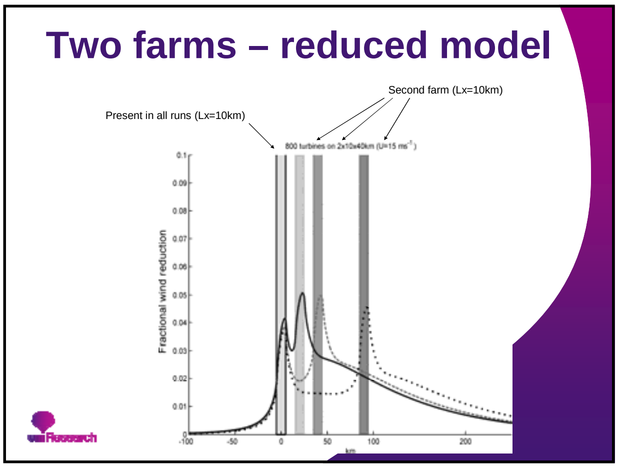
Doubling static stability in inversion:
- Wind reduction within farm is less



Two farms – reduced model

Second farm (Lx=10km)

Present in all runs (Lx=10km)



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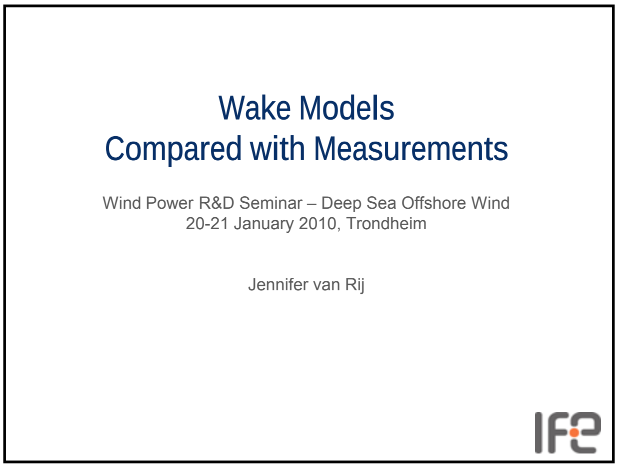
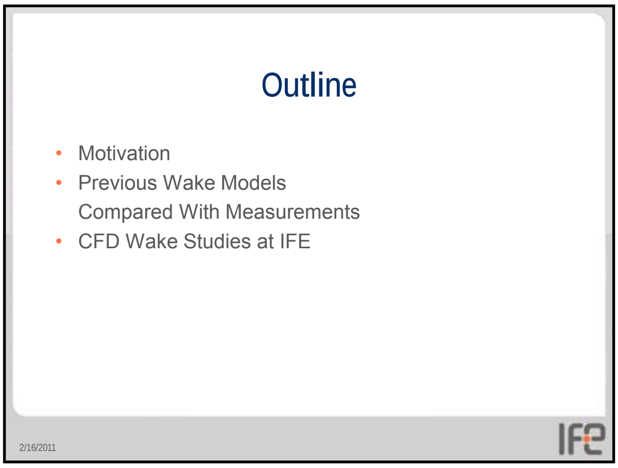


Wake Models Compared with Measurements

Wind Power R&D Seminar – Deep Sea Offshore Wind
20-21 January 2010, Trondheim

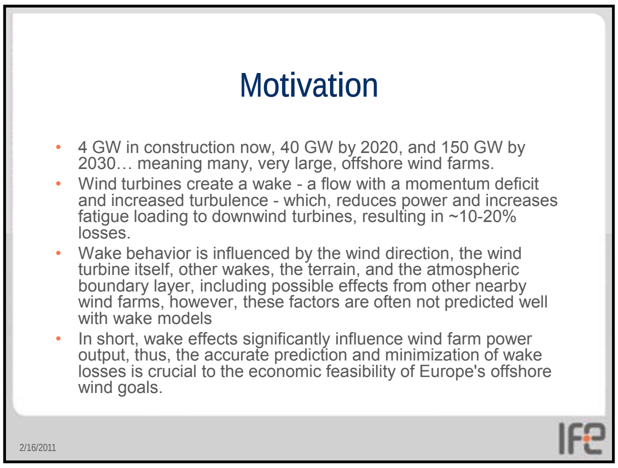
Jennifer van Rij



Outline

- Motivation
- Previous Wake Models Compared With Measurements
- CFD Wake Studies at IFE

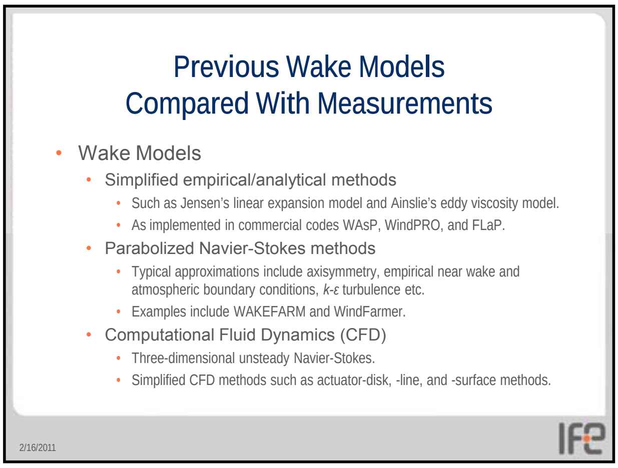
2/16/2011



Motivation

- 4 GW in construction now, 40 GW by 2020, and 150 GW by 2030… meaning many, very large, offshore wind farms.
- Wind turbines create a wake - a flow with a momentum deficit and increased turbulence - which, reduces power and increases fatigue loading to downwind turbines, resulting in ~10-20% losses.
- Wake behavior is influenced by the wind direction, the wind turbine itself, other wakes, the terrain, and the atmospheric boundary layer, including possible effects from other nearby wind farms, however, these factors are often not predicted well with wake models
- In short, wake effects significantly influence wind farm power output, thus, the accurate prediction and minimization of wake losses is crucial to the economic feasibility of Europe's offshore wind goals.

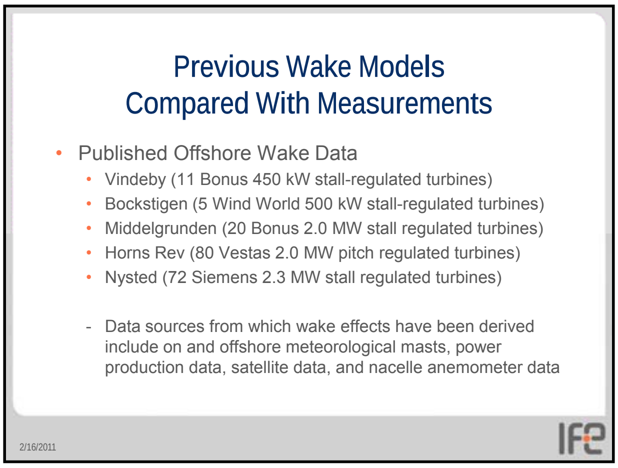
2/16/2011



Previous Wake Models Compared With Measurements

- Wake Models
  - Simplified empirical/analytical methods
    - Such as Jensen's linear expansion model and Ainslie's eddy viscosity model.
    - As implemented in commercial codes WAsP, WindPRO, and FLaP.
  - Parabolized Navier-Stokes methods
    - Typical approximations include axisymmetry, empirical near wake and atmospheric boundary conditions, *k-ε* turbulence etc.
    - Examples include WAKEFARM and WindFarmer.
  - Computational Fluid Dynamics (CFD)
    - Three-dimensional unsteady Navier-Stokes.
    - Simplified CFD methods such as actuator-disk, -line, and -surface methods.

2/16/2011



Previous Wake Models Compared With Measurements

- Published Offshore Wake Data
  - Vindeby (11 Bonus 450 kW stall-regulated turbines)
  - Bockstigen (5 Wind World 500 kW stall-regulated turbines)
  - Middelgrunden (20 Bonus 2.0 MW stall regulated turbines)
  - Horns Rev (80 Vestas 2.0 MW pitch regulated turbines)
  - Nysted (72 Siemens 2.3 MW stall regulated turbines)

  - Data sources from which wake effects have been derived include on and offshore meteorological masts, power production data, satellite data, and nacelle anemometer data

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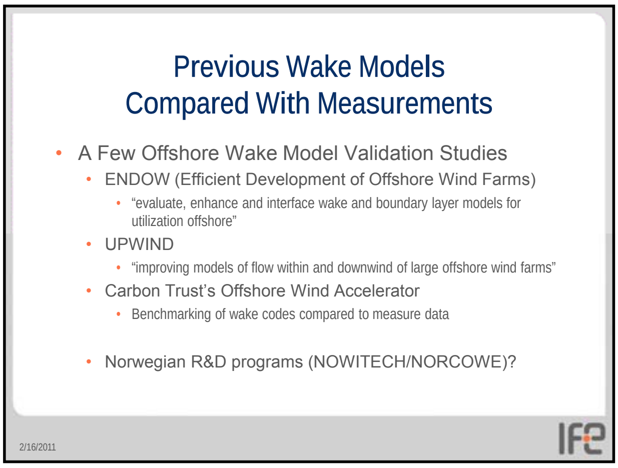

Previous Wake Models Compared With Measurements

- A Few Offshore Wake Model Validation Studies
  - ENDOW (Efficient Development of Offshore Wind Farms)
    - "evaluate, enhance and interface wake and boundary layer models for utilization offshore"
  - UPWIND
    - "improving models of flow within and downwind of large offshore wind farms"
  - Carbon Trust's Offshore Wind Accelerator
    - Benchmarking of wake codes compared to measure data

  - Norwegian R&D programs (NOWITECH/NORCOWE)?

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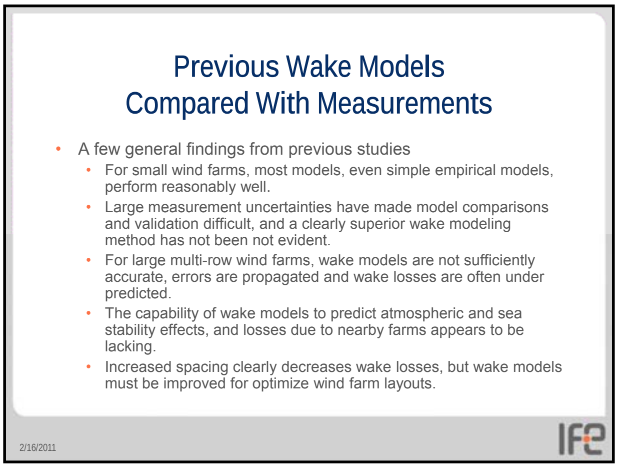
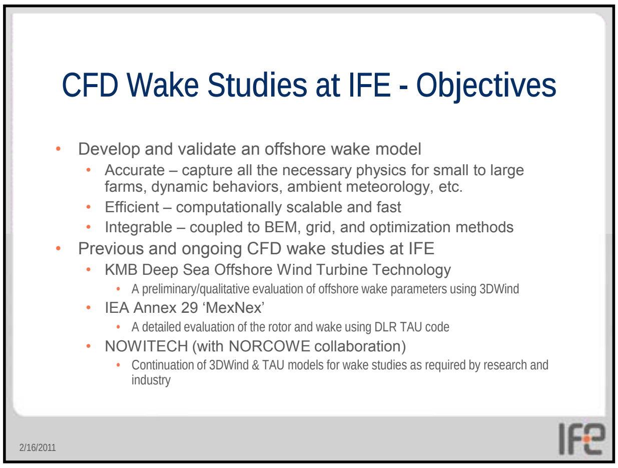


Previous Wake Models Compared With Measurements

- A few general findings from previous studies
  - For small wind farms, most models, even simple empirical models, perform reasonably well.
  - Large measurement uncertainties have made model comparisons and validation difficult, and a clearly superior wake modeling method has not been not evident.
  - For large multi-row wind farms, wake models are not sufficiently accurate, errors are propagated and wake losses are often under predicted.
  - The capability of wake models to predict atmospheric and sea stability effects, and losses due to nearby farms appears to be lacking.
  - Increased spacing clearly decreases wake losses, but wake models must be improved for optimize wind farm layouts.

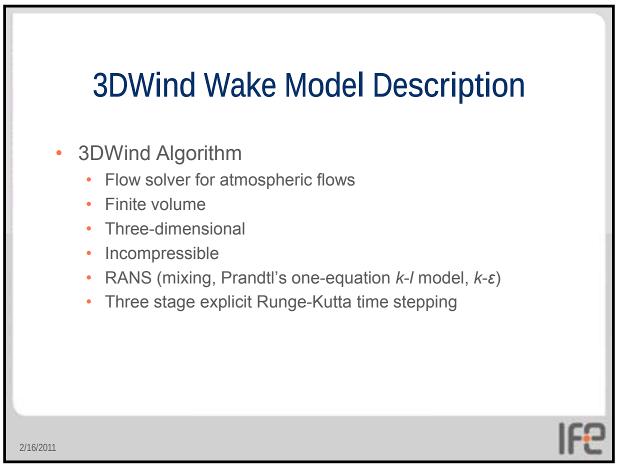
2/16/2011



CFD Wake Studies at IFE - Objectives

- Develop and validate an offshore wake model
  - Accurate – capture all the necessary physics for small to large farms, dynamic behaviors, ambient meteorology, etc.
  - Efficient – computationally scalable and fast
  - Integrable – coupled to BEM, grid, and optimization methods
- Previous and ongoing CFD wake studies at IFE
  - KMB Deep Sea Offshore Wind Turbine Technology
    - A preliminary/qualitative evaluation of offshore wake parameters using 3DWind
  - IEA Annex 29 ‘MexNex’
    - A detailed evaluation of the rotor and wake using DLR TAU code
  - NOWITECH (with NORCOWE collaboration)
    - Continuation of 3DWind & TAU models for wake studies as required by research and industry

2/16/2011



3DWind Wake Model Description

- 3DWind Algorithm
  - Flow solver for atmospheric flows
  - Finite volume
  - Three-dimensional
  - Incompressible
  - RANS (mixing, Prandtl’s one-equation k-l model, k-ε)
  - Three stage explicit Runge-Kutta time stepping

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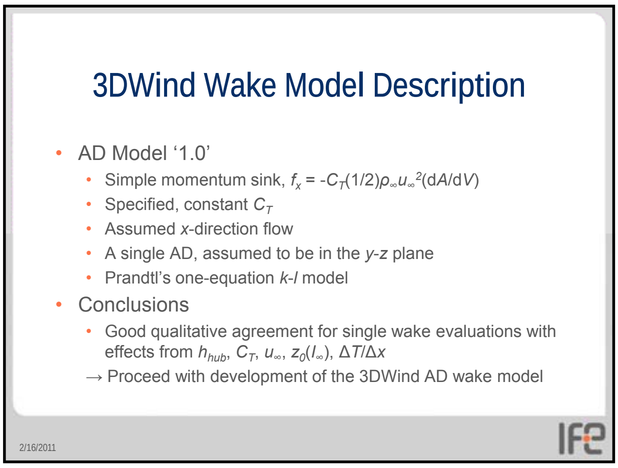

3DWind Wake Model Description

- AD Model ‘1.0’
  - Simple momentum sink, $f_x = -C_T(1/2)\rho_\infty u_\infty^2(dA/dV)$
  - Specified, constant C_T
  - Assumed x-direction flow
  - A single AD, assumed to be in the y-z plane
  - Prandtl’s one-equation k-l model
- Conclusions
  - Good qualitative agreement for single wake evaluations with effects from h_{hub}, C_T, u_∞, $z_0(I_\infty)$, $\Delta T/\Delta x$

  → Proceed with development of the 3DWind AD wake model

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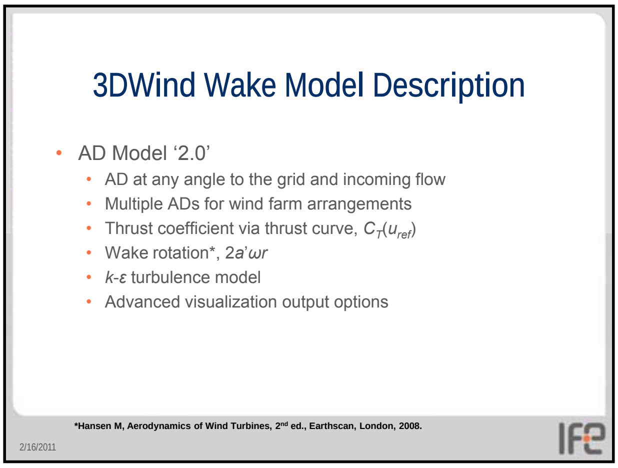

3DWind Wake Model Description

- AD Model ‘2.0’
  - AD at any angle to the grid and incoming flow
  - Multiple ADs for wind farm arrangements
  - Thrust coefficient via thrust curve, $C_T(u_{ref})$
  - Wake rotation*, $2a'\omega r$
  - k-ε turbulence model
  - Advanced visualization output options

*Hansen M, Aerodynamics of Wind Turbines, 2nd ed., Earthscan, London, 2008.

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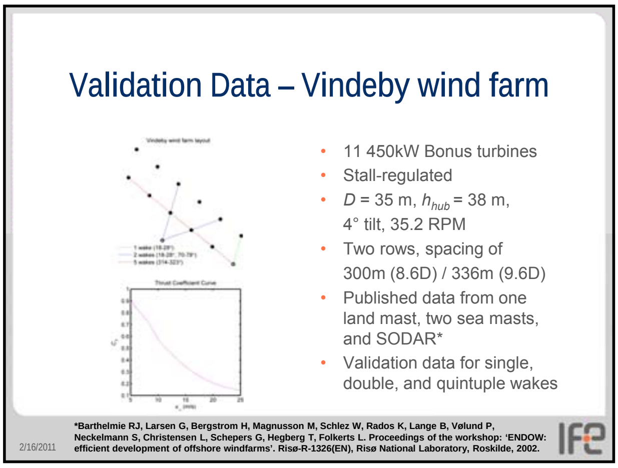

Validation Data – Vindeby wind farm

- 11 450kW Bonus turbines
- Stall-regulated
- D = 35 m, h_{hub} = 38 m, 4° tilt, 35.2 RPM
- Two rows, spacing of 300m (8.6D) / 336m (9.6D)
- Published data from one land mast, two sea masts, and SODAR*
- Validation data for single, double, and quintuple wakes

*Barthelmie RJ, Larsen G, Bergstrom H, Magnusson M, Schlez W, Rados K, Lange B, Vølund P, Neckelmann S, Christensen L, Schepers G, Hegberg T, Folkerts L. Proceedings of the workshop: ‘ENDOW: efficient development of offshore windfarms’. Risø-R-1326(EN), Risø National Laboratory, Roskilde, 2002.

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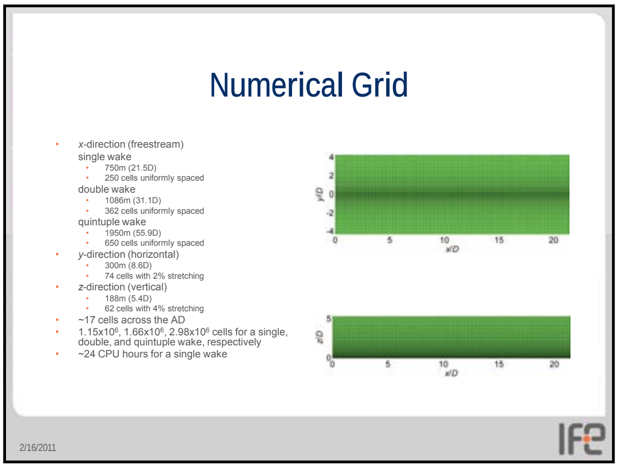

Numerical Grid

- *x*-direction (freestream)
  single wake
  - 750m (21.5D)
  - 250 cells uniformly spaced

  double wake
  - 1086m (31.1D)
  - 362 cells uniformly spaced

  quintuple wake
  - 1950m (55.9D)
  - 650 cells uniformly spaced
- *y*-direction (horizontal)
  - 300m (8.6D)
  - 74 cells with 2% stretching
- *z*-direction (vertical)
  - 188m (5.4D)
  - 62 cells with 4% stretching
- ~17 cells across the AD
- $1.15x10^6$, $1.66x10^6$, $2.98x10^6$ cells for a single, double, and quintuple wake, respectively
- ~24 CPU hours for a single wake

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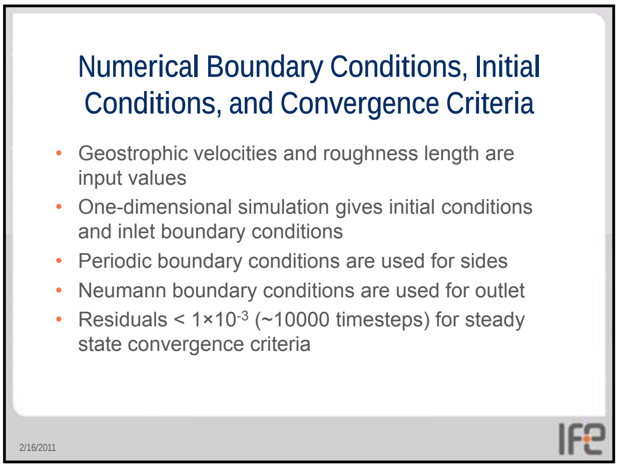

Numerical Boundary Conditions, Initial Conditions, and Convergence Criteria

- Geostrophic velocities and roughness length are input values
- One-dimensional simulation gives initial conditions and inlet boundary conditions
- Periodic boundary conditions are used for sides
- Neumann boundary conditions are used for outlet
- Residuals < 1×10^{-3} (~10000 timesteps) for steady state convergence criteria

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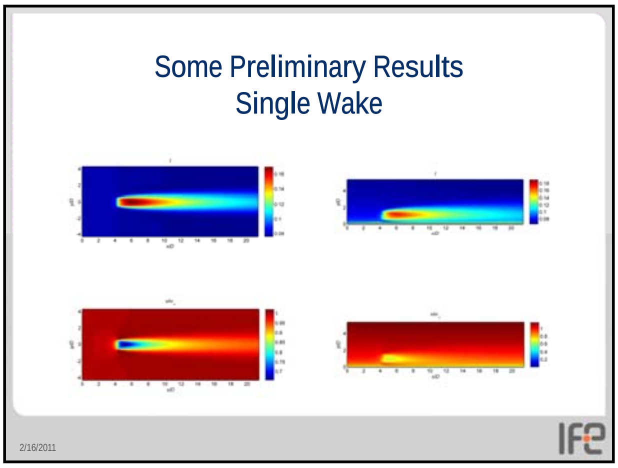

Some Preliminary Results Single Wake

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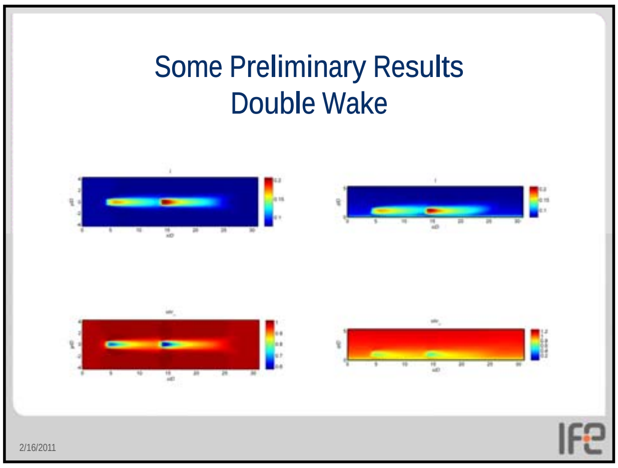
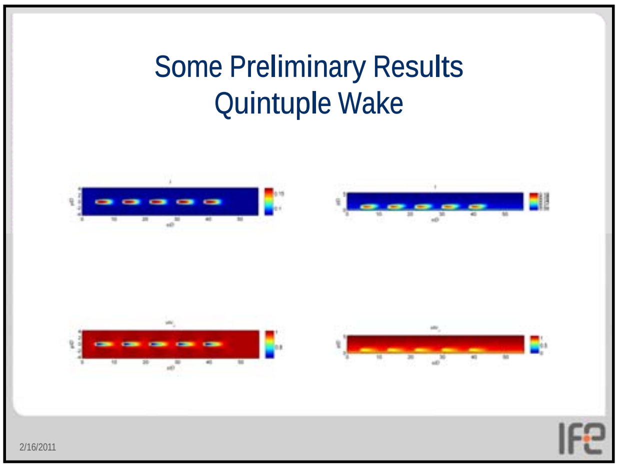


Some Preliminary Results Double Wake

2/16/2011



Some Preliminary Results Quintuple Wake

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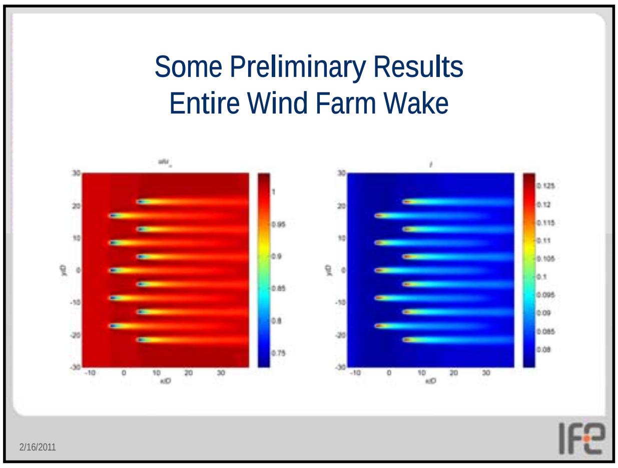
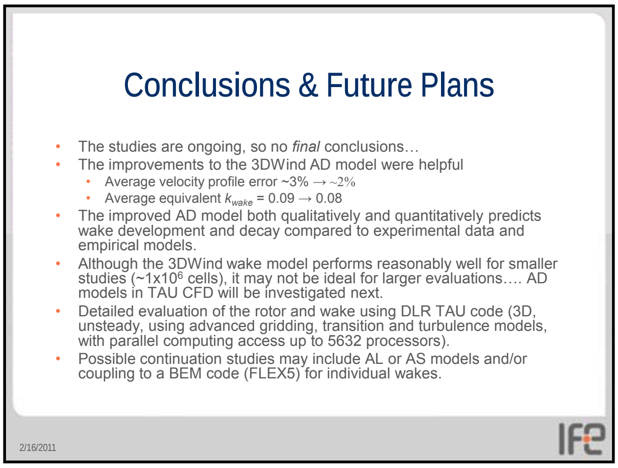


Some Preliminary Results Entire Wind Farm Wake

2/16/2011



Conclusions & Future Plans

- The studies are ongoing, so no *final* conclusions…
- The improvements to the 3DWind AD model were helpful
  - Average velocity profile error ~3% → ~2%
  - Average equivalent k_{wake} = 0.09 → 0.08
- The improved AD model both qualitatively and quantitatively predicts wake development and decay compared to experimental data and empirical models.
- Although the 3DWind wake model performs reasonably well for smaller studies (~1x10^6 cells), it may not be ideal for larger evaluations.… AD models in TAU CFD will be investigated next.
- Detailed evaluation of the rotor and wake using DLR TAU code (3D, unsteady, using advanced gridding, transition and turbulence models, with parallel computing access up to 5632 processors).
- Possible continuation studies may include AL or AS models and/or coupling to a BEM code (FLEX5) for individual wakes.

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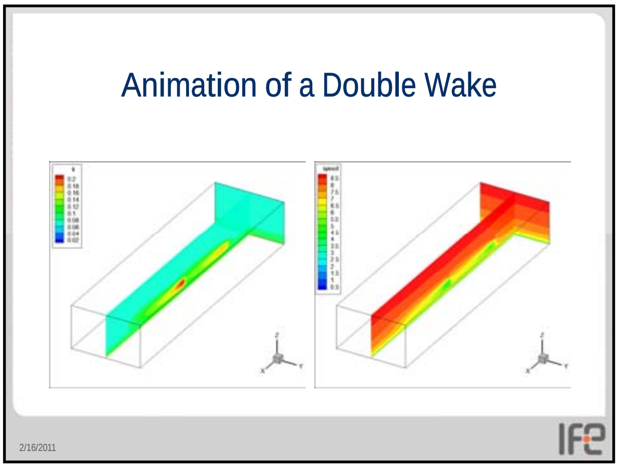

Animation of a Double Wake

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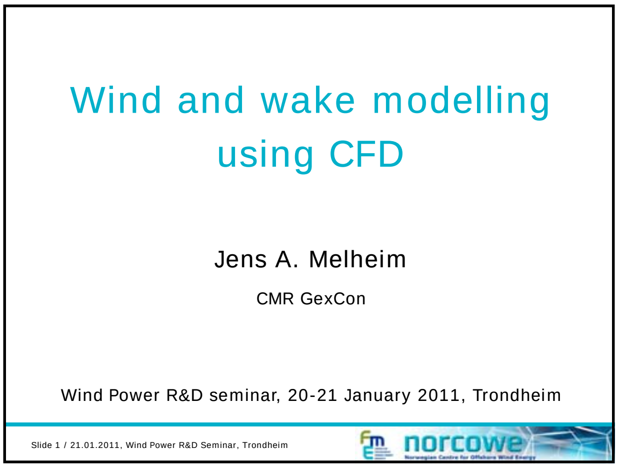
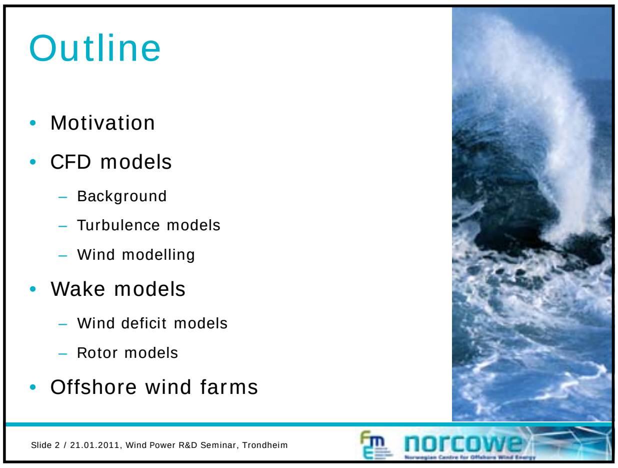


Wind and wake modelling using CFD

Jens A. Melheim

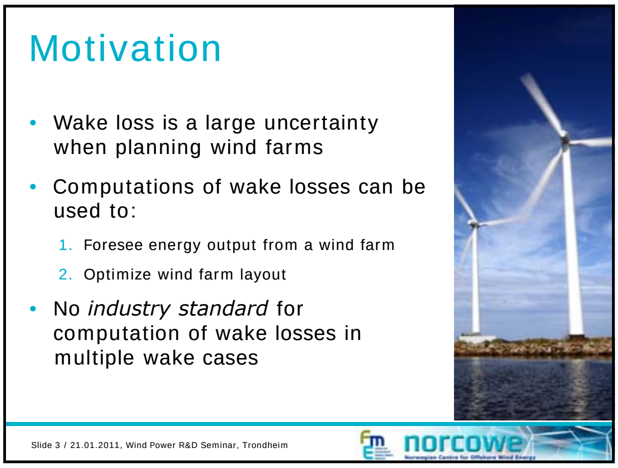
CMR GexCon

Wind Power R&D seminar, 20-21 January 2011, Trondheim



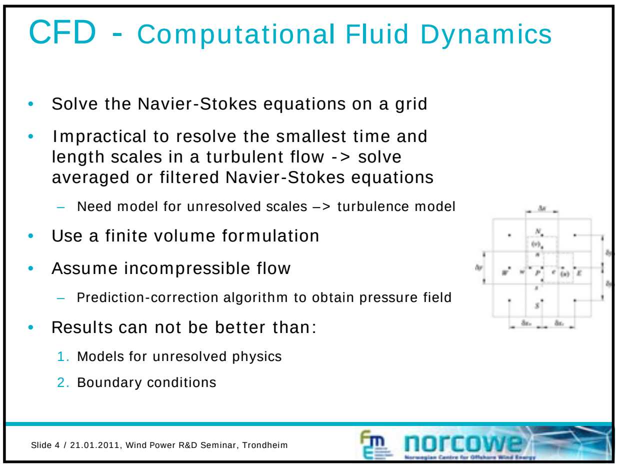
Outline

- Motivation
- CFD models
  - Background
  - Turbulence models
  - Wind modelling
- Wake models
  - Wind deficit models
  - Rotor models
- Offshore wind farms



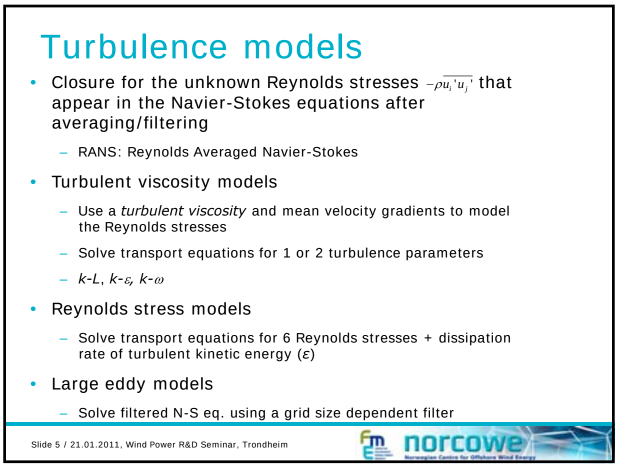
Motivation

- Wake loss is a large uncertainty when planning wind farms
- Computations of wake losses can be used to:
  1. Foresee energy output from a wind farm
  2. Optimize wind farm layout
- No *industry standard* for computation of wake losses in multiple wake cases



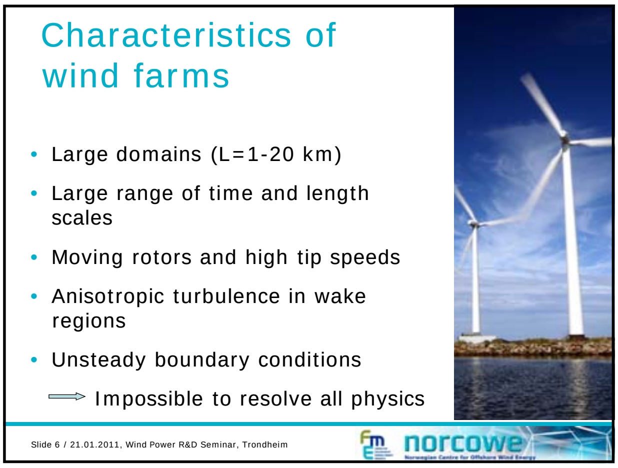
CFD - Computational Fluid Dynamics

- Solve the Navier-Stokes equations on a grid
- Impractical to resolve the smallest time and length scales in a turbulent flow -> solve averaged or filtered Navier-Stokes equations
  - Need model for unresolved scales –> turbulence model
- Use a finite volume formulation
- Assume incompressible flow
  - Prediction-correction algorithm to obtain pressure field
- Results can not be better than:
  1. Models for unresolved physics
  2. Boundary conditions



Turbulence models

- Closure for the unknown Reynolds stresses $-\rho \overline{u_i' u_j'}$ that appear in the Navier-Stokes equations after averaging/filtering
  - RANS: Reynolds Averaged Navier-Stokes
- Turbulent viscosity models
  - Use a *turbulent viscosity* and mean velocity gradients to model the Reynolds stresses
  - Solve transport equations for 1 or 2 turbulence parameters
  - k-L, k-ε, k-ω
- Reynolds stress models
  - Solve transport equations for 6 Reynolds stresses + dissipation rate of turbulent kinetic energy (ε)
- Large eddy models
  - Solve filtered N-S eq. using a grid size dependent filter



Characteristics of wind farms

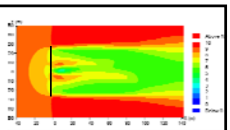
- Large domains (L=1-20 km)
- Large range of time and length scales
- Moving rotors and high tip speeds
- Anisotropic turbulence in wake regions
- Unsteady boundary conditions

⟹ Impossible to resolve all physics

Implications

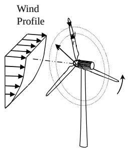
- Large domains (L=1-20 km)
  - Only RANS based models applicable without using super computers.
- Large span of time and length scales
  - Wall functions at ground / ocean
  - Blades cannot be resolved in detail
- Moving rotors with high tip speed
  - Average over a rotor swept
- Anisotropic turbulence in wake regions
  - Turbulent viscosity models are not accurate in the near wake
- Unsteady boundary conditions
  - Assume steady state when planning

Wake models



- Explicit wake models
  - Calculate wind speed deficit in the wake
  - WaSP, WindSim
- Parabolic models / Eddy viscosity models
  - Start ~2D downstream of turbine using Gaussian wake profiles
  - Solve simplified Navier-Stokes on axis-symmetric grid or 3D grid
  - ECN Wakefarmer, GH Windfarmer, FLaP (Uni Oldenburg)
- Full CFD models
  - Model turbine by momentum sink
  - NTUA CFD, Ellipsys3D, CENER, CRES, RGU-3D-NS

Wind turbine models



- Actuator Disc models
  - Model rotor area by a porous disk
  - Momentum sink uniformly distributed
  - No mature model for turbulence generation
- Actuator line / Actuator surface models
  - Model each blade using a line or a surface
  - Use BEM to calculate local forces
  - Time step restricted by the tip speed
- Direct methods
  - Geometry models of moving blades (moving grid)
  - Resolve flow at blade

Summary of wake models

Model	Pre	Cons	Multiple wakes?
Explict models	Quick Very easy to use	Need to tune parameters No physics solved	No
Parabolic models/ Eddy viscosity	Quick Easy to use	Terrain (2D models) Multiple wakes	Tuning needed
Full CFD with Actuator Disc model	Solve most physics Easy input	Slow Turbulence production Not accurate in near wake	Yes
Full CFD with Actuator Line/Surface	Solve most physics Accurate in near wake	Very slow Requires detailed blade and airfoil data	Maybe
Full CFD with direct blade model	Solve "all" physics Accurate in the near wake	Extremely slow Much work to setup	No

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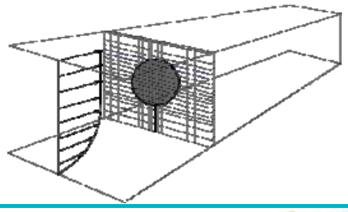
CFD – Actuator Disc

- Momentum sink in control volumes inside the rotor area – uniformly distributed over disc area
- Turbulence production caused by wind turbine
  - No established model for turbulence generation



Actuator Disc Improvement

- Blade Element Momentum (BEM) Theory yield a better distribution of forces than the traditional AD method.

AD:

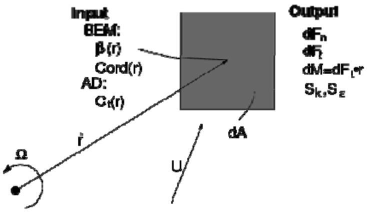
$$dF_n = C_t \frac{1}{2}\rho U_0^2 dA$$

$$dF_t = 0$$

BEM:

$$dF_n = F_L\cos(\phi) + F_D\sin(\phi)$$

$$dF_t = F_L\sin(\phi) - F_D\cos(\phi)$$



Turbulence production

- El Kasmin & Masson (2008): $S_\varepsilon = C_{\varepsilon 4}\frac{P_t^2}{\rho k}$
- Rethoré et al (2009) $S_U = -\frac{1}{2}C_x\left(aU_0\right)^2$

$$S_k = \frac{1}{2}C_x\left(\beta_p\left(aU_0\right)^3 - \beta_d kaU_0\right)$$

$$S_\varepsilon = \frac{1}{2}C_x\frac{\varepsilon}{k}\left(C_{\varepsilon 4}\beta_p\left(aU_0\right)^3 - C_{\varepsilon 5}\beta_d kaU_0\right)$$

- BEM $S_k = \alpha\left(dF_n - dF_t\right)aU_0$

$$S_\varepsilon = C_{1\varepsilon}\frac{\varepsilon}{k}S_k$$

A. El Kasmin & C. Masson (2008). *Journal of Wind Engineering in Industrial Aerodynamics* **96**:103-122

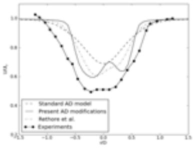
P.-E. Rethore et al. (2009). *EWEC 2009*

Sexbierum experiment

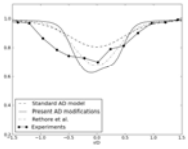
- West coast of the Netherlands
- Polenko/Holec WPS 30 wind turbine
- Wind 10 m/s at hub height (35 m)
- Turbulence intensity 10%
- Thrust coefficient C_t=0.7
- Measurements 2.5D, 5.5D and 8D downstream at hub height

Sexbierum experiment

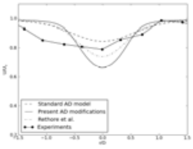
- Wake wind speed deficit:



x=2.5D



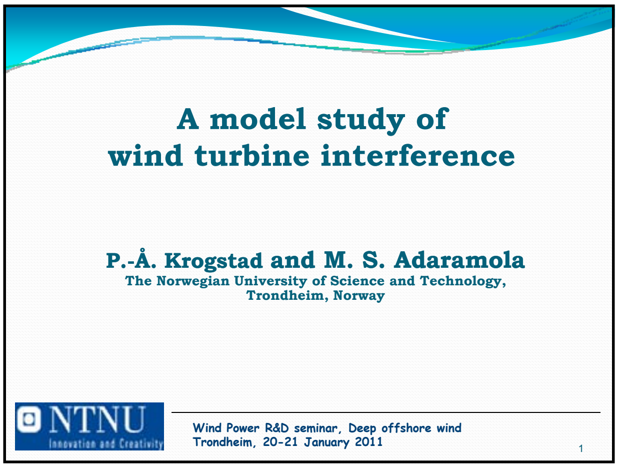
x=5.5D



x=8D

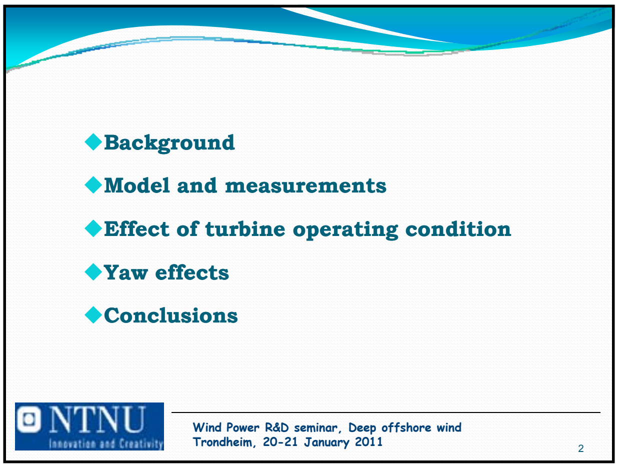
Conclusions

- The combination of full CFD with RANS based turbulence model and Actuator Disc is a promising technique for modelling of wake losses in wind farms
- Better understanding and modelling of the turbulence in the near-field of the rotor are needed
- Validation and benchmarking are key factors for success

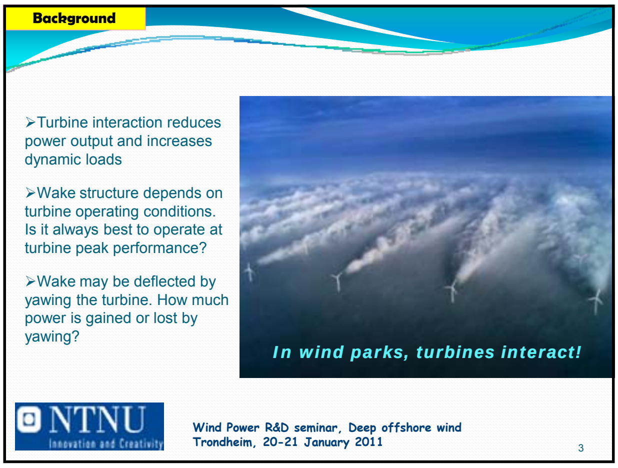


A model study of wind turbine interference

P.-Å. Krogstad and M. S. Adaramola
The Norwegian University of Science and Technology,
Trondheim, Norway



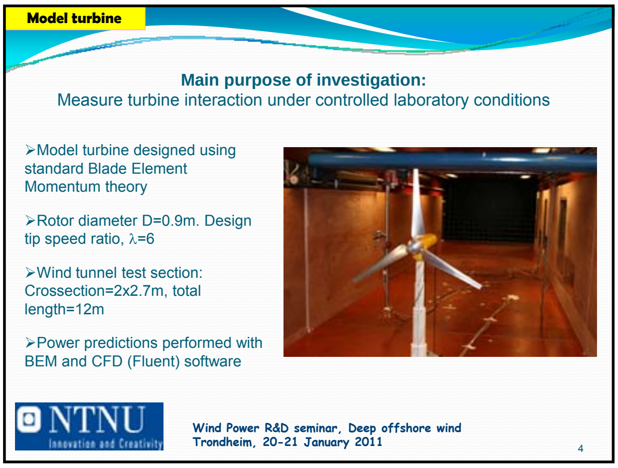
- ◆Background
- ◆Model and measurements
- ◆Effect of turbine operating condition
- ◆Yaw effects
- ◆Conclusions



Background

- ➢Turbine interaction reduces power output and increases dynamic loads
- ➢Wake structure depends on turbine operating conditions. Is it always best to operate at turbine peak performance?
- ➢Wake may be deflected by yawing the turbine. How much power is gained or lost by yawing?

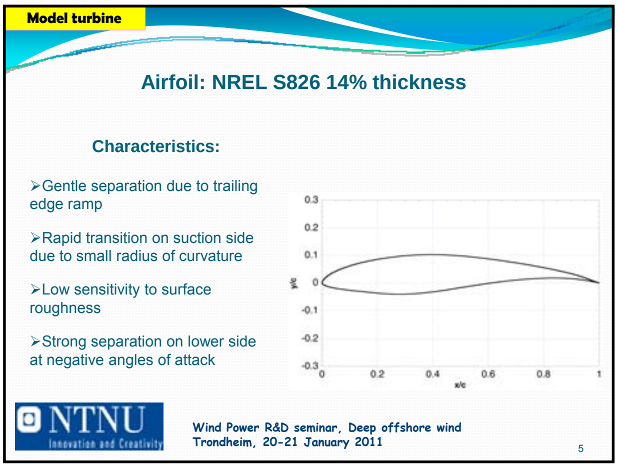
In wind parks, turbines interact!



Model turbine

Main purpose of investigation:
Measure turbine interaction under controlled laboratory conditions

- ➢Model turbine designed using standard Blade Element Momentum theory
- ➢Rotor diameter D=0.9m. Design tip speed ratio, λ=6
- ➢Wind tunnel test section: Crossection=2x2.7m, total length=12m
- ➢Power predictions performed with BEM and CFD (Fluent) software

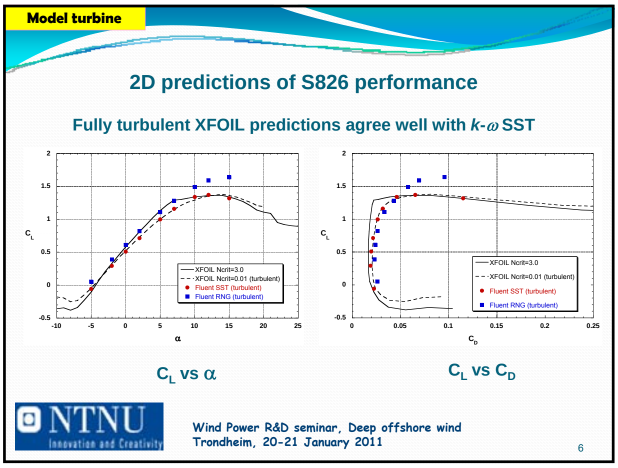


Model turbine

Airfoil: NREL S826 14% thickness

Characteristics:

- ➢Gentle separation due to trailing edge ramp
- ➢Rapid transition on suction side due to small radius of curvature
- ➢Low sensitivity to surface roughness
- ➢Strong separation on lower side at negative angles of attack



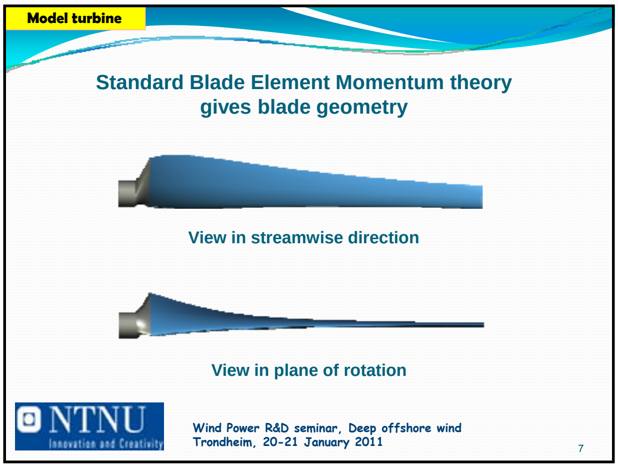
Model turbine

2D predictions of S826 performance

Fully turbulent XFOIL predictions agree well with *k-ω* SST

C_L vs α

C_L vs C_D



Model turbine

Standard Blade Element Momentum theory gives blade geometry

View in streamwise direction

View in plane of rotation

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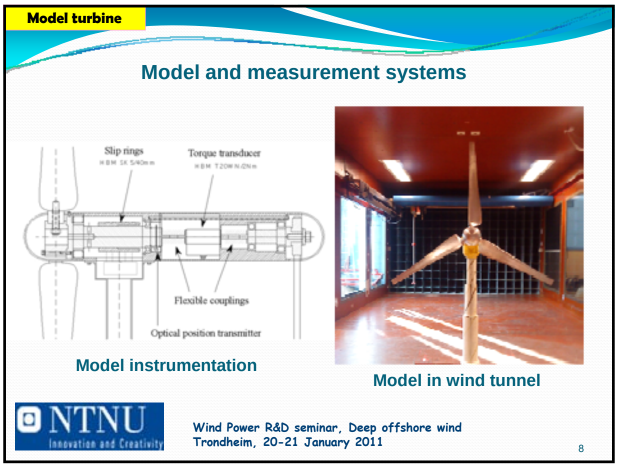
Trondheim, 20-21 January 2011



Model turbine

Model and measurement systems

Model instrumentation

Model in wind tunnel

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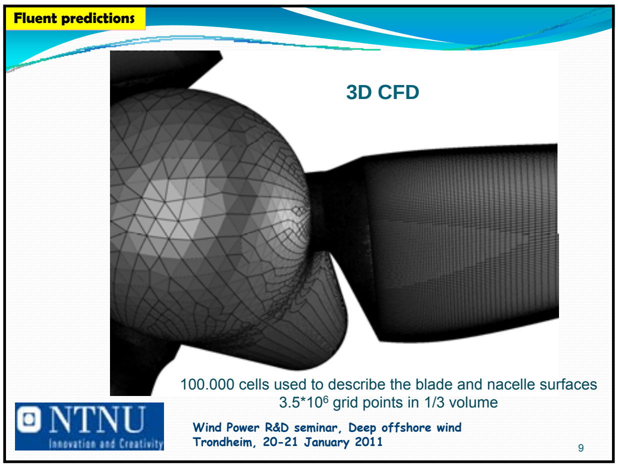

Fluent predictions

3D CFD

100.000 cells used to describe the blade and nacelle surfaces
3.5*10^6 grid points in 1/3 volume

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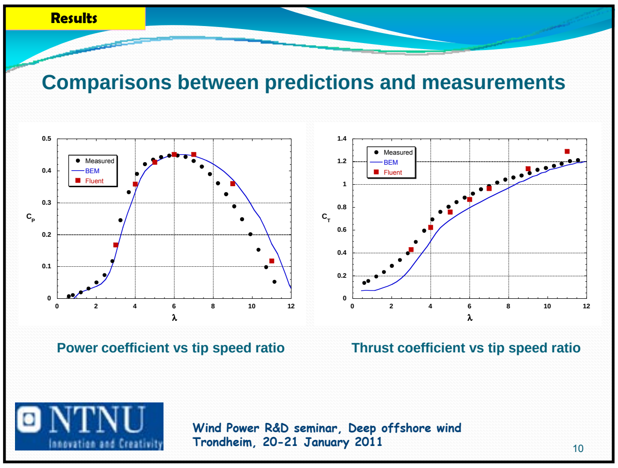

Results

Comparisons between predictions and measurements

Power coefficient vs tip speed ratio

Thrust coefficient vs tip speed ratio

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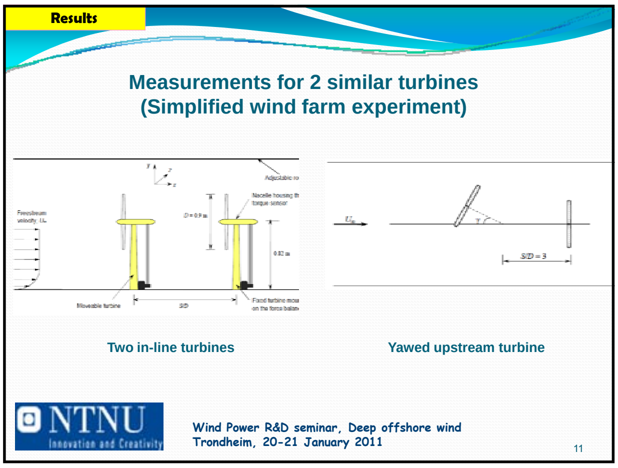
Trondheim, 20-21 January 2011



Results

Measurements for 2 similar turbines (Simplified wind farm experiment)

Two in-line turbines

Yawed upstream turbine

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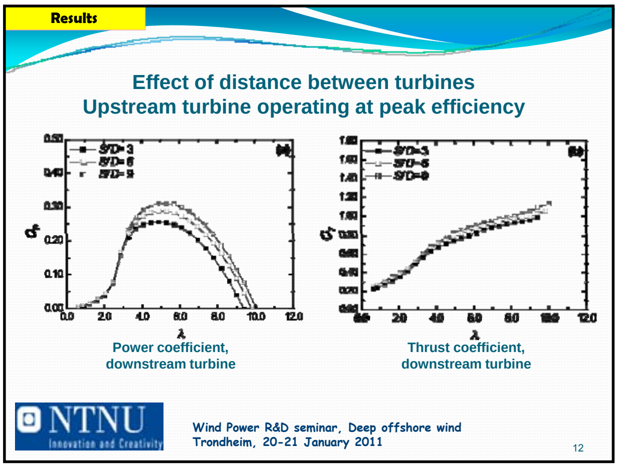

Results

Effect of distance between turbines Upstream turbine operating at peak efficiency

Power coefficient,
downstream turbine

Thrust coefficient,
downstream turbine

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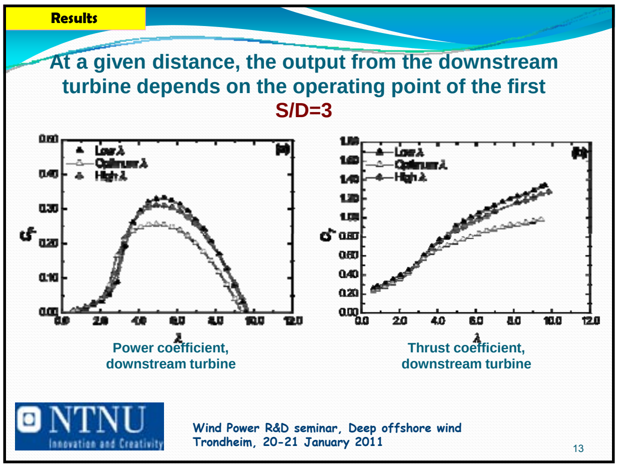
Trondheim, 20-21 January 2011



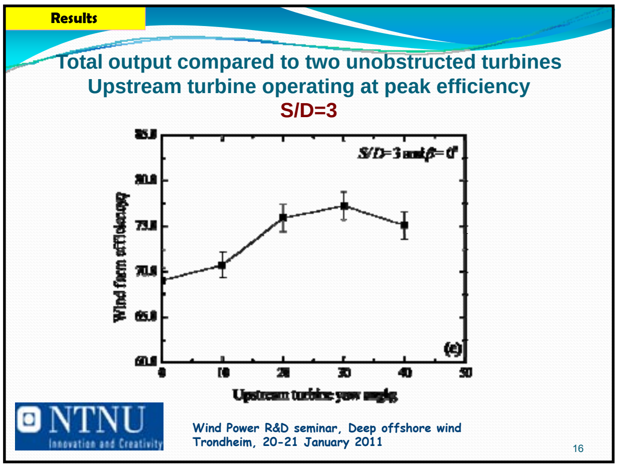
Results

At a given distance, the output from the downstream turbine depends on the operating point of the first

S/D=3

Power coefficient, downstream turbine

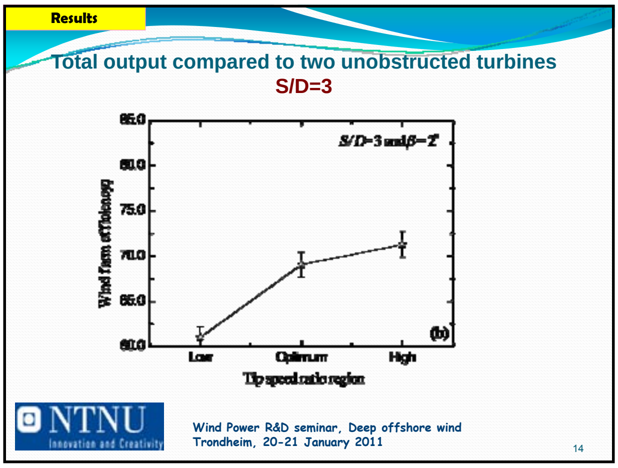
Thrust coefficient, downstream turbine



Results

Total output compared to two unobstructed turbines Upstream turbine operating at peak efficiency

S/D=3



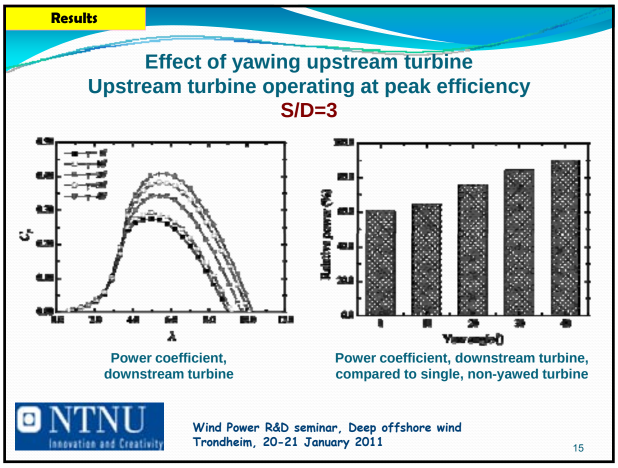
Results

Total output compared to two unobstructed turbines

S/D=3

Conclusions

- ➢ When two wind turbines are placed in-line and both operated at best efficiency, the output of a turbine at S=3D is less than 60% of that upstream
- ➢ The power reduction is influenced by the wake characteristics from the turbine upstream and therfore by its operating point
- ➢ By reducing the power extracted from the first, the TOTAL output may be increased
- ➢ Yawing a turbine reduces its power by $\cos^3\gamma$. But it also deflects the wake which increases the output further downstream
- ➢ Two turbines operating in-line at best efficiency may increase the total output from about 69% of two unobstructed turbines at zero yaw, to 78% when the first is yawed 30 degrees. (Figures taken for S/D=3.)



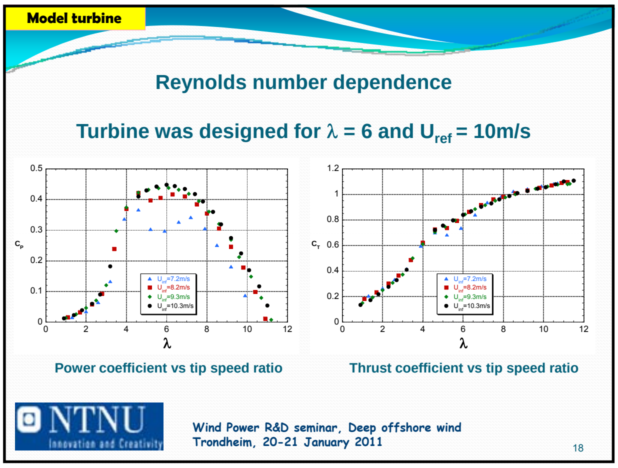
Results

Effect of yawing upstream turbine Upstream turbine operating at peak efficiency

S/D=3

Power coefficient, downstream turbine

Power coefficient, downstream turbine, compared to single, non-yawed turbine



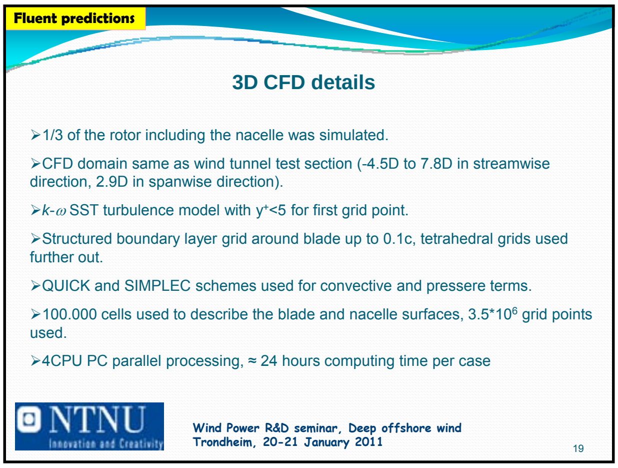
Model turbine

Reynolds number dependence

Turbine was designed for $\lambda = 6$ and $U_{ref} = 10m/s$

Power coefficient vs tip speed ratio

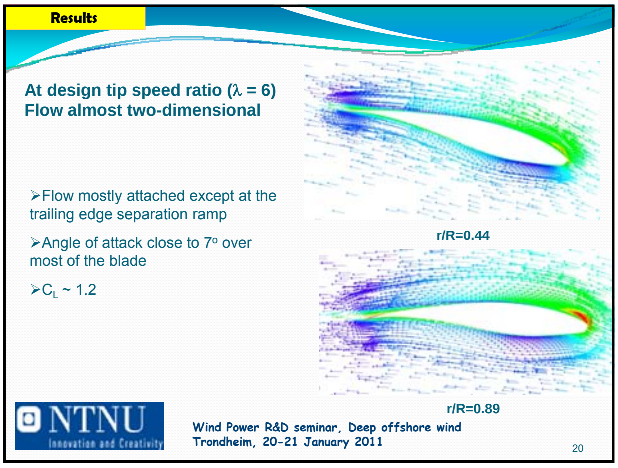
Thrust coefficient vs tip speed ratio



Fluent predictions

3D CFD details

- ➢1/3 of the rotor including the nacelle was simulated.
- ➢CFD domain same as wind tunnel test section (-4.5D to 7.8D in streamwise direction, 2.9D in spanwise direction).
- ➢*k-ω* SST turbulence model with $y^{+}<5$ for first grid point.
- ➢Structured boundary layer grid around blade up to 0.1c, tetrahedral grids used further out.
- ➢QUICK and SIMPLEC schemes used for convective and pressere terms.
- ➢100.000 cells used to describe the blade and nacelle surfaces, $3.5*10^{6}$ grid points used.
- ➢4CPU PC parallel processing, ≈ 24 hours computing time per case



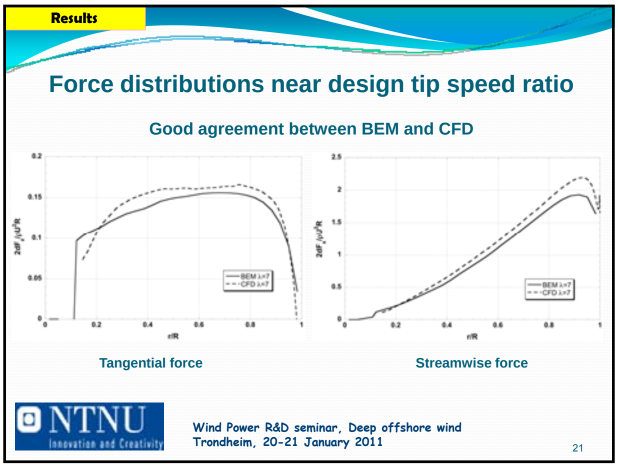
Results

At design tip speed ratio (λ = 6)
Flow almost two-dimensional

- ➢Flow mostly attached except at the trailing edge separation ramp
- ➢Angle of attack close to 7° over most of the blade
- ➢C_L ~ 1.2

r/R=0.44

r/R=0.89



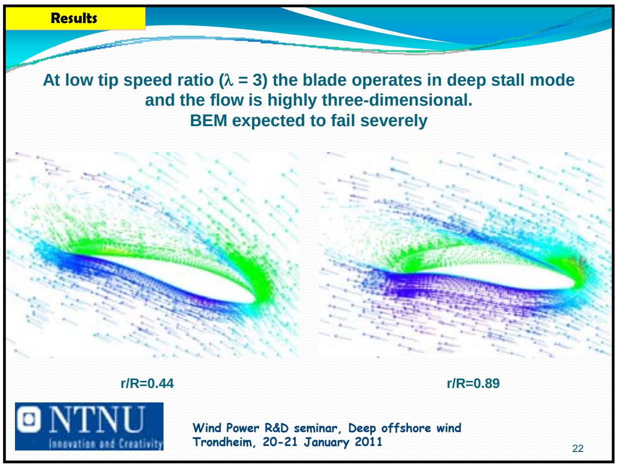
Results

Force distributions near design tip speed ratio

Good agreement between BEM and CFD

Tangential force

Streamwise force

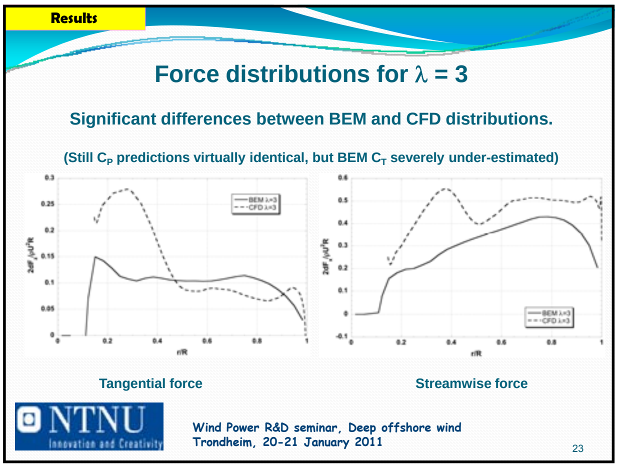


Results

At low tip speed ratio (λ = 3) the blade operates in deep stall mode and the flow is highly three-dimensional.
BEM expected to fail severely

r/R=0.44

r/R=0.89



Results

Force distributions for λ = 3

Significant differences between BEM and CFD distributions.

(Still C_P predictions virtually identical, but BEM C_T severely under-estimated)

Tangential force

Streamwise force

Closing session – Success stories from Offshore Wind Research, Development and Deployment

Carbon Trust's Offshore Wind Accelerator, Phil de Villiers, Carbon Trust

From Scanwind to GE – becoming a global player anchored in Mid-Norway,
Martin Degen, GE

HyWind – A success story – A catalyst with Access as an example,
Sjur Bratland, Statoil

Offshore wind farm forecasting and energy production, Jostein Mælan, StormGeo

Using research experiences in marine technology for advancing offshore wind technology, Prof. Torgeir Moan, NTNU

Research gives results, Espen B Christophersen, Research Council of Norway

Carbon Trust's Offshore Wind Accelerator

Accelerating progress of offshore wind energy through targeted R&D

NOWITECH
21 January 2011

Phil de Villiers

CARBON TRUST
DONG energy
e·on
MAINSTREAM RENEWABLE POWER
RWE The energy to lead
SCOTTISHPOWER RENEWABLES
SSE Renewables
Statkraft
Statoil

CARBON TRUST

Our mission is to accelerate the move to a low carbon economy

Independent company mainly funded by UK Government

We cut carbon now by

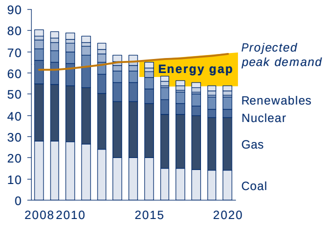
- Providing specialist advice and finance to help organisations cut carbon
- Setting standards for carbon reduction

We cut future carbon emissions by

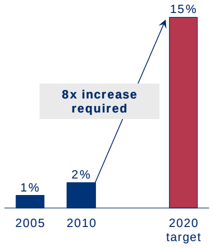
- Opening markets for low carbon technologies
- Leading industry collaborations to commercialise technologies
- Investing in early stage low carbon companies

UK faces an energy gap and tough renewable energy target

Installed capacity, projected demand (GW), 2008-2020



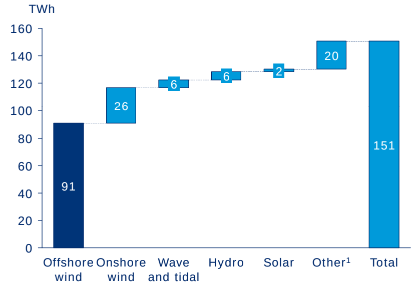
% of UK energy from renewables, 2005-2020



Source: Committee on Climate Change, 2008 (based on DECC Energy Model)

Mass deployment of offshore wind required to meet targets

Forecast UK 2020 electricity supply in 40% scenario

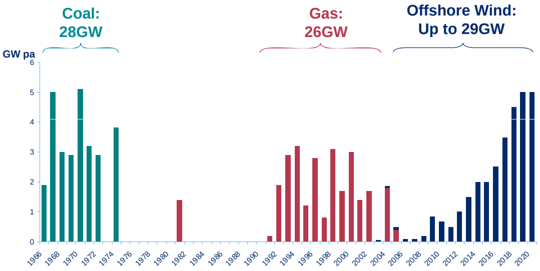


- Up to 25% of electricity to come from Offshore Wind
- 6,000 turbines to be installed by 2020

1. Landfill, co-firing, biomass
Source: Carbon Trust "Offshore wind power: big challenge, big opportunity", 2008; BCG analysis 2008

Deployment rates are very challenging but feasible

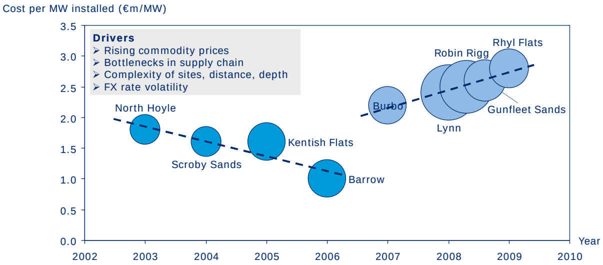
Build rate similar to coal in the 1970s and gas in the 1990s



Could create 70,000 jobs in UK by 2020

Source: Carbon Trust "Offshore wind power: big challenge, big opportunity", 2008; LEK Consulting, Renewable Energy Framework March 2006, Carbon Trust "Focus for Success", 2009

But cost reduction is essential



Drivers

- Rising commodity prices
- Bottlenecks in supply chain
- Complexity of sites, distance, depth
- FX rate volatility

Source: Emerging Energy Research, 2009

Increasing RD&D is critical

Increase project IRRs to accelerate deployment

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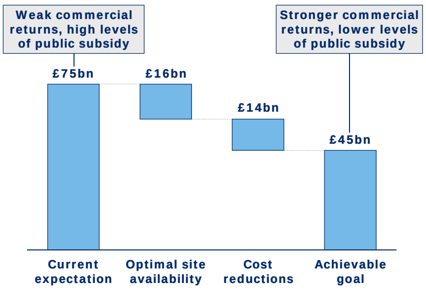


Source: Carbon Trust "Offshore wind power: big challenge, big opportunity", 2008

Offshore Wind Accelerator is a consortium to reduce costs

Objective: Reduce cost of energy by 10% through RD&D

CARBON TRUST

DONG energy

e.on

MAINSTREAM RENEWABLE POWER

RWE The energy to lead

SSE Renewables

SCOTTISHPOWER RENEWABLES

Statoil

Statkraft

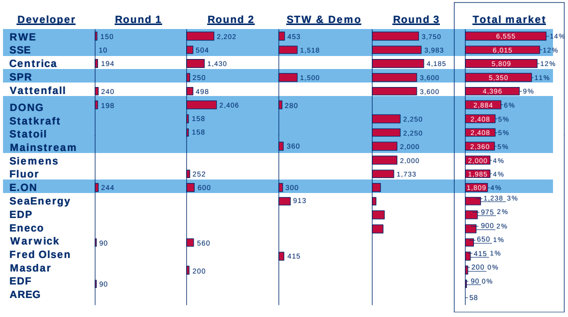
CARBON TRUST

- 8 developers + Carbon Trust
- Focusing on developing technologies for
  - Round 1 & 2 extensions
  - Round 3
  - Scottish Territorial Waters
- Total budget ~£40m
  - £10m for collaborative R&D
  - Up to £30m for demonstrations
  - Carbon Trust funds 1/3
- Commitment to 2014
  - Started October 2008

60% of UK market is in OWA: attractive for innovators

OWA developers have 30GW of licensed capacity in UK waters

CARBON TRUST



Developer	Round 1	Round 2	STW & Demo	Round 3	Total market
RWE	150	2,202	453	3,750	6,555 14%
SSE	10	504	1,518	3,983	6,015 12%
Centrica	194	1,430		4,185	5,809 12%
SPR		250	1,500	3,600	5,350 11%
Vattenfall	240	498		3,600	4,396 9%
DONG	198	2,406	280		2,884 6%
Statkraft		158		2,250	2,408 5%
Statoil		158		2,250	2,408 5%
Mainstream			360	2,000	2,360 5%
Siemens				2,000	2,000 4%
Fluor		252		1,733	1,985 4%
E.ON	244	600	300		1,809 4%
SeaEnergy			913		1,238 3%
EDP					975 2%
Eneco					900 2%
Warwick	90	560			650 1%
Fred Olsen			415		415 1%
Masdar		200			200 0%
EDF	90				90 0%
AREG					58

🟦 OWA Stage II partners

Source: RenewableUK (Jan 2010), The Crown Estate (May 2010)

OWA objectives

CARBON TRUST

- **Focus on commercial outcomes: reducing cost of energy by 10%**
- **Deliver innovations that can be implemented by offshore wind developers in time for Round 3 (~2015)**
- **Learn by drawing on the experiences of the different members**
  - Offshore wind, oil and gas, onshore wind
- **Encourage the best designers to deliver the innovations**
  - Let them keep their IP
  - Look internationally, not just to UK
  - Engage them on very specific challenges
- **Look to other industries for technology transfer**
  - Not just oil and gas, but also civil engineers, naval architects, manufacturers
- **Operate responsively to member needs, and cost effectively**

Objectives require very targeted R&D

OWA involves 90+ people from 8 Developers, 400+ companies

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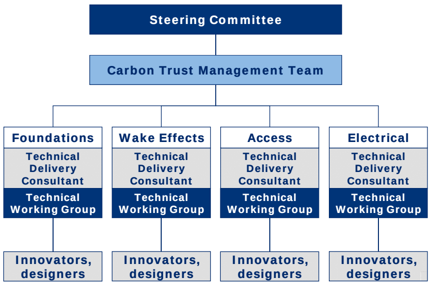


Steering Committee

Carbon Trust Management Team

Foundations	Wake Effects	Access	Electrical
Technical Delivery Consultant	Technical Delivery Consultant	Technical Delivery Consultant	Technical Delivery Consultant
Technical Working Group	Technical Working Group	Technical Working Group	Technical Working Group
Innovators, designers	Innovators, designers	Innovators, designers	Innovators, designers

90+ people

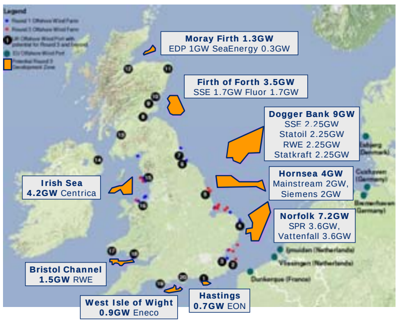
400+ companies

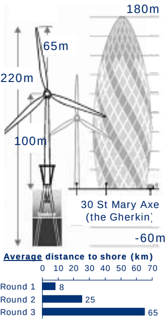
■ OWA partners
▨ Carbon Trust
□ 3rd party contractors

Farms will be large, far-shore, with bigger structures

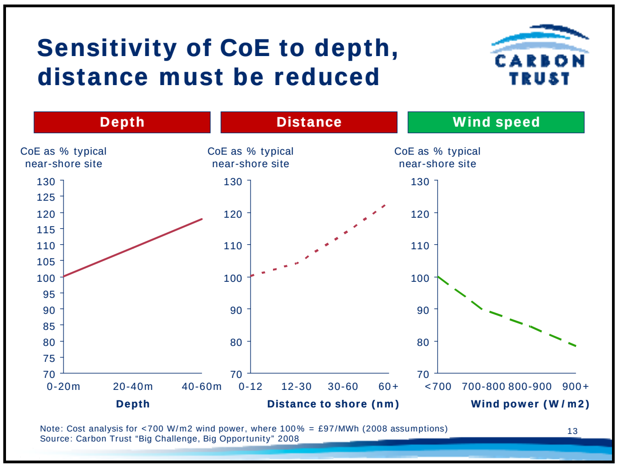
Round 3 zones

CARBON TRUST



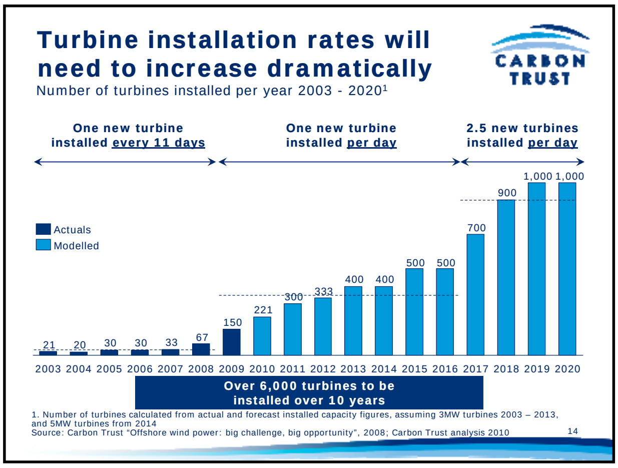


Source: UK Ports for the Offshore Wind Industry: Time to Act, DECC / BVG Associates, 5 February 2009, p.17; Financial Times, January 2010; Carbon Trust analysis



Sensitivity of CoE to depth, distance must be reduced

Note: Cost analysis for <700 W/m2 wind power, where 100% = £97/MWh (2008 assumptions)
Source: Carbon Trust "Big Challenge, Big Opportunity" 2008

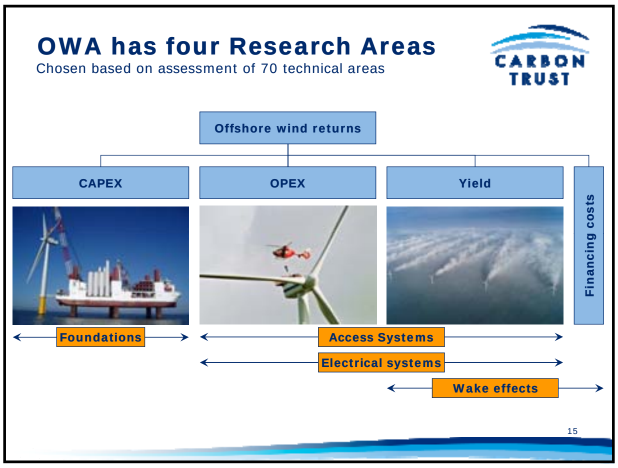


Turbine installation rates will need to increase dramatically

Number of turbines installed per year 2003 - 2020[1]

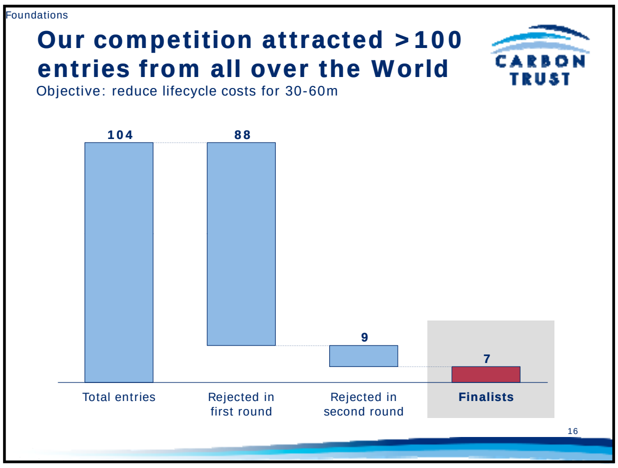
Over 6,000 turbines to be installed over 10 years

[1] Number of turbines calculated from actual and forecast installed capacity figures, assuming 3MW turbines 2003 – 2013, and 5MW turbines from 2014
Source: Carbon Trust "Offshore wind power: big challenge, big opportunity", 2008; Carbon Trust analysis 2010



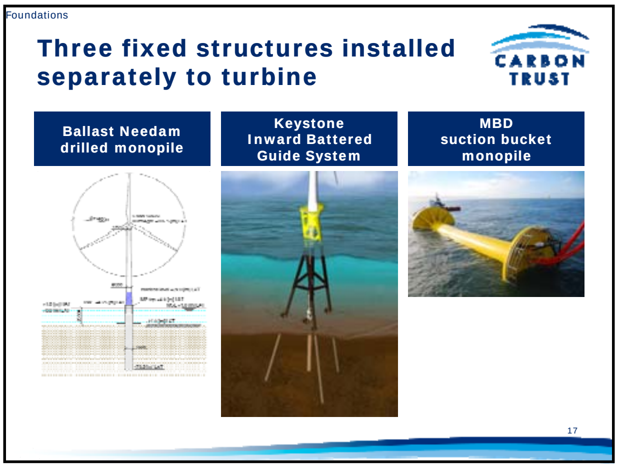
OWA has four Research Areas

Chosen based on assessment of 70 technical areas



Our competition attracted >100 entries from all over the World

Objective: reduce lifecycle costs for 30-60m

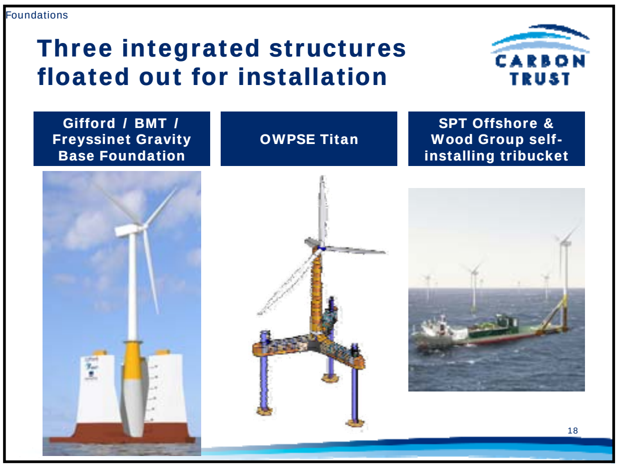


Three fixed structures installed separately to turbine

Ballast Needam drilled monopile

Keystone Inward Battered Guide System

MBD suction bucket monopile

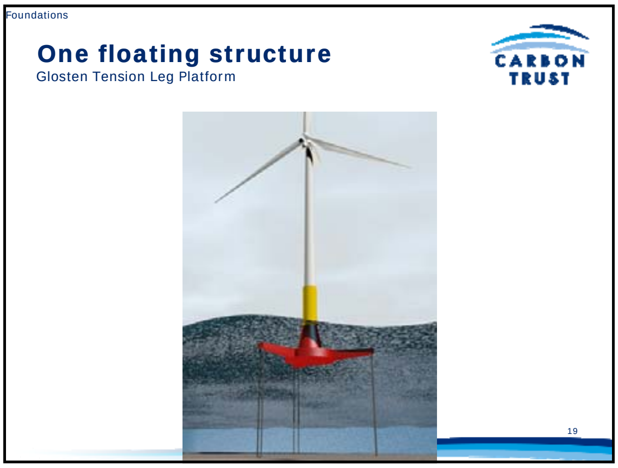


Three integrated structures floated out for installation

Gifford / BMT / Freyssinet Gravity Base Foundation

OWPSE Titan

SPT Offshore & Wood Group self-installing tribucket



Foundations

One floating structure

Glosten Tension Leg Platform

Foundations

Four structures short-listed for further development

Based on suitability for Round 3

Gifford-BMT-Freyssinet

Keystone

MBD

SPT Offshore & Wood Group

Foundations

Current focus: Mass production, and faster, cheaper installation

Fabrication

Airbus A320

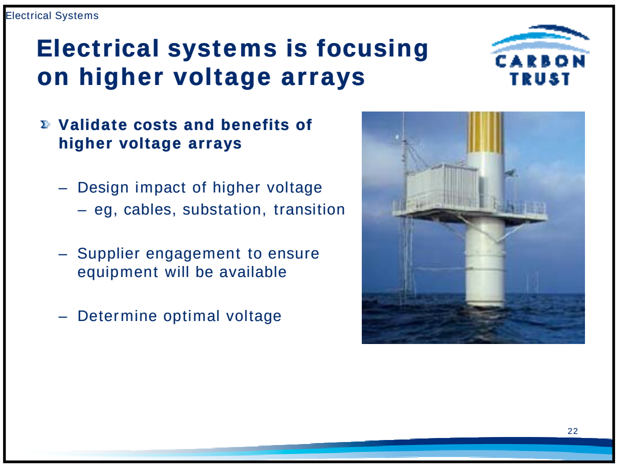
- Standardise, optimise, automate

Installation

IHC

- Improve utilisation rates

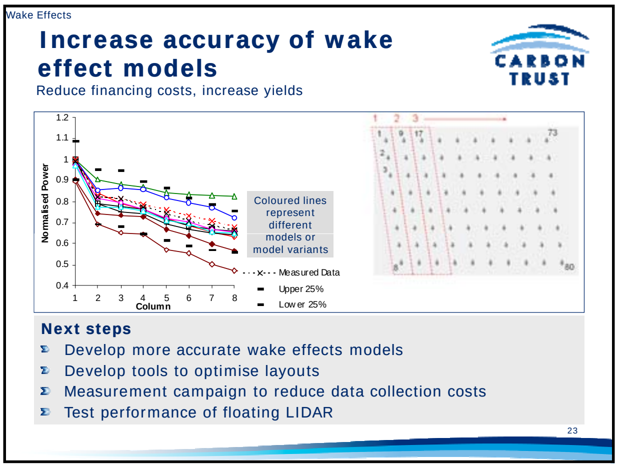
Next step: demonstrate concepts are ready for deployment



Electrical Systems

Electrical systems is focusing on higher voltage arrays

- **Validate costs and benefits of higher voltage arrays**
  - Design impact of higher voltage
    - eg, cables, substation, transition
  - Supplier engagement to ensure equipment will be available
  - Determine optimal voltage



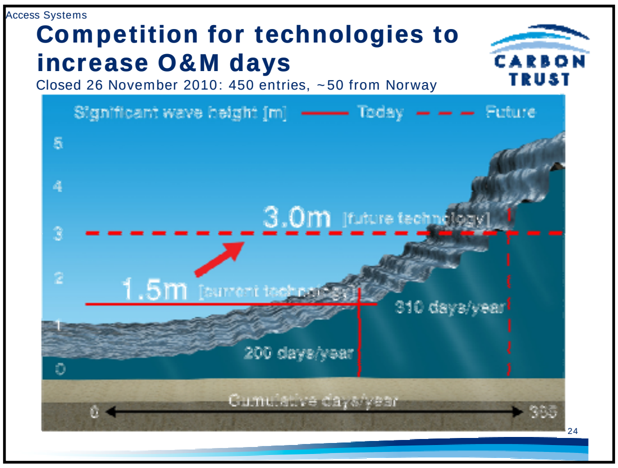
Wake Effects

Increase accuracy of wake effect models

Reduce financing costs, increase yields

Next steps

- Develop more accurate wake effects models
- Develop tools to optimise layouts
- Measurement campaign to reduce data collection costs
- Test performance of floating LIDAR



Access Systems

Competition for technologies to increase O&M days

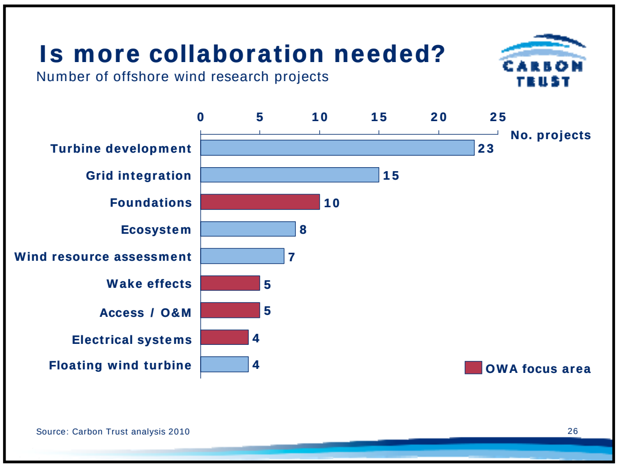
Closed 26 November 2010: 450 entries, ~50 from Norway

Conclusions

We believe OWA is a successful model for collaboration

- **Cost-effective approach for performing R&D**
  - Each members' annual contribution generates 12x research
- **Efficient forum for members to learn from each other**
- **Successful for screening the market for new technologies**
- **Promotes technology transfer from other industries**
  - Allowing new companies to enter the market
- **Very targeted R&D: Keeps focused on commercial returns**

…but we are still learning and would welcome further collaboration with research organisations and innovators



Is more collaboration needed?

Number of offshore wind research projects

Source: Carbon Trust analysis 2010

Questions

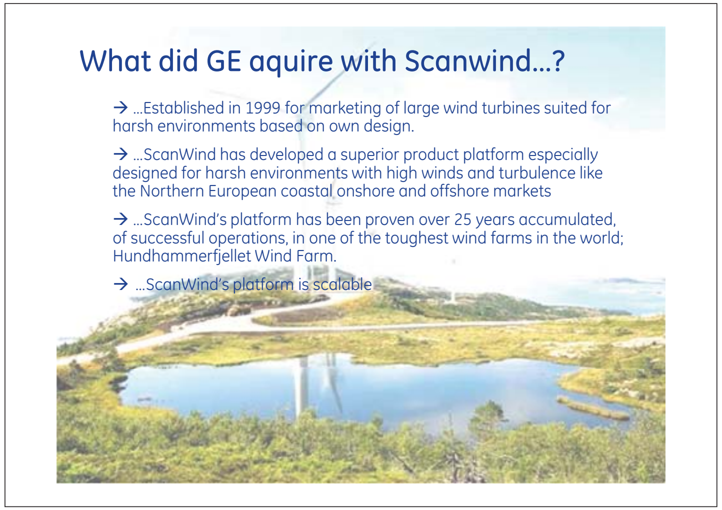
Phil de Villiers
phil.devilliers@carbontrust.co.uk
www.carbontrust.co.uk

GE Energy

From Scanwind to GE – becoming a global player anchored in Mid-Norway

Trondheim
January 2011

Martin Degen
GE Wind Energy
Nordic Region



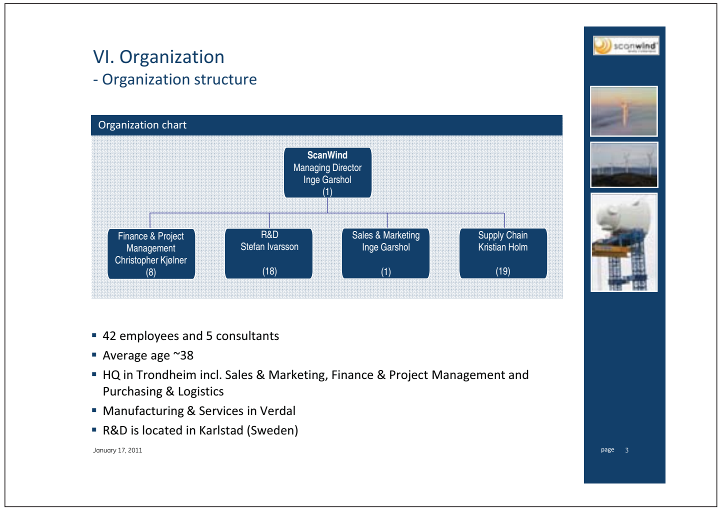
What did GE aquire with Scanwind…?

→ …Established in 1999 for marketing of large wind turbines suited for harsh environments based on own design.

→ …ScanWind has developed a superior product platform especially designed for harsh environments with high winds and turbulence like the Northern European coastal onshore and offshore markets

→ …ScanWind's platform has been proven over 25 years accumulated, of successful operations, in one of the toughest wind farms in the world; Hundhammerfjellet Wind Farm.

→ …ScanWind's platform is scalable



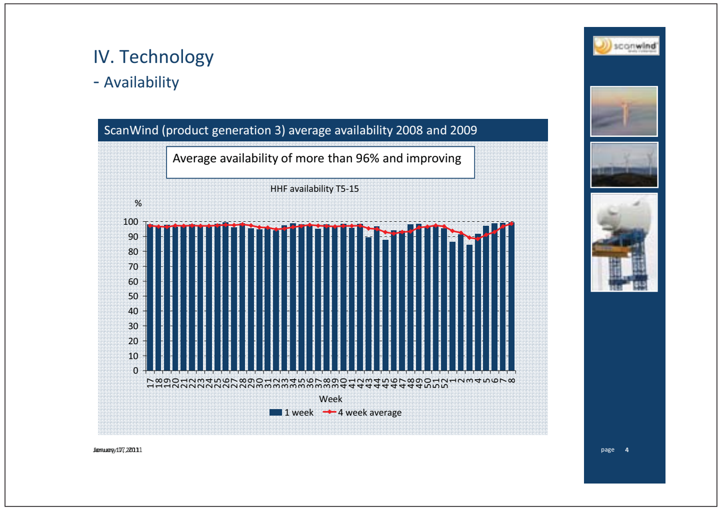
VI. Organization

- Organization structure

Organization chart

- 42 employees and 5 consultants
- Average age ~38
- HQ in Trondheim incl. Sales & Marketing, Finance & Project Management and Purchasing & Logistics
- Manufacturing & Services in Verdal
- R&D is located in Karlstad (Sweden)

January 17, 2011



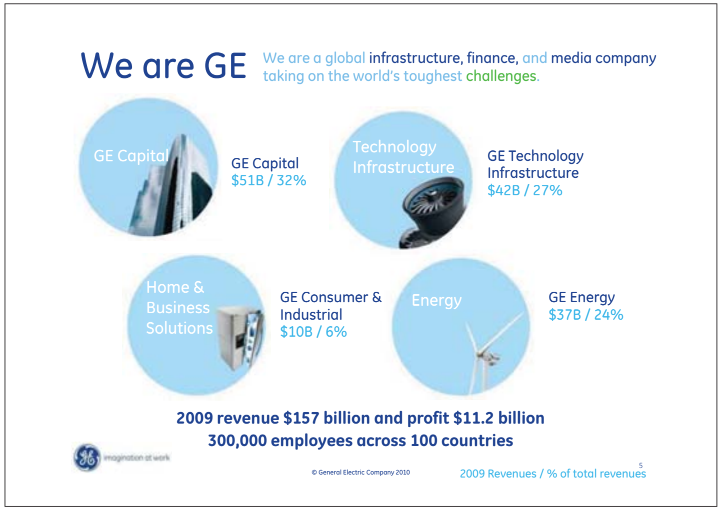
IV. Technology

- Availability

ScanWind (product generation 3) average availability 2008 and 2009

Average availability of more than 96% and improving

January 17, 2011



We are GE

We are a global infrastructure, finance, and media company taking on the world's toughest challenges.

GE Capital
$51B / 32%

GE Technology Infrastructure
$42B / 27%

GE Consumer & Industrial
$10B / 6%

GE Energy
$37B / 24%

2009 revenue $157 billion and profit $11.2 billion
300,000 employees across 100 countries

2009 Revenues / % of total revenues

Global Research

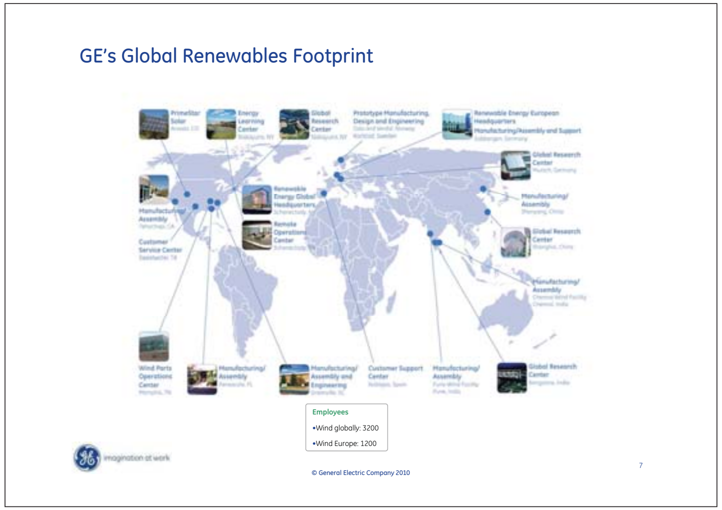
Began in Schenectady, New York in 1900

Founded with the focus to improve businesses through technology

Today: One of the world's most diverse industrial labs and the cornerstone of GE's commitment to technology

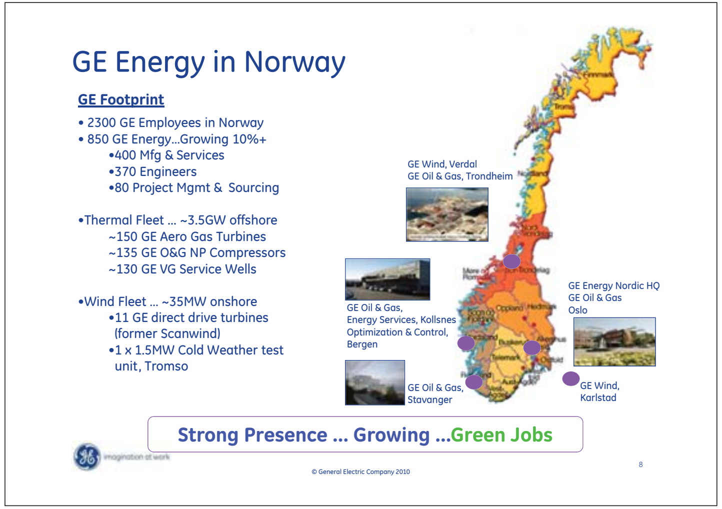
Niskayuna, New York
Munich, Germany
Bangalore, India
Shanghai, China

2,800 research employees
26,000 GE technologists worldwide
GE technology spend: ~$6B



GE's Global Renewables Footprint

Employees
- Wind globally: 3200
- Wind Europe: 1200



GE Energy in Norway

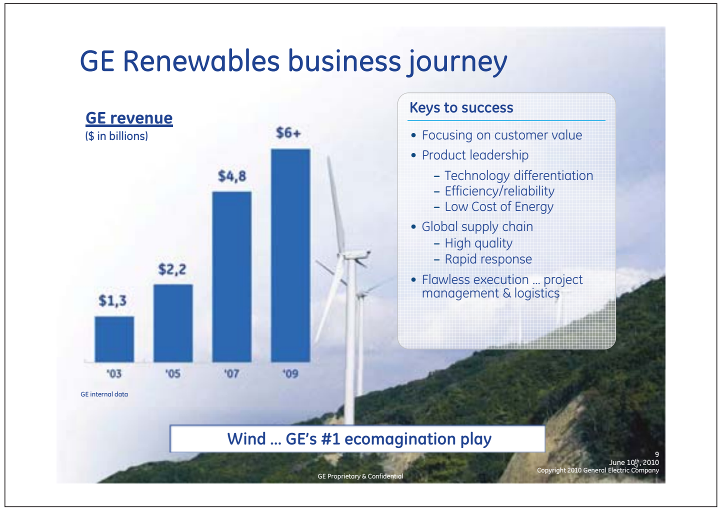
GE Footprint

- 2300 GE Employees in Norway
- 850 GE Energy…Growing 10%+
  - 400 Mfg & Services
  - 370 Engineers
  - 80 Project Mgmt & Sourcing

- Thermal Fleet … ~3.5GW offshore
  - ~150 GE Aero Gas Turbines
  - ~135 GE O&G NP Compressors
  - ~130 GE VG Service Wells

- Wind Fleet … ~35MW onshore
  - 11 GE direct drive turbines (former Scanwind)
  - 1 x 1.5MW Cold Weather test unit, Tromso

Strong Presence … Growing …Green Jobs



GE Renewables business journey

GE revenue
($ in billions)

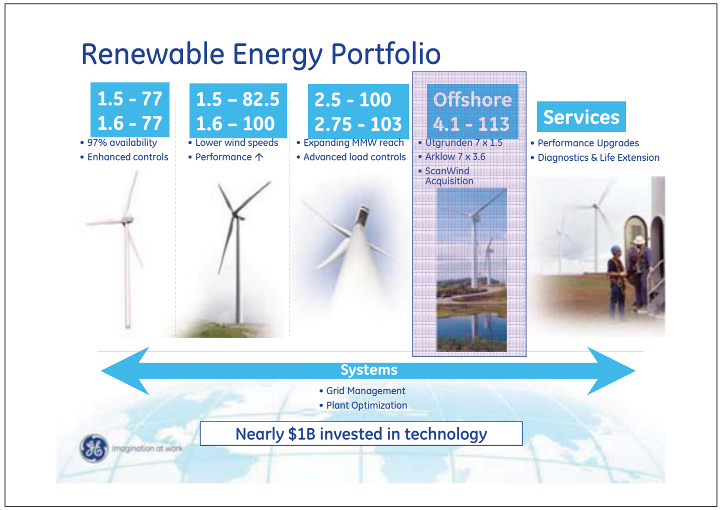
'03	'05	'07	'09
$1,3	$2,2	$4,8	$6+

GE internal data

Keys to success

- Focusing on customer value
- Product leadership
  - Technology differentiation
  - Efficiency/reliability
  - Low Cost of Energy
- Global supply chain
  - High quality
  - Rapid response
- Flawless execution … project management & logistics

Wind … GE's #1 ecomagination play



Renewable Energy Portfolio

1.5 - 77
1.6 - 77
- 97% availability
- Enhanced controls

1.5 – 82.5
1.6 – 100
- Lower wind speeds
- Performance ↑

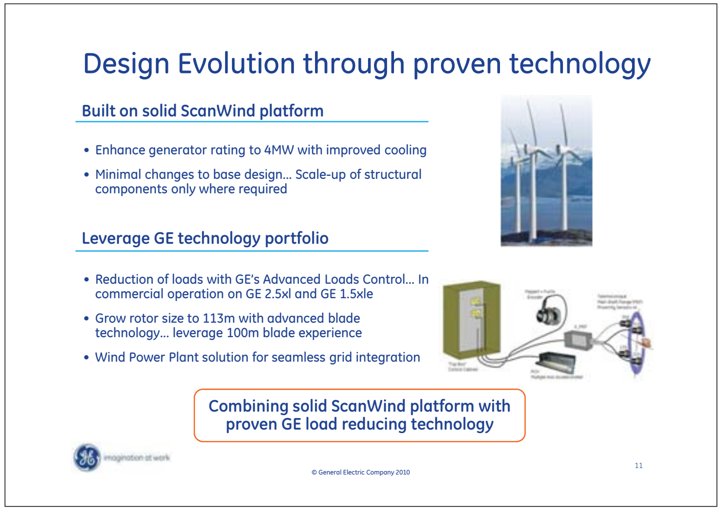
2.5 - 100
2.75 - 103
- Expanding MMW reach
- Advanced load controls

Offshore
4.1 - 113
- Utgrunden 7 x 1.5
- Arklow 7 x 3.6
- ScanWind Acquisition

Services
- Performance Upgrades
- Diagnostics & Life Extension

Systems
- Grid Management
- Plant Optimization

Nearly $1B invested in technology



Design Evolution through proven technology

Built on solid ScanWind platform

- Enhance generator rating to 4MW with improved cooling
- Minimal changes to base design… Scale-up of structural components only where required

Leverage GE technology portfolio

- Reduction of loads with GE's Advanced Loads Control… In commercial operation on GE 2.5xl and GE 1.5xle
- Grow rotor size to 113m with advanced blade technology… leverage 100m blade experience
- Wind Power Plant solution for seamless grid integration

Combining solid ScanWind platform with proven GE load reducing technology

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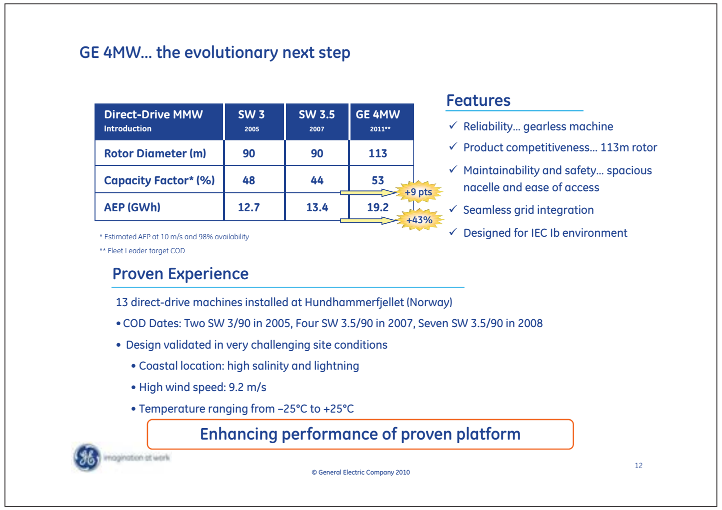


GE 4MW… the evolutionary next step

Direct-Drive MMW Introduction	SW 3 2005	SW 3.5 2007	GE 4MW 2011**
Rotor Diameter (m)	90	90	113
Capacity Factor* (%)	48	44	53
AEP (GWh)	12.7	13.4	19.2

* Estimated AEP at 10 m/s and 98% availability
** Fleet Leader target COD

Features

- ✓ Reliability… gearless machine
- ✓ Product competitiveness… 113m rotor
- ✓ Maintainability and safety… spacious nacelle and ease of access
- ✓ Seamless grid integration
- ✓ Designed for IEC Ib environment

Proven Experience

13 direct-drive machines installed at Hundhammerfjellet (Norway)
- COD Dates: Two SW 3/90 in 2005, Four SW 3.5/90 in 2007, Seven SW 3.5/90 in 2008
- Design validated in very challenging site conditions
  - Coastal location: high salinity and lightning
  - High wind speed: 9.2 m/s
  - Temperature ranging from –25°C to +25°C

Enhancing performance of proven platform

Right Technology
Industry's lowest LCOE in average water depth

High Reliability and Production

Low Opex

Right Partner
Through technology, supply chain, and safety

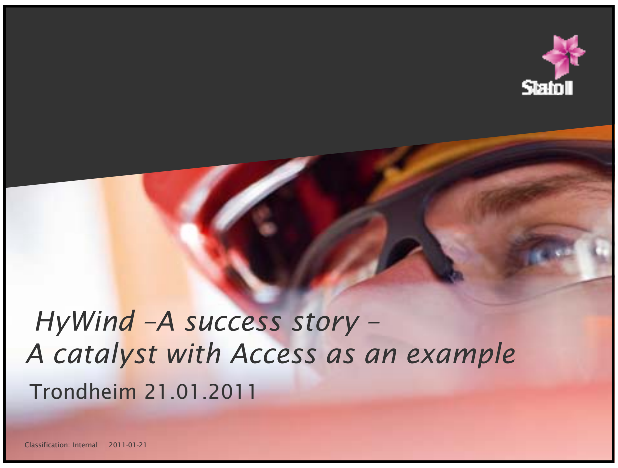
Technology Leader

Energy industry Leader

Right technology from the right partner… at the right time

Thank you

a product of
ecomagination™

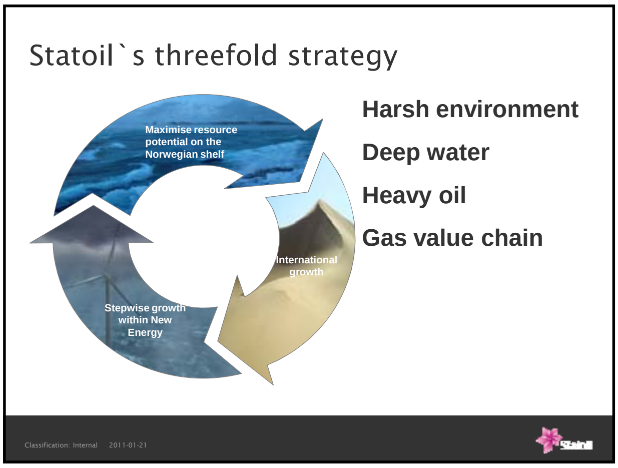


Statoil

HyWind –A success story –
A catalyst with Access as an example

Trondheim 21.01.2011

Classification: Internal 2011-01-21



Statoil`s threefold strategy

Maximise resource potential on the Norwegian shelf

International growth

Stepwise growth within New Energy

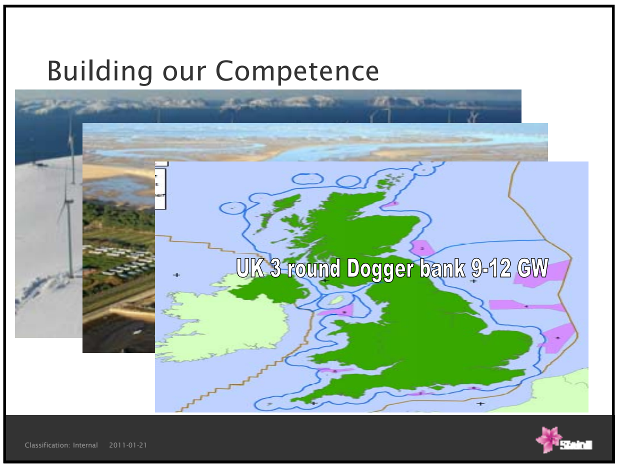
Harsh environment

Deep water

Heavy oil

Gas value chain

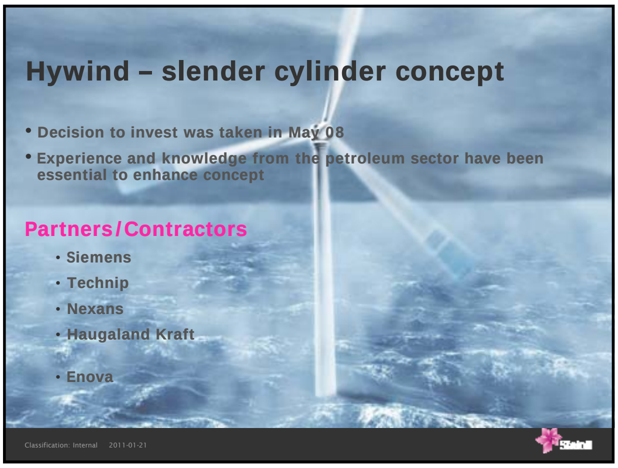
Classification: Internal 2011-01-21



Building our Competence

UK 3 round Dogger bank 9-12 GW

Classification: Internal 2011-01-21



Hywind – slender cylinder concept

- Decision to invest was taken in May 08
- Experience and knowledge from the petroleum sector have been essential to enhance concept

Partners/Contractors

- Siemens
- Technip
- Nexans
- Haugaland Kraft
- Enova

Classification: Internal 2011-01-21

Onshore on quay Stavanger

- Preassembly of tower, nacelle and rotor
- Turbine, tower and blades assembled

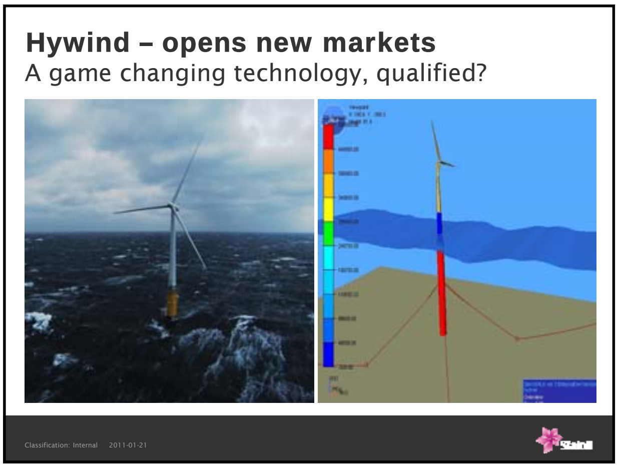
Classification: Internal 2011-01-21

Lift of upper tower and nacelle on 13 May 2009

Classification: Internal 2011-01-21

Hywind – Status after one year of operation

Classification: Internal 2011-01-21



Hywind – opens new markets

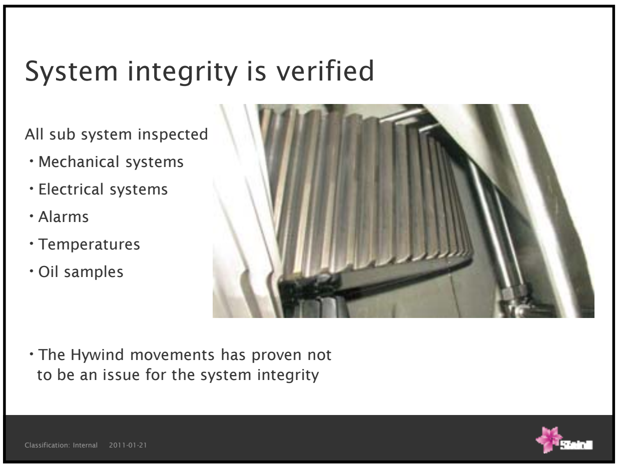
A game changing technology, qualified?

Classification: Internal 2011-01-21

One year of operation – The Hywind concept is qualified

- Production is as good as or better than other 2.3 MW Siemens wind power turbines
  - Loads factors above 40 %
- Wind turbine has preformed well. No drawbacks from being installed on a floater
  - Less alarms than anticipated
- Access and maintenance equal to other offshore wind installations
- All technical systems are working well

Classification: Internal 2011-01-21



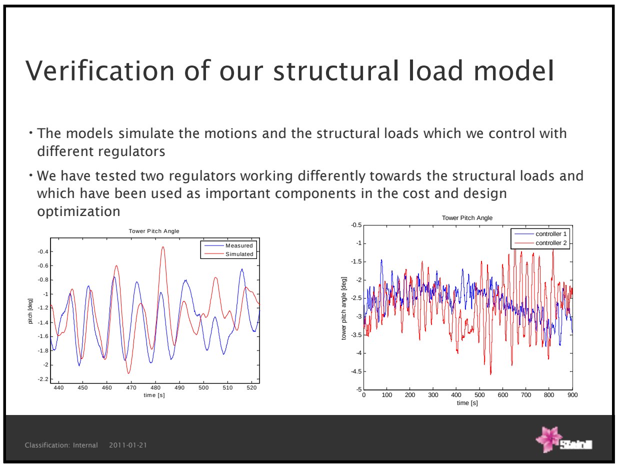
System integrity is verified

All sub system inspected

- Mechanical systems
- Electrical systems
- Alarms
- Temperatures
- Oil samples

- The Hywind movements has proven not to be an issue for the system integrity

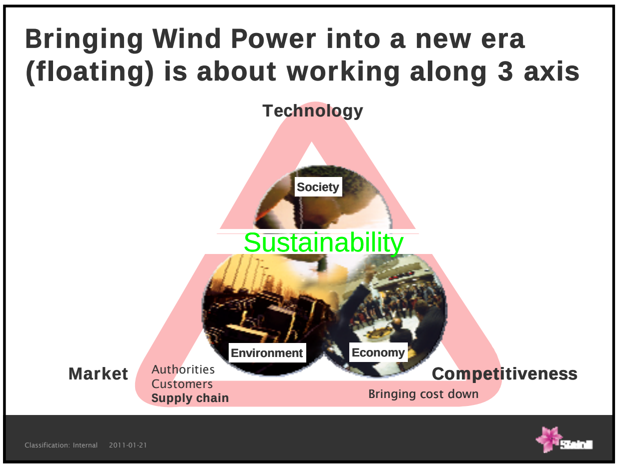
Classification: Internal 2011-01-21



Verification of our structural load model

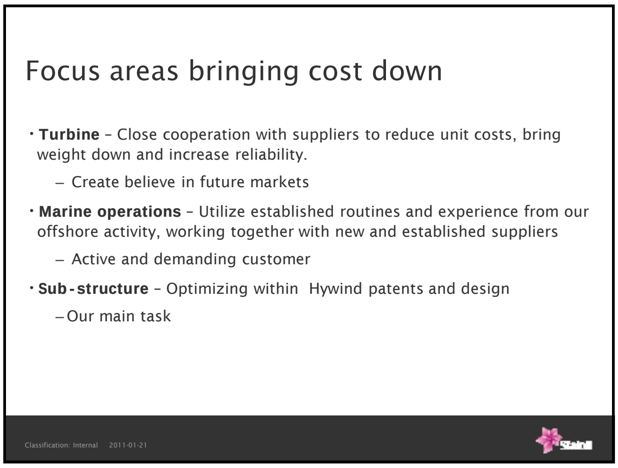
- The models simulate the motions and the structural loads which we control with different regulators
- We have tested two regulators working differently towards the structural loads and which have been used as important components in the cost and design optimization

Classification: Internal 2011-01-21



Bringing Wind Power into a new era (floating) is about working along 3 axis

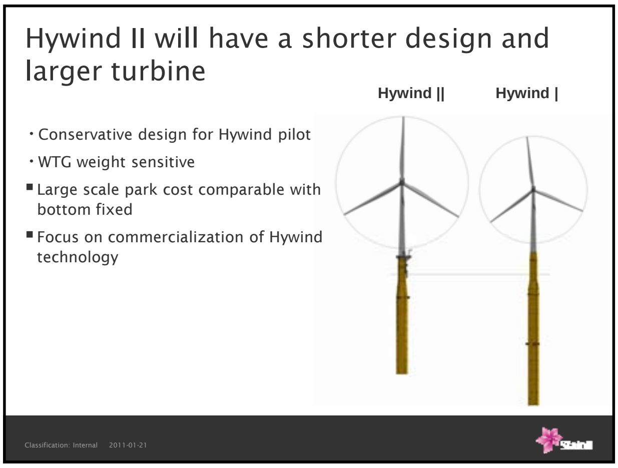
Classification: Internal 2011-01-21



Focus areas bringing cost down

- **Turbine** – Close cooperation with suppliers to reduce unit costs, bring weight down and increase reliability.
  - Create believe in future markets
- **Marine operations** – Utilize established routines and experience from our offshore activity, working together with new and established suppliers
  - Active and demanding customer
- **Sub-structure** – Optimizing within Hywind patents and design
  - Our main task

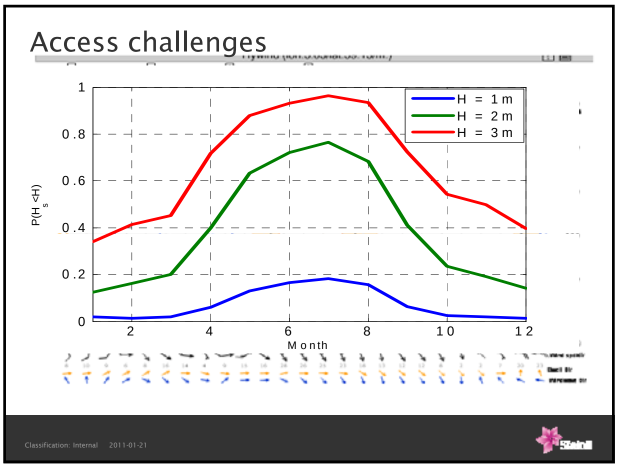
Classification: Internal 2011-01-21



Hywind II will have a shorter design and larger turbine

- Conservative design for Hywind pilot
- WTG weight sensitive
- Large scale park cost comparable with bottom fixed
- Focus on commercialization of Hywind technology

Classification: Internal 2011-01-21



Access challenges

Classification: Internal 2011-01-21

Fob Trim

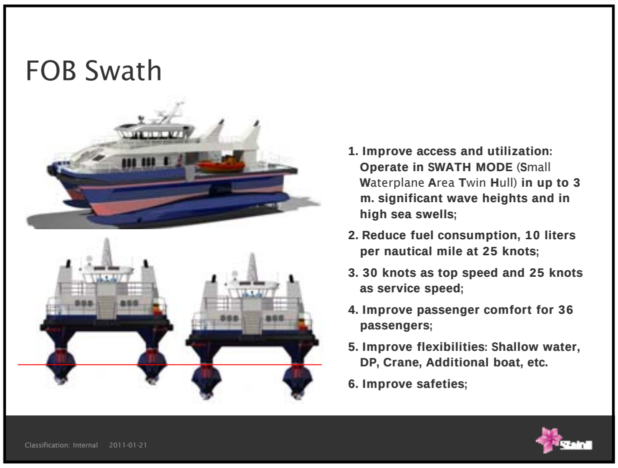
Classification: Internal 2011-01-21

Access challenging

Classification: Internal 2011-01-21

Buddy

Classification: Internal 2011-01-21



FOB Swath

1. **Improve access and utilization: Operate in SWATH MODE** (**S**mall **W**aterplane **A**rea **T**win **H**ull) **in up to 3 m. significant wave heights and in high sea swells;**
2. **Reduce fuel consumption, 10 liters per nautical mile at 25 knots;**
3. **30 knots as top speed and 25 knots as service speed;**
4. **Improve passenger comfort for 36 passengers;**
5. **Improve flexibilities: Shallow water, DP, Crane, Additional boat, etc.**
6. **Improve safeties;**

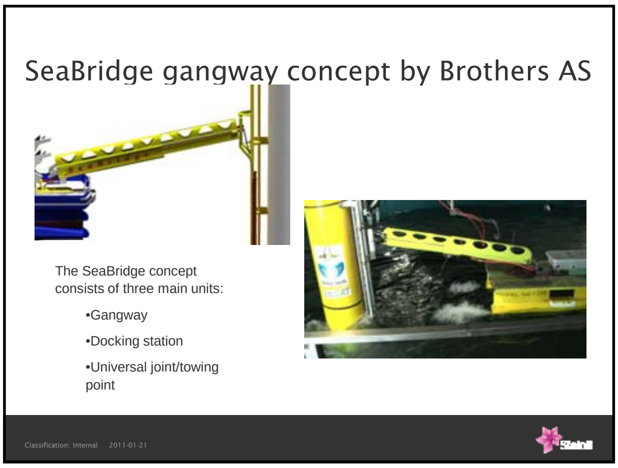
Classification: Internal 2011-01-21

FOB Swath seatrials

Classification: Internal 2011-01-21

Gangway by Undertun Industri

Classification: Internal 2011-01-21

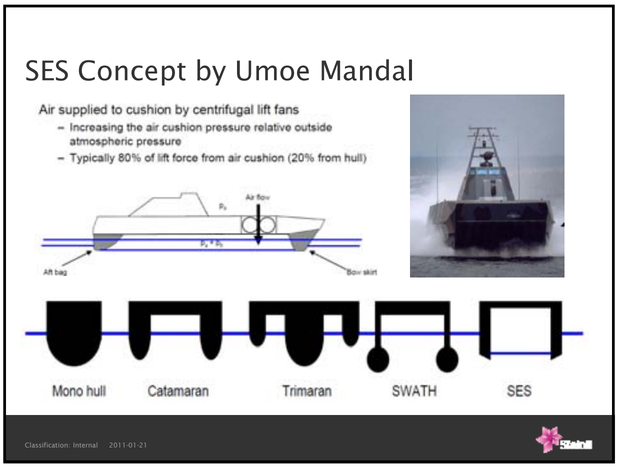


SeaBridge gangway concept by Brothers AS

The SeaBridge concept consists of three main units:

- Gangway
- Docking station
- Universal joint/towing point

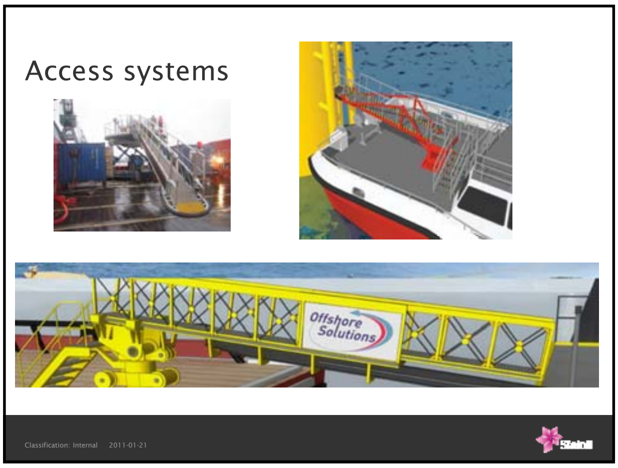
Classification: Internal 2011-01-21



SES Concept by Umoe Mandal

Air supplied to cushion by centrifugal lift fans
- Increasing the air cushion pressure relative outside atmospheric pressure
- Typically 80% of lift force from air cushion (20% from hull)

Classification: Internal 2011-01-21

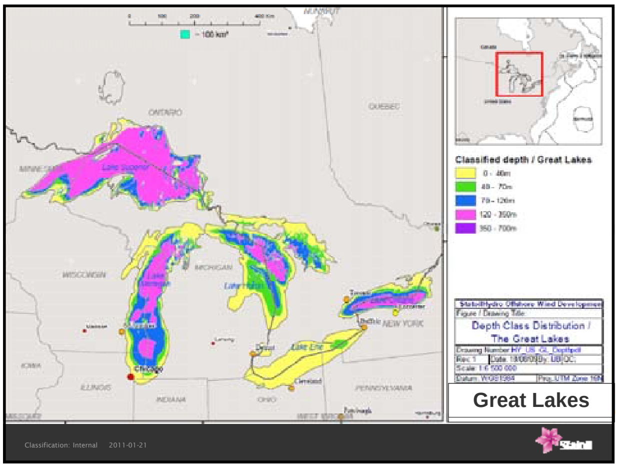


Access systems

Classification: Internal 2011-01-21

Markets

- Initial markets
  - Scotland
  - US
    - East coast –Maine, Great lakes
  - Norway
- Next phase
  - Asia –Japan
  - Spain/Portugal - Mediterranean
  - Greece, Egypt, Malta, France, Korea, Turkey, Brazil, Italy
- Third phase
  - South America, New Zealand, South Africa

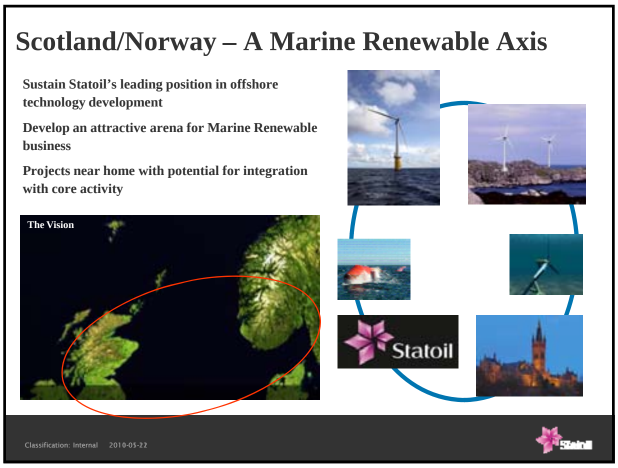


Classified depth / Great Lakes

🟨	0 - 40m
🟩	40 - 70m
🟦	70 - 120m
🟪	120 - 350m
🟪	350 - 700m

StatoilHydro Offshore Wind Development
Figure / Drawing Title:
Depth Class Distribution / The Great Lakes
Drawing Number HY_US_GL_Depthpdf
Rev: 1 Date: 19/06/09 By: UB/OC
Scale: 1:6 500 000
Datum: WGS1984 Proj. UTM Zone 16N

Great Lakes

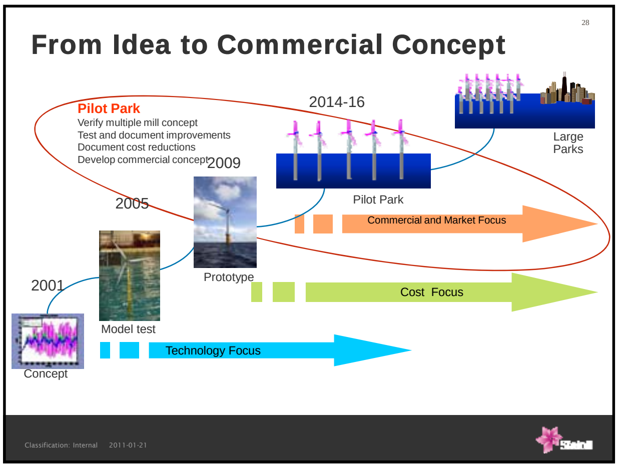


Scotland/Norway – A Marine Renewable Axis

Sustain Statoil's leading position in offshore technology development

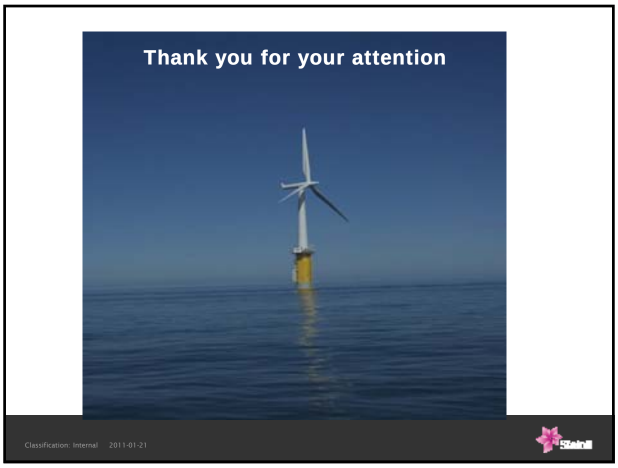
Develop an attractive arena for Marine Renewable business

Projects near home with potential for integration with core activity



From Idea to Commercial Concept

Pilot Park
Verify multiple mill concept
Test and document improvements
Document cost reductions
Develop commercial concept

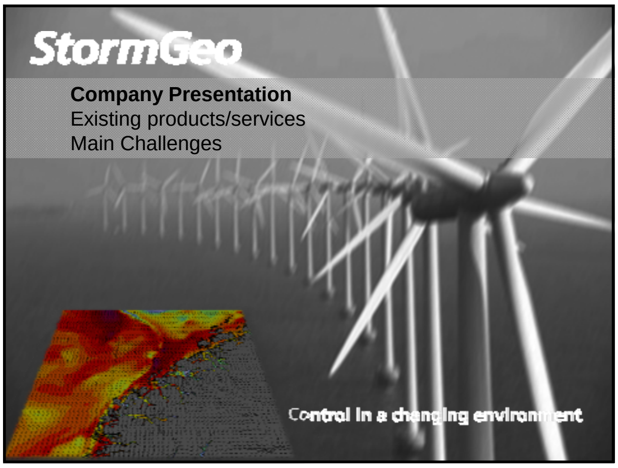


Thank you for your attention

StormGeo

Jostein Mælan, Sales and marketing Director

Bergen | Oslo | Stavanger | Stockholm | Copenhagen | Aberdeen

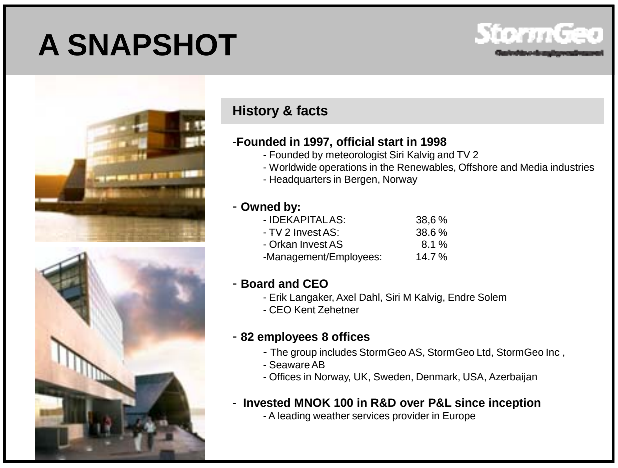


StormGeo

Company Presentation

Existing products/services

Main Challenges



A SNAPSHOT

History & facts

-**Founded in 1997, official start in 1998**
- Founded by meteorologist Siri Kalvig and TV 2
- Worldwide operations in the Renewables, Offshore and Media industries
- Headquarters in Bergen, Norway

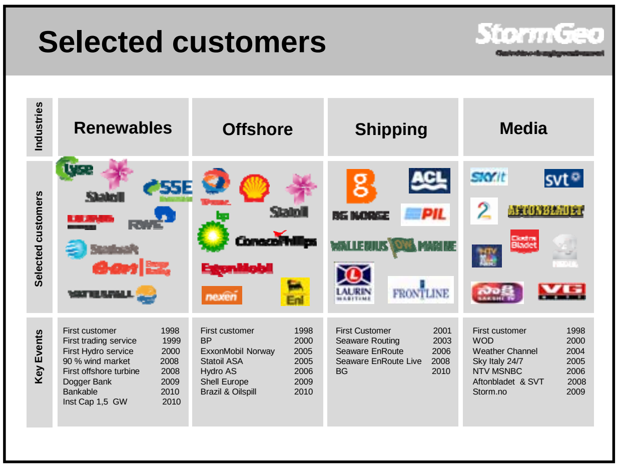
- **Owned by:**

- IDEKAPITAL AS:	38,6 %
- TV 2 Invest AS:	38.6 %
- Orkan Invest AS	8.1 %
-Management/Employees:	14.7 %

- **Board and CEO**
  - Erik Langaker, Axel Dahl, Siri M Kalvig, Endre Solem
  - CEO Kent Zehetner

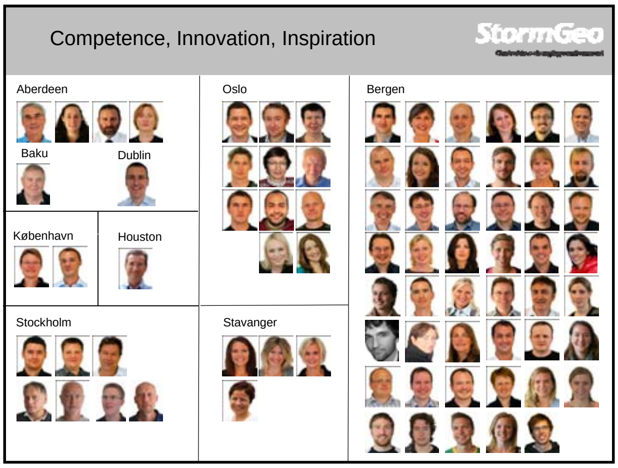
- **82 employees 8 offices**
  - The group includes StormGeo AS, StormGeo Ltd, StormGeo Inc ,
  - Seaware AB
  - Offices in Norway, UK, Sweden, Denmark, USA, Azerbaijan

- **Invested MNOK 100 in R&D over P&L since inception**
  - A leading weather services provider in Europe

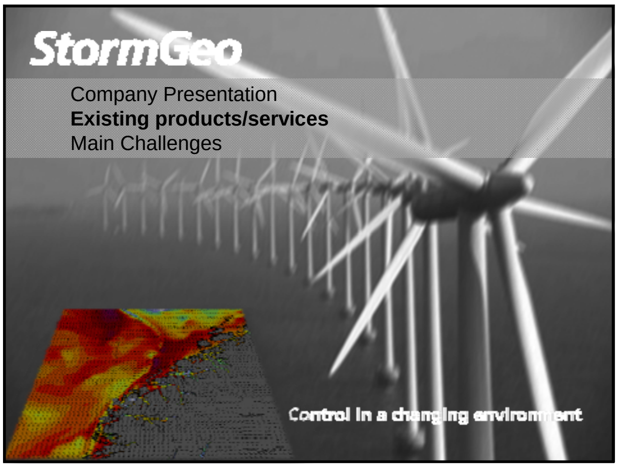


Selected customers

Industries	Renewables	Offshore	Shipping	Media
Selected customers				
Key Events	First customer 1998 First trading service 1999 First Hydro service 2000 90 % wind market 2008 First offshore turbine 2008 Dogger Bank 2009 Bankable 2010 Inst Cap 1,5 GW 2010	First customer 1998 BP 2000 ExxonMobil Norway 2005 Statoil ASA 2005 Hydro AS 2006 Shell Europe 2009 Brazil & Oilspill 2010	First Customer 2001 Seaware Routing 2003 Seaware EnRoute 2006 Seaware EnRoute Live 2008 BG 2010	First customer 1998 WOD 2000 Weather Channel 2004 Sky Italy 24/7 2005 NTV MSNBC 2006 Aftonbladet & SVT 2008 Storm.no 2009



Competence, Innovation, Inspiration

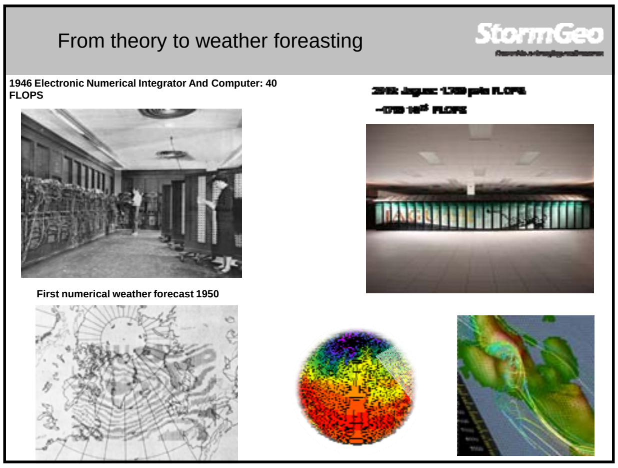


StormGeo

Company Presentation

Existing products/services

Main Challenges



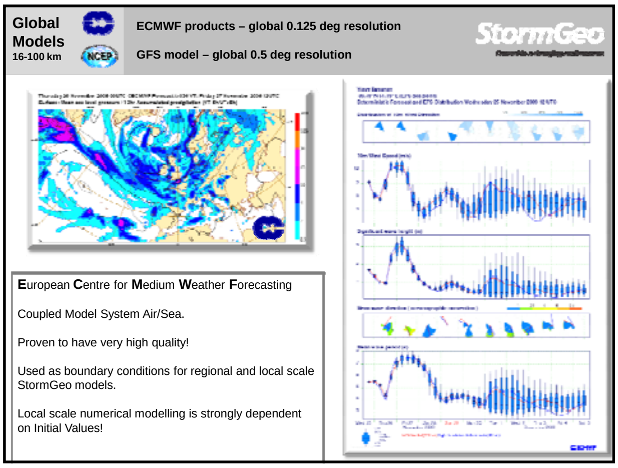
From theory to weather foreasting

1946 Electronic Numerical Integrator And Computer: 40 FLOPS

2010: Jaguar: 1.759 peta FLOPS

~1.759 10^{15} FLOPS

First numerical weather forecast 1950



Global Models

16-100 km

ECMWF products – global 0.125 deg resolution

GFS model – global 0.5 deg resolution

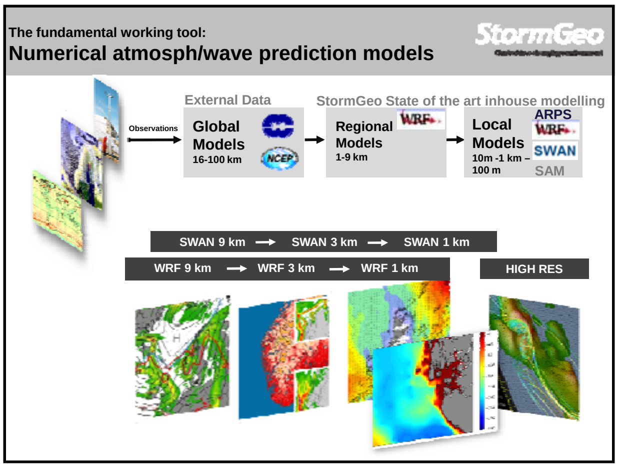
European **C**entre for **M**edium **W**eather **F**orecasting

Coupled Model System Air/Sea.

Proven to have very high quality!

Used as boundary conditions for regional and local scale StormGeo models.

Local scale numerical modelling is strongly dependent on Initial Values!



The fundamental working tool:

Numerical atmosph/wave prediction models

External Data

StormGeo State of the art inhouse modelling

Observations

Global Models
16-100 km

Regional Models
1-9 km

Local Models
10m -1 km – 100 m

ARPS

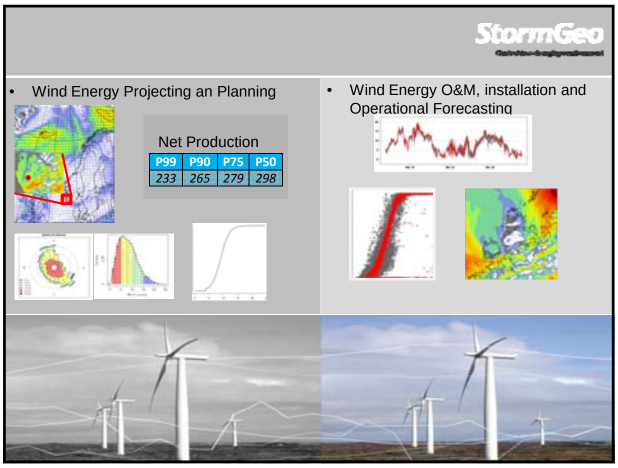
SWAN

SAM

SWAN 9 km → SWAN 3 km → SWAN 1 km

WRF 9 km → WRF 3 km → WRF 1 km

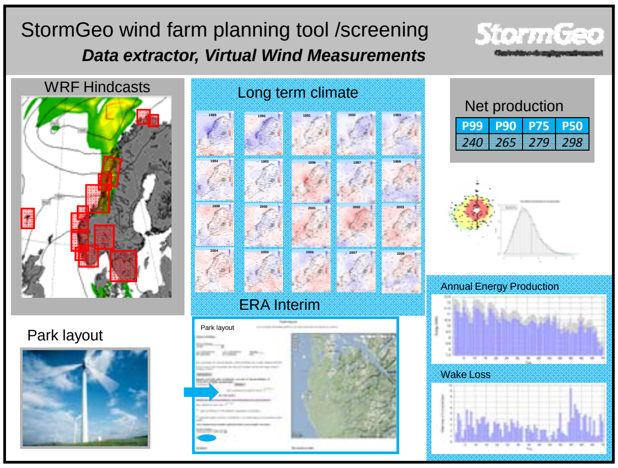
HIGH RES



- Wind Energy Projecting an Planning
- Wind Energy O&M, installation and Operational Forecasting

Net Production

P99	P90	P75	P50
233	265	279	298



StormGeo wind farm planning tool /screening

Data extractor, Virtual Wind Measurements

WRF Hindcasts

Long term climate

ERA Interim

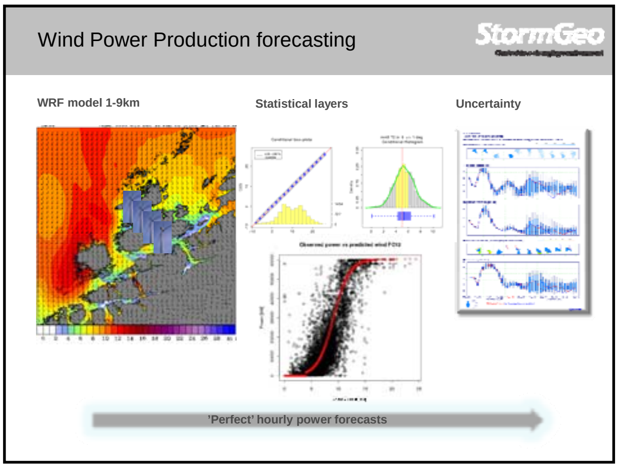
Net production

P99	P90	P75	P50
240	265	279	298

Annual Energy Production

Wake Loss

Park layout



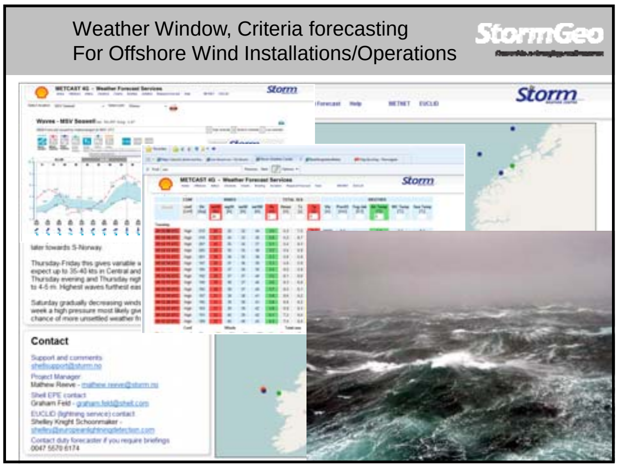
Wind Power Production forecasting

WRF model 1-9km

Statistical layers

Uncertainty

'Perfect' hourly power forecasts



Weather Window, Criteria forecasting For Offshore Wind Installations/Operations

later towards S-Norway

Thursday-Friday this gives variable … expect up to 35-40 kts in Central and … Thursday evening and Thursday nigh… to 4-5 m. Highest waves furthest eas…

Saturday gradually decreasing winds … week a high pressure most likely giv… chance of more unsettled weather fr…

Contact

Support and comments
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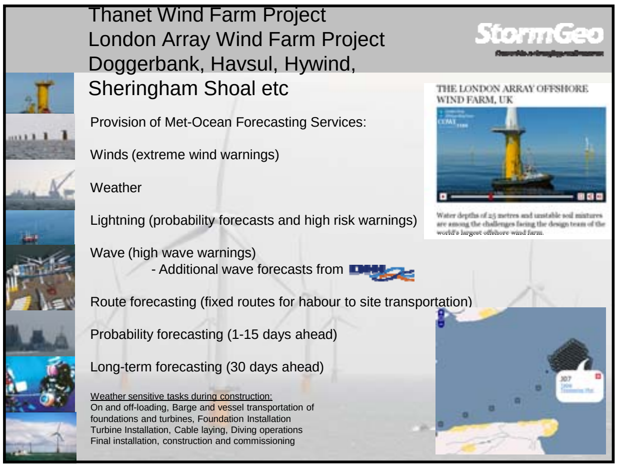
Shell EPE contact
Graham Feld - graham.feld@shell.com
EUCLID (lightning service) contact
Shelley Knight Schoonmaker -
shelley@europeanlightningdetection.com
Contact duty forecaster if you require briefings
0047 5570 6174



Thanet Wind Farm Project London Array Wind Farm Project Doggerbank, Havsul, Hywind, Sheringham Shoal etc

Provision of Met-Ocean Forecasting Services:

Winds (extreme wind warnings)

Weather

Lightning (probability forecasts and high risk warnings)

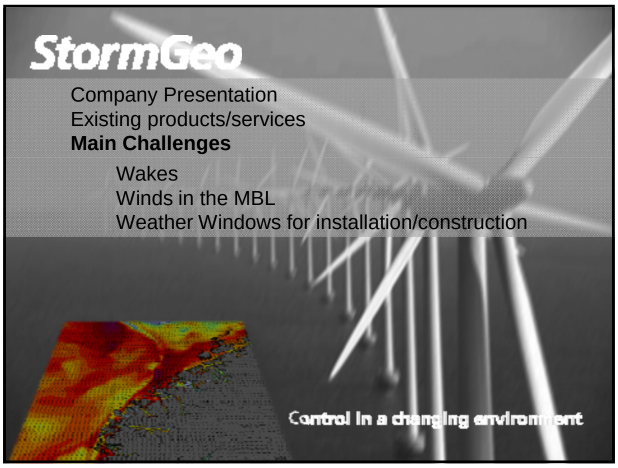
Wave (high wave warnings)
- Additional wave forecasts from DHI

Route forecasting (fixed routes for habour to site transportation)

Probability forecasting (1-15 days ahead)

Long-term forecasting (30 days ahead)

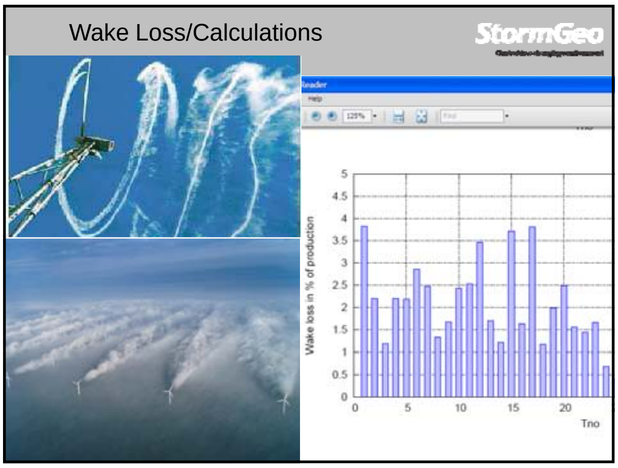
Weather sensitive tasks during construction:
On and off-loading, Barge and vessel transportation of foundations and turbines, Foundation Installation
Turbine Installation, Cable laying, Diving operations
Final installation, construction and commissioning



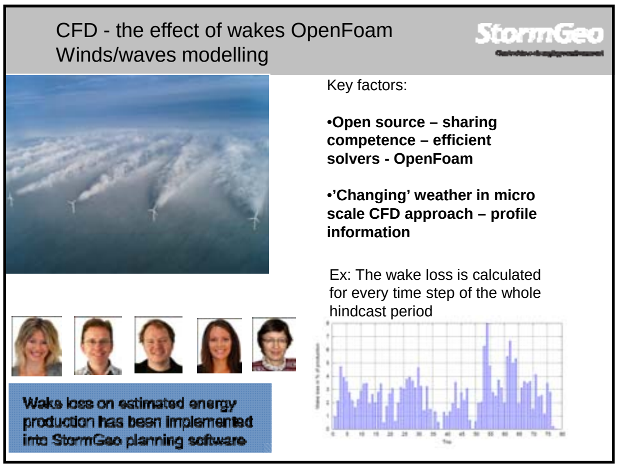
StormGeo

Company Presentation
Existing products/services
Main Challenges

Wakes
Winds in the MBL
Weather Windows for installation/construction



Wake Loss/Calculations



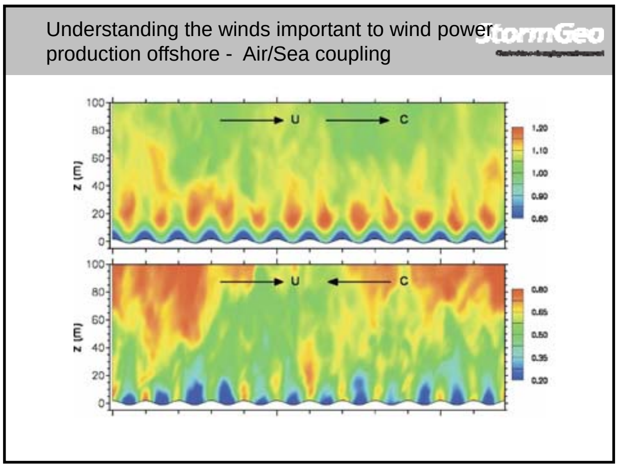
CFD - the effect of wakes OpenFoam Winds/waves modelling

Key factors:

- **Open source – sharing competence – efficient solvers - OpenFoam**
- **'Changing' weather in micro scale CFD approach – profile information**

Ex: The wake loss is calculated for every time step of the whole hindcast period

Wake loss on estimated energy production has been implemented into StormGeo planning software



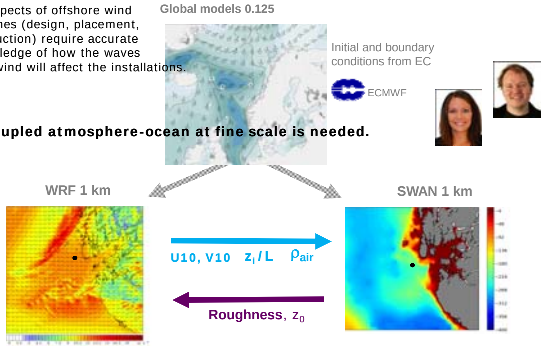
Understanding the winds important to wind power production offshore - Air/Sea coupling

RFF - Improved design criterias
WRF - SWAN Atmosphere / Wave Coupling

StormGeo

All aspects of offshore wind turbines (design, placement, production) require accurate knowledge of how the waves and wind will affect the installations.

A coupled atmosphere-ocean at fine scale is needed.



Understanding the winds important to wind power production offshore - Air/Sea coupling

StormGeo

A typical offshore wind picture….

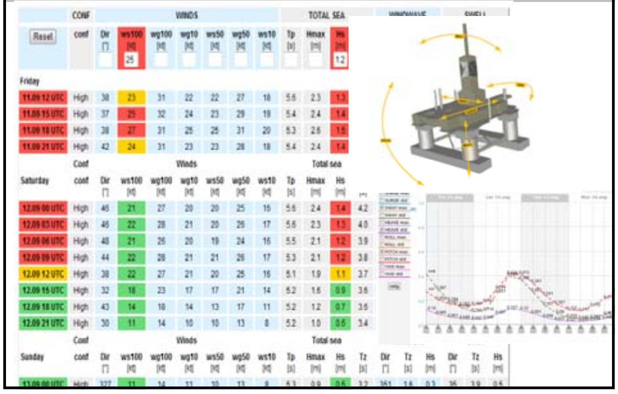
How does a ”non-flat” sea affect the wind fields, power production?

…and installation/construction?
…and support/maintenance work?

No waves - no wind!

Weather window for installation/construction

StormGeo



	CONF	WINDS							TOTAL SEA		
Reset	conf	Dir [°]	ws100 [kt]	wg100 [kt]	wg10 [kt]	ws50 [kt]	wg50 [kt]	ws10 [kt]	Tp [s]	Hmax [m]	Hs [m]
			25								1.2
Friday											
11.09 12 UTC	High	38	23	31	22	22	27	18	5.6	2.3	1.3
11.09 15 UTC	High	37	25	32	24	23	29	19	5.4	2.4	1.4
11.09 18 UTC	High	38	27	31	25	25	31	20	5.3	2.6	1.5
11.09 21 UTC	High	42	24	31	23	23	28	18	5.4	2.4	1.4

	Conf	Winds							Total sea			
Saturday	conf	Dir [°]	ws100 [kt]	wg100 [kt]	wg10 [kt]	ws50 [kt]	wg50 [kt]	ws10 [kt]	Tp [s]	Hmax [m]	Hs [m]	[s]
12.09 00 UTC	High	46	21	27	20	20	25	16	5.6	2.4	1.4	4.2
12.09 03 UTC	High	46	22	28	21	20	26	17	5.6	2.3	1.3	4.0
12.09 06 UTC	High	48	21	26	20	19	24	16	5.5	2.1	1.2	3.9
12.09 09 UTC	High	44	22	28	21	21	26	17	5.3	2.1	1.2	3.8
12.09 12 UTC	High	38	22	27	21	20	25	16	5.1	1.9	1.1	3.7
12.09 15 UTC	High	32	18	23	17	17	21	14	5.2	1.6	0.9	3.6
12.09 18 UTC	High	43	14	18	14	13	17	11	5.2	1.2	0.7	3.5
12.09 21 UTC	High	30	11	14	10	10	13	8	5.2	1.0	0.6	3.4

	Conf	Winds							Total sea									
Sunday	conf	Dir [°]	ws100 [kt]	wg100 [kt]	wg10 [kt]	ws50 [kt]	wg50 [kt]	ws10 [kt]	Tp [s]	Hmax [m]	Hs [m]	Tz [s]	Dir [°]	Tz [s]	Hs [m]	Dir [°]	Tz [s]	Hs [m]
13.09 00 UTC	High	327	11	14	11	10	13	8	5.1	0.9	0.5	3.2	351	1.6	0.3	35	3.9	0.5

Aquired Seaware, ship engineers

StormGeo

'Safety is the motivating factor'

R&D

StormGeo

Home » Centre areas » Focus Areas » WP1 - Wind & ocean conditions

Strategic focus areas
- WP1 - Wind & ocean conditions
  - Modelling of the marine boundary layer
  - Climatology of met/ocean conditions
  - Short-term forecasting
- WP2 - Technology & Innovations
- WP3 - Deployment & Operation
- WP4 - Wind farm optimisation
- WP5 - Common themes

WP1 - Wind and ocean conditions

The primary focus areas in the ... are the climatology of met/ocean conditions, and modelling of the marine boundary layer (MBL). The MBL is the atmospheric boundary layer over the ocean, and influences the ... aloft as well as ocean waves.

Modelling of the marine boundary layer

Optimal design, placement, and operation of offshore wind turbines ... to energy production and costs requires accurate descriptions of the loads from waves and wind on the individual production units, and hence detailed knowledge of the MBL. ... fluid dynamics (CFD) will be employed to model mesoscale atmospheric conditions ... -sea interactions. A specialised CFD tool for wind power applications called FLACS-W... will be developed, where the results obtained at mesoscale can be used as boundary conditions for more detailed simulations of offshore wind turbines and offshore wind farms. In parallel, the mesoscale model used (WRF) will be run in a large-eddy simulation (LES) mode nested within itself. The WRF model is also coupled to wave models (WAM and SWAN) so that relevant variables such as sea-surface roughness and vertical momentum transport) may be exchanged. The overall model system covers all relevant scales, from the global to the micro-scale. It may be used for climatology assessment, forecasts and case studies.

News

06. 09. 2010
Vel gjennomført sommerskole innen Large eddy simulation (LES) med 15 deltagere
read more >>

11. 01. 2010
Idar Barstad, Uni Research and NORCOWE in Dagsavisen
read more >>

18. 12. 2009
Wind power - the push offshore. Article on the Norwegian Trade Portal reviews the potential of Norwegian offshore wind power
read more >>

News archive >>

Calendar/ Upcoming Events

Industrial Partner

Thank you for listening.

StormGeo

Jostein Mælan, +47 97591144

jostein.maelan@stormgeo.com

Bergen | Oslo | Stavanger | Stockholm | Copenhagen | Aberdeen

Wind Power R&D seminar – deep sea offshore wind
January 20-21. 2011

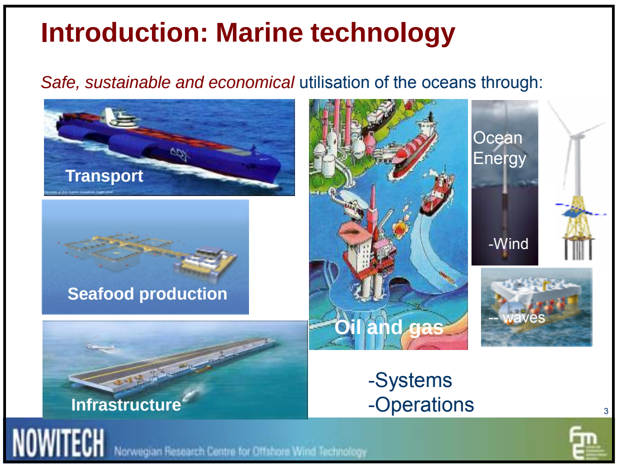
Using research experiences in marine technology for advancing offshore wind technology

by

Torgeir Moan

Outline

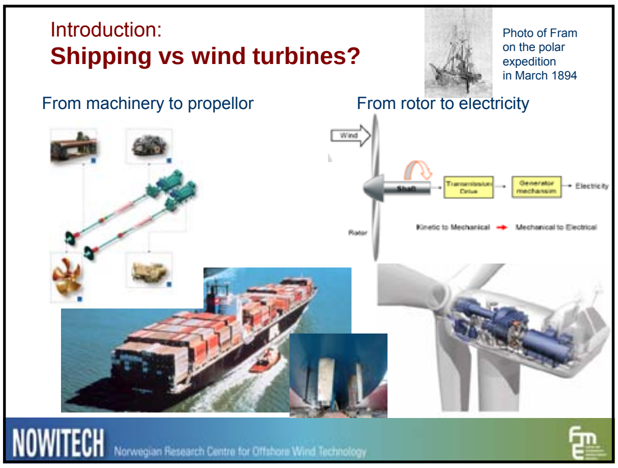
- Introduction
- Marine structures
  - serviceability
  - safety
  - example concepts
- Marine operations
- Research drivers
- Examples: sea loads & response, safety management, crack control, riser & umbilicals, wave energy converters
- Concluding remarks



Introduction: Marine technology

Safe, sustainable and economical utilisation of the oceans through:

-Systems
-Operations

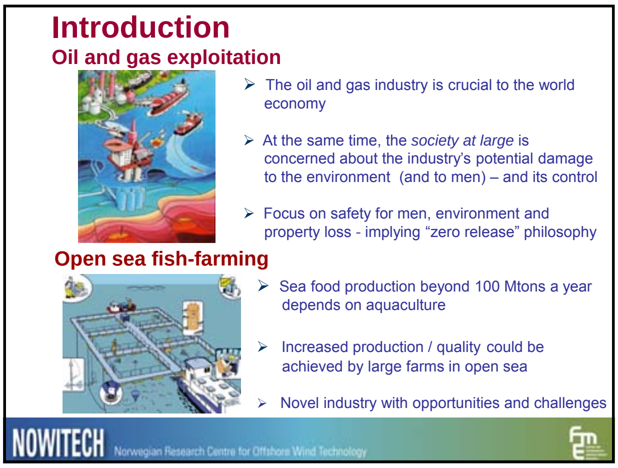


Introduction:
Shipping vs wind turbines?

Photo of Fram on the polar expedition in March 1894

From machinery to propellor

From rotor to electricity

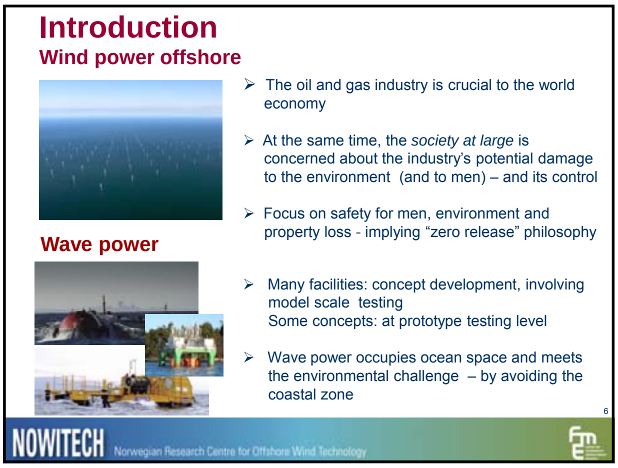


Introduction
Oil and gas exploitation

- The oil and gas industry is crucial to the world economy
- At the same time, the *society at large* is concerned about the industry's potential damage to the environment (and to men) – and its control
- Focus on safety for men, environment and property loss - implying "zero release" philosophy

Open sea fish-farming

- Sea food production beyond 100 Mtons a year depends on aquaculture
- Increased production / quality could be achieved by large farms in open sea
- Novel industry with opportunities and challenges

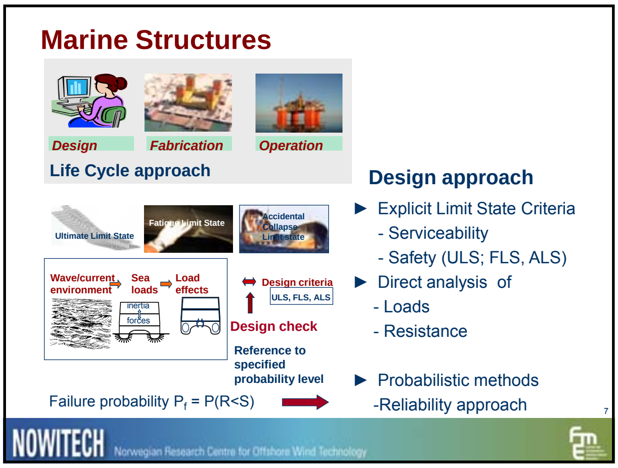


Introduction
Wind power offshore

- The oil and gas industry is crucial to the world economy
- At the same time, the *society at large* is concerned about the industry's potential damage to the environment (and to men) – and its control
- Focus on safety for men, environment and property loss - implying "zero release" philosophy

Wave power

- Many facilities: concept development, involving model scale testing
  Some concepts: at prototype testing level
- Wave power occupies ocean space and meets the environmental challenge – by avoiding the coastal zone



Marine Structures

Life Cycle approach

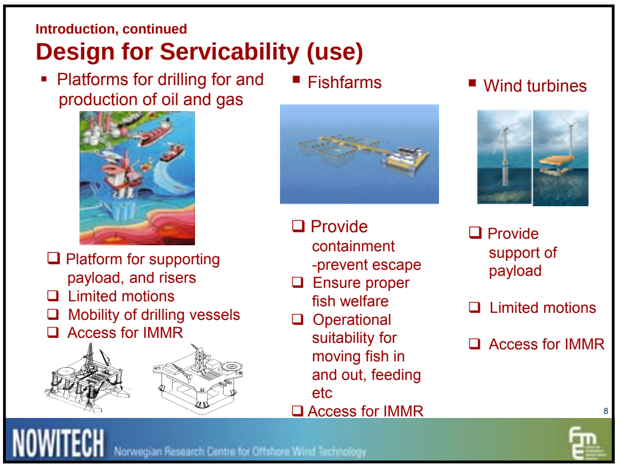
Design check

Reference to specified probability level

Failure probability $P_f = P(R<S)$

Design approach

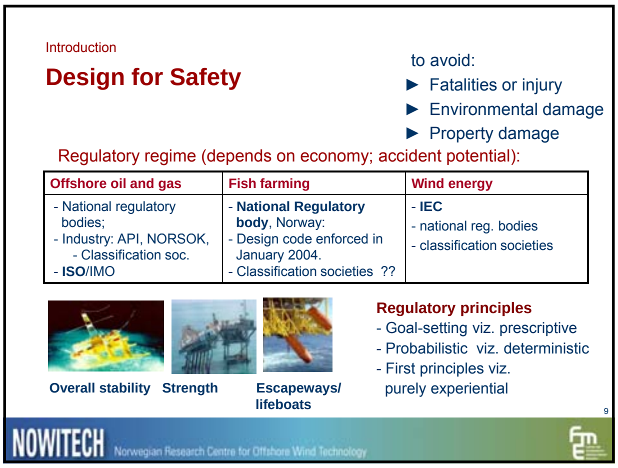
- Explicit Limit State Criteria
  - Serviceability
  - Safety (ULS; FLS, ALS)
- Direct analysis of
  - Loads
  - Resistance
- Probabilistic methods
  - Reliability approach



Introduction, continued

Design for Servicability (use)

- Platforms for drilling for and production of oil and gas
  - ☐ Platform for supporting payload, and risers
  - ☐ Limited motions
  - ☐ Mobility of drilling vessels
  - ☐ Access for IMMR
- Fishfarms
  - ☐ Provide containment -prevent escape
  - ☐ Ensure proper fish welfare
  - ☐ Operational suitability for moving fish in and out, feeding etc
  - ☐ Access for IMMR
- Wind turbines
  - ☐ Provide support of payload
  - ☐ Limited motions
  - ☐ Access for IMMR



Introduction

Design for Safety

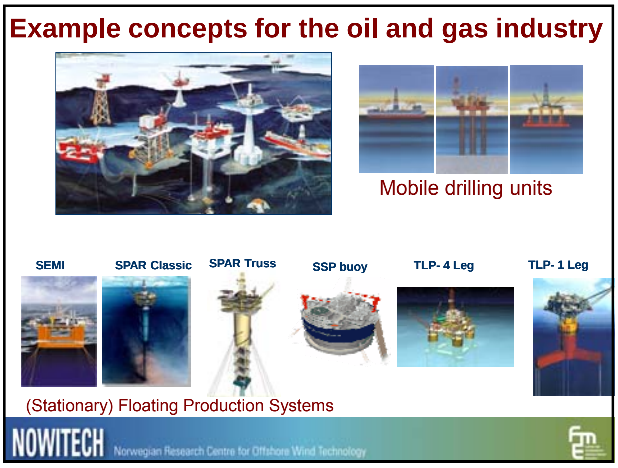
to avoid:

- Fatalities or injury
- Environmental damage
- Property damage

Regulatory regime (depends on economy; accident potential):

Offshore oil and gas	Fish farming	Wind energy
- National regulatory bodies; - Industry: API, NORSOK, - Classification soc. - **ISO**/IMO	- **National Regulatory body**, Norway: - Design code enforced in January 2004. - Classification societies ??	- **IEC** - national reg. bodies - classification societies

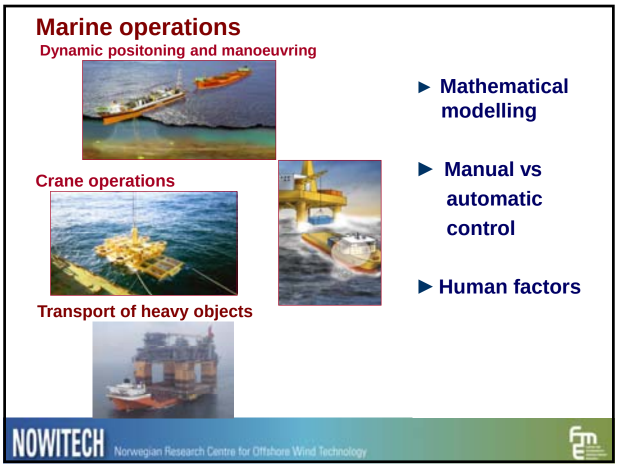
Regulatory principles
- Goal-setting viz. prescriptive
- Probabilistic viz. deterministic
- First principles viz. purely experiential



Example concepts for the oil and gas industry

Mobile drilling units

(Stationary) Floating Production Systems



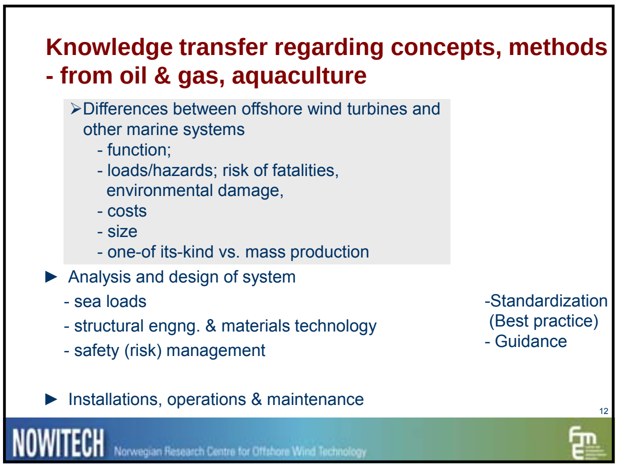
Marine operations

Dynamic positoning and manoeuvring

Crane operations

Transport of heavy objects

- **Mathematical modelling**
- **Manual vs automatic control**
- **Human factors**

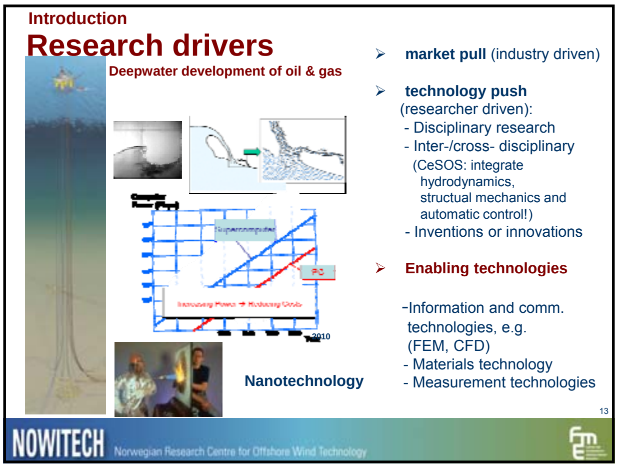


Knowledge transfer regarding concepts, methods - from oil & gas, aquaculture

- Differences between offshore wind turbines and other marine systems
  - function;
  - loads/hazards; risk of fatalities, environmental damage,
  - costs
  - size
  - one-of its-kind vs. mass production
- Analysis and design of system
  - sea loads
  - structural engng. & materials technology
  - safety (risk) management

-Standardization (Best practice)
- Guidance

- Installations, operations & maintenance



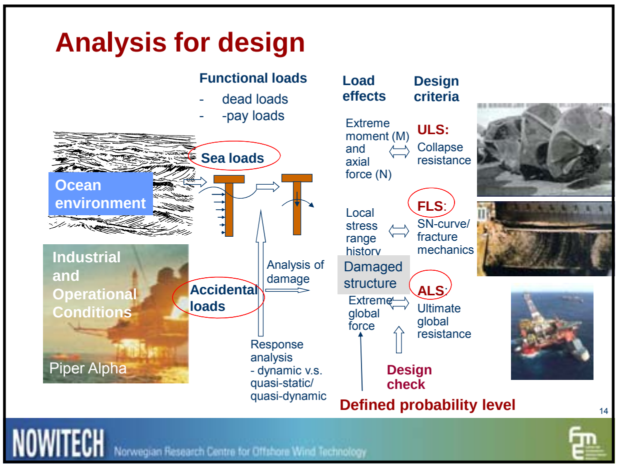
Introduction

Research drivers

Deepwater development of oil & gas

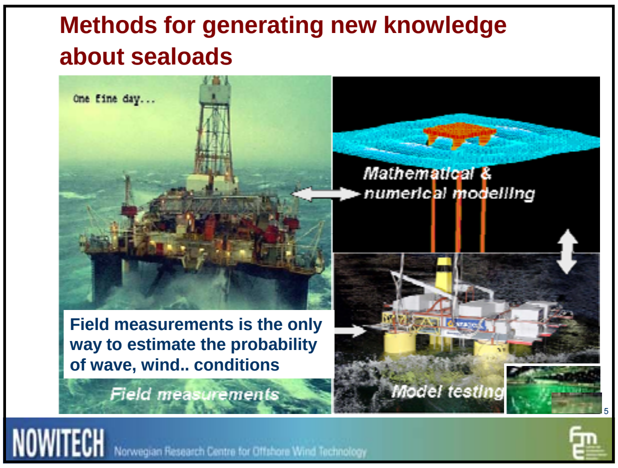
- **market pull** (industry driven)
- **technology push** (researcher driven):
  - Disciplinary research
  - Inter-/cross- disciplinary (CeSOS: integrate hydrodynamics, structural mechanics and automatic control!)
  - Inventions or innovations
- **Enabling technologies**
  - Information and comm. technologies, e.g. (FEM, CFD)
  - Materials technology
  - Measurement technologies

Nanotechnology



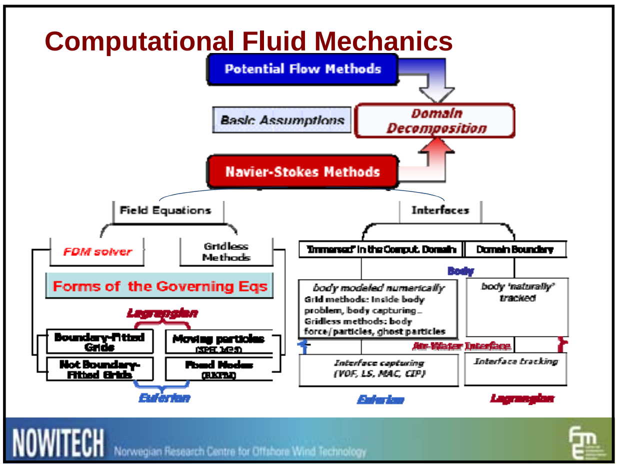
Analysis for design

Defined probability level

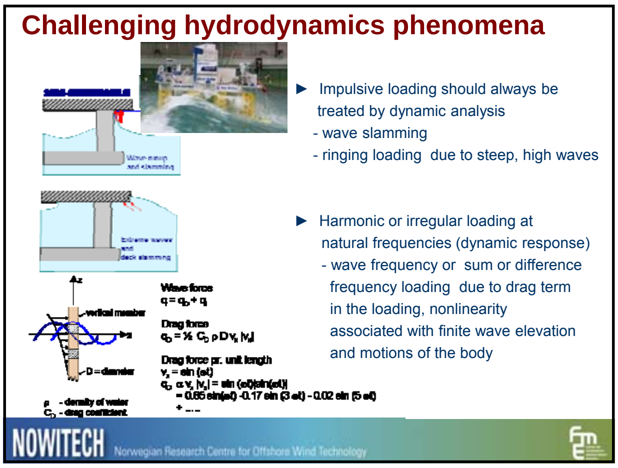


Methods for generating new knowledge about sealoads

Field measurements is the only way to estimate the probability of wave, wind.. conditions



Computational Fluid Mechanics



Challenging hydrodynamics phenomena

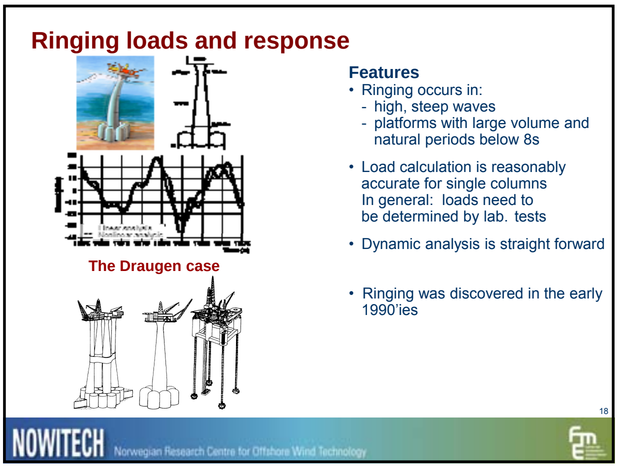
- Impulsive loading should always be treated by dynamic analysis
  - wave slamming
  - ringing loading due to steep, high waves
- Harmonic or irregular loading at natural frequencies (dynamic response)
  - wave frequency or sum or difference frequency loading due to drag term in the loading, nonlinearity associated with finite wave elevation and motions of the body

Wave force
$q = q_D + q_I$

Drag force
$q_D = ½ \ C_D \ \rho D v_x |v_x|$

Drag force pr. unit length
$v_x = \sin(\omega t)$
$q_D \propto v_x |v_x| = \sin(\omega t)|\sin(\omega t)|$
$= 0.85 \sin(\omega t) - 0.17 \sin(3\omega t) - 0.02 \sin(5\omega t)$
$+ ...$

ρ - density of water
C_D - drag coefficient

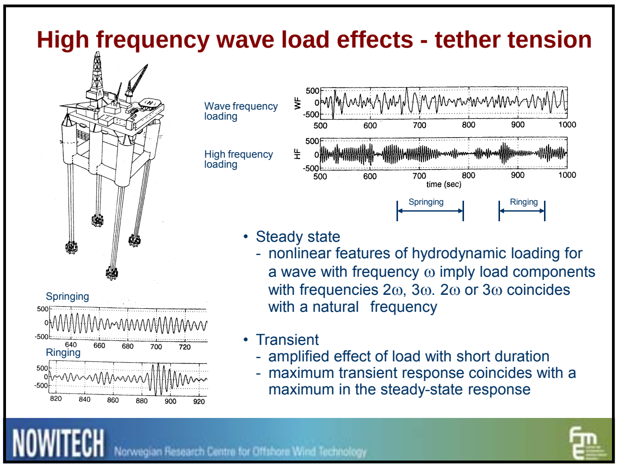


Ringing loads and response

The Draugen case

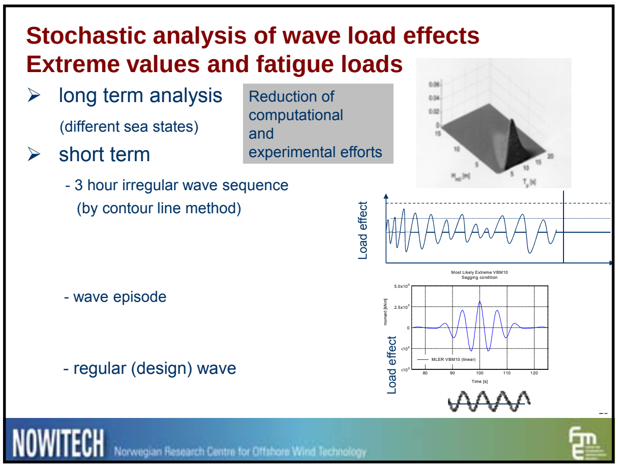
Features

- Ringing occurs in:
  - high, steep waves
  - platforms with large volume and natural periods below 8s
- Load calculation is reasonably accurate for single columns
  In general: loads need to be determined by lab. tests
- Dynamic analysis is straight forward
- Ringing was discovered in the early 1990'ies



High frequency wave load effects - tether tension

- Steady state
  - nonlinear features of hydrodynamic loading for a wave with frequency ω imply load components with frequencies 2ω, 3ω. 2ω or 3ω coincides with a natural frequency
- Transient
  - amplified effect of load with short duration
  - maximum transient response coincides with a maximum in the steady-state response

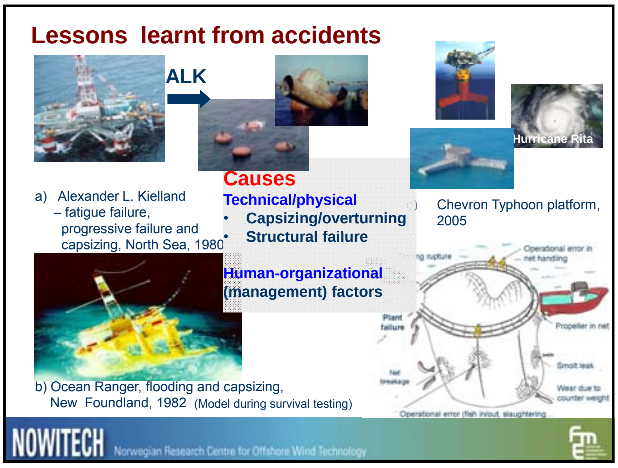


Stochastic analysis of wave load effects
Extreme values and fatigue loads

- long term analysis

  (different sea states)
- short term
  - 3 hour irregular wave sequence (by contour line method)
  - wave episode
  - regular (design) wave

Reduction of computational and experimental efforts



Lessons learnt from accidents

a) Alexander L. Kielland
– fatigue failure, progressive failure and capsizing, North Sea, 1980

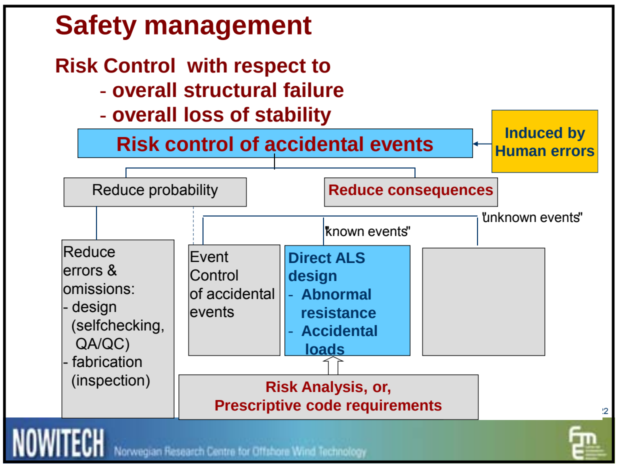
Causes

Technical/physical
- **Capsizing/overturning**
- **Structural failure**

Human-organizational (management) factors

Chevron Typhoon platform, 2005

b) Ocean Ranger, flooding and capsizing, New Foundland, 1982 (Model during survival testing)



Safety management

Risk Control with respect to
- **overall structural failure**
- **overall loss of stability**

Risk control of accidental events

Induced by Human errors

Reduce probability

Reduce consequences

"unknown events"

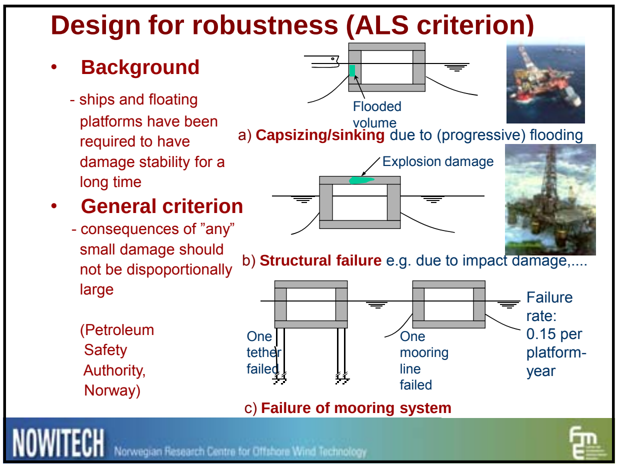
"known events"

Reduce errors & omissions:
- design (selfchecking, QA/QC)
- fabrication (inspection)

Event Control of accidental events

Direct ALS design
- **Abnormal resistance**
- **Accidental loads**

Risk Analysis, or, Prescriptive code requirements



Design for robustness (ALS criterion)

- **Background**
  - ships and floating platforms have been required to have damage stability for a long time
- **General criterion**
  - consequences of "any" small damage should not be dispoportionally large

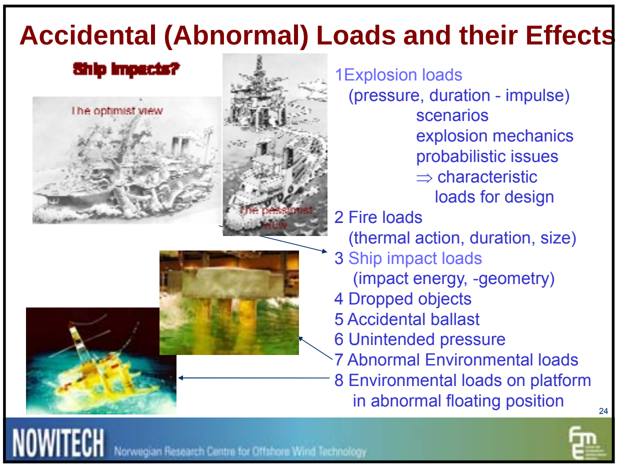
(Petroleum Safety Authority, Norway)

a) **Capsizing/sinking** due to (progressive) flooding

b) **Structural failure** e.g. due to impact damage,....

Failure rate: 0.15 per platform-year

c) **Failure of mooring system**



Accidental (Abnormal) Loads and their Effects

1Explosion loads
(pressure, duration - impulse)
scenarios
explosion mechanics
probabilistic issues
⇒ characteristic loads for design

2 Fire loads
(thermal action, duration, size)

3 Ship impact loads
(impact energy, -geometry)

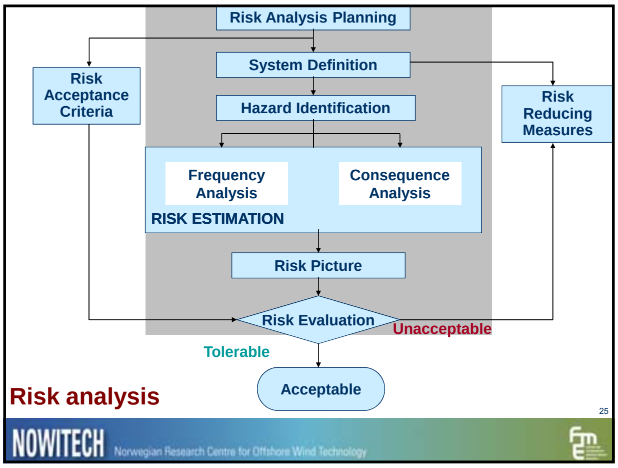
4 Dropped objects

5 Accidental ballast

6 Unintended pressure

7 Abnormal Environmental loads

8 Environmental loads on platform in abnormal floating position



Risk Analysis Planning

System Definition

Hazard Identification

Frequency Analysis

Consequence Analysis

RISK ESTIMATION

Risk Picture

Risk Evaluation

Unacceptable

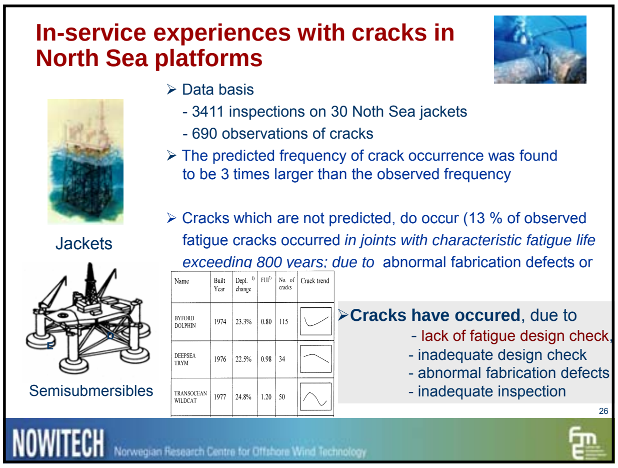
Tolerable

Acceptable

Risk Acceptance Criteria

Risk Reducing Measures

Risk analysis



In-service experiences with cracks in North Sea platforms

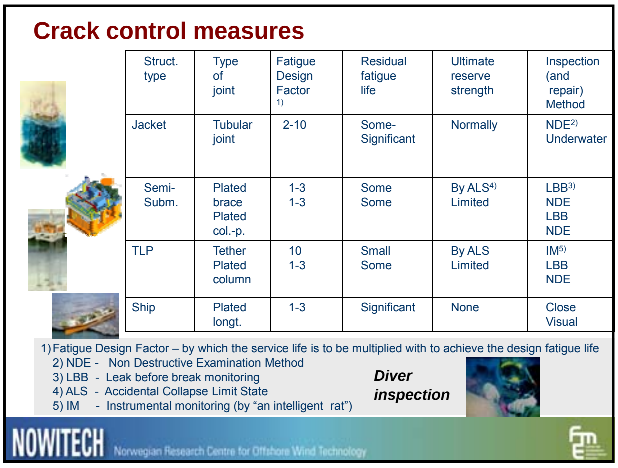
- Data basis
  - 3411 inspections on 30 Noth Sea jackets
  - 690 observations of cracks
- The predicted frequency of crack occurrence was found to be 3 times larger than the observed frequency
- Cracks which are not predicted, do occur (13 % of observed fatigue cracks occurred *in joints with characteristic fatigue life exceeding 800 years; due to* abnormal fabrication defects or

Jackets

Semisubmersibles

Name	Built Year	Depl. change 1)	FUI 2)	No. of cracks	Crack trend
BYFORD DOLPHIN	1974	23.3%	0.80	115	
DEEPSEA TRYM	1976	22.5%	0.98	34	
TRANSOCEAN WILDCAT	1977	24.8%	1.20	50	

- **Cracks have occured**, due to
  - lack of fatigue design check,
  - inadequate design check
  - abnormal fabrication defects
  - inadequate inspection

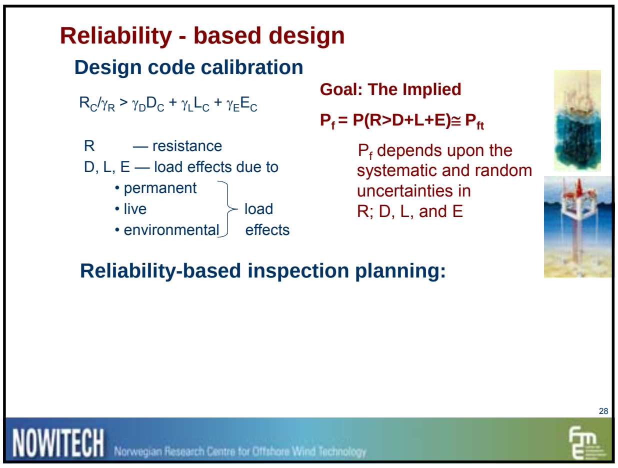


Crack control measures

Struct. type	Type of joint	Fatigue Design Factor 1)	Residual fatigue life	Ultimate reserve strength	Inspection (and repair) Method
Jacket	Tubular joint	2-10	Some-Significant	Normally	NDE 2) Underwater
Semi-Subm.	Plated brace Plated col.-p.	1-3 1-3	Some Some	By ALS 4) Limited	LBB 3) NDE LBB NDE
TLP	Tether Plated column	10 1-3	Small Some	By ALS Limited	IM 5) LBB NDE
Ship	Plated longt.	1-3	Significant	None	Close Visual

1) Fatigue Design Factor – by which the service life is to be multiplied with to achieve the design fatigue life
2) NDE - Non Destructive Examination Method
3) LBB - Leak before break monitoring
4) ALS - Accidental Collapse Limit State
5) IM - Instrumental monitoring (by "an intelligent rat")

Diver inspection



Reliability - based design

Design code calibration

$R_C/\gamma_R > \gamma_D D_C + \gamma_L L_C + \gamma_E E_C$

R — resistance
D, L, E — load effects due to
- permanent
- live
- environmental

load effects

Goal: The Implied

$P_f = P(R>D+L+E) \cong P_{ft}$

P_f depends upon the systematic and random uncertainties in R; D, L, and E

Reliability-based inspection planning:

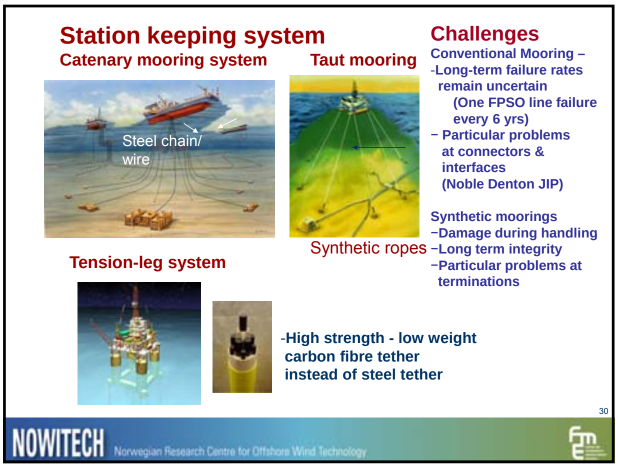
Safety of Marine Operations

- Considering automatic control and human factors

Anchor handling and other subsea operations (the "Bourbon Dolphin" case)

Research topics:

- hydrodynamic modelling of motions
- automatic control
- reliability and safety (human factors)



Station keeping system

Catenary mooring system

Taut mooring

Synthetic ropes

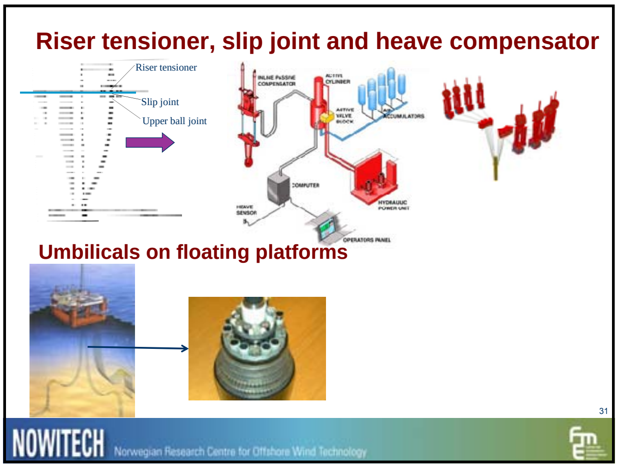
Tension-leg system

-High strength - low weight carbon fibre tether instead of steel tether

Challenges

Conventional Mooring –
- **Long-term failure rates remain uncertain**
  (One FPSO line failure every 6 yrs)
- **Particular problems at connectors & interfaces**
  (Noble Denton JIP)

Synthetic moorings
- **Damage during handling**
- **Long term integrity**
- **Particular problems at terminations**



Riser tensioner, slip joint and heave compensator

Umbilicals on floating platforms

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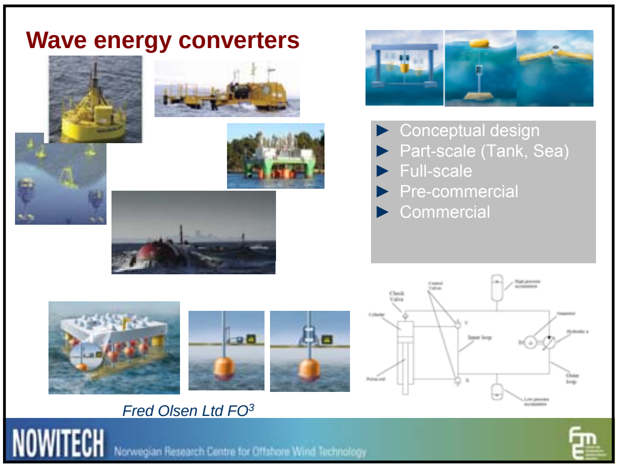

Wave energy converters

- ▶ Conceptual design
- ▶ Part-scale (Tank, Sea)
- ▶ Full-scale
- ▶ Pre-commercial
- ▶ Commercial

Fred Olsen Ltd FO^3

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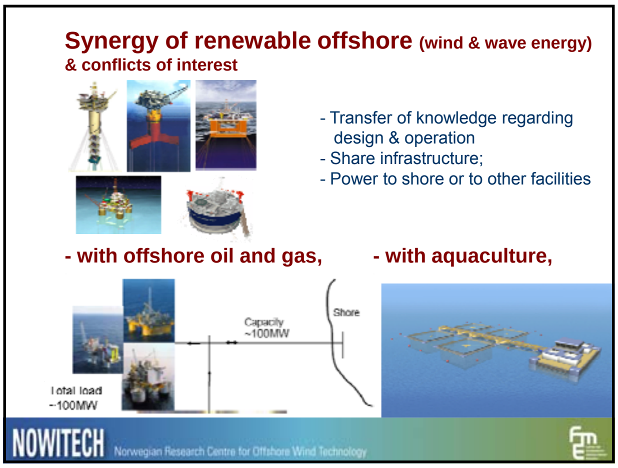

Synergy of renewable offshore (wind & wave energy) & conflicts of interest

- Transfer of knowledge regarding design & operation
- Share infrastructure;
- Power to shore or to other facilities

- with offshore oil and gas, **- with aquaculture,**

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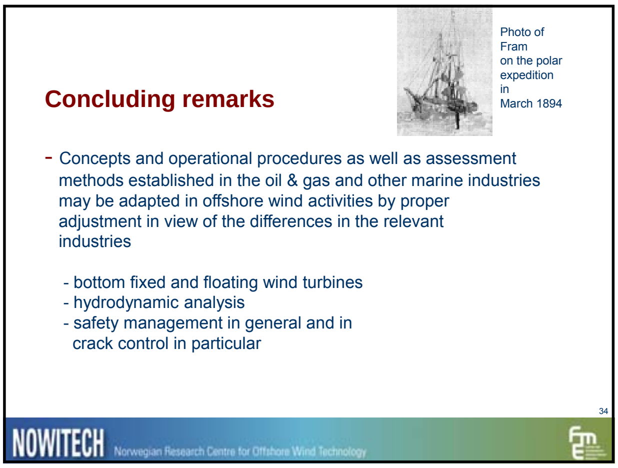

Concluding remarks

Photo of Fram on the polar expedition in March 1894

- Concepts and operational procedures as well as assessment methods established in the oil & gas and other marine industries may be adapted in offshore wind activities by proper adjustment in view of the differences in the relevant industries

  - bottom fixed and floating wind turbines
  - hydrodynamic analysis
  - safety management in general and in crack control in particular

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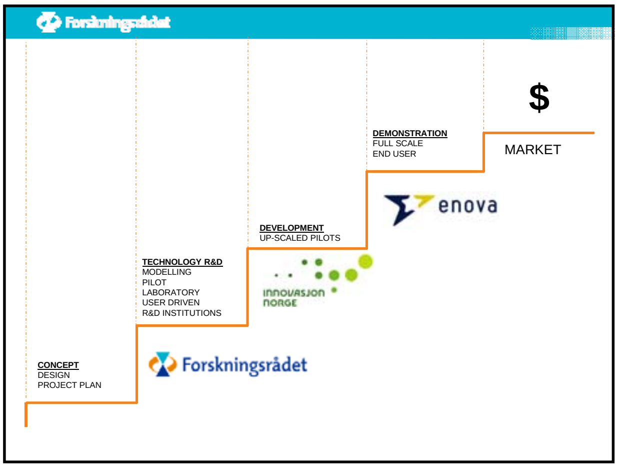
Forskningsrådet

R&D gives results

Deep Sea Offshore Wind R&D Seminar,
20. - 21. January 2011, Trondheim

Espen Borgir Christophersen, The Research Council of Norway



Forskningsrådet

CONCEPT
DESIGN
PROJECT PLAN

TECHNOLOGY R&D
MODELLING
PILOT
LABORATORY
USER DRIVEN
R&D INSTITUTIONS

DEVELOPMENT
UP-SCALED PILOTS

DEMONSTRATION
FULL SCALE
END USER

$
MARKET

Forskningsrådet

Examples of supported projects

- *ANGLE WIND*

New mechanical gearbox for drive train for wind turbines

- *NOWERI*

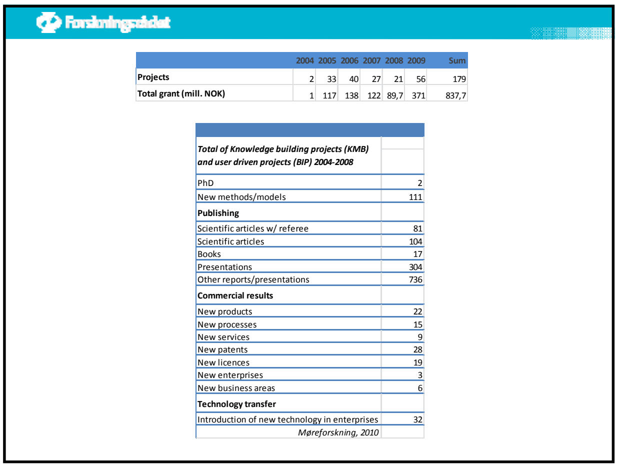
250 kW floating wind turbine
NORCOWE/NOWITECH - project
66 mill. NOK funding i 2010

- *INGENIUM AS*

Katamaranlekter med løftemekanismer

- *Alfanor 7125 AS*

Fred Olsen wind energy drive train

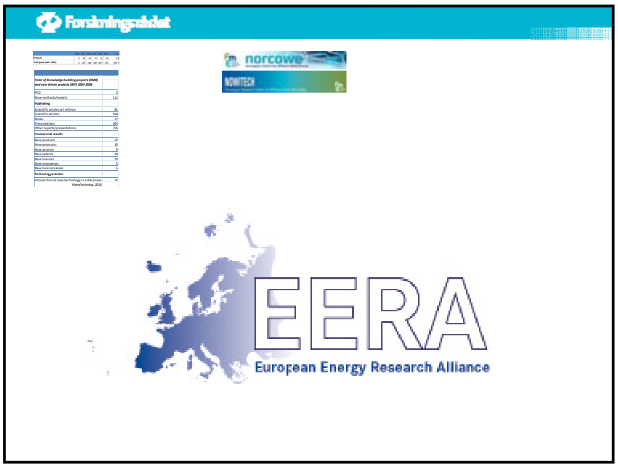


Forskningsrådet

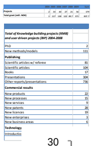
	2004	2005	2006	2007	2008	2009	Sum
Projects	2	33	40	27	21	56	179
Total grant (mill. NOK)	1	117	138	122	89,7	371	837,7

Total of Knowledge building projects (KMB) and user driven projects (BIP) 2004-2008	
PhD	2
New methods/models	111
Publishing	
Scientific articles w/ referee	81
Scientific articles	104
Books	17
Presentations	304
Other reports/presentations	736
Commercial results	
New products	22
New processes	15
New services	9
New patents	28
New licences	19
New enterprises	3
New business areas	6
Technology transfer	
Introduction of new technology in enterprises	32
Møreforskning, 2010	

Forskningsrådet



Forskningsrådet



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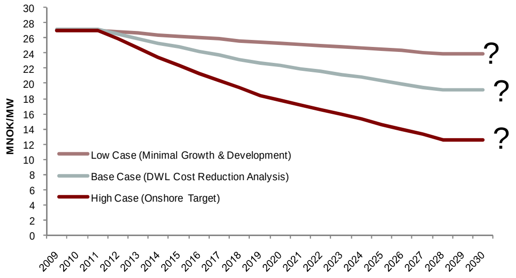

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