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Report

DeepWind2012
9th Deep Sea Offshore Wind R&D Seminar, 19 – 20 January 2012

Royal Garden Hotel, Trondheim, Norway

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ABSTRACT

This report includes the presentations from DeepWind2012, the 9th Deep Sea Offshore Wind R&D Seminar, 19 – 20 January 2012 in Trondheim, Norway. 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 outlook and innovations. The presentations and further conference details are also available at the conference web page www.sintef.no/deepwind_2012.

Full papers of selected presentations will be published online in Energy Procedia (Elsevier).

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F Wind farm modelling

Closing session

9th Deep Sea Offshore Wind R&D Seminar

19-20 January 2012, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY

	Thursday 19 January		
09.00	Registration & coffee		
	Opening session – offshore wind outlook Chairs: John Olav Tande, SINTEF/NOWITECH and Trond Kvamsdal, NTNU/NOWITECH		
09.30	Opening and welcome by chair		
09.40	*The European offshore wind market deployment: forecasts for 2020 – 2030;* Arapogianni Athanasia, EWEA		
10.10	*Status and plans for offshore wind in Japan;* Prof Chuichi Arakawa, University of Tokyo		
10.30	*Offshore wind research and development in USA;* Senu Sirnivas, NREL		
11.00	*Innovations in Offshore Wind Technology through R&D*, John Olav Tande, NOWITECH		
11.30	*Coupled fluid-structure interaction simulation;* Prof Yuri Bazilevs, University of California		
11.55	Summary and discussions by chair		
12.00	Lunch		
	Parallel sessions		
	A1) New turbine technology Chairs: Prof Ole G. Dahlhaug, NTNU, Prof Gerard J.W. van Bussel, TU Delft	**B1) Power system integration** Chairs: Prof Kjetil Uhlen, NTNU, Prof Olimpo Anaya-Lara, Strathclyde	**C1) Met-ocean conditions** Chairs: Prof J Reuder, Uni. of Bergen, Erik Berge, Kjeller Vindteknikk
13.00	Introduction by Chair	Introduction by Chair	Introduction by Chair
13.10	*DeepWind 5MW baseline design,* Uwe S. Paulsen, Risø DTU	*Voltage Source Converter HVDC Links – The state of the Art and Issues Going forward*, Dr Mike Barnes, University of Manchester	*Offshore meso-scale modelling, extremes, wakes and tall profiles*, Hans E. Jørgensen, DTU
13.40	*A Method for Analysis of VAWT Aerodynamic Loads under Turbulent Wind and Platform Motion,* Karl Merz, Post Doc, NTNU	*Control challenges and possibilities for large offshore wind farms*, Prof Olimpo Anaya-Lara, Univ. Strathclyde	
14.00	Multi-Rotors; A Solution to 20 MW and Beyond? Mike Branney, PhD stud, University of Strathclyde	*Coordinated control between wind and hydro power systems through HVDC links,* Atsede Endegnanew, SINTEF	*Sensor movement correction for direct turbulence measurements in the marine atmospheric boundary layer,* PhD stud Martin Flügge, University of Bergen
14.20	*Structural design and analysis of a 10 MW wind turbine blade*, Kevin Cox, PhD stud, NTNU	*Temporary Rotor Inertial Control of Wind Turbine to Support the Grid Frequency Regulation,* Bing Liu, PhD stud, NTNU	*Modelling the effect of ocean waves on the atmospheric and ocean boundary layers,* Alastair D. Jenkins, Uni Computing
14.40	*Effect of pitch and safety system design on dimensioning loads for offshore wind turbines during grid fault,* Lars Frøyd, PhD stud, NTNU	*Frequency and voltage control from an offshore wind farm connected to an oil platform in islanded operation*, Atle Rygg Årdal, SINTEF	*First results of turbulence measurements in a wind park with the Small Unmanned Meteorological Observer SUMO,* Prof Joachim Reuder, University of Bergen
15.00	Refreshments		
	A2) New turbine technology Chairs: Prof Ole G. Dahlhaug, NTNU, Prof Gerard J.W. van Bussel, TU Delft	**B2) Grid connection** Chairs: Prof Kjetil Uhlen, NTNU, Prof Olimpo Anaya-Lara, Strathclyde	**C2) Met-ocean conditions** Chairs: Prof J Reuder, Uni. of Bergen, Erik Berge, Kjeller Vindteknikk
15.30	Introduction by Chair	Introduction by Chair	Introduction by Chair
15.35	*A Modular Series Connected Converter for a High Voltage, Transformer-Less Offshore Wind Power Generator Drive,* Sverre Gjerde, PhD stud, NTNU	*Modelling and control of Multi-terminal VSC HVDC systems*, Jef Beerten, PhD stud, University of Leuven (KU Leuven)	*An insight into floating lidars for offshore wind measurements*, Matt Smith, Natural Power
15.55	*Large superconducting wind turbine generators,* A.B. Abrahamsen, DTU	*Fault-ride-through testing of wind turbines,* Helge Seljeseth, SINTEF	
16.15	*Technological advances in Hydraulic Drivetrains for Wind Turbines* Knud Erik Thomsen, ChapDrive	*Wind turbine model validation with measurements,* Jorun Marvik, SINTEF	*Comparison of met-mast and lidar measurements at Frøya*, Prof Lars Sætran, NTNU
16.35	*A novel tool for FEM analysis of offshore wind turbines with innovative visualizations techniques*, Paul E. Thomassen, Post Doc, NTNU	*The Assessment of Overvoltage protection in Offshore Wind Farms,* A.H. Soloot, PhD stud, NTNU	*Experiences and results from the Statoil Lidar measurements at Utsira*, Yngve Ydersbond, Kjeller Vindteknikk AS
16.55	Closing by Chair	Closing by Chair	Closing by Chair
17.00	**Poster session with refreshments** (see next page for list of posters)		

19.00	Dinner

9th Deep Sea Offshore Wind R&D Seminar

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Thursday 19 January

17.00 **Poster Session with refreshments**

1. *Effect of Forced Excitation on Wind Turbine with Dynamic Analysis in Deep Offshore Wind*, Prof Chuichi Arakawa, University of Tokyo
2. *Effect of Process Parameters on the Fatigue Properties of Composites for Wind Turbine Blades,* Prof Andreas T. Echtermeyer, NTNU
3. *Two-dimensional fluid-structure interaction,* Knut Nordanger, PhD stud, NTNU
4. *Incidence of the switching frequency on efficiency and power density of power conversion topologies for offshore wind turbines*, Rene A. Barrera, PhD stud, NTNU
5. *GPS Synchronisation of Harmonic and Transient Measurements in Offshore Wind Farms,* Łukasz Hubert Kocewiak, DONG Energy
6. *EMC Challenges During Harmonic and Transient Measurements in Offshore Wind Farms,* Łukasz Hubert Kocewiak, DONG Energy
7. *Benefits of Asymmetric HVDC Links for the North Sea Super Grid,* Til Kristian Vrana, PhD stud, NTNU
8. *Frequency and voltage control from an offshore wind farm connected to an oil platform in islanded operation,* Atle Rygg Årdal, SINTEF
9. *Challenges and rationale for laboratory testing in offshore grids research, Kjell Ljøkelsøy, SINTEF*
10. *An approach to model the statistics of wind speed and wind power increments on a 10min time scale,* Prof Hans Georg Beyer, University of Agder
11. *Upper Ocean Response to Large Wind Farm Effect in the Presence of Surface Gravity Waves,* Mostafa Bakhoday Paskyabi, PhD stud, University of Bergen,
12. *A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation – improvement to an existing tool ECUME,* Fanny Douard, EDF
13. *Selection of important RAMS parameters for 10MW reference wind turbine,* Zafar Hameed, PhD stud, NTNU
14. *Fatigue analysis of copper conductor for offshore wind turbines by experimental and FE method,* Fachri Nasution, PhD stud, NTNU
15. *Maintenance strategies for large offshore wind farms,* Matti Scheu, NTNU
16. *Mooring system optimization for floating wind turbines using frequency domain analysis,* Matthias Brommundt, NTNU
17. *Installation and sub-structures PLOCAN, a multiuse offshore platform*, José Joaquín Hernández-Brito, Plocan
18. *A novel tool for FEM analysis of offshore wind turbines with innovative visualization techniques,* Paul E. Thomassen, post doc, NTNU
19. *Iterative optimization approach for the design of full-height lattice towers for offshore wind turbines,* Daniel Zwick, PhD stud, NTNU
20. *Performance and turbulence measurements on an array of two model wind turbines*, F. Pierella, PhD stud, NTNU
21. *Active Power Control with Undead-Band Voltage & Frequency Droop for HVDC Converters in Large Meshed DC Grids*, Til Kristian Vrana, PhD stud NTNU
22. *Fully Nonlinear Wave Foricing on an Offshore Wind Turbine. Structural Response and Fatigue,* Signe Schløer, PhD stud, Technical University of Denmark
23. *Panel Vortex Code for wind turbines implemented on a GPU*, Lene Eliassen, University of Stavanger
24. *Yaw moments of a three-bladed wind turbine yaw error*, Tania Bracchi, PhD student, NTNU
25. *Gain scheduled and robust H∞ control above rated wind speed for wind turbines*, Fredrik Sandquist, PhD student, NTNU

9th Deep Sea Offshore Wind R&D Seminar

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	Friday 20 January		
	Parallel sessions		
	D) Operations & maintenance Chairs: Jørn Heggset, SINTEF, Stefan Faulstich, Fraunhofer	**E) Installation & sub-structures** Chairs: Hans-Gerd Busmann, Fraunhofer, Jørgen Krokstad, Statkraft	**F) Wind farm modelling** Chairs: Prof Trond Kvamsdal, NTNU, Uwe S. Paulsen, Risø DTU
08.30	Introduction by Chair	Introduction by Chair	Introduction by Chair
08.35	*Distributed, hierarchical sensor network enabling park wide control of O&M on demand*, Matthijs Leeuw, TNO	*Monopiles and the competitiveness versus jacket structures*, Prof Lars Bo Ibsen, Aalborg University	*Experimental results of the NOWITECH/NORCOWE wake blind test*, Pål Egil Eriksen, PhD stud, NTNU
09.05	*Occupational safety management in the offshore wind industry – status and challenges,* Eirik Albrechtsen, SINTEF	*Feasibility of Application of Spar-type Wind Turbine in a Moderate Water Depth*, Post.Doc Madjid Karimirad, NTNU	*Wake modelling*, Steffan Ivanell, University of Gotland
09.25	*Monitoring Offshore Wind Energy Use in Europe – Offshore WMEP,* Stefan Faulstich, Fraunhhofer IWES	*Effects of hydrodynamic modelling in fully coupled simulations of a semisubmersible wind turbine,* Phd stud. Marit I. Kvittem, NTNU	*Wake Modeling with the Actuator Disc concept,* Arne Reidar Gravdahl, WindSim AS
09.45	*On the development of Condition based Maintenance Strategy for Offshore Wind Farm: Requirement Elicitation Phase*, Idriss El-Thalji, VTT	*Improved pile foundation modeling for offshore wind turbine support structures with the Finite Element Method,* Phd stud. Eric Van Buren, NTNU	*Recent Advances in Modelling Wind Parks in STAR-CCM+*, Steve Evans, CD-adapco
10.05	*Hywind: Two years in operation, what have we learnt and where are we going?* Sverre Trollnes, Statoil	*The full-height lattice tower concept,* Prof Michael Muskulus, NTNU	*Offshore wind farm optimisation*, Trygve Skjold, GexCon
10.35	Closing by Chair	Closing by Chair	Closing by Chair
10.40	Refreshments		
	Closing session – Innovations in Offshore Wind Technology Chairs: John Olav Tande, SINTEF/NOWITECH and Ole G. Dahlhaug, NTNU/NOWITECH		
11.00	Introduction by Chair		
11.05	*Considerations when designing large wind turbines*, Torolf Pettersen, Blaaster		
11.35	*A floating multi-turbine platform*, Marc Lefranc, WindSea		
12.05	*Innovations in Offshore Wind Technology by We@Sea*, Jos Beurskens, ECN		
12.35	Awards and Closing by Chair		
13.00	Lunch		

LIST OF PARTICIPANTS

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Arne Reidar Gravdahl	WindSim AS
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Oddbjørn Malmo	Kongsberg Maritime, Lade
Ole Gunnar Dahlhaug	NTNU
Ole Havmøller	Statoil
Ole Svendgård	VIVA
Olimpo Anaya-Lara	University of Strathclyde
Paul Thomassen	NTNU
Per Christer Lund	Norwegian Embassy in Tokyo
Per Olav Haarberg	ChapDrive AS
Peter Kalsaas Fossum	NTNU
Petter Andreas Berthelsen	MARINTEK
Pål Arne Kastmann	Innovation Norway / Norwegian Embassy in Beijing
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Roald Haug	Bosch Rexroth
Roy Stenbro	IFE
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Senu Sirnivas	NREL
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Xisca Ferrer Gallardo	ChapDrive AS
Yngve Ydersbond	Kjeller Vindteknikk
Yongtao Yang	Det Norske Veritas
Yuri Bazilevs	University of California
Zafar Hameed	NTNU

3 Scientific Committee and Conference Chairs

An international Scientific Committee was established with participants from leading research institutes and universities for reviewing submissions and preparing the conference programme. The members of the Scientific Committee of DeepWind2012 are listed below.

Anaya-Lara, Olimpo, Strathclyde University
Berge, Erik, Kjeller Vindteknikk
Busmann, Hans-Gerd, Fraunhofer IWES
Bussel, Gerard J.W. van, TU Delft
Dahlhaug, Ole Gunnar, NTNU
Faulstich, Stefan, Fraunhofer IWES
Gjengedal, Terje, UMB
Heggset, Jørn, SINTEF
Krokstad, Jørgen, Statkraft
Kvamsdal, Trond, NTNU
Langen, Ivar, UiS
Leithead, William, Strathclyde University
Madsen, Peter Hauge, Risø DTU
Moan, Torgeir, NTNU
Moe, Geir, NTNU
Molinas, Marta, NTNU
Nielsen, Finn Gunnar, Statoil
Nygaard, Tor Anders, IFE
Reuder, Jochen, UiB
Sirnivas, Senu, NREL
Tande, John Olav, SINTEF
Uhlen, Kjetil, NTNU
Undeland, Tore, NTNU

The conference chairs were

- John Olav Giæver Tande, Director NOWITECH, senior scientist SINTEF Energy Research
- Trond Kvamsdal, head of NOWITECH Scientific Committee, Associate Professor NTNU
- Ole Gunnar Dahlhaug, Professor NTNU

Opening session - offshore wind outlook

Wind in our sails - The coming of Europe's offshore wind energy industry,
Arapogianni Athanasia, EWEA

Status and plans for offshore wind in Japan,
Prof Chuichi Arakawa, University of Tokyo

Offshore wind research and development in USA, Senu Sirnivas, NREL

Innovations in Offshore Wind Technology through R&D,
John Olav Tande, SINTEF Energi AS

Coupled fluid-structure interaction simulation,
Prof Yuri Bazilevs, University of California (No presentation available)

Wind in our Sails

The coming of Europe's offshore wind energy industry

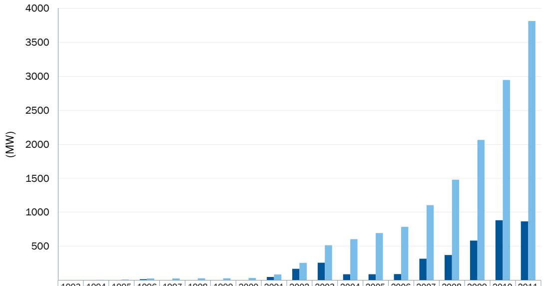
Arapogianni Athanasia – research officer
European Wind Energy Association

Trondheim, 19.01.2012

Outline

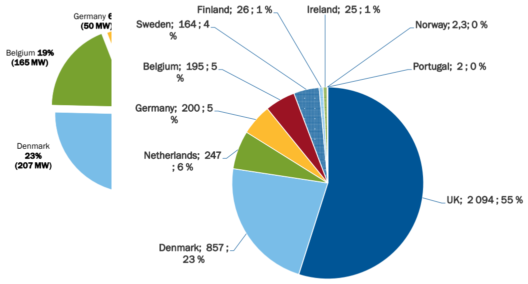
1. Offshore wind industry – End of 2011
2. Offshore wind industry in 2020 and 2030
3. Supply chain
    a) Wind turbines
    b) Substructures
    c) Grid connection
    d) Vessels
    e) Ports
4. Conclusions

Annual 2011 capacity :866.35 MW
Cumulative capacity (end 2011): 3,813 MW

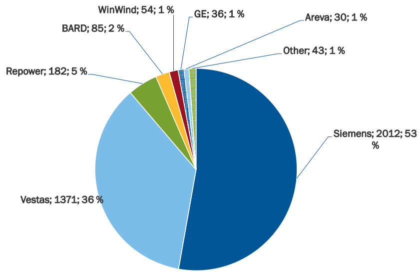


	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
■ Annual	0	2	5	17	0	3	0	4	51	170	259	90	90	93	318	373	584	883	866
■ Cumulative	5	7	12	29	29	32	32	36	86	256	515	605	695	787	1 106	1 479	2 063	2 946	3 813

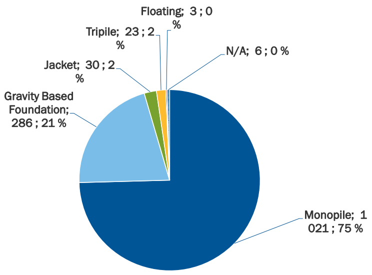
Share of new installed capacity in Europe in 2011



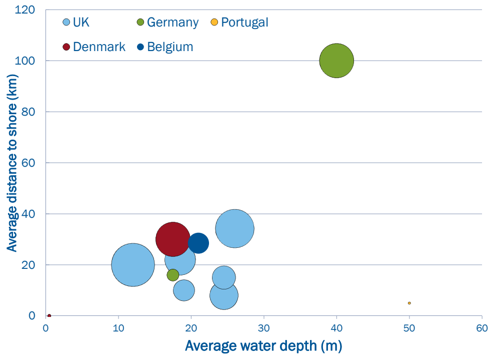
Wind turbine manufacturers' share in installations



Substructure types



2011 annual installation of offshore wind projects



Total offshore wind market outlook

Offshore wind energy market in the EU in 2011

- Total installed capacity of around 4,000 MW
- Meeting 0.4% of total EU electricity demand
- Annual installations of 1,000 MW
- Avoiding 9.9 Mt of CO_2 annually
- Total electricity production of 14.4 TWh
- Annual investments in wind turbines of €2.8 billion.

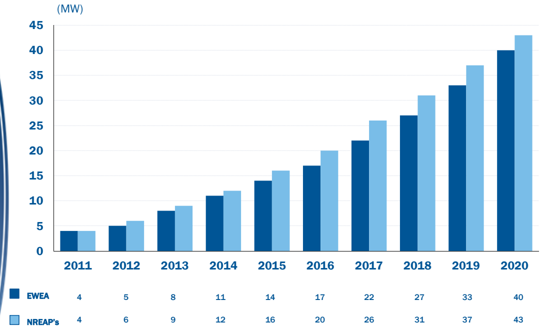
Offshore wind energy market in the EU in 2011

- Total installed capacity of 3,813 MW
- Meeting 0.4% of total EU electricity demand
- Annual installations of 866.35 MW
- Avoiding 9.9 Mt of CO_2 annually
- Total electricity production of 14.4 TWh
- Annual investments in wind turbines of €2.8 billion.

Outline

1. Offshore wind industry – End of 2011
2. Offshore wind industry in 2020 and 2030
3. Supply chain
    a) Wind turbines
    b) Substructures
    c) Grid connection
    d) Vessels
    e) Ports
4. Conclusions

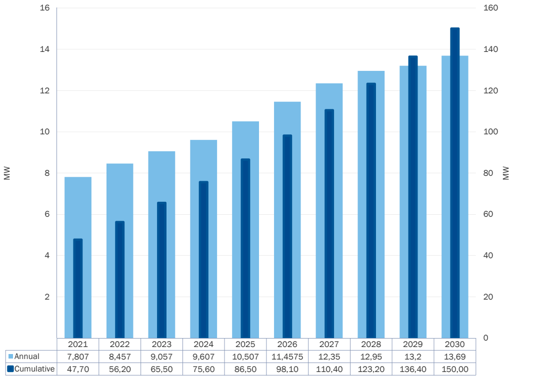
Offshore wind to 2020



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
EWEA	4	5	8	11	14	17	22	27	33	40
NREAP's	4	6	9	12	16	20	26	31	37	43

Offshore wind energy market in the EU in 2020

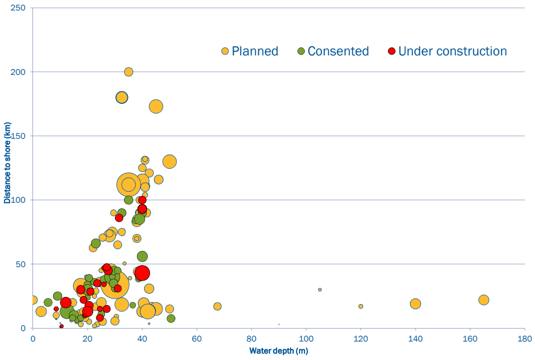
- Total installed capacity of 40,000 MW
- Meeting 4.2% of total EU electricity demand
- Annual installations of 6,900 MW
- Avoiding 102 Mt of CO_2 annually
- Total electricity production of 148 TWh
- Annual investments in offshore wind turbines of **€10.4 billion**
- Cumulative investments in offshore wind turbines of **€65.9 billion** in the period 2011 - 2020.



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Annual	7,807	8,457	9,057	9,607	10,507	11,4575	12,35	12,95	13,2	13,69
Cumulative	47,70	56,20	65,50	75,60	86,50	98,10	110,40	123,20	136,40	150,00

Offshore wind energy market in the EU in 2030

- Total installed capacity of 150,000 MW
- Annual installations of 13,700 MW
- Total electricity production of 562 TWh
- Meeting 13.9% of total EU electricity demand
- Avoiding 315 Mt of CO2 in 2030
- Annual investments in offshore wind turbines of €17 billion in 2030
- Cumulative investments of €145.2 billion from 2021 to 2030



Outline

1. Offshore wind industry – End of 2011
2. Offshore wind industry in 2020 and 2030
3. Supply chain
    a) Wind turbines
    b) Substructures
    c) Grid connection
    d) Vessels
    e) Ports
4. Conclusions

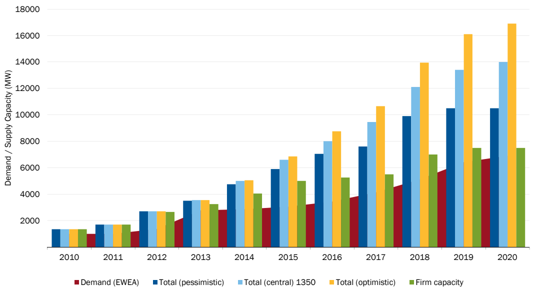
An offshore wind supply chain

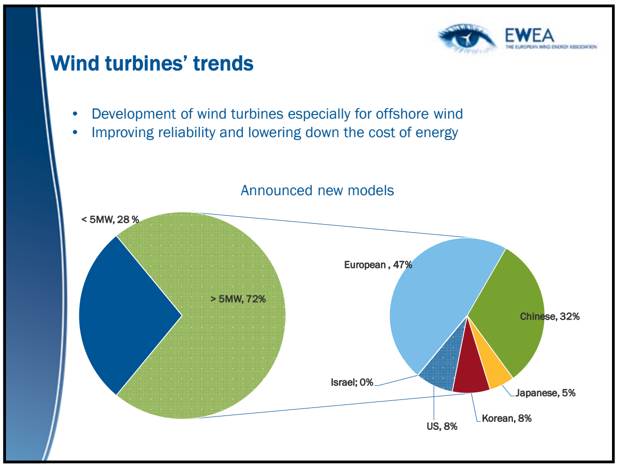
	Wind turbine Manufacturers	Structural fabricators	Electrical suppliers	Marine contractors	Cable suppliers	Cable installers	EPCI contractors	Port operators
Example incumbents	Siemens, Vestas, REpower, Areva	SIF, Smulders, Bladt, EEW, Weserwind, BiFAB, Aker	ABB, Siemens Energy, Alstom Grid	A2Sea, MPI, SHL, Geosea	Nexans, Prysmian, ABB NKT, Scanrope	Technip, CT Offshore, Global Marine, Visser&Smit	Fluor, Van Oord, ABJV, MT Hojgaard, DEME	Various
Example new entrants	BARD, GE, Doosan, Gamesa, Alstom, Nordex, Mitsubishi	H&W, TAG, Tata, Hereema, ZPMC, Shinan, Fabricom	C&G	Fred Olsen, Beluga, Inwind, GOAH, Sea Jacks	DRAKA, JDR	Beluga	Hochtief, Saipem, Technip, Subsea7	Various
Level 1	✔	✓	✔	✓	✓	✔	✔	✓
Level 2	×	✔	✔	✔	✔	✔	×	✔
Level 3	×	✓	✓	✓	✓	✓	×	✓

Legend:
Ticks and crosses represent likelihood of positioning at relevant Level in the contractual hierarchy:

✔ Likely
✓ Possible
× Unlikely

Supply and demand for offshore wind turbine technology in Europe





Wind turbines' trends

- Development of wind turbines especially for offshore wind
- Improving reliability and lowering down the cost of energy

Announced new models

Outline

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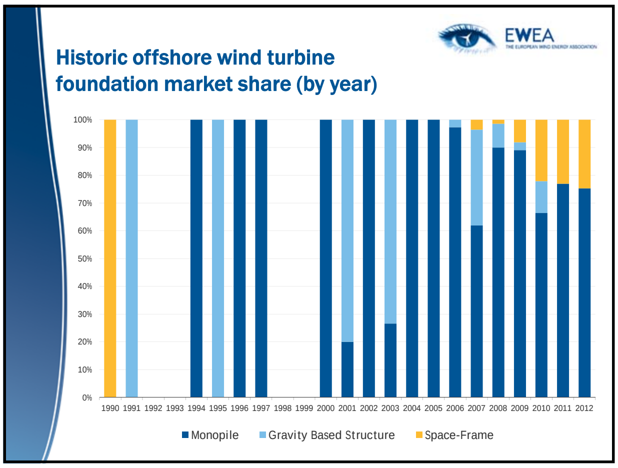
4. Conclusions



Historic offshore wind turbine foundation market share (by year)

Outline

1. Offshore wind industry – End of 2011
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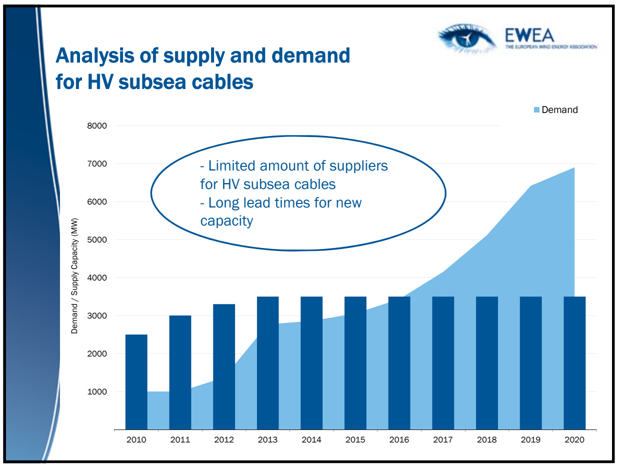
4. Conclusions



Analysis of supply and demand for HV subsea cables

- Limited amount of suppliers for HV subsea cables
- Long lead times for new capacity

Outline

1. Offshore wind industry – End of 2011
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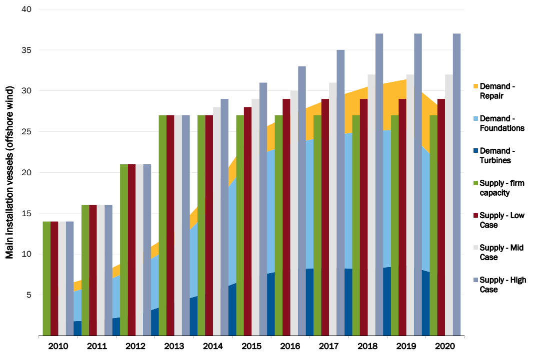
   e) Ports
4. Conclusions

Projected offshore installation vessel supply and demand (vessels per annum)



Outline

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Example of European ports for offshore wind construction

No	Port	MP¹	M²	OWE³
1	Aalborg	●	●	✓
2	Aarhus	⭘	⭘	✓
3	Barrow	●	⭘	✓
4	Belfast	●	⭘	✓
5	Bremerhaven	●	●	✓
6	Brest	⭘	⭘	×
7	Caen	○	○	×
8	Cherbourg	⭘	⭘	×
9	Copenhagen	⭘	⭘	×
10	Cape Firth	⭘	⭘	×
11	Cuxhaven	●	●	✓
12	Dieppe	⭘	⭘	×
13	Dundee	⭘	⭘	×
14	Dunkirk	●	⭘	✓
15	Eemshaven	●	⭘	✓
16	Emden	●	●	✓
17	Esbjerg	●	●	✓

No	Port	MP¹	M²	OWE³
18	Frederikshvn.	○	○	✓
19	Gdansk	⭘	⭘	×
20	Great Yarmouth	●	⭘	✓
21	Hartlepool & tees	⭘	⭘	✓
22	Humber	⭘	●	✓
23	Hunterston	⭘	⭘	×
24	Le Havre	⭘	⭘	×
25	Zeebrugge	⭘	⭘	×
26	Lubmin	⭘	●	✓
27	Malmo	⭘	⭘	×
28	Medway	⭘	●	×
29	Methil	●	●	✓
30	Milford H	⭘	⭘	×
31	Montrose	⭘	⭘	×
32	Mostyn	●	○	✓
33	Newhaven	⭘	○	×
34	Nyborg	●	⭘	✓

No	Port	MP¹	M²	OWE³
35	Peterhead	○	○	×
36	Portland	⭘	○	×
37	Ramsgate	●	○	✓
38	Riga	○	⭘	×
39	Rostock	●	●	✓
40	Rotterdam	●	●	✓
41	Sassnitz	●	⭘	✓
42	Southampton	⭘	⭘	×
43	St Malo	○	○	×
44	St Nazaire	⭘	⭘	×
45	Stavanger	⭘	⭘	✓
46	Swansea	⭘	⭘	×
47	Tallin	⭘	⭘	✓
48	Tyneside	⭘	⭘	×
49	Vlissingen	⭘	⭘	✓
50	Wismar	⭘	⭘	×

Notes:
1. "MP": suitable as Mobilisation Port
2. "M": Manufacturing infrastructure serving the offshore wind sector
3. "OWE": Offshore Wind Experience

Legend:
● Currently or likely in future
⭘ Possible in future
○ Unlikely

Supply chain – Wind in our Sails – More details

- Supply chain is dynamic and responding to challenges through investments in innovation:
    - Turbines
    - Substructures
    - Electrical infrastructure
    - Vessels
    - Ports

www.ewea.org → Publications → Reports

Conclusions

- The European Union leads the world in offshore wind power with almost 4,000MW already installed
- This major industrial development will bring a significant number of jobs and create development opportunities for European companies
- However, there are still challenges ahead and support is needed:
    - Favorable national framework conditions: NREAPs, licensing and permitting procedures, maritime spatial planning, reinforcement of onshore networks
    - Support from the EU: stable post-2020 legislative framework, offshore grid

Thank you

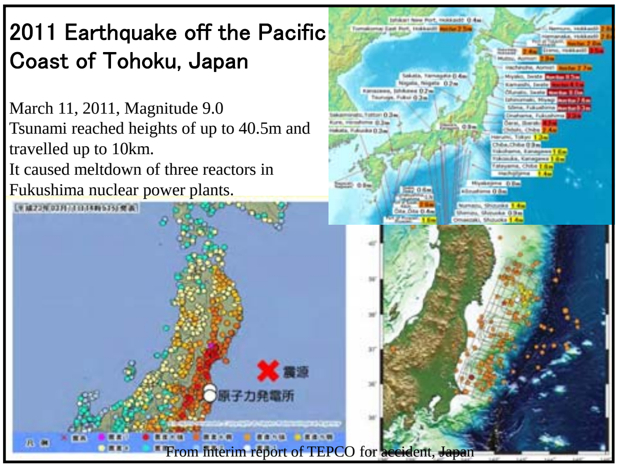
9th Deep Sea Offshore Wind R&D Seminar, 19-20 January 2012, Trondheim, NORWAY

Status and plans for offshore wind in Japan

Chuichi Arakawa
The University of Tokyo

- This wind farm withstood Tsunami on 3.11
- 7 units of 2MW Wind Turbine
- Being developed as private sector for future such as more 7 units and Giga-watt farm

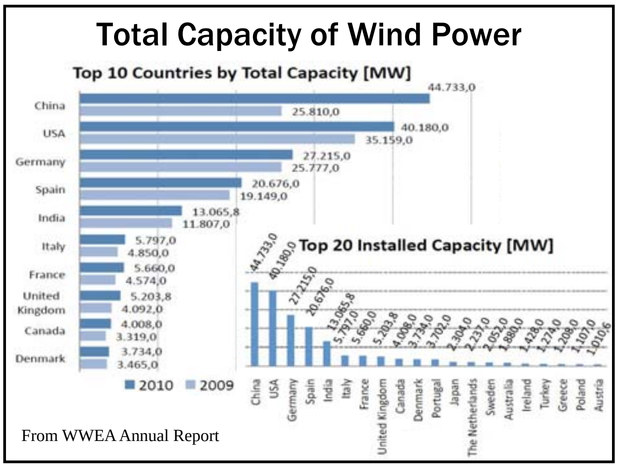
Kamisu, Japan / 2MW x 7



2011 Earthquake off the Pacific Coast of Tohoku, Japan

March 11, 2011, Magnitude 9.0
Tsunami reached heights of up to 40.5m and travelled up to 10km.
It caused meltdown of three reactors in Fukushima nuclear power plants.

From interim report of TEPCO for accident, Japan



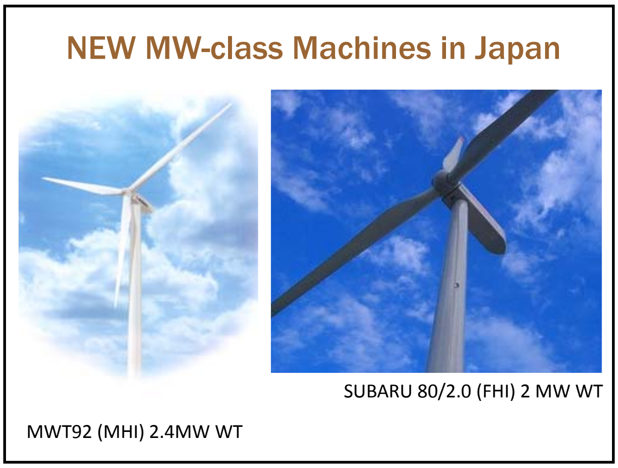
Total Capacity of Wind Power

From WWEA Annual Report

New Guideline for Wind Turbines in Japan and Asian Area

Typhoon Attack

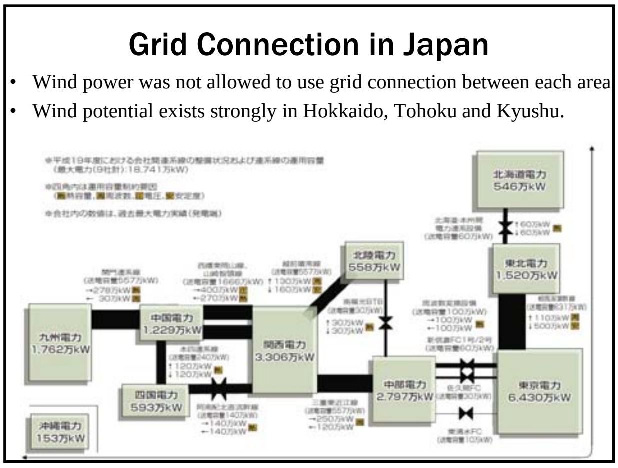
Miyako Island was hit by huge Typhoon #14 on 11.Sep.2003 and all 7 WT were destroyed;
3 fallen down, 3 lost blades,
1 lost nacelle roof



NEW MW-class Machines in Japan

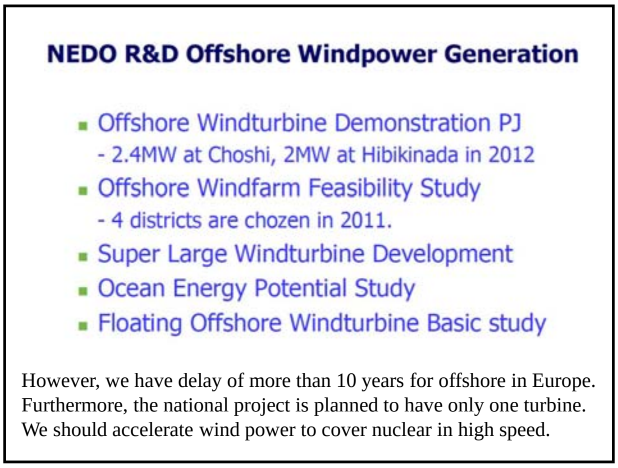
SUBARU 80/2.0 (FHI) 2 MW WT

MWT92 (MHI) 2.4MW WT



Grid Connection in Japan

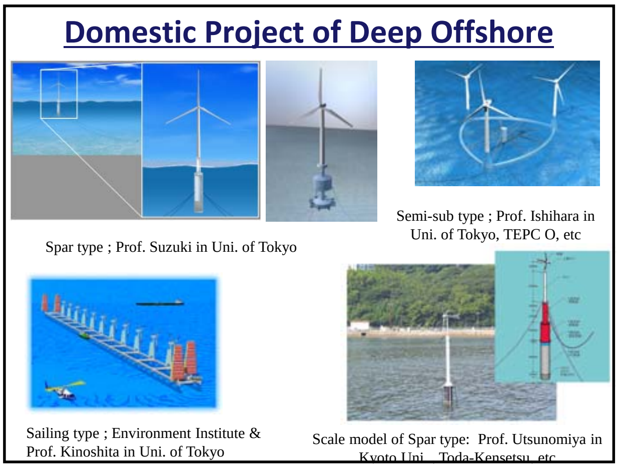
- Wind power was not allowed to use grid connection between each area
- Wind potential exists strongly in Hokkaido, Tohoku and Kyushu.



NEDO R&D Offshore Windpower Generation

- Offshore Windturbine Demonstration PJ
  - 2.4MW at Choshi, 2MW at Hibikinada in 2012
- Offshore Windfarm Feasibility Study
  - 4 districts are chozen in 2011.
- Super Large Windturbine Development
- Ocean Energy Potential Study
- Floating Offshore Windturbine Basic study

However, we have delay of more than 10 years for offshore in Europe.
Furthermore, the national project is planned to have only one turbine.
We should accelerate wind power to cover nuclear in high speed.



Domestic Project of Deep Offshore

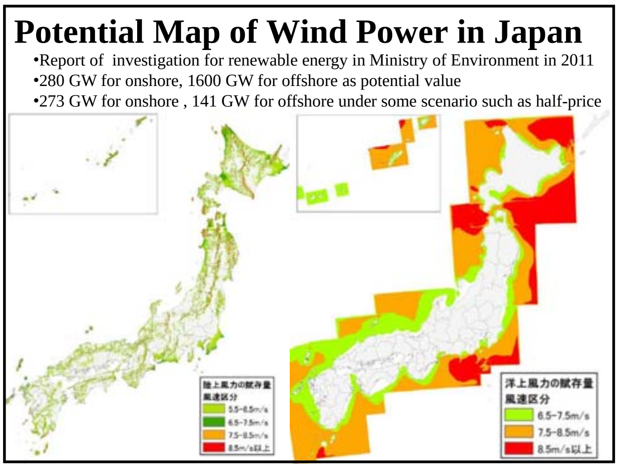
Spar type ; Prof. Suzuki in Uni. of Tokyo

Semi-sub type ; Prof. Ishihara in Uni. of Tokyo, TEPC O, etc

Sailing type ; Environment Institute & Prof. Kinoshita in Uni. of Tokyo

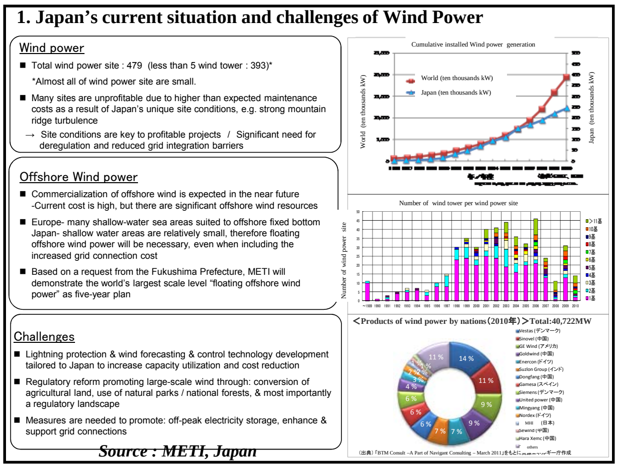
Scale model of Spar type: Prof. Utsunomiya in Kyoto Uni., Toda-Kensetsu, etc

After the Disaster on March 11, 2011



Potential Map of Wind Power in Japan

- Report of investigation for renewable energy in Ministry of Environment in 2011
- 280 GW for onshore, 1600 GW for offshore as potential value
- 273 GW for onshore , 141 GW for offshore under some scenario such as half-price



1. Japan's current situation and challenges of Wind Power

Wind power

- Total wind power site : 479 (less than 5 wind tower : 393)*
  *Almost all of wind power site are small.
- Many sites are unprofitable due to higher than expected maintenance costs as a result of Japan's unique site conditions, e.g. strong mountain ridge turbulence
  → Site conditions are key to profitable projects / Significant need for deregulation and reduced grid integration barriers

Offshore Wind power

- Commercialization of offshore wind is expected in the near future
  -Current cost is high, but there are significant offshore wind resources
- Europe- many shallow-water sea areas suited to offshore fixed bottom
  Japan- shallow water areas are relatively small, therefore floating offshore wind power will be necessary, even when including the increased grid connection cost
- Based on a request from the Fukushima Prefecture, METI will demonstrate the world's largest scale level "floating offshore wind power" as five-year plan

Challenges

- Lightning protection & wind forecasting & control technology development tailored to Japan to increase capacity utilization and cost reduction
- Regulatory reform promoting large-scale wind through: conversion of agricultural land, use of natural parks / national forests, & most importantly a regulatory landscape
- Measures are needed to promote: off-peak electricity storage, enhance & support grid connections

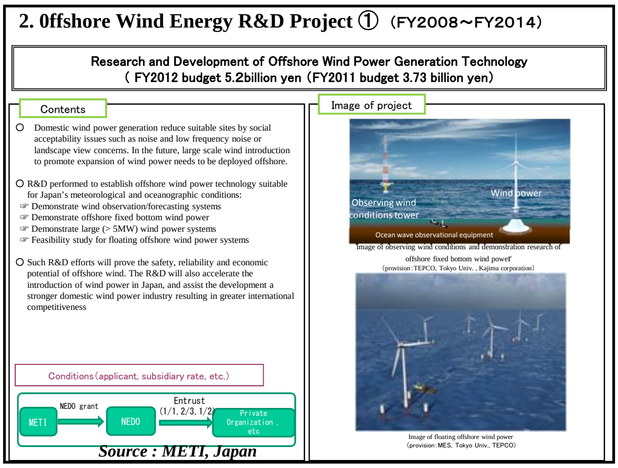
Cumulative installed Wind power generation

Number of wind tower per wind power site

＜Products of wind power by nations（2010年）＞Total:40,722MW

（出典）「BTM Consult –A Part of Navigant Consulting – March 2011」をもとに資源エネルギー庁作成

Source : METI, Japan



2. 0ffshore Wind Energy R&D Project ① （FY2008～FY2014）

Research and Development of Offshore Wind Power Generation Technology
(FY2012 budget 5.2billion yen（FY2011 budget 3.73 billion yen）

Contents

○ Domestic wind power generation reduce suitable sites by social acceptability issues such as noise and low frequency noise or landscape view concerns. In the future, large scale wind introduction to promote expansion of wind power needs to be deployed offshore.

○ R&D performed to establish offshore wind power technology suitable for Japan's meteorological and oceanographic conditions:
☞ Demonstrate wind observation/forecasting systems
☞ Demonstrate offshore fixed bottom wind power
☞ Demonstrate large (> 5MW) wind power systems
☞ Feasibility study for floating offshore wind power systems

○ Such R&D efforts will prove the safety, reliability and economic potential of offshore wind. The R&D will also accelerate the introduction of wind power in Japan, and assist the development a stronger domestic wind power industry resulting in greater international competitiveness

Conditions（applicant, subsidiary rate, etc.）

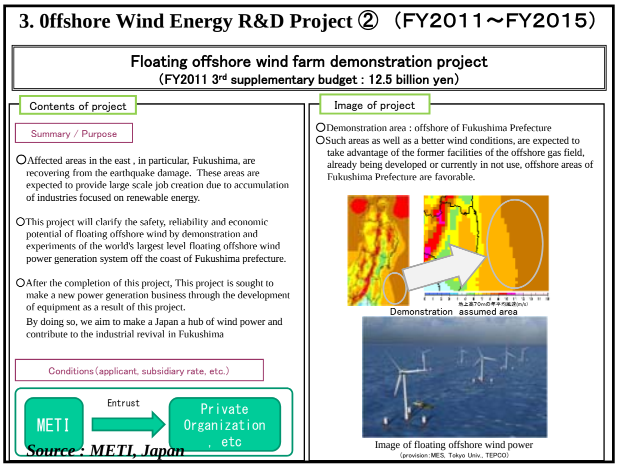
METI → NEDO grant → NEDO → Entrust (1/1, 2/3, 1/2) → Private Organization , etc

Image of project

Image of observing wind conditions and demonstration research of offshore fixed bottom wind power
（provision:TEPCO, Tokyo Univ. , Kajima corporation）

Image of floating offshore wind power
（provision:MES, Tokyo Univ., TEPCO）

Source : METI, Japan



3. 0ffshore Wind Energy R&D Project ② （FY2011～FY2015）

Floating offshore wind farm demonstration project
（FY2011 3rd supplementary budget : 12.5 billion yen）

Contents of project

Summary / Purpose

○Affected areas in the east , in particular, Fukushima, are recovering from the earthquake damage. These areas are expected to provide large scale job creation due to accumulation of industries focused on renewable energy.

○This project will clarify the safety, reliability and economic potential of floating offshore wind by demonstration and experiments of the world's largest level floating offshore wind power generation system off the coast of Fukushima prefecture.

○After the completion of this project, This project is sought to make a new power generation business through the development of equipment as a result of this project.
By doing so, we aim to make a Japan a hub of wind power and contribute to the industrial revival in Fukushima

Conditions（applicant, subsidiary rate, etc.）

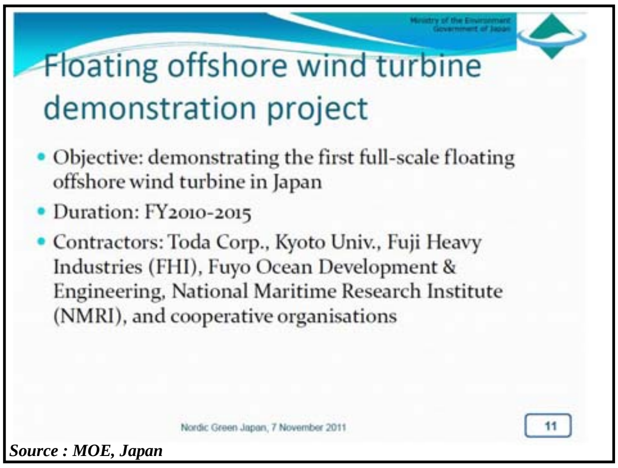
Source : METI, Japan

Image of project

○Demonstration area : offshore of Fukushima Prefecture
○Such areas as well as a better wind conditions, are expected to take advantage of the former facilities of the offshore gas field, already being developed or currently in not use, offshore areas of Fukushima Prefecture are favorable.

Demonstration assumed area

Image of floating offshore wind power
（provision：MES, Tokyo Univ., TEPCO）



Floating offshore wind turbine demonstration project

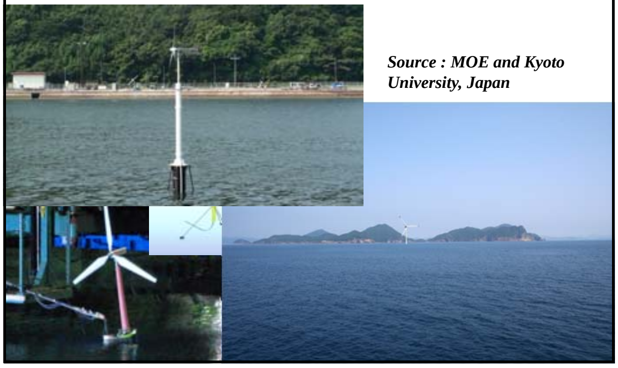
- Objective: demonstrating the first full-scale floating offshore wind turbine in Japan
- Duration: FY2010-2015
- Contractors: Toda Corp., Kyoto Univ., Fuji Heavy Industries (FHI), Fuyo Ocean Development & Engineering, National Maritime Research Institute (NMRI), and cooperative organisations

Nordic Green Japan, 7 November 2011

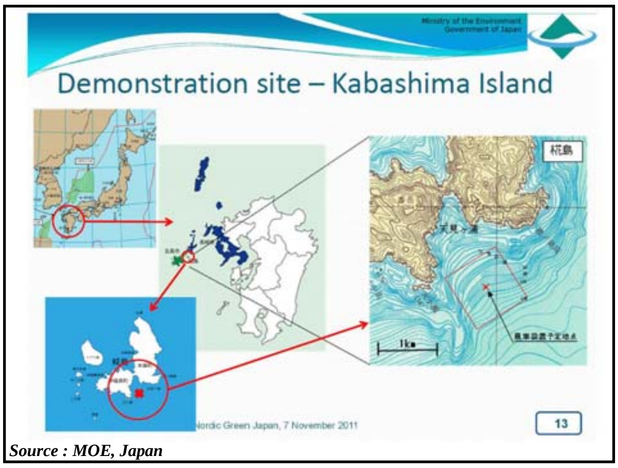
11

Source : MOE, Japan

Floating type of offshore by Ministry of Environment (MOE)



Source : MOE and Kyoto University, Japan

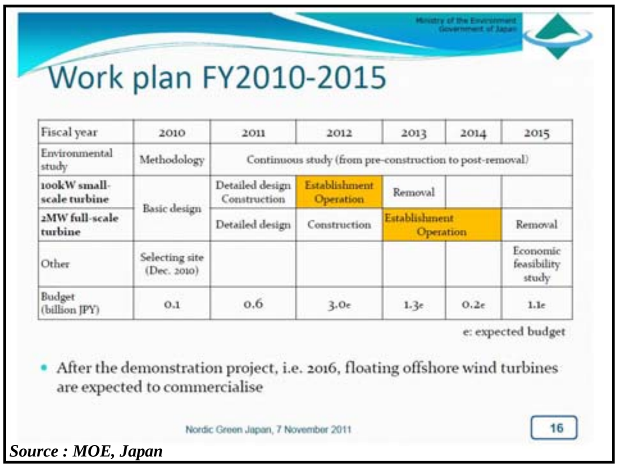


Demonstration site – Kabashima Island

Nordic Green Japan, 7 November 2011

13

Source : MOE, Japan



Work plan FY2010-2015

Fiscal year	2010	2011	2012	2013	2014	2015
Environmental study	Methodology	Continuous study (from pre-construction to post-removal)				
100kW small-scale turbine	Basic design	Detailed design Construction	Establishment Operation	Removal		
2MW full-scale turbine		Detailed design	Construction	Establishment Operation		Removal
Other	Selecting site (Dec. 2010)					Economic feasibility study
Budget (billion JPY)	0.1	0.6	3.0e	1.3e	0.2e	1.1e

e: expected budget

- After the demonstration project, i.e. 2016, floating offshore wind turbines are expected to commercialise

Nordic Green Japan, 7 November 2011

16

Source : MOE, Japan

Concluding Remarks

For Onshore Wind Power

- Social acceptance is essential to avoid the influence of infrasound, landscape, bird-strike and so on.
- Primary grid connection of wind power is important with the electric power company using the connections with other areas.

For Offshore Wind Power

- Offshore wind power has large potential due to the huge area of ocean around Japanese island of EEZ 6th.
- Deep offshore system will be a key technology for future development of wind power and recovery from the disaster.
- Fisherman's right will be reasonably taken into account for cooperating with developer instead of compensation.
- Penetration of wind power in Japan is important, not the research and technology.

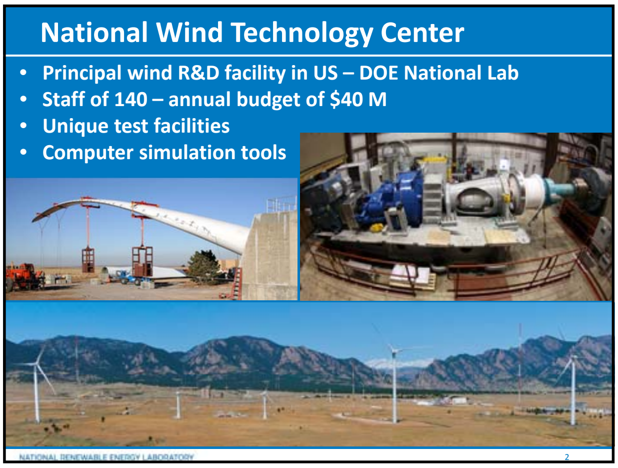
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

US Offshore Wind

Deepwind 2012

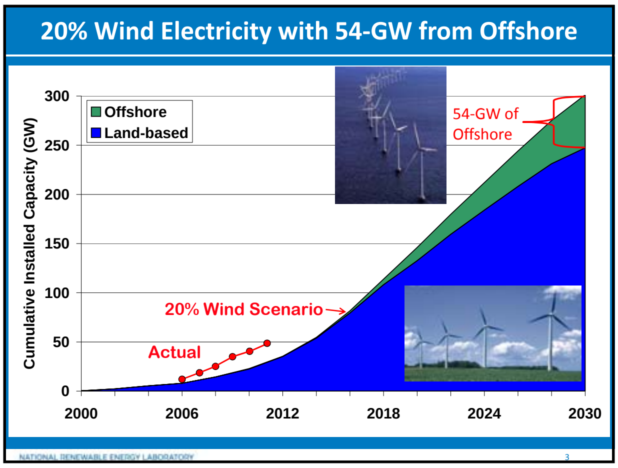
Senu Sirnivas

19th January 2012

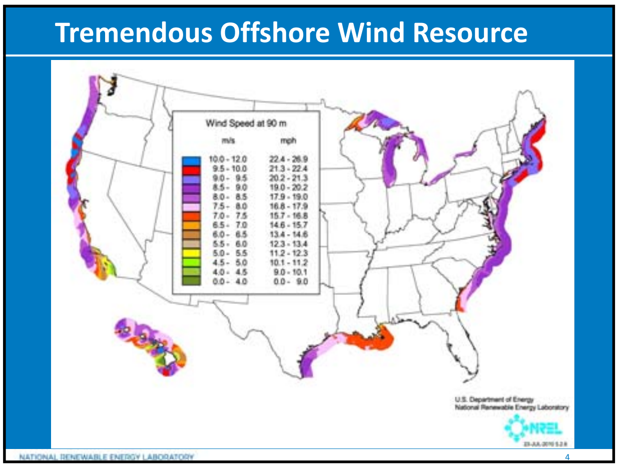


National Wind Technology Center

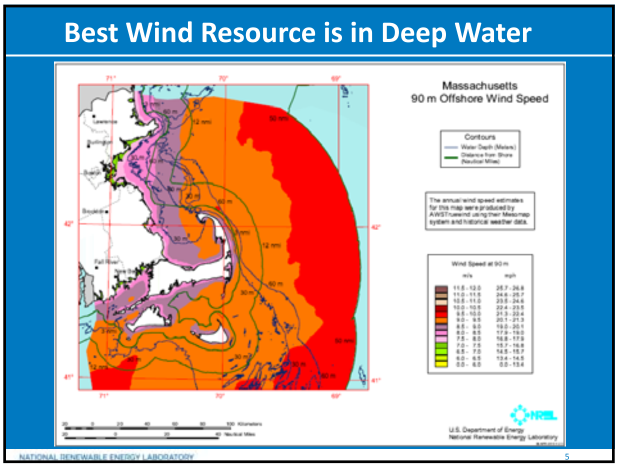
- Principal wind R&D facility in US – DOE National Lab
- Staff of 140 – annual budget of $40 M
- Unique test facilities
- Computer simulation tools



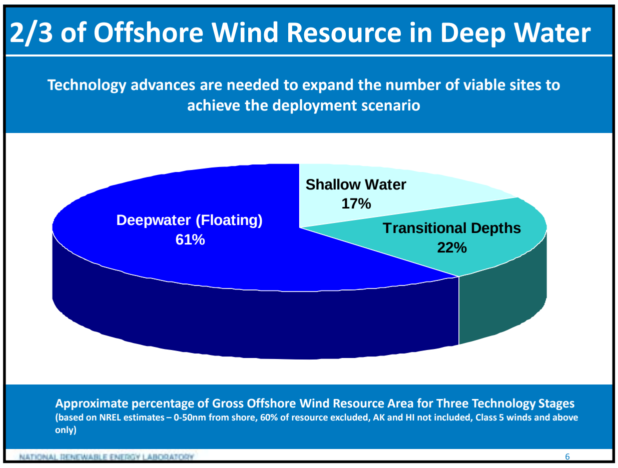
20% Wind Electricity with 54-GW from Offshore



Tremendous Offshore Wind Resource



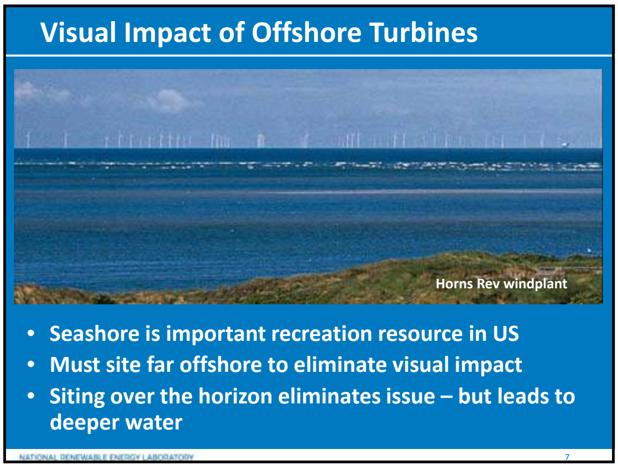
Best Wind Resource is in Deep Water



2/3 of Offshore Wind Resource in Deep Water

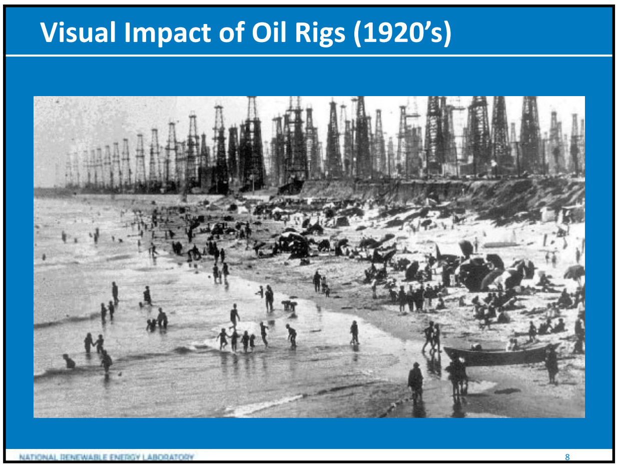
Technology advances are needed to expand the number of viable sites to achieve the deployment scenario

Approximate percentage of Gross Offshore Wind Resource Area for Three Technology Stages
(based on NREL estimates – 0-50nm from shore, 60% of resource excluded, AK and HI not included, Class 5 winds and above only)

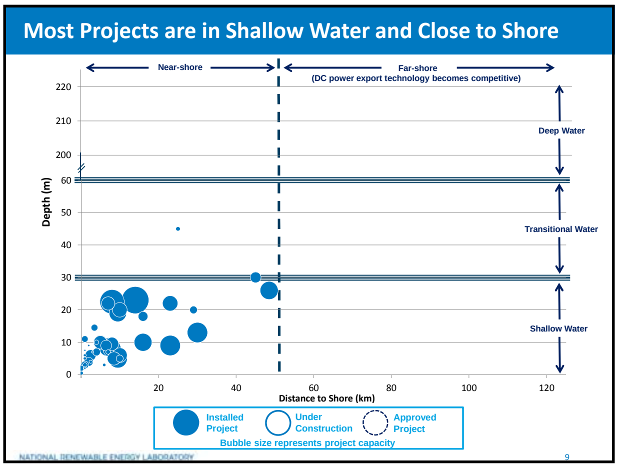


Visual Impact of Offshore Turbines

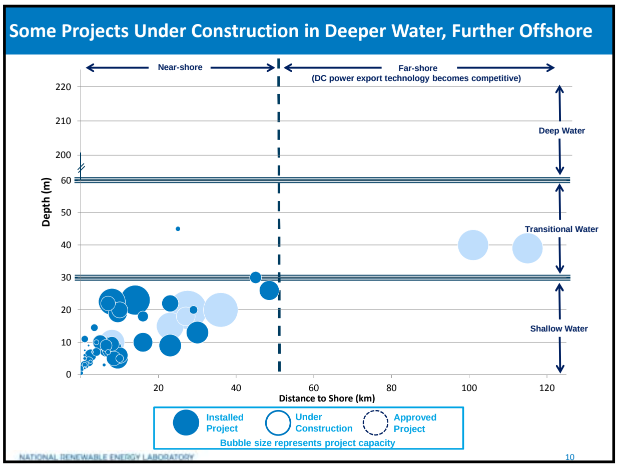
- Seashore is important recreation resource in US
- Must site far offshore to eliminate visual impact
- Siting over the horizon eliminates issue – but leads to deeper water



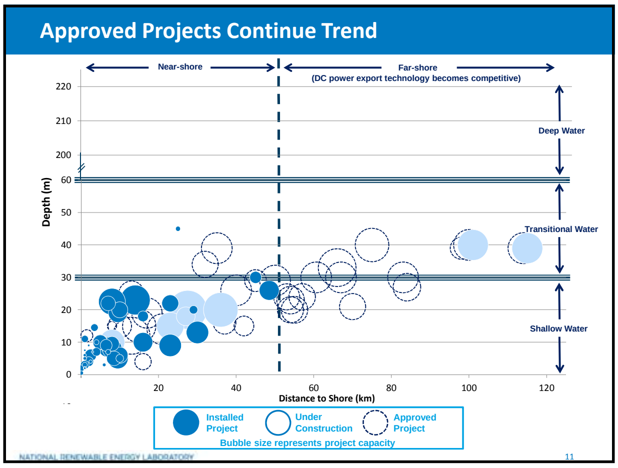
Visual Impact of Oil Rigs (1920's)



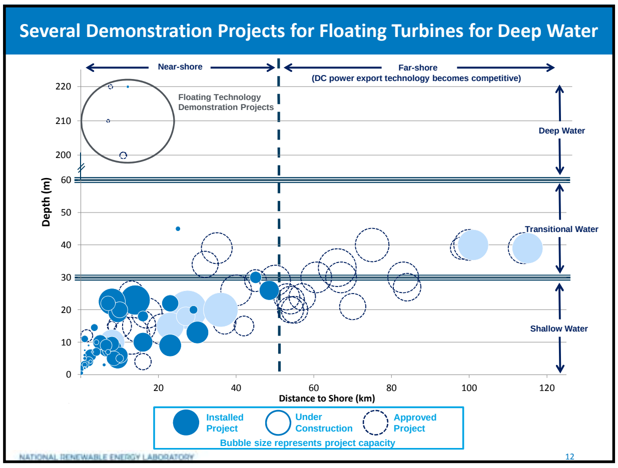
Most Projects are in Shallow Water and Close to Shore



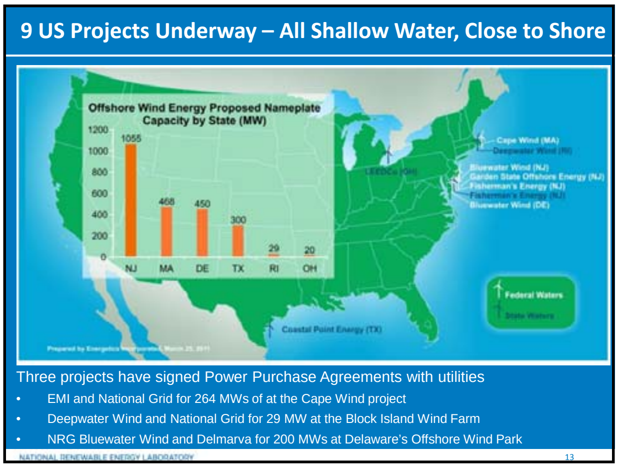
Some Projects Under Construction in Deeper Water, Further Offshore



Approved Projects Continue Trend



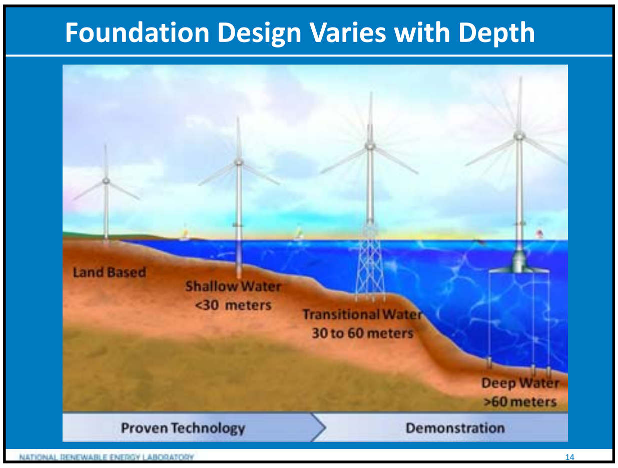
Several Demonstration Projects for Floating Turbines for Deep Water



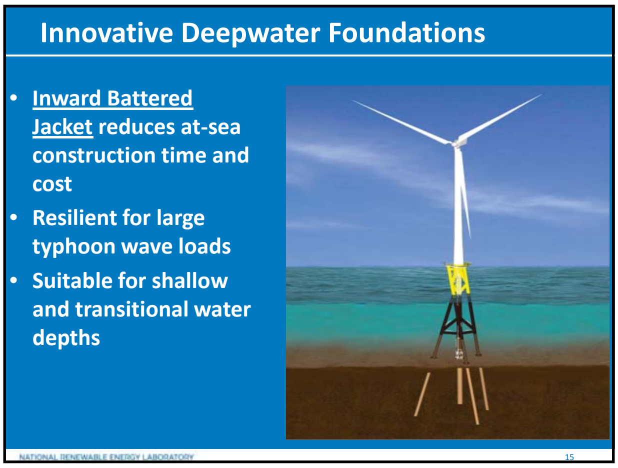
9 US Projects Underway – All Shallow Water, Close to Shore

Three projects have signed Power Purchase Agreements with utilities

- EMI and National Grid for 264 MWs of at the Cape Wind project
- Deepwater Wind and National Grid for 29 MW at the Block Island Wind Farm
- NRG Bluewater Wind and Delmarva for 200 MWs at Delaware's Offshore Wind Park

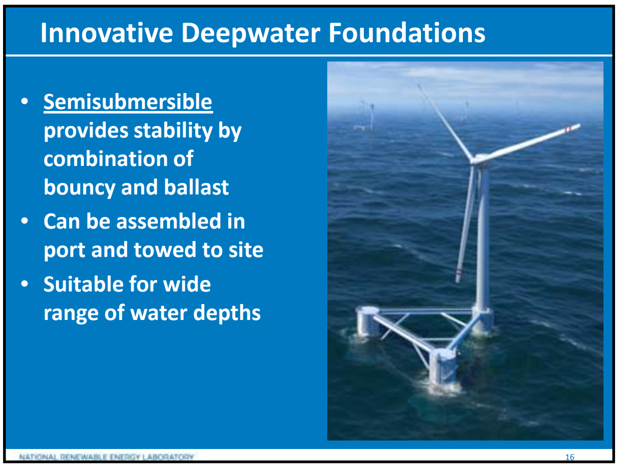


Foundation Design Varies with Depth



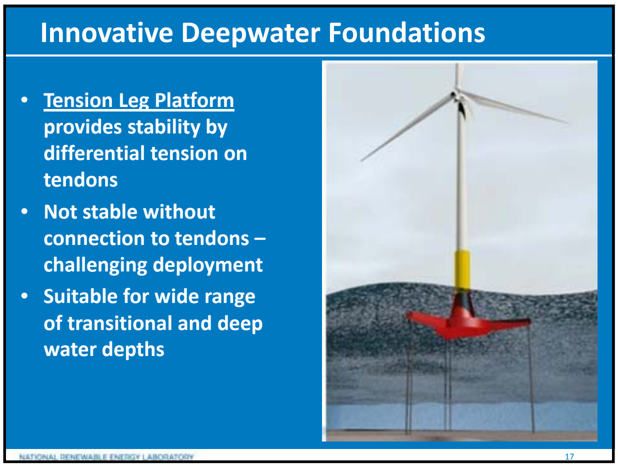
Innovative Deepwater Foundations

- Inward Battered Jacket reduces at-sea construction time and cost
- Resilient for large typhoon wave loads
- Suitable for shallow and transitional water depths



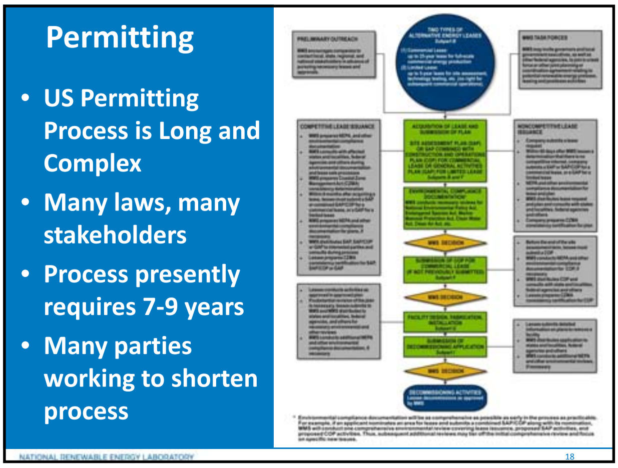
Innovative Deepwater Foundations

- Semisubmersible provides stability by combination of bouncy and ballast
- Can be assembled in port and towed to site
- Suitable for wide range of water depths



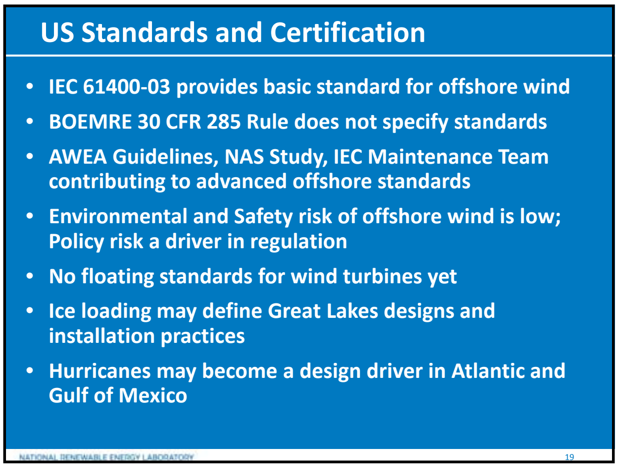
Innovative Deepwater Foundations

- Tension Leg Platform provides stability by differential tension on tendons
- Not stable without connection to tendons – challenging deployment
- Suitable for wide range of transitional and deep water depths



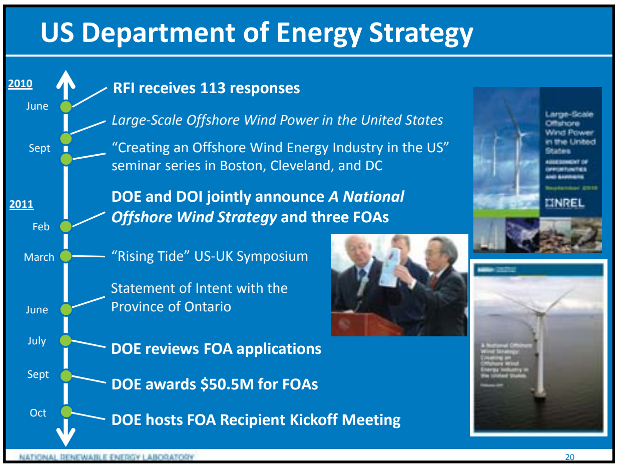
Permitting

- US Permitting Process is Long and Complex
- Many laws, many stakeholders
- Process presently requires 7-9 years
- Many parties working to shorten process



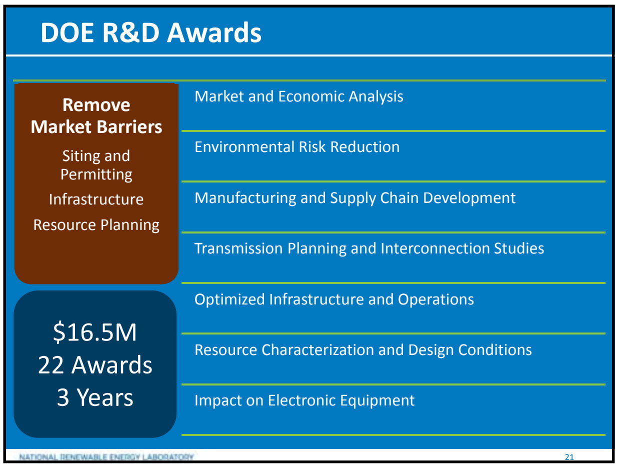
US Standards and Certification

- IEC 61400-03 provides basic standard for offshore wind
- BOEMRE 30 CFR 285 Rule does not specify standards
- AWEA Guidelines, NAS Study, IEC Maintenance Team contributing to advanced offshore standards
- Environmental and Safety risk of offshore wind is low; Policy risk a driver in regulation
- No floating standards for wind turbines yet
- Ice loading may define Great Lakes designs and installation practices
- Hurricanes may become a design driver in Atlantic and Gulf of Mexico



US Department of Energy Strategy

2010
June — RFI receives 113 responses
— *Large-Scale Offshore Wind Power in the United States*
Sept — "Creating an Offshore Wind Energy Industry in the US" seminar series in Boston, Cleveland, and DC
2011
Feb — DOE and DOI jointly announce *A National Offshore Wind Strategy* and three FOAs
March — "Rising Tide" US-UK Symposium
June — Statement of Intent with the Province of Ontario
July — DOE reviews FOA applications
Sept — DOE awards $50.5M for FOAs
Oct — DOE hosts FOA Recipient Kickoff Meeting

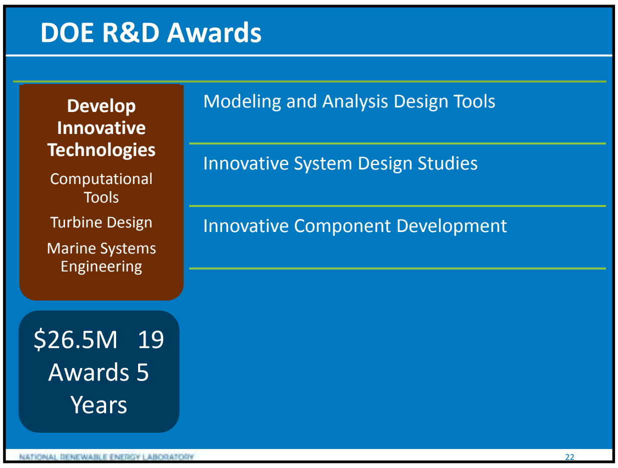


DOE R&D Awards

Remove Market Barriers
Siting and Permitting
Infrastructure
Resource Planning

$16.5M
22 Awards
3 Years

- Market and Economic Analysis
- Environmental Risk Reduction
- Manufacturing and Supply Chain Development
- Transmission Planning and Interconnection Studies
- Optimized Infrastructure and Operations
- Resource Characterization and Design Conditions
- Impact on Electronic Equipment



DOE R&D Awards

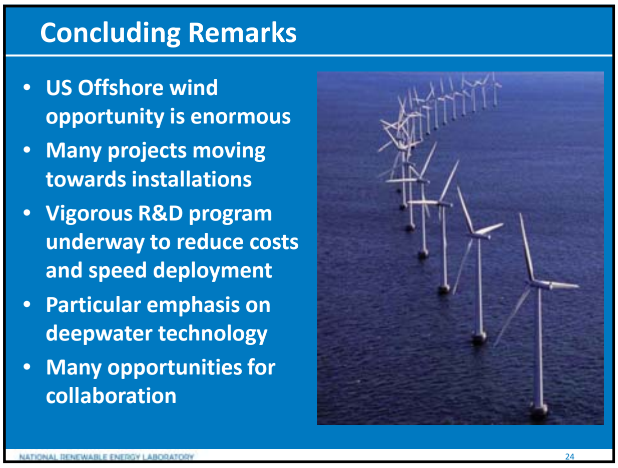
Develop Innovative Technologies
Computational Tools
Turbine Design
Marine Systems Engineering

$26.5M 19
Awards 5
Years

- Modeling and Analysis Design Tools
- Innovative System Design Studies
- Innovative Component Development

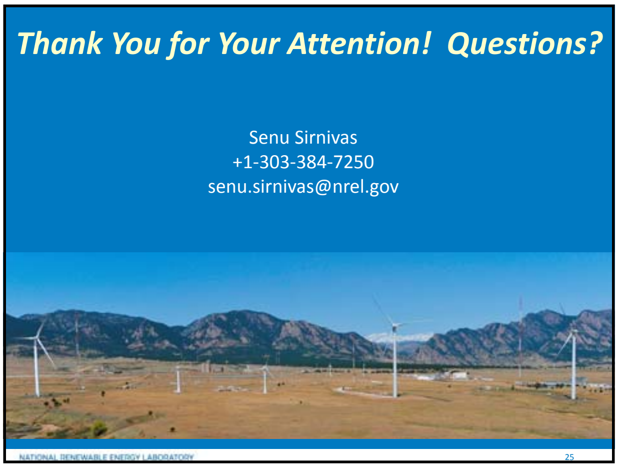
Opportunities for International Collaboration

- Many opportunities for international collaboration
- Hurricanes and typhoons
- Deepwater technology
- Standards and Certification
- Foundation and mooring system design for varying seabed conditions
- Improved operations and maintenance procedures
- Reliability data



Concluding Remarks

- US Offshore wind opportunity is enormous
- Many projects moving towards installations
- Vigorous R&D program underway to reduce costs and speed deployment
- Particular emphasis on deepwater technology
- Many opportunities for collaboration



Thank You for Your Attention! Questions?

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senu.sirnivas@nrel.gov

Innovations in Offshore Wind Technology through R&D

www.nowitech.no

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

NOWITECH in brief

- **NOWITECH is a NOK 320 millions* joint research effort on offshore wind technology, co-financed by the Research Council of Norway, industry and research partners, incl. 25 PhD/post doc grants.**
- **The Objective is pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms. Emphasis is on technology for deep sea (+30 m).**
- **Our Vision is large scale deployment of deep sea offshore wind turbines, and to be an internationally leading research community on offshore wind technology enabling industry partners to be in the forefront.**

***~EUR 40 millions ~USD 60 millions**

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
TU Delft
Massachusetts Institute of Technology
NREL
Nanyang Technological University

Industry partners

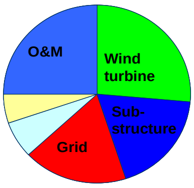
Vestas
Vestavind Offshore
NTE
Statkraft
FEDEM Fedem Technology AS
GE
Statoil
DONG energy
EDF
Statnett
Fugro Oceanor
Devold AMT
SmartMotor
AkerSolutions
DNV

Associate industry partners

NORWEA Norsk vindkraftforening
EnergiNorge
Navitas Network
NCE Instrumentation
enova
Innovation Norway
NVE

Research Challenges

NOWITECH focus area



LPC distribution of offshore wind farm (example)

Key issue: Innovations reducing cost of energy from offshore wind

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Many exciting floating concepts


DeepWind

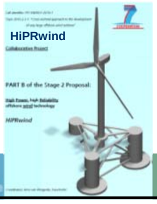

WindFloat


HyWind (2009, 2,3 MW)

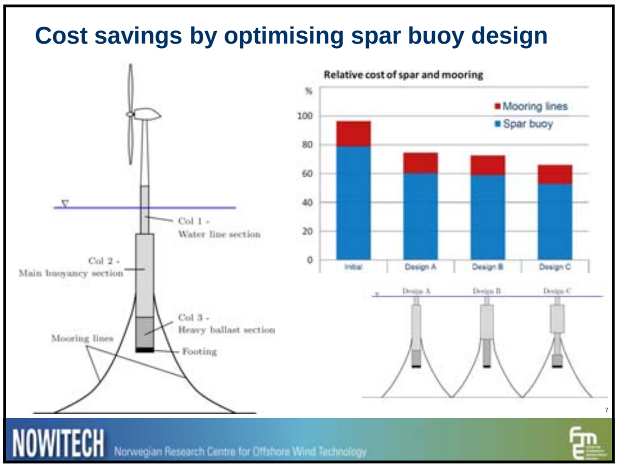

SWAY


WindSea

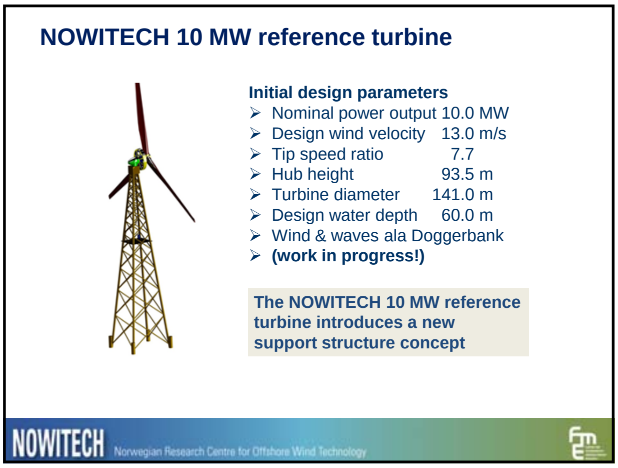

BlueH (2007, 80 kW)


HiPRwind


NREL/MIT



Cost savings by optimising spar buoy design



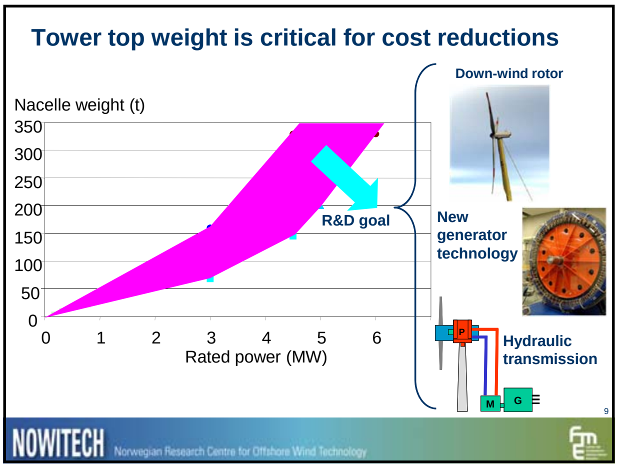
NOWITECH 10 MW reference turbine

Initial design parameters

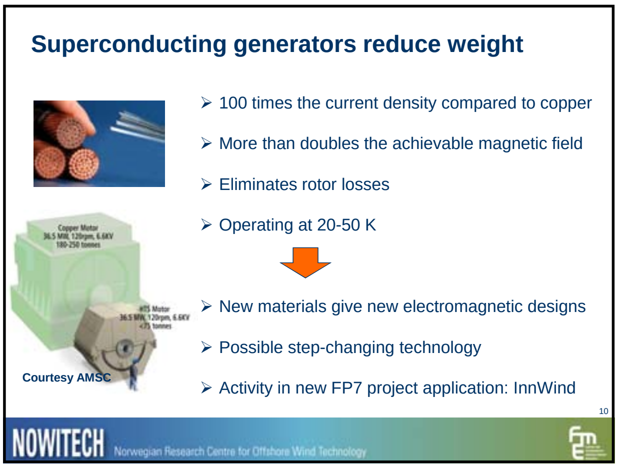
Nominal power output	10.0 MW
Design wind velocity	13.0 m/s
Tip speed ratio	7.7
Hub height	93.5 m
Turbine diameter	141.0 m
Design water depth	60.0 m

- Wind & waves ala Doggerbank
- **(work in progress!)**

The NOWITECH 10 MW reference turbine introduces a new support structure concept



Tower top weight is critical for cost reductions

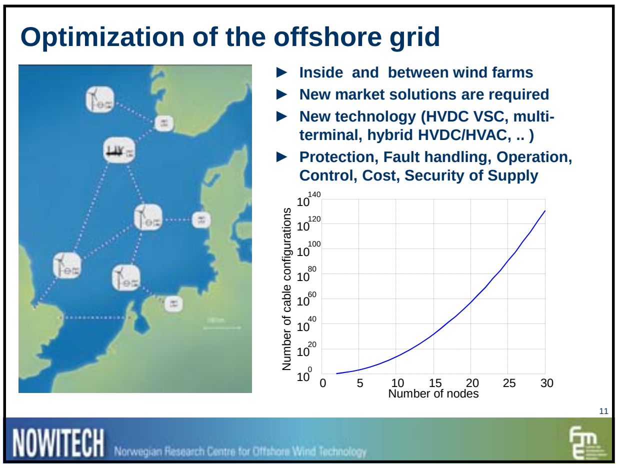


Superconducting generators reduce weight

- 100 times the current density compared to copper
- More than doubles the achievable magnetic field
- Eliminates rotor losses
- Operating at 20-50 K

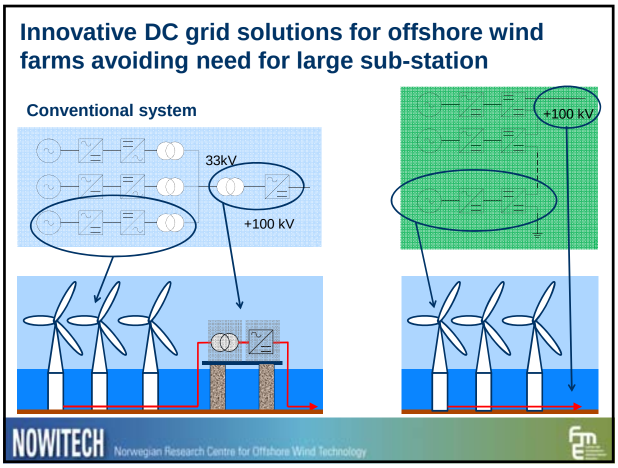
- New materials give new electromagnetic designs
- Possible step-changing technology
- Activity in new FP7 project application: InnWind

Courtesy AMSC

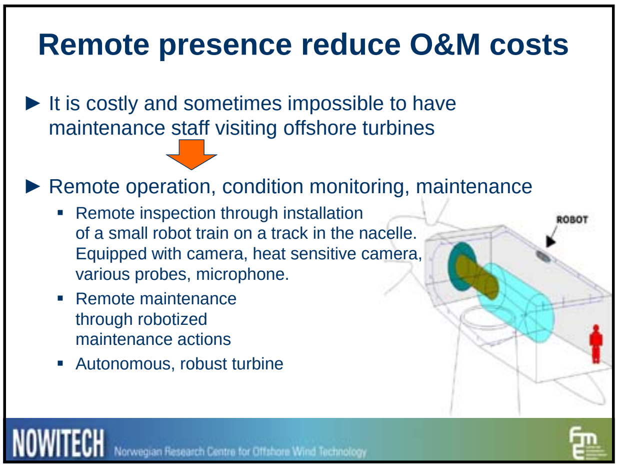


Optimization of the offshore grid

- Inside and between wind farms
- New market solutions are required
- New technology (HVDC VSC, multi-terminal, hybrid HVDC/HVAC, ..)
- Protection, Fault handling, Operation, Control, Cost, Security of Supply

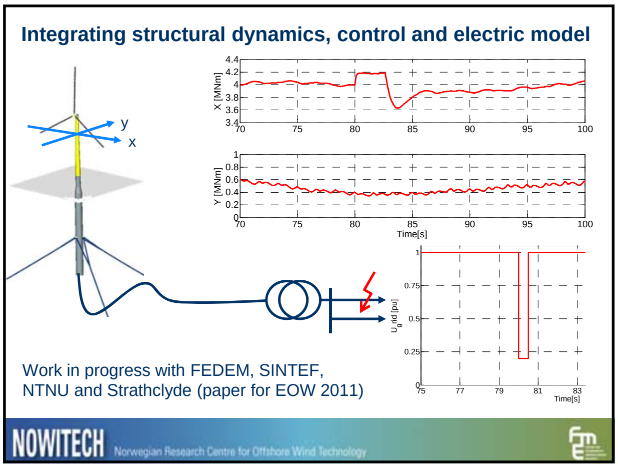


Innovative DC grid solutions for offshore wind farms avoiding need for large sub-station



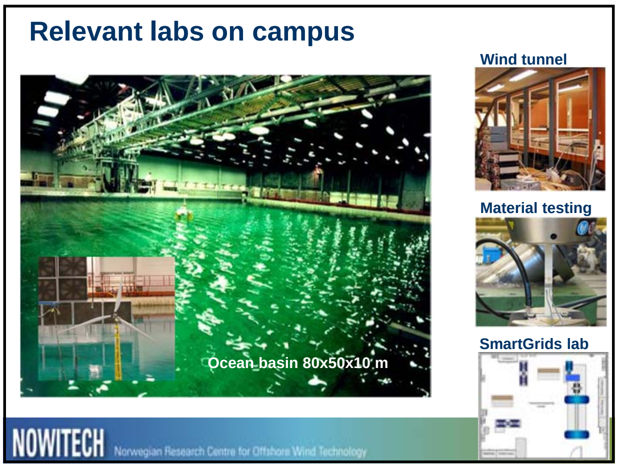
Remote presence reduce O&M costs

- It is costly and sometimes impossible to have maintenance staff visiting offshore turbines
- Remote operation, condition monitoring, maintenance
  - Remote inspection through installation of a small robot train on a track in the nacelle. Equipped with camera, heat sensitive camera, various probes, microphone.
  - Remote maintenance through robotized maintenance actions
  - Autonomous, robust turbine

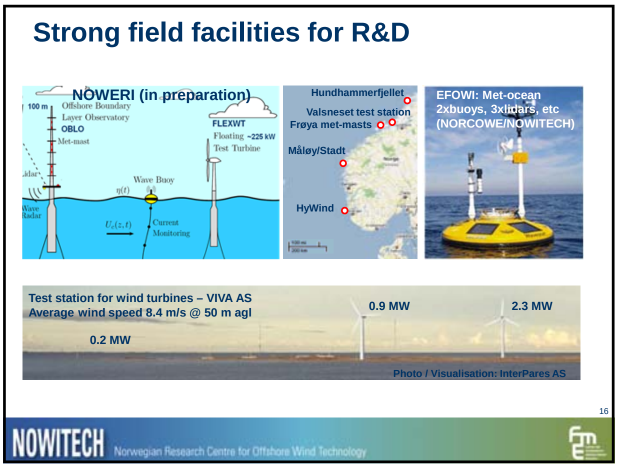


Integrating structural dynamics, control and electric model

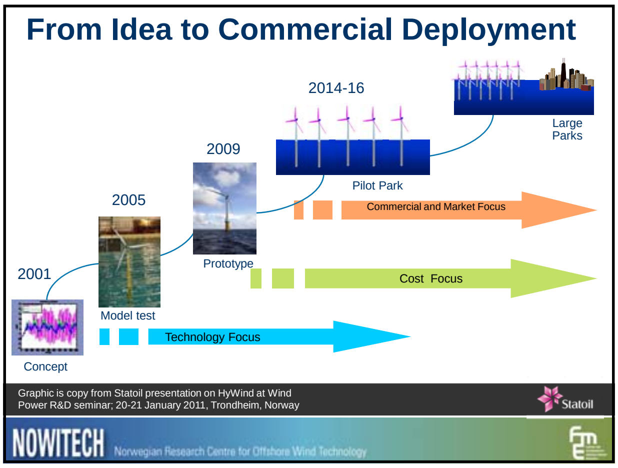
Work in progress with FEDEM, SINTEF, NTNU and Strathclyde (paper for EOW 2011)



Relevant labs on campus



Strong field facilities for R&D



From Idea to Commercial Deployment

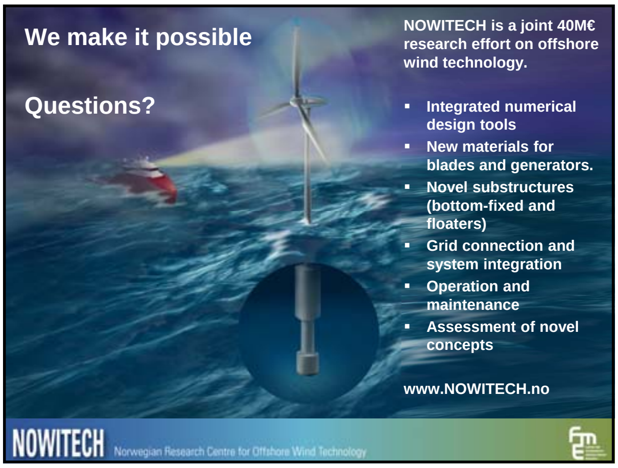
Graphic is copy from Statoil presentation on HyWind at Wind Power R&D seminar; 20-21 January 2011, Trondheim, Norway

THE HAVSUL CONCEPT BY VESTAVIND OFFSHORE

- Norway's only granted license for a full scale offshore wind farm
- 350 MW installed effect – estimated yearly energy production up to 1-1,3 TWh
  - Floatable foundation solutions for fixed offshore wind turbines
  - Inshore assembly of complete windmill including foundation, tower, nacelle and blades
  - Offshore installation in one operation, without the need for special purpose vessels

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
- Test and demonstration, also in large scale, is vital to bring research results into the market place



We make it possible

Questions?

NOWITECH is a joint 40M€ research effort on offshore wind technology.

- **Integrated numerical design tools**
- **New materials for blades and generators.**
- **Novel substructures (bottom-fixed and floaters)**
- **Grid connection and system integration**
- **Operation and maintenance**
- **Assessment of novel concepts**

www.NOWITECH.no

A1 New turbine technology

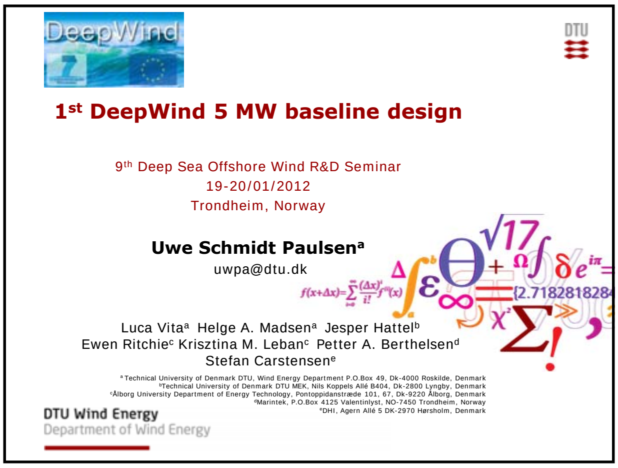
1st DeepWind 5MW baseline design, Uwe S. Paulsen, Risø DTU

A Method for Analysis of VAWT Aerodynamic Loads under Turbulent Wind and Platform Motion, Karl Merz, Post Doc, NTNU

Multi-Rotors; A Solution to 20 MW and Beyond? Mike Branney, PhD stud, Univ. of Strathclyde

Structural design and analysis of a 10 MW wind turbine blade,
Kevin Cox, Phd stud, NTNU

Effect of pitch and safety system design on dimensioning loads for offshore wind turbines during grid fault, Lars Frøyd, PhD stud, NTNU



DeepWind

1st DeepWind 5 MW baseline design

9th Deep Sea Offshore Wind R&D Seminar
19-20/01/2012
Trondheim, Norway

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uwpa@dtu.dk

Luca Vita[a] Helge A. Madsen[a] Jesper Hattel[b]
Ewen Ritchie[c] Krisztina M. Leban[c] Petter A. Berthelsen[d]
Stefan Carstensen[e]

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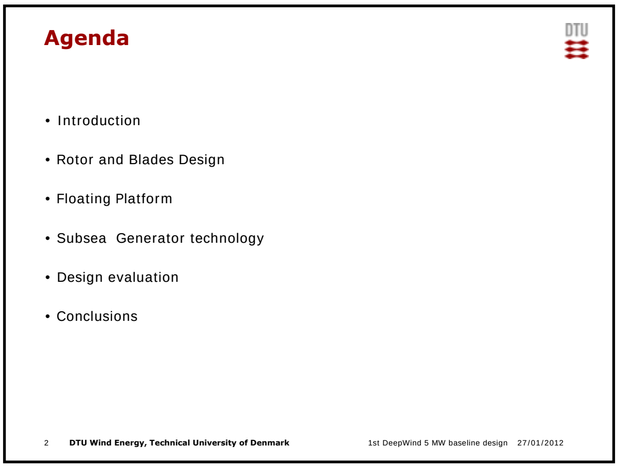
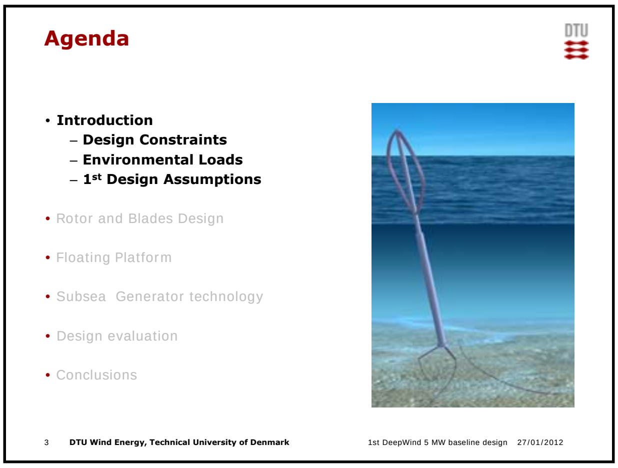
[b]Technical University of Denmark DTU MEK, Nils Koppels Allé B404, Dk-2800 Lyngby, Denmark
[c]Ålborg University Department of Energy Technology, Pontoppidanstræde 101, 67, Dk-9220 Ålborg, Denmark
[d]Marintek, P.O.Box 4125 Valentinlyst, NO-7450 Trondheim, Norway
[e]DHI, Agern Allé 5 DK-2970 Hørsholm, Denmark

DTU Wind Energy
Department of Wind Energy



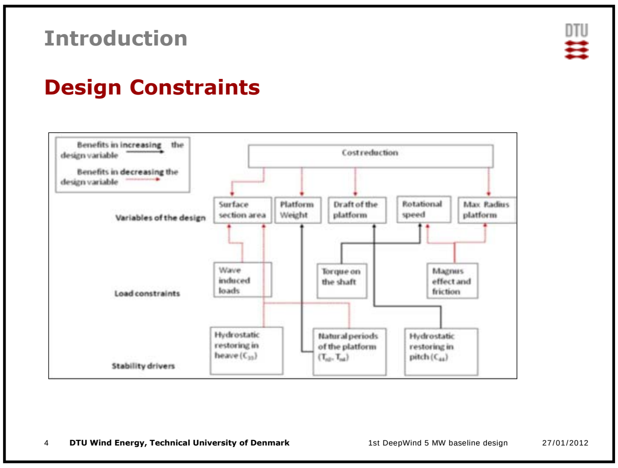
Agenda

- Introduction
- Rotor and Blades Design
- Floating Platform
- Subsea Generator technology
- Design evaluation
- Conclusions



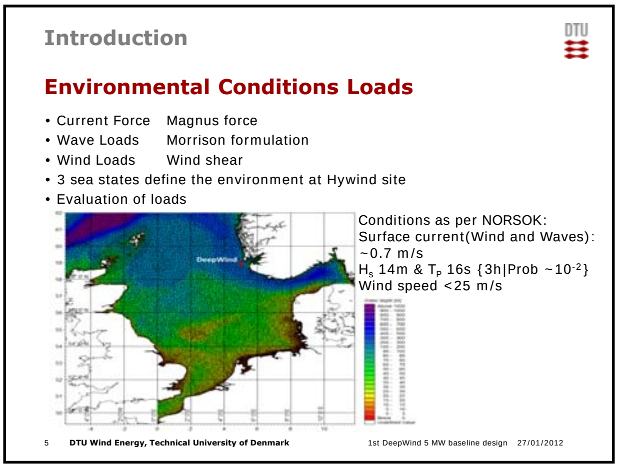
Agenda

- **Introduction**
  - **Design Constraints**
  - **Environmental Loads**
  - **1st Design Assumptions**
- Rotor and Blades Design
- Floating Platform
- Subsea Generator technology
- Design evaluation
- Conclusions



Introduction

Design Constraints

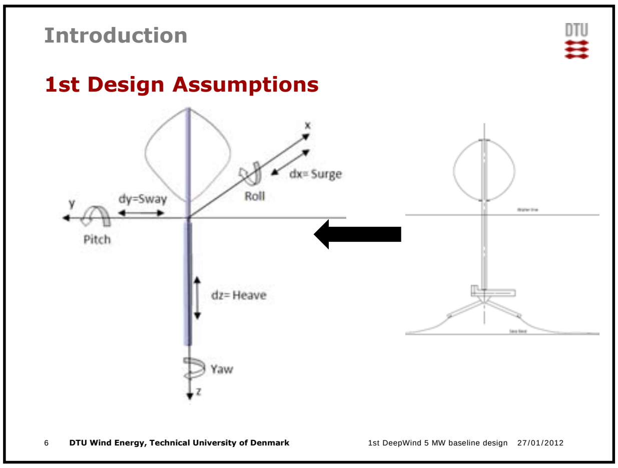


Introduction

Environmental Conditions Loads

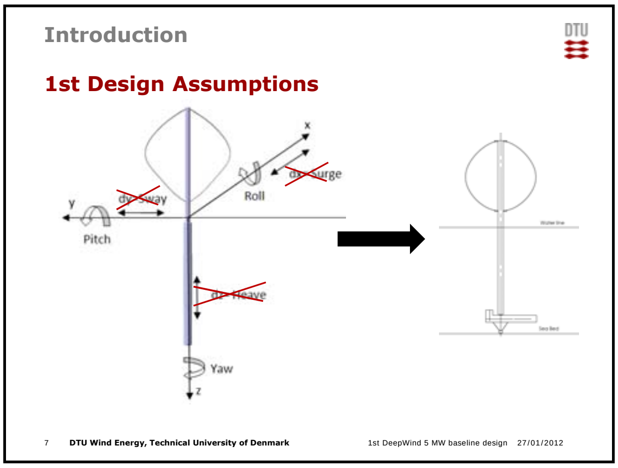
- Current Force Magnus force
- Wave Loads Morrison formulation
- Wind Loads Wind shear
- 3 sea states define the environment at Hywind site
- Evaluation of loads

Conditions as per NORSOK:
Surface current(Wind and Waves):
~0.7 m/s
H_s 14m & T_P 16s {3h|Prob ~10^{-2}}
Wind speed <25 m/s



Introduction

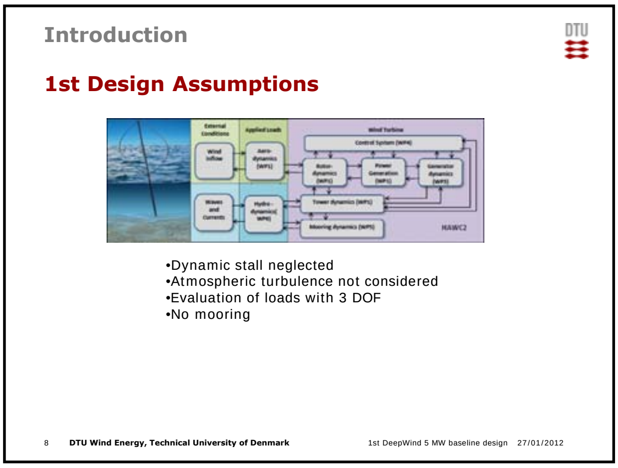
1st Design Assumptions



Introduction

1st Design Assumptions

7 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012



Introduction

1st Design Assumptions

- Dynamic stall neglected
- Atmospheric turbulence not considered
- Evaluation of loads with 3 DOF
- No mooring

8 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012

Agenda

- Introduction
- **Rotor and Blades Design**
  - **Rotor design**
  - **Blade design**
- Floating Platform
- Subsea Generator technology
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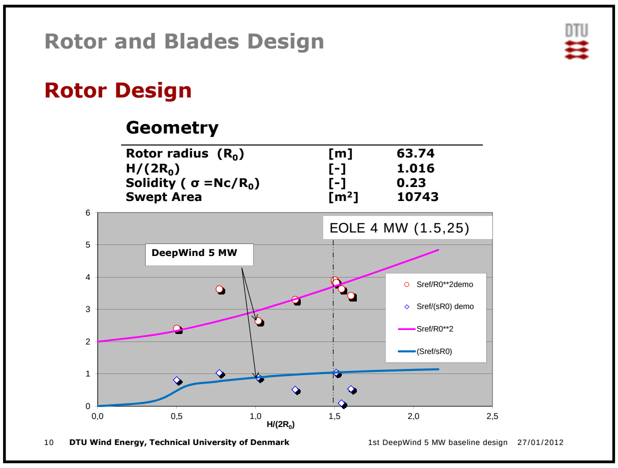
9 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012



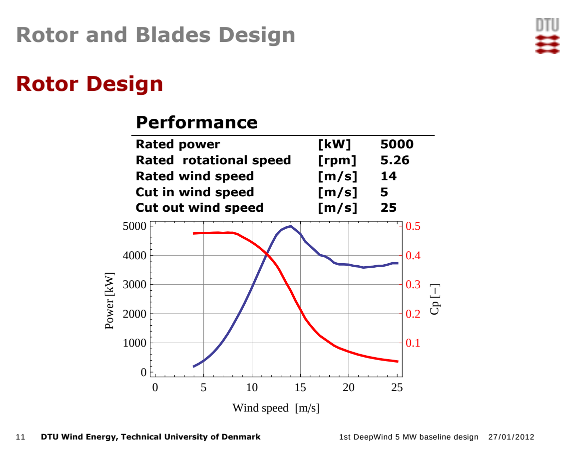
Rotor and Blades Design

Rotor Design

Geometry

Rotor radius (R_0)	**[m]**	**63.74**
$H/(2R_0)$	**[-]**	**1.016**
Solidity ($\sigma = Nc/R_0$)	**[-]**	**0.23**
Swept Area	**[m²]**	**10743**

10 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012



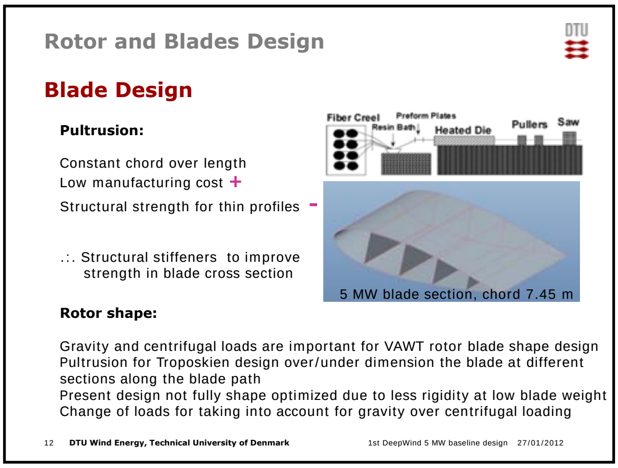
Rotor and Blades Design

Rotor Design

Performance

Rated power	**[kW]**	**5000**
Rated rotational speed	**[rpm]**	**5.26**
Rated wind speed	**[m/s]**	**14**
Cut in wind speed	**[m/s]**	**5**
Cut out wind speed	**[m/s]**	**25**

11 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012



5 MW blade section, chord 7.45 m

Rotor and Blades Design

Blade Design

Pultrusion:

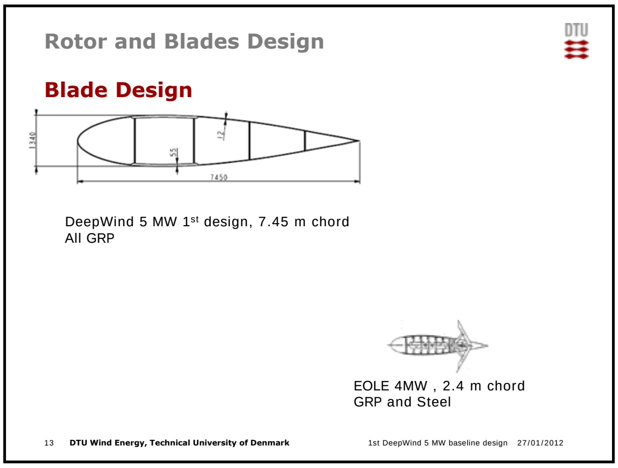
Constant chord over length
Low manufacturing cost +
Structural strength for thin profiles -

.:. Structural stiffeners to improve strength in blade cross section

Rotor shape:

Gravity and centrifugal loads are important for VAWT rotor blade shape design
Pultrusion for Troposkien design over/under dimension the blade at different sections along the blade path
Present design not fully shape optimized due to less rigidity at low blade weight
Change of loads for taking into account for gravity over centrifugal loading

12 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012

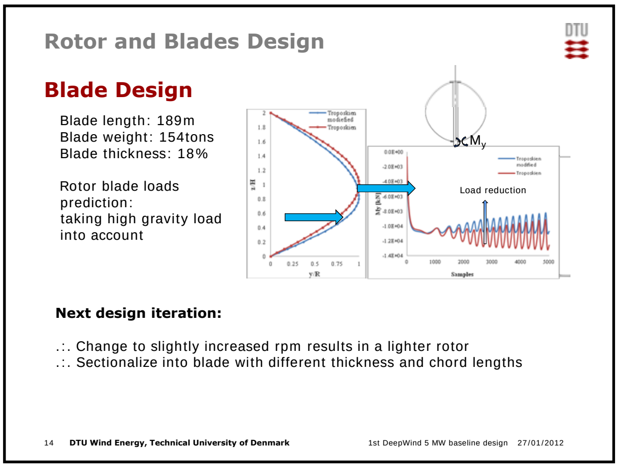


Rotor and Blades Design

Blade Design

DeepWind 5 MW 1st design, 7.45 m chord
All GRP

EOLE 4MW , 2.4 m chord
GRP and Steel



Rotor and Blades Design

Blade Design

Blade length: 189m
Blade weight: 154tons
Blade thickness: 18%

Rotor blade loads prediction:
taking high gravity load into account

Next design iteration:

.:. Change to slightly increased rpm results in a lighter rotor
.:. Sectionalize into blade with different thickness and chord lengths

Agenda

- Introduction
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- **Floating Platform**
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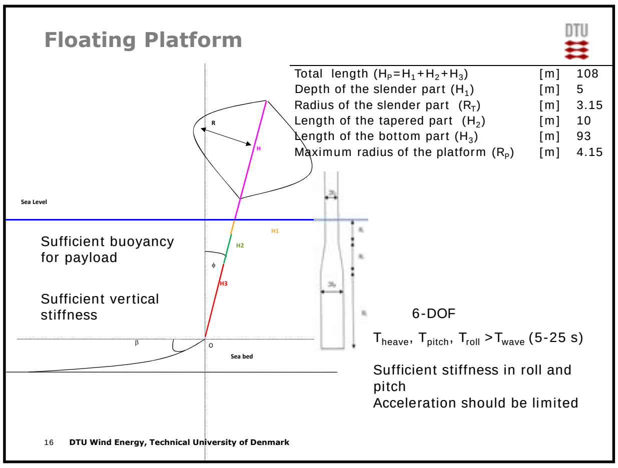
- Design evaluation
- Conclusions



Floating Platform

Total length ($H_P=H_1+H_2+H_3$)	[m]	108
Depth of the slender part (H_1)	[m]	5
Radius of the slender part (R_T)	[m]	3.15
Length of the tapered part (H_2)	[m]	10
Length of the bottom part (H_3)	[m]	93
Maximum radius of the platform (R_P)	[m]	4.15

Sufficient buoyancy for payload

Sufficient vertical stiffness

6-DOF

T_{heave}, T_{pitch}, T_{roll} >T_{wave} (5-25 s)

Sufficient stiffness in roll and pitch
Acceleration should be limited

Agenda

- Introduction
- Rotor and Blades Design
- Floating Platform
- **Subsea Generator technology**
  - **Generator state of the art**
  - **Design approach**
  - **First iteration dimensions of 5 MW direct drive generator**
- Design evaluation
- Conclusions

Subsea Generator technology

Generator state of the art

- possible solutions
  - SCIG - Squirrel Cage Induction Generator (Radial Flux RF)
  - DFIG – Doubly Fed Induction Generator(Radial Flux RF)
  - EESG - Electrically Excited Synchronous Generator (Radial Flux RF)
  - PMSG - PM Synchronous Generator(Radial Flux RF)
  - TFPM - Transverse Flux PM Generator
  - AFPM – Axial Flux PM Generator
- Advantages and disadvantages of candidates were investigated

- SWOT analysis was performed to filter the list down to:
  - ❑Synchronous PM (radial flux)
  - ❑Synchronous Electrically excited (radial flux)
  - ❑Transverse flux PM

Subsea Generator technology

Generator state of the art

- possible solutions
  - SCIG - Squirrel Cage Induction Generator (Radial Flux RF)
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  - ☐Synchronous Electrically excited (radial flux)
  - ☒Transverse flux PM

Subsea Generator technology

DeepWind Generator design approach

- Design algorithms for the machines was implemented in code language
  - Usual design rules for power station generators were applied(also subsea environment)
  - Output from design approach:
    - » Dimensions of generator
    - » Mass of active and inactive materials
    - » Losses
- For given output, the R_P ~RPM^{-1}
- For lower RPM, number of poles increases, so the leakage field (thereby decreasing efficiency). This effect will be minimized by optimization measures of the magnetic field.
- Though cooling conditions are unknown, thermal effects for each candidate are simulated for design rules.
- Power electronic converter features multi kilovolt connection
- Control of shaft speed for control of power flow

Subsea Generator technology

First Iteration Dimension for 5 MW Direct Drive Generator

- 5 MW mechanical power at estimated 5.26 rpm and 9.1 MNm shaft torque render a 400 pole 17.53 Hz transverse flux generator design with a pole pitch of around 7.85cm

  - This corresponds to an air-gap diameter of around 10 m outer diameter of around 10.5 m, with a core length of around 1.4 m.

  - Mass of Copper, Iron and permanent magnet materials of around 90 metric tons

  - Design fits reasonable with the platform design

Agenda

- Introduction
- Rotor and Blades Design
- Floating Platform
- Subsea Generator technology
- **Design Evaluation**
- Conclusions

Design evaluation

- Design of floating turbine and platform system evaluated with HAWC2
  - Combinations of different direction of waves and currents with respect to wind direction for analysis of loads

- Main results:
  - Platform stability shows that the large inertia of the rotor affects the pitch and the roll mode towards a large natural period
  - Rotor inclination less than 12º in combinations of wave and currents relative to wind direction and inclination less than 6º in still water
  - The tower section at sea water level displaces for the most critical situation about 2 tube diameters both along and perpendicular to wind direction, for still water 1.7 and 0.1 tube diameters, respectively
  - Maximum loads calculated occur at the larger values of the wave height (most critical sea state). SF of 2
  - Mean loads are depending on currents direction. SF of 4.

Agenda

- Introduction
- Rotor and Blades Design
- Floating Platform
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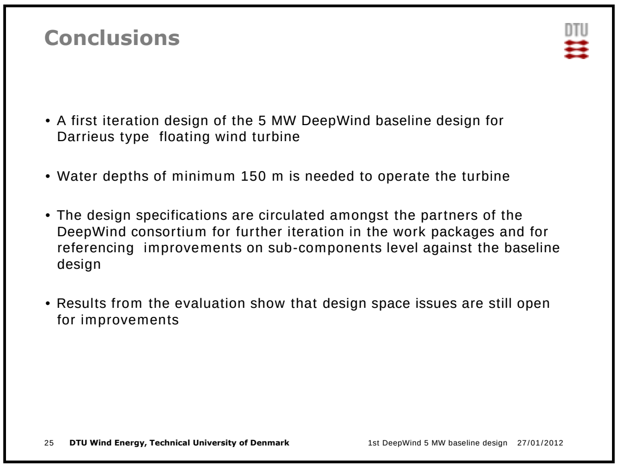
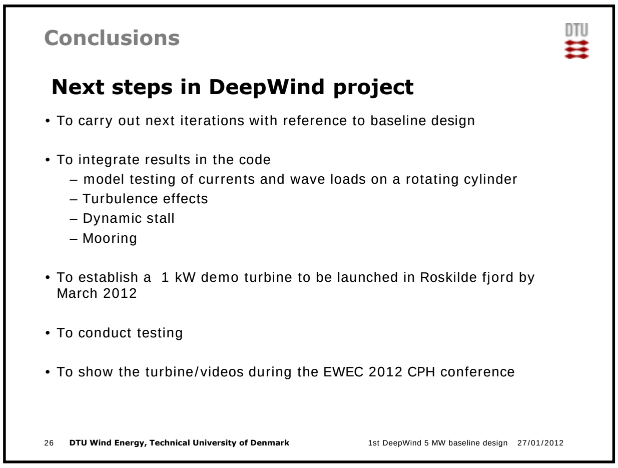
- Design evaluation
- **Conclusions**



Conclusions

- A first iteration design of the 5 MW DeepWind baseline design for Darrieus type floating wind turbine
- Water depths of minimum 150 m is needed to operate the turbine
- The design specifications are circulated amongst the partners of the DeepWind consortium for further iteration in the work packages and for referencing improvements on sub-components level against the baseline design
- Results from the evaluation show that design space issues are still open for improvements

25 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012



Conclusions

Next steps in DeepWind project

- To carry out next iterations with reference to baseline design
- To integrate results in the code
  - model testing of currents and wave loads on a rotating cylinder
  - Turbulence effects
  - Dynamic stall
  - Mooring
- To establish a 1 kW demo turbine to be launched in Roskilde fjord by March 2012
- To conduct testing
- To show the turbine/videos during the EWEC 2012 CPH conference

26 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012

Thanks to
DeepWind consortium
EU

27 **DTU Wind Energy, Technical University of Denmark** 1st DeepWind 5 MW baseline design 27/01/2012

A Method for Analysis of VAWT Aerodynamic Loads under Turbulent Wind and Platform Motion

Karl O. Merz
Department of Civil Engineering
NTNU

9th Deep Sea Offshore Wind R&D Seminar
January 19, 2012

Conclusions

A dynamic inflow method for HAWTs was adapted for VAWTs.

This required the definition of "ghost blades" in order to provide a continuous record of forces (including dynamic stall) for the dynamic inflow calculation.

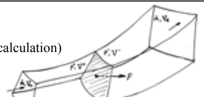
A study of a simplified model of a floating VAWT indicates that dynamic inflow is not required for predicting overall rotor loads and platform motion, in a turbulent windfield.

Dynamic inflow still provides some advantages, namely that iteration is not required to calculate induced velocities.

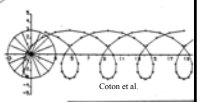
It is numerically stable.

Under anomalous conditions, dynamic inflow provides a smooth (and physically realistic) change in induced velocity under abrupt changes in operating conditions.

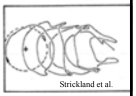
Overview of existing VAWT aerodynamic methods



Blade Element Momentum
- Simple to implement and interpret
  - (can be checked with a hand calculation)
- Implicit representation of the wake

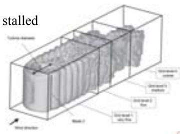


Coton et al.



Strickland et al.

Wake Vortex
- Explicit model of vorticity in the wake
- Superposition of undisturbed flow and induced velocity
- Can be
  - "simple" (prescribed wake)
  - intermediate (free wake – lines, panels)
  - advanced (vorticity transport – cells)
- Advantage over BEM decreases when flow is stalled
  - vortex wake is less well-defined
  - uncertainties in dynamic stall models



Scheurich et al.

Sibuet Watters et al.

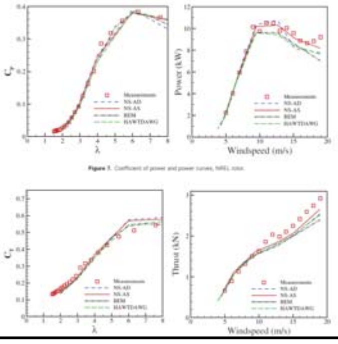
Full flow domain CFD
- Solve Navier Stokes with a turbulence model
- Can be
  - advanced (actuator line or surface)
  - more advanced (blades with boundary layers)

Strickland JH, et al. A vortex model of the Darrieus turbine: an analytical and experimental study. Journal of Fluids Engineering 101 (1979) 500-505. Coton FN, et al. An aerodynamic prediction method for use in vertical axis wind turbine design. Proceedings of the 13th British Wind Energy Association Conference, Swansea, UK, 10-12 April 1991, pp 269-274. Scheurich F, et al. Simulating the aerodynamic performance and wake dynamics of a vertical-axis wind turbine. Wind Energy 14 (2011) 159-177. Sibuet Watters C, et al. Application of the actuator surface concept to wind turbine rotor aerodynamics. Wind Energy 13 (2010) 433-447.

Overview of existing VAWT aerodynamic methods

Key: get a good estimate of induced velocity on the surface swept by the blades, when the windspeed is below rated. (Above rated induced velocity becomes less important.)

I like simple. Use BEM for initial design studies, control system analysis, etc. If needed, refine/verify/certify using more advanced methods.



NREL UAE research turbine (HAWT)

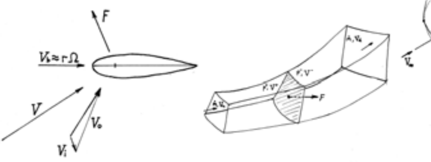
NS-AD: Navier-Stokes, actuator disk
NS-AS: Navier-Stokes, actuator surface
BEM: Blade element momentum
HAWTDAWG: prescribed wake vortex

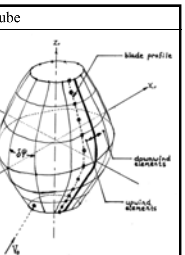
Sibuet Watters C, et al. Application of the actuator surface concept to wind turbine rotor aerodynamics. Wind Energy 13 (2010) 433-447.

BEM for VAWTs: Double-Multiple Streamtube

Single element on the swept surface: induced velocity by momentum balance

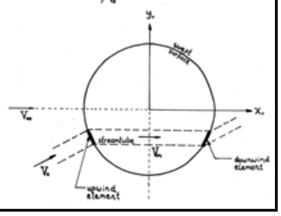
$$F = -2\rho A_e f\ |(V_0 + fV_i)\cdot n|\ V_i$$





"Double-multiple streamtube": assumptions about flow through the rotor interior

(Things get a bit uncertain when local flow is not aligned with the mean wind direction.)



BEM for VAWTs: Existing Implementations for Turbulent Wind; HAWT Dynamic Inflow

Existing VAWT-BEM implementations assume that the induced velocity is either:
- calculated upfront based upon mean flow and thereafter held constant (Homicz)
- or
- calculated iteratively such that the momentum equation is satisfied at each timestep (Malcolm).

$$F = -2\rho A_e f\ |(V_0 + fV_i)\cdot n|\ V_i$$

HAWTs: BEM with **dynamic inflow**

TUDk model (Snel and Schepers):

$$v' + \tau_1 \frac{dv'}{dt} = v_q + 0.6\tau_1 \frac{dv_q}{dt}; \qquad \tau_1 = \frac{1.1}{1-1.3a}\left(\frac{R}{|V_0|}\right) \qquad a = \frac{|V_i|}{|V_0|}.$$

$$v + \tau_2 \frac{dv}{dt} = v'. \qquad \tau_2 = \left[0.39 - 0.26\left(\frac{r}{R}\right)^2\right]\tau_1$$

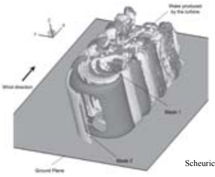
A time-lag on induced velocity which represents wake development
No iteration: $(V_0 + f\,V_i)$ is evaluated based on values from the previous timestep.

Homicz GF. Numerical Simulation of VAWT Stochastic Aerodynamic Loads Produced by Atmospheric Turbulence: VAWT-SAL Code. Report SAND91-1124, Sandia National Laboratories, Albuquerque, NM, USA, 1991. Malcolm DJ. Darrieus rotors subject to turbulent inflow. Engineering Structures 10 (1988) 125-134. Snel H, Schepers JG. Joint Investigation of Dynamic Inflow Effects and Implementation of an Engineering Method. Report ECN-C--94-107, Energy Research Centre of the Netherlands, Petten, The Netherlands, 1995.

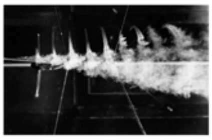
Dynamic Inflow for VAWTs

The HAWT TUDk method was adapted to VAWTs. Same equations, using $r/R = 0.7$

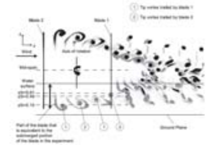
Why should the HAWT model be applicable to VAWTs? Similarity in wake structure.

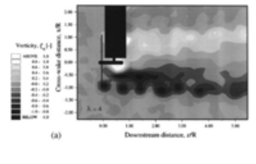


Scheurich et al.



Vermeer et al.





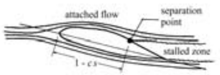
Scheurich F, et al. Simulating the aerodynamic performance and wake dynamics of a vertical-axis wind turbine. Wind Energy 14 (2011) 159-177. Vermeer LJ, et al. Wind turbine wake aerodynamics. Progress in Aerospace Sciences 39 (2003) 467-510.

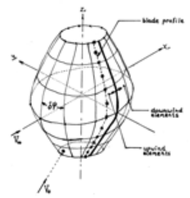
Ghost Blades for Dynamic Inflow Forces

Problem:

The blades need a dynamic stall model that evolves with blade motion.

Dynamic inflow needs a continuous record of forces at fixed locations on the swept surface.





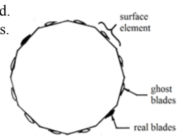
Solution: ghost blades.

Ghost blades rotate about the azimuth just as real blades.

Forces/dynamic stall are calculated at both real and ghost blades.

Forces at the surface elements (dynamic inflow) are interpolated.

Forces for structural analysis are taken only from the real blades.



Dynamic Inflow on Floating VAWTs

Hypothesis:

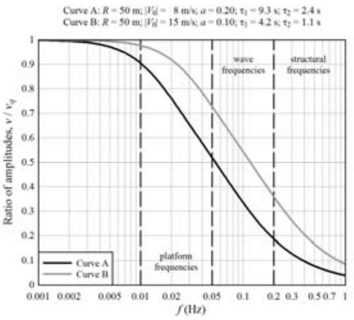
Dynamic inflow might influence the motions of a floating platform.

$$v' + \tau_1 \frac{dv'}{dt} = v_q + 0.6\tau_1 \frac{dv_q}{dt};$$

$$v + \tau_2 \frac{dv}{dt} = v'.$$

$$\tau_1 = \frac{1.1}{1 - 1.3a}\left(\frac{R}{|V_0|}\right)$$

$$\tau_2 = \left[0.39 - 0.26\left(\frac{r}{R}\right)^2\right]\tau_1$$

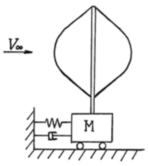


Simple Model of a Floating VAWT

Simple platform model, generic rotor

$D = 130$ m

$M = 5\times10^6$ kg



Turbulent windfield (Mann)

$I = 0.2$

Rigid blades

Simple induction generator

$\Omega = 0.5$ rad/s

$dT/d\Omega = 2\times10^9$ Nms/rad

Time-domain simulation

Mann J. Wind field simulation. Probabilistic Engineering Mechanics 13 (1998) 269-282.

Induced Velocity

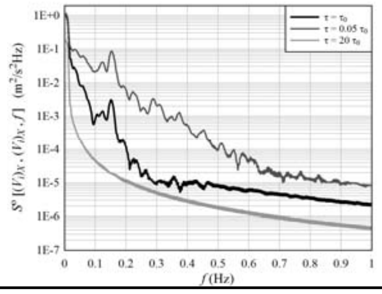
Compare:

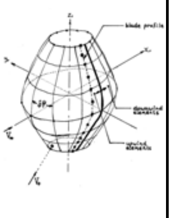
Constant V_i

Dynamic inflow

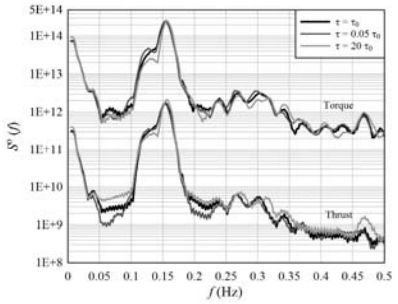
Quasi-steady V_i (as would be obtained by iteration at each timestep)

(Simulated by adjusting the time constants)

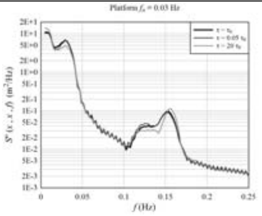


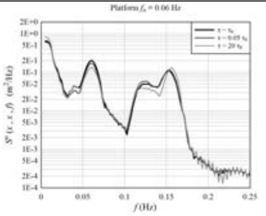


Rotor Load Spectra

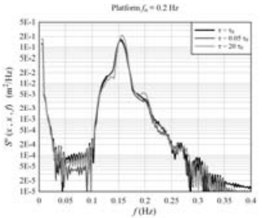


Platform Displacement Spectra





Spring stiffness *K* tuned to give three platform natural frequencies: 0.03, 0.06, 0.20 Hz



Results

Dynamic inflow is not required for predicting overall rotor loads and platform motion, in a turbulent windfield.

This is really nice, because it means that for platform and control system design studies, a table of rotor loads can be generated upfront.

Calculate the average incoming wind velocity vector, including platform motion.
Find the rotor azimuth angle Ψ relative to the average wind velocity vector.
Look up the first couple Fourier components in Ψ, based upon V_∞ and Ω, to find global rotor loads.

Example of torque:

$$T = \overline{T} + T_1 \cos(N_b\Psi + \epsilon_1) + T_2 \cos(2N_b\Psi + \epsilon_2)$$

where $\overline{T}$, T_1, T_2, ϵ_1 and ϵ_2 are functions of V_∞ and Ω, determined as best-fits to BEM time series.

Conclusions

A dynamic inflow method for HAWTs was adapted for VAWTs.

This required the definition of "ghost blades" in order to provide a continuous record of forces (including dynamic stall) for the dynamic inflow calculation.

A study of a simplified model of a floating VAWT indicates that dynamic inflow is not required for predicting overall rotor loads and platform motion, in a turbulent windfield.

Dynamic inflow still provides some advantages, namely that iteration is not required to calculate induced velocities.

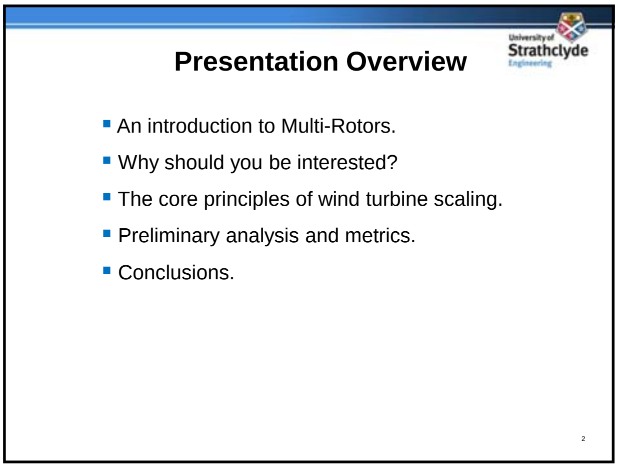
It is numerically stable.

Under anomalous conditions, dynamic inflow provides a smooth (and physically realistic) change in induced velocity under abrupt changes in operating conditions.

Multi-Rotors: A Solution to 20MW and Beyond?

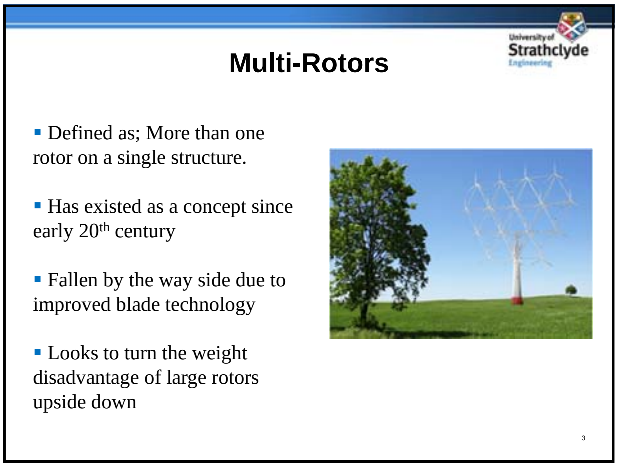
Michael Branney
PhD Student

Wind Energy System Doctoral Training Centre



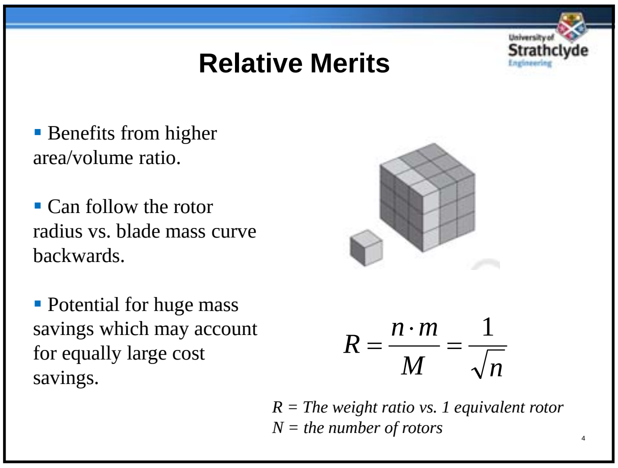
Presentation Overview

- An introduction to Multi-Rotors.
- Why should you be interested?
- The core principles of wind turbine scaling.
- Preliminary analysis and metrics.
- Conclusions.



Multi-Rotors

- Defined as; More than one rotor on a single structure.
- Has existed as a concept since early 20th century
- Fallen by the way side due to improved blade technology
- Looks to turn the weight disadvantage of large rotors upside down

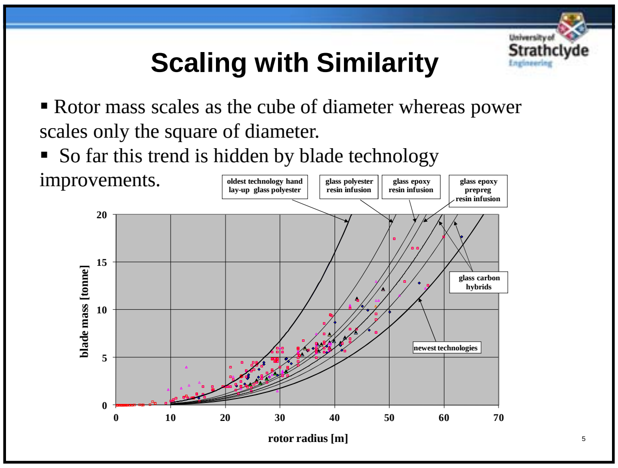


Relative Merits

- Benefits from higher area/volume ratio.
- Can follow the rotor radius vs. blade mass curve backwards.
- Potential for huge mass savings which may account for equally large cost savings.

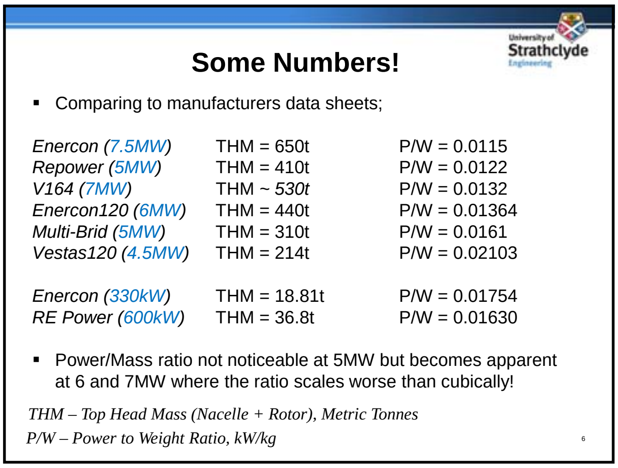
$$R = \frac{n \cdot m}{M} = \frac{1}{\sqrt{n}}$$

R = The weight ratio vs. 1 equivalent rotor
N = the number of rotors



Scaling with Similarity

- Rotor mass scales as the cube of diameter whereas power scales only the square of diameter.
- So far this trend is hidden by blade technology improvements.



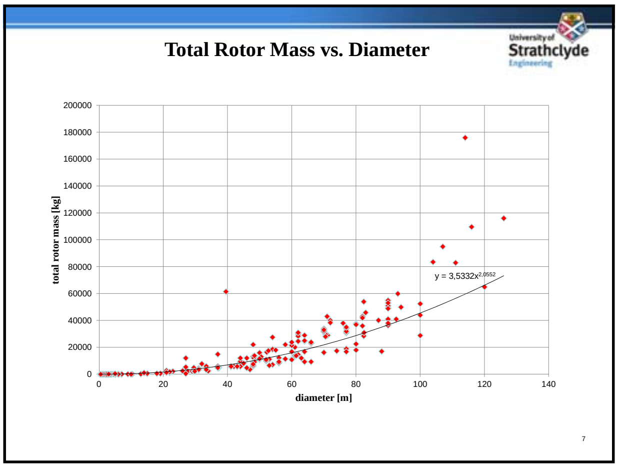
Some Numbers!

- Comparing to manufacturers data sheets;

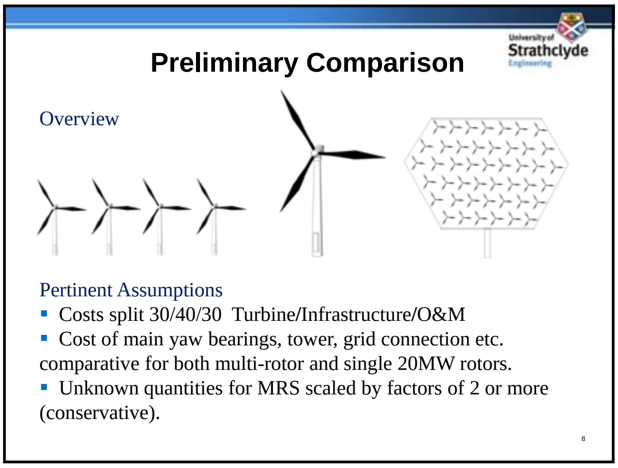
Enercon (7.5MW)	THM = 650t	P/W = 0.0115
Repower (5MW)	THM = 410t	P/W = 0.0122
V164 (7MW)	THM ~ *530t*	P/W = 0.0132
Enercon120 (6MW)	THM = 440t	P/W = 0.01364
Multi-Brid (5MW)	THM = 310t	P/W = 0.0161
Vestas120 (4.5MW)	THM = 214t	P/W = 0.02103
Enercon (330kW)	THM = 18.81t	P/W = 0.01754
RE Power (600kW)	THM = 36.8t	P/W = 0.01630

- Power/Mass ratio not noticeable at 5MW but becomes apparent at 6 and 7MW where the ratio scales worse than cubically!

THM – Top Head Mass (Nacelle + Rotor), Metric Tonnes
P/W – Power to Weight Ratio, kW/kg



Total Rotor Mass vs. Diameter

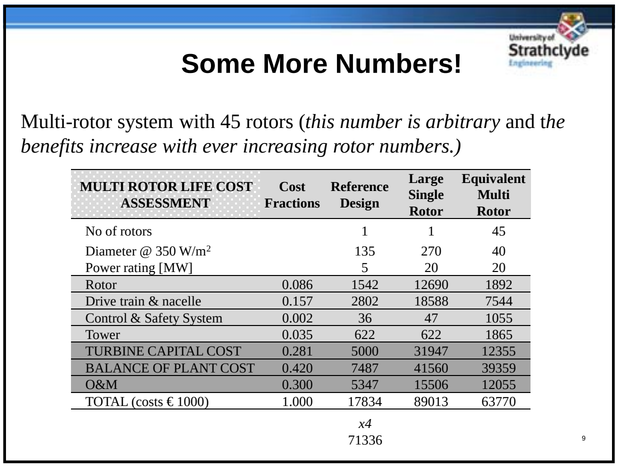


Preliminary Comparison

Overview

Pertinent Assumptions

- Costs split 30/40/30 Turbine/Infrastructure/O&M
- Cost of main yaw bearings, tower, grid connection etc. comparative for both multi-rotor and single 20MW rotors.
- Unknown quantities for MRS scaled by factors of 2 or more (conservative).



Some More Numbers!

Multi-rotor system with 45 rotors (*this number is arbitrary* and *the benefits increase with ever increasing rotor numbers.)*

MULTI ROTOR LIFE COST ASSESSMENT	Cost Fractions	Reference Design	Large Single Rotor	Equivalent Multi Rotor
No of rotors		1	1	45
Diameter @ 350 W/m^2		135	270	40
Power rating [MW]		5	20	20
Rotor	0.086	1542	12690	1892
Drive train & nacelle	0.157	2802	18588	7544
Control & Safety System	0.002	36	47	1055
Tower	0.035	622	622	1865
TURBINE CAPITAL COST	0.281	5000	31947	12355
BALANCE OF PLANT COST	0.420	7487	41560	39359
O&M	0.300	5347	15506	12055
TOTAL (costs € 1000)	1.000	17834	89013	63770

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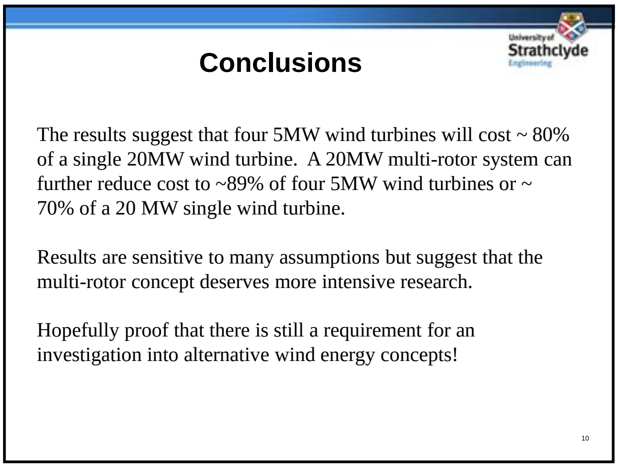
71336

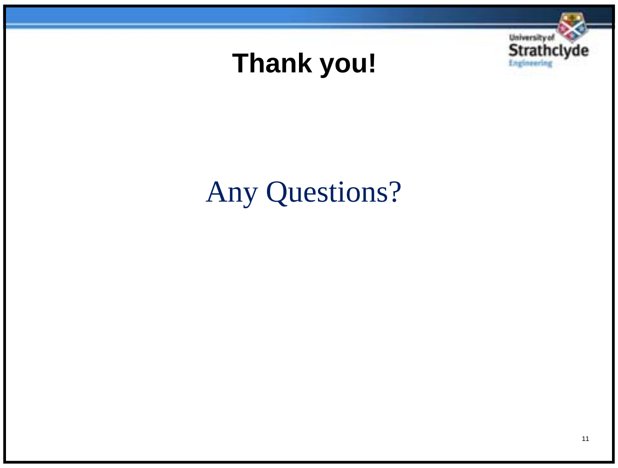


Conclusions

The results suggest that four 5MW wind turbines will cost ~ 80% of a single 20MW wind turbine. A 20MW multi-rotor system can further reduce cost to ~89% of four 5MW wind turbines or ~ 70% of a 20 MW single wind turbine.

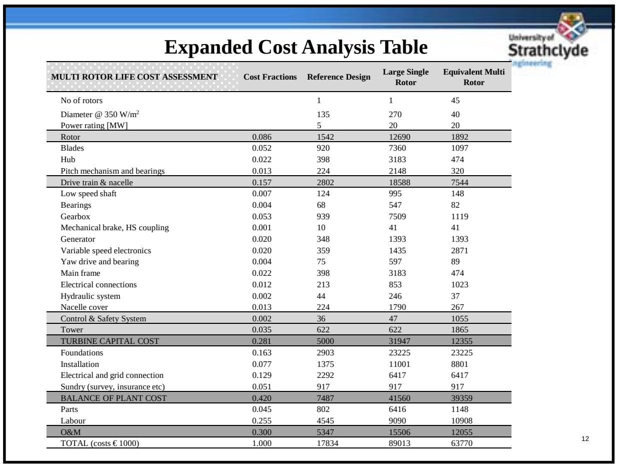
Results are sensitive to many assumptions but suggest that the multi-rotor concept deserves more intensive research.

Hopefully proof that there is still a requirement for an investigation into alternative wind energy concepts!



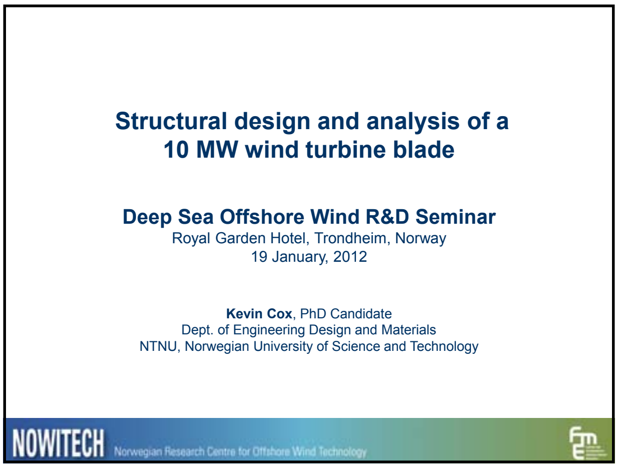
Thank you!

Any Questions?



Expanded Cost Analysis Table

MULTI ROTOR LIFE COST ASSESSMENT	Cost Fractions	Reference Design	Large Single Rotor	Equivalent Multi Rotor
No of rotors		1	1	45
Diameter @ 350 W/m^2		135	270	40
Power rating [MW]		5	20	20
Rotor	0.086	1542	12690	1892
Blades	0.052	920	7360	1097
Hub	0.022	398	3183	474
Pitch mechanism and bearings	0.013	224	2148	320
Drive train & nacelle	0.157	2802	18588	7544
Low speed shaft	0.007	124	995	148
Bearings	0.004	68	547	82
Gearbox	0.053	939	7509	1119
Mechanical brake, HS coupling	0.001	10	41	41
Generator	0.020	348	1393	1393
Variable speed electronics	0.020	359	1435	2871
Yaw drive and bearing	0.004	75	597	89
Main frame	0.022	398	3183	474
Electrical connections	0.012	213	853	1023
Hydraulic system	0.002	44	246	37
Nacelle cover	0.013	224	1790	267
Control & Safety System	0.002	36	47	1055
Tower	0.035	622	622	1865
TURBINE CAPITAL COST	0.281	5000	31947	12355
Foundations	0.163	2903	23225	23225
Installation	0.077	1375	11001	8801
Electrical and grid connection	0.129	2292	6417	6417
Sundry (survey, insurance etc)	0.051	917	917	917
BALANCE OF PLANT COST	0.420	7487	41560	39359
Parts	0.045	802	6416	1148
Labour	0.255	4545	9090	10908
O&M	0.300	5347	15506	12055
TOTAL (costs € 1000)	1.000	17834	89013	63770

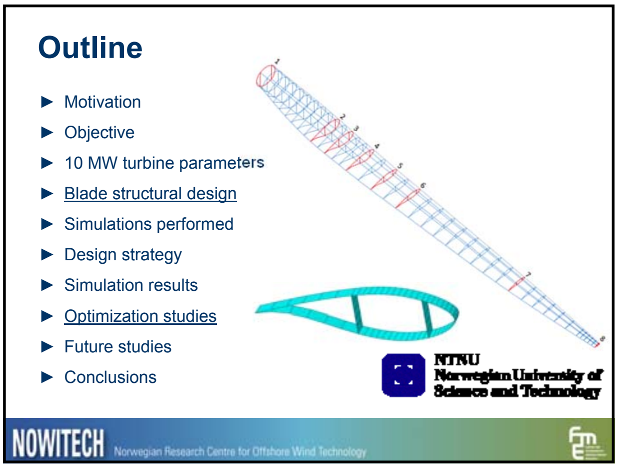


Structural design and analysis of a 10 MW wind turbine blade

Deep Sea Offshore Wind R&D Seminar

Royal Garden Hotel, Trondheim, Norway
19 January, 2012

Kevin Cox, PhD Candidate
Dept. of Engineering Design and Materials
NTNU, Norwegian University of Science and Technology



Outline

- ► Motivation
- ► Objective
- ► 10 MW turbine parameters
- ► Blade structural design
- ► Simulations performed
- ► Design strategy
- ► Simulation results
- ► Optimization studies
- ► Future studies
- ► Conclusions

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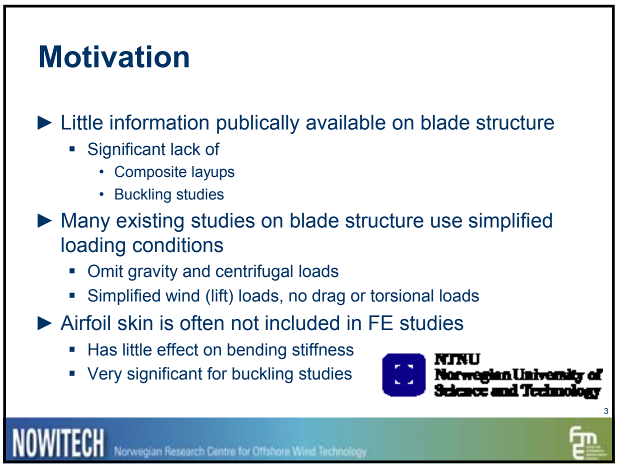

Motivation

- ► Little information publically available on blade structure
  - Significant lack of
    - Composite layups
    - Buckling studies
- ► Many existing studies on blade structure use simplified loading conditions
  - Omit gravity and centrifugal loads
  - Simplified wind (lift) loads, no drag or torsional loads
- ► Airfoil skin is often not included in FE studies
  - Has little effect on bending stiffness
  - Very significant for buckling studies

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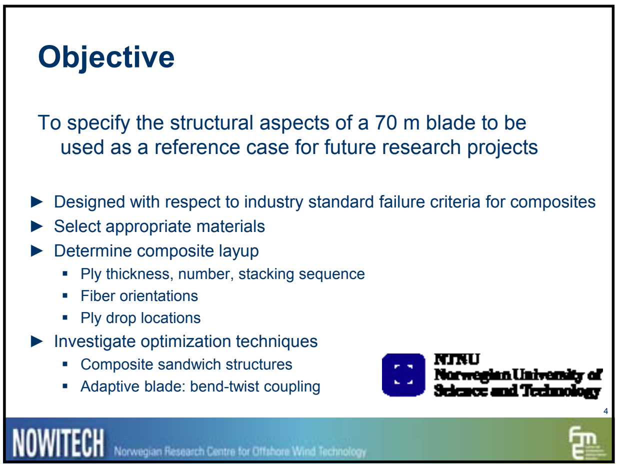

Objective

To specify the structural aspects of a 70 m blade to be used as a reference case for future research projects

- ► Designed with respect to industry standard failure criteria for composites
- ► Select appropriate materials
- ► Determine composite layup
  - Ply thickness, number, stacking sequence
  - Fiber orientations
  - Ply drop locations
- ► Investigate optimization techniques
  - Composite sandwich structures
  - Adaptive blade: bend-twist coupling

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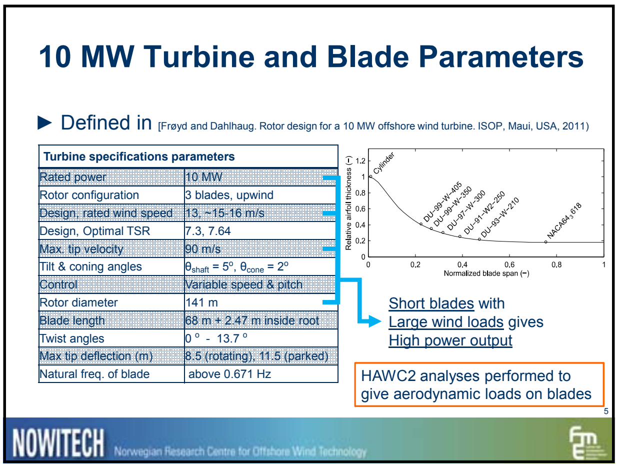


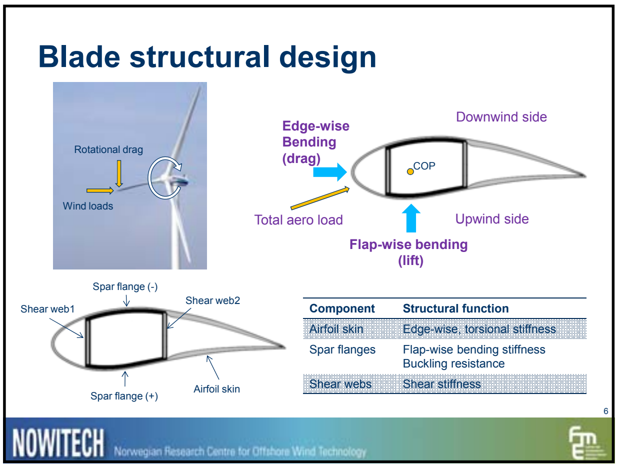
10 MW Turbine and Blade Parameters

► Defined in [Frøyd and Dahlhaug. Rotor design for a 10 MW offshore wind turbine. ISOP, Maui, USA, 2011)

Turbine specifications parameters	
Rated power	10 MW
Rotor configuration	3 blades, upwind
Design, rated wind speed	13, ~15-16 m/s
Design, Optimal TSR	7.3, 7.64
Max. tip velocity	90 m/s
Tilt & coning angles	$\theta_{shaft} = 5^o$, $\theta_{cone} = 2^o$
Control	Variable speed & pitch
Rotor diameter	141 m
Blade length	68 m + 2.47 m inside root
Twist angles	0 ° - 13.7 °
Max tip deflection (m)	8.5 (rotating), 11.5 (parked)
Natural freq. of blade	above 0.671 Hz

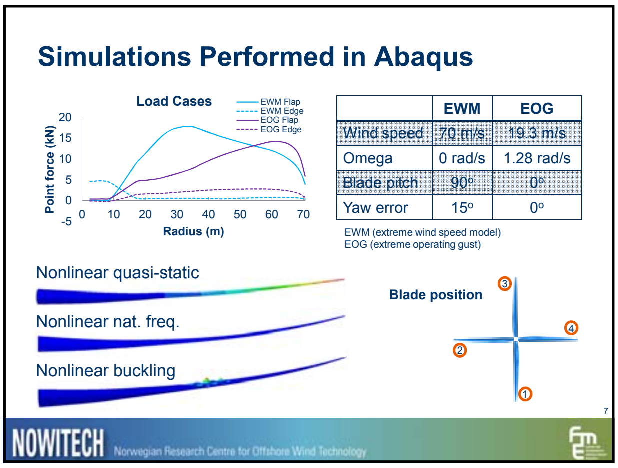
Short blades with Large wind loads gives High power output

HAWC2 analyses performed to give aerodynamic loads on blades



Blade structural design

Component	Structural function
Airfoil skin	Edge-wise, torsional stiffness
Spar flanges	Flap-wise bending stiffness Buckling resistance
Shear webs	Shear stiffness



Simulations Performed in Abaqus

	EWM	EOG
Wind speed	70 m/s	19.3 m/s
Omega	0 rad/s	1.28 rad/s
Blade pitch	90°	0°
Yaw error	15°	0°

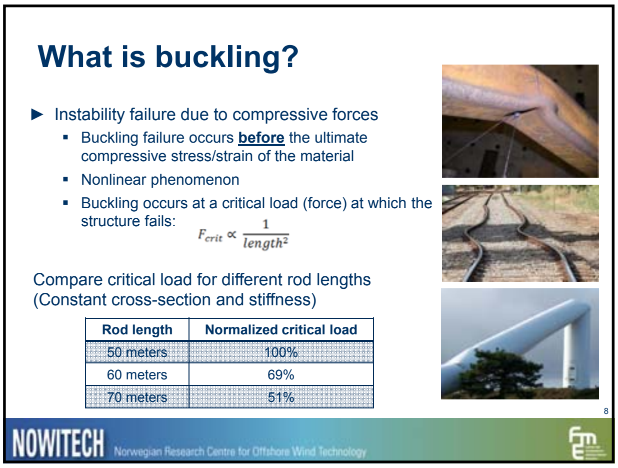
EWM (extreme wind speed model)
EOG (extreme operating gust)

Nonlinear quasi-static

Nonlinear nat. freq.

Nonlinear buckling

Blade position



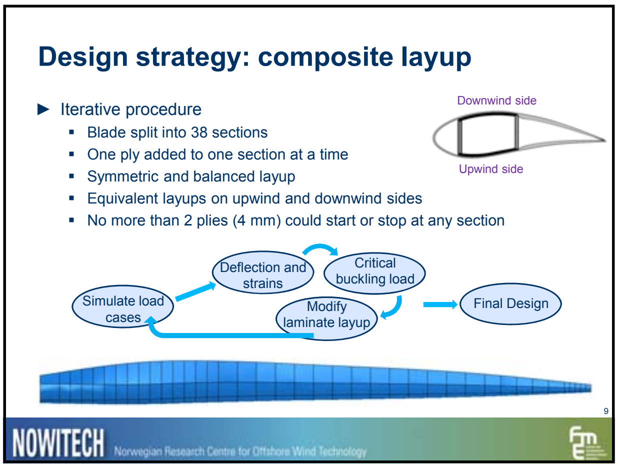
What is buckling?

- Instability failure due to compressive forces
  - Buckling failure occurs **before** the ultimate compressive stress/strain of the material
  - Nonlinear phenomenon
  - Buckling occurs at a critical load (force) at which the structure fails:

$$F_{crit} \propto \frac{1}{length^2}$$

Compare critical load for different rod lengths
(Constant cross-section and stiffness)

Rod length	Normalized critical load
50 meters	100%
60 meters	69%
70 meters	51%



Design strategy: composite layup

- Iterative procedure
  - Blade split into 38 sections
  - One ply added to one section at a time
  - Symmetric and balanced layup
  - Equivalent layups on upwind and downwind sides
  - No more than 2 plies (4 mm) could start or stop at any section

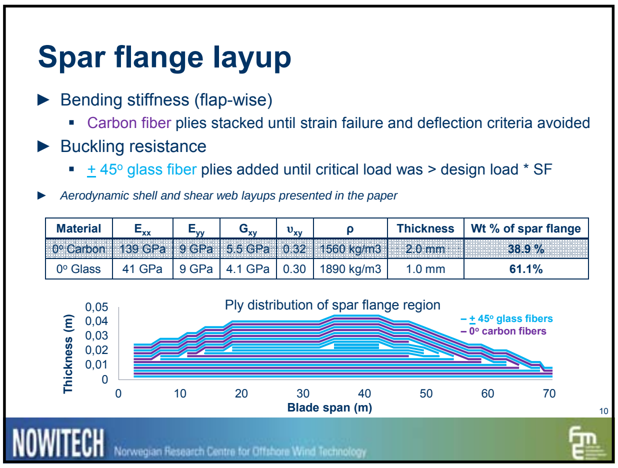
Simulate load cases

Deflection and strains

Critical buckling load

Modify laminate layup

Final Design

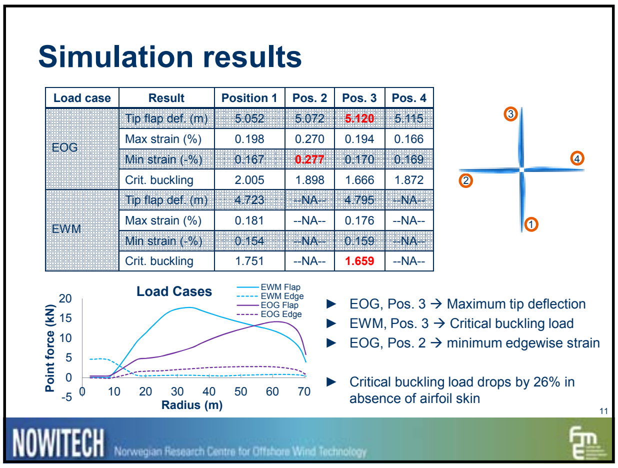


Spar flange layup

- Bending stiffness (flap-wise)
  - Carbon fiber plies stacked until strain failure and deflection criteria avoided
- Buckling resistance
  - ± 45° glass fiber plies added until critical load was > design load * SF
- *Aerodynamic shell and shear web layups presented in the paper*

Material	E_{xx}	E_{yy}	G_{xy}	υ_{xy}	ρ	Thickness	Wt % of spar flange
0° Carbon	139 GPa	9 GPa	5.5 GPa	0.32	1560 kg/m3	2.0 mm	**38.9 %**
0° Glass	41 GPa	9 GPa	4.1 GPa	0.30	1890 kg/m3	1.0 mm	**61.1%**

Ply distribution of spar flange region

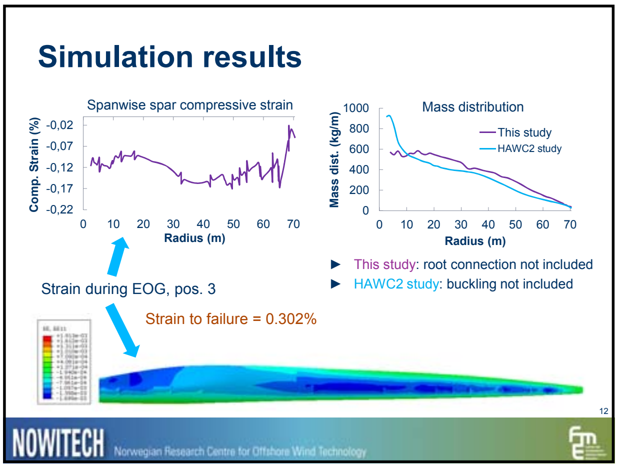


Simulation results

Load case	Result	Position 1	Pos. 2	Pos. 3	Pos. 4
EOG	Tip flap def. (m)	5.052	5.072	5.120	5.115
	Max strain (%)	0.198	0.270	0.194	0.166
	Min strain (-%)	0.167	0.277	0.170	0.169
	Crit. buckling	2.005	1.898	1.666	1.872
EWM	Tip flap def. (m)	4.723	--NA--	4.795	--NA--
	Max strain (%)	0.181	--NA--	0.176	--NA--
	Min strain (-%)	0.154	--NA--	0.159	--NA--
	Crit. buckling	1.751	--NA--	**1.659**	--NA--

- EOG, Pos. 3 → Maximum tip deflection
- EWM, Pos. 3 → Critical buckling load
- EOG, Pos. 2 → minimum edgewise strain

- Critical buckling load drops by 26% in absence of airfoil skin

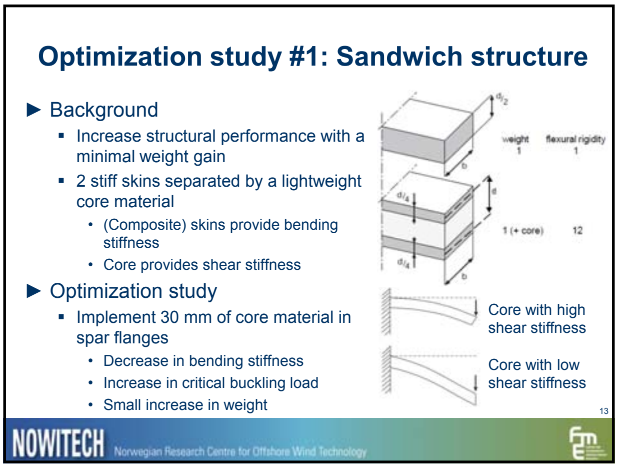


Simulation results

- This study: root connection not included
- HAWC2 study: buckling not included

Strain during EOG, pos. 3

Strain to failure = 0.302%

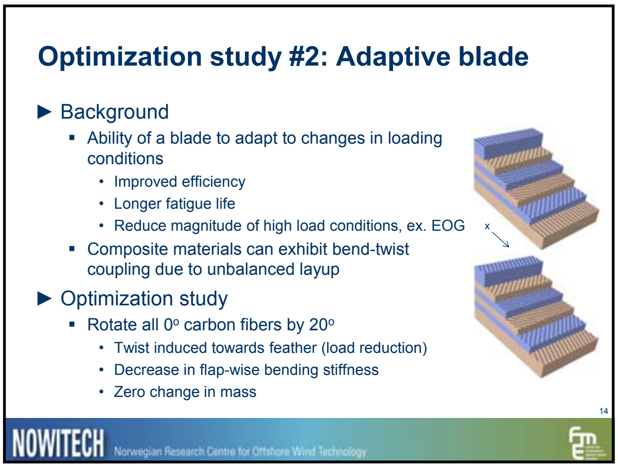


Optimization study #1: Sandwich structure

- ▶ Background
  - Increase structural performance with a minimal weight gain
  - 2 stiff skins separated by a lightweight core material
    - (Composite) skins provide bending stiffness
    - Core provides shear stiffness
- ▶ Optimization study
  - Implement 30 mm of core material in spar flanges
    - Decrease in bending stiffness
    - Increase in critical buckling load
    - Small increase in weight

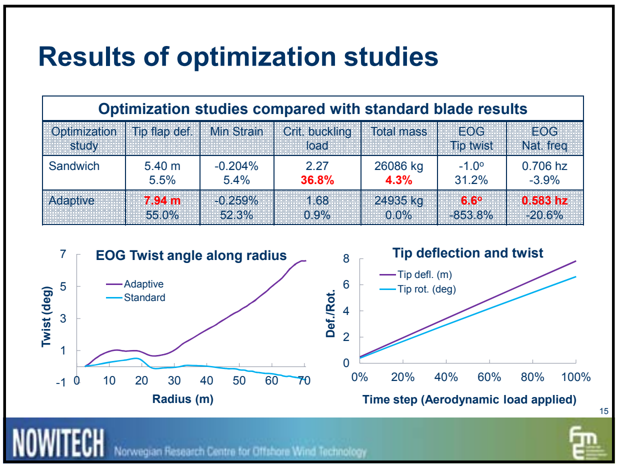
Core with high shear stiffness

Core with low shear stiffness



Optimization study #2: Adaptive blade

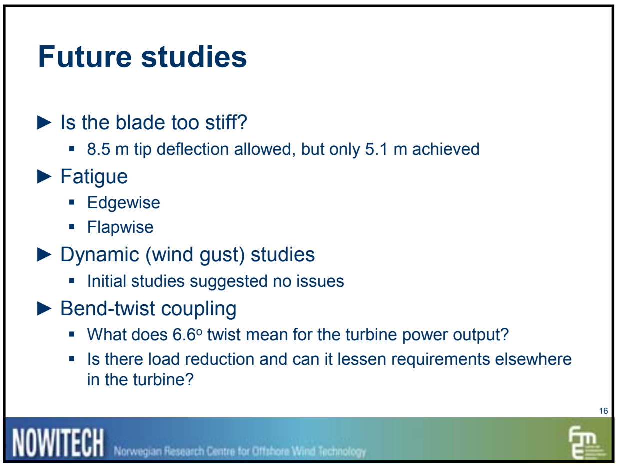
- ▶ Background
  - Ability of a blade to adapt to changes in loading conditions
    - Improved efficiency
    - Longer fatigue life
    - Reduce magnitude of high load conditions, ex. EOG
  - Composite materials can exhibit bend-twist coupling due to unbalanced layup
- ▶ Optimization study
  - Rotate all 0° carbon fibers by 20°
    - Twist induced towards feather (load reduction)
    - Decrease in flap-wise bending stiffness
    - Zero change in mass



Results of optimization studies

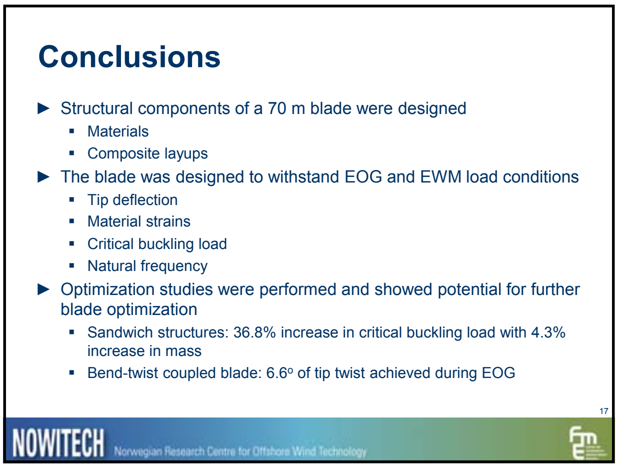
Optimization studies compared with standard blade results

Optimization study	Tip flap def.	Min Strain	Crit. buckling load	Total mass	EOG Tip twist	EOG Nat. freq
Sandwich	5.40 m 5.5%	-0.204% 5.4%	2.27 **36.8%**	26086 kg **4.3%**	-1.0° 31.2%	0.706 hz -3.9%
Adaptive	**7.94 m** 55.0%	-0.259% 52.3%	1.68 0.9%	24935 kg 0.0%	**6.6°** -853.8%	**0.583 hz** -20.6%



Future studies

- ▶ Is the blade too stiff?
  - 8.5 m tip deflection allowed, but only 5.1 m achieved
- ▶ Fatigue
  - Edgewise
  - Flapwise
- ▶ Dynamic (wind gust) studies
  - Initial studies suggested no issues
- ▶ Bend-twist coupling
  - What does 6.6° twist mean for the turbine power output?
  - Is there load reduction and can it lessen requirements elsewhere in the turbine?



Conclusions

- ▶ Structural components of a 70 m blade were designed
  - Materials
  - Composite layups
- ▶ The blade was designed to withstand EOG and EWM load conditions
  - Tip deflection
  - Material strains
  - Critical buckling load
  - Natural frequency
- ▶ Optimization studies were performed and showed potential for further blade optimization
  - Sandwich structures: 36.8% increase in critical buckling load with 4.3% increase in mass
  - Bend-twist coupled blade: 6.6° of tip twist achieved during EOG

Questions

Thank you for your attention!

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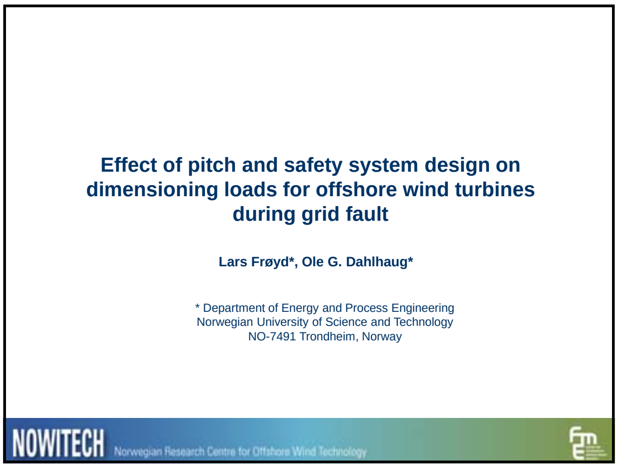

Effect of pitch and safety system design on dimensioning loads for offshore wind turbines during grid fault

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Norwegian University of Science and Technology
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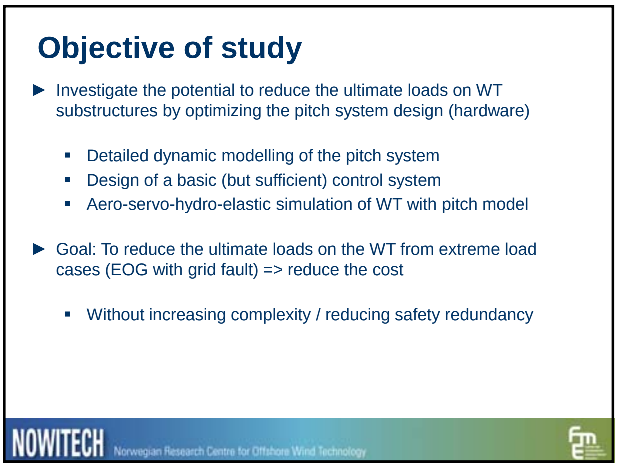
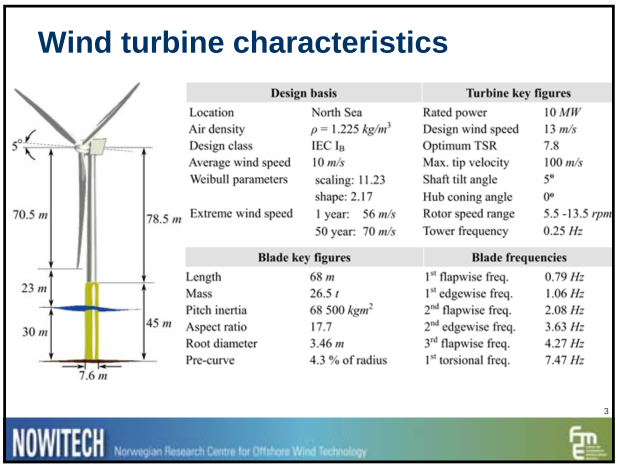


Objective of study

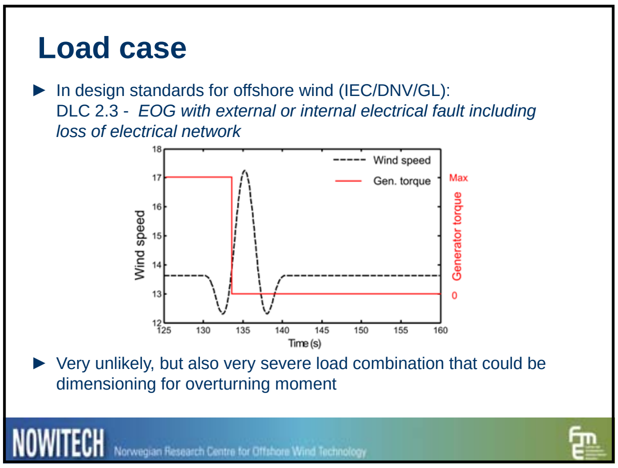
- Investigate the potential to reduce the ultimate loads on WT substructures by optimizing the pitch system design (hardware)
    - Detailed dynamic modelling of the pitch system
    - Design of a basic (but sufficient) control system
    - Aero-servo-hydro-elastic simulation of WT with pitch model
- Goal: To reduce the ultimate loads on the WT from extreme load cases (EOG with grid fault) => reduce the cost
    - Without increasing complexity / reducing safety redundancy



Wind turbine characteristics

Design basis		Turbine key figures	
Location	North Sea	Rated power	10 *MW*
Air density	$\rho = 1.225\ kg/m^3$	Design wind speed	13 *m/s*
Design class	IEC I_B	Optimum TSR	7.8
Average wind speed	10 *m/s*	Max. tip velocity	100 *m/s*
Weibull parameters	scaling: 11.23	Shaft tilt angle	5°
	shape: 2.17	Hub coning angle	0°
Extreme wind speed	1 year: 56 *m/s*	Rotor speed range	5.5 -13.5 *rpm*
	50 year: 70 *m/s*	Tower frequency	0.25 *Hz*

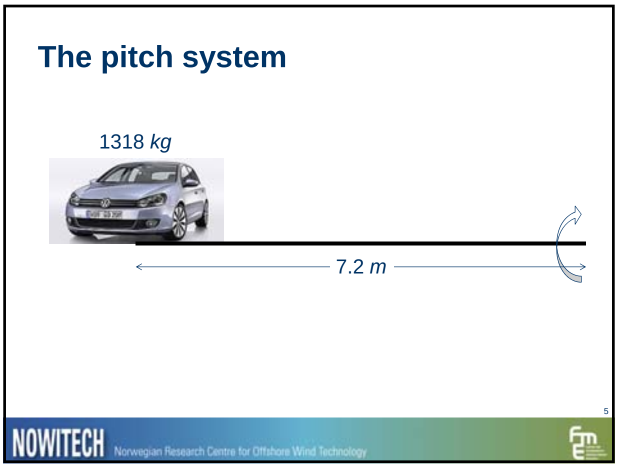
Blade key figures		Blade frequencies	
Length	68 *m*	1st flapwise freq.	0.79 *Hz*
Mass	26.5 *t*	1st edgewise freq.	1.06 *Hz*
Pitch inertia	68 500 kgm^2	2nd flapwise freq.	2.08 *Hz*
Aspect ratio	17.7	2nd edgewise freq.	3.63 *Hz*
Root diameter	3.46 *m*	3rd flapwise freq.	4.27 *Hz*
Pre-curve	4.3 % of radius	1st torsional freq.	7.47 *Hz*



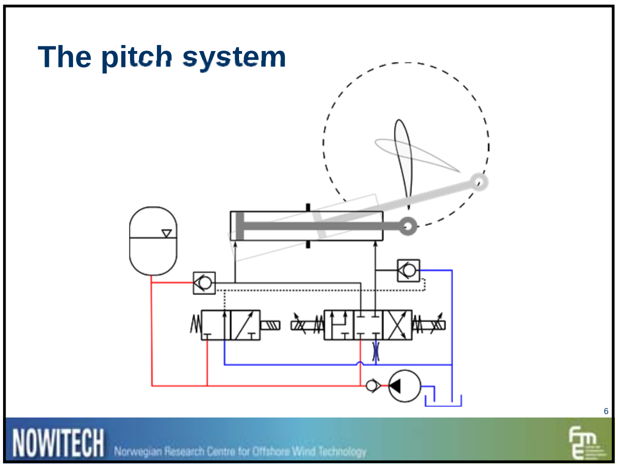
Load case

- In design standards for offshore wind (IEC/DNV/GL):
  DLC 2.3 - *EOG with external or internal electrical fault including loss of electrical network*

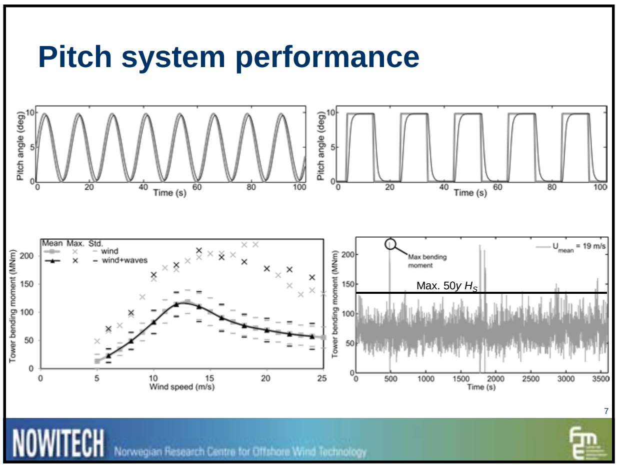
- Very unlikely, but also very severe load combination that could be dimensioning for overturning moment



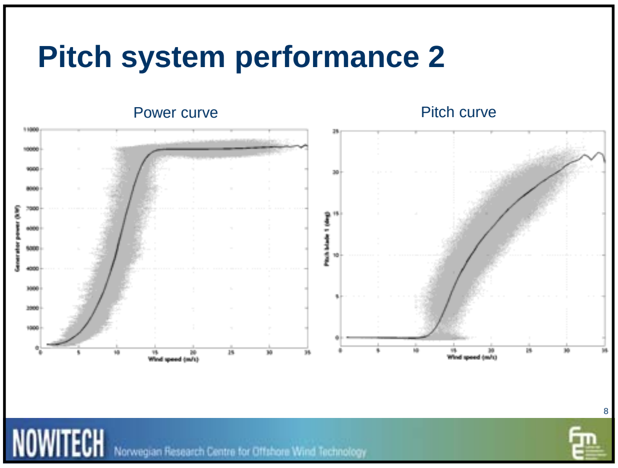
The pitch system



The pitch system



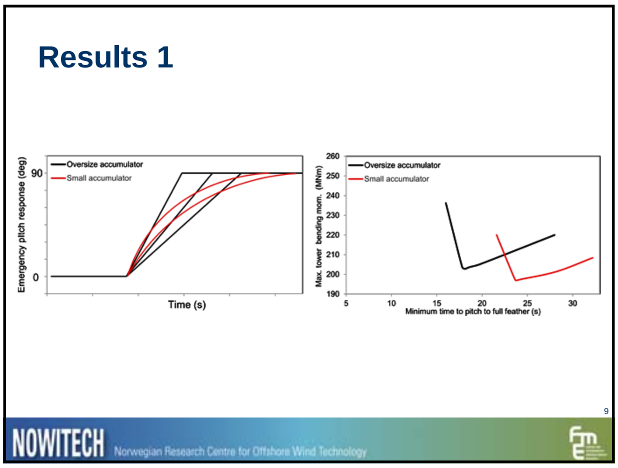
Pitch system performance



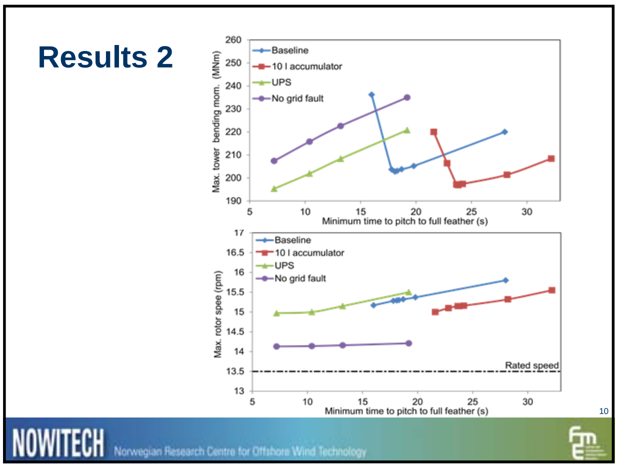
Pitch system performance 2

Power curve

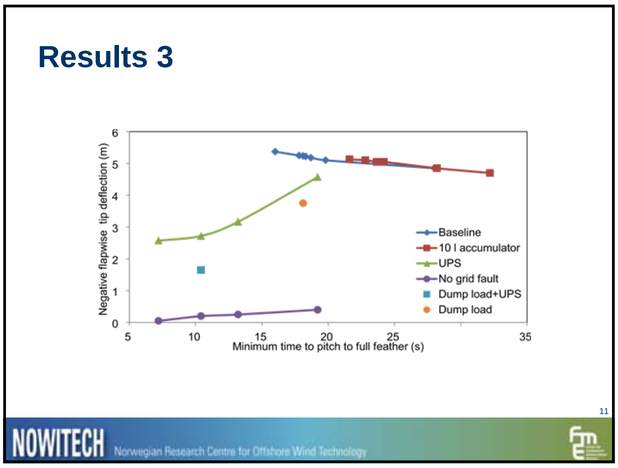
Pitch curve



Results 1



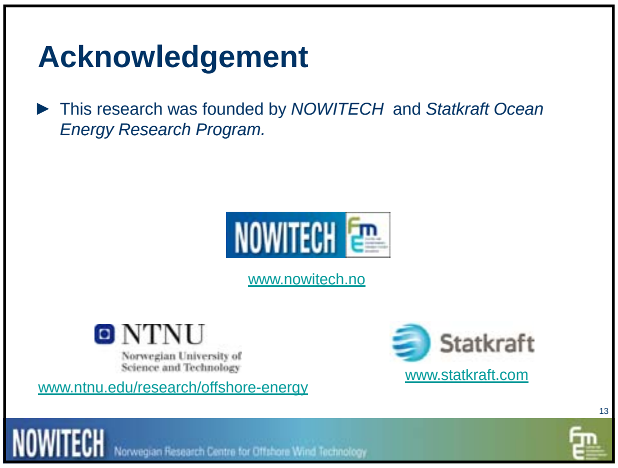
Results 2



Results 3

Conclusion

- The loads during an emergency shutdown depend heavily on the pitch velocity, and both too high or too low velocities will increase the bending moments in the tower and foundation
- The maximum tower bending moment was, however, not dominated by the loads during grid fault, but rather by the loads during an EOG *without* fault
- It is possible to reduce these loads (somewhat) by increasing the dimensions of the pitch system (considerably).
- The only thing that appears to be dominated by the grid fault is the negative flapwise blade deflection, which is most relevant for a downwind turbine.
- It is possible to reduce this deflection using UPS and dump load.



Acknowledgement

- This research was founded by *NOWITECH* and *Statkraft Ocean Energy Research Program.*

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A2 New turbine technology

A Modular Series Connected Converter for a 10 MW, 36 kV, Transformer- Less Offshore Wind Power Generator Drive, Sverre Gjerde, PhD stud, NTNU

Large superconducting wind turbine generators, A.B. Abrahamsen, DTU

Technological advances in Hydraulic Drivetrains for Wind Turbines,
Knud Erik Thomsen, Chapdrive

ASHES: A novel tool for FEM analysis of offshore wind turbines with innovative visualizations techniques, Paul E. Thomassen, Post Doc, NTNU

A Modular Series Connected Converter for a 10 MW, 36 kV, Transformer-Less Offshore Wind Power Generator Drive

Sverre Skalleberg Gjerde

Supervisor: Tore M. Undeland

Jan. 19, 2012

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Outline

- Introduction
- Proposed converter solution
- Control system
  - Structure
- Simulation results
  - The simulation model
  - Case I: no DC-droop
  - Case II: DC-Droop
- Conclusion
- 10 MW Reference turbine

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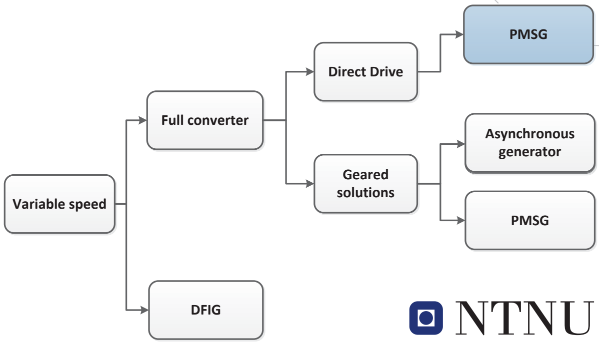
Introduction-I

Electric drive train for offshore wind turbine



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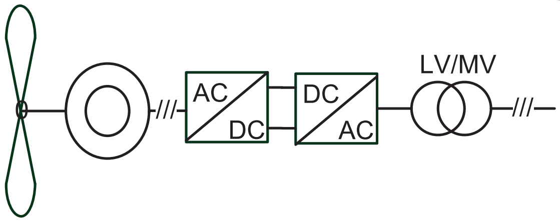
Introduction-I

Electric drive train for offshore wind turbine



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Introduction-II - 10 MW turbine

Challenges when going for a 10 MW wind turbine

- Weight of generator
- Low voltage => high currents
- Location of transformer vs. cabling size.

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Why 10 MW turbine?

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Introduction-II - 10 MW turbine

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- Low voltage => high currents
- Location of transformer vs. cabling size.

Why 10 MW turbine?

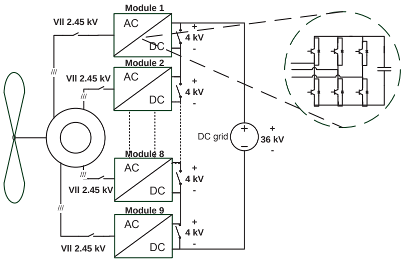
The cost of energy from offshore wind power is high.
Cost is driven both by total rating and number of turbines.

Introduction-III

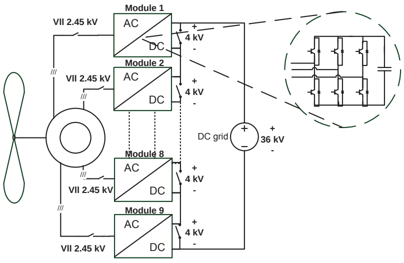
Motivation for Transformer-Less Offshore Generator Drive:

- Reduce weight of nacelle
- Opens possibilities for modularity
- Facilitates operation and maintenance

Converter topology

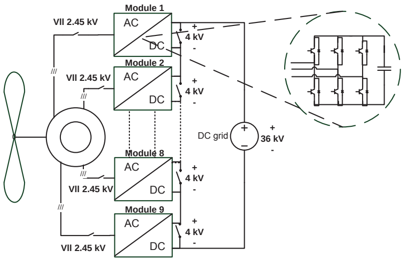


Converter topology



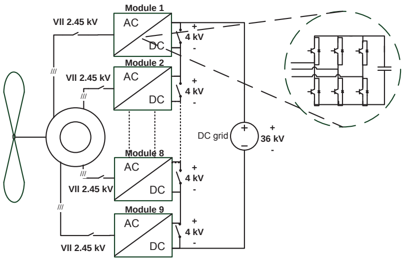
- Modular construction

Converter topology



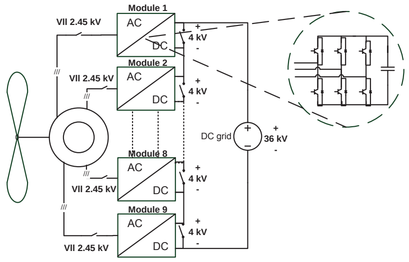
- Modular construction
- Standard three phase VSC modules

Converter topology



- Modular construction
- Standard three phase VSC modules
- Series connected on DC-side

Converter topology



- Modular construction
- Standard three phase VSC modules
- Series connected on DC-side
- Medium voltage stress on windings

Features

Advantages:

Features

Advantages:

- No distribution transformer

Features

Advantages:

- No distribution transformer
- Modularity

Features

Advantages:

- No distribution transformer
- Modularity
- Redundancy

Features

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- Behaviour as 9 standard 3-phase drives

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Disadvantages:

Features

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Disadvantages:

- DC short circuit protection not inherent from topology

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- Communication between modules
- DC-bus balance needed

Features

Advantages:

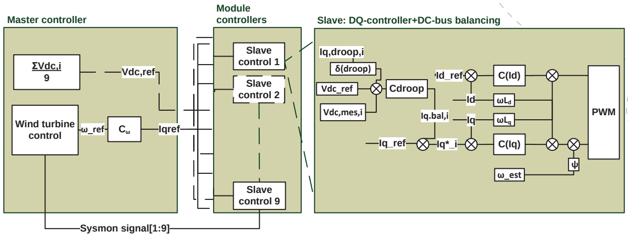
- No distribution transformer
- Modularity
- Redundancy
- Behaviour as 9 standard 3-phase drives

Disadvantages:

- DC short circuit protection not inherent from topology
- Communication between modules
- DC-bus balance needed
- Not standard system

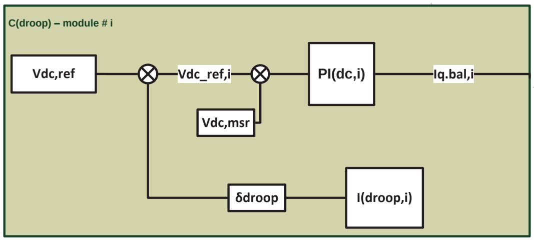
Main control system

Structure



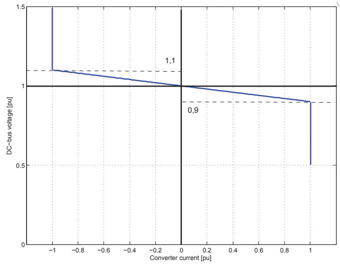
- Main control strategy - Controlling power (speed)
- Additional objective: Maintain all 9 DC-bus voltages equal

DC-bus balancing control



- PI-regulator for dynamic control
- Droop control for static regulation
- Controller output: Addition to torque reference

Droop characteristics



- Limit: 1 ± 0.1 pu (DC-voltage)
- $I_{droop} = 0 \rightarrow V_{dc,ref,i} = V_{dc,nom}$

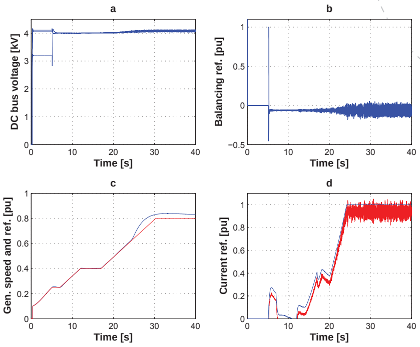
Simulations in PSCAD

The following assumptions were made for the simulation model

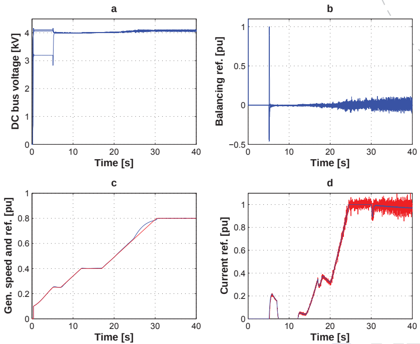
- Each module of the generator can be represented by a 3-phase generator model
- Stiff mechanical shaft
- Semiconductors → ideal switches
- The DC-grid can be represented by a DC-voltage source (infinite bus) and a resistor for the losses

---

Case I: PI-controller



Case II: Droop



Conclusion

- Modular converter for high voltage transformer-less generator drive

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- Modular converter for high voltage transformer-less generator drive
- Control system proposed

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- Droop controller introduced for removal of steady state deviation of DC-bus control

Conclusion

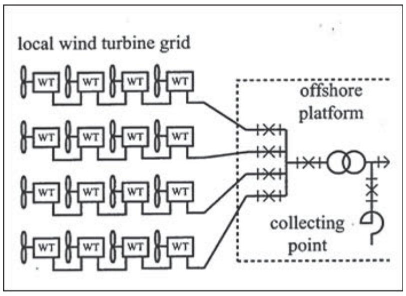
- Modular converter for high voltage transformer-less generator drive
- Control system proposed
- Droop controller introduced for removal of steady state deviation of DC-bus control
- Simulation results shows the effectiveness of the droop

10 MW reference turbine

Electrical definitions

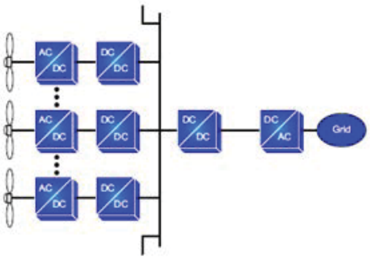
- Wind farm grid structure
- Generator design base
- Converter design base
- Transformer definitions

Definition of collection grid-I

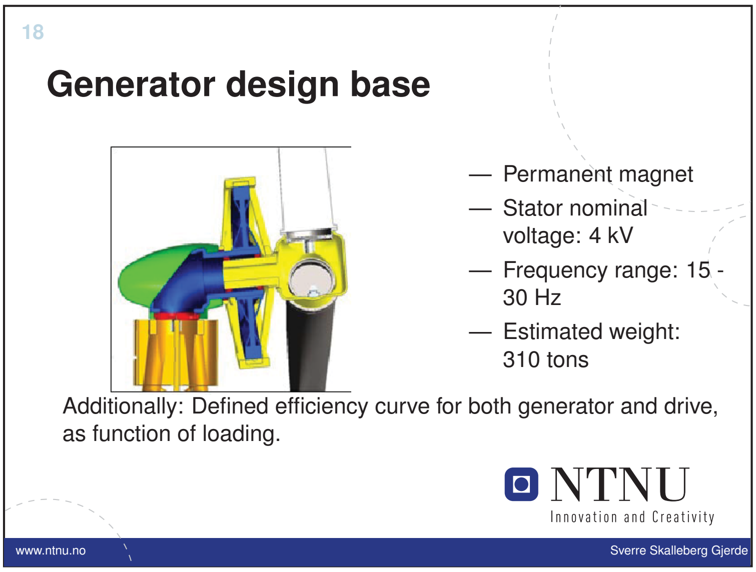


- 36 kV AC
- 50 Hz
- Grid code to apply: UK

Definition of collection grid-II



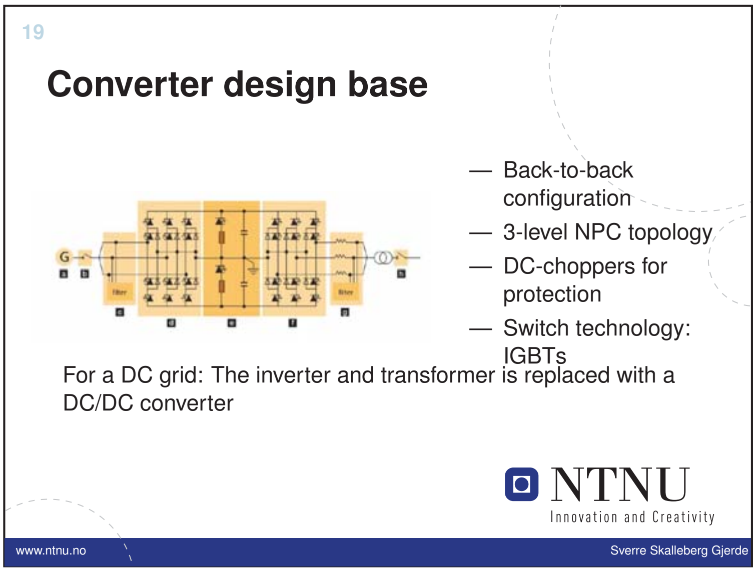
- 36 kV DC
- Grid code to apply: UK



Generator design base

- Permanent magnet
- Stator nominal voltage: 4 kV
- Frequency range: 15 - 30 Hz
- Estimated weight: 310 tons

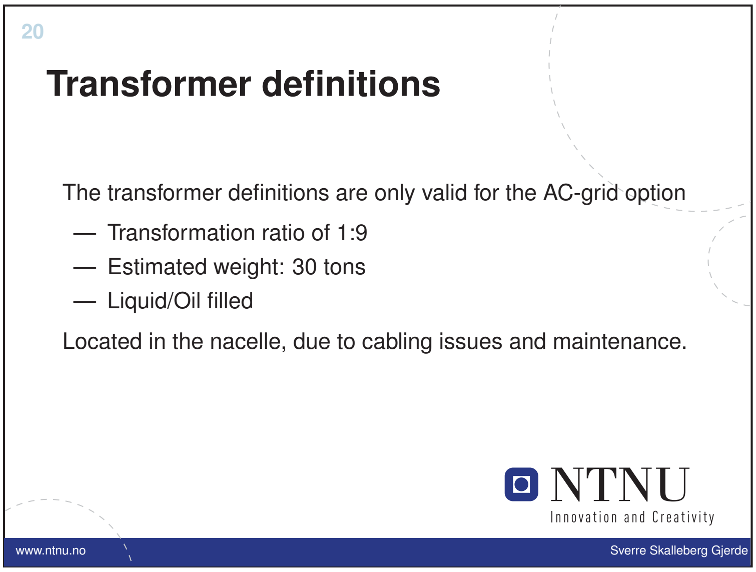
Additionally: Defined efficiency curve for both generator and drive, as function of loading.



Converter design base

- Back-to-back configuration
- 3-level NPC topology
- DC-choppers for protection
- Switch technology: IGBTs

For a DC grid: The inverter and transformer is replaced with a DC/DC converter

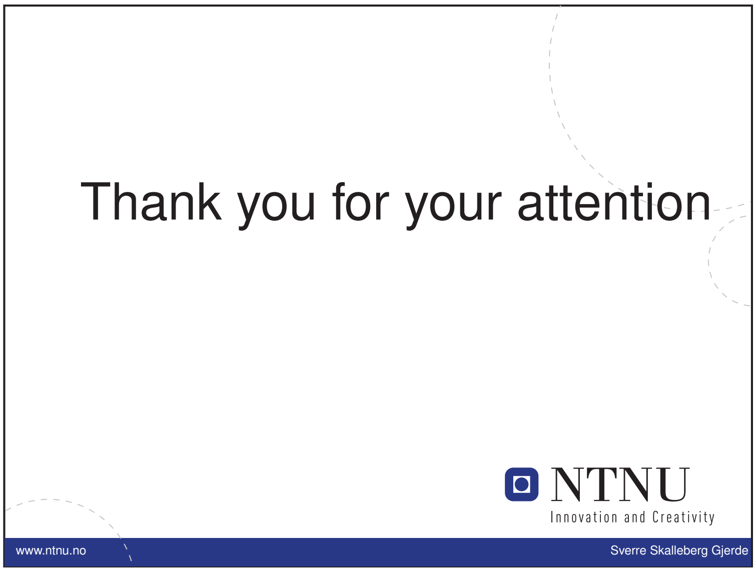


Transformer definitions

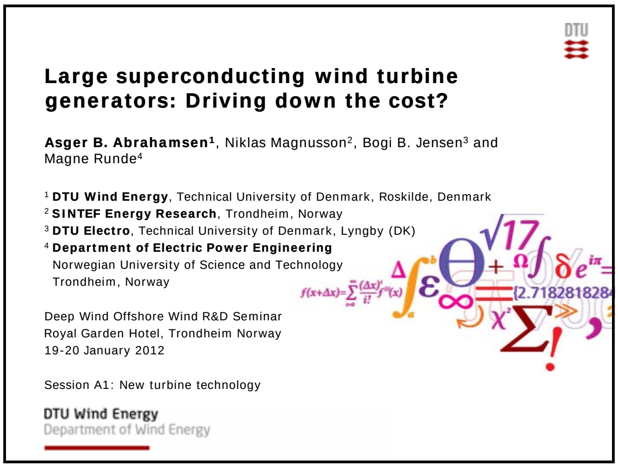
The transformer definitions are only valid for the AC-grid option

- Transformation ratio of 1:9
- Estimated weight: 30 tons
- Liquid/Oil filled

Located in the nacelle, due to cabling issues and maintenance.



Thank you for your attention



Large superconducting wind turbine generators: Driving down the cost?

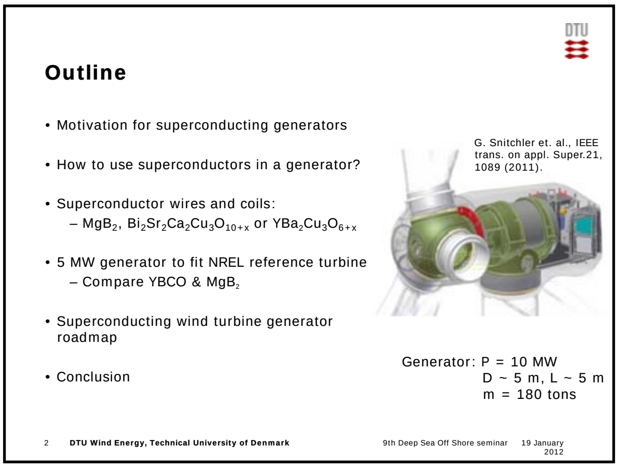
Asger B. Abrahamsen[1], Niklas Magnusson[2], Bogi B. Jensen[3] and Magne Runde[4]

[1] **DTU Wind Energy**, Technical University of Denmark, Roskilde, Denmark
[2] **SINTEF Energy Research**, Trondheim, Norway
[3] **DTU Electro**, Technical University of Denmark, Lyngby (DK)
[4] **Department of Electric Power Engineering**
Norwegian University of Science and Technology
Trondheim, Norway

Deep Wind Offshore Wind R&D Seminar
Royal Garden Hotel, Trondheim Norway
19-20 January 2012

Session A1: New turbine technology

DTU Wind Energy
Department of Wind Energy

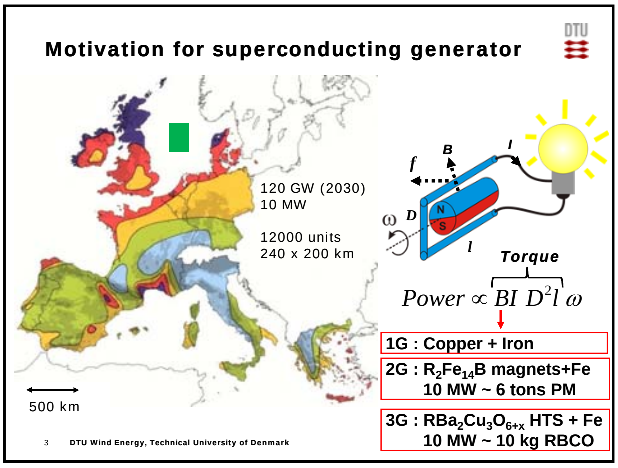


Outline

- Motivation for superconducting generators
- How to use superconductors in a generator?
- Superconductor wires and coils:
  - MgB_2, $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ or $YBa_2Cu_3O_{6+x}$
- 5 MW generator to fit NREL reference turbine
  - Compare YBCO & MgB_2
- Superconducting wind turbine generator roadmap
- Conclusion

G. Snitchler et. al., IEEE trans. on appl. Super.21, 1089 (2011).

Generator: P = 10 MW
D ~ 5 m, L ~ 5 m
m = 180 tons



Motivation for superconducting generator

120 GW (2030)
10 MW

12000 units
240 x 200 km

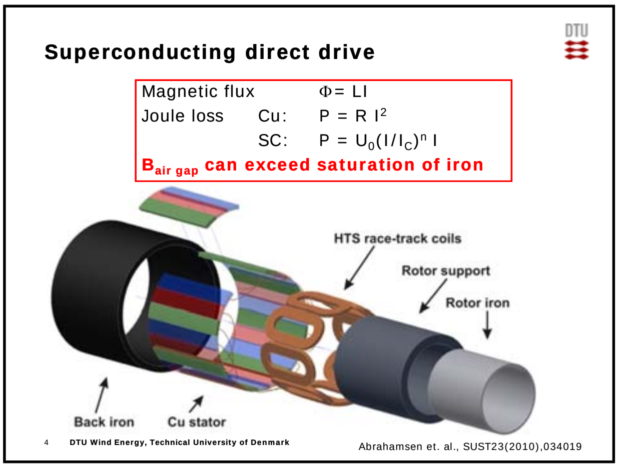
500 km

$$Power \propto \underbrace{BI\,D^2 l}_{Torque}\,\omega$$

1G : Copper + Iron

2G : $R_2Fe_{14}B$ magnets+Fe
10 MW ~ 6 tons PM

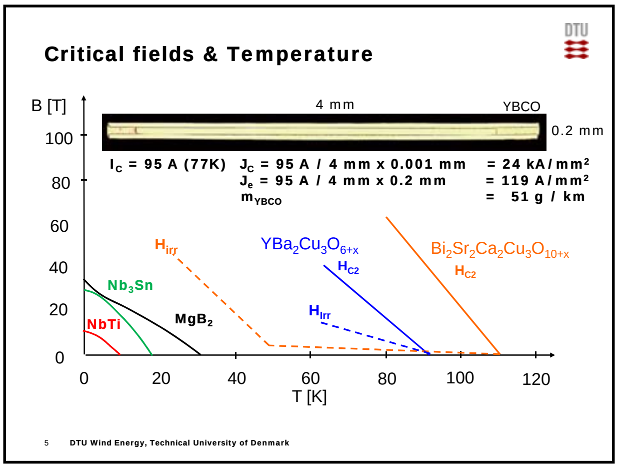
3G : $RBa_2Cu_3O_{6+x}$ HTS + Fe
10 MW ~ 10 kg RBCO



Superconducting direct drive

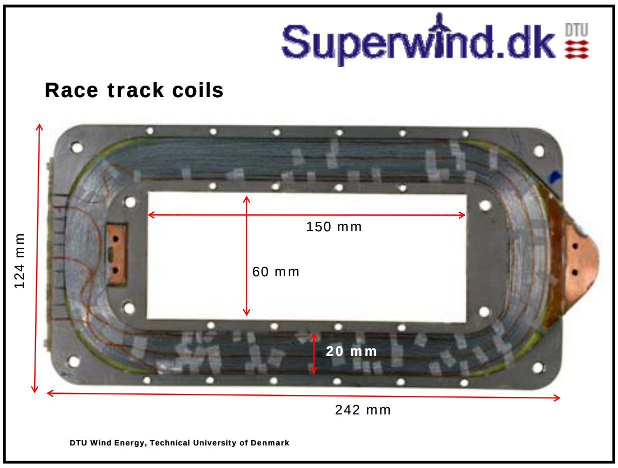
Magnetic flux $\Phi = LI$
Joule loss Cu: $P = R\,I^2$
SC: $P = U_0(I/I_C)^n\,I$
$B_{air\ gap}$ can exceed saturation of iron

Abrahamsen et. al., SUST23(2010),034019



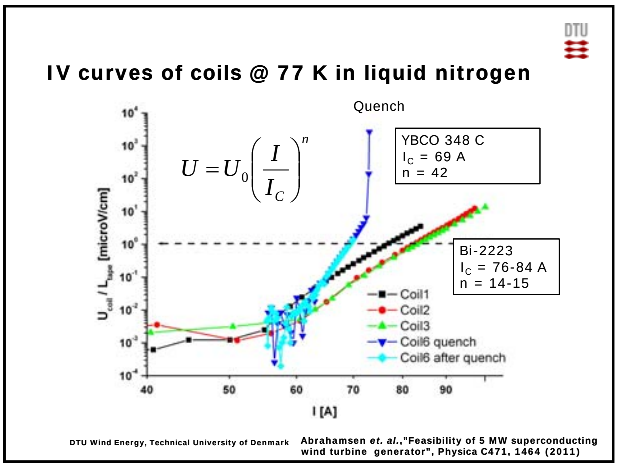
Critical fields & Temperature

I_C = 95 A (77K) J_C = 95 A / 4 mm x 0.001 mm = 24 kA/mm²
J_e = 95 A / 4 mm x 0.2 mm = 119 A/mm²
m_{YBCO} = 51 g / km



Superwind.dk

Race track coils



IV curves of coils @ 77 K in liquid nitrogen

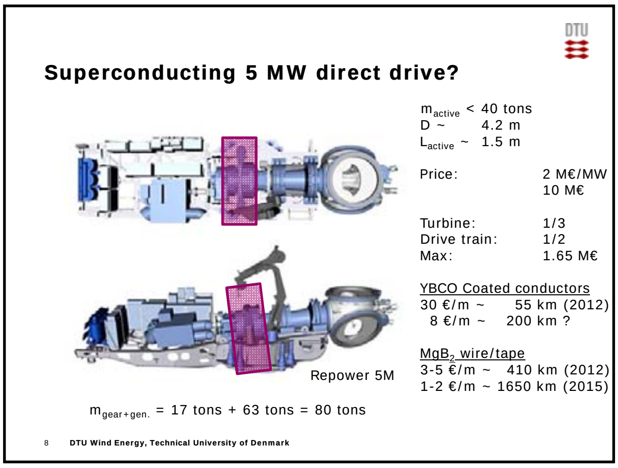
Quench

$$U = U_0\left(\frac{I}{I_C}\right)^n$$

YBCO 348 C
I_C = 69 A
n = 42

Bi-2223
I_C = 76-84 A
n = 14-15

Abrahamsen *et. al.*,"Feasibility of 5 MW superconducting wind turbine generator", Physica C471, 1464 (2011)



Superconducting 5 MW direct drive?

m_{active} < 40 tons
D ~ 4.2 m
L_{active} ~ 1.5 m

Price: 2 M€/MW
10 M€

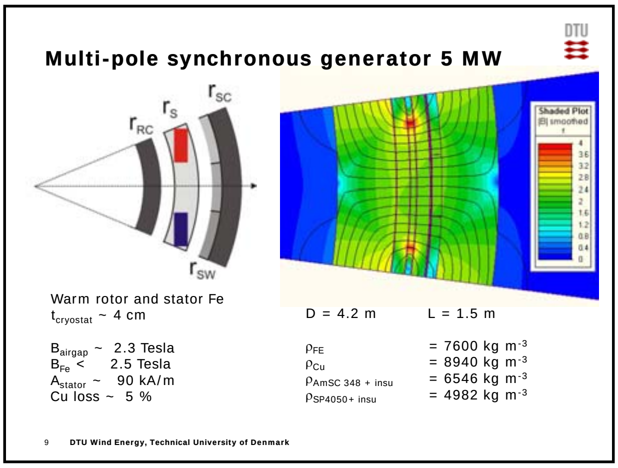
Turbine: 1/3
Drive train: 1/2
Max: 1.65 M€

YBCO Coated conductors
30 €/m ~ 55 km (2012)
8 €/m ~ 200 km ?

MgB_2 wire/tape
3-5 €/m ~ 410 km (2012)
1-2 €/m ~ 1650 km (2015)

Repower 5M

$m_{gear+gen.}$ = 17 tons + 63 tons = 80 tons



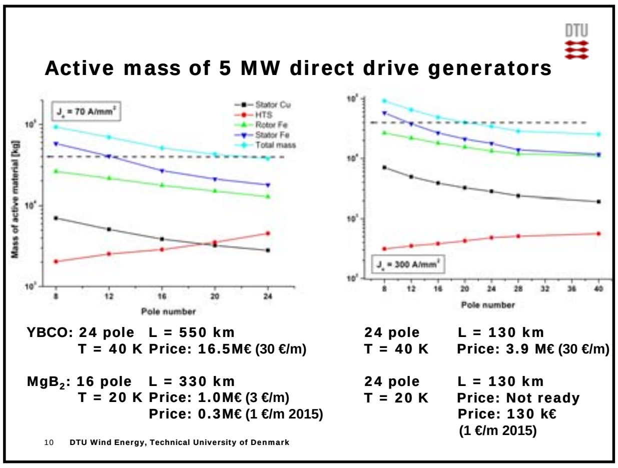
Multi-pole synchronous generator 5 MW

Warm rotor and stator Fe
$t_{cryostat}$ ~ 4 cm

B_{airgap} ~ 2.3 Tesla
B_{Fe} < 2.5 Tesla
A_{stator} ~ 90 kA/m
Cu loss ~ 5 %

D = 4.2 m L = 1.5 m

ρ_{FE} = 7600 kg m^{-3}
ρ_{Cu} = 8940 kg m^{-3}
$\rho_{AmSC\ 348\ +\ insu}$ = 6546 kg m^{-3}
$\rho_{SP4050+\ insu}$ = 4982 kg m^{-3}



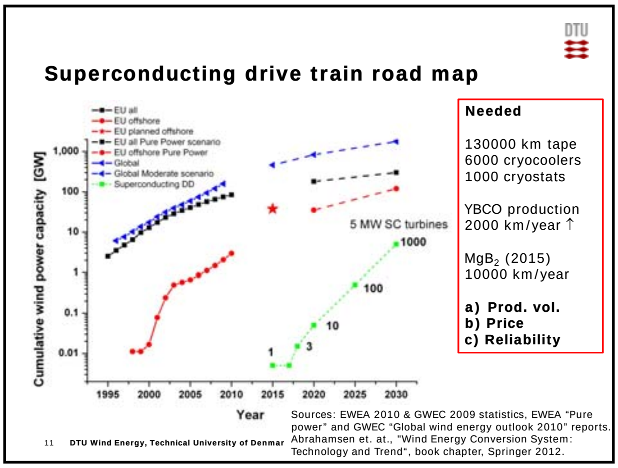
Active mass of 5 MW direct drive generators

YBCO: 24 pole L = 550 km
T = 40 K Price: 16.5M€ (30 €/m)

24 pole L = 130 km
T = 40 K Price: 3.9 M€ (30 €/m)

MgB_2: 16 pole L = 330 km
T = 20 K Price: 1.0M€ (3 €/m)
Price: 0.3M€ (1 €/m 2015)

24 pole L = 130 km
T = 20 K Price: Not ready
Price: 130 k€
(1 €/m 2015)



Superconducting drive train road map

Needed

130000 km tape
6000 cryocoolers
1000 cryostats

YBCO production
2000 km/year ↑

MgB_2 (2015)
10000 km/year

a) Prod. vol.
b) Price
c) Reliability

Sources: EWEA 2010 & GWEC 2009 statistics, EWEA "Pure power" and GWEC "Global wind energy outlook 2010" reports. Abrahamsen et. at., "Wind Energy Conversion System: Technology and Trend", book chapter, Springer 2012.

Conclusion

- Superconducting direct drive offers higher torque in the same package
- Air gap flux density higher than saturation of iron is possible
- Race track coils of high temperature superconductors obtained
- Superconductor properties extrapolated to 5 MW direct drive generator
- Electromagnetic - thermal – structural design challenge
  - Trade off between high operation temperature, high current density and cost
  - YBCO: T = 40 K J_e ok Cost: Too high
  - MgB_2: T = 20 K, J_e close Cost: Close – Promising
- SC roadmap: Start addressing reliability as production volume is scaled up!

ChapDrive

Technological advances in Hydraulic Drivetrains for Wind Turbines

9th Deep Sea Offshore Wind R&D Seminar
DeepWind 2012

Knud Erik Thomsen, ChapDrive

Contents

Company background

- ❑ Developed by leading scientists and product developers in hydraulic systems and turbine technology since 2004. The company was formally founded in 2006.
- ❑ 20 employees in Norway, Denmark, UK and China
- ❑ Current funding secured in 2010 - EUR 10 mill from the investors:
  - ❑ NorthZone Ventures, Statoil Venture, Hafslund Venture, Viking Venture and Investinor

From left: Headquarter in Trondheim, subsidiary in Denmark, workshop in Trondheim and test site at Valsnes

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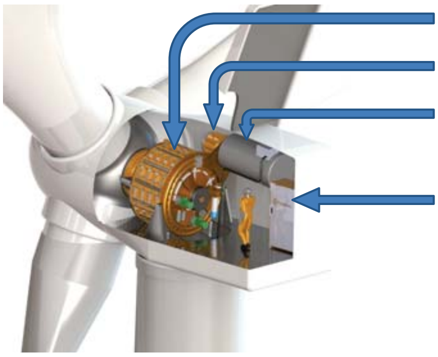
ChapDrive compact and integrated variable hydraulic drivetrain



Pump

Motor

Synchronous generator

Control System

Perfection via Simplicity

Technological advantages

ChapDrive offers a unique alternative gearless solution

Robust light-weight variable hydraulic drivetrain with synchronous generator and fewer critical components

- ❑ **No mechanical gearbox** - causing high maintenance costs on today's wind turbines
- ❑ **No frequency converter** - causing the highest failure rates and most down time on today's wind turbines
- ❑ **No need for permanent magnets** - high cost rare earth materials
- ❑ **No transformer**

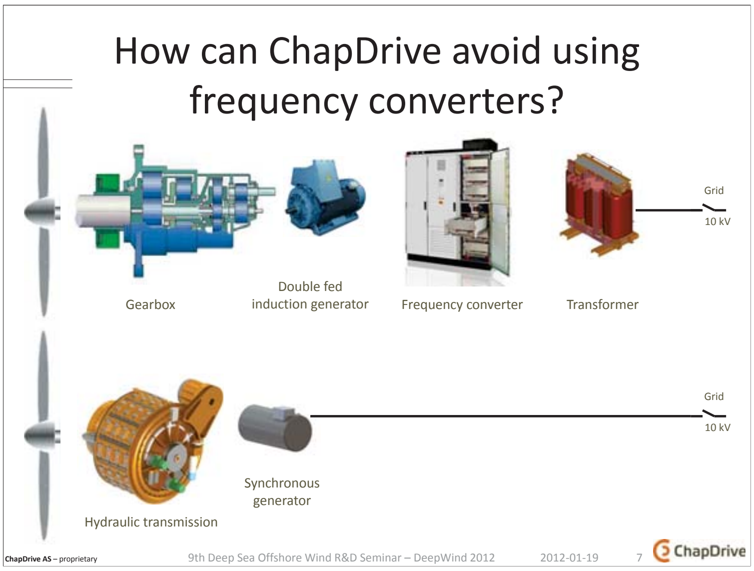
Why are frequency converters needed in today's wind turbines?

Purpose of the frequency converter:

- ❑ **Variable speed control**
  - ❑ Optimises energy production
- ❑ **Dynamic load control**
  - ❑ Reduces power and torque fluctuations, extreme loads etc.
- ❑ **Grid control**
  - ❑ Stabilises the grid via reactive power control, low voltage ride through control etc.

History:

- ❑ Up till 1990: No frequency converters
- ❑ 1990 till today: 25 – 30% of rated power frequency converters in combination with double feed induction generators, DFIG
- ❑ Future turbines: Full scale frequency converters, 100 % of rated power in combination with medium speed permanent magnet generators or direct drive permanent magnet generators



How can ChapDrive avoid using frequency converters?

Gearbox

Double fed induction generator

Frequency converter

Transformer

Grid

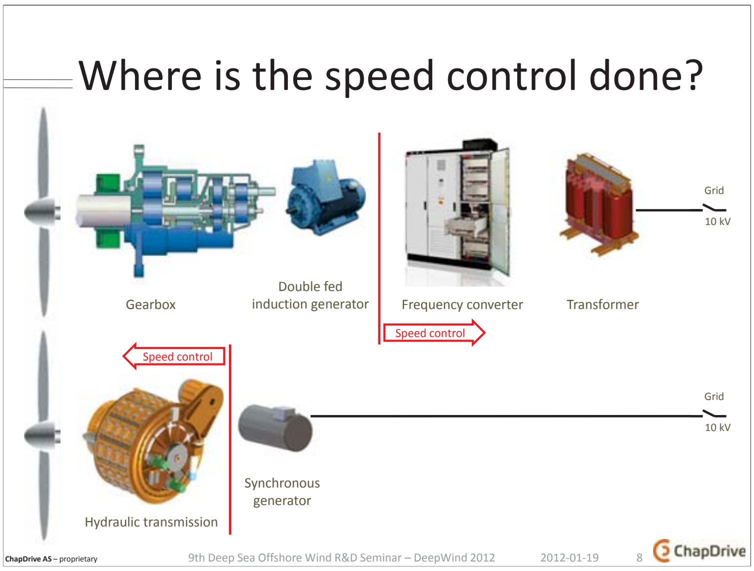
10 kV

Hydraulic transmission

Synchronous generator

Grid

10 kV



Where is the speed control done?

Gearbox

Double fed induction generator

Frequency converter

Transformer

Grid

10 kV

Speed control

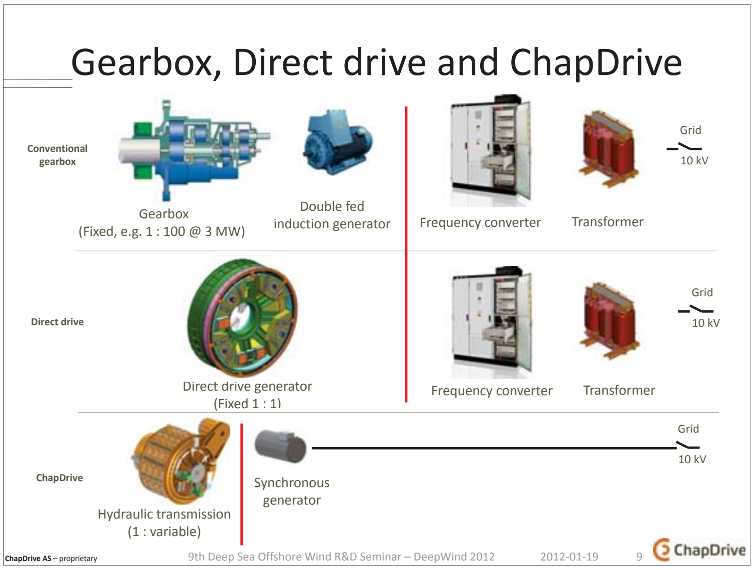
Speed control

Hydraulic transmission

Synchronous generator

Grid

10 kV



Gearbox, Direct drive and ChapDrive

Conventional gearbox

Gearbox
(Fixed, e.g. 1 : 100 @ 3 MW)

Double fed induction generator

Frequency converter

Transformer

Grid

10 kV

Direct drive

Direct drive generator
(Fixed 1 : 1)

Frequency converter

Transformer

Grid

10 kV

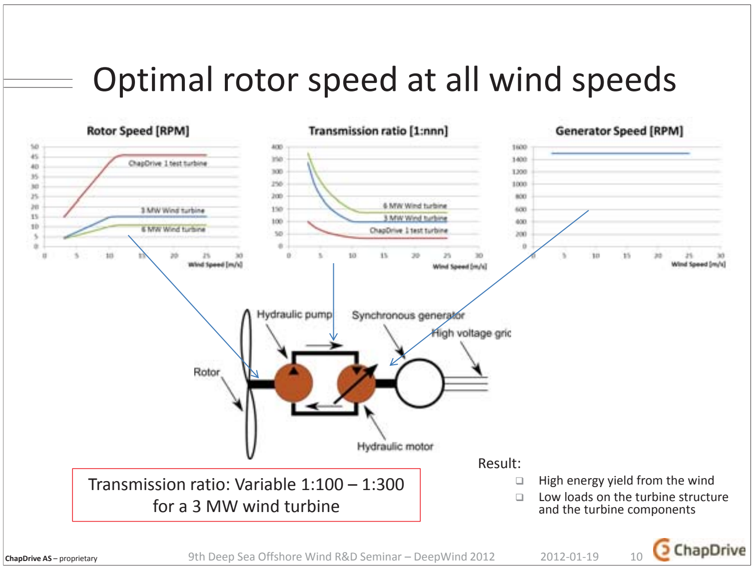
ChapDrive

Hydraulic transmission
(1 : variable)

Synchronous generator

Grid

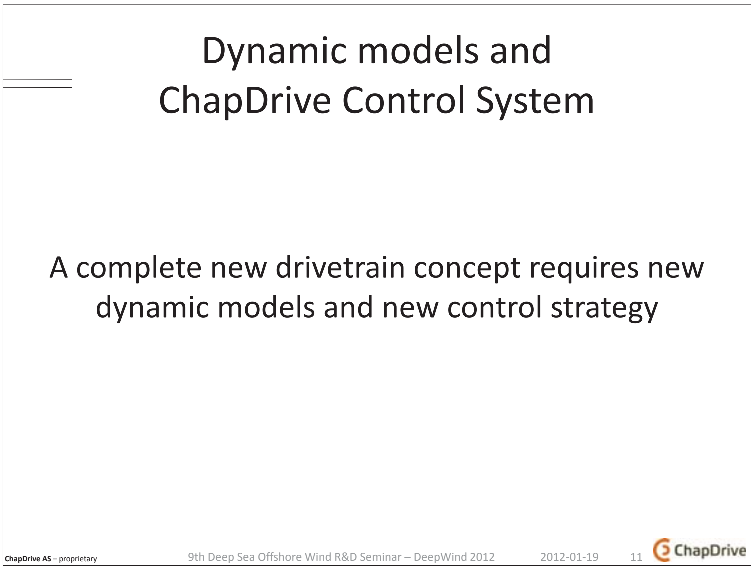
10 kV



Optimal rotor speed at all wind speeds

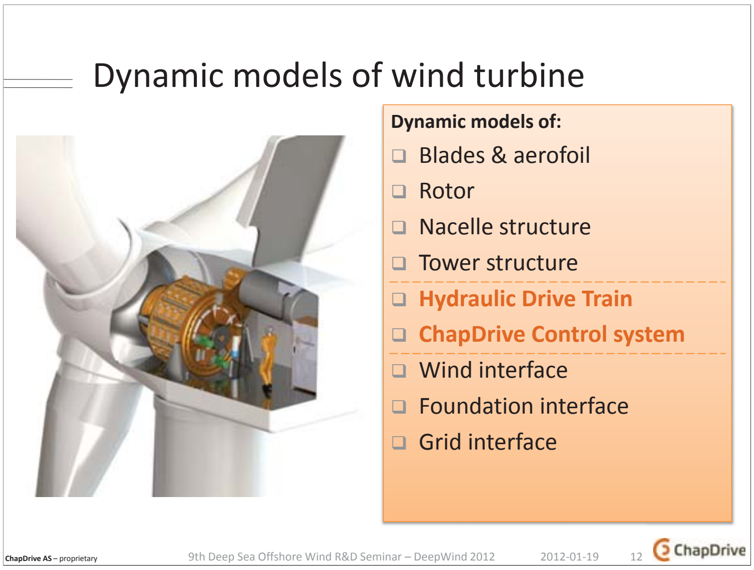
Transmission ratio: Variable 1:100 – 1:300 for a 3 MW wind turbine

Result:
- ❑ High energy yield from the wind
- ❑ Low loads on the turbine structure and the turbine components



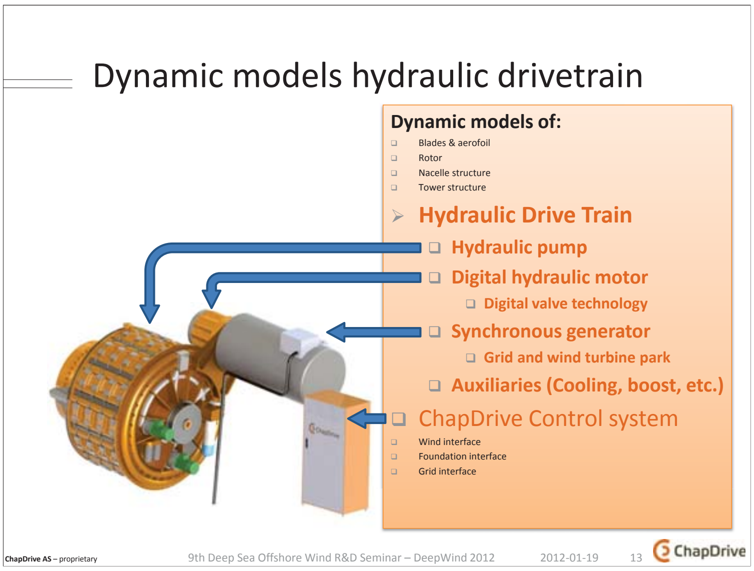
Dynamic models and ChapDrive Control System

A complete new drivetrain concept requires new dynamic models and new control strategy



Dynamic models of wind turbine

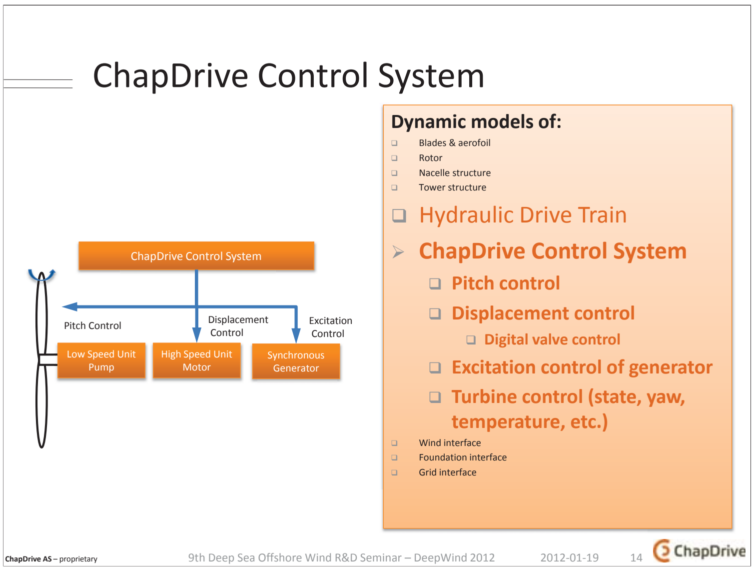
Dynamic models of:
- ❑ Blades & aerofoil
- ❑ Rotor
- ❑ Nacelle structure
- ❑ Tower structure
- ❑ **Hydraulic Drive Train**
- ❑ **ChapDrive Control system**
- ❑ Wind interface
- ❑ Foundation interface
- ❑ Grid interface



Dynamic models hydraulic drivetrain

Dynamic models of:

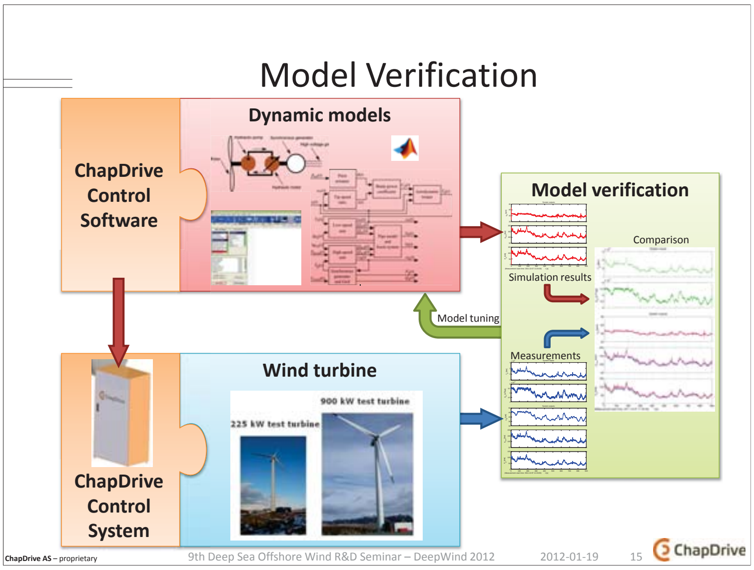
- ❑ Blades & aerofoil
- ❑ Rotor
- ❑ Nacelle structure
- ❑ Tower structure
- ➢ **Hydraulic Drive Train**
  - ❑ **Hydraulic pump**
  - ❑ **Digital hydraulic motor**
    - ❑ **Digital valve technology**
  - ❑ **Synchronous generator**
    - ❑ **Grid and wind turbine park**
  - ❑ **Auxiliaries (Cooling, boost, etc.)**
- ❑ ChapDrive Control system
- ❑ Wind interface
- ❑ Foundation interface
- ❑ Grid interface



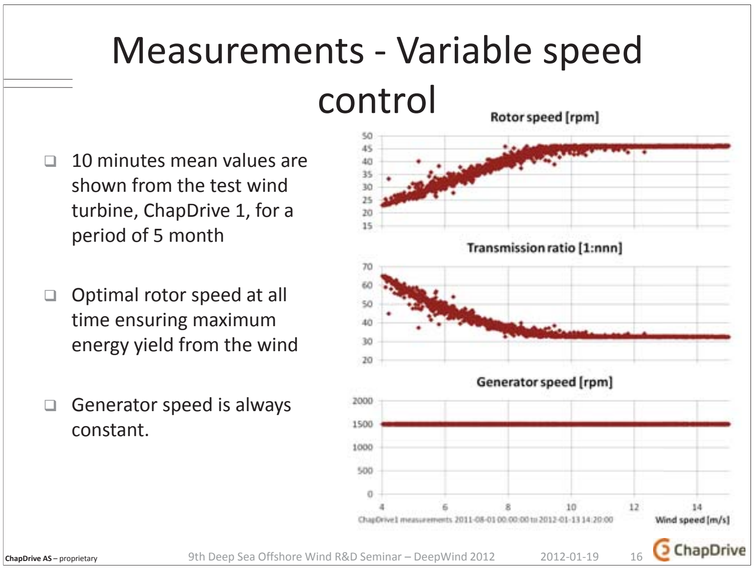
ChapDrive Control System

Dynamic models of:

- ❑ Blades & aerofoil
- ❑ Rotor
- ❑ Nacelle structure
- ❑ Tower structure
- ❑ Hydraulic Drive Train
- ➢ **ChapDrive Control System**
  - ❑ **Pitch control**
  - ❑ **Displacement control**
    - ❑ **Digital valve control**
  - ❑ **Excitation control of generator**
  - ❑ **Turbine control (state, yaw, temperature, etc.)**
- ❑ Wind interface
- ❑ Foundation interface
- ❑ Grid interface

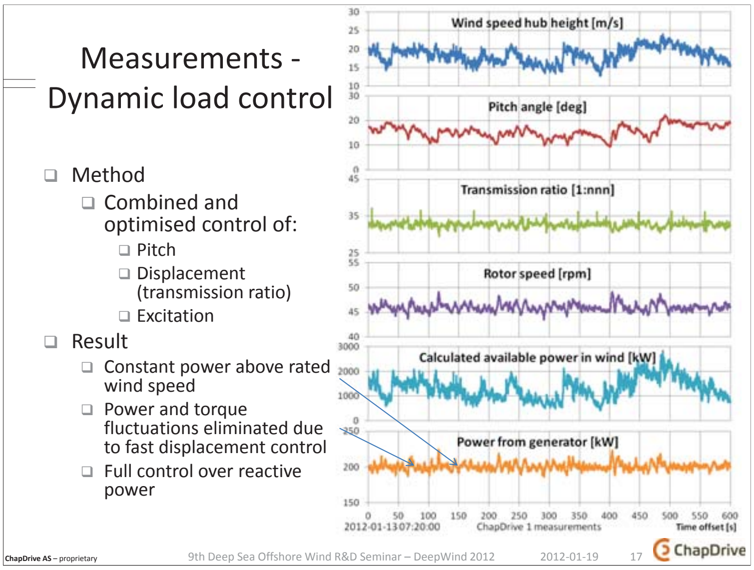


Model Verification



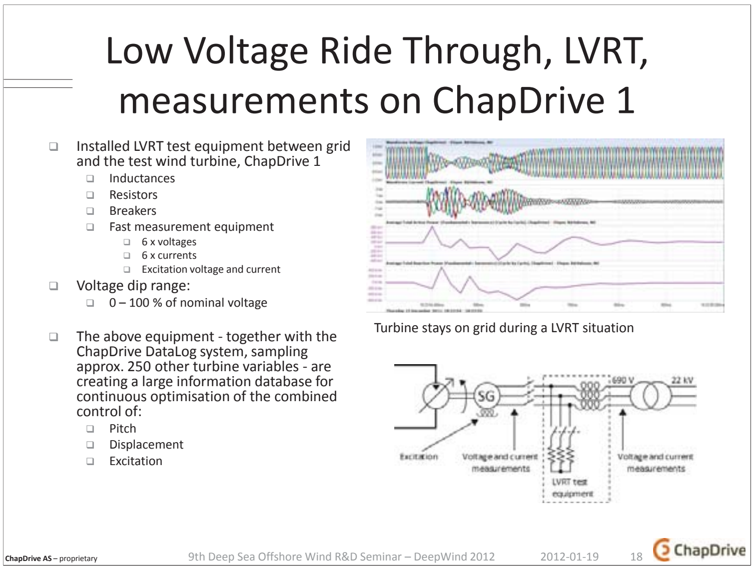
Measurements - Variable speed control

- ❑ 10 minutes mean values are shown from the test wind turbine, ChapDrive 1, for a period of 5 month
- ❑ Optimal rotor speed at all time ensuring maximum energy yield from the wind
- ❑ Generator speed is always constant.



Measurements - Dynamic load control

- ❑ Method
  - ❑ Combined and optimised control of:
    - ❑ Pitch
    - ❑ Displacement (transmission ratio)
    - ❑ Excitation
- ❑ Result
  - ❑ Constant power above rated wind speed
  - ❑ Power and torque fluctuations eliminated due to fast displacement control
  - ❑ Full control over reactive power



Low Voltage Ride Through, LVRT, measurements on ChapDrive 1

- ❑ Installed LVRT test equipment between grid and the test wind turbine, ChapDrive 1
  - ❑ Inductances
  - ❑ Resistors
  - ❑ Breakers
  - ❑ Fast measurement equipment
    - ❑ 6 x voltages
    - ❑ 6 x currents
    - ❑ Excitation voltage and current
- ❑ Voltage dip range:
  - ❑ 0 – 100 % of nominal voltage
- ❑ The above equipment - together with the ChapDrive DataLog system, sampling approx. 250 other turbine variables - are creating a large information database for continuous optimisation of the combined control of:
  - ❑ Pitch
  - ❑ Displacement
  - ❑ Excitation

Turbine stays on grid during a LVRT situation

Conclusion

ChapDrive has demonstrated that the combination of a variable hydraulic drivetrain and new optimised control strategy can eliminate the need for:

- **Mechanical gearbox**
- **Frequency converter (*)**
- **Permanent magnets**
- **Transformer**

All contributing to reduced Cost of Energy, CoE

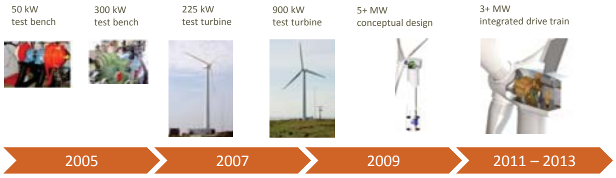
(*) The combination of a variable hydraulic transmission, a synchronous generator and the **ChapDrive Control System** has taken over the tasks of the full scale frequency converter seen in nearly all new wind turbine developments. These tasks are:

- **Variable speed control**
  - Optimises energy production
- **Dynamic load control**
  - Reduces power and torque fluctuations, extreme loads etc.
- **Grid control**
  - Stabilises the grid via reactive power control, low voltage ride through control etc.

ChapDrive technology verification history and future

- Hydraulic transmissions are robust and will reduce top weight for wind turbines
- High efficiency hydraulic technology enables competitive efficiency
- Development is driven by the industry for mobile hydraulic systems
- ChapDrive will install such technology in the 225 kW test turbine in H1 2012
- ChapDrive's hydraulic solution is verified in fully operational 225 and 900 kW test turbines
- ChapDrive is now developing a 3.x MW integrated drivetrain based on high efficiency hydraulic technology

Technology verification and development well progressed since company inception



Question and answer

Thank you for your attention!

ChapDrive

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Trondheim
7030 Norway

www.chapdrive.com

ASHES: A Novel Tool for FEM analysis of Wind Turbines

with innovative visualization techniques

Content:

1. Introduction: Status for aeroelastic software
2. ASHES:
   1. What?
   2. Why?
   3. Benchmarking (OC4, Norcowe/Nowitech Blindtest)
   4. DEMO (hopefully live…)
   5. What's next?

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1. (Incomplete) status for Aeroelastic software

- Def: Coupled analysis of a wind turbine including:
  - Aerodynamics
  - Blades/rotor
  - Tower
  - Control system
- Mode shape analysis, Multi Body Systems, and/or FEM

- Main results:
  - Natural frequency analysis
  - Time domain simulation (for fatigue design)
- Recent trend:
  - Adapting for offshore wind turbines
  - Moving to FEM analysis

- There are many different codes in use and under development, e.g.:
  - NREL: FAST (free and open source)
  - DTU: Flex (quasi-commercial)
  - Risø: HAWC2 (half-commercial)
  - GL GH: Bladed (leading commercial program)
  - Many others!

Content:

1. Status for aeroelastic software
2. ASHES:
   1. What?
   2. Why?
   3. Benchmarking (OC4, Norcowe/Nowitech Blindtest)
   4. DEMO (hopefully live…)
   5. What's next?

2.1 ASHES: What is it?

- Aero-Servo-Hydro-Elastic-Simulation
- Developed at NTNU, so-far funded mostly by the Statkraft Ocean Energy Research Program
- How we hope it will be different:
  - Simultaneous focus on
    - Numerical results
    - GUI (Graphical User Interface)
    - Visualization
  - Fun to use

- New users groups:
  - Traditional: Experienced professionals
  - New: Inexperienced professionals
  - New: Students
- Based on an object oriented FEM framework with full access to C++ source code

2.2 ASHES: Why bother?

- Does the world really need another aeroelastic code?

Signs there are reasons to bother:

- The huge interest indicates that it makes sense!
- International cooperation
  - OC4 project
- Google isn’t interested (yet)
- The market (wind energy) has a huge growth

2.3 ASHES Benchmarking

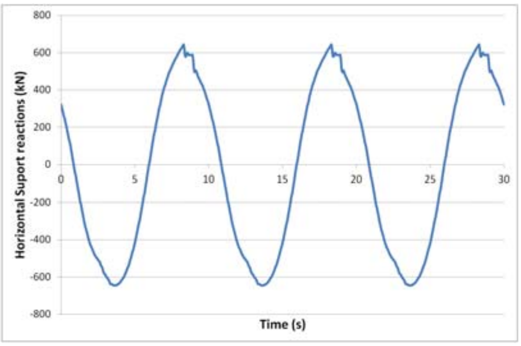
A. OC4 project
B. NORCOWE/NOWITECH Wind tunnel blindtest
C. Comparison with other experimental data from NTNU

A. The OC4 project

- Offshore Code Comparison Collaboration Continuation
  - Continuation of OC3
- http://www.ieawind.org/Task_30
- Phase 1: 5MW WT with tubular tower and jacket on 45 m depth
- (Later: Phase 2: Semi-sub floater)
- 15 different codes and groups actively taking part
- Paper for ISOPE 2012

OC4 Load case 2.3a, Airy wave H=6m, T=10s, no wind

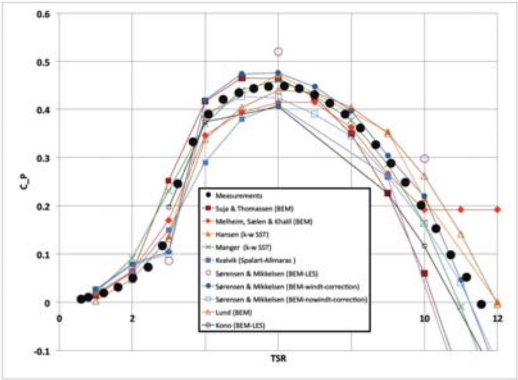
Sensor 53: Sum of horizontal support reactions



NORCOWE/NOWITECH Blindtest Workshop

- Calculations for a model wind turbine tested in the NTNU wind tunnel
- Test of the BEM implementation

Cp curve



C. Comparison with experimental data from NTNU

- Tidal turbine in towing tank (Celine Faudot/Ole G. Dahlhaug)
- Yawed rotor in wind tunnel (Tania Bracchi/Per Åge Krogstad)

ASHES Demo

ASHES: What is it? Part II GUI focus

- An effective and attractive GUI is expected from a modern tool
- The GUI is very useful also in the development process
- NB: A non-GUI option will also be provided for the end user

Real-time analysis

- No video
- Start-Pause-Stop
- Increase – decrease analysis speed

Effective visualization

- Simple vs. complex
- Investigate
  - Blade visualization
  - Load visualization
  - Velocity triangle

“Professional” software development practices

- Source control
  - Effective and safe development
  - Enables (international) hands-on cooperation
- Object oriented programming
  - Visual studio, C++
- Documentation, testing
- “Group” programming

2.4 ASHES: What’s next?

- New functionality governed by needs from ongoing research, benchmarking ,and model tests
- Flexible (FE) blades also in time domain analysis
- Blade design and optimization (MSc thesis project)

- Advanced wave models
- Combined waves and current (for tidal turbine)
- Define and run multiple analyses
- Optimization for speed
- Make available for pilot users

B1 Power system integration

Voltage Source HVDC – Overview, Dr Mike Barnes, University of Manchester

Control challenges and possibilities for large offshore wind farms,
Prof Olimpo Anaya-Lara, Univ. of Strathclyde

Coordinated control between wind and hydro power systems through HVDC links, Atsede Endegnanew, SINTEF Energi AS

Temporary Rotor Inertial Control of Wind Turbine to Support the Grid Frequency Regulation, Bing Liu, PhD stud, NTNU

Stability Improvements in Oil Platforms from Wind Turbines,
Atle Rygg Årdal, SINTEF Energi AS

Voltage Source HVDC - Overview

Mike Barnes

Tony Beddard

Note: This is a version with images removed which have copyrighted other than from the University of Manchester, for web publication. Should a conference attendees want a fuller version, please contact mike.barnes@manchester.ac.uk

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Contents

1. Background – LCC and VSC
2. Multi-terminal
3. Circuit Breakers
4. Cable Modelling
5. Availability
6. Concluding comments

AC vs DC

Issue	AC	DC
Voltage conversion	Transformers	Power electronics
Protection	Current and voltage fall to zero twice per cycle	Breakers complex
Transmission distance	Limited by reactive power consumption	No Reactive power requirement (on DC side)
System cost	Cheap terminal cost Line or cable more expensive per mile	Expensive terminal Cheaper line or cable cost per mile
Space requirement	Lower terminal footprint Greater line footprint	Greater terminal footprint Lower line footprint
Interconnected systems	Must have same frequency and phase	Asynchronous connection

In early 20th Century technology available meant AC was preferred for transmission

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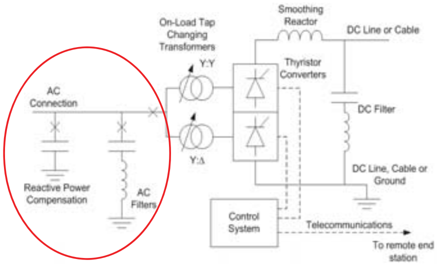
Revival of DC
High Voltage Transmission



- Initially Current Source (thyristor based)
  - Large station footprint
  - Strong AC system needed

Operation:

- Thyristor control delays current flow with respect to input voltage
- Phase shift controls real power flow (P)
- Phase shift draws large amounts of reactive power (Q)

Current-Source (CS) or Line-Commutated Converter (LCC) Examples

- Yunnan-Guangdong (2009)
  - 5000MW, +/-800kV Bipolar
  - 1418km
- Three Gorges (2004)
  - 3000MW, +/-500kV Bipolar
  - 940km
- Melo (2011)
  - 500MW, Back-to-Back

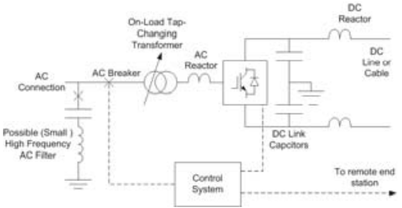
However:

- Need to connect vast amounts of offshore wind
- Need to interconnect more networks, even those unsynchronised

Issues with CS-HVDC:

- Station footprint
- Need for 'strong' AC network to connect to
- Needs to use mass-impregnated oil cable

New Power Generation / New Solution - Voltage Source (VS) HVDC



- Main advantages of VSC over CS:
  - Smaller footprint (offshore platform cheaper)
  - Power direction in cable changed by current (keep same polarity V, use cheaper XLPE cable)
  - No need for reactive power generation to supply converter

---

Evolution of VSC-HVDC Technology

Technology	Year first scheme commissioned	Converter Type	Losses per converter (%)	Switching frequency (Hz)	Example Project
HVDC Light 1st Gen	1997	Two-Level	3	1950	Gotland
HVDC Light 2nd Gen	2000	Three-level Diode NPC	2.2	1500	Eagle Pass
	2002	Three-level Active NPC	1.8	1350	Murraylink
HVDC Light 3rd Gen	2006	Two-Level with OPWM	1.4	1150	Estlink
HVDC Plus	2010	MMC	1	<150*	Trans Bay Cable
HVDC MaxSine	2014IP	MMC	1	<150*	SuperStation
HVDC Light 4th Gen	2015IP	CTL	1	=>150*	Dolwin 2

*switching frequency is for a single module/cell.

CS vs VSC HVDC

- Current Source – HVDC – Available since 1950's
  - Loss 0.8% per converter station
- Voltage Source Converter – HVDC
  - Loss 1.1% per converter station
  - Much smaller footprint
  - Newer technology (since 1997)

ZDF

First Offshore Installation

- Troll
  - 1&2 – 88MW (2005), 3&4 – 100MW (2015)
  - +/-60kV DC, 70km
  - 132kV AC on shore to 56kV or 66kV offshore

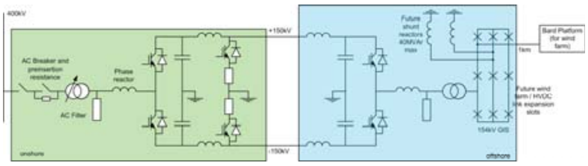
First Offshore Windfarm: BorWin1 2009

-First wind farm installation: BorWin1=80x5MW turbines
-ABB 2-level converter
-Only existing offshore VSC-HVDC windfarm connection

Cable data

Voltage	+/-150 kV DC
Power	400 MW
Insulation	Polymeric HVDC Light

BorWin1 - Design



Design for maximising availability and minimising maintenance:
-DC choppers onshore
-No tap-changing transformer offshore

-Planned in service date 2009/10.

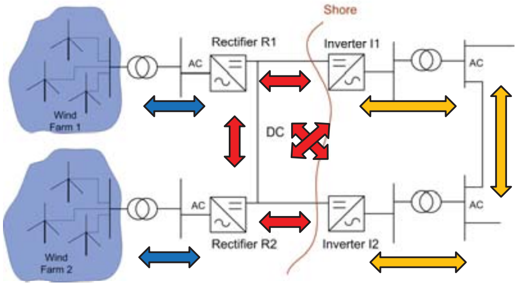
First Multi-Level Converter

- Trans Bay Cable - 2010
  - First MMC Multilevel system

Issues

- Many, but key issues include:
  - Multi-terminal control
  - Breakers
  - Availability
  - Cable Modelling

2. Multi-Terminal Control

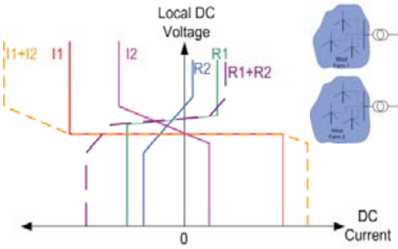


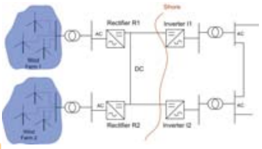
- How to control?
  - Levels / hierarchy / software algorithms
- Hardware to facilitate control

Prior Art

- Shin-Shinano
  - 50MVAx3 back-to-back GTO VSC-HVDC
- SACOI CS-HVDC 3-terminal link
  - 200MW/50MW/200MW
- Hydro-Quebec
  - CS-HVDC
  - Planned at 5-terminal, installed as 3
  - Most usually run effectively as point-to-point

Present proposed control



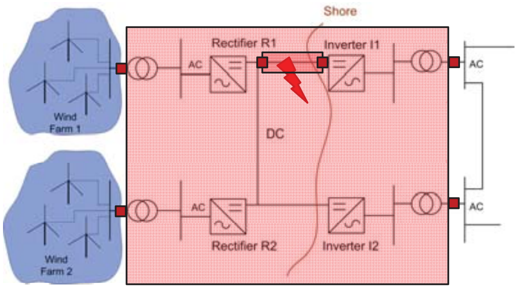


- Local droop-line control at each station
- Super-imposed master-slave central control (telecommunications)

However

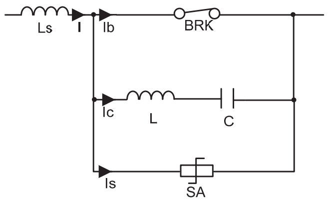
- No operational experience with VS-HVDC multi-terminal systems which are:
  - large scale
  - not co-located
- Planned systems:
  - Tres-Amigas – Texas
  - Scotland-Shetland Offshore
  - North Sea in Europe
  - Atlantic Offshore Wind Connection

Circuit Breakers



- How to manage DC fault?
  - No DC circuit breakers
  - Faults cleared on AC side (at present)

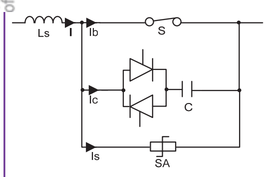
3. Breakers Available - Limited



- Passive Resonance Breaker
  - Test designs constructed
  - Relatively low interruption speed
- Based on Metallic Return Transfer Breaker in CS-HVDC
  - Full Current, Limited Voltage

HVDC Breaker Review

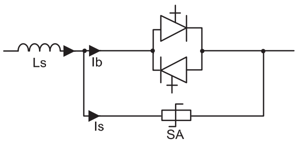
- Preferred topologies



Hybrid Circuit Breaker

•Low on-state losses

•Relatively slow interruption speed

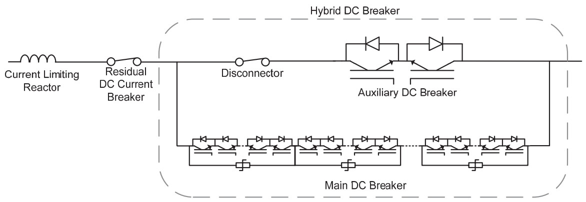


Solid-state Circuit Breaker

•High on-state losses

•Fast Interruption speed

ABB Patent



- Medium Voltage Prototype Built

4. HVDC Cable Modelling

•No standard model

•What models are commercially available?

•Differences between the models

•Background theory

•Implementation

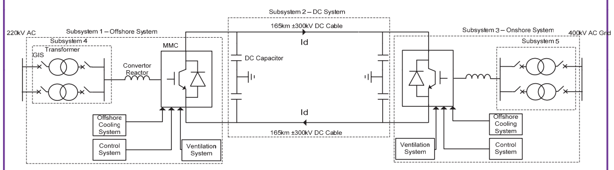
HVDC Cable Models

- **Pi-Section**
  - Lumps cable's RLC parameters
  - Adequate for steady state simulations with short lengths of cable
  - Computational intensive if many pi-sections are required
- **Bergeron Model**
  - Represents distributed nature of LC with R lumped
  - Does not account for frequency dependent nature of parameters
- **Frequency dependent models**
  - Distributed RLC model frequency dependency of all parameters
  - Mode model does not account for frequency dependent transformation matrix.
  - Phase model said to be the most robust and numerically accurate cable model commercially available

---

5. VSC-HVDC Availability Analysis

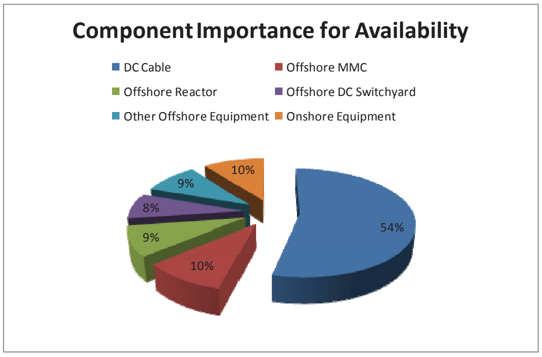
- Typical Radial Scheme for an UK Round 3 Windfarm:
  - Determine overall availability of scheme
  - Identify key components which effect the scheme
- Availability statistics are next to non-existent



Radial VSC-HVDC Scheme

Results

Overall energy availability of 96.5%



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6. In Conclusion

- Absence of history, data and experience with voltage-source HVDC
  - Offshore/ MMC
- No defined standards
  - Hardware or Control
- Intra-operability issue (for multi-manufacturer systems)
- Developing technology
- Unavailability: cables, instrumentation and software, transformers
- Reliability: Big question is how to manage multi-terminal

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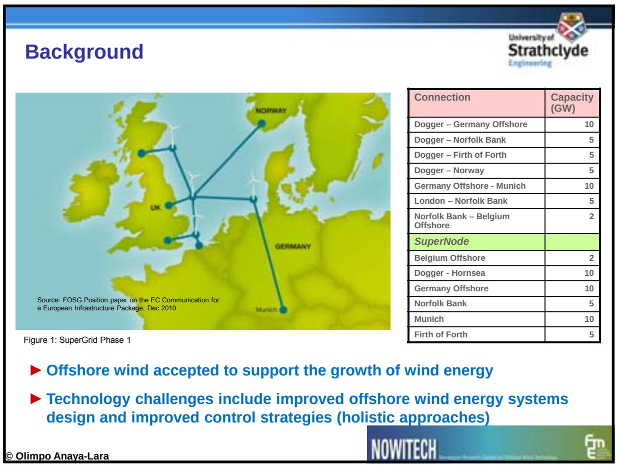
Control challenges and opportunities for large offshore wind farms

Olimpo Anaya-Lara, University of Strathclyde/NTNU
John O. Tande, SINTEF Energy Research
Kjetil Uhlen, NTNU
Tore Undeland, NTNU



Background

Source: FOSG Position paper on the EC Communication for a European Infrastructure Package, Dec 2010

Figure 1: SuperGrid Phase 1

Connection	Capacity (GW)
Dogger – Germany Offshore	10
Dogger – Norfolk Bank	5
Dogger – Firth of Forth	5
Dogger – Norway	5
Germany Offshore - Munich	10
London – Norfolk Bank	5
Norfolk Bank – Belgium Offshore	2
SuperNode	
Belgium Offshore	2
Dogger - Hornsea	10
Germany Offshore	10
Norfolk Bank	5
Munich	10
Firth of Forth	5

- Offshore wind accepted to support the growth of wind energy
- Technology challenges include improved offshore wind energy systems design and improved control strategies (holistic approaches)

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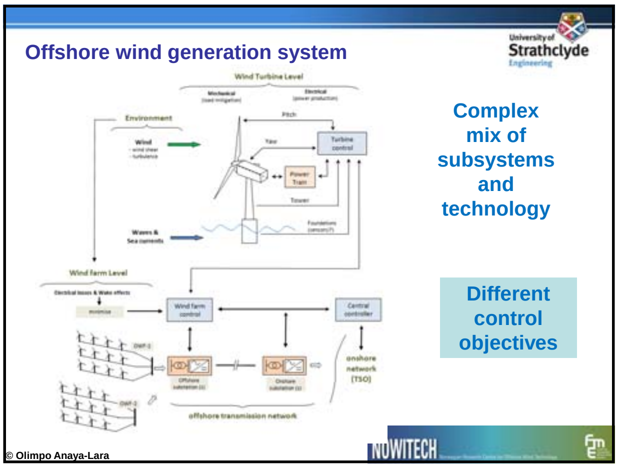

Offshore wind generation system

Complex mix of subsystems and technology

Different control objectives

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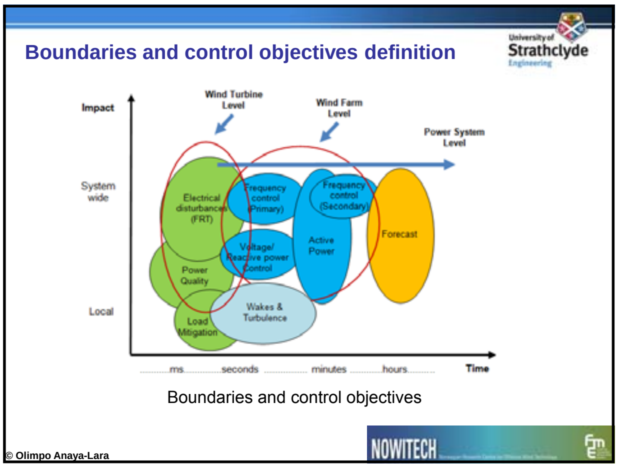

Boundaries and control objectives definition

Boundaries and control objectives

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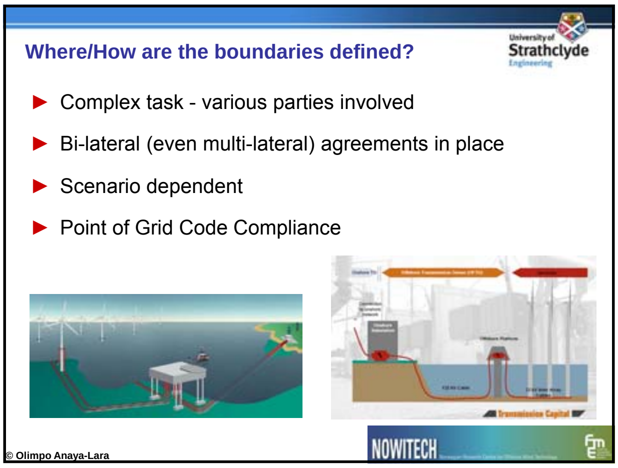

Where/How are the boundaries defined?

- Complex task - various parties involved
- Bi-lateral (even multi-lateral) agreements in place
- Scenario dependent
- Point of Grid Code Compliance

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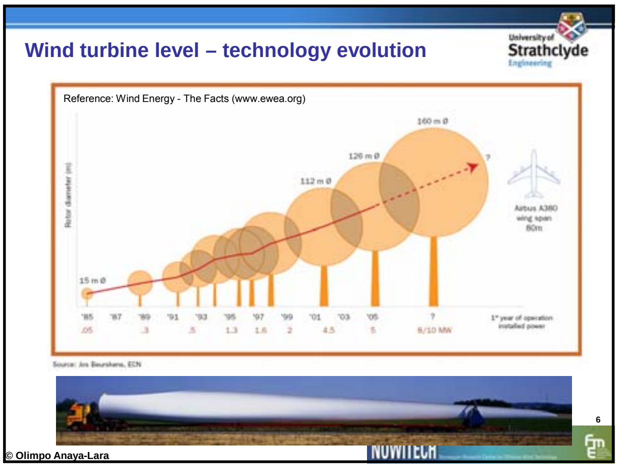

Wind turbine level – technology evolution

Reference: Wind Energy - The Facts (www.ewea.org)

Source: Jos Beurskens, ECN

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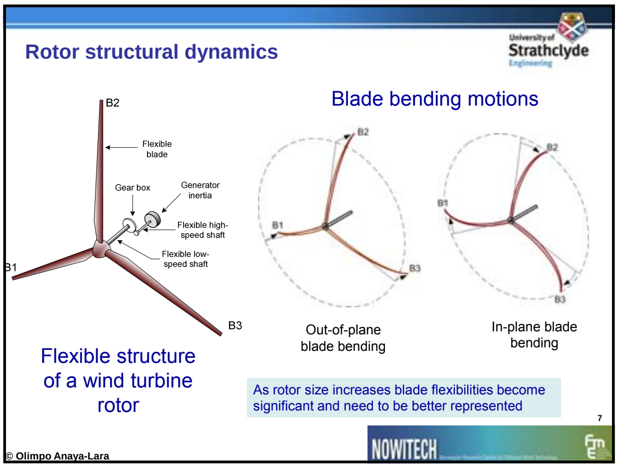


Rotor structural dynamics

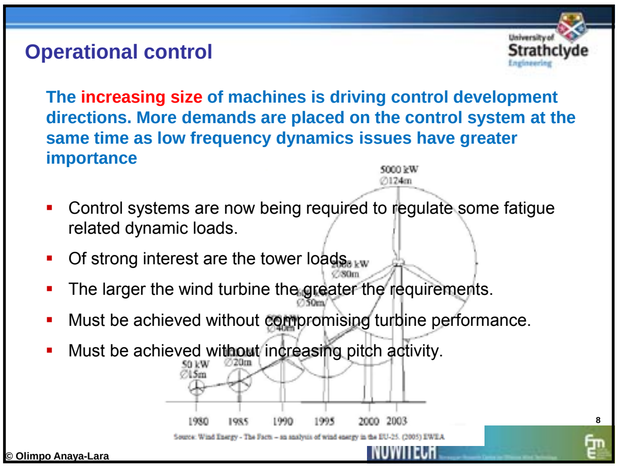
Flexible structure of a wind turbine rotor

Blade bending motions

Out-of-plane blade bending

In-plane blade bending

As rotor size increases blade flexibilities become significant and need to be better represented

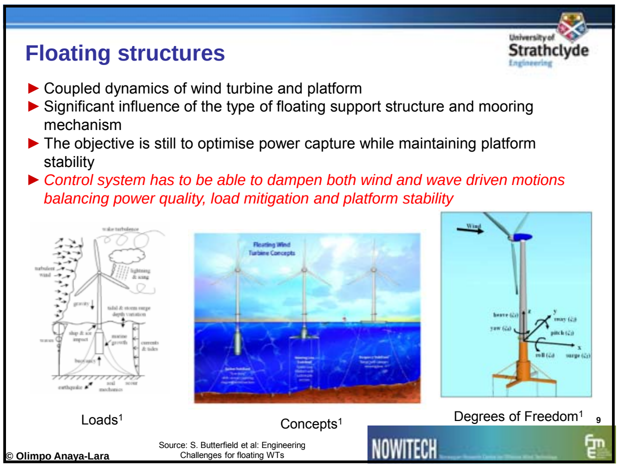


Operational control

The increasing size of machines is driving control development directions. More demands are placed on the control system at the same time as low frequency dynamics issues have greater importance

- Control systems are now being required to regulate some fatigue related dynamic loads.
- Of strong interest are the tower loads.
- The larger the wind turbine the greater the requirements.
- Must be achieved without compromising turbine performance.
- Must be achieved without increasing pitch activity.

Source: Wind Energy - The Facts – an analysis of wind energy in the EU-25. (2005) EWEA



Floating structures

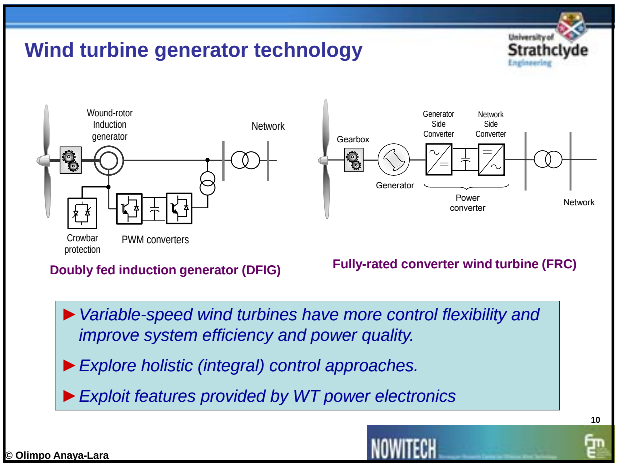
- ► Coupled dynamics of wind turbine and platform
- ► Significant influence of the type of floating support structure and mooring mechanism
- ► The objective is still to optimise power capture while maintaining platform stability
- ► *Control system has to be able to dampen both wind and wave driven motions balancing power quality, load mitigation and platform stability*

Loads[1]

Concepts[1]

Degrees of Freedom[1]

Source: S. Butterfield et al: Engineering Challenges for floating WTs

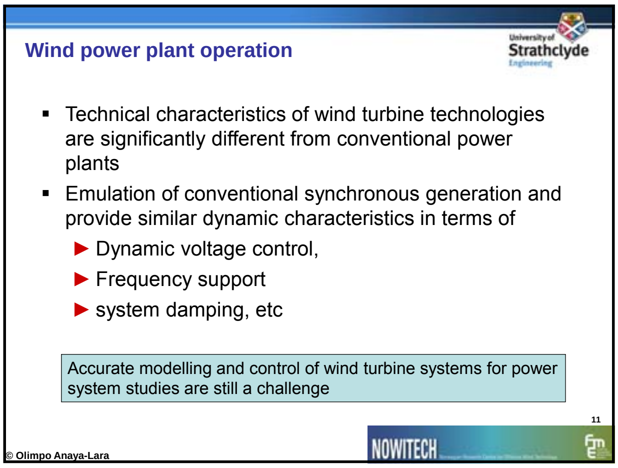


Wind turbine generator technology

Doubly fed induction generator (DFIG)

Fully-rated converter wind turbine (FRC)

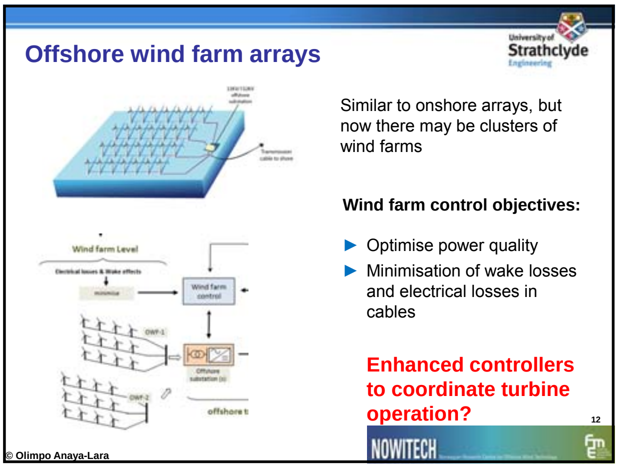
- ► *Variable-speed wind turbines have more control flexibility and improve system efficiency and power quality.*
- ► *Explore holistic (integral) control approaches.*
- ► *Exploit features provided by WT power electronics*



Wind power plant operation

- Technical characteristics of wind turbine technologies are significantly different from conventional power plants
- Emulation of conventional synchronous generation and provide similar dynamic characteristics in terms of
  - ► Dynamic voltage control,
  - ► Frequency support
  - ► system damping, etc

Accurate modelling and control of wind turbine systems for power system studies are still a challenge



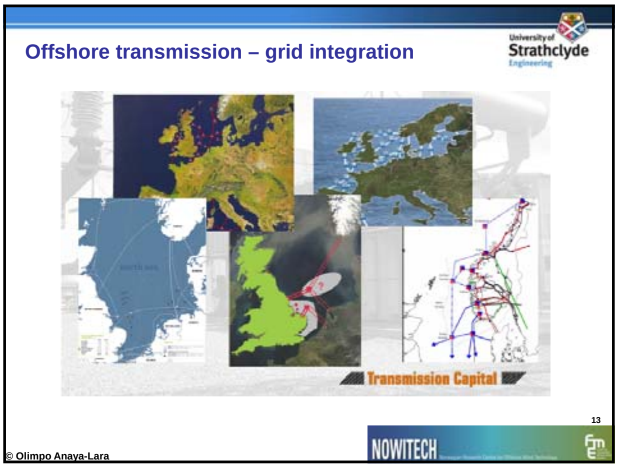
Offshore wind farm arrays

Similar to onshore arrays, but now there may be clusters of wind farms

Wind farm control objectives:

- ► Optimise power quality
- ► Minimisation of wake losses and electrical losses in cables

Enhanced controllers to coordinate turbine operation?



Offshore transmission – grid integration

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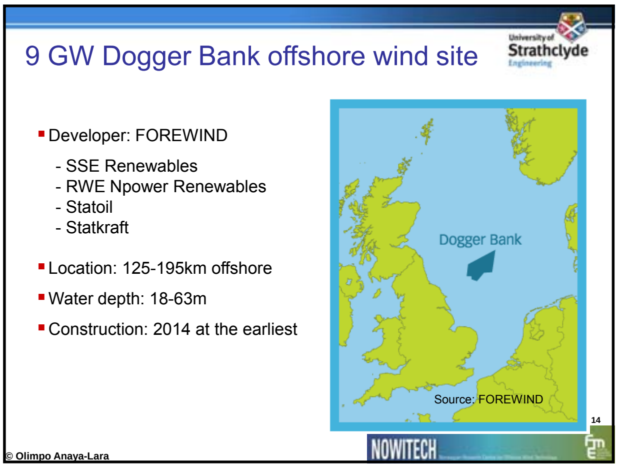

9 GW Dogger Bank offshore wind site

- Developer: FOREWIND
  - SSE Renewables
  - RWE Npower Renewables
  - Statoil
  - Statkraft
- Location: 125-195km offshore
- Water depth: 18-63m
- Construction: 2014 at the earliest

Source: FOREWIND

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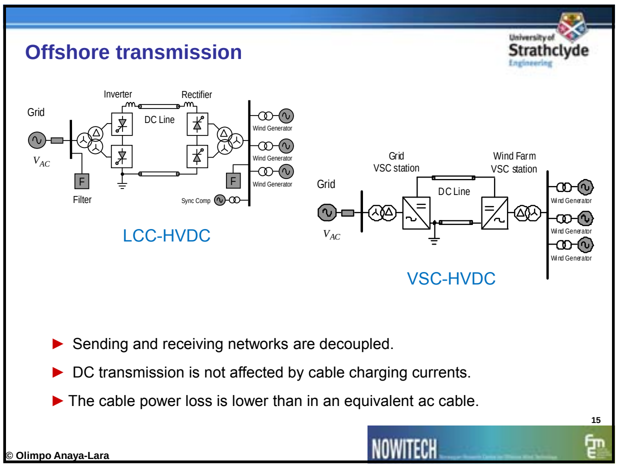

Offshore transmission

LCC-HVDC

VSC-HVDC

- ► Sending and receiving networks are decoupled.
- ► DC transmission is not affected by cable charging currents.
- ► The cable power loss is lower than in an equivalent ac cable.

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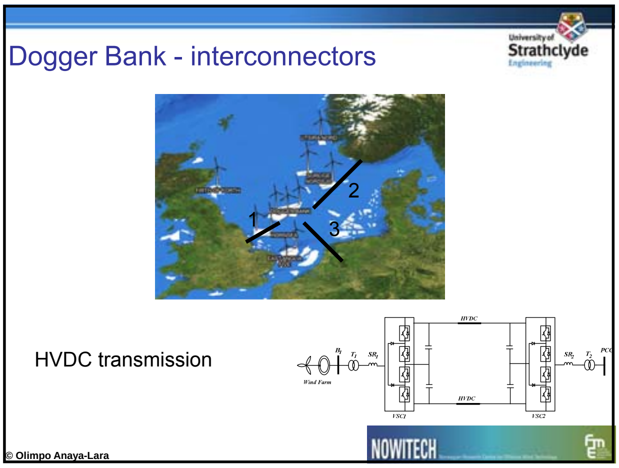

Dogger Bank - interconnectors

HVDC transmission

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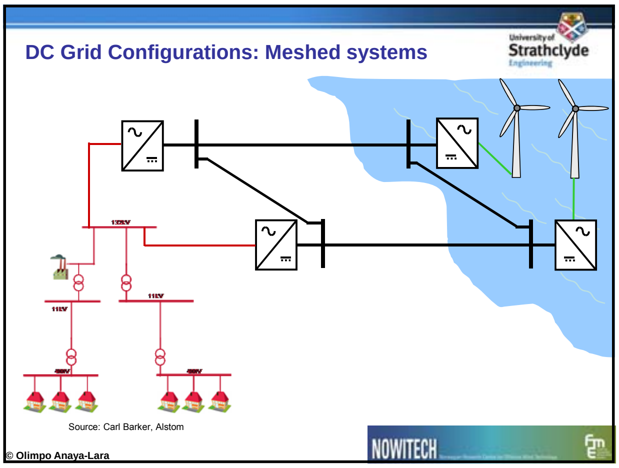

DC Grid Configurations: Meshed systems

Source: Carl Barker, Alstom

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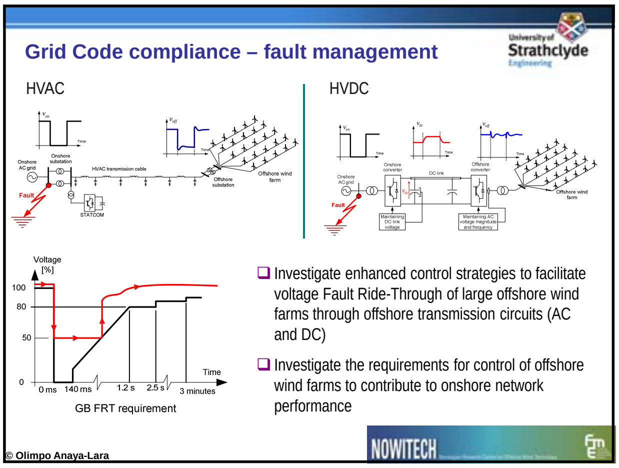

Grid Code compliance – fault management

GB FRT requirement

- ❑ Investigate enhanced control strategies to facilitate voltage Fault Ride-Through of large offshore wind farms through offshore transmission circuits (AC and DC)
- ❑ Investigate the requirements for control of offshore wind farms to contribute to onshore network performance

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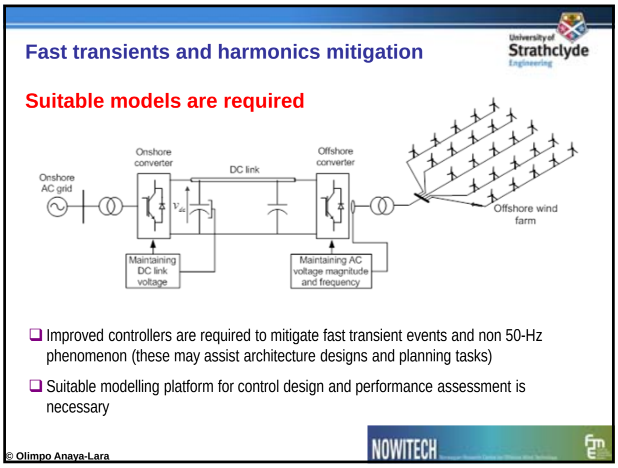

Fast transients and harmonics mitigation

Suitable models are required

- ❑ Improved controllers are required to mitigate fast transient events and non 50-Hz phenomenon (these may assist architecture designs and planning tasks)
- ❑ Suitable modelling platform for control design and performance assessment is necessary

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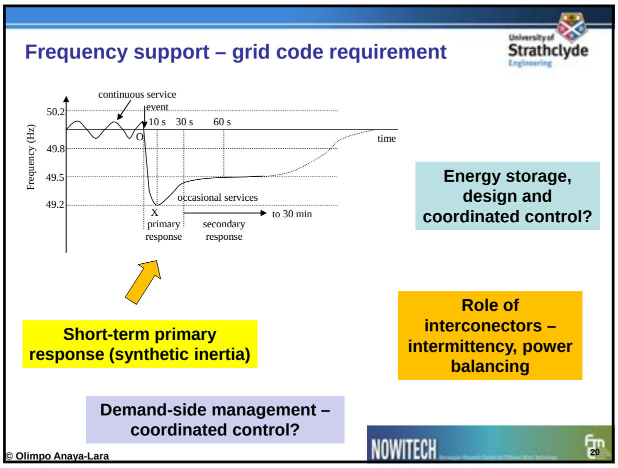

Frequency support – grid code requirement

Energy storage, design and coordinated control?

Short-term primary response (synthetic inertia)

Role of interconectors – intermittency, power balancing

Demand-side management – coordinated control?

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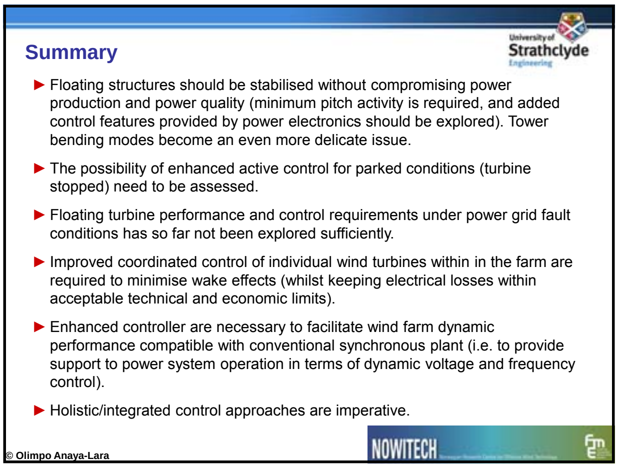

Summary

- ► Floating structures should be stabilised without compromising power production and power quality (minimum pitch activity is required, and added control features provided by power electronics should be explored). Tower bending modes become an even more delicate issue.
- ► The possibility of enhanced active control for parked conditions (turbine stopped) need to be assessed.
- ► Floating turbine performance and control requirements under power grid fault conditions has so far not been explored sufficiently.
- ► Improved coordinated control of individual wind turbines within in the farm are required to minimise wake effects (whilst keeping electrical losses within acceptable technical and economic limits).
- ► Enhanced controller are necessary to facilitate wind farm dynamic performance compatible with conventional synchronous plant (i.e. to provide support to power system operation in terms of dynamic voltage and frequency control).
- ► Holistic/integrated control approaches are imperative.

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Coordinated control between wind and hydro power systems through HVDC links

by
Atsede G. Endegnanew
E. V. Øyslebø
D. Huertas-Hernando
B.H. Bakken
SINTEF Energy Research

DeepWind, 19-20 January 2012, Trondheim, Norway

Introduction

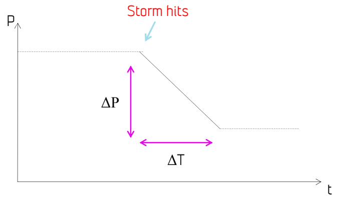
- Demonstrate secure power system control using hydro power plants in Norway to balance storm shut down of a wind farm in Denmark
- Three control systems applied to different part of the power system
  - Wind farm
  - HVDC cables
  - Hydro power units
- Coordinated control to improve system dynamic performance

Model description

- Nordic synchronous power system: Norway, Sweden, Eastern Denmark, and Finland
- Continental European synchronous system: West Denmark and rest of UCTE
- Aggregated generation and load
- UCTE denoted by a single bus
- Primary control: 6% droop and ±0.2 Hz
- Wind farms are modeled as a negative load
- Initial power flows on the HVDC lines are taken from from NordPool data from 11 November 2010

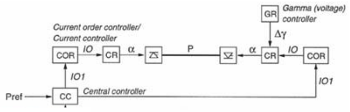
Storm Controller

- Implemented in each wind turbine
- Delay ramping to zero
- Shut down is modelled with power production change ΔP and time span ΔT
- Average wind speeds above 25 m/s



HVDC Controller

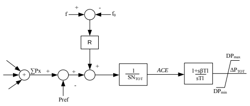
- Same basic control topology as the original structure
- Constant current control mode



- The central controller has an additional input ΔP
  - compensate for a given power imbalance
  - ΔP signal comes from Ramp Following Controller (RFC)

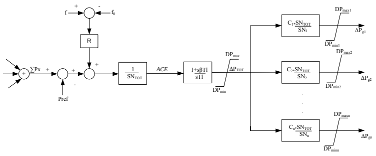
Ramp Following Controller (RFC)

- Two inputs: frequency deviation and power flow deviation
- Gets signal from ACE in two interconnected areas, change in load, change in production or flow on HVDC
- HVDC cable track changes in wind power production



Load Frequency Controller (LFC)

- Area control error (ACE) shared among several generators
- Generators contribute according to their ratings

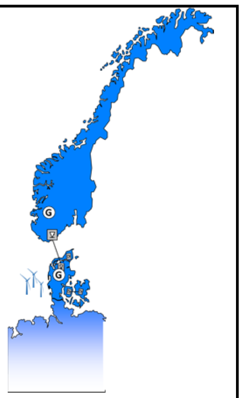


Studied Cases (1)

- Two cases
  - Case A: Horns Rev 2 => ΔP=209 MW
  - Case B: Six (planned) offshore wind farms => ΔP=2000 MW
- Initial power flow
  - German-Danish border
  - HVDC links: from West Denmark to the Nordic system
- Shut down from full production to zero production in 15 minutes
- Studied results
  - Power flows on German-Danish border and HVDC links
  - Nordic frequency
  - Generating units in Denmark and Norway

Studied Cases (2)

- LFC in Danmark:
  - ± 90 MW capacity
  - Three largest thermal generators
  - Monitor the German-Danish border flows
- LFC in Norway
  - ± 375 MW capacity
  - 3 aggregated hydro power plants
  - Monitor the AC-transmission with Sweden and HVDC connections with Denmark



Simulation Results (1)

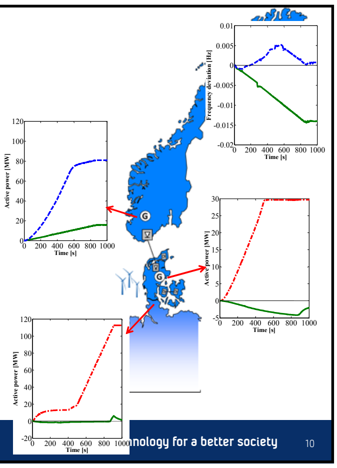
Case A => ΔP=209 MW

- RFC-HVDC-control and LFC in Denmark removes German-Danish border imbalance
- Nordic frequency deviation can be avoided by using LFC controllers in Norway

🟥 LFC in Denmark

🟩 HVDC control + LFC in Denmark

🟦 HVDC control + LFC in Denmark + LFC in Norway



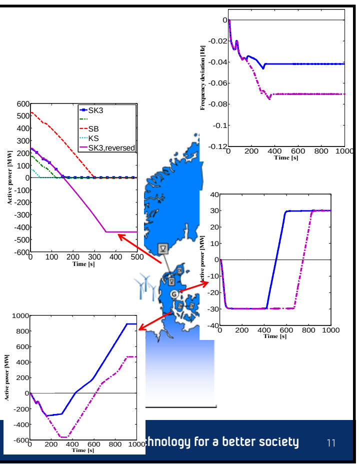
Simulation Results (2)

Case B => ΔP=2000 MW

- Excess power observed in the Western Danish power system
- Reversing the power flow on SK3 reduces the steady state imbalance at the German-Danish border
- Nordic frequency deviation remains within allowed limits

HVDC control + LFC in Denmark + LFC in Norway

HVDC control, SK3 reversed + LFC in Denmark + LFC in Norway



Conclusion

- Coordination between the controllers either removes (Case A) or significantly reduces (Case B) the power imbalance
- Nordic frequency deviations can be avoided/reduced by using LFC in Norway
- Reversing power flow on Skagerrak3 helps in reducing the German-Danish border imbalance but increases the frequency deviation in the Nordic synchronous system
- Exporting the imbalance to Norway is feasible and advantageous to the West Danish power system.
- The presented balancing actions require reservation of capacity on HVDC links and hydro generation units in Norway if they were to be implemented in the real system

Thank You for your attention!

Questions?

Temporary Rotor Inertial Control of Wind Turbine to Support the Grid Frequency Regulation

Bing Liu, Kjetil Uhlen, Tore Undeland

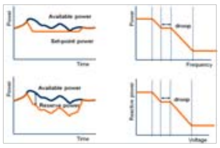
Department of Electric Power Engineering, NTNU

The 9th Deep Sea Offshore Wind R&D Seminar
19-20 January 2012, Trondheim, NORWAY

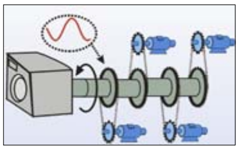
Why power system needs inertial control?

Frequency control by keeping balance between generation and consumption.

Long term balance : by power reservation



Short term balance : by rotating kinetic energy



This study focuses on variable speed wind turbine's capability of providing inertia response to support the grid frequency regulation, especially for short-term frequency drop in low inertia grid.

Frequency control requirements to wind turbines

Nordic Grid Code 2007:

Frequency control. Automatic control of the **wind turbine** active production as a function of the system frequency must be possible. The control function must be proportional to frequency deviations and must be provided with a dead-band. The detailed settings will be provided by the TSO.

Hydro-Québec requires **wind farm** to be able to contribute to reduce large (0.5 Hz), short-term (10 s) frequency deviation.*

* Technical Requirements for the Connection of Generation Facilities to the Hydro-Québec Transmission System: Supplementary Requirements for Wind Generation, Hydro-Québec, Tech. Rep., May 2003, revised 2005.

What is inertia?

Typical 2.0 MW wind turbine has:

Inertia is the resistance of physical object to a change in its state of motion. *
Rotating objective inertia:
$J = m r^2$

⇨ $J_{\text{wind turbine}} = 40k * (37.5/3)^2$
$= 6.25 * 10^6$ Kg.m^2

Energy stored in rotor mass:
$E = 0.5 J \omega_m^2$

⇨ $E_{\text{wind turbine}} = 0.5 J \omega_m^2$
$= 0.5 * J * 1.75^2$
$= 9.57 * 10^6$ J =

20 ton

@ 80km/h

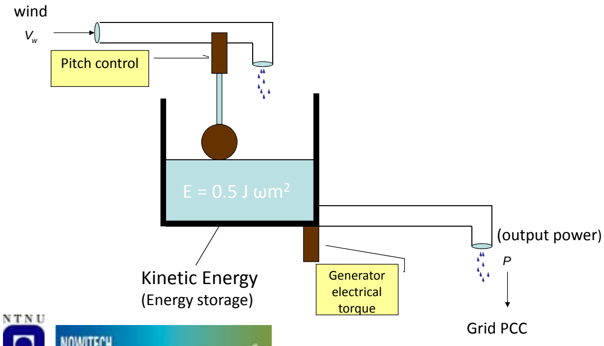
Inertia Constant is defined as the kinetic energy stored in the rotor at rated speed divided by the VA base.
$H = E/S = 0.5 J \omega_m^2 / S$

⇨ $H = E/S = 4.79$ s

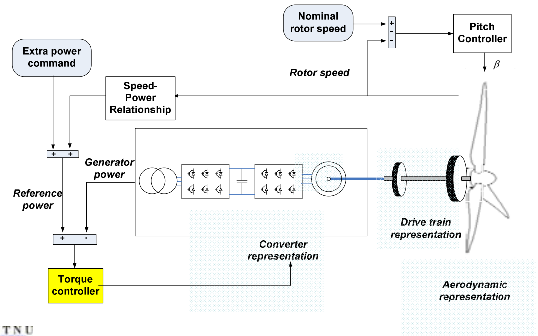
Similar as conventional power generation

* From Wikipedia

Inertial Control is similar as Liquid Level System

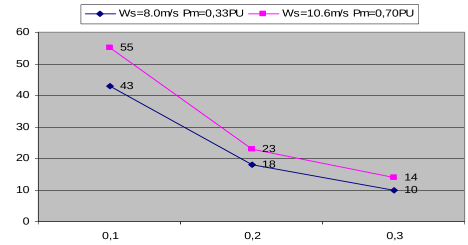


Wind turbine modeling for inertial control



How is the inertial control ability?

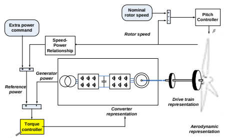
Y: Time before reach minimal 70% rotor speed (s)
X: extra power reference in PU

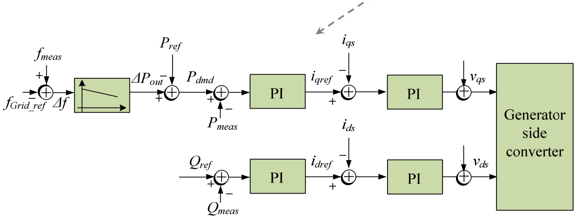


WTG Rating	5 MW
Control	Variable Speed, collective Pitch
Rotor Diameter	126 m
Hub Height	90 m
Rated Tip speed	80 m/s

Vector Controller for generator side converter

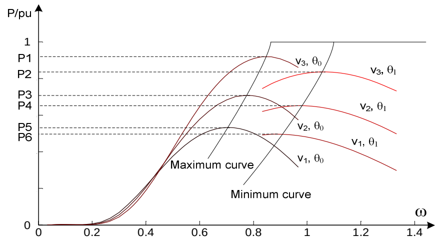
-Torque Control executed in *q* axis.
-Faster than load angle control strategy*.



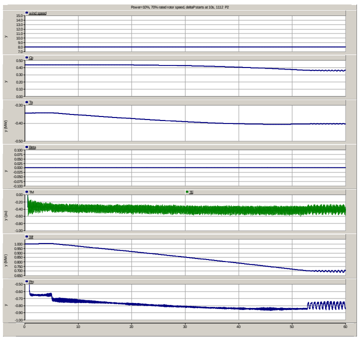


* P109, Wind Energy Generation: Model and Control, Olimpo A. et al.

Power reservation by pitching for long-term frequency response



Simulation: Wind turbine parameters when Power reference=110%, starts at 10s.



Wind speed (m/s)

Power co efficiency

Air dynamic torque (PU)

Pitch angle

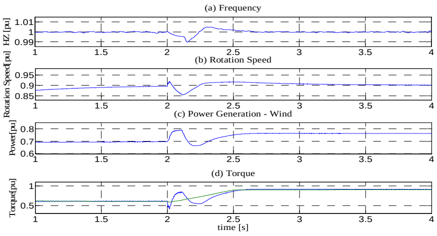
Generator mechanic torque (PU)

Power output (MW)

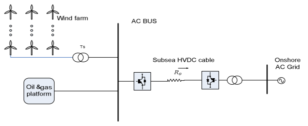
Rotor speed (PU)

0 s Time (s) 60 s

Frequency response with pitch control and inertial response control combined method implemented



Rated (base) apparent power	400 MVA	1.0 pu
Rated (base) voltage, offshore AC	115 kV	1.0 pu
Rated (base) voltage, HVDC link	120 kV	1.0 pu
System Frequency f_{ref}	50 HZ	1.0 pu
150-km dc transmission line		
Resistance per km	0.0217	
Inductance per km	0.792mH	



How to make wind parks “grid frequency friendly” ?

- ✓Wind parks need react to changes in grid frequency
- ✓Short-term inertial response capability is limited
- ✓Need to combine with long-term pitch control

Thanks!

感謝！

Temporary Rotor Inertial Control of Wind Turbine to Support the Grid Frequency Regulation

Bing Liu, Kjetil Uhlen, Tore Undeland

Department of Electric Power Engineering, NTNU

The 9th Deep Sea Offshore Wind R&D Seminar
19-20 January 2012, Trondheim, NORWAY

DeepWind 2012 – Trondheim Jan. 19th 2012

Stability Improvements in Oil Platforms from Wind Turbines

Atle Rygg Årdal
Research Scientist
SINTEF Energy Research

Co-authors: Kamran Sharifabadi (Statoil), Tore Undeland (NTNU)

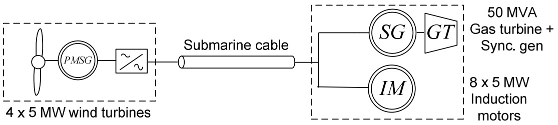
Agenda

- Background/Motivation
- Case Description
- Voltage Source Converters in WTGs
- WTG Frequency Control
- WTG Voltage Control
- Conclusions

Background/Motivation

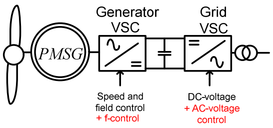
- Master Thesis at NTNU + research work in NOWITECH
- Small isolated power systems
  - Need for stability improvement
- Benefits from interconnecting WTGs with oil platforms? How?

Case Description



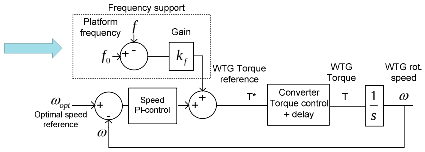
- PSCAD/EMTDC simulation study
- Conventional oil platform power system control
  - Automatic Voltage Control + Governor Droop Control
- Control time-delays weaken transient response…

Voltage Source Converters in WTGs

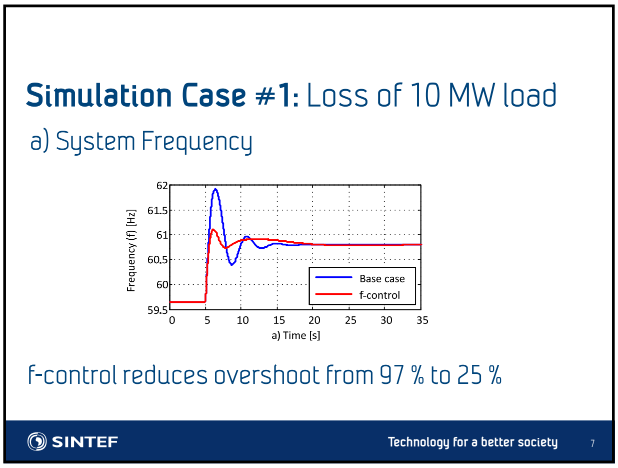


- Enables variable speed operation
- Fast and decoupled control to generator and grid
- Independent control of reactive power
- Control strategies to achieve stability improvements?

WTG Frequency Control



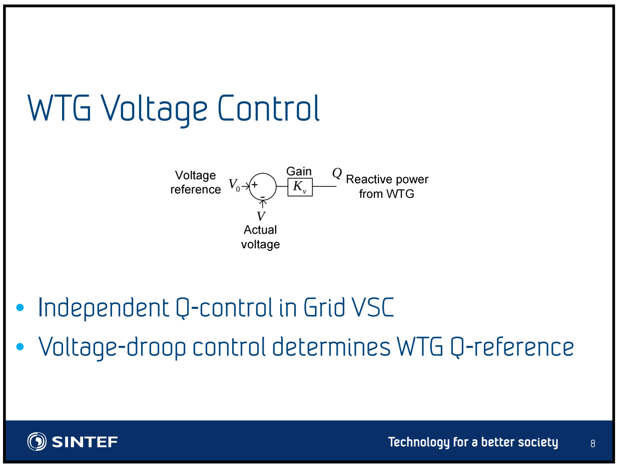
- Vector control of torque/speed (Generator VSC)
- Additional frequency su pport with droop gain



Simulation Case #1: Loss of 10 MW load

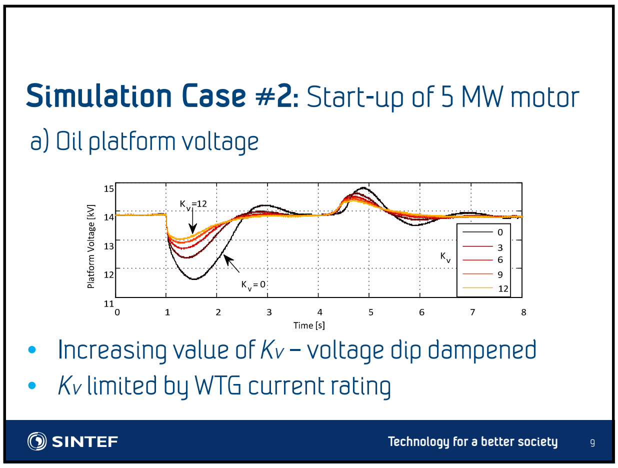
a) System Frequency

f-control reduces overshoot from 97 % to 25 %



WTG Voltage Control

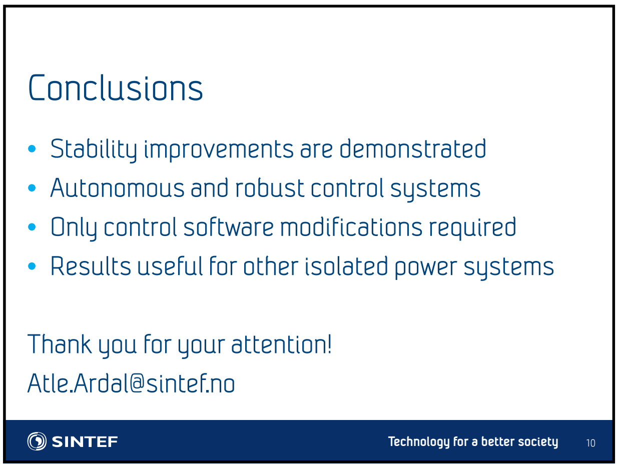
- Independent Q-control in Grid VSC
- Voltage-droop control determines WTG Q-reference



Simulation Case #2: Start-up of 5 MW motor

a) Oil platform voltage

- Increasing value of K_v – voltage dip dampened
- K_v limited by WTG current rating



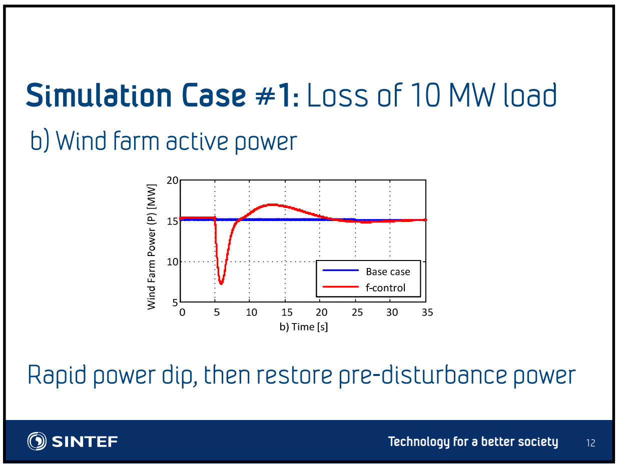
Conclusions

- Stability improvements are demonstrated
- Autonomous and robust control systems
- Only control software modifications required
- Results useful for other isolated power systems

Thank you for your attention!

Atle.Ardal@sintef.no

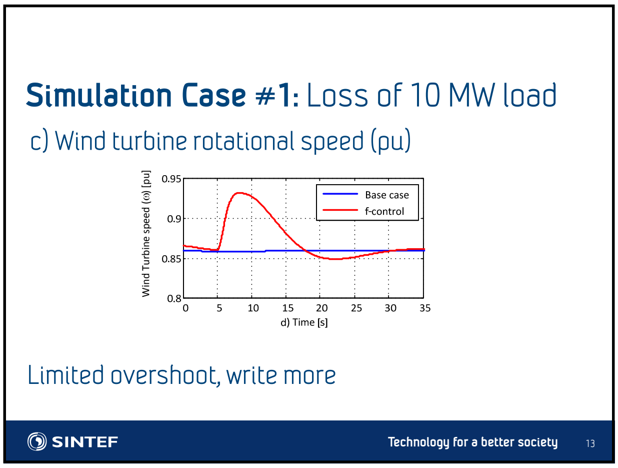
Additional slides…….



Simulation Case #1: Loss of 10 MW load

b) Wind farm active power

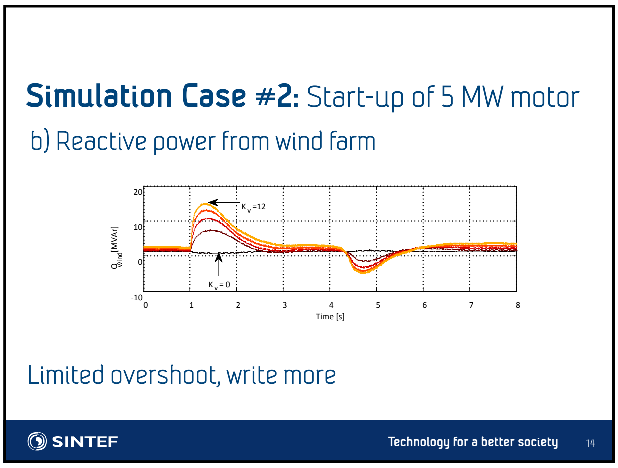
Rapid power dip, then restore pre-disturbance power



Simulation Case #1: Loss of 10 MW load

c) Wind turbine rotational speed (pu)

Limited overshoot, write more



Simulation Case #2: Start-up of 5 MW motor

b) Reactive power from wind farm

Limited overshoot, write more

B2 Grid connection

Modelling and control of Multi-terminal VSC HVDC systems,
Jef Beerten, PhD stud, University of Leuven

Fault-ride-through testing of wind turbines, Helge Seljeseth, SINTEF Energi AS

Wind turbine model validation with measurements,
Jorun Marvik, SINTEF Energi AS

The Assessment of Overvoltage protection in Offshore Wind Farms,
Amir H. Soloot, PhD stud, NTNU

KATHOLIEKE UNIVERSITEIT
LEUVEN

Modeling and control of Multi-terminal VSC HVDC Systems

Jef Beerten

University of Leuven (KU Leuven), Belgium

VSC HVDC at KU Leuven

prof. Ronnie Belmans & prof. Dirk Van Hertem

- PhD projects
  - VSC HVDC in AC meshed grids (Stijn Cole, finished 2010)
  - Integration of Multi-terminal VSC HVDC (Jef Beerten)
  - Optimal investment strategies for offshore wind (Hakan Ergun)
  - …
- Projects (2006 – …)
  - Randstad HVDC (2006 – 2007)
  - BelGer – Nemo (2006 – 2007)
  - Imera power (2007 – 2009)

VSC HVDC at KU Leuven

- Member of CIGRE WG on HVDC (2006 – …)
  - B4.46 – Economic Aspects of VSC HVDC
  - B4.52 – DC Grids Feasibility Study
  - B4.58 –Load flow and Direct Voltage Control in a HVDC Grid
  - B4/B5.59 – Control and Protection of HVDC Grids
  - C4/B4/C1 - Influence of Embedded HVDC Transmission on System Security and AC Network Performance
- Master thesis (2008 - …)
  - Loss minimization (Gilles Daelemans*)
  - Economics of AC and DC wind farm connections (Bram Van Eeckhout*)
  - MTDC protection (Kenny De Kerf*)
  - Connecting Belgium and th UK (Frederik Leung Shun*)
  - VSC HVDC Connected variable speed operated wind farms (Pieter Hellings)
  - DC voltage control (Carlos Dierckxsens*)
  - HVDC connected large-scale solar plants (Philippe Hoylaerts*)
  - Multi-terminal HVDC and wind (Stijn Vandenbroucke*)

**: in cooperation with ABB Sweden*

VSC HVDC at KU Leuven
Publications: Journal

- Beerten J., Cole S., Belmans R.: "Generalized Steady-State VSC MTDC Model for Sequential AC/DC Power Flow Algorithms.," IEEE Transactions on Power Systems, accepted for publication., 2012.
- Dierckxsens C, Srivastava K., Reza M., Cole S., Beerten J., Belmans R.: "A Distributed DC Voltage Control Method for VSC MTDC Systems," Journal: Electric Power Systems Research, vol. 82,, 2012; pp.54– 58.
- De Kerf K., Srivastava K., Reza M., Bekaert D., Cole S., Van Hertem D., Belmans R.: "Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems," IET GTD, April, 2011; pp. 496 - 503.
- Buijs P., Bekaert D., Cole S., Van Hertem D., Belmans R.: " Transmission investments in Europe: Going beyond standard solutions," Energy Policy: volume 39, issue 3, 2011; pp. 1794-1801.
- Van Hertem D., Ghandhari M.: "Multi-terminal VSC HVDC for the European supergrid: Obstacles," Renewable and Sustainable Energy Reviews, Volume 14, Issue 9, ISSN 1364-0321, 2011; pp. 3156-3163.
- Cole S., Beerten J., Belmans R.: "Generalized Dynamic VSC MTDC Model for Power System Stability Studies," IEEE Trans. on Power Systems, vol.25, no.3, August, 2010; pp. 1655-1662.
- Cole S., Belmans R.: " Transmission of bulk power. The History and Applications of Voltage-Source Converter High-Voltage Direct Current Systems. ," IEEE Industrial Electronics Magazine , September 2009, 2009; pp. 19-24.
- Van Eeckhout B., Van Hertem D., Reza M., Srivastava K., Belmans R.: "Economic comparison of VSC HVDC and HVAC as transmission system for a 300 MW offshore wind farm," ETEP, 2009

VSC HVDC at KU Leuven
Publications: Conference I

- Ergun H., Van Hertem D., Belmans R.: "Multi level optimization for offshore grid planning.," Cigrè International Symposium The Electric Power System of the future, Integrating supergrids and microgrids., Bologna-Italy, September 13-16, 2011.
- Beerten J., Van Hertem D., Belmans R.: "VSC MTDC Systems with a Distributed DC Voltage Control - A Power Flow Approach," Proc. IEEE PowerTech 2011, Trondheim, Norway, June 19-23, 2011
- Leung Shun E., Reza M., Srivastava K., Cole S., Van Hertem D., Belmans R.: "Influence of VSC HVDC on Transient Stability: Case study of the Belgian grid," , July 29, 2010
- Ergun H., Van Hertem D., Belmans R.: "CoST Of Wind - Appropriate Connection Selection Tool for Offshore Wind Farms," International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks or Offshore Wind Power Plants, Quebec, October 18-19, 2010
- Van Hertem D., Eriksson R., Söder L., Ghandhari M.: "Coordination of Multiple Power Flow Controlling Devices in Transmission Systems," IET ACDC edition:9, London, UK, October 20-21, 2010
- Westermann D., Van Hertem D., Küster A., Klöckl B., Atmuri R., Rauhala T.: "Voltage Source Converter (VSC) HVDC for Bulk Power Transmission – Technology and Planning Method," IET ACDC edition:9, London, UK, October 20-21, 2010
- Beerten J., Cole S., Belmans R.: "Implementation Aspects of a Sequential AC/DC Power Flow Computation Algorithm for Multi-terminal VSC HVDC Systems," Proc. IET ACDC2010, London, October 20-21, 2010

VSC HVDC at KU Leuven
Publications: Conference II

- Beerten J., Cole S., Belmans R.: "A Sequential AC/DC Power Flow Algorithm for Networks Containing Multi-terminal VSC HVDC Systems.," IEEE PES GM'10.
- Daelemans G., Srivastava K., Reza M., Cole S., Belmans R.: "Minimization of steady state losses in meshed networks using VSC HVDC," IEEE PES GM'09.
- Buijs P., Cole S., Belmans R.: " TEN-E revisited: opportunities for HVDC technology," EEM'09, Leuven, Belgium, May 27-29, 2009; 6 pages.
- Cole S., Van Hertem D., Belmans R.: " VSC HVDC as an Alternative Grid Investment in Meshed Grids," ICIS, Rotterdam, The Netherlands, 10-12 November, 2008; 6 pages.
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- Cole S., Van Hertem D., Pardon I., Belmans R.: " Randstad HVDC: A Case Study of VSC HVDC Bulk Power Transmission in a Meshed Grid," Security and Reliability of Electric PowerSystems, Cigré regional meeting, Tallinn, Estonia , June 18-20 , 2007; pp. 83-89.
- Cole S., Van Hertem D., Belmans H.: " Connecting Belgium and Germany using HVDC: A
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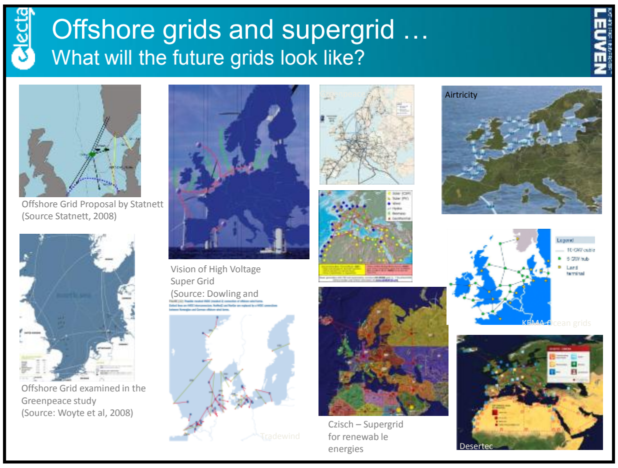
- July 2007 , 2007; 5 pages.
- Van Hertem D., Verboomen J., Cole S., Kling W., Belmans R.: " Influence of phase shifting transformers and HVDC on power system losses," IEEE PES 2007.



Offshore grids and supergrid …
What will the future grids look like?

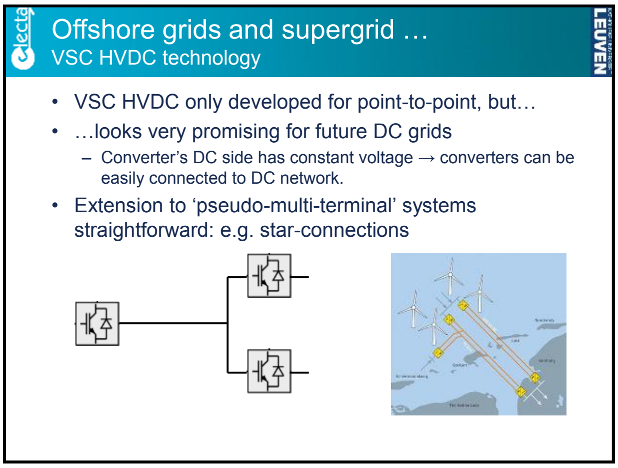
Offshore Grid Proposal by Statnett
(Source Statnett, 2008)

Vision of High Voltage
Super Grid
(Source: Dowling and

Airtricity

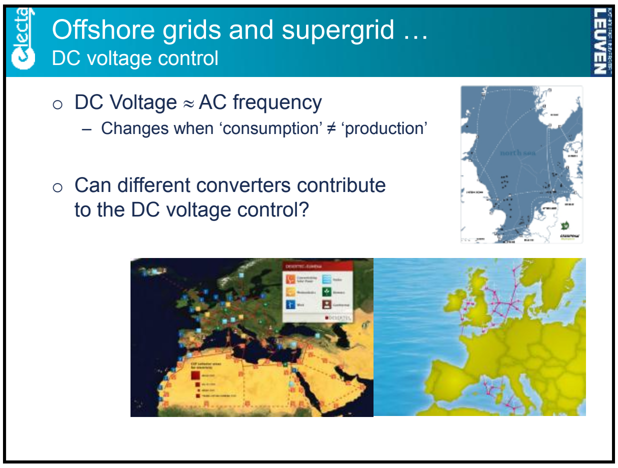
Offshore Grid examined in the
Greenpeace study
(Source: Woyte et al, 2008)

Czisch – Supergrid
for renewab le
energies



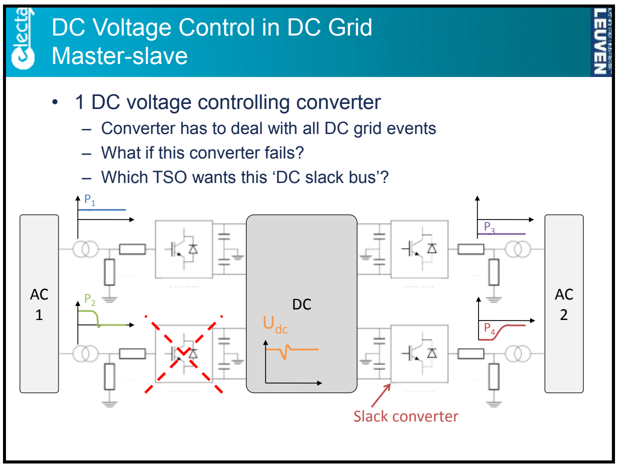
Offshore grids and supergrid …
VSC HVDC technology

- VSC HVDC only developed for point-to-point, but…
- …looks very promising for future DC grids
  - Converter's DC side has constant voltage → converters can be easily connected to DC network.
- Extension to 'pseudo-multi-terminal' systems straightforward: e.g. star-connections



Offshore grids and supergrid …
DC voltage control

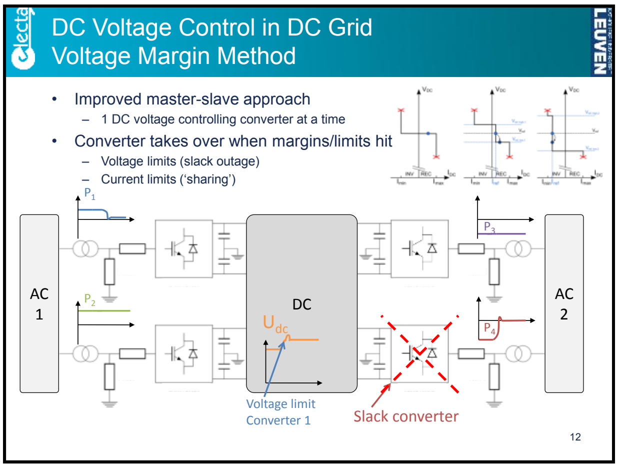
- ○ DC Voltage ≈ AC frequency
  - Changes when 'consumption' ≠ 'production'
- ○ Can different converters contribute to the DC voltage control?



DC Voltage Control in DC Grid
Master-slave

- 1 DC voltage controlling converter
  - Converter has to deal with all DC grid events
  - What if this converter fails?
  - Which TSO wants this 'DC slack bus'?

Slack converter

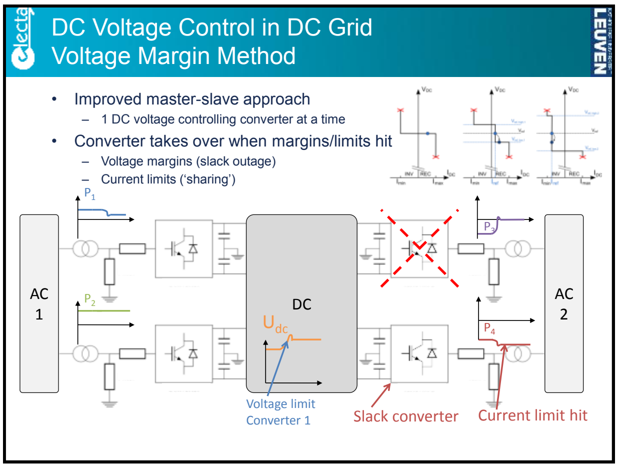


DC Voltage Control in DC Grid
Voltage Margin Method

- Improved master-slave approach
  - 1 DC voltage controlling converter at a time
- Converter takes over when margins/limits hit
  - Voltage limits (slack outage)
  - Current limits ('sharing')

Voltage limit
Converter 1

Slack converter



DC Voltage Control in DC Grid
Voltage Margin Method

- Improved master-slave approach
  - 1 DC voltage controlling converter at a time
- Converter takes over when margins/limits hit
  - Voltage margins (slack outage)
  - Current limits ('sharing')

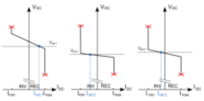
Voltage limit
Converter 1

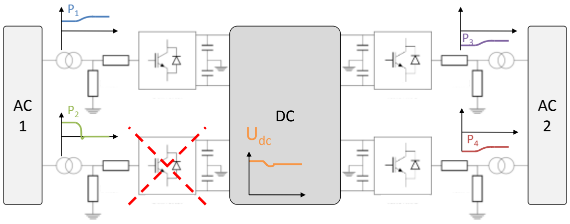
Slack converter

Current limit hit

DC Voltage Control in DC Grid
Voltage droop

- Distributed DC voltage control
  - Often referred to as ‘distributed slack bus’
  - Based on DC voltage droop





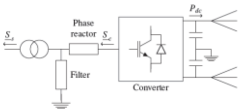
Modeling VSC HVDC Systems

- Steady-state (power flow control)
  - Effect on AC and DC power flows
  - Overall grid state after disturbance
  - N-1 contingency analyses
  - DC voltage droop settings (primary control)
  - Starting point for restorative actions (secondary control)
- Dynamics
  - AC and/or DC system interactions (transient stability)
  - Fast converter dynamics + switching (EMTP)

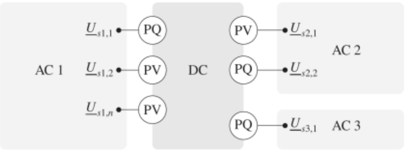
Different time scales
→ different programs and modeling requirements

Power flow modeling

- **Combined/unified approach (AC+DC)**
  - Solution of AC and DC grid together
  - Extension of Jacobian matrix
  - → *Only one iterative problem*



- **Sequential approach (AC, DC)**
  1. Use DC grid variables as inputs to solve the AC equations
  2. Use AC grid variables as inputs to solve the DC equations
  - → *Easy extension of existing power flow programs*



AC/VSC MTDC power flow
DC grid power flow

- DC grid power flow equations:

$$P_{dc_i} = 2U_{dc_i}\sum_{\substack{j=1\\ j\neq i}}^{n} Y_{dc_{ij}}\cdot(U_{dc_i}-U_{dc_j}) \qquad I_{dc_i} = \sum_{\substack{j=1\\ j\neq i}}^{n} Y_{dc_{ij}}\cdot(U_{dc_i}-U_{dc_j})$$

with power-voltage droop

$$P_{dc_i} = P_{dc,0_i} - \frac{1}{k_i}(U_{dc_i}-U_{dc,0_i})$$

with current-voltage droop:

$$I_{dc_i} = I_{dc,0_i} - \frac{1}{k_i}(U_{dc_i}-U_{dc,0_i})$$

- Defining modified active power vector,

$$X_{dc} = [\underbrace{P_{dc_1}}_{\text{slack}}, \underbrace{P_{dc_2}\ldots P_{dc_k}}_{P-\text{control}}, \underbrace{I_{dc,0_{k+1}}\ldots I_{dc,0_l}}_{U-I\text{ droop}}, \underbrace{P_{dc,0_{l+1}}\ldots P_{dc,0_m}}_{U-P\text{ droop}}, \underbrace{0\ldots 0}_{\text{outage}}]^T$$

- the set of equations can be solved using a NR iteration.

$$\left(U_{dc}\frac{\partial X_{dc}}{\partial U_{dc}}\right)^{(j)}\cdot\frac{\Delta U_{dc}}{U_{dc}}^{(j)} = \Delta X_{dc}^{(j)} \qquad \Delta X_{dc_i}^{(j)} = \begin{cases} P_{dc_i}^{(k)} - P_{dc_i}(U_{dc}^{(j)}) & \forall i:\ 2 < i \le k \\ I_{dc,0_i} - I_{dc,0_i}(U_{dc}^{(j)}) & \forall i:\ k \le i \le l \\ P_{dc,0_i} - P_{dc,0_i}(U_{dc}^{(j)}) & \forall i:\ l \le i \le m \\ -P_{dc_i}(U_{dc}^{(j)}) & \forall i:\ m < i \le n \end{cases}$$

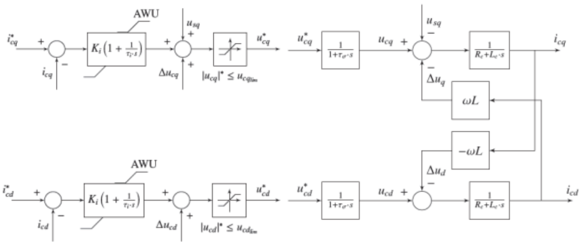
Modeling VSC HVDC Systems

- Steady-state (power flow control)
  - Effect on AC and DC power flows
  - Overall grid state after disturbance
  - N-1 contingency analyses
  - DC voltage droop settings (primary control)
  - Starting point for restorative actions (secondary control)
- Dynamics
  - AC and/or DC system interactions (transient stability)
  - Fast converter dynamics + switching (EMTP)

Different time scales
→ different programs and modeling requirements

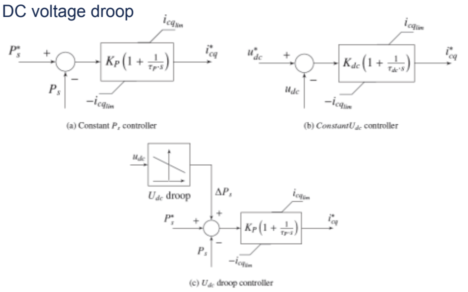
Transient stability modeling

- Converter dynamics
- Power electronics time delay
- Decoupled current control (limits and AWU)



Transient stability modeling

- Outer q control loop
  - Constant active power control
  - Constant DC voltage control
  - DC voltage droop



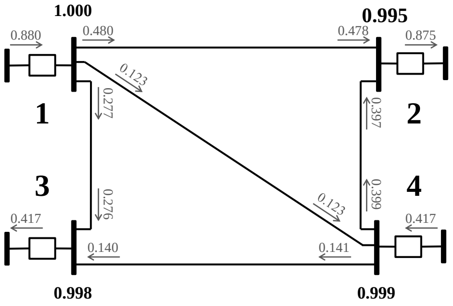
(a) Constant P_s controller

(b) ConstantU_{dc} controller

(c) U_{dc} droop controller

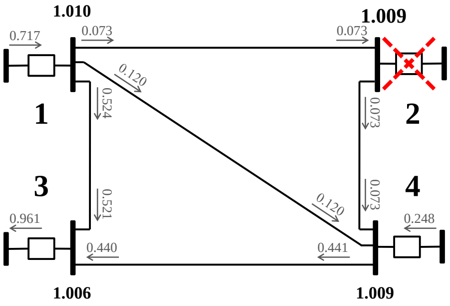
Linking steady-state and dynamics

- DC power flow before converter outage

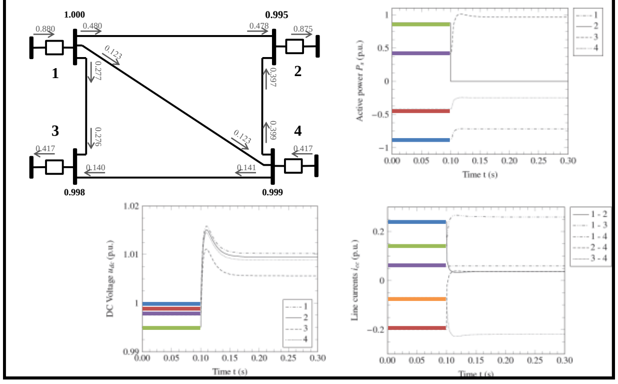


Linking steady-state and dynamics

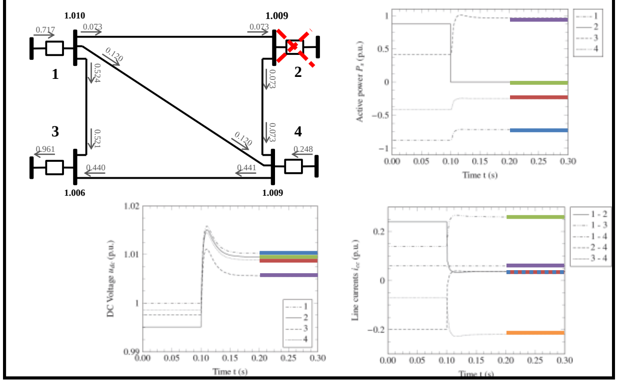
- DC power flow **after** converter outage



Linking steady-state and dynamics



Linking steady-state and dynamics



Conclusions

- Steady-state and dynamic models serve different purposes
  - Power flow algorithms allow to study the post-disturbance effect of control strategies, droop values, limits, … on the steady-state powers and voltage.
  - Transient models allow to study the dynamic interactions between the converters and the dynamic effect of control schemes, droop values, limits, …
- When properly modeled, the results of the power flow analysis are in line with the steady-state post-disturbance dynamic results.

ETEST Mobile test lab

FRT - Fault ride through

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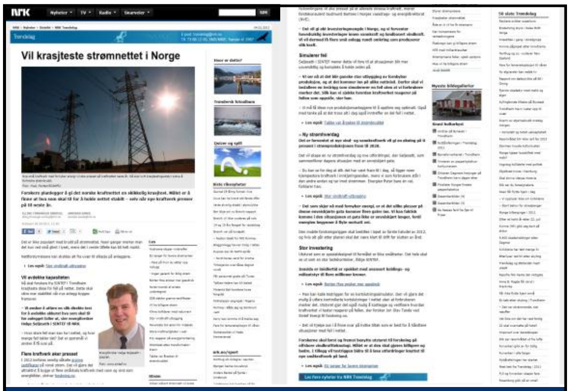

Vil krasjteste strømnettet i Norge

http://www.nrk.no/nyheter/distrikt/nrk_trondelag/1.7811565

Background and Rationale

- Build competence and new knowledge
- Develop and validate numerical tools and technical solutions.
- To test and validate the best measures and technical solutions for desired FRT capabilities
- "On site" real test of generation units:
  - "Ride-through" capabilities
  - Respons in current and voltage during and after voltage dips (faults)
- Useful experiences and knowledge:
  - "Protection optimaliztion"
  - Local network conditions and protection adaption?
- Contribute to cost effective network integration of renewable generation

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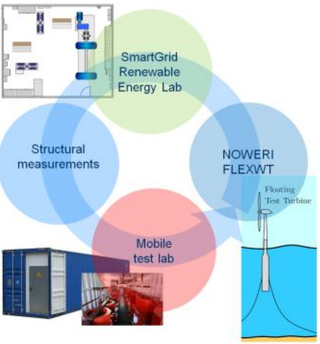

Users:

- Research & Industry

Main Objectives:

- Industrial value creation, and more cost-effective offshore wind farms
- Build competence and gain new knowledge
- Develop and validate numerical tools and technical solutions

Vision:

- an internationally leading research community on offshore wind technology enabling industry partners to be in the forefront

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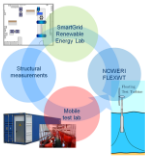
Operation

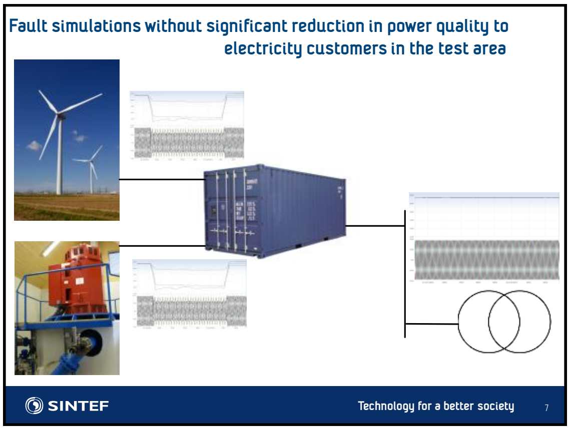
- Research/research projects
- Will be possible to rent for ex. for power companies, network operators and developers and vendors of generation solutions/units.
  - Development purposes
  - Testing/verification of new types of generation units, protection solutions etc
- Testing of:
  - Wind power units
  - Small scale hydropower units
  - …
- Decision are not made on maximum power capabilities for the tests lab
  - Different situation with synchronous machine VS power electronics

---

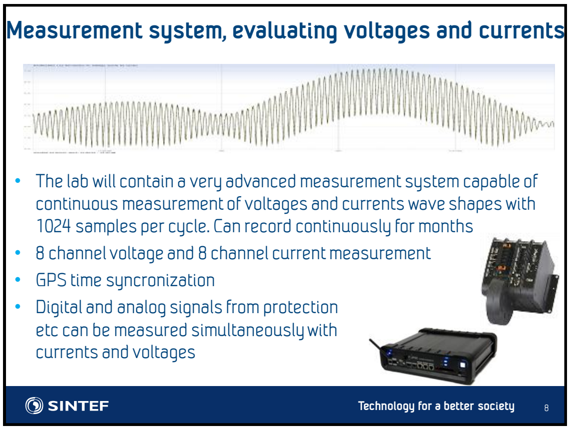
STATUS

- Purchase is 100 % financed by Norwegian Research council
- Operational cost must be covered by research projects and contractual (hired) tests
- Currently reviewing and selecting:
  - Technical solution
  - Power rating
  - Supplier/vendor (price/power rating/volum/weight/functionalities)
- Maximum power probably in the range 4 to 8 MVA
- Target: Final decision and order in February – March and delivery of test lab during autumn 2012



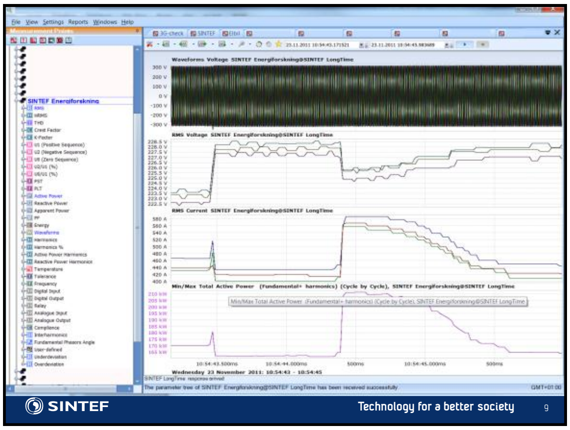


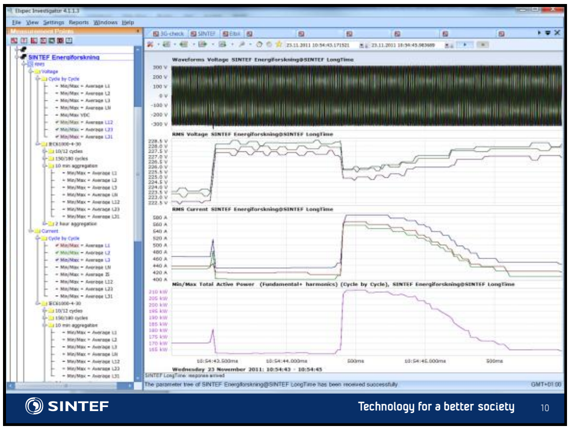
Fault simulations without significant reduction in power quality to electricity customers in the test area

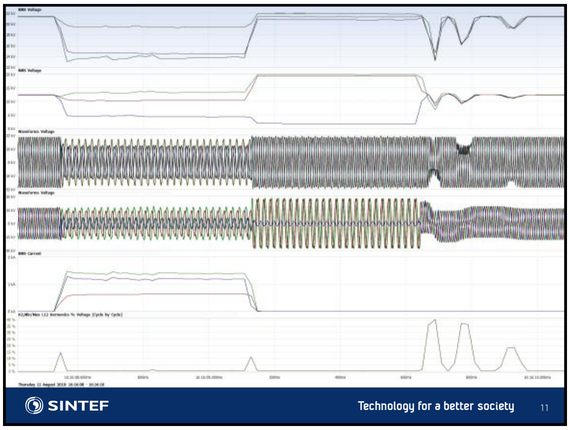


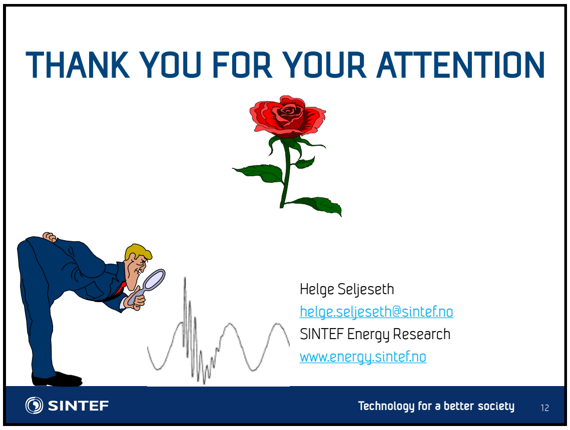
Measurement system, evaluating voltages and currents

- The lab will contain a very advanced measurement system capable of continuous measurement of voltages and currents wave shapes with 1024 samples per cycle. Can record continuously for months
- 8 channel voltage and 8 channel current measurement
- GPS time syncronization
- Digital and analog signals from protection etc can be measured simultaneously with currents and voltages









THANK YOU FOR YOUR ATTENTION

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9th Deep Sea Offshore Wind R&D Seminar, 19-20 January 2012, Trondheim

Wind turbine model validation with measurements

- Comparison between measured and simulated responses to voltage dips in the grid

Jorun Marvik (presenting) and Atsede Endegnanew, SINTEF Energy Research

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Outline

- Background; benchmark test procedure, measurement collection
- Wind turbine 1 model validation results
- Wind turbine 2 model validation results
- Summary/Conclusions

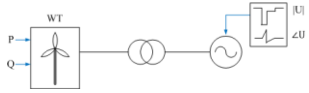
Background

- Important to predict wind turbine responses to grid disturbances
- Grid codes regulate how wind turbines should respond to disturbances in the grid
- Compliance with grid code verified through measurements or simulations
- Model validation to assure that simulation results can be trusted

---

IEA Wind Annex 21 benchmark test procedure

- Required measurements: time-series of instantaneous voltage and current in all three phases → measured voltages and currents are converted to fundamental, positive sequence rms values
- Input to simulations: voltage amplitude and phase angle time series, to controllable voltage source
- Validation: comparing simulated responses of active and reactive power with positive sequence active and reactive power calculated from measured voltages and currents



Measurement collection

- Elspec G4430/G4420 blackbox instruments – continuous sampling of voltage and current in all three phases. Measurements are stored in a central database at SINTEF Energy Research
- Post-processing of data: by instrument software,(Elspec Investigator), and by Matlab toolbox developed at SINTEF Energy Research. Elspec Investigator does not provide the phase angle
- Sampling rate: 51.2 kHz/25.6 kHz
- Time synchronization: GPS/SNTP
- Wind turbine 1: fixed speed turbine, directly connected induction generator
- Wind turbine 2: variable speed turbine (gearless), full-power converter interfaced synchronous generator,

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Outline

- Background; benchmark test procedure, measurement collection
- Wind turbine 1 model validation results
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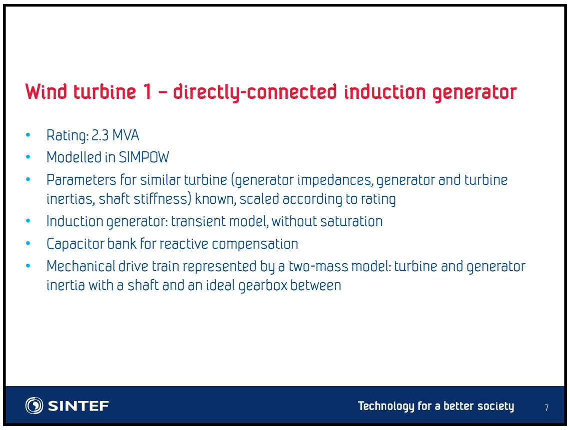
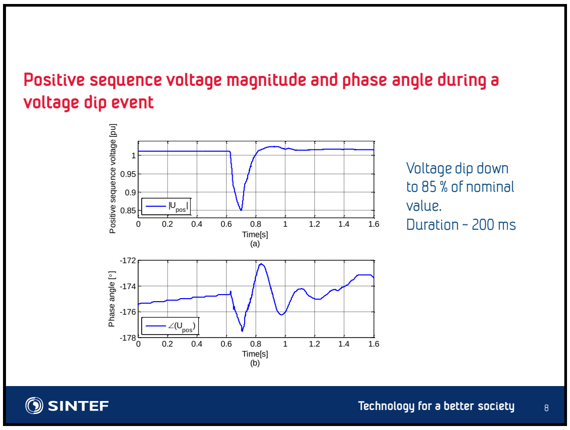
- Summary/Conclusions



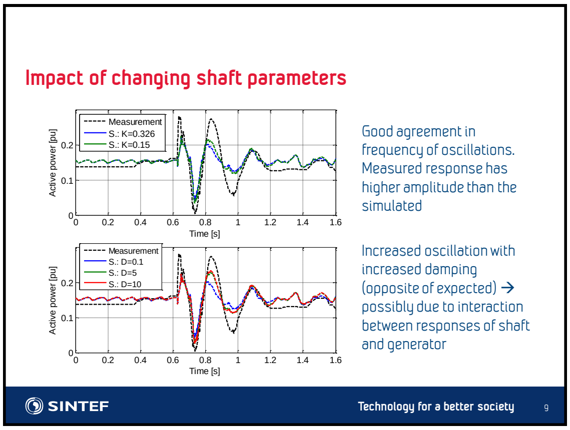
Wind turbine 1 – directly-connected induction generator

- Rating: 2.3 MVA
- Modelled in SIMPOW
- Parameters for similar turbine (generator impedances, generator and turbine inertias, shaft stiffness) known, scaled according to rating
- Induction generator: transient model, without saturation
- Capacitor bank for reactive compensation
- Mechanical drive train represented by a two-mass model: turbine and generator inertia with a shaft and an ideal gearbox between



Positive sequence voltage magnitude and phase angle during a voltage dip event

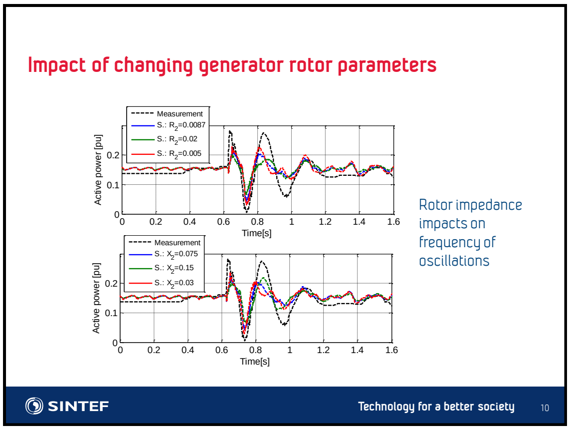
Voltage dip down to 85 % of nominal value.
Duration ~ 200 ms



Impact of changing shaft parameters

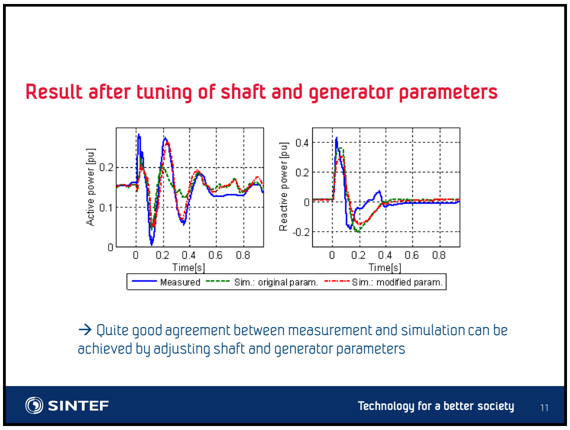
Good agreement in frequency of oscillations. Measured response has higher amplitude than the simulated

Increased oscillation with increased damping (opposite of expected) → possibly due to interaction between responses of shaft and generator



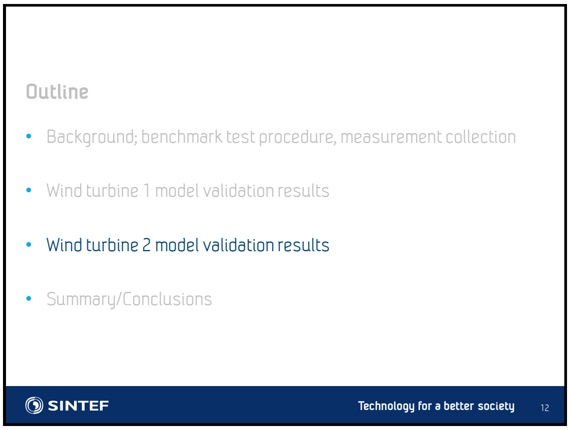
Impact of changing generator rotor parameters

Rotor impedance impacts on frequency of oscillations



Result after tuning of shaft and generator parameters

→ Quite good agreement between measurement and simulation can be achieved by adjusting shaft and generator parameters

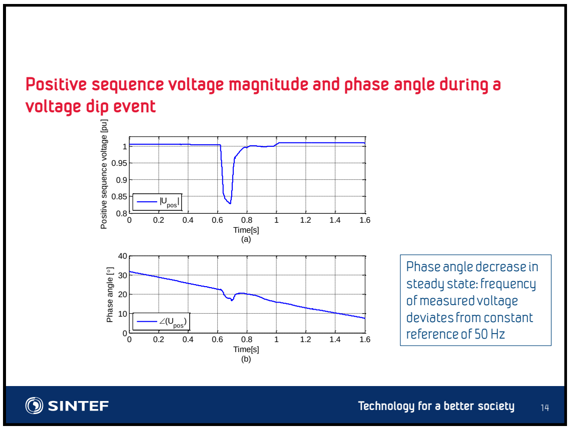


Outline

- Background; benchmark test procedure, measurement collection
- Wind turbine 1 model validation results
- Wind turbine 2 model validation results
- Summary/Conclusions

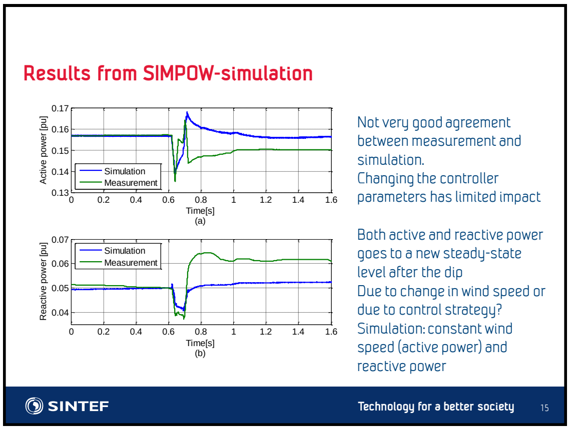
Wind turbine 2 – variable speed, full-power converter

- Rating: 2.3 MVA
- Modelled in SIMPOW and PSCAD
- No parameters known, typical/default model parameters used
- Synchronous generator: transient model, without saturation
- SIMPOW – Full Power Converter Wind Turbine model described in manual. Includes wind turbine and generator model. Speed, pitch and AC-voltage control systems.
- PSCAD – own developed converter. Generator and turbine not included in the model.



Positive sequence voltage magnitude and phase angle during a voltage dip event

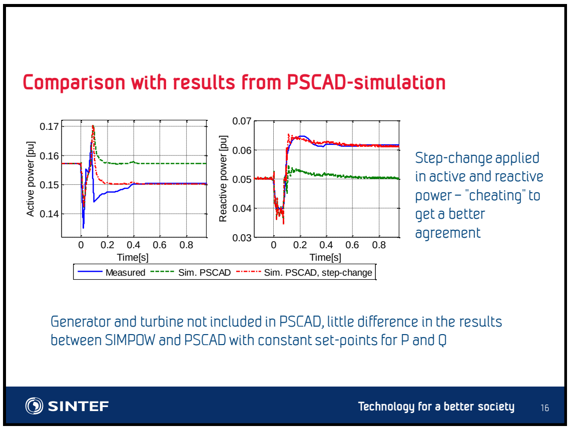
Phase angle decrease in steady state: frequency of measured voltage deviates from constant reference of 50 Hz



Results from SIMPOW-simulation

Not very good agreement between measurement and simulation.
Changing the controller parameters has limited impact

Both active and reactive power goes to a new steady-state level after the dip
Due to change in wind speed or due to control strategy?
Simulation: constant wind speed (active power) and reactive power



Comparison with results from PSCAD-simulation

Step-change applied in active and reactive power – "cheating" to get a better agreement

Generator and turbine not included in PSCAD, little difference in the results between SIMPOW and PSCAD with constant set-points for P and Q

Outline

- Background; benchmark test procedure, measurement collection
- Wind turbine 1 model validation results
- Wind turbine 2 model validation results
- Summary/Conclusions

Summary/Conclusions

- Validation of models important to ensure that simulation results can be trusted
- Fixed speed wind turbine with directly-connected induction generator: quite good agreement between measured and simulated responses in active and reactive power.
  - Better agreement could be achieved by adjusting shaft and generator parameters.
- Variable speed wind turbine with full-power frequency converter: response to voltage disturbance depends on converter parameters and control strategy. Hard to obtain good agreement between measurement and simulation without knowledge about the converter and corresponding control system.

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Norwegian Research Centre for Offshore Wind Technology

The Assessment of overvoltage protection in Offshore Wind Farms”

Amir Hayati Soloot
Hans Kristian Høidalen
Bjørn Gustavsen

9th Deep Sea Offshore Wind R&D Seminar
19-01-2012

Contents

- Introduction
- Motivation of the PhD project

  “Analysis of switching transients in wind parks with focus on prevention of destructive effects”
- OWF Components Modeling
- Simulation Results
- Conclusion

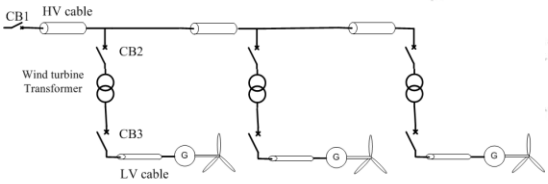
Introduction

- Number of Offshore Wind Farm (OWF) installations in Europe has grown significantly in the last decade.
- The share of OWF in wind power market has later been drastically increased from 0.12% to 9.5% during 2000-2010.
- Due to the increased distance of OWFs from shore and adverse weather conditions in oceans, a main criterion in OWF design and operation is high reliability, with **little maintenance**.
- Therefore, critical overvoltages should be investigated.

Motivations of project

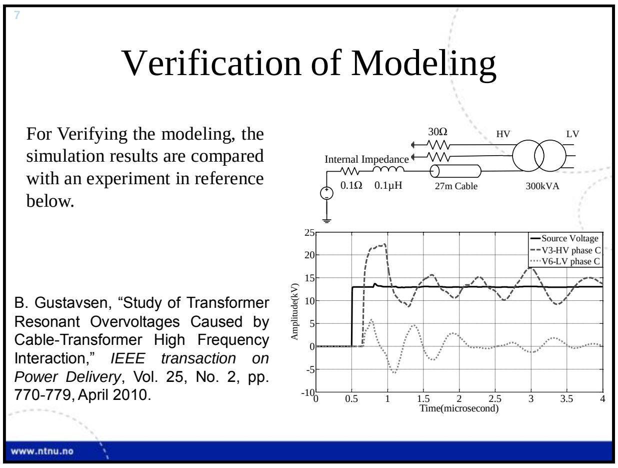
1. Assessing the critical overvoltages due to energization of Offshore Wind Farm and the prevention methods.
2. Analyzing the distribution of switching overvoltage inside transformer winding

A row of Offshore Wind Farm



OWF Components Modeling

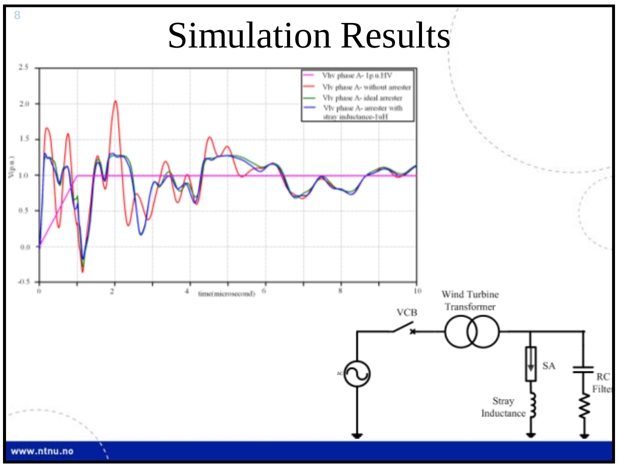
- The main components in OWFs with AC systems for the switching transient investigations are:
  - Wind Turbine Transformer → transformer terminal measurement & vector fitting
  - cables → JMarti model
  - Vacuum Circuit Breakers (VCB) → ideal switch with variable rise times due to prestrikes
  - surge arresters → model based on V-I curve of commercial SA and considering stray inductance for ground leads.
  - and RC filter → for lowering the overvoltage amplitudes
  - Note: During the OWF energization, the power converters are not initiated. Thus, wind turbine generators are not connected to WTTs.



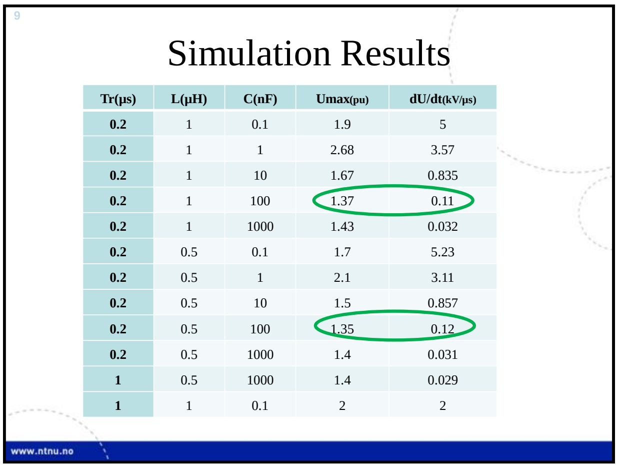
Verification of Modeling

For Verifying the modeling, the simulation results are compared with an experiment in reference below.

B. Gustavsen, "Study of Transformer Resonant Overvoltages Caused by Cable-Transformer High Frequency Interaction," *IEEE transaction on Power Delivery*, Vol. 25, No. 2, pp. 770-779, April 2010.

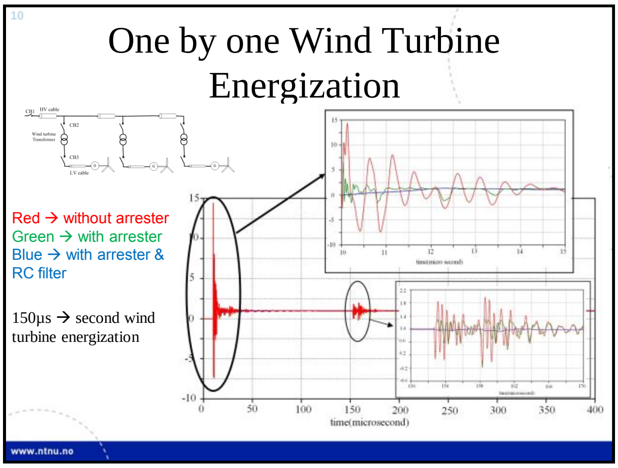


Simulation Results



Simulation Results

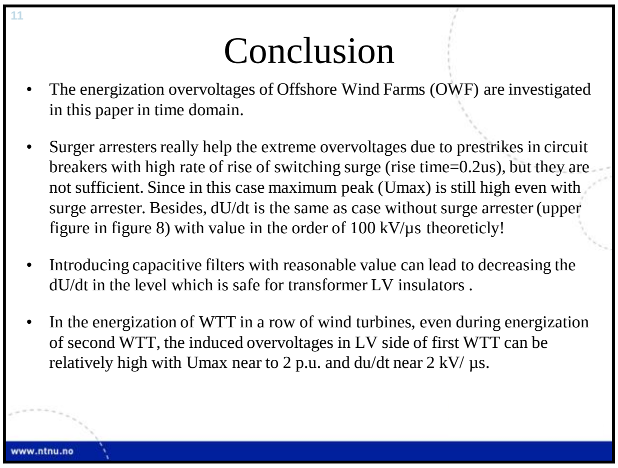
Tr(µs)	L(µH)	C(nF)	Umax(pu)	dU/dt(kV/µs)
0.2	1	0.1	1.9	5
0.2	1	1	2.68	3.57
0.2	1	10	1.67	0.835
0.2	1	100	1.37	0.11
0.2	1	1000	1.43	0.032
0.2	0.5	0.1	1.7	5.23
0.2	0.5	1	2.1	3.11
0.2	0.5	10	1.5	0.857
0.2	0.5	100	1.35	0.12
0.2	0.5	1000	1.4	0.031
1	0.5	1000	1.4	0.029
1	1	0.1	2	2



One by one Wind Turbine Energization

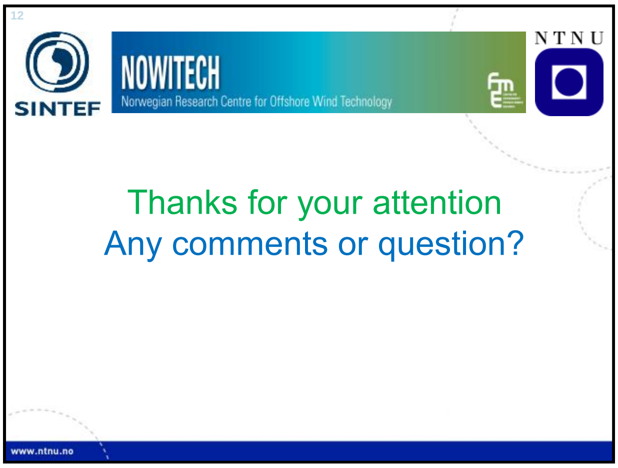
Red → without arrester
Green → with arrester
Blue → with arrester & RC filter

150µs → second wind turbine energization



Conclusion

- The energization overvoltages of Offshore Wind Farms (OWF) are investigated in this paper in time domain.
- Surger arresters really help the extreme overvoltages due to prestrikes in circuit breakers with high rate of rise of switching surge (rise time=0.2us), but they are not sufficient. Since in this case maximum peak (Umax) is still high even with surge arrester. Besides, dU/dt is the same as case without surge arrester (upper figure in figure 8) with value in the order of 100 kV/µs theoreticly!
- Introducing capacitive filters with reasonable value can lead to decreasing the dU/dt in the level which is safe for transformer LV insulators .
- In the energization of WTT in a row of wind turbines, even during energization of second WTT, the induced overvoltages in LV side of first WTT can be relatively high with Umax near to 2 p.u. and du/dt near 2 kV/ µs.



SINTEF

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NTNU

Thanks for your attention
Any comments or question?

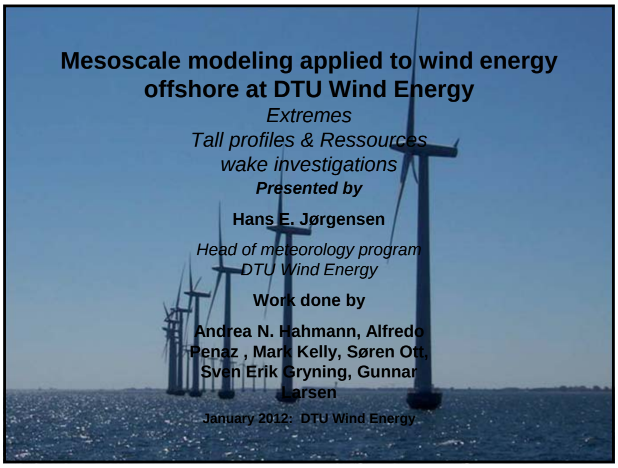
C1 Met-ocean conditions

Mesoscale modeling applied to wind energy offshore at DTU Wind Energy, Hans E. Jørgensen, DTU

Sensor movement correction for direct turbulence measurements in the marine atmospheric boundary layer, Martin Flügge, PhD stud, Univ. of Bergen

Modelling the effect of ocean waves on the atmospheric and ocean boundary layers, Alastair D. Jenkins, Uni Computing

First results of turbulence measurements in a wind park with the Small Unmanned Meteorological Observer SUMO, Prof Joachim Reuder, Univ. of Bergen



Mesoscale modeling applied to wind energy offshore at DTU Wind Energy

Extremes
Tall profiles & Ressources
wake investigations
Presented by

Hans E. Jørgensen

Head of meteorology program
DTU Wind Energy

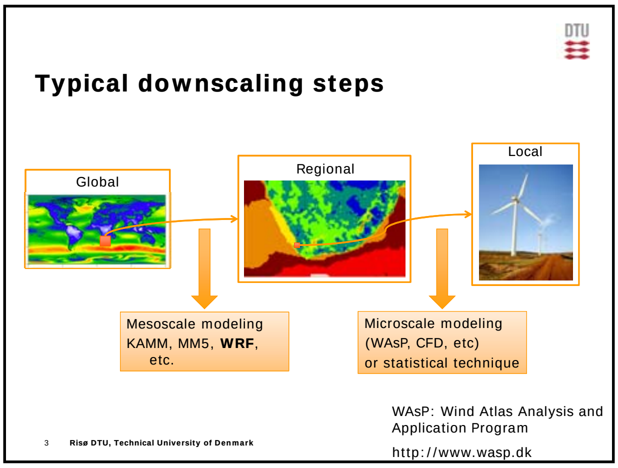
Work done by

Andrea N. Hahmann, Alfredo Penaz , Mark Kelly, Søren Ott, Sven Erik Gryning, Gunnar Larsen

January 2012: DTU Wind Energy

Outline

- Modeling for wind energy resource mapping
  - method
  - verification
  - coupling to micro-scale models
  - issues
- Long-term stability and wind profile from mesoscale models
- Wind variability occurs at variety of time scales
- Mesoscale modeling applied to extreme winds estimation
- Some comments on Wake measurements and Modelling offshore
- Other uses; final remarks

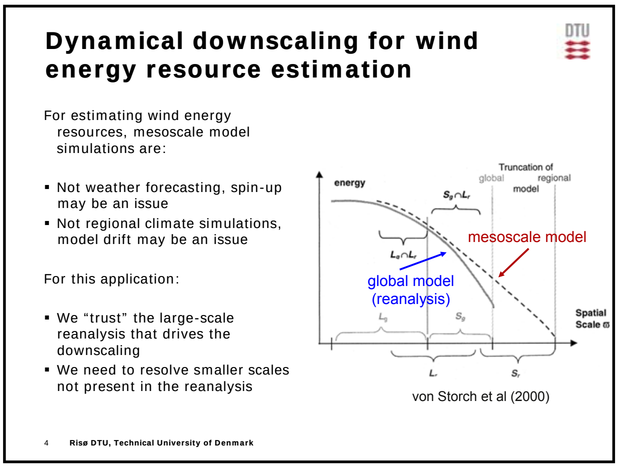


Typical downscaling steps

Mesoscale modeling
KAMM, MM5, **WRF**,
etc.

Microscale modeling
(WAsP, CFD, etc)
or statistical technique

WAsP: Wind Atlas Analysis and Application Program
http://www.wasp.dk



Dynamical downscaling for wind energy resource estimation

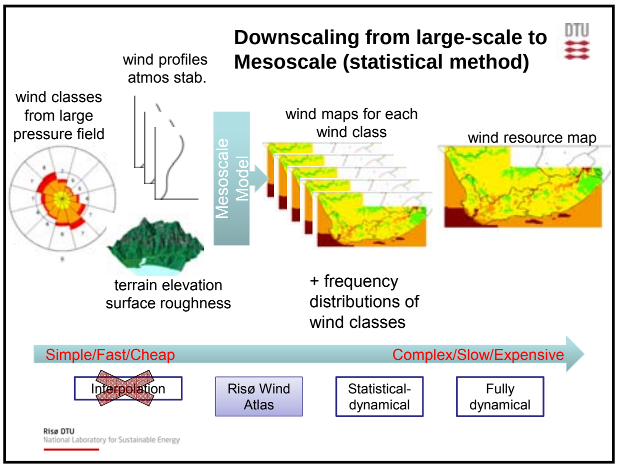
For estimating wind energy resources, mesoscale model simulations are:

- Not weather forecasting, spin-up may be an issue
- Not regional climate simulations, model drift may be an issue

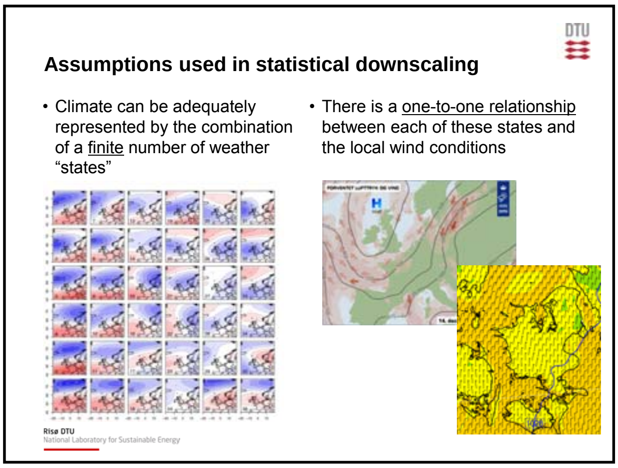
For this application:

- We “trust” the large-scale reanalysis that drives the downscaling
- We need to resolve smaller scales not present in the reanalysis

von Storch et al (2000)

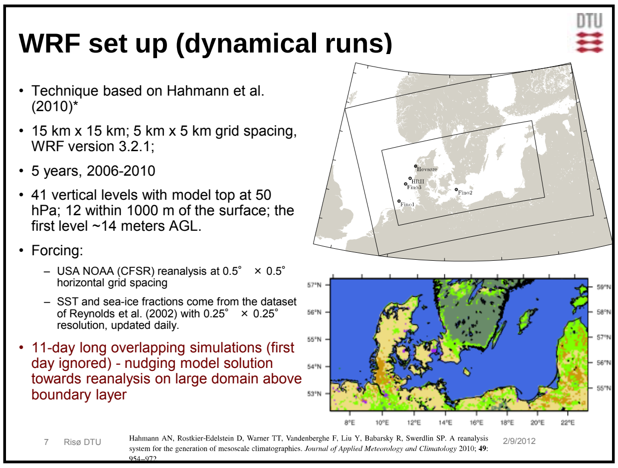


Downscaling from large-scale to Mesoscale (statistical method)



Assumptions used in statistical downscaling

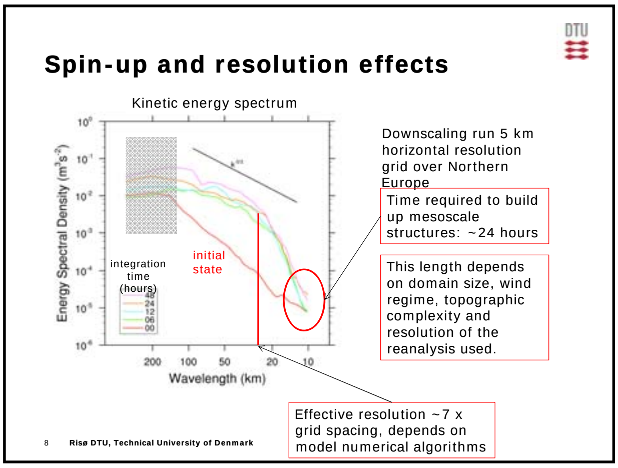
- Climate can be adequately represented by the combination of a finite number of weather “states”
- There is a one-to-one relationship between each of these states and the local wind conditions



WRF set up (dynamical runs)

- Technique based on Hahmann et al. (2010)*
- 15 km x 15 km; 5 km x 5 km grid spacing, WRF version 3.2.1;
- 5 years, 2006-2010
- 41 vertical levels with model top at 50 hPa; 12 within 1000 m of the surface; the first level ~14 meters AGL.
- Forcing:
  - USA NOAA (CFSR) reanalysis at 0.5° × 0.5° horizontal grid spacing
  - SST and sea-ice fractions come from the dataset of Reynolds et al. (2002) with 0.25° × 0.25° resolution, updated daily.
- 11-day long overlapping simulations (first day ignored) - nudging model solution towards reanalysis on large domain above boundary layer

Hahmann AN, Rostkier-Edelstein D, Warner TT, Vandenberghe F, Liu Y, Babarsky R, Swerdlin SP. A reanalysis system for the generation of mesoscale climatographies. *Journal of Applied Meteorology and Climatology* 2010; **49**: 954–972



Spin-up and resolution effects

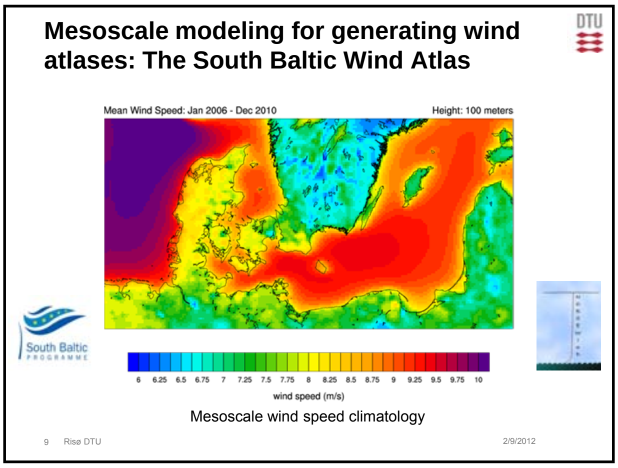
Kinetic energy spectrum

Downscaling run 5 km horizontal resolution grid over Northern Europe

Time required to build up mesoscale structures: ~24 hours

This length depends on domain size, wind regime, topographic complexity and resolution of the reanalysis used.

Effective resolution ~7 x grid spacing, depends on model numerical algorithms



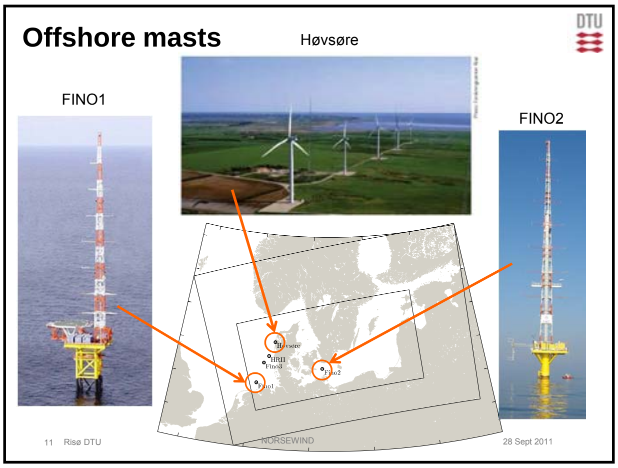
Mesoscale modeling for generating wind atlases: The South Baltic Wind Atlas

Mesoscale wind speed climatology

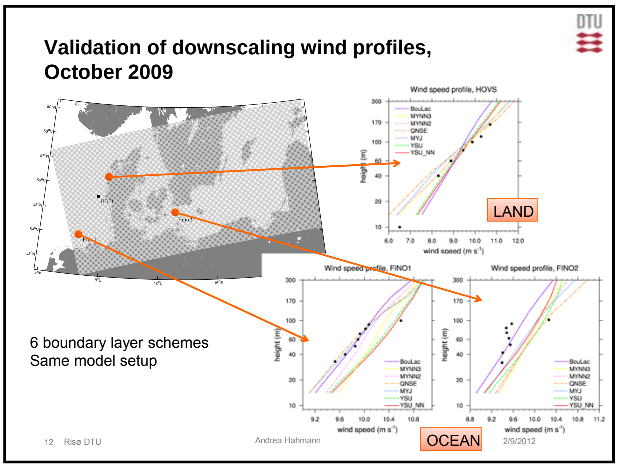
Sensitivity study – PBL scheme, October 2009

Table 2: Summary of PBL schemes used the model sensitivity study.

Scheme	*Reference*	*Closure type*	*Surface scheme*
YSU	Hong et al. (2006)	1st order	M-O scheme
MYJ	Janjic (2001)	TKE 1.5 order	M-O scheme
QNSE	Sukoriansky et al. (2006)	TKE 1.5 order	QNSE
MYNN2	Nakanishi and Niino (2006)	TKE 1.5 order	MYNN
MYNN3	Nakanishi and Niino (2006)	TKE 2.5 order	MYNN
BouLac	Bougeault and Lacarrère (1989)	TKE 1.5 order	M-O scheme



Offshore masts



Validation of downscaling wind profiles, October 2009

6 boundary layer schemes
Same model setup

Diagnosis of the wind shear

Høvsøre test center, Denmark

The parameter α is often used to diagnose the shape of the wind profile. It comes from the expression

$$\frac{u(z_1)}{u(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha}$$

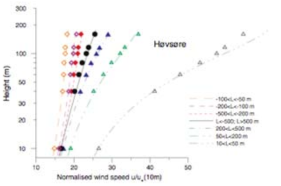
where $u(z_1)$ and $u(z_2)$ are the wind speeds at heights z_1 and z_2, respectively. α varies with height, surface roughness length, and atmospheric stability. Using similarity theory, for neutral conditions, surface roughness length of 5 cm, and z_1=10 and z_2=60 m, α=0.162. Smaller (larger) values represent unstable (stable) atmospheric BL conditions.

Boundary-Layer Meteorol (2007) 124:251–268
DOI 10.1007/s10546-007-9166-9

ORIGINAL PAPER

On the extension of the wind profile over homogeneous terrain beyond the surface boundary layer

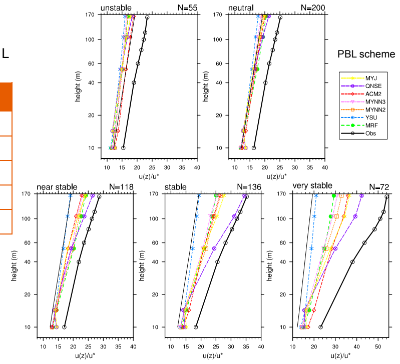
Sven-Erik Gryning · Ekaterina Batchvarova · Burghard Brümmer · Hans Jørgensen · Søren Larsen



Wind profiles grouped according to observed stability at Høvsøre, Denmark, October 2009

Stability classes according to the observed Obukhov length L (Gryning et al. 2007)

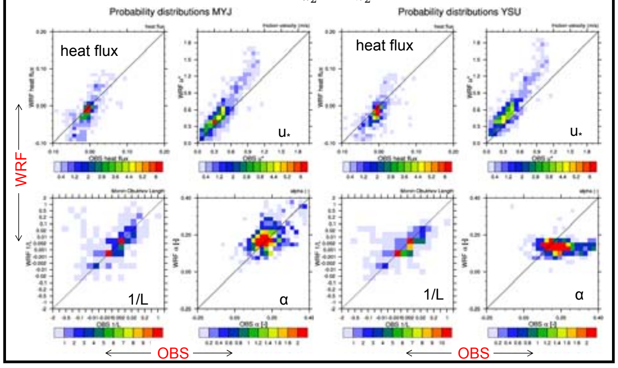
Monin-Obukhov Length	stability class
-500<L<-50	unstable
L <-500; L>500	neutral
200<L<500	near-stable
50<L<200	stable
10<L<50	very stable



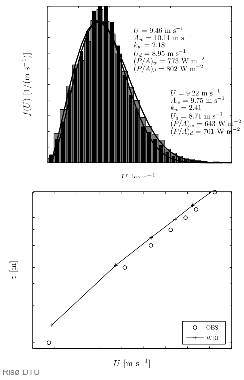
Draxl et al (2011) submitted to Wind Energy

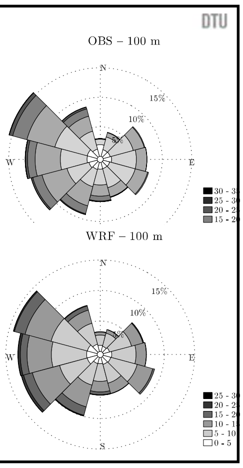
Choice of parameterizations is important

$$\frac{u_1}{u_2} = \left(\frac{z_1}{z_2}\right)^{\alpha}$$; shear exponent; 10-60 m



Verification at Høvsøre





Verification

Mean column wind speed (30-100 meters)

Scheme	*Høvsøre BIAS*	*Fino1 BIAS*	*Fino2 BIAS*	*Høvsøre RMSE*	*Fino1 RMSE*	*Fino2 RMSE*
YSU	0.11	0.38	0.47	3.32	3.01	3.48
MYJ	-0.28	0.01	0.32	3.01	3.15	3.13
QNSE	-0.39	-0.03	0.47	3.40	3.37	3.95
MYNN2	-0.15	0.13	0.42	3.23	3.18	3.51
MYNN3	-0.10	0.30	0.43	2.89	3.19	3.71
BouLac	0.17	0.02	0.11	3.84	2.96	2.87

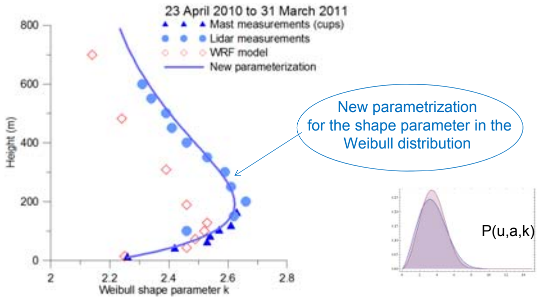
90 or 100-meter wind speed

Scheme	*Høvsøre BIAS*	*Fino1 BIAS*	*Fino2 BIAS*	*Høvsøre RMSE*	*Fino1 RMSE*	*Fino2 RMSE*
YSU	-0.22	0.38	0.59	0.67	0.46	0.60
MYJ	-0.24	0.05	0.45	0.65	0.49	0.55
QNSE	-0.17	0.01	0.62	0.72	0.51	0.68
MYNN2	-0.12	0.08	0.50	0.70	0.48	0.59
MYNN3	-0.10	0.24	0.50	0.63	0.48	0.62
BouLac	-0.35	0.01	0.22	0.76	0.44	0.49

Based on these (and other) statistics – choose MYJ PBL scheme

---

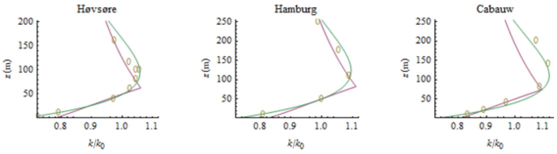
Tall measurements at Høvsøre and Verification WRF (weibull k profile)



New parametrization for the shape parameter in the Weibull distribution

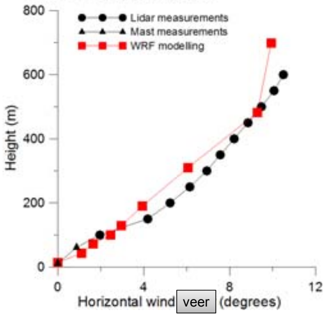
WRF model under predicts the shape parameter parameter.

New model of k to in Wasp 11

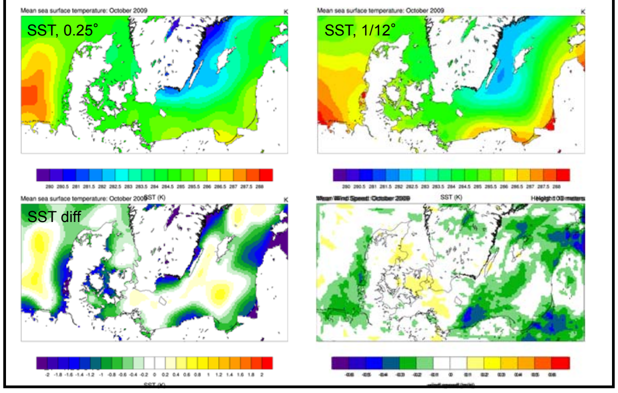


Measurements on Wind veer

Based on one year of measurements at Høvsøre within the sea sector (200 to 340 degrees and a wind speed higher than 4 m/s)



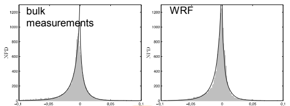
However, simulations can also be sensitive to the choice of boundary conditions…



Determination of long-term stability by mesoscale model data

- For most applications, estimates of wind and wind shear at 100 m are required. At this level the effect of atmospheric stability is important
- Most offshore measurement sites (e.g., Lidar) do not have means to estimate stability
- Long-term stability is required for:
  - input to micro-scale models (e.g. WAsP)
  - "Lift" satellite-derived wind measurements (QuikSCAT, SAR) to hub height
- It could be possible to use mesoscale models output (like WRF) to derive stability

Long-term stability at M2: Kelly and Gryning (2010)



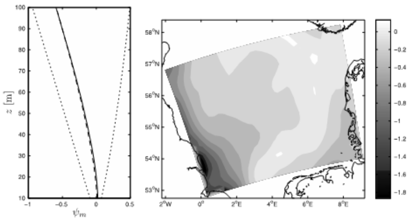
$$P = n_{\pm} \frac{C_{\pm}}{\sigma_{\pm}} \frac{\exp\left[-\left(C_{\pm}\left|1/L\right|/\sigma_{\pm}\right)^{2/3}\right]}{\Gamma\left[1+3/2\right]}$$

$$\sigma_{\pm} = \frac{g}{\langle\overline{T}\rangle} \frac{\left\langle\left(\overline{w'\theta'_v} - \langle\overline{w'\theta'_v}\rangle_{\pm}\right)^2\right\rangle^{1/2}}{\langle u_*^3\rangle}$$

Theoretical formulation of the distribution of atmospheric stability (1/L) at Horns Rev M2

Kelly M, Gryning S-E. Long-term wind profiles based on similarity theory. *Boundary-Layer Meteorology* 2010; **136**: 377–390.

Long-term stability correction



Ψ(z/L) at 70 meters

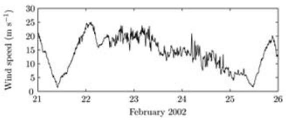
$$\left\langle \frac{\kappa u(z)}{u_*} \right\rangle = \ln\left(\frac{z}{z_o}\right) - \langle\psi_m(z/L)\rangle \quad \text{where} \quad \langle\psi_m(z/L)\rangle \neq \psi_m(z/\langle L\rangle)$$

$$\langle\psi_m(z/L)\rangle = -n_+ \frac{3\sigma_+}{C_+} b'\, z + n_-\ f_-(\sigma_-, C_-, \beta, z)$$

Parameters that can be derived from WRF simulation

Peña and Hahmann (2011) Wind Energy

Severe wind variability - time scales and definitions



*Thanks to Dong Energy and Vattenfall for the observations

- Abrupt changes in statistical properties of the time series
- Need an objective way to describe hour-scale wind fluctuations

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Int. J. Climatol. **31**: 1584–1595 (2011)
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Claire Vincent

Wind fluctuations over the North Sea

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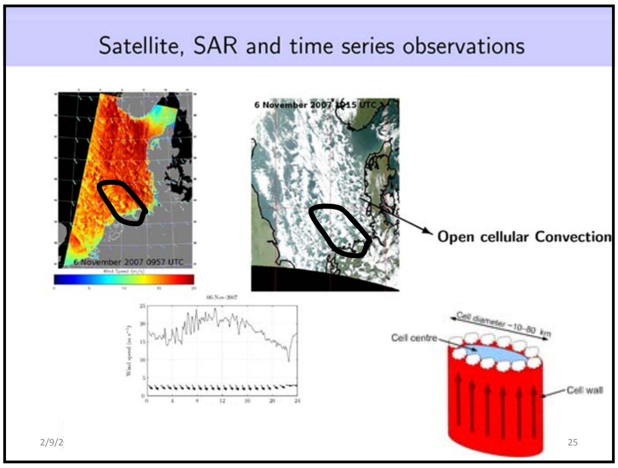
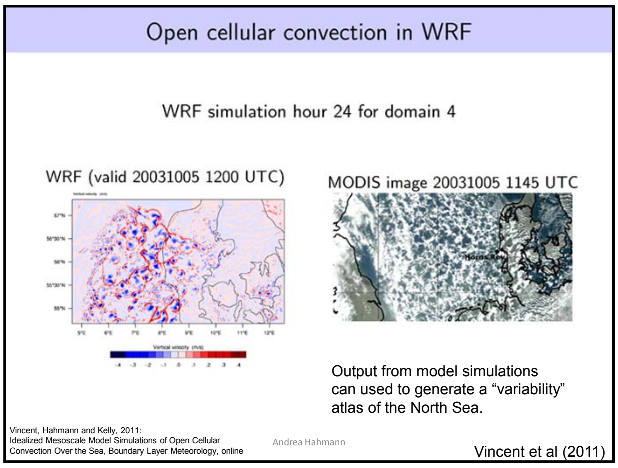


Satellite, SAR and time series observations



Open cellular convection in WRF

WRF simulation hour 24 for domain 4

WRF (valid 20031005 1200 UTC)

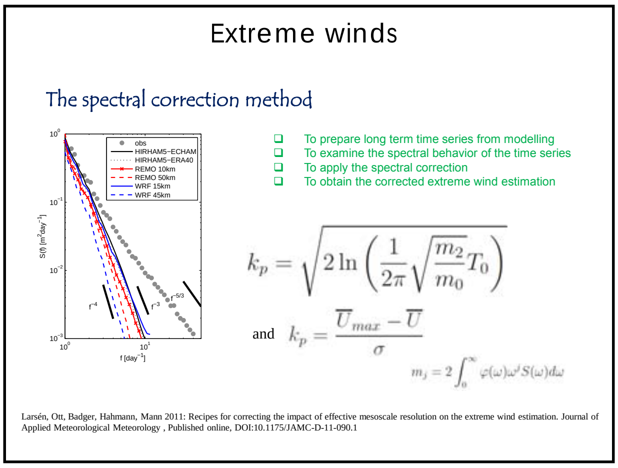
MODIS image 20031005 1145 UTC

Output from model simulations can used to generate a “variability” atlas of the North Sea.

Vincent, Hahmann and Kelly, 2011:
Idealized Mesoscale Model Simulations of Open Cellular Convection Over the Sea, Boundary Layer Meteorology, online

Andrea Hahmann

Vincent et al (2011)



Extreme winds

The spectral correction method

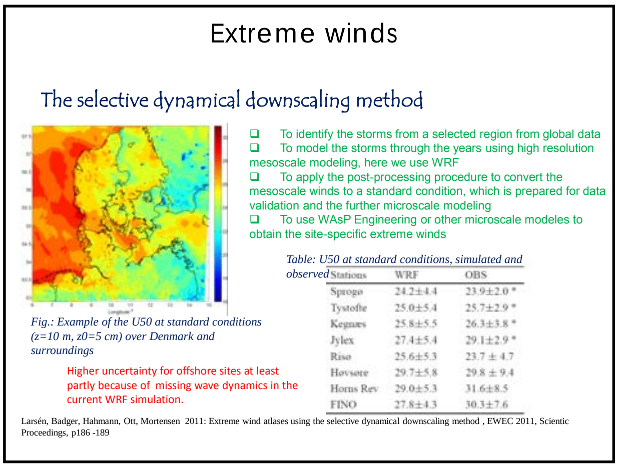
- ❑ To prepare long term time series from modelling
- ❑ To examine the spectral behavior of the time series
- ❑ To apply the spectral correction
- ❑ To obtain the corrected extreme wind estimation

$$k_p = \sqrt{2\ln\left(\frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}T_0\right)}$$

and $k_p = \frac{\overline{U}_{max} - \overline{U}}{\sigma}$

$$m_j = 2\int_0^\infty \varphi(\omega)\omega^j S(\omega)d\omega$$

Larsén, Ott, Badger, Hahmann, Mann 2011: Recipes for correcting the impact of effective mesoscale resolution on the extreme wind estimation. Journal of Applied Meteorological Meteorology , Published online, DOI:10.1175/JAMC-D-11-090.1



Extreme winds

The selective dynamical downscaling method

- ❑ To identify the storms from a selected region from global data
- ❑ To model the storms through the years using high resolution mesoscale modeling, here we use WRF
- ❑ To apply the post-processing procedure to convert the mesoscale winds to a standard condition, which is prepared for data validation and the further microscale modeling
- ❑ To use WAsP Engineering or other microscale modeles to obtain the site-specific extreme winds

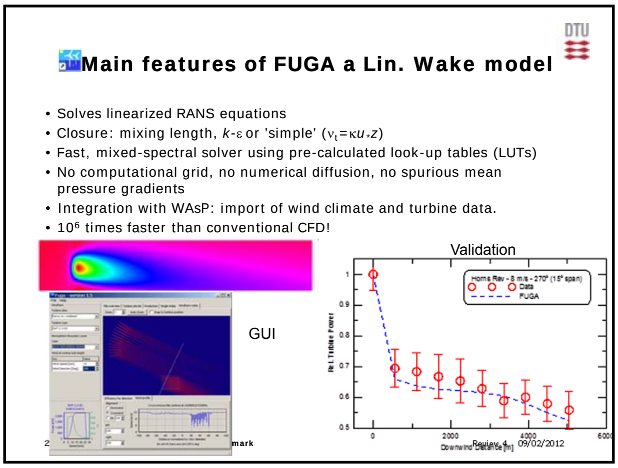
Fig.: Example of the U50 at standard conditions (z=10 m, z0=5 cm) over Denmark and surroundings

Higher uncertainty for offshore sites at least partly because of missing wave dynamics in the current WRF simulation.

Table: U50 at standard conditions, simulated and observed

Stations	WRF	OBS
Sprogø	24.2±4.4	23.9±2.0 *
Tystofte	25.0±5.4	25.7±2.9 *
Kegnæs	25.8±5.5	26.3±3.8 *
Jylex	27.4±5.4	29.1±2.9 *
Risø	25.6±5.3	23.7 ± 4.7
Høvsøre	29.7±5.8	29.8 ± 9.4
Horns Rev	29.0±5.3	31.6±8.5
FINO	27.8±4.3	30.3±7.6

Larsén, Badger, Hahmann, Ott, Mortensen 2011: Extreme wind atlases using the selective dynamical downscaling method , EWEC 2011, Scientic Proceedings, p186 -189

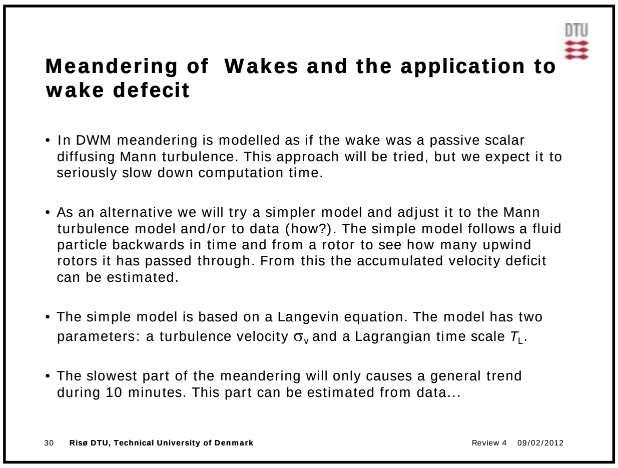


Main features of FUGA a Lin. Wake model

- Solves linearized RANS equations
- Closure: mixing length, k-ε or ’simple’ ($\nu_t = \kappa u_* z$)
- Fast, mixed-spectral solver using pre-calculated look-up tables (LUTs)
- No computational grid, no numerical diffusion, no spurious mean pressure gradients
- Integration with WAsP: import of wind climate and turbine data.
- 10^6 times faster than conventional CFD!

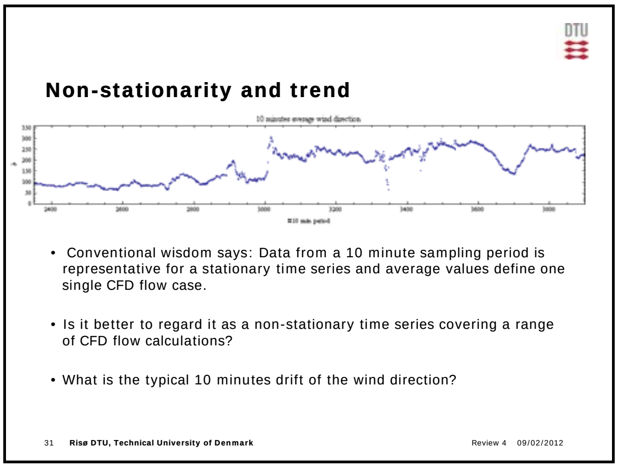
GUI

Validation



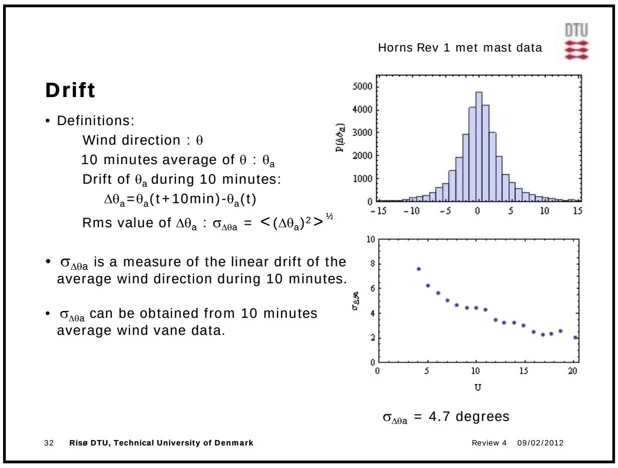
Meandering of Wakes and the application to wake deficit

- In DWM meandering is modelled as if the wake was a passive scalar diffusing Mann turbulence. This approach will be tried, but we expect it to seriously slow down computation time.
- As an alternative we will try a simpler model and adjust it to the Mann turbulence model and/or to data (how?). The simple model follows a fluid particle backwards in time and from a rotor to see how many upwind rotors it has passed through. From this the accumulated velocity deficit can be estimated.
- The simple model is based on a Langevin equation. The model has two parameters: a turbulence velocity σ_v and a Lagrangian time scale T_L.
- The slowest part of the meandering will only causes a general trend during 10 minutes. This part can be estimated from data...



Non-stationarity and trend

- Conventional wisdom says: Data from a 10 minute sampling period is representative for a stationary time series and average values define one single CFD flow case.
- Is it better to regard it as a non-stationary time series covering a range of CFD flow calculations?
- What is the typical 10 minutes drift of the wind direction?

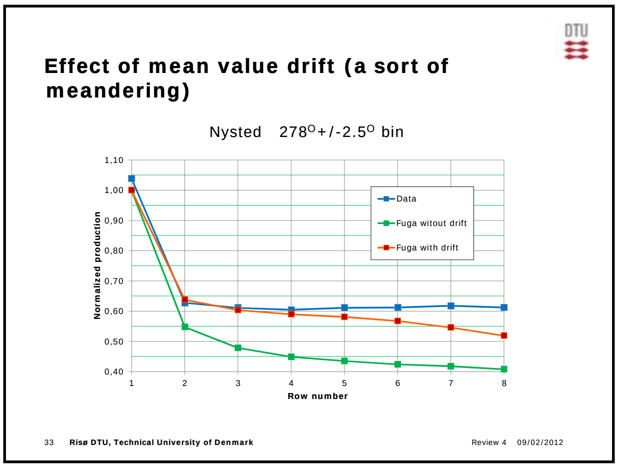


Horns Rev 1 met mast data

Drift

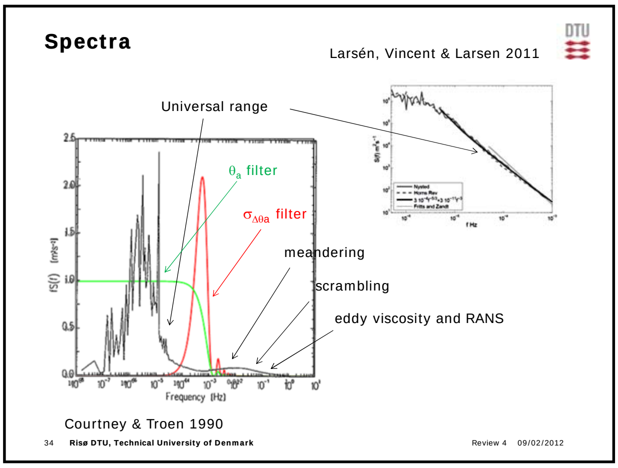
- Definitions:
  Wind direction : θ
  10 minutes average of θ : θ_a
  Drift of θ_a during 10 minutes:
  $\Delta\theta_a = \theta_a(t+10\text{min}) - \theta_a(t)$
  Rms value of $\Delta\theta_a$: $\sigma_{\Delta\theta a} = <(\Delta\theta_a)^2>^{½}$
- $\sigma_{\Delta\theta a}$ is a measure of the linear drift of the average wind direction during 10 minutes.
- $\sigma_{\Delta\theta a}$ can be obtained from 10 minutes average wind vane data.

$\sigma_{\Delta\theta a}$ = 4.7 degrees



Effect of mean value drift (a sort of meandering)

Nysted 278^{O}+/-2.5^{O} bin



Spectra

Larsén, Vincent & Larsen 2011

Universal range

θ_a filter

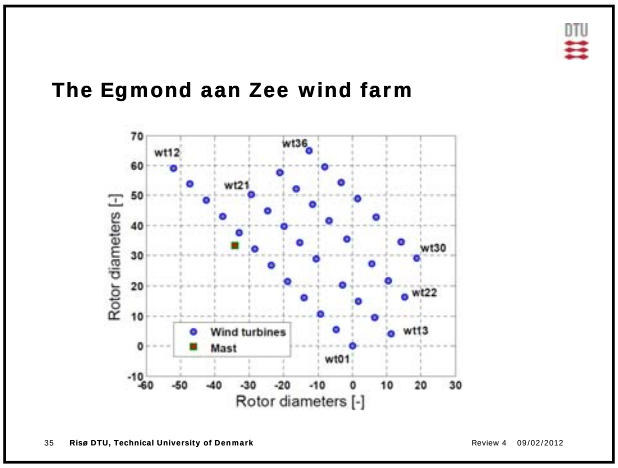
$\sigma_{\Delta\theta a}$ filter

meandering

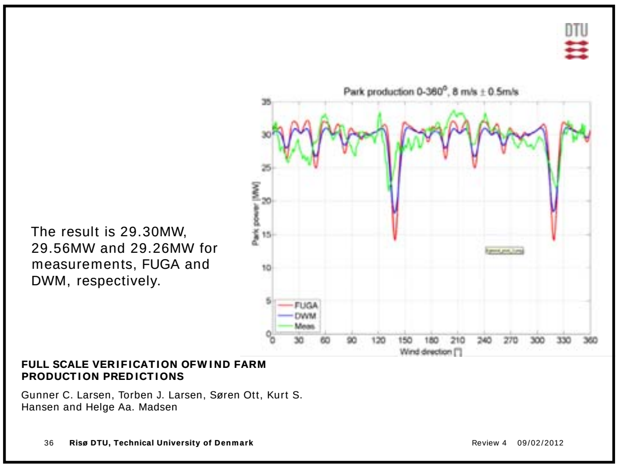
scrambling

eddy viscosity and RANS

Courtney & Troen 1990



The Egmond aan Zee wind farm



The result is 29.30MW, 29.56MW and 29.26MW for measurements, FUGA and DWM, respectively.

FULL SCALE VERIFICATION OFWIND FARM PRODUCTION PREDICTIONS

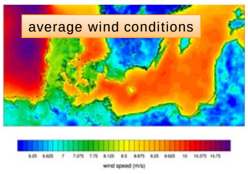
Gunnar C. Larsen, Torben J. Larsen, Søren Ott, Kurt S. Hansen and Helge Aa. Madsen

Summary of applications of mesoscale modeling activities

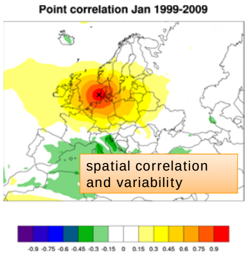
Meso-scale modeling offshore have proven to be very use full according the following list:

- Wind power resources and forecasting
  - power distribution modeling
  - combination of dynamical and statistical methods
  - Wind atlas applications (extremes, variability, correlations etc)
  - assimilation of wind farm data (nacelle winds and yaw angles)
  - Prediction of the meandering characteristic for wake deficit – used for optimizing windfarm layout
- Forecasting icing occurrence and ice amount on turbine blades in cold climate
- External design parameters for wind farm design (extremes, shear, veer not turbulence -sofar)

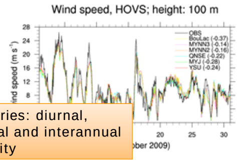
Dynamical downscaling applications



average wind conditions



spatial correlation and variability



time series: diurnal, seasonal and interannual variability

Studies of other wind-related atmospheric conditions: icing, severe temporal variability, predictability, etc.

Sensor movement correction for direct turbulence measurements in the marine atmospheric boundary layer

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Joachim Reuder[1]
[1]Geophysical institute, University of Bergen, Norway
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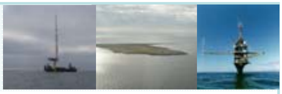
January 19th, 2012

Background



Increased development of sustainable energy sources to mitigate climate change → construction of offshore wind farms in deep water

Main issue:

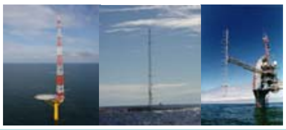
- Only sparse «real» offshore turbulence measurements have been performed in the MABL
- More measurements under real offshore conditions are needed to characterize the air-sea boundary layer
- Most of the measurements taken between 2m – 50m above the sea surface
- Floating offshore wind turbines will reach the height of 150m above the sea surface

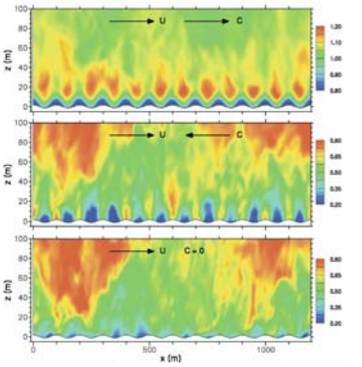
Why characterize the MABL?

Direct turbulence measurements in the MABL will distinctly improve the understanding of the turbulent momentum transfer in the lower atmosphere and the corresponding exchange processes with the sea surface.

↓↓

This is essential for the prediction of offshore wind directions and wind speeds in the lower atmosphere





Contours of the modeled u component of the horizontal wind field for cases with moving and stationary waves. The nondimensional field shown is ū/Ug.

Results from Sullivan et al,2008 suggest that surface waves influence the lower part of the boundary layer in horizontal and vertical wind directions

Measurement techniques

All turbulence measurements that have been collected on floating platforms need to be corrected for platform motion and orientation

There are four ways to do the correction:

- *Covariance (eddy correlation)* → direct measurement
- *Inertial-dissipation*
- *Mean profiles*
- *Bulk aerodynamic methods*

→ indirect measurements

(Fairall and Larsen 1986)

Direct covariance estimates from moving platforms

Main issue: part of the fluctuating velocity is due to platform motion that must be removed before the computation of the fluxes.

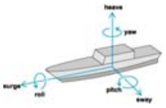
Contamination sources:

- instantaneous tilt of the anemometer due to variations in pitch, roll and heading
- angular velocities at the anemometer due to rotation of the platform about its local coordinate system axes
- translational velocities of the platform with respect to a fixed frame of reference

(Edson et al. 1998; Hare et al. 1992)

Direct covariance estimates from moving platforms

Using roll (Φ), pitch (θ), and yaw (Ψ) to describe the platform orientation the wind velocity vector in a fixed reference frame can be written as



$$\mathbf{U}_{true} = \mathbf{T}(\mathbf{U}_{obs} + \mathbf{\Omega}_{obs} \times \mathbf{R}) + \mathbf{V}_{mot},$$

(Edson et al. 1998)

where $\mathbf{V}_{mot} = \mathbf{V}_{lp} + \mathbf{V}_{hp}$

$\mathbf{U}_{true}$ – desired wind vector in the reference coordinate system

$\mathbf{T}$ – coordinate transformation matrix for rotation from platform coordinate system to the reference coordinate

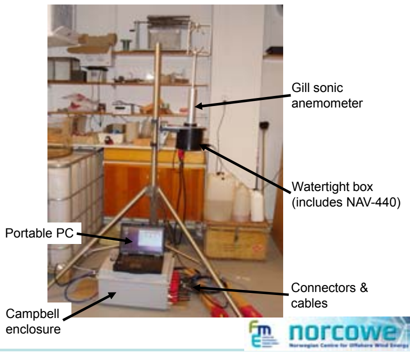
$\mathbf{U}_{obs}$ – measured wind velocity in the platform frame

$\mathbf{\Omega}_{obs}$ – angular velocity vector of the platform coordinate system

$\mathbf{R}$ – position vector of the wind sensor with respect to the motion package

$\mathbf{V}_{mot}$ – translational velocity vector

Eddy correlation system



Campaign

- Field campaign at Martha's Vineyard Coastal Observatory (Massachusetts) between April 13 – June 29, 2010
- Measurement site is located 3.2 km south of Martha's Vineyard in a water depth of 15 meter
- DCFS measurements from both Air Sea Interaction Tower and a buoy with "strapped down system" moored 600 meters away from the ASIT
- Operation height of the sonic anemometer was 4 meter above the mean sea level on both the tower and buoy

Preliminary results

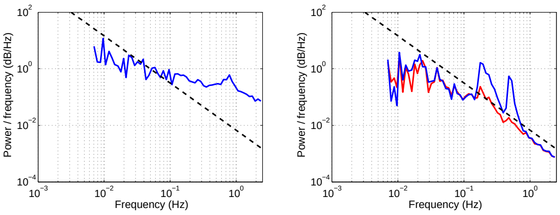


Figure: The measured (blue) and corrected (red) horizontal U-velocity power spectra from the ASIT (left) and the buoy (right). The measurements were taken simultaneously in a 20 minute period starting at 23:00h UTC on May10, 2010 with an eastward wind. The left panel shows ASIT measurements contaminated by flow distortion from the tower legs. The dashed line indicates the -5/3 slope in the inertial subrange.

Preliminary results

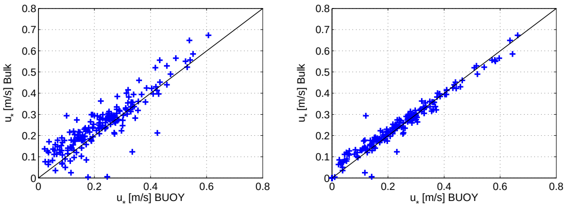


Figure: Uncorrected (left) and corrected (right) friction velocity estimates from the buoy data versus friction velocity estimates computed by the bulk method. The fluxes are shown for a 10 day period and represent averages over 20 minutes.

Preliminary results

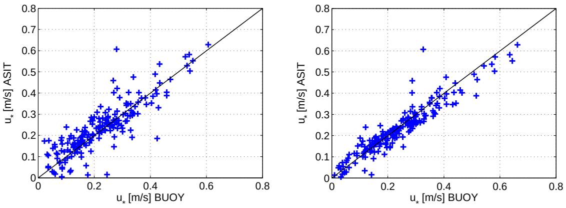


Figure: Uncorrected (left) and corrected (right) friction velocity estimates from the buoy data versus ASIT. The fluxes are shown for a 10 day period and represent averages over 20 minutes.

Summary and Outlook

We want to measure turbulence in the MABL

↓

Measurements from floating platforms, e.g. ships or buoys

↓↓

Post-processing and correction of the gathered data to account for the platforms attitude

The experience and results of this study will be used and applied for the development and deployment of two own turbulence flux buoys.

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- Edson, J.B., A. A. Hinton, K. E. Prada, J. E. Hare and C. W. Fairall, 1998: Direct covariance flux estimates from mobile platforms at sea. *Journal of Atmospheric and Ocean Technology*, **15**(2), 547-562
- Fairall, C. W. and S. E Larson, 1986: Inertial-dissipation methods and turbulent fluxes at the air-ocean interface. *Boundary-Layer Meteorology*, **34**(3), 287-301
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- Sullivan, P. P., J. B. Edson, T. Hristov and J. C. McWillams, 2008: Large-eddy simulations and observations of atmospheric marine boundary layers above nonequlibrium surface waves. *Journal of the Atmospheric Sciences*, **65**(4), 1225-1245

Eddy correlation system

Gill R3A-100 sonic anemometer:

- sampling rate up to 100Hz
- both binary and ASCII output available
- can provide an average of a fixed numbers of readings

Crossbow NAV440 (IMU):

- integrated GPS and Attitude & Heading reference system (AHRS)
- utilizes low drift MEMS-based inertial sensors with GPS
- will be housed inside a watertight box at the sensor head

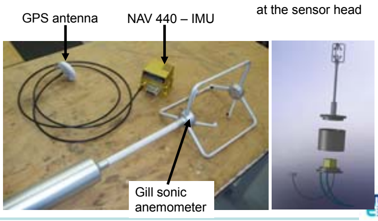


Figure 3: The systems anemometer and the NAV440 with GPS antenna.

Eddy correlation system

Figure 4: The Campbell enclosure with MOXA, power supply and connectors.

MOXA UC-7420:

- act as data logger and control unit for the system
- RISC based ready-to-run LINUX computer
- CF and USB-port for adding external memory
- using WLAN all recorded data will be send to an external PC and saved on hard disk

Measurement techniques

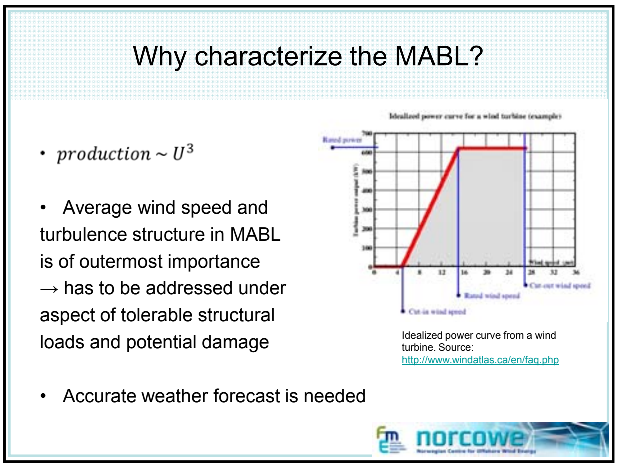
- Indirect methods have been used to avoid application of correction algorithms due to platform motion and flow distortion
- The indirect methods gives only an estimate of the turbulent fluxes
- The indirect methods depend on additional poorly understood parameterizations to account for the interaction between the wave field and the surface fluxes

(Edson et al. 1998)

Goal of present study

Improvement of the motion correction algorithm of Edson et al. (1998)

- The angles (yaw, pitch, roll) are found by complimentary filtering with a predefined cut-off frequency.
- In the present study, the high-pass filter that is applied to the accelerations before and after its integration has a different cut-off frequency.



Why characterize the MABL?

- $production \sim U^3$

- Average wind speed and turbulence structure in MABL is of outermost importance → has to be addressed under aspect of tolerable structural loads and potential damage

- Accurate weather forecast is needed

Idealized power curve from a wind turbine. Source: http://www.windatlas.ca/en/faq.php

Modelling the effect of ocean waves on the atmospheric and ocean boundary layers

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

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Introduction

- Ocean waves affect wind power generation:
  - Directly
  - Via the atmosphere
  - Via the ocean
- Direct effects:
  - forces on structures;
  - slamming of steep waves;
  - spray: corrosion/icing.

Introduction 2

- Via atmosphere:
  - waves change the air–sea momentum flux;
  - affect the aerodynamic turbulent roughness length;
  - change the wind velocity profile;
  - generate airflow oscillations
- Via the ocean:
  - air bubbles affecting corrosion and marine biology;
  - wave-induced currents;
  - breaking-wave induced and bottom turbulence;
  - effects on marine ecology
  - drift/dispersion of pollutants, oil spills, floating objects etc.

We present

- Modelling ocean waves and their effect on the atmospheric lower boundary
  - Roughness length affected by momentum flux from air to wave field
- Modelling the effect of the waves on the ocean:
  - One-dimensional turbulence model
  - Idealised current profile
  - Temperature profile, comparison with observations

The atmosphere

- Atmospheric model: Weather Research and Forecasting (WRF)
  - Freely available, large community of developers/users
- Wave model: WAM
  - Available free of charge, used for global/regional/shelf simulations since c. 1990
- Coupling scheme: MCEL
  - Freely available, development funded by US Dept. of Defence
  - Can interpolate/couple models with different grids

Atmosphere model

- WRF
  - state-of-the-art non-hydrostatic mesoscale model
  - developed for numerical weather prediction and related appliation
- Polar stereographic, 30 km×30 km grid
- Default YSU planetary boundary layer (PBL) scheme
- Default Monin-Obukhov surface-layer physics
  - modified to import a variable Charnock coefficient calculated from the wave model variables every 60 minutes, using the MCEL coupling scheme

Turbulent neutral boundary layer

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

$u_* = (\tau/\rho_a)^{1/2}$ = friction velocity

$z_0 = \alpha {u_*}^2/g$ $\quad\alpha$ = Charnock parameter

$\kappa \approx 0.4$ $\quad$ von Kármán constant

Wave model

- WAM Cycle 4
- Grid 0.4° longitude × 0.2° latitude
- Driven by wind speed and direction at 10 m above surface
  - Every 60 minutes, interpolated from WRF grid by MCEL scheme
- Computes air-to-wave (τ_w) and total air-to-sea ($\tau = \rho_a {u_*}^2$) momentum flux
- τ_w/τ and u_* are fed back to the WRF model every 60 minutes

Model coupling

- Model Coupling Environment Library (MCEL)
- CORBA-based client-server based coupling framework, may be used for couple numerical models with differing domains and grid resolutions.

- Within WRF, we apply the algorithm of Janssen (1991) and Brown and Wolf (2009) as follows: If wave-model information is available,

$$\alpha_v = \min\left(\frac{\alpha_{\min}}{\sqrt{1-(\tau_w/\tau)}}, \alpha_{\max}\right), \qquad (1)$$

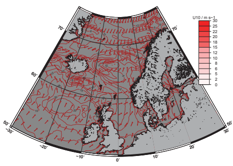
$$z_0 = (\alpha_v {u_*}^2/g) + z_{0\min}, \qquad (2)$$

where α_v is the variable Charnock parameter, $\alpha_{\min} = 0.01$ and $\alpha_{\max} = 0.31$. $z_{0\min} = 1.59 \times 10^{-5}$ m. Where no wave-model information is available, a constant Charnock parameter of 0.0185 is used.

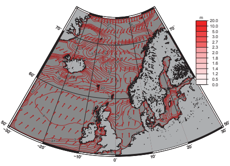
Results, atmosphere–wave coupling

- Main result: Charnock parameter and roughness length are enhanced where the waves are developing rapidly and the sea is not fully developed.
- Occurs where the wind is changing rapidly with time or where the fetch is reduced (the wind is blowing offshore)
- Both situations may be described as ‘young wave’ conditions with a low *wave age* c_p/u_*, where c_p is the celerity of the dominant waves.
- This will tend to produce a reduced wind speed and increased turbulence at a $O(100\,\mathrm{m})$ wind turbine height.

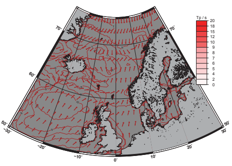
WAM wave model results after 24 hours’ simulation



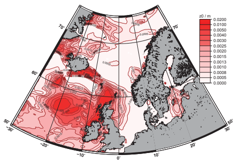
Wind 10 m



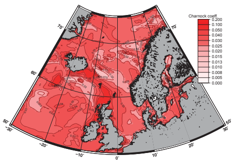
Hs, wave dir.



Tp, wave dir.

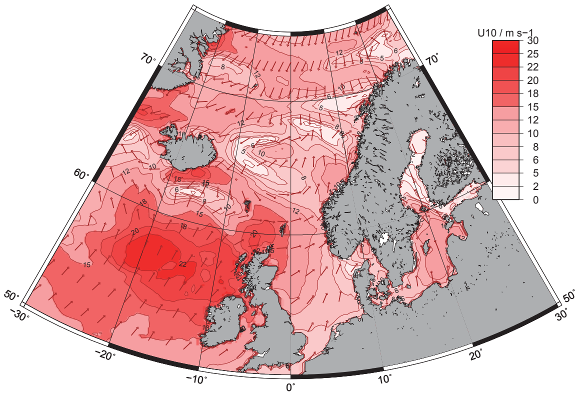


Roughness length / m

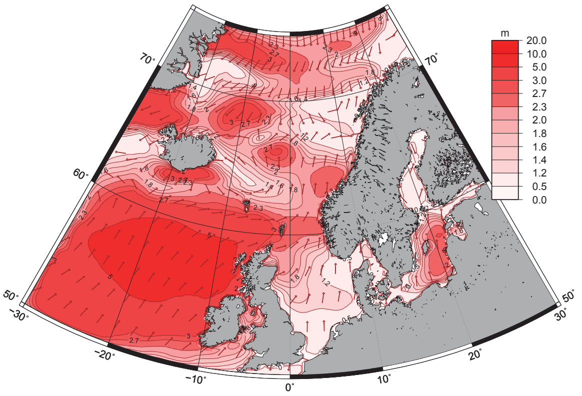


Charnock parameter

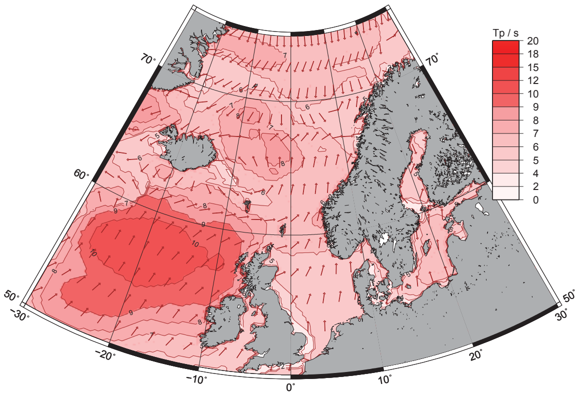
Wind at 10 m height



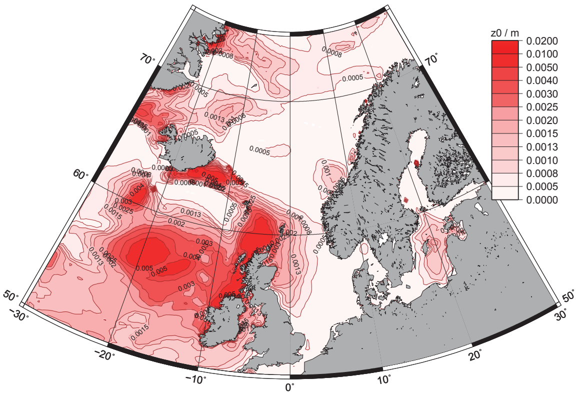
Significant wave height and wave direction



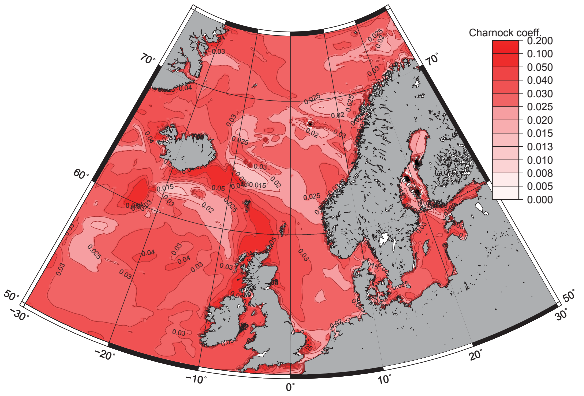
Peak wave period and direction

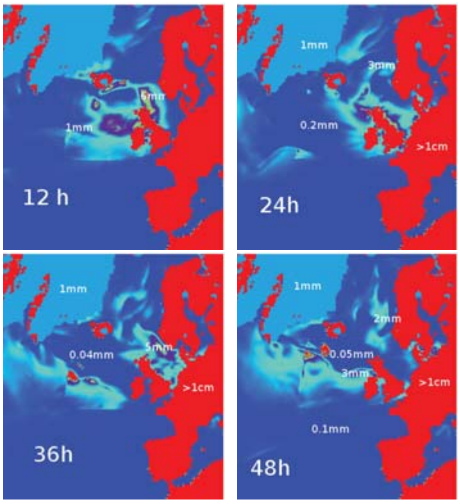


Roughness length / metres



Charnock parameter





Roughness length in WRF model domain

Ocean boundary-layer study

- We apply the one-dimensional General Ocean Turbulence Model (GOTM, Burchard 2002), and add the influence of surface waves.
- The momentum and energy equations are modified to include the surface wave stress, wind energy input, wave dissipation, and Stokes drift.
- The Stokes drift is considered as a wave property, and the model equations are for the Eulerian current

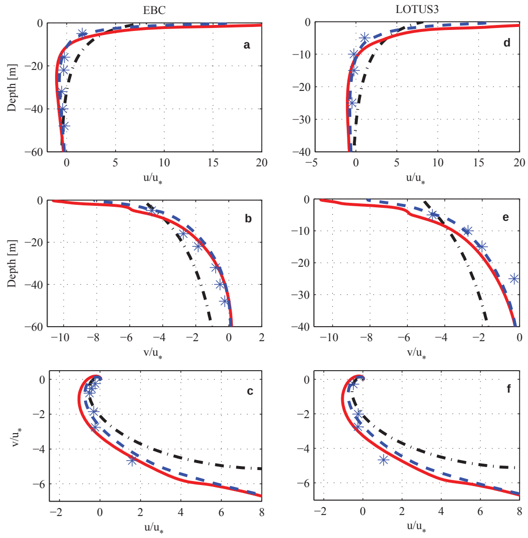
- A modified k-ϵ turbulence closure model is used, with an upper flux boundary condition

$$\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial z} = -F_k, \tag{3}$$

where σ_k is the turbulent Schmidt number and F_k is the transfer of kinetic and potential energy to enhance the near-surface TKE.

Comparison with ocean measurements

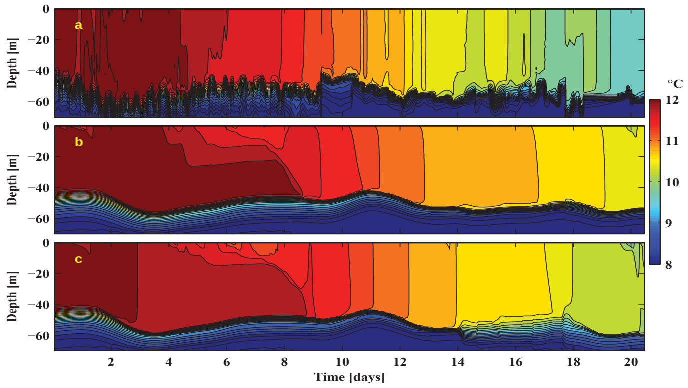
- Long Long Term Upper Ocean Study (LOTUS3), Sargasso Sea, and Eastern Boundary Current (EBC) experiment, eastern North Pacific
- PROVESS, northern North Sea, October 1966
- Ocean Weather Station (OWS) Papa, northern Pacific, 1966
- Wave field is assume to be fully developed, with a Donelan–Pierson wave spectrum.



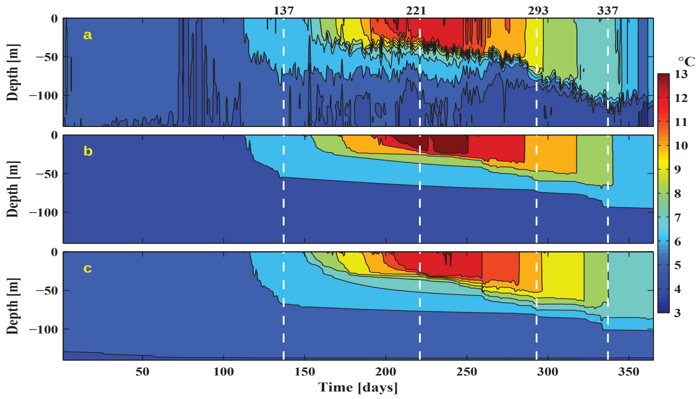
GOTM turbulence model runs, with (solid) and without (dashed) wave forcing

GFEM model with waves: dash-dotted

EBC and LOTUS3 observations indicated by [*]



Sea temperature, northern North Sea, 7–27 October 1966 (a) observed temperature; (b) GOTM results without waves, (c) GOTM with wave forcing



Sea temperature, OWS Papa (N. Pacific), year 1966
(a) observations, (b) GOTM results without waves,
(c) GOTM results with idealized Donelan–Pierson wave forcing

Conclusion

- Wave–atmosphere interaction results: primarily an enhancement of the surface aerodynamic roughness during rapidly-developing and short-fetch conditions.
- indicate a modest reduction of mean wind speed and increase in turbulence intensity at wind turbine hub height.
- Since the wave-induced momentum flux may differ in direction from that of the wind, it may be advantageous to allow for a difference in the directions of wind and stress in subsequent versions of the coupled model system.

Conclusion 2

- Wave-ocean interaction results show that including wave forcing decreases the deviation of temperature evolution and mixed-layer dynamics from those of in observations, thus affecting the sub-surface focres and ocean environment in marine wind-power generation areas.
- Stokes drift is a dominant wave effect which increases surface drift speed and turning angle of upper ocean current.
- Some uncertainties in the results because of contamination by advection
- Future studies should ideally make more detailed measurements in the near-surface layer of the ocean and a better estimate of breaking-wave effects.

First results of turbulence measurements in a wind park with the Small Unmanned Meteorological Observer SUMO

J. Reuder and M. Jonassen
Geophysical Institute, University of Bergen
joachim.reuder@gfi.uib.no

Outline

- ☐ introduction
- ☐ presentation of the SUMO system
- ☐ description of the measurement site and campaign
- ☐ first results
- ☐ pitfalls and lessons learned
- ☐ outlook

Background

the structure of and the processes in the lowest few hundreds of meters in the marine atmospheric boundary layer (MABL) are poorly understood

- average wind profile
- wind shear
- turbulence intensity
- atmospheric stability
- non-stationary lower boundary layer (waves)

established measurement methods (masts, lidars, sodar, sodar RASS) are infrastructural demanding, expensive and rather inflexible

developments in microelectronics and miniaturiazition of sensors and components allows now for the implementation of flow and turbulence measurements also on very small and lightweight micro-UAS (Unmanned Aircraft System)

SUMO (Small Unmanned Meteorological Observer)

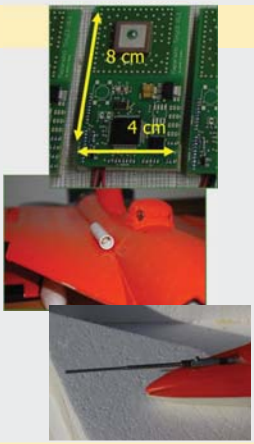
vehicle type	fixed wing UAS
DIMENSIONS	
wingspan	0.80 m
length	0.75 m
height	0.23 m
propeller diameter	227 mm (9"x6")
take-off weight	600 g
PROPULSION	
motor	electric brushless
motor type	AXI2212/26
motor power	120 W
battery type	lithium-polymer (3 cells)
battery capacity	2.4 Ah/11.1 V
SPEED AND ENDURANCE	
minimum speed	8 m/s
maximum speed	42 m/s
cruise speed	15 m/s
horizontal range	< 10 km
vertical range	> 4 km
flight duration	< 40 min

SUMO operation – ground control station (GCS)

SUMO sensors

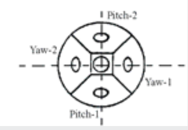
- **autonomous navigation**:
  Paparazzi, an open source auto pilot system (including GPS and IMU)

- **temperature sensor**:
  SHT75 by Sensirion (± 0.5 K)
- **humidity sensor**:
  SHT75 Sensirion (± 1.8 %)
- **temperature sensor**:
  Pt1000 (± 0.3 K)
- **pressure sensor**:
  SCP 1000 by VTI Technologies
- **IR thermopile**:
  surface temperature monitoring
- **5-hole probe:**
  for 100 Hz measurement of the 3D wind vector



SUMO turbulence sensor

miniaturized 5-hole probe from Aeroprobe Inc., USA (3 mm diameter)
differential pressure measurements (static-dynamic, left right, up-down)
provides flow velocity and angles of sideslip and attack with 100 Hz resolution



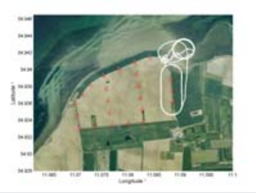
SUMO campaigns

campaign/region	scientific topics	# of flights	max. alt. a.g.l.	time
FLOHOF, Hofsjökull, Central Iceland	instationary gravity waves, evaluation of ABL schemes in WRF	30	3580 m	summer 2007
Svalbard	system test polar region	44	1470 m	winter 2008
Coburg, Germany	nocturnal BL	25	2450 m	summer 2008
FLUXPAT III, Jülich, Germany	BL and inhomogeneous surfaces	34	800 m	summer 2008
Svalbard	polar BL; simultaneous flights; evaluation of ABL schemes in WRF	85	1500 m	spring 2009
MOSO, Iceland	orographic flow modification; land-sea breeze	68	2990 m	summer 2009
Andfjorden, Northern Norway	characterization of MBL; search and rescue	4	1600 m	fall 2009
Lolland Denmark	turbulence in a wind park	70	100 m	spring 2011
BLLAST, France	convective boundary layer transition	299	1600 m	summer 2011

Measurement campaign Lolland, Denmark

- 5 days, May 9-13, 2011
- funded by the Danish (energinet.dk) ForskEL project “Autonomous Aerial Sensors for Wind Power Meteorology (project number 10268)

  (DTU Risø, University of Bergen, Aalborg University, University of Braunschweig, University of Tübingen)
- Nøjsomheds Odde wind farm owned and operated by Dong Energy
- 21 Bonus 1000 turbines (1 MW, hub height 55 m, diameter 52 m)
- a total of 70 flights, 20 with the advanced 5-hole probe turbulence system



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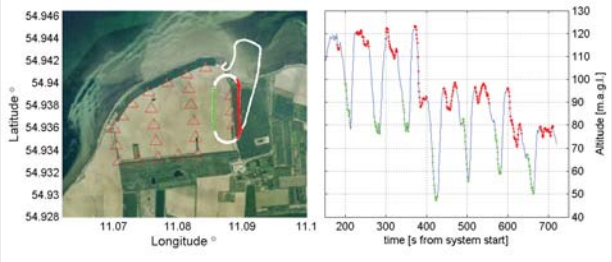
turbulence measurements



- insufficient altitude control of the autopilot (incomplete fine-tuning of the control parameters after change of attitude control by IMU instead of IR horizon)
- difficult to correct turbulence measurements for aircraft movement (2 unsynchronized data loggers with different measurement frequencies; turbulence probe 100 Hz, autopilots attitude 10 Hz)

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turbulence measurements

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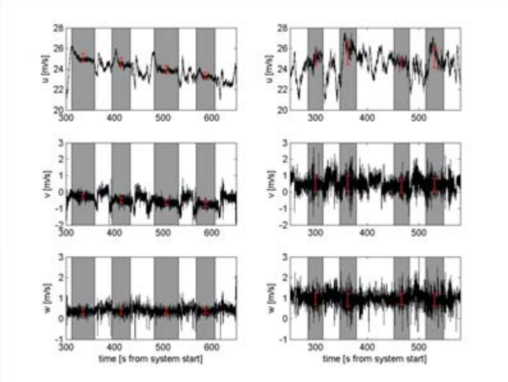
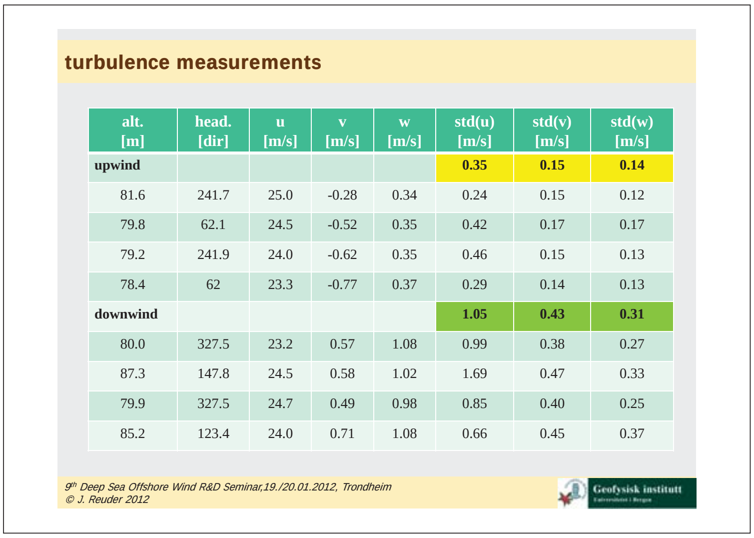
turbulence measurements





turbulence measurements

alt. [m]	head. [dir]	u [m/s]	v [m/s]	w [m/s]	std(u) [m/s]	std(v) [m/s]	std(w) [m/s]
upwind					**0.35**	**0.15**	**0.14**
81.6	241.7	25.0	-0.28	0.34	0.24	0.15	0.12
79.8	62.1	24.5	-0.52	0.35	0.42	0.17	0.17
79.2	241.9	24.0	-0.62	0.35	0.46	0.15	0.13
78.4	62	23.3	-0.77	0.37	0.29	0.14	0.13
downwind					**1.05**	**0.43**	**0.31**
80.0	327.5	23.2	0.57	1.08	0.99	0.38	0.27
87.3	147.8	24.5	0.58	1.02	1.69	0.47	0.33
79.9	327.5	24.7	0.49	0.98	0.85	0.40	0.25
85.2	123.4	24.0	0.71	1.08	0.66	0.45	0.37

9th Deep Sea Offshore Wind R&D Seminar,19./20.01.2012, Trondheim
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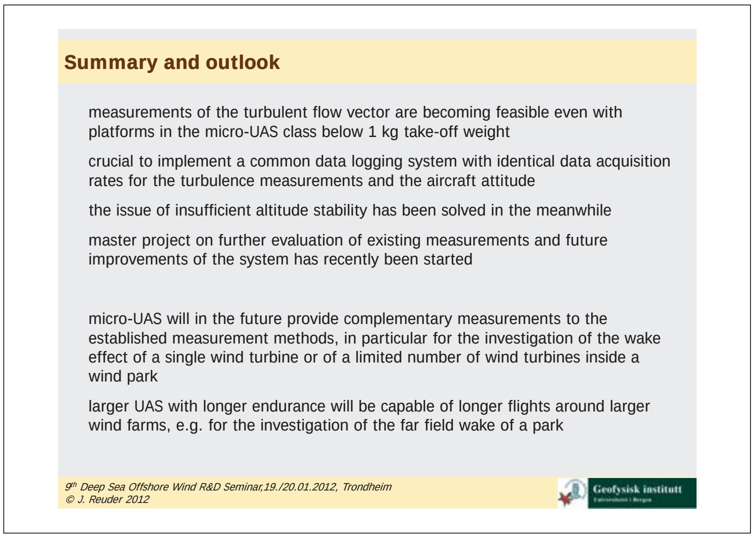

Summary and outlook

measurements of the turbulent flow vector are becoming feasible even with platforms in the micro-UAS class below 1 kg take-off weight

crucial to implement a common data logging system with identical data acquisition rates for the turbulence measurements and the aircraft attitude

the issue of insufficient altitude stability has been solved in the meanwhile

master project on further evaluation of existing measurements and future improvements of the system has recently been started

micro-UAS will in the future provide complementary measurements to the established measurement methods, in particular for the investigation of the wake effect of a single wind turbine or of a limited number of wind turbines inside a wind park

larger UAS with longer endurance will be capable of longer flights around larger wind farms, e.g. for the investigation of the far field wake of a park

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Thanks for your attention !!!

and do not forget:
Next time you hear SUMO…

…you should think about flying !!!

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C2 Met-ocean conditions

An insight into floating lidars for offshore wind measurements,
Matt Smith, Natural Power

Comparison of met-mast and lidar measurements at Frøya,
Prof Lars Sætran, NTNU

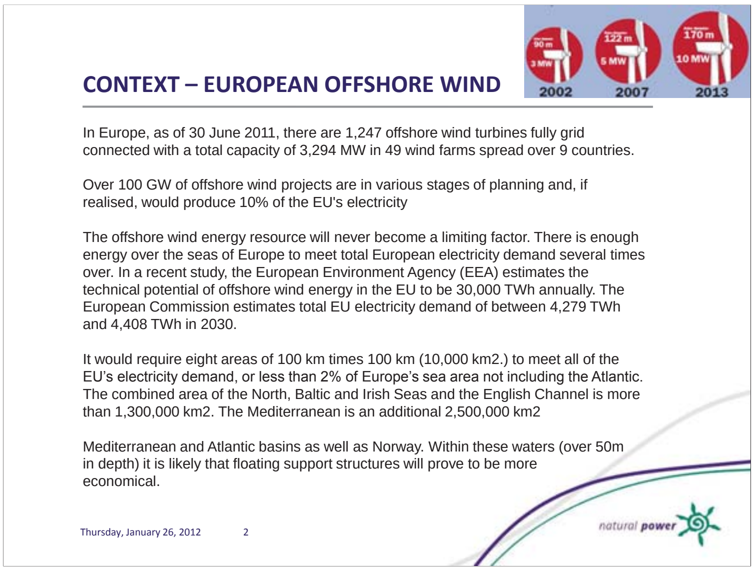
Experiences and results from the Statoil's LIDAR measurement Campaign at
Utsira, Yngve Ydersbond, Kjeller Vindteknikk AS

An insight into lidars for offshore wind measurements

natural power

Matt Smith
Wind Lidar Innovations

January 2012



CONTEXT – EUROPEAN OFFSHORE WIND

In Europe, as of 30 June 2011, there are 1,247 offshore wind turbines fully grid connected with a total capacity of 3,294 MW in 49 wind farms spread over 9 countries.

Over 100 GW of offshore wind projects are in various stages of planning and, if realised, would produce 10% of the EU's electricity

The offshore wind energy resource will never become a limiting factor. There is enough energy over the seas of Europe to meet total European electricity demand several times over. In a recent study, the European Environment Agency (EEA) estimates the technical potential of offshore wind energy in the EU to be 30,000 TWh annually. The European Commission estimates total EU electricity demand of between 4,279 TWh and 4,408 TWh in 2030.

It would require eight areas of 100 km times 100 km (10,000 km2.) to meet all of the EU's electricity demand, or less than 2% of Europe's sea area not including the Atlantic. The combined area of the North, Baltic and Irish Seas and the English Channel is more than 1,300,000 km2. The Mediterranean is an additional 2,500,000 km2

Mediterranean and Atlantic basins as well as Norway. Within these waters (over 50m in depth) it is likely that floating support structures will prove to be more economical.

CONTENTS

- Introduction to Lidar
- Reasons for Lidar measurements offshore
- Offshore lidar history, acceptance and best practice
- Existing platforms, monopiles, tilt ups and other fixed solutions for lidar
- Floating lidars - why the industry wants them
- Floating lidars – two main product developments
- Floating lidars - what is available today
- Going forwards – power performance testing offshore turbines

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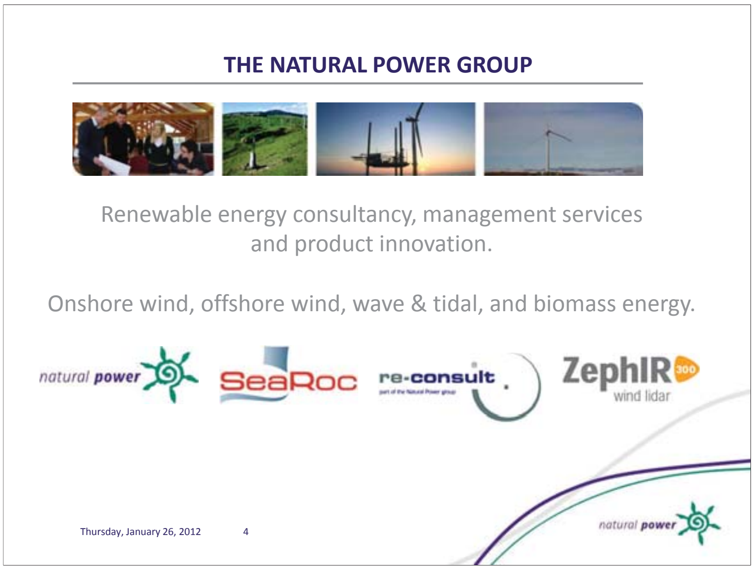

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natural power SeaRoc re-consult ZephIR 300 wind lidar

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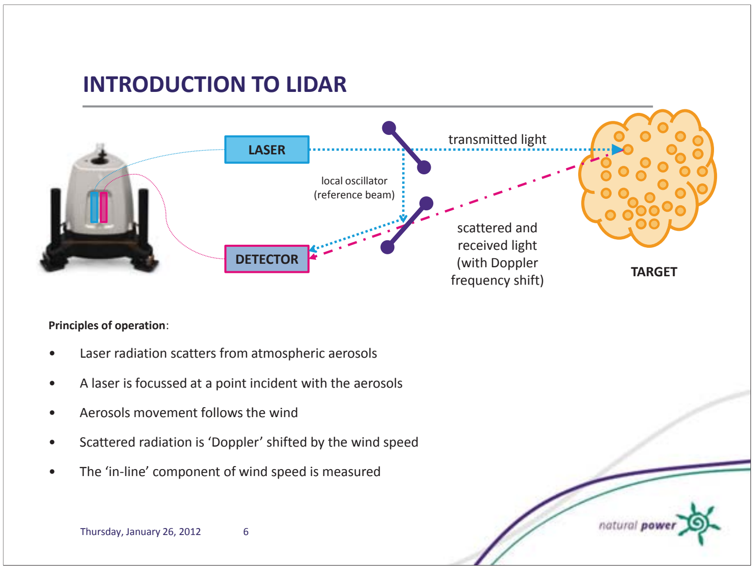
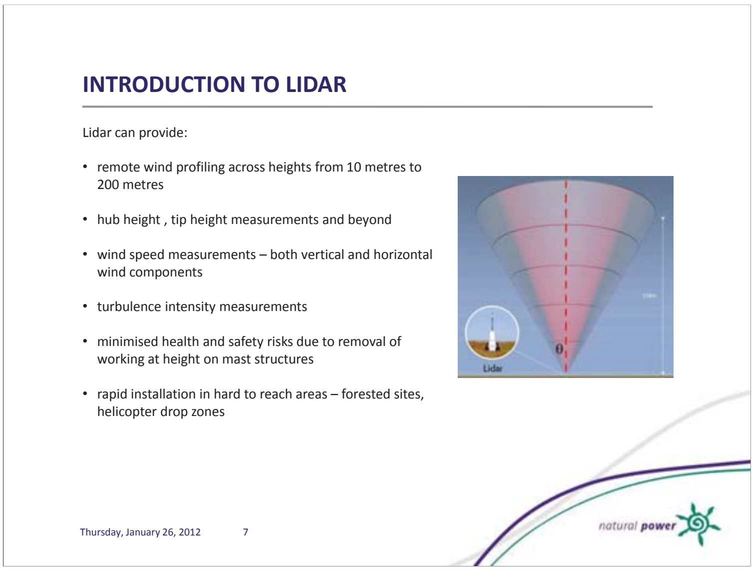


INTRODUCTION TO LIDAR

Principles of operation:

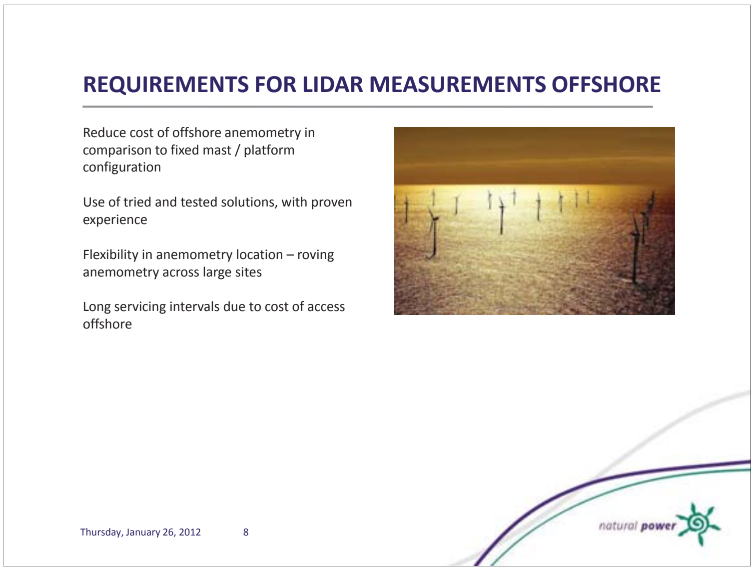
- Laser radiation scatters from atmospheric aerosols
- A laser is focussed at a point incident with the aerosols
- Aerosols movement follows the wind
- Scattered radiation is 'Doppler' shifted by the wind speed
- The 'in-line' component of wind speed is measured



INTRODUCTION TO LIDAR

Lidar can provide:

- remote wind profiling across heights from 10 metres to 200 metres
- hub height , tip height measurements and beyond
- wind speed measurements – both vertical and horizontal wind components
- turbulence intensity measurements
- minimised health and safety risks due to removal of working at height on mast structures
- rapid installation in hard to reach areas – forested sites, helicopter drop zones



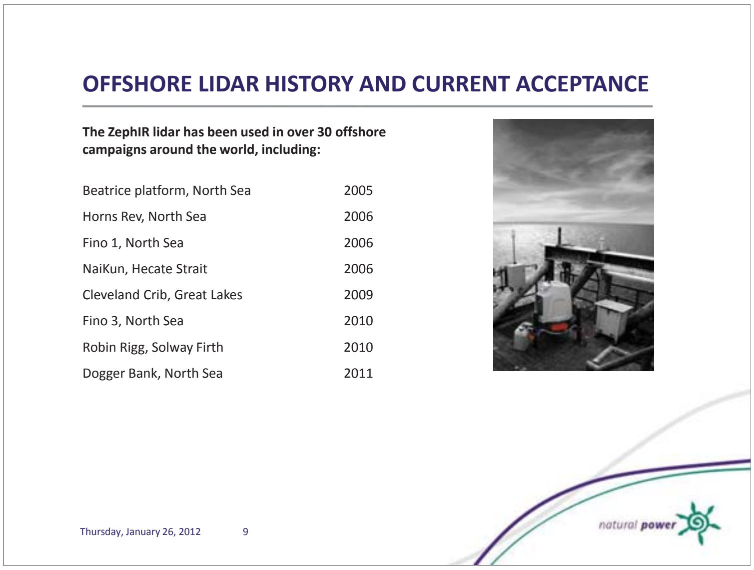
REQUIREMENTS FOR LIDAR MEASUREMENTS OFFSHORE

Reduce cost of offshore anemometry in comparison to fixed mast / platform configuration

Use of tried and tested solutions, with proven experience

Flexibility in anemometry location – roving anemometry across large sites

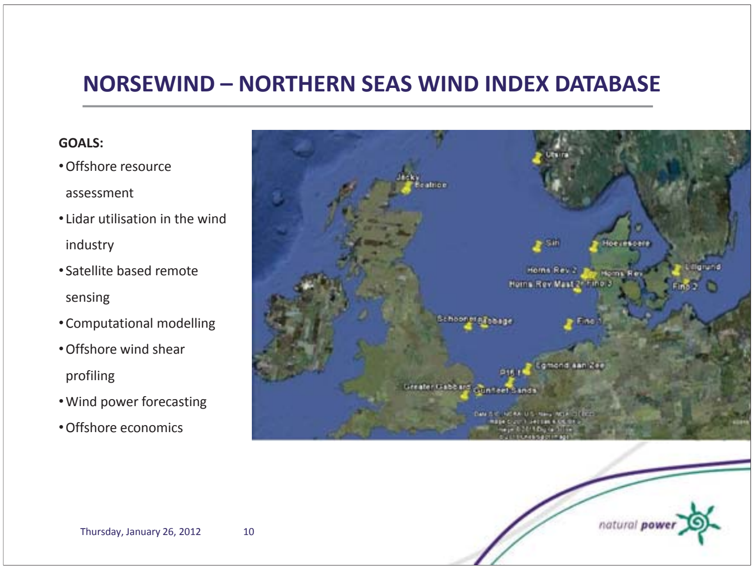
Long servicing intervals due to cost of access offshore



OFFSHORE LIDAR HISTORY AND CURRENT ACCEPTANCE

The ZephIR lidar has been used in over 30 offshore campaigns around the world, including:

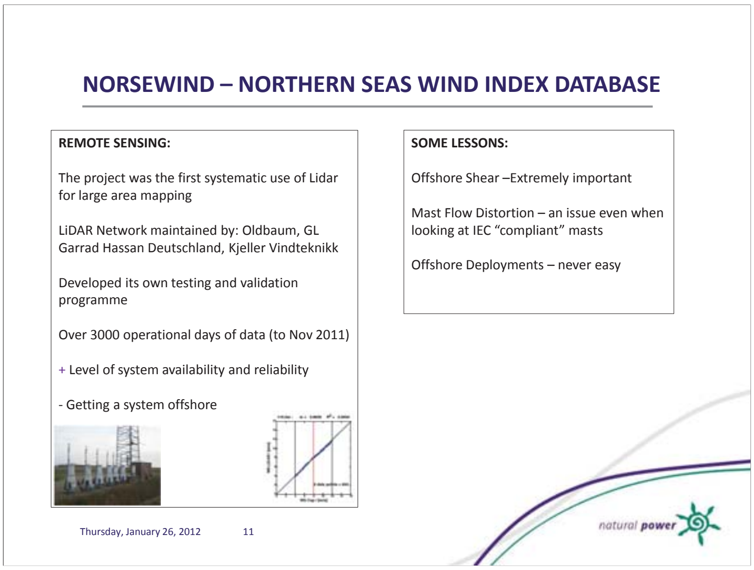
Beatrice platform, North Sea	2005
Horns Rev, North Sea	2006
Fino 1, North Sea	2006
NaiKun, Hecate Strait	2006
Cleveland Crib, Great Lakes	2009
Fino 3, North Sea	2010
Robin Rigg, Solway Firth	2010
Dogger Bank, North Sea	2011



NORSEWIND – NORTHERN SEAS WIND INDEX DATABASE

GOALS:

- Offshore resource assessment
- Lidar utilisation in the wind industry
- Satellite based remote sensing
- Computational modelling
- Offshore wind shear profiling
- Wind power forecasting
- Offshore economics



NORSEWIND – NORTHERN SEAS WIND INDEX DATABASE

REMOTE SENSING:

The project was the first systematic use of Lidar for large area mapping

LiDAR Network maintained by: Oldbaum, GL Garrad Hassan Deutschland, Kjeller Vindteknikk

Developed its own testing and validation programme

Over 3000 operational days of data (to Nov 2011)

\+ Level of system availability and reliability

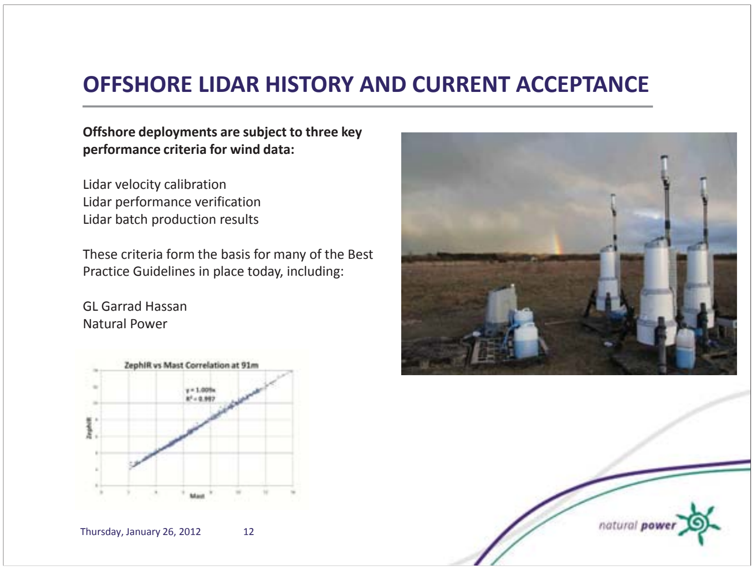
\- Getting a system offshore

SOME LESSONS:

Offshore Shear –Extremely important

Mast Flow Distortion – an issue even when looking at IEC "compliant" masts

Offshore Deployments – never easy



OFFSHORE LIDAR HISTORY AND CURRENT ACCEPTANCE

Offshore deployments are subject to three key performance criteria for wind data:

Lidar velocity calibration
Lidar performance verification
Lidar batch production results

These criteria form the basis for many of the Best Practice Guidelines in place today, including:

GL Garrad Hassan
Natural Power

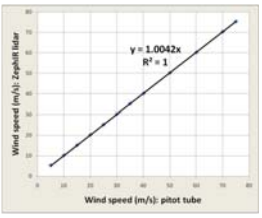
LIDAR VELOCITY CALIBRATION

Velocity calibration depends only on laser frequency and sampling rate of analogue-to-digital converter

Drift of these quantities over extended periods and temperature ranges is <0.1%

Recent measurements in a high-specification wind tunnel confirm very close agreement over a wide velocity range (up to 75m/s)

Lidar was operating at range 3.3m, beam aligned with flow, 50Hz data rate, integrated over 2 seconds; no seeding in tunnel



Acknowledgement: LM Windpower, Risø DTU and NKT Photonics

LIDAR PERFORMANCE VERIFICATION AT RS TEST SITE

Natural Power has established its remote sensing test site close to Pershore, UK

90m mast in flat terrain (disused airfield)

Speed data from paired cups at 4 heights; direction data from vanes at 2 levels

Lidar verification process devised in collaboration with GLGH

Instrumentation conforms with IEC recommendations

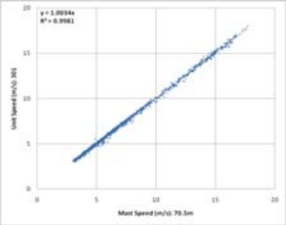
LIDAR BATCH PRODUCTION RESULTS

Standard performance verification example for ZephIR 300 unit

Calibration consistency has been analysed for new and returning units

Statistical analysis of regression slopes for 15 ZephIR 300 units shows standard deviation of <0.5% at all heights

Results provide confidence in ZephIR lidar for bankable offshore resource assessment



BEST PRACTICE APPLICATIONS

The following table summarises Natural Power's present position on the acceptability of different ZephIR campaign configurations where ZephIR is being used as the primary measurement device for the purposes of finance level resource and energy yield analysis

	Offshore	Simple terrain	Complex/Forested
Single ZephIR, no co-located mast	YES	YES	NO
Single ZephIR with co-located mast	YES	YES	YES*

*Mast should be at least 15 m above the tree tops. Volume-to-point conversion calculations may be required (discussed later).

It is assumed in all cases that the ZephIR unit is subject to pre-and post campaign verification on a suitably-equipped calibration test site (see following slides).

OFFSHORE BEST PRACTICE

ZephIR can be recommended as a primary wind measurement system for offshore wind farms.

There is a significant and consistent body of evidence to support the use of ZephIR in offshore conditions as the sole data capture system.

Consider the installation of two Lidar systems for redundancy and to enable continued data to be collected during service intervals.

Where redundant ZephIRs are not practical or possible, consideration should be given to the installation of a short mast (20m above platform height) in order that there is a second source of wind measurements.

This should be done in the interests of data coverage, and not for wind speed measurement validation.

OFFSHORE BEST PRACTICE

Power supplies and communication systems should be scoped to provide double redundancy and be remotely manageable.

A pre-campaign test of ZephIR against a tall reference mast is required. A post-campaign test is also recommended.

As a minimum, offshore measurements should be conducted at the base of the planned rotor height, hub height and rotor top.

Post-processing and filtering of measurements should be carried out in accordance with best-practice for mast-based campaigns, in addition to any guidelines provided by the OEM.

Installation of a ZephIR on a sub-station platform can provide a permanent wind data solution on offshore projects. (see opposite which shows a ZephIR installed on the sub-station platform of E.ON's Robin Rigg 180MW offshore wind farm in the Solway Firth, SW Scotland)

METHODOLOGY FOR INITIAL FEASIBILITY STUDIES

Based on the use of an initial onshore ZephIR deployment
- Ideally at nearest point of coast to project location
- Quick and low cost installation, compared to a platform in early stages
- Ideally mains powered and secure

Derive offshore data point from validated meso-scale wind climate model (i.e. Vortex)
- Provides long-term (10-yr.) wind resource statistics and time series data

Correlation of onshore ZephIR data with meso-scale model data
- Perform correlation every 3 months (if required)
- Allows meso-scale model to be tuned to real data and prediction uncertainty reduced
- Derived site wind resource statistics can be used to perform an energy yield analysis

This method permits early, low-cost resource analysis, and delivers energy yield reports with lower uncertainty than can be otherwise achieved (without an offshore platform)

Offshore on-site data collection will still typically be required to provide full and final finance-grade analysis (see narec Case Study)...

NAREC: CASE STUDY IN THE NORTH SEA

narec offshore wind demonstrator project (Northumberland, UK)

Phase 1: Onshore building mounted ZephIR, <5km from project location
Onshore ZephIR data correlated with long-term offshore Vortex meso-scale model data, as per methodology described above
Data and results used to underpin ongoing resource analysis, energy yield prediction and site classification reports for the site owner and prospective site tenants (turbine OEMs)

Phase 2: A second ZephIR and a tall met. mast are to be platform-mounted offshore
Onshore ZephIR to remain in-situ to provide consistency and allow extension of data period
All data will be utilised to produce finance-grade energy yield prediction and site classification reports, with minimised prediction uncertainty

Public domain reports by Natural Power (publicly funded project):
http://www.narec.co.uk/testing_development/offshore_demonstration_site/report_downloads/

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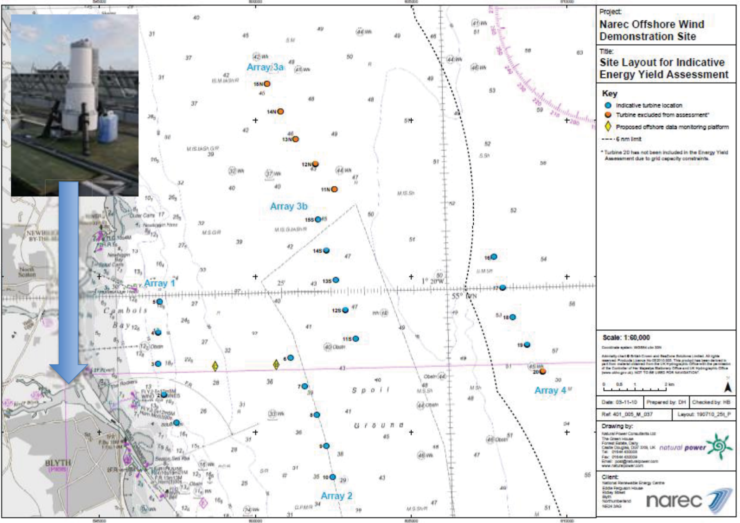
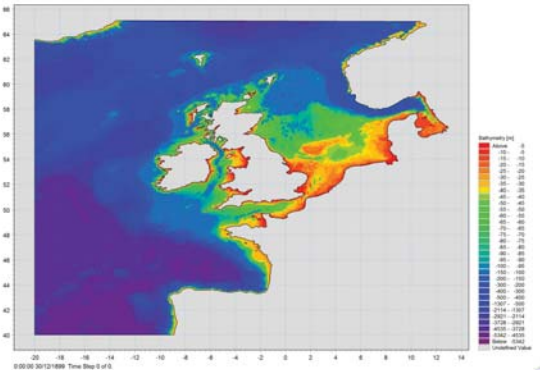
narec: Onshore ZephIR location and proposed platform location(s)



EUROPEAN WATER DEPTHS



USE OF EXISTING PLATFORMS

The use of existing platforms offers a “quick” way to get offshore:

- Research Stations
- Light houses
- Sub stations
- Oil and gas platforms

In the Offshore Wind Industry there has been an increase in size of Meteorological Mast platforms to allow for fitting or retro fit of Lidar. The design is not only relevant to the structure but has an impact on power budget and control systems.

TRADITIONAL PLATFORM SOLUTIONS

In the Offshore Wind Industry we have seen an increase in size of Meteorological Mast platforms to allow for fitting or retro fit of Lidar.

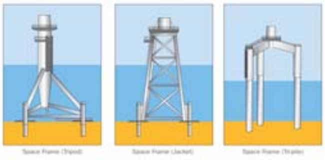
The design is not only relevant to the structure but has an impact on power budget (navigation aids) and control systems.

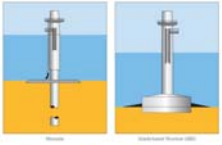
The costs associated with steel, power, installation and maintenance are all affected by the mix of mast and lidar. These round of installations will further boost the confidence in lidar only measurement campaigns.

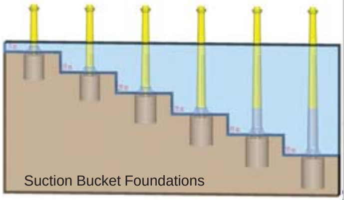
This is especially relevant when you consider the development of deep water turbines.

TRADITIONAL PLATFORM SOLUTIONS

Type of substructure	Brief physical description	Suitable water depths	Advantages	Limitations
Monopile steel	One supporting pillar	10 – 30m	Easy to manufacture, experience gained on previous projects	Piling noise, and competitiveness depending on seabed conditions and turbine weight
Monopile concrete, installed by drilling	One supporting pillar	10 – 40m	Combination of proven methods, Cost effective, less environmental (noise) impact, industrialisation possible	Heavy to transport
Gravity base	Concrete structure, used at Thornton bank	Up to 40m and more	No piling noise, inexpensive	Transportation can be problematic for heavy turbines. It requires a preparation of the seabed. Need heavy equipment to remove it
Suction bucket	Steel cylinder with sealed top pressed into the ocean floor	n.a.	No piling, relatively easy to install, easy to remove	Very sensitive to seabed conditions
Tripod / quadropod	3/4-legged structure	Up to 30m and more	High strength. Adequate for heavy large-scale turbines	Complex to manufacture, heavy to transport
Jacket	Lattice structure	> 40m	Less noise. Adequate for heavy large-scale turbines	Expensive so far. Subject to wave loading and fatigue failure. Large offshore installation period (first piles, later on placing of structure and grouting) therefor sensitive for weather impact






Suction Bucket Foundations

DEEP WATER TURBINES

Country	Project name	Principal partner	Description
Norway	Hywind	Statoil	Hywind is the first full scale grid-connected floating prototype (using spar class technology). It was installed off Karmøy island on the south-west coast of Norway in 2009 with a Siemens 2.3 MW machine.
Norway	Karmøy	Sway	Sway is building a prototype spar class floating design with the ambition of deploying a 5 MW turbine in 2013.
France	Vertiwind	Technip	In association with Nénuphar, Converteam and EDF Energies, Technip have launched a project to test a pre-industrial prototype of a vertical-axis floating wind turbine.
France	Winflo	Nass & Wind	In partnership with Saipem, DCNS and InVivo, Winflo is a 2.5 MW moored floating jacket class prototype to be installed off the coast of Brittany. Currently under development.
Spain	Zèfir Test Station	Catalonia Institute for Energy Research	In collaboration with a number of major industry players the Zèfir Test Station programme is intended to further deep water developments around Spain in two phases, the second of which involves installing eight turbines on floating structures at water depths of over 100 m.
Europe	HiPRwind	EU project consortium	Five-year programme with a total budget of €19.8 million to develop a new floating platform for "very large" offshore turbines.
Spain	Azimut Project	Gamesa	In partnership with Alstom Wind, Acciona and Iberdrola, the Azimut Project has the objective of providing the groundwork for the development in around 2020 of a 15 MW offshore turbine.
Portugal	Windfloat	Principle Power	In partnership with EDP and InovCapital, the Windfloat Project intends to install a full-scale Vestas V80 2 MW turbine for 12 months of testing in 2011. The Windfloat is a floating jacket design with novel features.
Italy	-	BlueH	A multi-national group of companies based in the Netherlands have developed a TLP concept consisting of a larger structure with several piles implanted in the surface. An off-grid prototype with an inactive turbine for visualisation purposes was installed 21 km off Brindisi, Italy in 100 m deep waters during 2007/8.

TWO MAIN FLOATING LIDAR PRODUCT DEVELOPMENTS

Free floating lidar - free-motion platforms with motion compensation
Device floats on the water surface and compensate the motion of the buoy either:

- physically (using devices such as gimbals) or;
- in the processing of data (through algorithms)

"Free floating" lidars are useful tools for the industry but can have higher uncertainty attached to their data; particularly in more extreme offshore wave conditions.

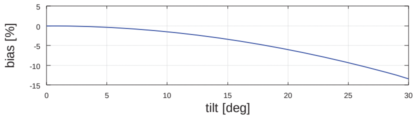
It is difficult to validate these compensations without experiencing all of the possible waves but they still offer a valuable insight into offshore wind conditions.

Motion-restricted floating lidar
Motion of the floating platform is minimised as much as possible removing the need for motion compensation, aiming to spend as much time as possible with the device within 5 degrees of vertical without there being large vertical or horizontal movements.

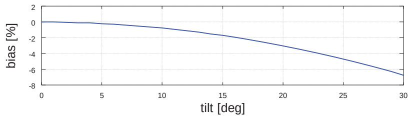
Easier to validate wind data as scenario is more representative of a lidar based on a fixed platform offshore or based at ground level onshore.

EFFECT OF TILT ON DATA – MOTION STABLE PLATFORM

Static tilt
This may occur due to tides or steady currents. It should be possible to correct for steady state tilt using the ZephIR's inbuilt tilt sensor. For tilt less than 5°, bias is seen as 1% or less.



Low frequency periodic tilt (0.01 Hz)
The averaging effect of a periodic (sinusoidal) tilt motion reduces the error by a factor of approximately 2, relative to the static case. For the cases of static and low frequency periodic tilt, vertical wind speed has no effect except at very high tilt angles. For tilt less than 5°, bias is seen as 0.25% or less.



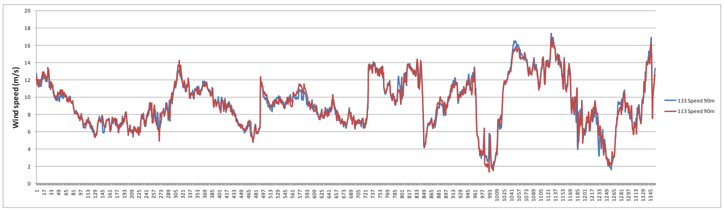
FLOATING PLATFORM LIDAR CASE STUDIES

"SeaZephIR" – production lidar mounted on spar buoy for platform stability

Concept trialled in 2009: two ZephIR units deployed off coast of Norway, LandZephIR on small island, SeaZephIR buoy anchored out to sea

Separation of units 800m: excellent correlation obtained

COMPARISON BETWEEN SEA- AND LAND-BASED LIDARS



Wind speed time series data from height 90m above sea level:
SeaZephIR data in red
LandZephIR data in blue
Data plotted here from 5-23 November 2009

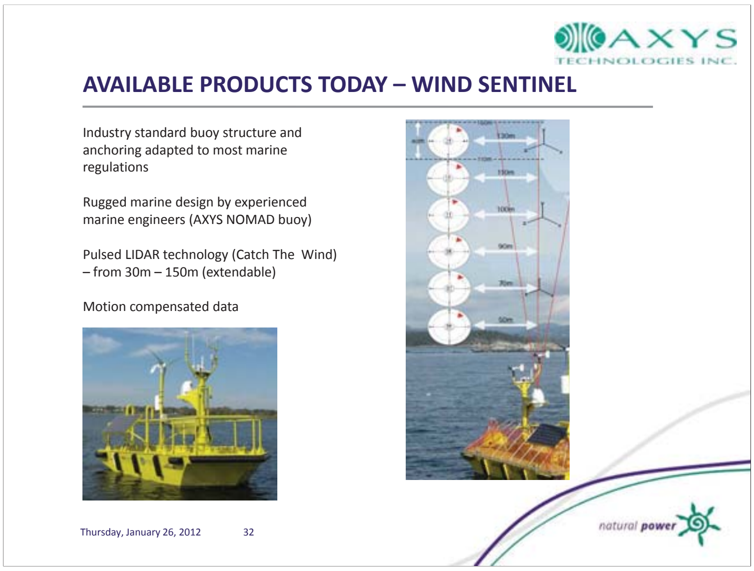
AVAILABLE PRODUCTS TODAY - FLIDAR

Industry standard buoy structure and anchoring adapted to most marine regulations

Rugged marine design by experienced marine engineers (GeoSea)

Pulsed LIDAR technology (Leosphere) – from 40m to 200m

Mechanical stabilisation and software correction algorithms



AVAILABLE PRODUCTS TODAY – WIND SENTINEL

Industry standard buoy structure and anchoring adapted to most marine regulations

Rugged marine design by experienced marine engineers (AXYS NOMAD buoy)

Pulsed LIDAR technology (Catch The Wind) – from 30m – 150m (extendable)

Motion compensated data

AVAILABLE PRODUCTS TODAY – WAVESCAN ZEPHIR

Marine designed by experts at Fugro Oceanor

Mounted on the existing successful Fugro Wavescan buoy

Continuous Wave ZephIR lidar measuring from 10m-200m

Currently at pre-production prototype, testing being conducted Sletringen light house, Frøya.

AVAILABLE PRODUCTS TODAY – SEA ZEPHIR

Industry standard stable tension leg buoy structure and anchoring adapted to most marine regulations

Rugged marine design by experienced marine engineers (SeaRoc)

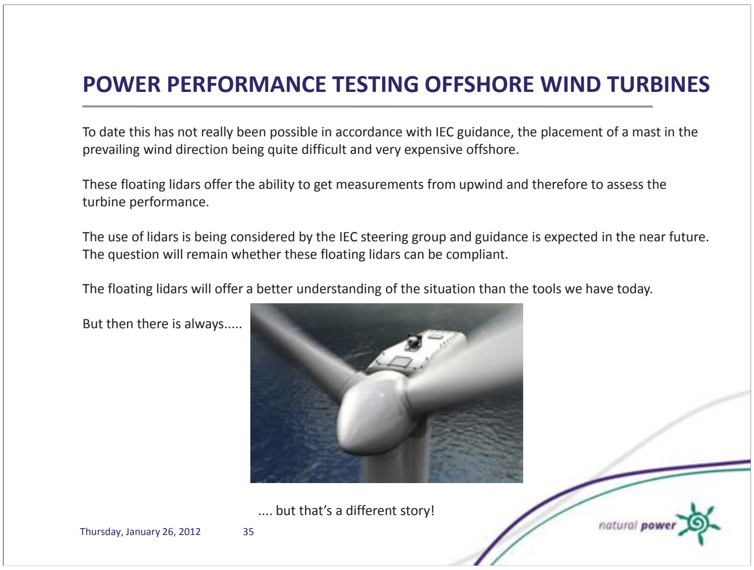
Continuous Wave LIDAR technology (ZephIR) – from 10m to 200m

Inherently stable platform, no motion compensation

Energy autonomous

Satellite communication

Data retrieval and analysis via web interfaces (vuWind)



POWER PERFORMANCE TESTING OFFSHORE WIND TURBINES

To date this has not really been possible in accordance with IEC guidance, the placement of a mast in the prevailing wind direction being quite difficult and very expensive offshore.

These floating lidars offer the ability to get measurements from upwind and therefore to assess the turbine performance.

The use of lidars is being considered by the IEC steering group and guidance is expected in the near future. The question will remain whether these floating lidars can be compliant.

The floating lidars will offer a better understanding of the situation than the tools we have today.

But then there is always.....

.... but that's a different story!

9th Deep Sea Offshore Wind R&D Seminar
19-20 January 2012, Royal Garden Hotel,
Kjøpmannsgata 73, Trondheim, NORWAY

Comparison of met–mast and lidar measurements at Frøya

Prof Lars Sætran, NTNU

•Goal:

- •Data for Wind Energy Relevant for Offshore Wind
- •Forecasting the wind behaviour of upcoming wind
- •Temporal Wind Characterictics
- •Turbulent Characteristics
- •Spatial Correlation

INSTRUMENTATION

Windcube

Anemometers, Temperature Sensors and Wind cube

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 12: View from the mast

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

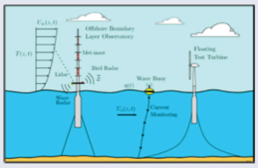
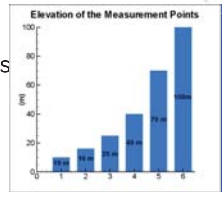


Figure 1: Offshore Wind measurements

Sonic Anemometers

- •Gill Anemometers
  - Range 0 – 65 m/s
  - Accuracy ±2 % @ 12 m/s
  - Resolution 0.01 m/s
  - Offset ±0.01 m/s
- •Temperature Sensors
- •6 Levels
- •2 Anemometers at Each Level
- •1 Hz Sampling rate



Lidar:

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

Figure 4: Leosphere Windcube

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)

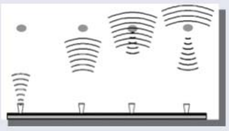


Figure 2: Lidar physical principle

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)

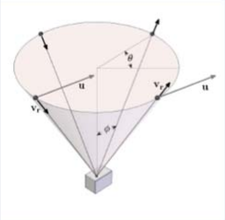


Figure 3: Leosphere lidar

- Indirect Measurement: (40m to 200m)
- Speed range: $0 - 46m/s$
- Accuracy $\pm 2^o; \pm 0.2m/s$
- Sampling freq: ca. $0.9Hz$
- 3D measurements
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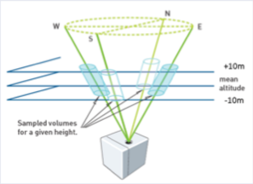


Figure 5: Offshore Wind measurements

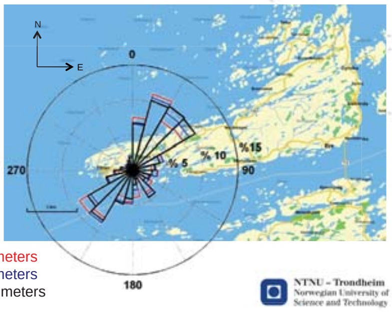
Some Results From the Wind Measurements at Titran Test Site

G. Tasar, F. Pierella, L. Sætran,
Department of Energy and Process Engineering, Norwegian University of Science and Technology,
7491 Trondheim, Norway

RESULTS

Prevailing Wind Directions

- North east and south west directions are dominating
- South west direction can be estimated as ocean wind



40 meters
70 meters
100 meters

NTNU – Trondheim
Norwegian University of Science and Technology

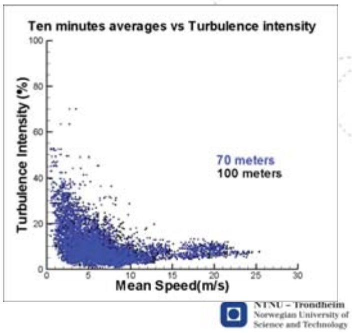
Some Results From the Wind Measurements at Titran Test Site

G. Tasar, F. Pierella, L. Sætran,
Department of Energy and Process Engineering, Norwegian University of Science and Technology,
7491 Trondheim, Norway

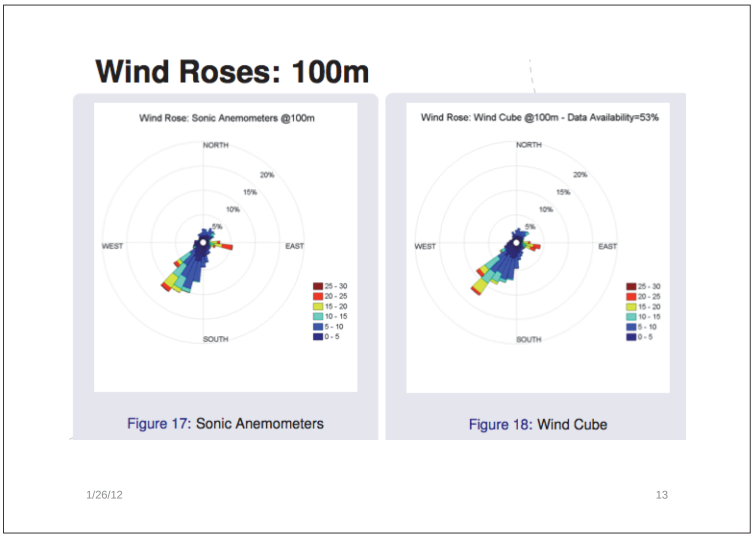
RESULTS

Ten Minutes Averaging & Turbulence Intensity Distributon

- Ten minutes average of the wind speed fits in a pattern
- Lower speeds has higher turbulence intensity



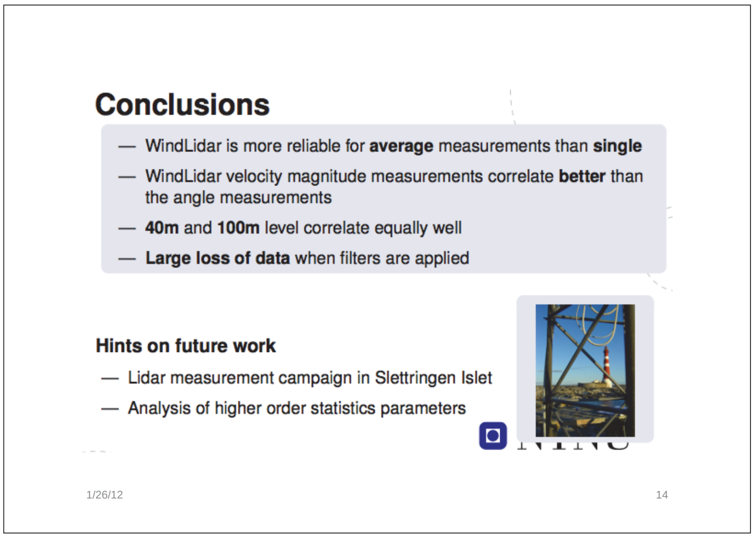
NTNU – Trondheim
Norwegian University of Science and Technology



Wind Roses: 100m

Figure 17: Sonic Anemometers

Figure 18: Wind Cube

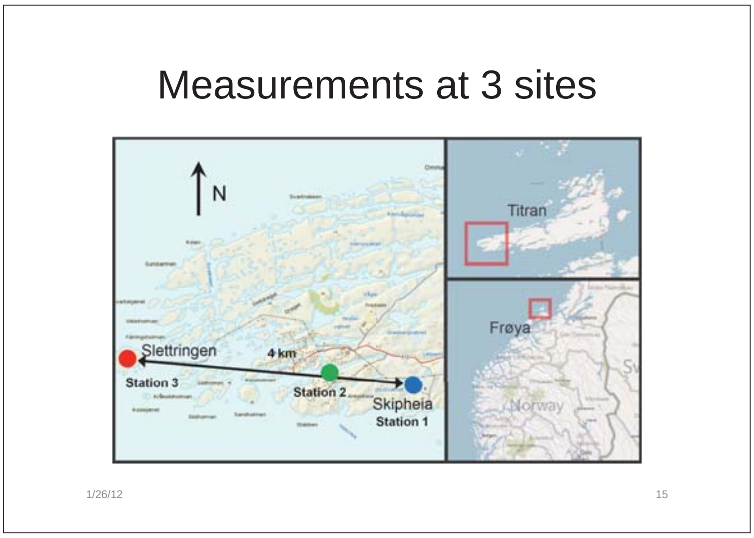


Conclusions

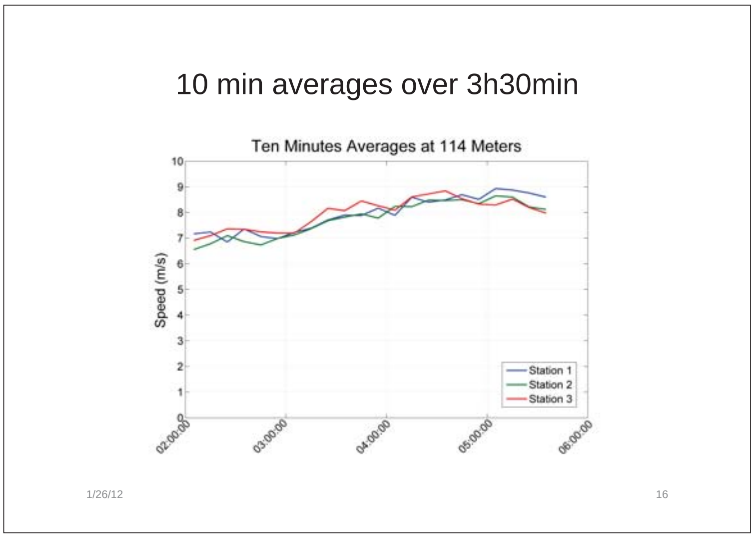
- WindLidar is more reliable for **average** measurements than **single**
- WindLidar velocity magnitude measurements correlate **better** than the angle measurements
- **40m** and **100m** level correlate equally well
- **Large loss of data** when filters are applied

Hints on future work

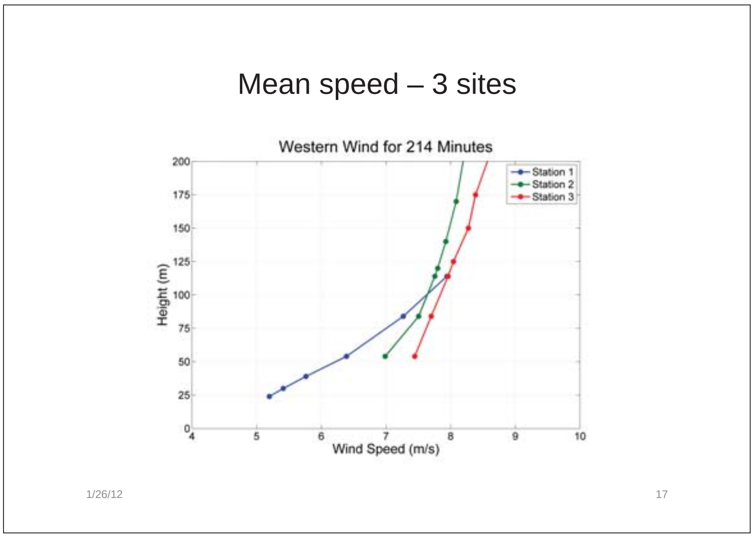
- Lidar measurement campaign in Slettringen Islet
- Analysis of higher order statistics parameters



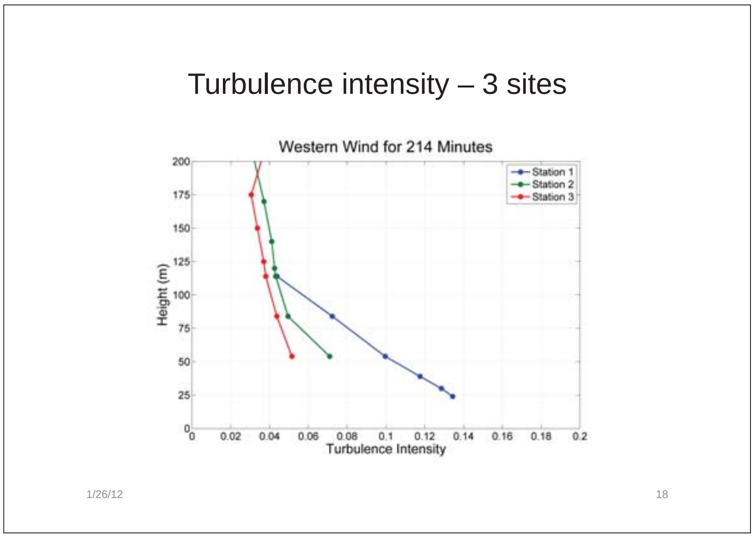
Measurements at 3 sites



10 min averages over 3h30min



Mean speed – 3 sites



Turbulence intensity – 3 sites

Exp on 3 sites for measuring “duration” and spatial “extent” of wind gusts

Short-term wind forecasting

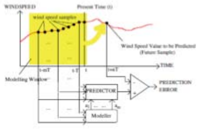
- Interested in time horizon from a few seconds to 30min ahead

- Short-term forecasting for:
- Electricity Market
- Regulation Actions

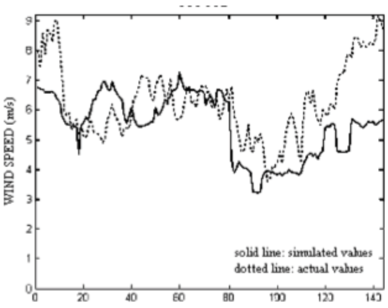
- Methods of forecasting statistical in nature and divided the following subclasses:
- Artificial Neural Network
- Time-series Models - must prove superior to a most simple approach:

P(t+T)=P(t)

i.e. the output of a turbine at time t+T, is the same as the output at time t.



Forecasting: experiments and modelling



Turbine wake studies

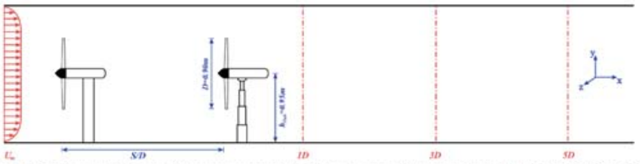


Fig. 1. Experimental setup and axial measurement stations downstream of the second model turbine at 1D, 3D and 5D

Power extracted from the wind

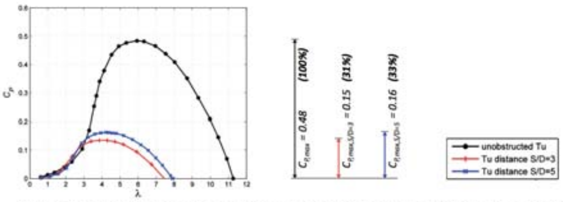


Fig. 2. Power curves of the second model wind turbine operated unobstructed, *S/D=3* downstream and *S/D=5* downstream of the first turbine

2^{nd} turbine wake

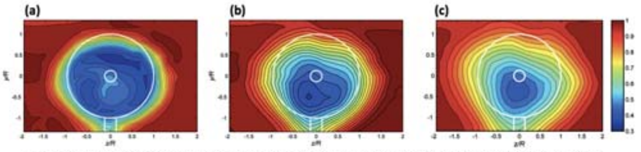


Fig. 3. Normalized mean velocity U_M/U_∞ [-] in the wake behind the array of two model turbines separated *S/D=3*: (a) 1D downstream; (b) 3D downstream; (c) 5D downstream

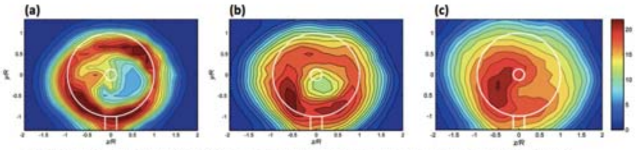
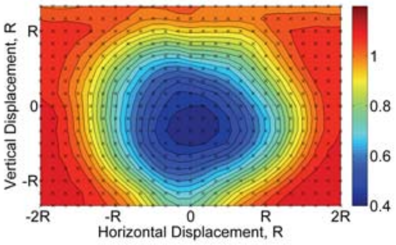
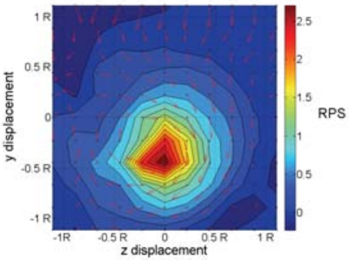


Fig. 4. Turbulence intensity u'/U_M [%] in the wake behind the array of two model turbines separated *S/D=3*: (a) 1D downstream; (b) 3D downstream; (c) 5D downstream

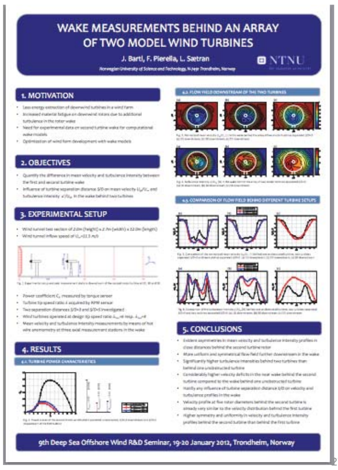
Wake - 3D downstream the **second** turbine (5D separation distance, TSR=6)



Swirl in turbine wake, 3D downstream, TSR=6 (RPS= "rounds pr second")



Take a look at Jan Bartl's poster (this afternoon)



WAKE MEASUREMENTS BEHIND AN ARRAY OF TWO MODEL WIND TURBINES

J. Bartl, F. Pierella, L. Sætran

Norwegian University of Science and Technology, N-7491 Trondheim, Norway

1. MOTIVATION

- Less energy extraction of downwind turbines in a wind farm
- Increased material fatigue on downwind rotors due to additional turbulence in the rotor wake
- Need for experimental data on second turbine wake for computational wake models
- Optimization of wind farm development with wake models

2. OBJECTIVES

- Quantify the difference in mean velocity and turbulence intensity between the first and second turbine wake
- Influence of turbine separation distance S/D on mean velocity and turbulence intensity in the wake behind two turbines

3. EXPERIMENTAL SETUP

- Wind tunnel test section of 2.0m (height) x 2.7m (width) x 12.0m (length)
- Wind tunnel inflow speed of 11.5 m/s
- Power coefficient measured by torque sensor
- Turbine tip speed ratio λ acquired by RPM sensor
- Two separation distances S/D=3 and S/D=5 investigated
- Wind turbines operated at design tip speed ratio
- Mean velocity and turbulence intensity measurements by means of hot wire anemometry at three axial measurement stations in the wake

4. RESULTS

4.1 TURBINE POWER CHARACTERISTICS

4.2 FLOW FIELD DOWNSTREAM OF THE TWO TURBINES

4.3 COMPARISON OF FLOW FIELD BEHIND DIFFERENT TURBINE SETUPS

5. CONCLUSIONS

- Evident asymmetries in mean velocity and turbulence intensity profiles in close distances behind the second turbine rotor
- More uniform and symmetrical flow field further downstream in the wake
- Significantly higher turbulence intensities behind two turbines than behind one unobstructed turbine
- Considerably higher velocity deficits in the near wake behind the second turbine compared to the wake behind one unobstructed turbine
- Hardly any influence of turbine separation distance S/D on velocity and turbulence profiles in the wake
- Velocity profile at five rotor diameters behind the second turbine is already very similar to the velocity distribution behind the first turbine
- Higher symmetry and uniformity in velocity and turbulence intensity profiles behind the second turbine than behind the first turbine

9th Deep Sea Offshore Wind R&D Seminar, 19-20 January 2012, Trondheim, Norway

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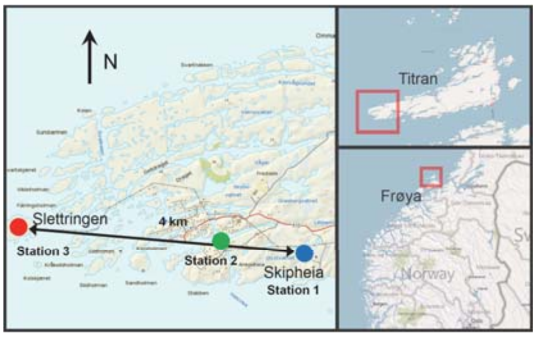
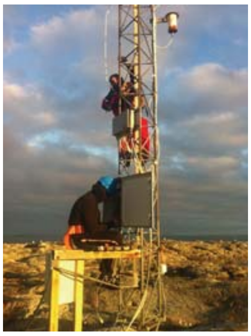
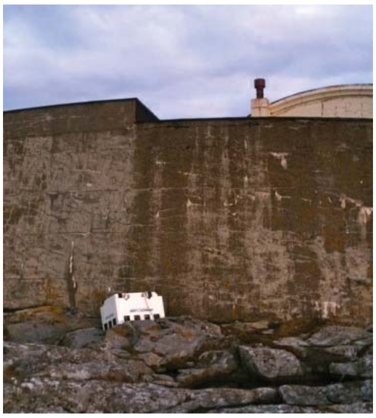
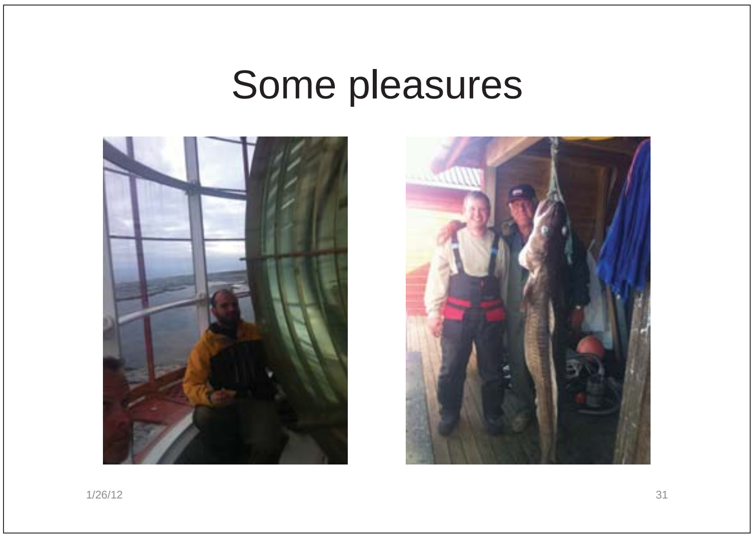


Field work



Some setbacks





Some pleasures

1/26/12

Experiences and Results from Statoil's LIDAR Measurement Campaign at Utsira

Presented by
Yngve Ydersbond, Kjeller Vindteknikk

Main contributors: Peter Rothmund, Espen Åkervik, Erik Berge, Wei He (Statoil)

Offshore Measurements at Utsira

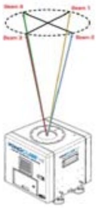
- The Utsira measurement campaign is part of Statoil's contribution to the EU-project NORSEWIND (Northern Seas Wind Index Database)
- Detailed CFD-model runs have been conducted to filter out the effects of the island . "True" offshore profiles for the Utsira site will be presented as part of NORSEWIND by summer 2012
- The Utsira LIDAR has been operated by Kjeller Vindteknikk and experiences with the LIDAR are presented here

Utsira Measurement Site

- Offshore sector from South to North
- LIDAR located 27 m. AMSL

LIDAR Equipment

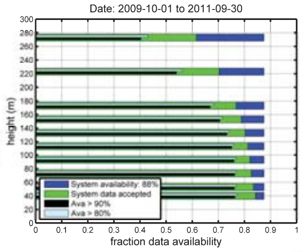
- Leosphere Windcube v1
- The 37th Windcube produced by Leosphere (1st of January 2009)
- Connected to power grid and communicating with 3G



Availability of Measurements

Period	40 m	53 m	73 m	93 m	113 m	133 m	153 m	173 m	223 m	273 m
2009-Oct to 2010-Sep (1st yr)	87 %	87 %	87 %	86 %	85 %	83 %	81 %	77 %	63 %	47 %
2010-Oct to 2011-Sep (2nd yr)	66 %	66 %	66 %	66 %	65 %	63 %	61 %	57 %	45 %	34 %
2009-Oct to 2011-Sep (2 yrs)	76 %	76 %	76 %	76 %	75 %	73 %	71 %	67 %	54 %	40 %

- Valid 10-min data (> 90 % valid 1-sec data)
- "Clear sky" leads to low data retrieval
- Unstable software in combination with poor network coverage leads to system down time

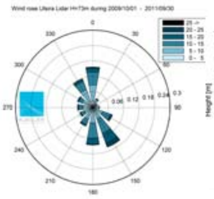


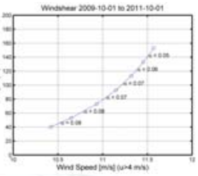
Operation and Maintenance

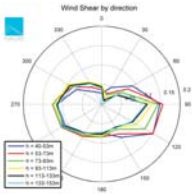
- New rotational stage and updated software in August 2011 (~2 years of operation)
- Frequent control of operation, unstable software needing reboot etc.
- Site visit about every 4 weeks, refill wiper fluid or manual reboot
- New wiper engine and blades

Measurement Results

Measurement height	40 m	53 m	73 m	93 m	113 m	133 m	153 m	173 m	223 m	273 m
Wind speed (2 years) [m/s]	9.3	9.5	9.8	10.0	10.2	10.4	10.5	10.8	11.4	12.0



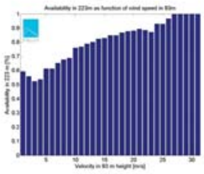


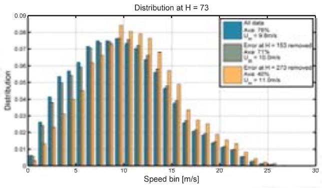


- Necessary to correct for inhomogeneous wind fields
- Correct for speed up caused by topography

Accuracy of Measurements

- No reference measurements
- Low wind shear and turbulence is advantageous
- Stricter validation process for Windcubes produced today
- Availability of measurements dependent on wind speed





Ongoing Campaigns with LIDAR at Kjeller Vindteknikk

- Utsira campaign is in its 3rd year. Works very well after maintenance during summer 2011.
- Two Leosphere Windcube v2 LIDARs deployed in eastern Norway

Experiences

- The availability of valid measurements over the two first years is 76% in 73 m and 71% in 153 m.
- Follow manufacturers maintenance program to ensure proper function and updated hardware and software
- Plan for frequent site visits with trained personnel
- The measurement availability may be dependent on parameters the lidar measures (e.g. wind speed)

Posters

Effect of Forced Excitation on Wind Turbine with Dynamic Analysis in Deep Offshore Wind,
Prof Chuichi Arakawa, Univ. of Tokyo

Flow past fixed circular cylinder at Re 3900 using the Spalart-Allmaras turbulence model,
Knut Nordanger, PhD stud, NTNU

GPS Synchronisation of Harmonic and Transient Measurements in Offshore Wind Farms,
Iván Arana, DONG Energy

EMC Challenges during Harmonic and Transient Measurements in Offshore Wind Farms,
Iván Arana, DONG Energy

Incidence of the switching frequency on efficiency and power density of power conversion topologies for offshore wind turbines, Rene A. Barrera, PhD stud, NTNU

Benefits of Asymmetric HVDC Links for the North Sea Super Grid, Til Kristian Vrana, PhD stud, NTNU

Stability improvements in Oil Platforms from Wind Turbines Atle Rygg Årdal, SINTEF Energi AS

Challenges and rationale for laboratory testing in offshore grids research, Kjell Ljøkelsøy,
SINTEF Energi AS

An approach to model the statistics of wind speed and wind power increments on a 10min time scale, Prof Hans Georg Beyer, University of Agder

Upper Ocean Response to Large Wind Farm Effect in the Presence of Surface Gravity Waves,
Mostafa B. Paskyabi, PhD stud, University of Bergen

A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation – improvement to an existing tool ECUME, Fanny Douard, EDF

Selection of important RAMS parameters for 10MW reference wind turbine, Zafar Hameed,
PhD stud, NTNU

Fatigue analysis of copper conductor for offshore wind turbines by experimental and FE method,
Fachri Nasution, PhD stud, NTNU

Maintenance strategies for large offshore wind farms, Matti Scheu, NTNU

Mooring system optimization for floating wind turbines using frequency domain analysis,
Matthias Brommundt, NTNU

PLOCAN, a multiuse offshore test site in the Atlantic Ocean, José Joaquín Hernández-Brito, Plocan

A novel tool for FEM analysis of offshore wind turbines with innovative visualization techniques,
Paul E. Thomassen, Post Doc, NTNU

Iterative optimization approach for the design of full-height lattice towers for offshore wind turbines,
Daniel Zwick, PhD stud, NTNU

Wake measurements behind an array of two model wind turbines, J. Bartl, NTNU

Active Power Control with Undead-Band Voltage & Frequency Droop for HVDC Converters in Large
Meshed DC Grids, Til Kristian Vrana, PhD stud, NTNU

Fully Nonlinear Wave Forcing on an Offshore Wind Turbine. Structural Response and Fatigue,
Signe Schløer, PhD stud, Technical Univ. of Denmark

Panel Vortex Code for wind turbines implemented on a GPU, Lene Eliassen, Univ. of Stavanger

Yaw moments of a three-bladed wind turbine yaw error, Tania Bracchi, PhD stud, NTNU

Gain scheduled and robust $H\infty$ control above rated wind speed for wind turbines, Fredrik Sandquist,
PhD stud, NTNU

Effect of Forced Excitation on Wind Turbine with Dynamic Analysis in Deep Offshore Wind

Mitsumasa Iino[a], Makoto Iida[b], Chuichi Arakawa[c]
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THE UNIVERSITY OF TOKYO

Introduction

One of the unique problems of floating offshore wind turbines is negative damping of tower pitching motion. The reason is that the increase of wind speed causes the decrease of thrust force of the rotor.

The equation of motion for single degree of freedom of nacelle (Jonkman [*1])

.

$$\left(\frac{I_{Mass}+A_{Radiation}}{L^2}\right)\ddot{x}+\left(\frac{B_{Radiation}+B_{Viscous}}{L^2}+\frac{\partial T}{\partial V}\right)\dot{x}+\left(\frac{C_{Hydrostatic}+C_{Lines}}{L^2}\right)x=T_0$$

L : Hub height
x : Nacelle fore - aft displacement
T_0 : Thrust force in equilibrium

$\frac{\partial T}{\partial V}$ **⇒Negative Damping**

As nacelle oscillates backward, relative inflow wind speed decreases. This decrease causes the change of thrust force. With blade pitch control, thrust force increases with this decrease of wind speed. Then, nacelle moves more backward.(Fig.1)

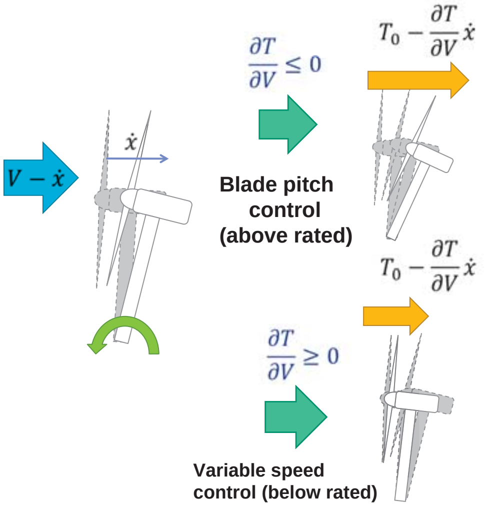


Figure 1 Change of Thrust Force with Tower Pitching Motion

Simulation Methods

We simulated change of thrust force by analysis of the turbine for wind tunnel testing[*2]. To simulate the relative wind speed change, oscillating inflow speed and rigid turbine model are used(Fig.3). Two controls are tested: Blade pitch control and variable speed control. Pitch control observes generator speed.

Turbine Type	Horizontal Axis
Rotor Diameter	1.5m
Number of Blades	3 bladed
Tower Height	0.8m
Hub Height	0.95m
Generator	Coreless DC motor

Figure 2 Modeled Wind Turbine[*2]

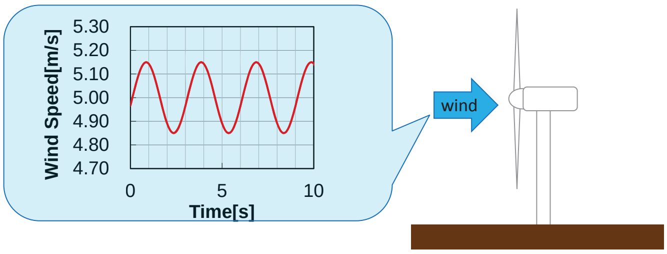


Figure 3 Simulation Condition

Variable speed control maintains optimal tip speed ratio. GH bladed is used for this simulation.

Results

Fig4. shows time-series of thrust force and wind speed with variable speed control. The fluctuation of thrust force and wind speed shows the same sign. This means $\partial T/\partial V \ge 0$ and negative damping is not caused.

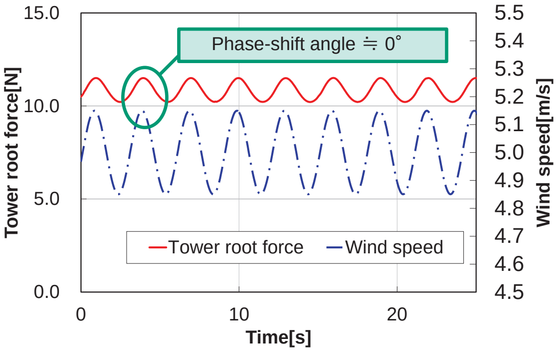


Figure 4 Wind Speed and Tower Root Force with Variable Speed Control

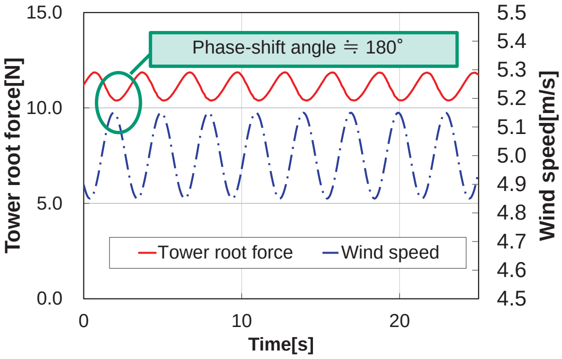


Figure 5 Wind Speed and Tower Root Force with Blade Pitch Control

Fig5. shows time-series of thrust force and wind speed with variable speed control. The fluctuation of thrust force and wind speed shows the same sign. This means $\partial T/\partial V \le 0$ and negative damping can be caused.

Conclusion

Traditional blade pitch control above rated wind speed can cause the negative damping of the wind turbine. In addition, this phenomenon can be observed by small scale turbine for wind tunnel testing.

Future work

We are planning to introduce the new control variables such as nacelle speed or thrust force. By observing nacelle speed, pitch control is not disturbed with relative wind speed change caused by nacelle motion. Furthermore, by observing thrust force, we think thrust force decreasing can be prevented with both pitch and variable speed control.

References

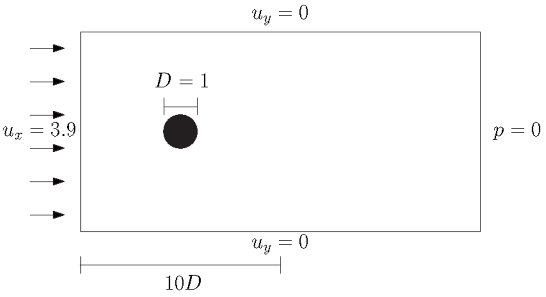
[1] J. M. Jonkman, "Influence of Control on the Pitch Damping of a Floating Wind Turbine," NREL,March, 2008.
[2] T. Chujo, S. Ishida, Y. Minami, and T. Nimura, "Model experiments on the motion of a spar type floating wind turbine in wind and waves," Proceedings of the ASME2011 30th International Conference on Ocean Offshore and Arctic Engineering, 2011.

Flow past fixed circular cylinder at Re 3900 using the Spalart-Allmaras turbulence model

Knut Nordanger, PhD Candidate, Dept. of Mathematical Sciences, NTNU
Trond Kvamsdal, NTNU and Runar Holdahl, SINTEF ICT

Problem description

Flow past a fixed 2D circular cylinder placed in a fluid with $Re = 3900$ is investigated.



The computed values for Strouhal number and average drag are compared with experimental results found in [1].

Numerical code

The incompressible Navier-Stokes equations are solved using the IFEM code developed at SINTEF ICT Applied Mathematics. This code is based on isogeometry, i.e. the same set of basis functions are used for both the geometry representation and the analysis. Non-uniform rational B-splines (NURBS) are used. The fluid solver uses a Chorin projection scheme. Equal order approximations for velocity and pressure are used, i.e. Q_1/Q_1, Q_2/Q_2 and Q_3/Q_3. Variable time steps are determined by the CFL-condition.

Solution strategy

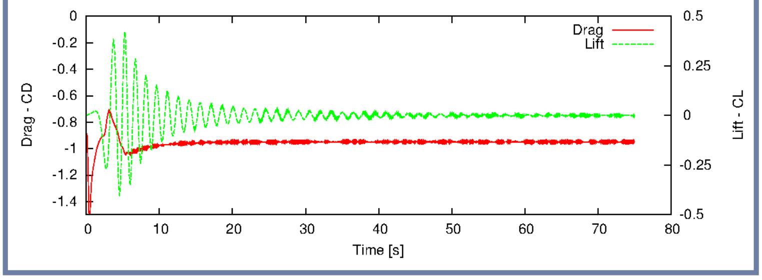
Turbulence model

The one-equation turbulence model Spalart-Allmaras [2] is applied for the simulations. It is developed for aerodynamic flows and commonly used for determining lift and drag coefficients of airfoils at high Reynolds numbers.

Boundary layer

In order to sufficiently resolve the boundary layer for the Spalart-Allmaras turbulence model we choose the distance from the cylinder to the first knot line (i.e. node in finite elements) as a dimensionless wall distance, $y^+ = 1$.

Drag and lift



References

[1] A.G. Kravchenko and P. Moin. “Numerical studies of flow over a circular cylinder at ReD=3900”. In: *Physics of Fluids* 12.2 (2000), pp. 403–417.

[2] P.R. Spalart and S.R. Allmaras. “One-equation turbulence model for aerodynamic flows”. In: *Recherche aerospatiale* 1 (1994), pp. 5–21.

Numerical results

The numerical results are compared to experimental values of 0.99 for average drag and 0.21 for the Strouhal number in [1]. In conclusion, for basis functions of order 3 for both velocity and pressure the results for mean drag are acceptable. However, deviations for the Strouhal number are much larger. Accurate time resolution is not one of the strengths for the Spalart-Allmaras turbulence model, which is better suited for Reynolds numbers far higher than 3900.

			Results		Deviation	
Approx.	**Avg. Δt**	**n_{el}**	**Mean drag**	**Strouhal**	**Mean drag**	**Strouhal**
Q1/Q1	0.00500	10200	0.7924	0.1884	-19.96%	-10.30%
Q1/Q1	0.00425	14880	0.7745	0.1879	-21.77%	-10.53%
Q2/Q2	0.00934	10200	0.8950	0.1820	-9.60%	-13.35%
Q2/Q2	0.00832	14880	0.8749	0.1815	-11.63%	-13.59%
Q3/Q3	0.01254	10200	0.9574	0.1736	-3.29%	-17.34%
Q3/Q3	0.01206	14880	0.9501	0.1716	-4.03%	-18.27%

GPS synchronisation of harmonic and transient measurements in offshore wind farms

Łukasz Hubert Kocewiak, Iván Arana, Jesper Hjerrild, Troels Sørensen, Claus Leth Bak, Joachim Holbøll

DONG Energy, Aalborg University, Danmarks Tekniske Universitet

Abstract

The GPS synchronization challenges during the development, construction and installation of a measurement system for multi-point, high-speed and long-term data logging is described in this paper. The presented measurement system was tested in a rough offshore environment at Avedøre Holme (see Figure 1) and Gunfleet Sands Offshore wind farms. The paper will describe the application of GPS technology in synchronised measurements carried out at Avedøre Holme and Gunfleet Sands wind farms. Different aspects of software development and hardware configuration in order to optimise measurement system reliability during offshore measurements will be presented. Also real-life examples of results from both offshore measurement campaigns will be described. Some limitations and improvements of the measurement system will be explained based on measurements from both harmonic and transient measurements.

Figure 1 Avedøre Holme Offshore Wind Farm and measurement points.

Objectives

Accurate measurements of harmonic and transient phenomena in offshore wind farms are essential for data analysis and model creation/validation of components or subsystems. These models can be further used in simulation tools during the development of offshore wind farms. In order to observe the harmonic and transients in the collection grid without any misleading disturbances, a great deal of effort was taken to make the measurements as accurate as possible.

The measurement system developed here was designed taking into account the special application, requirements and environment of offshore wind farms (OWFs). Here, the access is limited due to weather conditions and significant operational costs; hence a robust and trustful measurement system is important. The synchronization of measurement systems in different locations is one important aspect taken into account in the development process of a flexible measurements system for harmonic and transient measurements in OWFs.

Methods

Synchronisation board

Specially designed EMC-proof boxes were equipped with cooling system in order to keep constant ambient temperature. If the ambient temperature differs from the calibration temperature by more than ±5° C the temperature compensated crystal oscillator (TCXO) will be affected by drift and introduce additional synchronization uncertainties.

Software development

In software development it is of special importance to implement synchronization support in the easiest way as possible. In case of transient measurements synchronization delays affected by the software layer can affect the whole measurement process. It was decided that the measurement software will start according to the time reference obtained from timing and synchronization board. A time reference is an external source of timestamp that provides periodic time updates. It is possible to provide time reference from GPS satellites, IEEE 1588 masters, or IRIG-B sources. As mentioned earlier each of the sources provides periodic time updates. In case of GPS satellites broadcast the current time once per second, on the second's boundary. The synchronization board has the oscillator (clock) accuracy of 1ppm which provides accurate time reference every second (PPS).

Synchronisation uncertainties

Used for offshore measurement purposes receivers provide a 1 pps on-time pulse. The GPS receiver is limited to using SPS the uncertainty is defined by the top row in Table 1. It shows that there is a 50 % probability that a given on-time pulse from GPS will be within ±115 ns of UTC. The 1σ uncertainty of GPS (~68 % probability) is ±170 ns, and the 2σ uncertainty (95 %) is ±340 ns [3], [4].

Service	Uncertainty (ns) 50th percentile	Uncertainty (ns) 1σ	Uncertainty (ns) 2σ
SPS	±115	±170	±340
PPS	±68	±100	±200

Table 1 Timing uncertainty of GPS in One-Way Mode

To achieve uncertainties presented in Table 1 one has to calibrate receiver and antenna delays, and estimate synchronization errors. The antenna providing reliable performance in harsh radio frequency (RF) jamming environments was connected to the receiver and mounted outdoors where it had clear, unobstructed view of the sky. This condition can be easily satisfied in large OWFs situated far from natural barriers and effects such as multipath propagation [5] due to the signal reflection, and high dilution of precision (DOP) when detected satellites are close together in the sky, can be neglected. Positional accuracy was improved due to the fact that the WTs and the substation at GFS OWF are situated far from each other and naturally are far from multipath reflectors (see [6]).

Pulse-per-second signal accuracy measured during measurement campaign at Gunfleet Sands OWF is shown in Figure 2. The accuracy is even better than provided by the manufacturer (15 ns, 1σ).

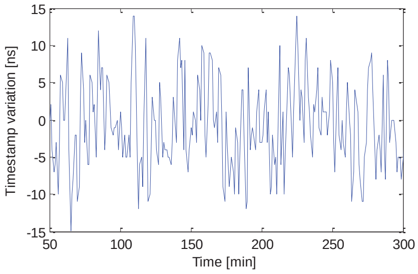


Figure 2 Variation of pulse-per-second signal synchronized with a GPS timestamp using phase-locked loop

Installation considerations

The measurement equipment in the wind turbines in Avedøre and Gunfleet Sands was installed in the basement of the wind turbine, where the service technicians do not require going often. In the transformer platform the measurement equipment was installed in the 33kV switchgear room, close to the voltage and current probes. It is important to mention, that the installation of the GPS antennas in Avedøre and Gunfleet Sands had to be done in open space outside the wind turbines and the transformer platform, in order to receive the best signal from the satellites. Nevertheless, the measurement equipment should be installed indoor, in a controlled environment. These two opposite requirements for the entire measurement system had to be fulfilled.

Results

Some of the transient measurements during the switching in of the VCB in the AVV wind turbine are shown in Figure 3. In this figure the voltage and current on the MV side of the transformer are shown, as well as the LV side voltage. It is possible to see in this figure the high frequency voltage oscillation caused by the pre-strike in the VCB that is transfer to the LV side as well as the inrush current of the transformer. The VCB model validation, as well as the wind turbine transformer and external grid validation has been reported in [7].

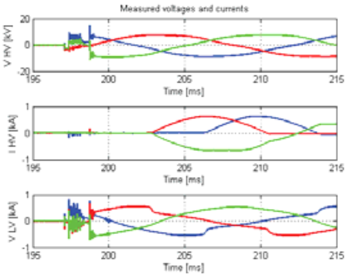


Figure 3 Measured three-phase voltages and currents, during the closing operation of the MV VCB in the wind turbine.

Discussion

During the removal of the measurement equipment in GFS, after 8 months of measurements, it was noticed that one of the GPS antennas was damaged. The antenna presented high level of corrosion in the metallic lower part of the antenna. Only the antenna in one of the wind turbines presented this corrosion. Due to this deterioration, the coaxial cable connected to the antenna, was also damaged, and had to be repaired afterwards. The metallic part of the antenna was simply cleaned. The damage in the antenna clearly shows the harsh environment to which the offshore wind turbines are subjected. In practice, this is solved by carefully isolating the equipment inside the turbine tower from the offshore environment.

Acknowledgment

The Industrial Ph.D. project "Harmonics in Large Offshore Wind Farms" is supported by the Danish Ministry of Science, Technology and Innovation, project number 08-044839. The measurement campaigns were sponsored by Dong Energy´s Sider3.6 R&D project.

Gunfleet Sands Offshore Wind Farm

9th Deep Sea Offshore Wind R&D Seminar,
19-20 January 2012, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY

EMC of Harmonic and Transient Measurement Equipment in Offshore Wind Farms

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DONG Energy, Aalborg University, Danmarks Tekniske Universitet

Abstract

The electromagnetic compatibility (EMC) and interference (EMI) aspects during the development, construction, testing and installation of a measurement system for multi-point, high-speed and long-term data logging is described in this paper. The presented measurement system was tested in a rough offshore environment at Avedøre Holme and Gunfleet Sands (see Figure 1) offshore wind farms. The paper clearly presents possible electromagnetic interference in wind turbines that can affect measurements. Also the application of appropriate mitigation techniques such as data acquisition board configuration, coaxial cable leading, as well as usage of EMC-proof boxes for high frequency measurements is described. Some measurement results focused on dealing with EMI are also presented and explained.

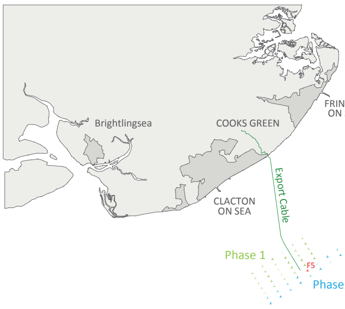


Figure 1 Gunfleet Sands Offshore Wind Farm and measurement points.

Objectives

The most likely scenario for incompatibility occurs when a relatively high power circuit (i.e. power converter) is located near a very sensitive receptor (e.g. sensors, cables, measuring head unit). Switch-mode high power density converters commonly used in nowadays wind turbines are potential generators of EMI due to the switching action of the converter. The switching action generates a spectrum of the switching frequency and its harmonics which can interfere the measurement process. The main purpose of presented studies is to develop and optimize measurements system for wind turbine measurements. Dealing with the EMI becomes crucial in case of harmonic measurements (low amplitude) and transient measurements (wide frequency spectrum).

Figure 2 EMC box installed in the transformer platform at Gunfleet Sands Offshore Wind Farm.

Methods

If during measurements the transfer of electromagnetic energy from source (emitter) equipment, which in a wind turbines is the main power circuit, through a coupling path to a receptor (receiver), which is the measurement equipment, an EMI occurs.

Before any measurements are carried out it is recommended to perform test of EMI in the environment. Also in case of offshore measurements such test measurements were done. The first step is to perform open circuit measurements (see Figure 4) in the field and compare with laboratory expectations. According to central limit theorem one should expect normally distributed noise in open circuit measurements.

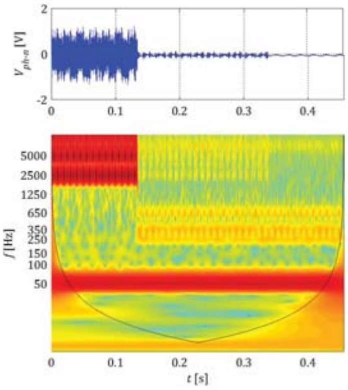


Figure 3 Continuous wavelet transform showing electromagnetic interference in the wind turbine.

All measurement set-ups face some level of error due to systematic (bias) and random (noise) error sources. By appropriate design of the system, sensor selection, sensor installation, sensor calibration, data acquisition (DAQ) calibration and an accurate synchronization board; the systematic and random error can be significantly reduced. Moreover, in order to reduce electromagnetic interference (EMI) from the power system to the measurement system, a custom made EMC box (see Figure 2) was designed as well as sophisticated shielding solutions.

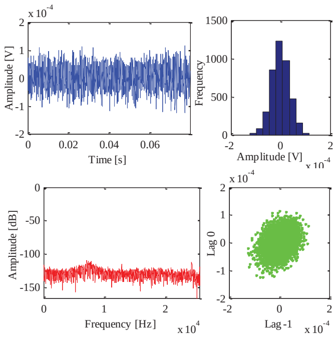


Figure 4 5 Open circuit measurement carried out in the lab and normally distributed histogram (top), open circuit measurements estimated spectrum and lag plot (bottom).

Results

It was observed that the crosstalk for adjacent channels is lower than -80dB in used for harmonic measurement dynamic signal acquisition board. Taking into consideration cross-talk from adjacent channels additional harmonic components can be seen at the top of Gaussian noise.

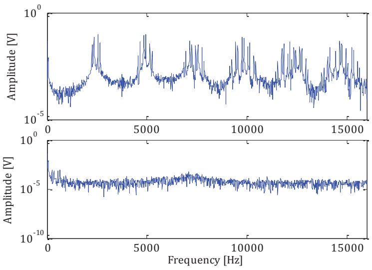


Figure 5 Estimated spectrum of open circuit channel during wind turbine production (top) and during not switching operation (bottom).

Time-frequency representation of measured continuous-time signals achieved using continuous wavelet transform is (Figure 3). The figure shows how different frequency components affects measured open circuit channel from the data acquisition board working inside the wind turbine. It can be seen that within the first period (0-0.14 s) the wind turbine is producing and frequency components around 2.5 kHz and 5 kHz generated by the modulator of the grid-side converter can be easily observed. Later the wind turbine is stopped and only harmonics affected by the external network can be measured.

This shows that the analysis of frequency components above 2 kHz can provide inaccurate results. This also indicates that sample rate above 4 kS/s/ch is not necessary for long-term harmonic measurements. Please note that in practise the noise level in the estimated spectrum is also strongly dependent on the window length of analysed signal.

Conclusions

EMI during measurements in offshore wind farms is an important issue and requires special considerations. It was shown that grid-side converters in wind turbines can be significant sources of possible interference during measurements. In case of harmonic measurements, where frequency components of amplitude around 2% of the nominal fundamental value are analysed, appropriate attenuation of interference distortions is crucial.

It was shown that dealing with different type of interference can by means of appropriate data acquisition system adjustment, shielding (see Figure 2), sensors adjustment and filtering. Of course sometimes it is difficult if even impossible to perfectly attenuate unwanted electromagnetic coupling. In that case appropriate interference assessment is needed which can be later taken into consideration during data processing and analysis.

Acknowledgment

The authors would like to express their appreciation and gratefully acknowledge the contributions of Leif Svinth Christensen from Vestas Wind Systems A/S for his help in measurement sensors configurationThe measurement campaigns were sponsored by Dong Energy´s SIDER3.6 R&D project.

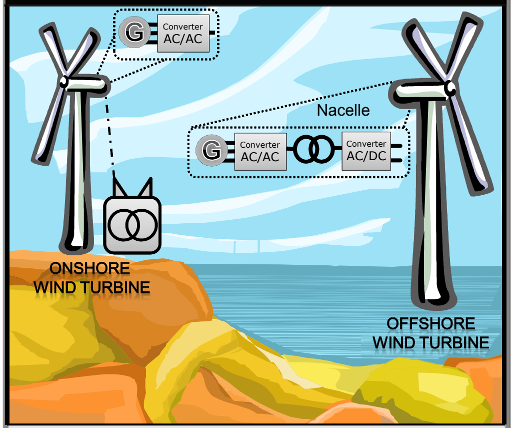
Gunfleet Sands Offshore Wind Farm

9th Deep Sea Offshore Wind R&D Seminar,
19-20 January 2012, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY

Incidence of the Switching Frequency on Efficiency and Power Density of Power Conversion Topologies for Offshore Wind Turbines

Rene A. Barrera, PhD-student, Marta Molinas, Advisor, Dept. of Electric Power Engineering, NTNU

Offshore Wind Turbine Challenges

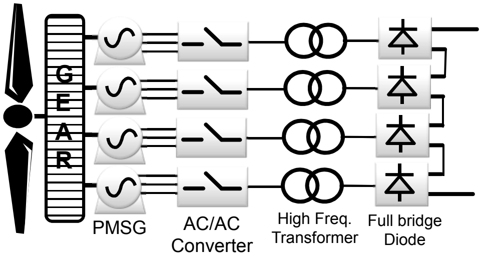


Optimal design targeting two objectives

1. **Maximize power density (ρ) of conversion system:** Minimize weight/Size for a given power. Increase the Frequency.
2. **Maximize efficiency (Ƞ)**: Reduce power losses. Less conversion stages.

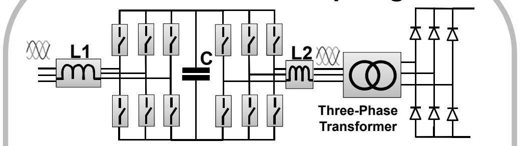
Identify frequency for best operation of overall system

Schematic Configuration Multi-generator Turbine

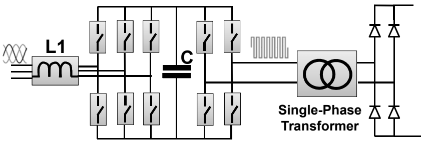


PMSG: Permanent Magnet Synchronous Generator
Wind Turbine Power Rated 2.5 MW
Four Power Modules of 625 KW

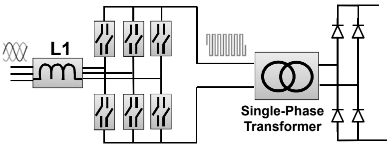
AC/AC Converters Topologies



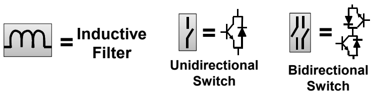
Back-to-Back Converter: 3-phase sine wave output (B2B-3P)



Back-to-Back Converter: 1-phase square wave output (B2B-1P)



Reduced Matrix Converter (RMC)



Semiconductors Devices

Semiconductors Losses= Conduction + Switching

$$P_{Cond} = K_{CE1} I_{C(avg)} + K_{CE2} {I_{C(rms)}}^2$$

$$P_{switch} = \frac{1}{T}\int_{t_0}^{t_0+T} \left(E_{sw-on} + E_{sw-off} + E_{sw-rr}\right) dt$$

$$E_{sw} = \frac{E_{test}}{V_{test} \cdot I_{test}} V_{CE} I_C$$

Turn on, Turn off Reverse Recovery

Constants can be found in the datasheet of the device.

Heat sink volume approx. With 200% of switch volume (Water cooling)

$$Vol_{conv} = 3 \cdot Vol_{device} \cdot n_{switch}$$

DC-Link Capacitor

$$C = \frac{I_{rms}}{4\sqrt{2} \cdot \Delta V_{dc\%} \cdot V_{dc} \cdot f}$$

Capacitor volume with proportional model from the capacitor reference ICAR LNK- 8PX-600-110

$$Vol_{capac.} = \frac{C \cdot {V_{dc}}^2}{C_{ref} \cdot {V_{ref}}^2} \cdot Vol_{ref}$$

Magnetics components Transformer and Inductive Filters

$$P_{Core} = K_{Core} Vol_{Core} \cdot f^{\alpha} \cdot B^{\beta}$$

Constants can be found in the datasheet of the core magnetic material.

$$P_{cu} = \sum_{i=1}^{nw} K_{cu(i)} \cdot \frac{\rho_{cu} N_{(i)} MLT_{(i)}}{A_{w(i)}} \cdot {I^2}_{(i)}$$

Kcu: factor due skin and proximity effect, and depends of frequency.

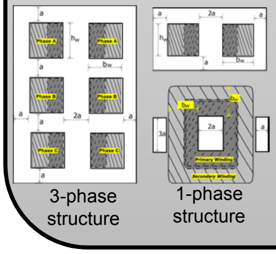
Thermal Constraint

$$P_{Core} + P_{cu} \leq h_T \cdot A_t \cdot \Delta T_{max}$$

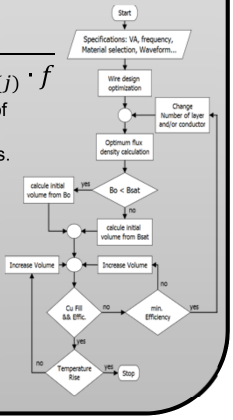
Inductive Filter

$$L_{(j)} = \frac{V_{dc}}{12\sqrt{2} \cdot \Delta I_{\%(j)} \cdot I_{(j)} \cdot f}$$

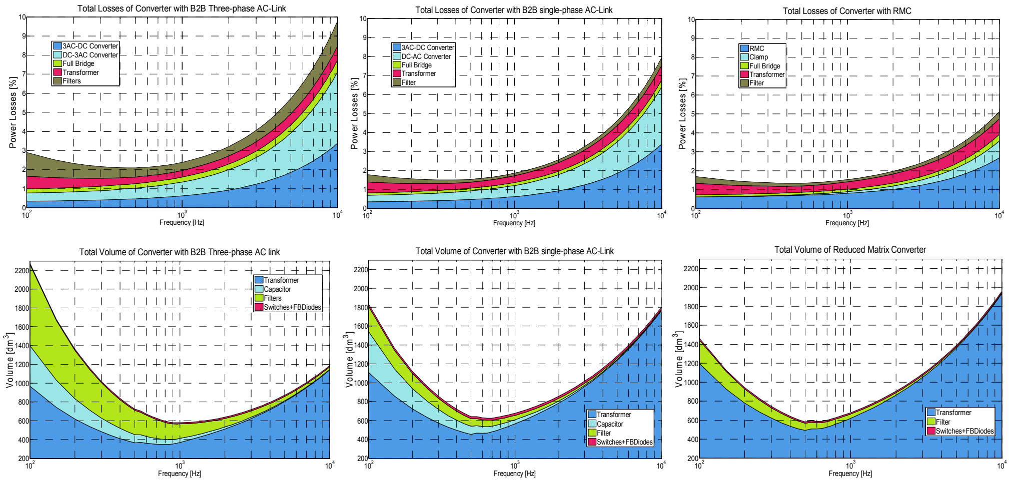
Transformer Volume is result of iterative process with parameterized core dimensions.

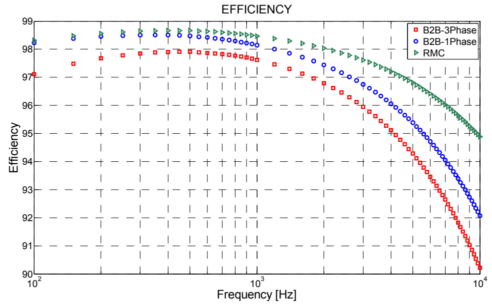


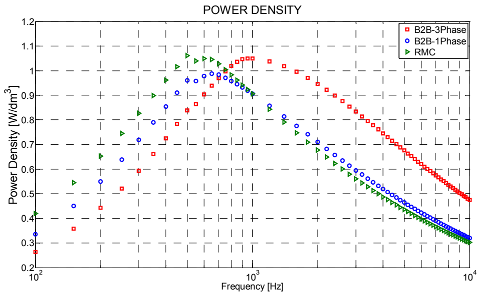
3-phase structure
1-phase structure



Results







Conclusions

As Frequency increases semiconductor losses becomes more dominant in the total losses. Topologies with fewer stages and number of switches will have higher efficiency.

There is a frequency at which there is a minimum volume. At low frequencies, the volume of the capacitor and the inductive filter is comparable to the volume of the transformer, but at high frequencies the required values of capacitance and inductance allow a reduction of the sizes of these elements, then the transformer is the one who dominates the volume for high frequencies.

Topologies with three-phase AC-Link will have higher power density at high frequencies, while topologies that avoid the use of capacitance at lower frequencies will be preferred.

NTNU
Norwegian University of Science and Technology

Benefits of Asymmetric HVDC Links for the North Sea Super Grid

SINTEF

Til Kristian Vrana Daniel Huertas-Hernando Olav Bjarte Fosso

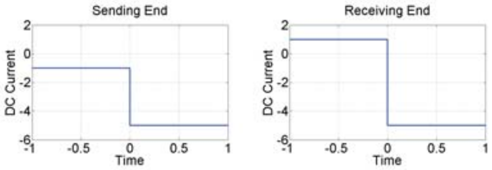
Asymmetric HVDC Links

Unidirectional HVDC Systems

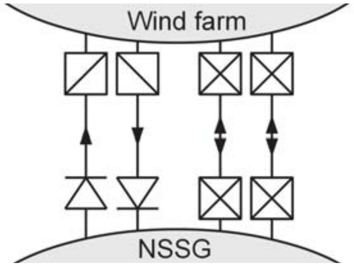
HVDC Technology Overview

HVDC Type	Voltage		Current	
	Amplitude	Sign	Amplitude	Sign
Bi.-VSC	Fixed	Fixed	Variable	Variable
Uni.-VSC	Fixed	Fixed	Variable	Fixed
Bi.-CSC	Fixed	Variable	Variable	Fixed
Uni.-CSC	Fixed	Fixed	Variable	Fixed
Uni.-Hyb.	Fixed	Fixed	Variable	Fixed

DC Fault Currents


Sending End
Receiving End

Section of the NSSG with Protection



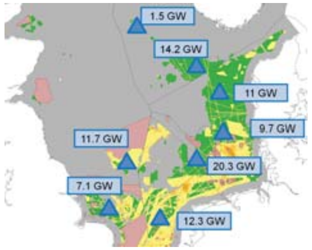
The WindSpeed Project

Grand Design Scenario V05

Offshore Cluster Ratings

Offshore Cluster	Generation [MW]
Ijmuiden	12300
Hornsea	7100
Doggerbank	11700
Gaia	20300
DanTysk	9700
Dansk	11000
Norsk-S	14200
Norsk-SW	1500

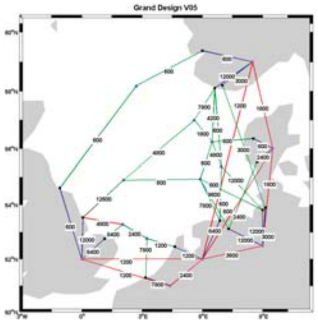
Offshore Cluster Scenario Map



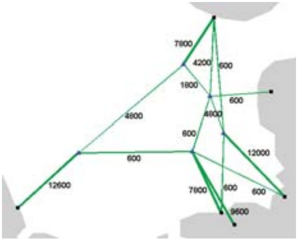
Meshed Offshore Grid Link Information

Node	Strongest Link to	Length [km]
Doggerbank	England	197
Gaia	Ger. + Neth.	164
DanTysk	Germany	193
Norsk-S	Norway	154

Optimised Grid Structure



Meshed Offshore Grid



Results

Cost Calculation

Identification of Inherently Asymmetric Links

$$P_{1,Uni} = P_1 - P_{Load} - \sum_{i=2}^{n} P_i$$

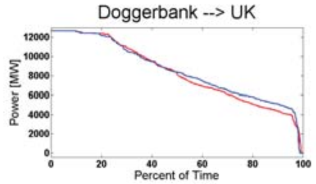
Meshed Offshore Grid Link Ratings

Node	P1	P2-∞	Load	P1-Bi	P1-Uni
Doggerbank	12600	5400	200	5600	7000
Gaia	17400	1800	300	2100	15300
DanTysk	12000	6000	100	6100	5900
Norsk-S	7800	6600	400	7000	800
Total	49800	------	-------	20800	29000

Costs and Benefits

Technical Solution	Investment Cost [M€]
All Bidirectional	45409
Bi- and Unidirectional	42715

Additional Unidirectional Transmission Capacity



Conclusion

Many HVDC systems of the NSSG will be operated unidirectional (scenario = 42%)
These systems should also be designed unidirectional
Protection for unidirectional HVDC systems is less complicated
Relevant cost savings are achievable with asymmetric HVDC link design (scenario = 6%)

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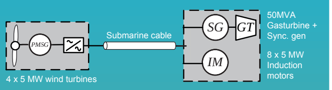
Photo: Øyvind Hagen/Statoil



Voltage and frequency control in offshore wind turbines connected to isolated oil platform power systems

Stability Improvements in Oil Platforms from Wind Turbines

Challenge

Offshore wind turbines have potential to supply offshore oil and gas platforms in the North Sea with electric energy. For remote located facilities it is attractive to pursue a solution where the wind turbines and oil platform operate in an isolated system. To study the operational properties of a system with these characteristics is necessary to identify possible advantages and disadvantages. Oil platform power systems are microgrids with large load units. The stability is therefore weaker than in the onshore power grid.

This study demonstrates how added voltage and frequency control in wind turbines equipped with full power electronic converters can improve the voltage and frequency stability in offshore oil and gas installations.

Conclusions

- Wind turbines with Voltage Source Converters can significantly improve the power system stability in oil platforms.
- **Frequency control:** The WTG rotational energy is used to provide a temporary frequency support that reduce the frequency overshoot from 97 to 25 %
- **Voltage control:** Grid side VSC controls reactive power independently of generator. Dampened voltage dip during motor start (16 % to 6 %).
- **Further work:** develop a joint control structure with WTG voltage and frequency control for the best possible utilisation of the VSC

System overview

Fictitious case: 20 MW wind farm connected to an oil platform with 40 MW peak load. Isolated system operation.

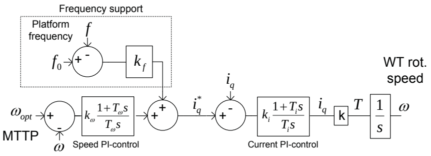
PSCAD model with the following features:

- Wind turbine model - aggregated equivalent of four 5 MW turbines.
  - Aerodynamic model + pitch control, Permanent Magnet Synchronous Generator (PMSG), Voltage Source Converter (VSC).
- 4 km transmission cable
- The oil platform model reflects an existing installation, able to cover its own load in stand-alone operation.
  - **Generating unit:** gas turbine + generator (50 MVA)
  - **Load:** 8 fixed speed 5 MW induction motors

Control systems

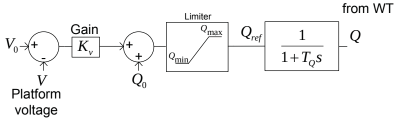
Added WTG frequency control

WTG rotating mass as energy storage. Added control blocks in the VSC, temporary frequency control can be achieved. Similar to ordinary droop control, but the speed control loop will counteract and eventually remove the frequency control term.



Added WTG voltage control

The VSC can supply fast control of reactive power - potential voltage stabilization. A voltage-droop controller supports operation of the AVR - especially during transient events.



Simulation results

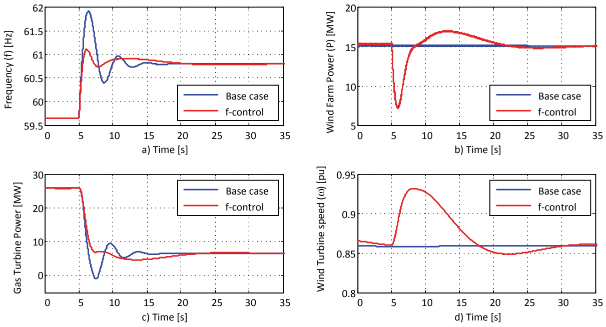
Simulation case #1: Loss of 10 MW load

Base case: Gas turbine adjust production alone – wind turbines delivering maximum power

f-control: Wind turbines sense a frequency imbalance after loss of load – temporary drop in power to damp the frequency oscillations.

Observations:

- Oscillations heavily reduced with f-control implemented (97 % to 25 % overshoot)
- New steady-state frequency obtained after 20 s. according to GT droop setting
- Wind turbine power output recover after 20 s.
- Wind turbine rotor overspeed to 0.93 pu., recover after 35 s.

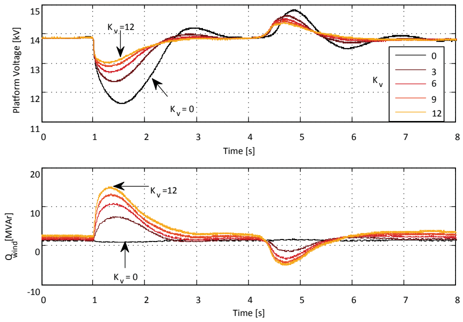


Simulation case #2: Start-up of 5 MW induction motor

High reactive power consumption during start-up – voltage dip
Voltage-droop gain K_v varied from 0 (base case) to 12

Observations:

- Voltage dip is severe (16 %) without voltage-droop (K_v = 0)
- Increasing value of Kv dampen the oscillations significantly, 6 % dip for K_v = 12
- Converter current limitations can constrain the maximum delivered reactive power, and hence the value of K_v.



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Challenges and rationale for laboratory research of offshore grids

Windpower grid laboratory facilities at SINTEF Energy/NTNU

Why lab experiments?

- Complement to simulations. Model verification.
- Gives insight into complex systems were little operating experience exist, where it is not well known which model simplifications are valid
- Simulations - Assumptions and choice of simplifications are critical. Tends to answer expected questions
- Laboratory experiments may reveal unexpected issues
- Use of real converter control system gives the complexity of the full scale version

Laboratory design considerations

- Simplification: Choose what to represent well and what to omit.
- Modularity: Fixed installation gives ease of use while building blocks give flexibility.

Scale: Choice of power level:

- Low power (< kW): Low cost, space. Small damage potential. Easily modified. Losses give short time constants, and large damping of oscillations. This gives large deviations from real world.
- High power (> MW): Close to full scale. Real equipment can be tested. Gives safety issues. Not easily modified.

Prime movers: Replaced by electric motors. Turbine/engine and governor model gives torque reference signal to vectorcontrol motordrive inverters.

Converters:

- Commercial; Low cost, easily available.
- Custom made: Full insight into control system, no black boxes.

Power lines, cables:

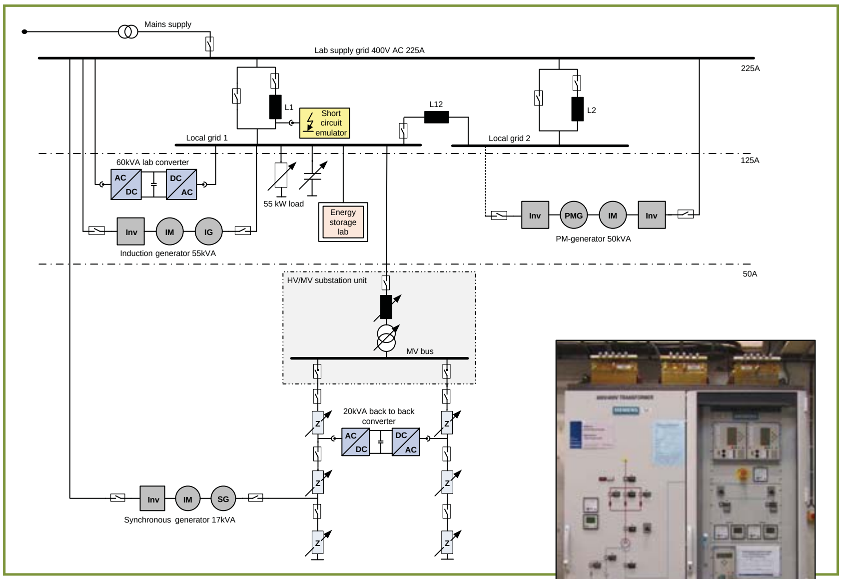
- Saturation of inductors must be avoided, ruins experiments.
- Choice of complexity according to experiment needs:
  - Simple three phase inductors for load flow experiments
  - Common mode inductors for ground current handling
  - RLC networks or PI equivalent for wideband models

The laboratory network at SINTEF/NTNU

- Power grid model, network with multiple busbars and lines.
- 50 kW unit rating. 400V supply voltage.

Suitable for experiments within a wide range of fields:

- Windpower integration
- Weak grid and island mode grid operation
- Fault and transient handling
- Smartgrid systems
- Distributed energy production system
- Converter dominated grids
- Converter control algorithms
- Multiterminal HVDC networks
- Testing of electrical machine prototypes

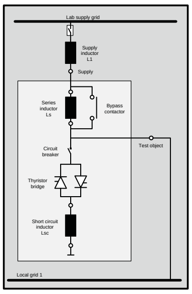


LabView based distributed data aquisition and control system.

- Emulates centralized network control system. (SCADA)
- Hall element based current sensors give DC current measuring capability.

55 kVA wind turbine emulator. Fixed speed induction generator.

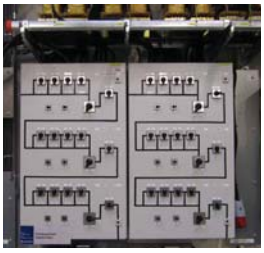
50 kW low speed (30rpm) Permanent Magnet Synchronous generator



Short circuit emulator.

17 kW hydropower generator model. Control equipment typically found in 1-10 MW power plants.

Transformer substation, model with busbar and protection relays typical for 66kV/22kV substation.



Distribution line model, RLC line section equivalents.

60 kVA AC/DC converter units with inhouse developed FPGA based control system.

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$$\Delta v(t) = v(t+\Delta t) - v(t) \qquad (1)$$

An approach to model the statistics of wind speed increments on a 10min time scale

Hans Georg Beyer
University of Agder, Department of Engineering, Grimstad, Norway

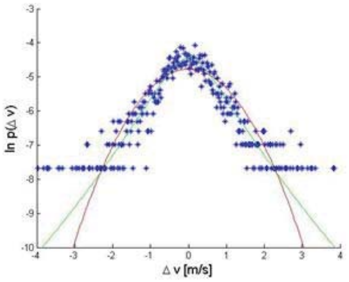
For the grid management knowledge on wind power gradients in the time scale of several minutes up to hours is of importance. Whereas for on-shore sites the respective wind and power output statistics – mainly on an hourly time scale - have been extensively studied, knowledge on to what extend the respective characteristics can be transferred to off-shore conditions is lacking. As a contribution to bridge this gap, an analysis is performed on the basis of data from the Norwegian off-shore HyWind project located close to the Norwegian western shore.
Measured wind speed data are used to extract information on the distribution function of gradients of these sets. Aim is to set up a model to predict the probability of occurrence of gradients in wind speed and power.

Data from an off shore location
at the south-western Norwegian shore are analyzed.
Data stem from the HyWind project located
10 km south of Karmøy peninsula, wind data used are 500s averages.

Under inspection are the wind speed increments Δv for over time step (v(t) initial wind speed):

$$\Delta v = v(t+\Delta t) - v(t)$$

➡ Distribution of increments does not follow a Gaussian distribution ➡



Probability density (PDF) of wind speed increments following time step with wind speed 9.5 m/s < v(t) < 10.5.
+ Gaussian distribution with same standard dev.
+ Castaing distribution (see below)

Model for probability density of
wind speed increments
as used for short
time turbulences data: Castaing distribution

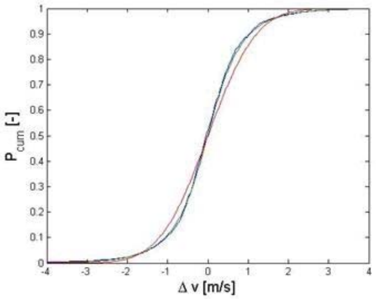
$$P(\Delta v) = \frac{1}{2\pi\lambda}\int_0^\infty \frac{1}{\sqrt{\beta}} \exp\left[-\frac{1}{2}\left(\frac{1}{\lambda}\ln\frac{\beta}{\beta_s}\right)^2 - \frac{1}{2}\beta(\Delta v)^2\right] d\beta$$

Parameters determined by standard dev. σ and kurtosis *k*

$$\lambda = \sqrt{\ln\frac{k}{3}} \qquad \beta_s = \frac{1}{\sigma_s^2}\sqrt{\frac{k}{3}}$$

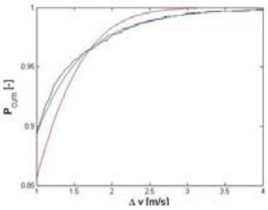
Application of model for cumulative distribution (CDF) of increments following time step with
9.5m/s < v(t) < 10.5m/s

* data
--- Gaussian
--- model

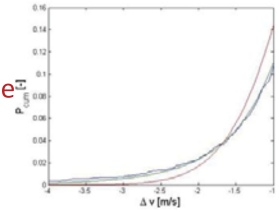


magnified
sections
of CDF

hight positive
increments



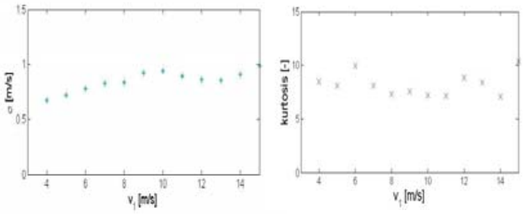
hight negative
increments



Model
- initialised with empirical values of standard dev. and curtosis

gives good presentation of PDF of increments starting from moderate initial wind speeds

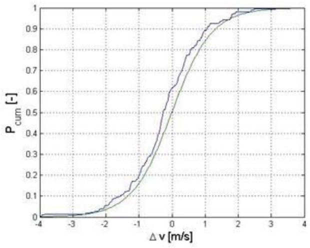
standard dev. and kurtosis of increments
for various initial wind speeds



to be parametrized

Limits of the PDF-model:
fails to present
the asymmetric PDF
incase of
initial wind speed at
the limits of the data set.
Example:
initial wind speed 20m/s.
Model extension required.

* data, --- model



Upper Ocean Response to Large Wind Farm Effect in the Presence of Surface Gravity Waves

Mostafa Bakhoday Paskyabi and Ilker Fer
Institute of Geophysics, University of Bergen, Allegaten 70, 5007 Bergen, Norway

Abstract

In this study, effect of large wind turbine on the upper ocean upwelling in the presence of wave is studied numerically. The parameters involved in the sea-states are extracted based on the two-dimensional wave spectrum. A modified shallow water wave is obtained that shows the influence of Stokes drift and wave parameterizations besides wind turbine farm characterestic length on upper ocean response.

Large Wind turbine and Wind Stress

➢Shallow water Governing Modified Equations

By vertical integrating momentum and continuity equations in the presence of wave effect, the following differential equations are obtained

$$\frac{\partial(uh)}{\partial t} - f(v+vs) + \mathbf{F}_{ds}^{x} = -\frac{\partial(u^2h+0.5gh^2)}{\partial x} - \frac{\partial(uvh)}{\partial y} + \frac{1}{\rho_w}(\tau_x - \tau_x^w - \tau_B^x)$$
$$\frac{\partial(vh)}{\partial t} + f(u+us) + \mathbf{F}_{ds}^{y} = -\frac{\partial(uvh)}{\partial x} - \frac{\partial(v^2h+0.5gh^2)}{\partial y} + \frac{1}{\rho_w}(\tau_y - \tau_y^w - \tau_B^y)$$
$$\frac{\partial h}{\partial t} + \left(\frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y}\right) = 0 \qquad (1)$$

where u and v are the mass transports in the x and y directions, By assuming a thin layer of fluid with density ρ_0 and thickness h overlying a deep, motionless abyssal layer, assuming constant wind and wave characteristics, and by ignoring bottom friction and wave-induced momentum redistribution term $\mathbf{F}_{ds}$, the following expression is obtained:

$$\frac{\partial}{\partial t}\left[f_{cor}^2 - g'h_0\nabla^2\right]h = f_{cor}\nabla\cdot\mathbf{U_s} - \frac{f_{cor}}{\rho_w}\nabla\times\vec{\tau} + \frac{f_{cor}}{\rho_w}\nabla\times\vec{\tau}_{in} \qquad (2)$$

where g' is reduced gravity, f_{cor} is the Coriolis parameter, $\vec{\tau}_{in}$ and $\vec{\tau}$ are the wave-induced and wind stresses. is the Stokes drift $\mathbf{U}_S$.

In this study for constant wind and wave the following analytical expression is proposed $\Lambda = \Lambda_{init} - \Delta\Lambda_* \mathbf{P}(X,Y)$ in which X and Y show the horizontal axes, Λ is wind-wave forcing vector, $\Delta\Lambda_*$ is wind-wave forcing fluctuation, and $\mathbf{P}$ gives the distribution of forcing behind wind farm.

➢Numerical Methods

To model shallow water wave (Eq. 1 and 2), we use a wave-modified finite volume, classical finite element technique, and finite difference approximation on horizontal Arakawa C-grid. To confirm obtained results performance, the Regional Ocean Modelling System (ROMS) is applied. Here, we just present a short description of Finite Volume technique.

➢Finite Volume Technique

The conservation form of Eq. (1) can be written as

$$\frac{\partial\boldsymbol{\theta}}{\partial t} + \frac{\partial\mathbf{F}(\boldsymbol{\theta})}{\partial x} + \frac{\partial\mathbf{G}(\boldsymbol{\theta})}{\partial y} = \mathbf{S}(t) \qquad (3)$$

where source term is given as

$$\mathbf{S}(t) = \frac{1}{\rho_w}\begin{bmatrix} 0 \\ \tau_x - \tau_{in}^x - \tau_B^x \\ \tau_y - \tau_{in}^y - \tau_B^y \end{bmatrix} + \begin{bmatrix} 0 \\ f_{cor}(v+v_s) - \mathbf{F}_{ds}^x \\ -f_{cor}(u+u_s) - \mathbf{F}_{ds}^y \end{bmatrix}$$

We use Lax-Friedrichs technique as a member of finite volume (FV) to discretize homogenous version of Eq. (3) as

$$\boldsymbol{\theta}_{i,j}^{n+1} = \boldsymbol{\theta}_{i,j}^{n} - \frac{\Delta t}{\Delta x}\left(\mathbf{F}_{i+\frac{1}{2},j}^{n+\frac{1}{2}} - \mathbf{F}_{i-\frac{1}{2},j}^{n+\frac{1}{2}}\right) - \frac{\Delta t}{\Delta y}\left(\mathbf{G}_{i,j+\frac{1}{2}}^{n+\frac{1}{2}} - \mathbf{G}_{i,j-\frac{1}{2}}^{n+\frac{1}{2}}\right)$$

in which

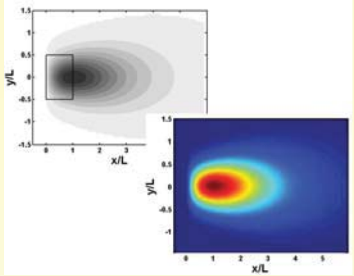
$$\mathbf{F}_{i+\frac{1}{2},j}^{n++\frac{1}{2}} = \frac{\mathbf{F}(\boldsymbol{\theta}_{i,j}^n) + \mathbf{F}(\boldsymbol{\theta}_{i+1,j}^n)}{2} - \frac{1}{2}\left|\lambda\left(\frac{\boldsymbol{\theta}_{i,j}^n + \boldsymbol{\theta}_{i+1,j}^n}{2}\right)\right|\left(\boldsymbol{\theta}_{i+1,j}^n - \boldsymbol{\theta}_{i,j}^n\right)$$

λ is non-linear advection speed. The external force is imposed to technique by following ordinary differential equation

$$\frac{\partial\boldsymbol{\theta}}{\partial t} = \mathbf{S}(t)$$

Large Wind turbine and Wind Stress and Wave parameters

Wind and wave forcing are determined in this study based on introducing a shape function shown in Fig. 1.



wind stress is calculated by

$$\vec{\tau} = \rho_a C_D \mathbf{U}_{10}|\mathbf{U}_{10}|$$

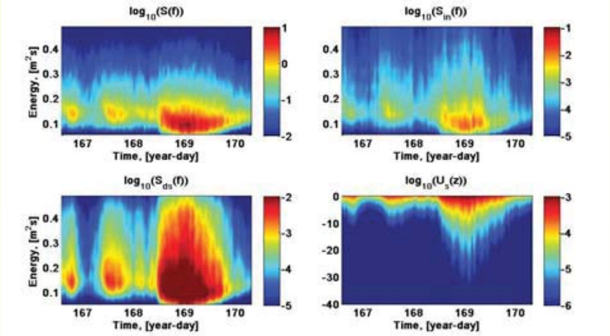
in which ρ_a is the air-side density, C_D is drag coefficient, and $\mathbf{U}_{10}$ is the wind speed vector at height 10 meter. Computation of wave Stress is more complex than of wind stress. If $E(f,\theta)$ is the wave energy spectrum, the wave-induced stress will be defined as

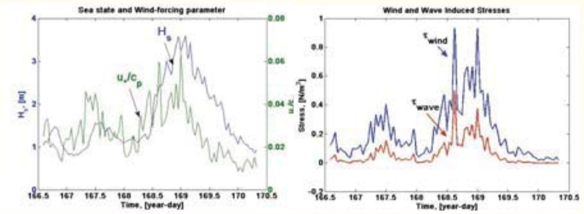
$$\vec{\tau}_{in} = 2\pi\rho_w \iint_{f,\theta} f\,\hat{\mathbf{K}}\, S_{in}(f,\theta)\,d\theta\,df \qquad (4)$$

where f is frequency, θ is the wave direction, $\mathbf{K} = \hat{\mathbf{K}}k$ is the horizontal wavenumber vector with modulus k and direction $\hat{\mathbf{K}}$, and $S_{in}(f,\theta)$ is the wind-energy input source term that in this study we use exponential growth rate to construct this term [2]. Further, using wave energy spectrum, Stokes drift is given as

$$\mathbf{U}_s = 4\pi \iint_{f,\theta} f\,\mathbf{K}\,E(f,\theta)\,e^{-2k|z|}\,d\theta\,df \qquad (5)$$

Here, z is depth. The contribution to the Stokes drift is maximal in the peak region of the wave spectrum and in the near-surface the short waves give a significant contribution to $\mathbf{U}_s$.





Above two figures show wave parametrizations for the real data acquired by a buoy in the Sletringen region, Norway.

Numerical Results

As first numerical example, the finite element simulation of linearized version of Eq. (2) is presented. The next figure shows the simulation results with and without wave forcing for t=1 and $a^2 = 1$ is the ration of the Rossby deformation to wind farm characteristic length L : $a = \sqrt{g'h_0}/(f_{cor}L)$

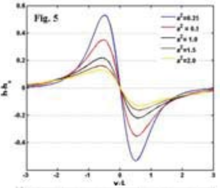


Fig. 5

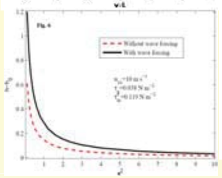


Fig. 6

➢In fact, this parameter states how large the internal deformation radius is compared to the size of wind turbine farm (Fig. 5). The maximum value of pycnocline and the strength of upwelling as a function of a is shown in figure 6. It can be seen that the amplitude of response decreases rapidly with a that highlights the role of physical size of wind wake in upper ocean response [1].

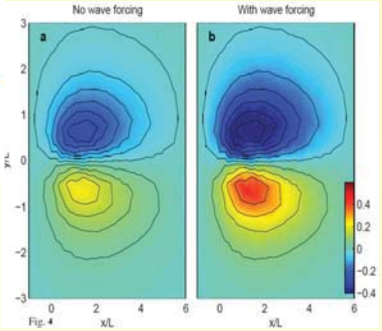


Fig. 4

➢Figure 4 shows the rising of pycnocline in the southern side of wind farm and corresponding falling due to geostrophic adjustment on the northern side. Further, including wave effect modifies ocean response by larger amplitude of pycnocline height.

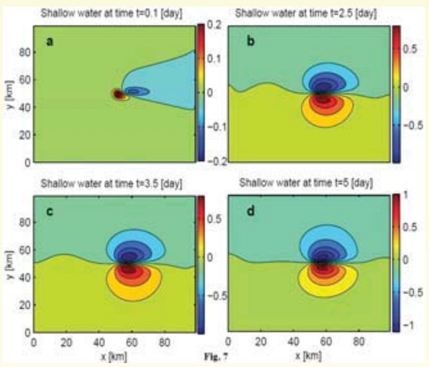


Fig. 7

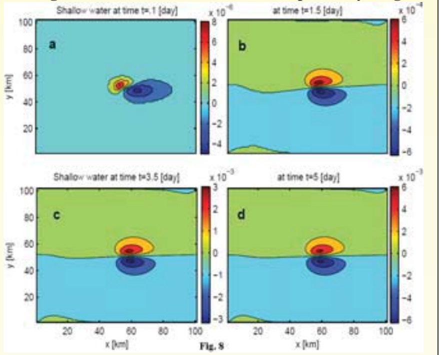


Fig. 8

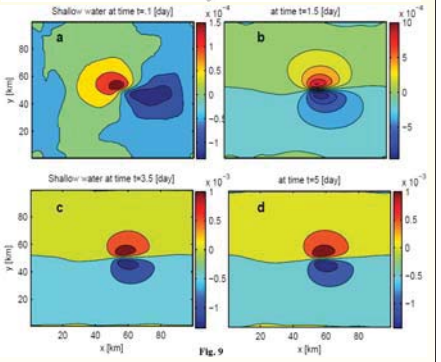


Fig. 9

➢Figures 7, 8 and 9 shows the linear FV runs, non-linear finite difference runs in the presence of bottom friction and advection term, and ROMS results. For more details read [2]

Conclusion

➢Results showed that the max amplitude of pycnocline height with the wave effect is greater than that in no-wave case and this height approach to zero when a goes to infinity in both cases. Including non-linear term, horizontal diffusion, and the bottom friction led to decreasing of the strength of eddies. But, the amplitude of disturbances in the lee regions of the farm becomes weaker after almost three days.

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Selection of important RAMS parameters for 10MW reference wind turbine

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Basis of 10 MW wind turbine

- A comparison of 5, 10 and 20 MW wind turbines
- A simple scaling up is not applicable
- A new machine with new challenges

		Reference wind turbine 5 MW	Extrapolated turbine 10 MW	Extrapolated virtual turbine 20 MW
Rating	MW	5.00	10.00	20.00
Wind regime		IEC class 1B [2]	IEC class 1B	IEC class 1B
No of blades		3	3	3
Rotor orientation		Upwind	Upwind	Upwind
Control		Variable speed, control pitch	Variable speed, control pitch	Variable speed, control pitch
Rotor diameter	M	126	178	252
Hub height	M	90	116	153
Max. rotor speed	Rpm	12	9	6
Rotor mass	Tones	122	305	770
Tower top mass	Tones	320	760	880
Tower mass	Tones	347	983	2,780
Theoretical electricity production	GWh	369	774	1,626

Source : Upwind 2011

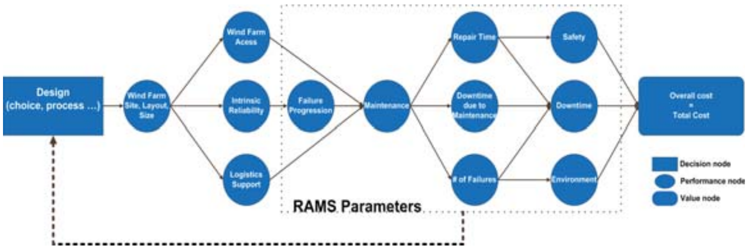
Need

- To extract maximum wind potential
- To produce cheap power
- To protect the environment
- To revolutionize the wind turbine industry

Objective

- To identify important parameters to conduct the RAMS (Reliability, availability, maintainability and safety) analysis in an efficient and cost effective way

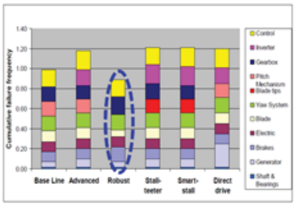
Generic framework



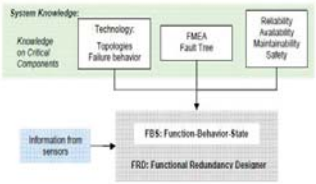
- A generic framework to develop relationship between design and RAMS
- A process to identify important RAMS parameters
- A way to understand how design of big machines influence operational issues
- A feedback mechanism to improve the design based on real data from operations
- A decision support tool to identify bottleneck stations from design to operations

Important challenges and issues

- To make the big machines viable and efficient to attract investors
- To verify the feasibility of latest concepts
  - Direct drive
  - Self maintenance machines

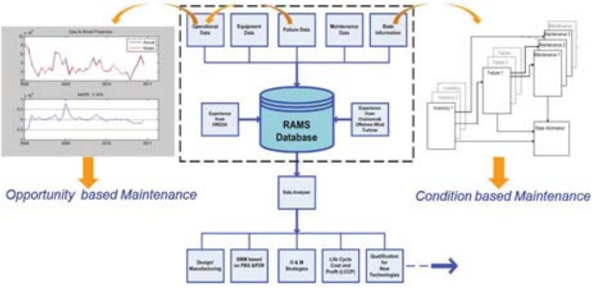


Source: Bussel et al,2001

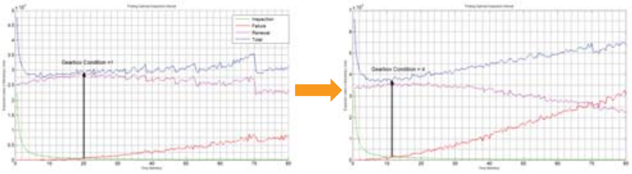


Source: Echavarria, et al 2007

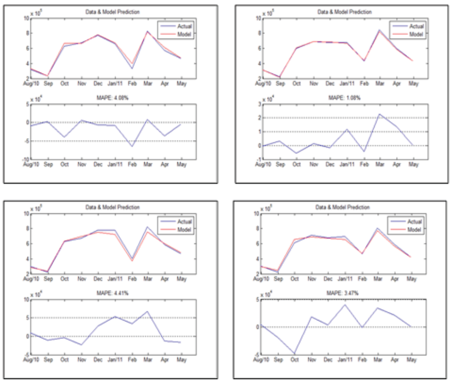
- To identify RAMS parameters through a database with possible implications



- To search for the design of a new condition monitoring system
- To optimize the operational strategies by identifying suitable intervals



- To predict the expected power output in wind farm layout



- To connect smoothly with the power grid
- To improve the design from operation experience
- To learn from the experience of the relevant industries

Conclusions

- Consideration of RAMS aspects may prove beneficial to the designers
- Identification of important RAMS parameters are crucial to have optimal operational strategies
- Reductions in operational costs may make the big machines viable and competitive with the existing state of the art ones
- Cooperation between the designers and RAMS personnel will be helpful in making big machines more reliable and efficient

Fatigue Analysis of Copper Conductor for Offshore Wind Turbines by Experimental and FE Methods

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** Norwegian Marine Technology Research Institute, MARINTEK, Trondheim

Abstract

The objective of this work was to investigate the fatigue performance of a 95 mm^2 copper conductor. The compacting procedure applied during the manufacturing process causes geometrical irregularities in the wires. Specimens from different layers have been tested in tension-tension mode with a stress-ratio, R = 0.1. The irregularities have been measured and through numerical studies applied to asses the resulting bending stresses in tension loading. When this is accounted for, the fatigue behavior of the core and the outer layer seems to be similar. This indicates that the difference in observed fatigue data between different layers of wires can be explained by surface irregularities. However, this needs to be supported by more data.

Objectives

The objective of this work was to investigate the fatigue performance of a 95 mm^2 copper conductor by experimental test and finite element analysis

Methods

A. Experimental Method

The specimens used in this work were taken from a 95 mm^2 copper conductor (ETP copper), designated by the UNS C11000 series. The definition of ETP copper is related to copper alloy purity of at least 99.95% and characterized by a very high electrical conductivity and ductility. The conductor cross section consisted of 19 wires, each with a diameter of 2.5 mm. A centre wire is followed by six and twelve helically wound wires in two layers (see Fig. 1). The specimens were cut, straightened and terminated at the ends using tubular aluminium tubes filled by standard high strength glue (see Fig. 2). Due to the opposite lay angles of the helical layers, the surface irregularities were found to be periodic with a wavelength of approximation 20 mm with a mean thickness reduction amplitude of 0.44 mm with a coefficient of variation (COV) of 0.063, illustrated in Fig. 3. The fatigue specimens were tested in constant amplitude axial tension corresponding to nominal stress ranges ($\Delta\sigma$) of 130, 160, 190 and 220 MPa. The nominal stress range is based on a constant area of 5 mm^2. The loading test frequency, f , was 2 Hz harmonic loading (sinusoidal) with R-ratio, R = 0.1. The cyclic axial load was applied using a standard fatigue testing machine. The specimens were clamped in both ends. see Fig. 4.

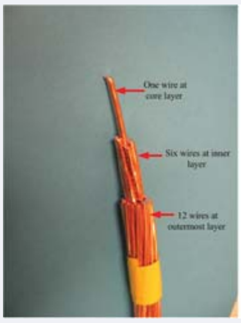

Figure 1. Full cross-section of stranded copper conductor

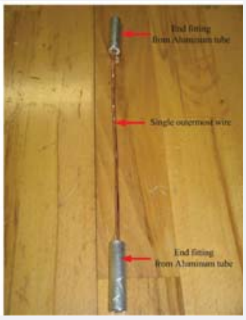

Figure 2. An individual outer wire with Aluminium tubes at both ends

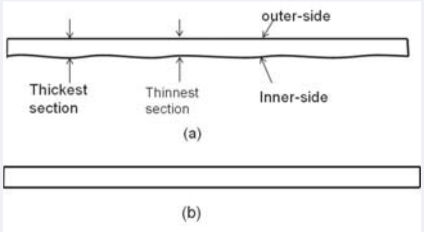

Figure 3. a) Geometrical surface of outer wire including irregularities. b) Geometrical surface of smooth centre wire

Figure 4. Detailed at both ends of specimen are clamped against rotation

B. FE Method

A finite element model was made in order to investigate the effects from measured thickness irregularities and material plasticity with respect to the expected stress range at the material surface. This was performed by applying a 100 mm long elasto-plastic beam model, using the measured strain-stress curve, a kinematic hardening model and element eccentricities according to the average measured thickness irregularity (see Fig. 5). The computer code Uflex3d was applied, using 48 integration points in the cross-section.

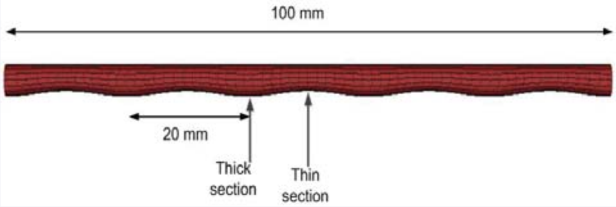

Figure 5. FE model of outer wire including irregularities

Results

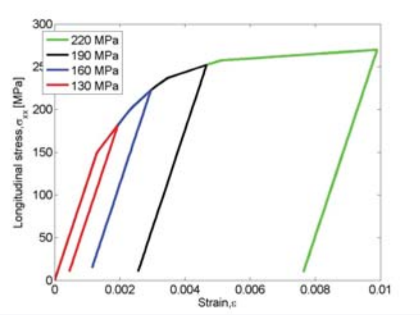

Figure 6. Strain-stress result of outer wire for each nominal stress ranges

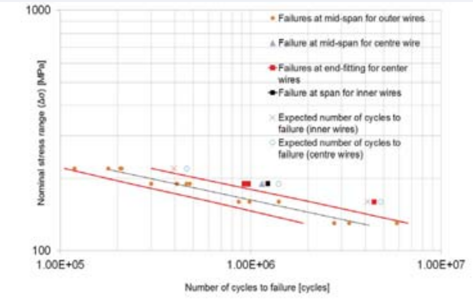

Figure 7. S-N data based on nominal stress ranges, with S-N curve based on the outer wire data.

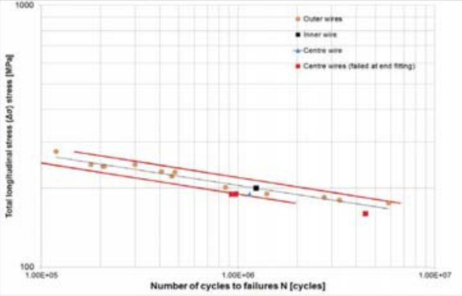

Figure 8. S-N data based on maximum longitudinal stress ranges (including bending stresses), with S-N curve based on the outer wire data

Conclusions

Fatigue testing of single wire specimens taken from a 95 mm^2 copper conductor has been carried out. This has been combined with systematic measurements of observed surface irregularities resulting from the manufacturing process and FE analysis to predict their effect on the surface stresses. The results indicates that the differences seen in fatigue performance between layers can be explained by inherent variations in surface irregularities. However, more data are needed in order to conclude on this, both with respect to the copper conductor investigated here and other conductor geometries.

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8. UFLEX3D Version 1.0.1 (User Manual)

9th Deep Sea Offshore Wind R&D Seminar, 19 – 20 January 2012, Trondheim, Norway

Maintenance strategies for large offshore wind farms

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Motivation & Objectives

- Around 30 % of the Cost of Energy from offshore wind generation due to operation and maintenance
- Aim was to develop a method and an implementation as a tool in MATLAB for simulating the operational phase of an offshore wind farm
- Evaluation of cost saving potential due to variation of maintenance strategy and fleet

Modeling Wind and Wave Conditions

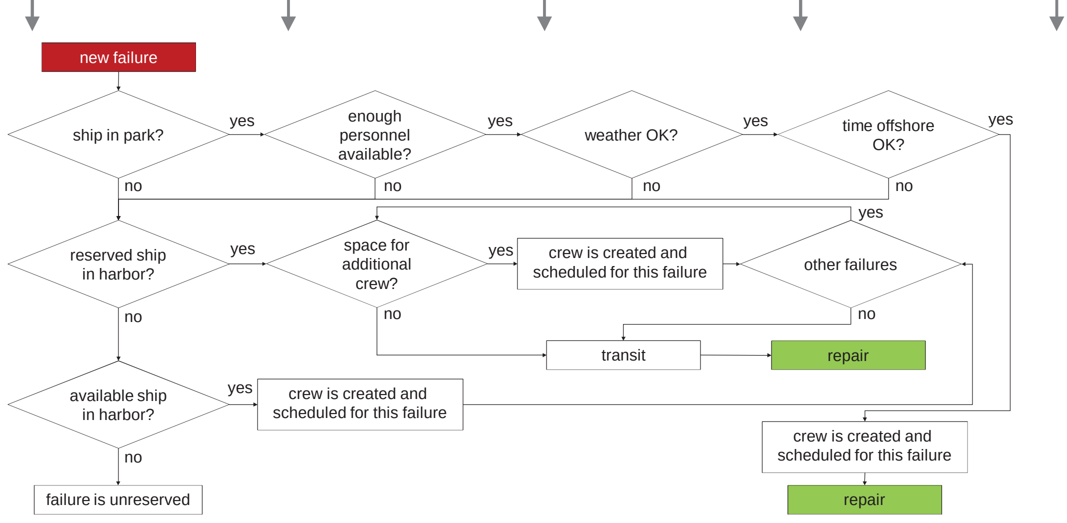
- Significant wave height time series simulated with a discrete -time Markov chain
- Wind speed time series simulated by random sampling from the conditional probability distribution with respect to wave height

Reference Park

- 500 Turbines à 5 MW
- Location: UK East coast
- Onshore reliability data
- Two types of maintenance vessels: ordinary and cranes

Simulation

Input: Weather conditions // Park / Turbine / Fleet data



new failure

ship in park? — yes → enough personnel available? — yes → weather OK? — yes → time offshore OK? — yes → crew is created and scheduled for this failure → repair

no → reserved ship in harbor? — yes → space for additional crew? — yes → crew is created and scheduled for this failure → other failures — yes / no → transit → repair

space for additional crew? — no → transit → repair

reserved ship in harbor? — no → available ship in harbor? — yes → crew is created and scheduled for this failure

available ship in harbor? — no → failure is unreserved

Simulation Output & Exemplary Results

Input

- Historical wind speed and wave height time series
- ERA Interim dataset: 1989 – 2010 in 6 h intervals

Output

- Wind speed and significant wave height time series in 6 h intervals

Availability versus Fleet variation

- Highest availabilities with largest fleet.
- Curves are converging:
  From a certain allowable wave height for the maintenance vessels onwards (around 1.8 m)
  a smaller fleet is sufficient.

Production losses versus Availability

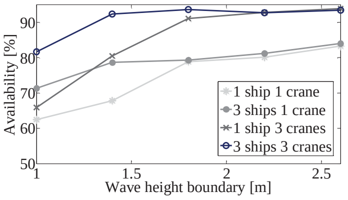
- Almost linear relationship between production losses (P) and availability (A):

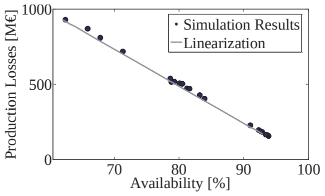
PL(A) = (0.62 - A)·2460 M€ + 929 M€.

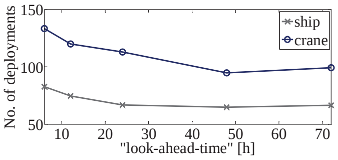
- Influence of wind averaged out

Number of ship and crane deployments versus accuracy of weather forecast

- Weather forecast of 24 hr sufficient for ordinary maintenance vessels
- Weather forecast of 48 hr sufficient for crane vessels (longer operations)

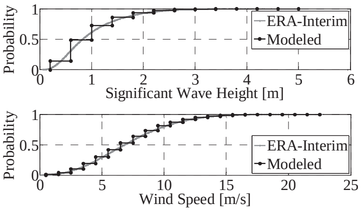


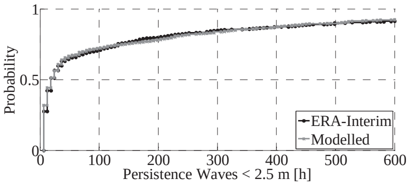




Validation

- Mean Values
- Standard Errors
- Linear Correlations
- Persistence CDFs (weather window distribution)
- Good agreement between simulated and historical data





Conclusions

- An accurate weather model based on a finite state Markov chain for significant wave heights and conditional probability distributions for wind speed was developed
- Significant changes in availability could be discerned (monetarily quantified by production losses), dependent on the composition of maintenance fleet and vessel characteristics (allowable wave height)

9th Deep Sea Offshore Wind R&D Seminar

Trondheim, Norway, 19th – 20th January, 2012

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Germany

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MOORING SYSTEM OPTIMIZATION FOR FLOATING WIND TURBINES USING FREQUENCY DOMAIN ANALYSIS

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Norwegian University of Science and Technology

BACKGROUND

For stationkeeping of floating wind turbines proper mooring systems are required to keep the translational and rotational movements of the platform within an adequate range. Due to economic reasons it is necessary to minimize mooring system costs, while not exceeding mooring line breaking strength and platform drift constraints. As an example application, a symmetric semi-submersible design with three columns is analyzed.

The work presented here emphasizes cost minimization of catenary mooring systems for wind turbines of the semi-submersible type. A frequency domain analysis is performed, where environmental loads due to wind, waves and current are considered separately. The tool determines the optimum mooring line orientations and lengths, constrained by ultimate load conditions, limits on platform movement and seabed conditions.

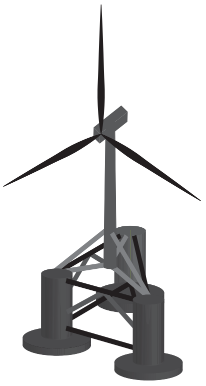

Fig. 1 Semi-submersible design

MOORING SYSTEM OPTIMIZATION

Design constraints:

1. The mooring system has to be dimensioned to with stand ultimate load conditions.
2. The loading at the drag embedded anchors should be solely horizontal.
3. The translational and rotational excursions of the floater have to be within specified limits.

Primary design parameters:

1. Horizontal distance from fairlead to anchor
2. Length of mooring lines
3. Size of the chain
4. Angle of mooring lines (with respect to a global coordinate system)

Spectral analysis:

The spectral analysis includes the most important first order effects, i.e., environmental loads from wind, current, wind sea and ocean swell. The equilibrium position of the floater due to mean wind and current loads is solved as a multidimensional root-finding problem, using a simplex direct search method.

Nonlinearity in the force-displacement characteristic in the catenary equation requires linaerization of the mooring stiffness matrix at the equilibrium position. The spectral loads from aerodynamic and hydrodynamic contributions are superimposed and the system response is computed over the significant frequency range.

For each degree of freedom the spectra of displacements can be computed and subsequently the autospectra of mooring line tension at the fairlead can be derived.

Damping:

Hydrodynamic damping is composed of a potential and a viscous part. Aerodynamic damping, sea-floor friction, mooring line damping and wave-drift damping are neglected.

INITIAL LINE CONFIGURATION

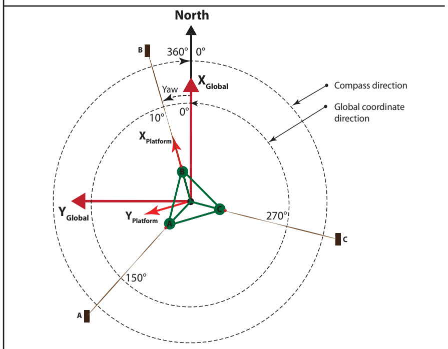

Fig. 2 Initial mooring line configuration

Coordintate system definition:

The X-axis in the global coordinate system is directed towards north compass direction, the X-Y plane coincides with the free water surface and the Z-axis points upwards. The motion of the floater is described relative to the global fixed coordinate system, with a positive rotation counterclockwise.

A propagation direction of zero degree denotes that the environmental loading arrives from compass North direction.

Initial mooring line configuration:

The angles are 10, 130 and 250 degrees with respect to the global coordinate system. An initial total line length of 1000 m was chosen.

ENVIRONMENTAL LOADS AND SITE CONDITIONS

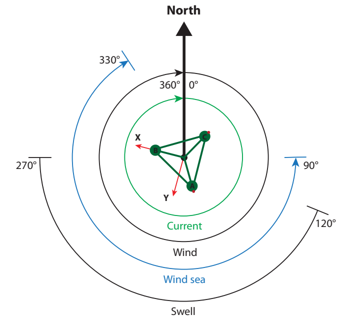

Fig. 3 Directional spreading of environmental loads

Two different load conditions were analyzed for the Greater Ekofisk area in the North Sea (75 m water depth), an extreme event and an operational case. The extreme load case describes a turbine shut down in a survival 50-year storm condition with a 100-year severe wave loading and 10-year current. In the operating state the maximum thrust on the rotor is applied when the mean wind speed is close to the rated wind speed.

Directional spreading:

The most severe loading from each direction has to be considered in the optimization of asymmetrical mooring systems. Site data indicates that environmental loads are biased from certain directions and are unlikely to come from other directions.

RESULTS AND DISCUSSION

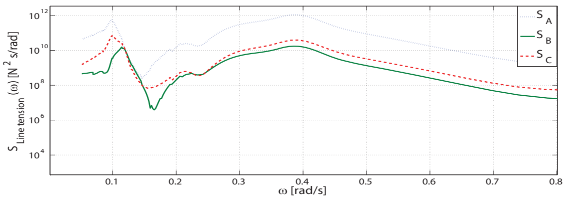

Fig. 4 Mooring line tension spectra for extreme loading (heading direction of 120°)

The spectral wind loads have a contribution of up to 29.7% of all spectral loads. The wind spectrum contains a lot of energy at low frequencies, which can contribute to low-frequency resonant oscillations of moored floating structures.

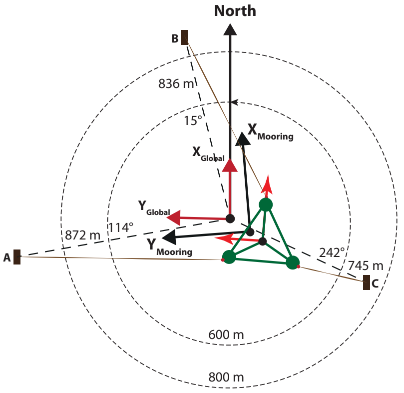

Fig. 5 Line configuration at Ekofisk

CONCLUSION

o The total line length is 85% of the initial symmetrical design
--> the tool minimizes the line length of a floating wind turbine mooring system under site specific environmental loading, resulting in the optimal angle, line length and horizontal distance between anchor, and fairlead.

o Spectral wind loads should be considered in the mooring system design. The low-frequency contributions from wind lead to excitations in platform pitch and hence in higher mooring line peak tensions.

o Time domain simulations are needed to verify and further optimize the obtained mooring design.

ACKNOWLEDGEMENT

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PLOCAN, a multiuse offshore test site in the Atlantic Ocean

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Operation and maintenance

The Oceanic Platform of the Canary Islands (PLOCAN) is a multi-purpose service centre composed of a set of large infrastructures to support research, technology and innovation in the marine and maritime sector in the North-East Central-Atlantic Ocean. The mission of the centre is to promote long-term observation and sustainability of the ocean. It will facilitate multidisciplinary approach, clustering and cost-effective combination of services such as observatories, test site, base for underwater vehicles, training and innovation hub.

PLOCAN will contain a set of experimental facilities and laboratories on the ground, an offshore platform located on the edge/shore of the continental shelf and deep observation sites, some of them connected by cable. It will have sensors, vehicles, vessels, etc. This will be an ocean platform of unique features to start a permanent occupation, in order to operate in oceanic deep waters.

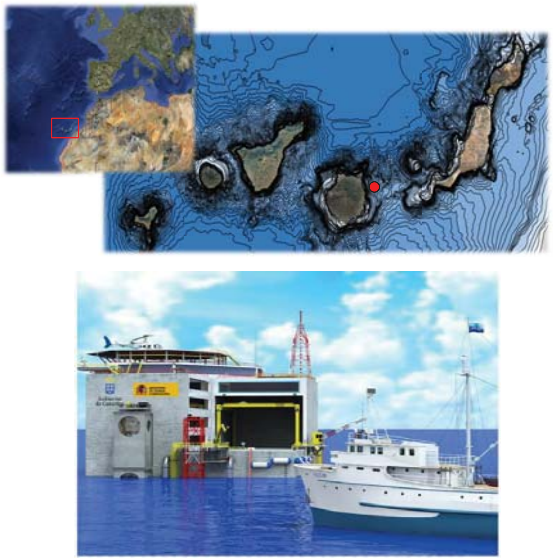

Figure 1. Location

Observatory

The concept of "ocean observatory" is used here as a set of infrastructures that allows the characterization and study of its surrounding space, from the seabed to the atmosphere, in scales of nanometres to hundreds of kilometres and from microseconds to decades. PLOCAN will initially provide support for observation at three different locations and environments: the ESTOC site (European Station for Time-Series in the Ocean Canary Islands), the deep-sea cabled observatory, and the surrounding waters cabled and standalone observatories near the PLOCAN offshore infrastructure.

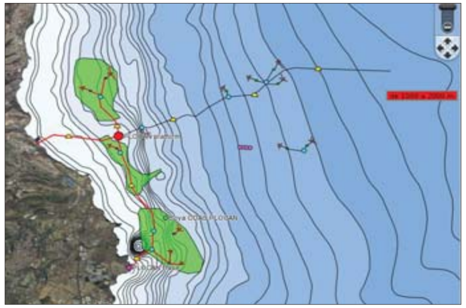

Figure 2. Observatory deployment

Test site

The main mission is to accelerate and lower the cost of all types of tests, ocean technology development, prototyping and marine experiments. To improve sustainability and cost efficiency, the ocean energy test site services integrate observation facilities. Testing is designed and implemented in order to avoid any disturbance in a controlled environment and take advantage of the observatory facilities. The support to the initial 8 km^2 test area will be enhanced by the offshore platform. The area will mainly be used for testing wind and wave energy converters. A submarine electrical infrastructure to evacuate up to 10 MW is under design.

Last year the first technical demonstrator of a wave energy converter of 70 kW was tested (Project WELCOME) while another two new prototypes are scheduled for 2012.

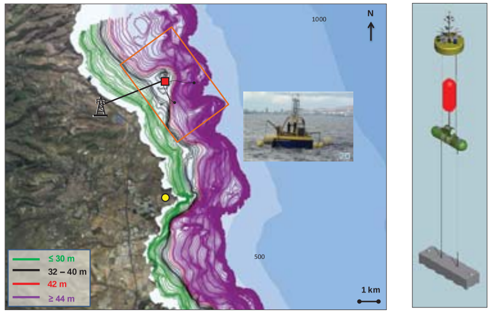

Figure 3. Test site deployment and WELCOME prototype.

VIMAS

PLOCAN offers a base for the support and development of new technology for underwater vehicles. The concept of base for vehicles, instruments and machines (VIMAS) is used here like the place, facilities and services that optimize (to simplify, to lower the price, to make more trustworthy) all the operations of these ocean devices. The operations include maintenance, testing, transport, deployment, anchorage, gathering, connections, supply, etc.

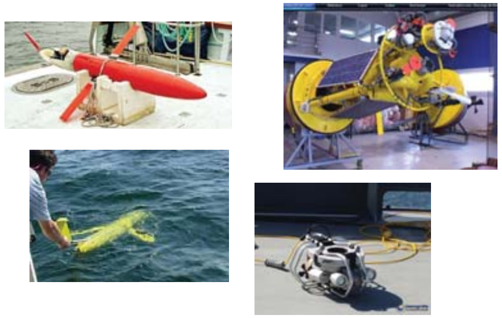

Figure 4. Gliders, ROVs and buoys

PLOCAN PLATAFORMA OCEÁNICA DE CANARIAS

ASHES:
A novel tool for FEM analysis of offshore wind turbines with innovative visualization techniques

Statkraft Ocean Energy Research Program

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NTNU – Trondheim
Norwegian University of Science and Technology

Abstract

Specialized software analysis tools are needed for safe and economic design of offshore wind turbines. Many tools are today in active development both in the academic and commercial world. Typically, the existing programs utilize a combination of modal analysis, multi-body dynamics and the finite element method. However, professionals and students in the offshore wind turbine business alike, often struggle with the multidisciplinary complexity of offshore wind turbines.

ASHES is a novel analysis and design tool for horizontal axis offshore wind turbines. In the growing plethora of wind turbine analysis software, ASHES seeks to distinguish itself on three areas:

1. Innovative visualization and graphical user interface techniques in order to assist the study and understanding of the wind turbine.
2. Computational efficiency.
3. Integrating design and code verification in a single tool

Innovative Visualization Techniques

We believe that effective graphical visualization can be as an important output from an analysis as traditional numerical results. In particular this is the case when it comes to correct interpretation of data and identifying possible design improvements. Thus, implementation of visualization and investigation of effective visualization capabilities are a priority.

Visualization is built around *the real-time analysis* capabilities of the framework, thus giving the software the touch and feel of a "desk-top laboratory" - input parameters can be changed in the middle of the analysis etc.

Among features that are/will be visualized are:

- Loading on blades and tower broken down according to source (thrust, torque, gravity, etc), incl. scaling.
- Deformation of blades and tower, incl. scaling.
- Sea surface, wind, waves, and current
- Exact blade geometry as well as blade pitch and twist
- Detailed investigation of the load triangle

In Figure 1 the OC4 jacket[3] is shown in a deformed state. Aerodynamic loading on the rotor and hydrodynamic on the jacket is shown. On the rotor the thrust and torque components on every blade element is shown. Additionally the total thrust is shown in the hub. For the jacket the wave loading represented as drag and inertia loading are shown. The blades are visualized by drawing leading edge, trailing edge, and the chord for each blade element.

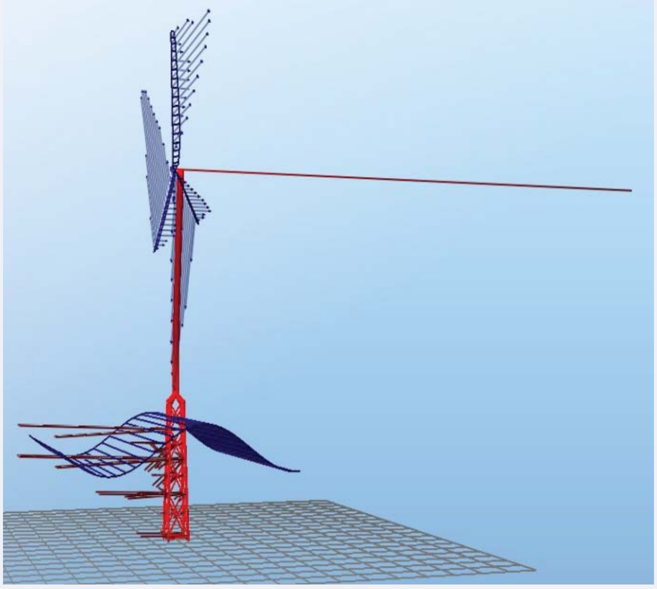


Figure 1: Screen dump from ASHES showing the OC4 jacket[3]

Computational Efficiency

ASHES is based on an object-oriented finite element framework. The framework was developed to form a basis for any specialized finite element analysis tool, e.g. - as in this case - an offshore wind turbine. The choice of object-oriented implementation is founded on the assumption that an improved and more effective development cycle can be achieved while maintaining at least the same computational efficiency as traditional implementations (e.g. using procedural Fortran). The computational efficiency of the framework has been benchmarked in [1].

Computational efficiency is foremost an issue when a bulk of analysis results are needed, i.e. typically for code verification when visualization is of limited interest. We are working to satisfy this use of the tool by considering interesting possibilities like:

- Convenient use of multiple cores and/or multiple computers
- Convenient specification of analysis cases (typically load cases)

Benchmarking and Validation

Benchmarking and validation of analysis results are considered essential also in the short term. Three benchmarking initiatives have currently been performed / are currently underway:

•*NOWITECH/NORCOWE Model Wind Turbine Blind Test* [2]. BEM results have been benchmarked against BEM and CFD codes. Results show good agreement with measurements and other codes, see Figure 2

•*IEA Wind Annex 30 OC4 project [3]*: Results are currently being produced.

•Benchmarking against tidal turbine model tests. Results from towing tank experiments for a 1.5m diameter tidal turbine is being benchmarked [4]. ASHES is being extended to tidal turbines as a part of this work.

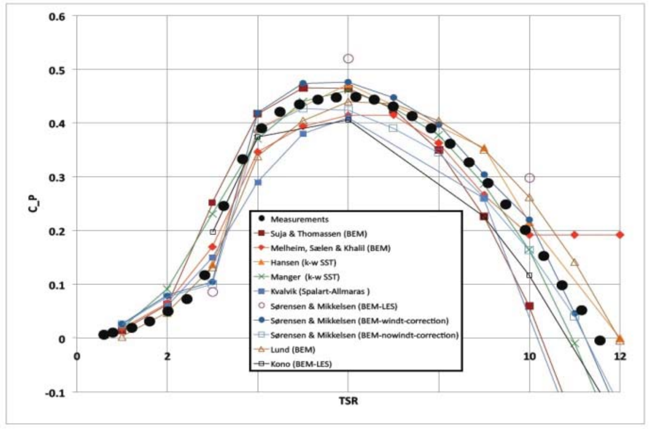


Figure 2: Power curve from NOWITECH/NORCOWE blind test [2]. ASHES results have been submitted by Suja and Thomassen

References

1. Jang, J., 2007, "Characterization of live modeling performance boundaries for computational structural mechanics ", PhD Thesis, University of Washington.
2. Krogstad, P. Å. and Eriksen, P. E., 2011, "Blind test Workshop. Calculations for a model wind turbine. Summary report.", NTNU, Norway.
3. IEA Wind Annex 30, The OC4 project. http://www.ieawind.org/Task_30/Task30_OC4_JacketCode.html
4. Faudot, C. and Dahlhaug, O. G., 2011, "Tidal turbine blades: Design and dynamic loads estimation using CFD and Blade Element Momentum theory," OMAE 2011, Rotterdam, the Netherlands

Acknowledgements

This work is a part of the Statkraft Ocean Energy Research Program.

The Dept. of Civil engineering, NTNU, funded the work carried out by IAESTE student Anja Grant. The funding from both is greatly appreciated.

The FEM framework was originally developed by Dr. Jaewon Jang and Prof. Greg Miller, University of Washington. Their help and contribution to this work is greatly appreciated.

ITERATIVE OPTIMIZATION APPROACH FOR THE DESIGN OF FULL-HEIGHT LATTICE TOWERS FOR OFFSHORE WIND TURBINES

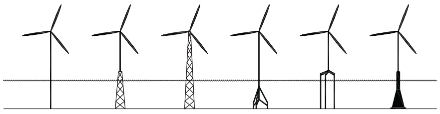
NTNU
Norwegian University of Science and Technology

PhD candidate: Daniel Zwick
Supervisors: Michael Muskulus, Geir Moe

Department of Civil and Transport Engineering

SUPPORT STRUCTURE CONCEPTS

Installations of bottom-fixed offshore wind farms in intermediate water depth are until now based on more or less the same construction idea: the support structure of the rotor nacelle assembly (RNA) is a combination of a multi-member (jacket, tripile, tripod), tubular (monopile) or gravity based substructure with a tubular tower. The latter is known from onshore wind turbines. A transition piece located at a certain level above the water surface is connecting the two structural parts.

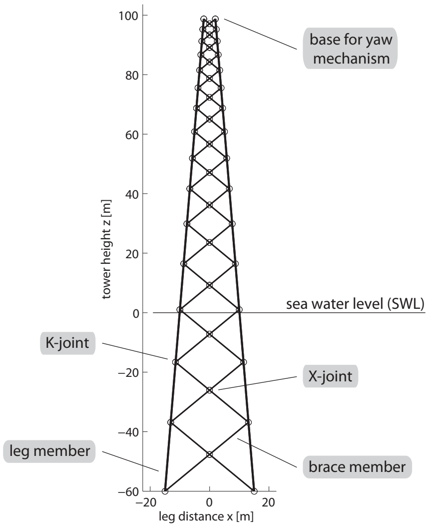


Bottom-fixed support structure concepts
for intermediate water depth

A new design approach of a full-height lattice tower has been developed by the Department of Civil and Transport Engineering at NTNU, in which the traditional tubular tower is replaced by a space frame structure going all the way from seabed to RNA. The aims of this approach are a reduction in steel weight and a simplification of the installation, and thereby a reduction of total cost of the support structure, compared with known solutions.

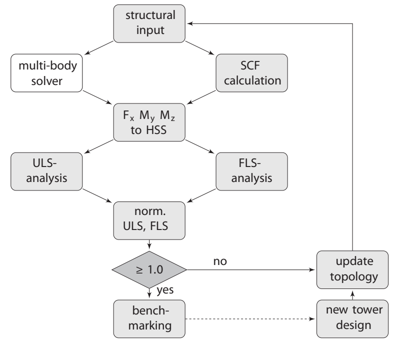
FULL-HEIGHT LATTICE TOWER DESIGN

The design of a full-height lattice tower presented here, provides directly support for the turbine nacelle, without transition to a tubular tower. The structure is characterised by leg and brace members, welded together in K- and X-joints.



	constant dimensions	optimized design
tower height [m]	158.70	158.70
leg/brace		
diameter [m]	1.6/0.8	1.6/0.8
thickness [mm]	73/34	49..63/20..34
number of sections	15	15
tower weight [t]	3082	2283

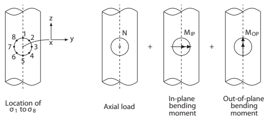
ITERATIVE OPTIMIZATION APPROACH



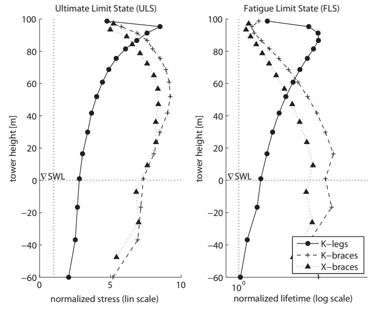
structural input
multi-body solver
SCF calculation
F_x M_y M_z to HSS
ULS-analysis
FLS-analysis
norm. ULS, FLS
≥ 1.0
no
yes
update topology
bench-marking
new tower design

The iterative optimization approach is based on two main steps. First the analysis of a specific tower design with a multi-body solver, and second the post-processing of calculated time series of forces and moments for each member and joint. Each tower model is analysed for the ultimate limit state (ULS) and the fatigue limit state (FLS). The analysis includes the calculation of stress concentration factors (SCF) to determine hot spot stresses (HSS) in the joints of the lattice tower.

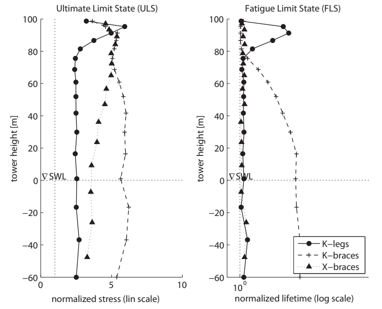
Superposition of stresses for tubular joints (DNV-RP-C203)



OPTIMIZATION RESULTS

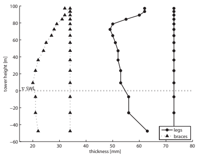


constant member dimensions over tower height



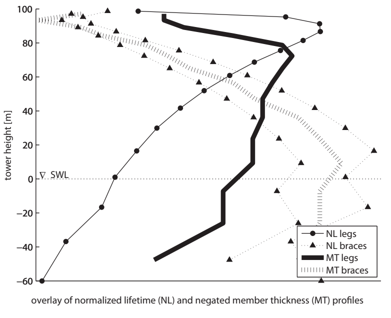
optimized member dimensions according to loads

STRUCTURAL BEHAVIOR OF OPTIMIZED DESIGN



Members were changed section-wise with constant dimension in each section. This leads to dependencies between parameters that are optimized, since legs and braces are physically connected in K-joints and the variation of one of these members results in a changed behavior for the connected member, too.

Adjusting brace dimensions leads to changes in both K- and X-joints for brace elements. This limits the possibility to optimize leg and brace members for both K- and X-joints at the same time.



comparing lifetime and thickness profiles

10MW NOWITECH REFERENCE TURBINE

A full-height lattice tower for the installation of the proposed 10MW NOWITECH reference turbine in 60m water depth was chosen as case. The rotor has a diameter of 141m and the concept is a horizontal axis three bladed offshore wind turbine.

Simulation runs with 13.5m/s turbulent wind (16% turbulence intensity) and an irregular sea state with JONSWAP spectrum (H_S=4m, T_P=9s) were performed for aligned wind and wave direction to provide initial load conditions. The model was build in FEDEM Windpower with a bottom-fixed foundation.

SUMMARY

Since several design parameters lead to significant changes in the tower topology of a full-height lattice tower and time-domain analyses are time consuming and expensive, an effective optimization approach is needed to be able to reduce the number of necessary simulation runs.

An approach was presented, where results from the analysis of a design with constant member dimensions over tower height were analysed and translated into an expectation of the member dimension profile over tower height for an optimized design.

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9th Deep Sea Offshore Wind R&D Seminar, 19.-20. January 2012, Trondheim, Norway

WAKE MEASUREMENTS BEHIND AN ARRAY OF TWO MODEL WIND TURBINES

NTNU
Det skapende universitet

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1. MOTIVATION

- Less energy extraction of downwind turbines in a wind farm
- Increased material fatigue on downwind rotors due to additional turbulence in the rotor wake
- Need for experimental data on second turbine wake for computational wake models
- Optimization of wind farm development with wake models

2. OBJECTIVES

- Quantify the difference in mean velocity and turbulence intensity between the first and second turbine wake
- Influence of turbine separation distance *S/D* on mean velocity U_M/U_∞ and turbulence intensity u'/U_M in the wake behind two turbines

3. EXPERIMENTAL SETUP

- Wind tunnel test section of *2.0m* (height) x *2.7m* (width) x *12.0m* (length)
- Wind tunnel inflow speed of $U_\infty=11.5$ *m/s*

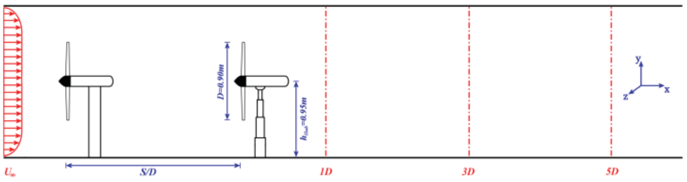


Fig. 1. Experimental setup and axial measurement stations downstream of the second model turbine at 1D, 3D and 5D

- Power coefficient C_P measured by torque sensor
- Turbine tip speed ratio λ acquired by RPM sensor
- Two separation distances *S/D=3* and *S/D=5* investigated
- Wind turbines operated at design tip speed ratio $\lambda_{Tu1}=6$ resp. $\lambda_{Tu2}=4$
- Mean velocity and turbulence intensity measurements by means of hot wire anemometry at three axial measurement stations in the wake

4. RESULTS

4.1. TURBINE POWER CHARACTERISTICS

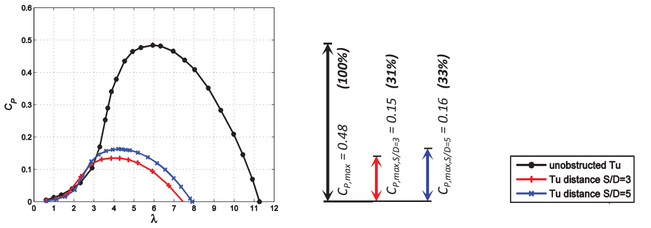


Fig. 2. Power curves of the second model wind turbine operated unobstructed, *S/D=3* downstream and *S/D=5* downstream of the first turbine

4.2. FLOW FIELD DOWNSTREAM OF THE TWO TURBINES

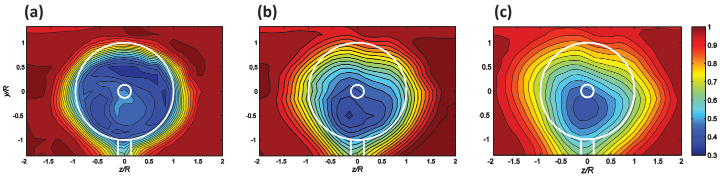


Fig. 3. Normalized mean velocity U_M/U_∞ [-] in the wake behind the array of two model turbines separated *S/D=3*: (a) 1D downstream; (b) 3D downstream; (c) 5D downstream

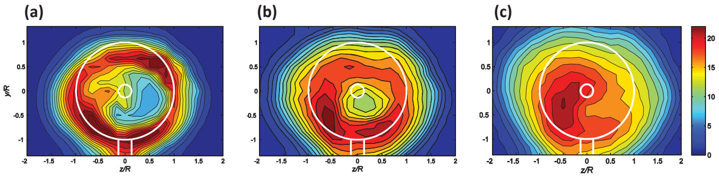


Fig. 4. Turbulence intensity u'/U_M [%] in the wake behind the array of two model turbines separated *S/D=3*: (a) 1D downstream; (b) 3D downstream; (c) 5D downstream

4.3. COMPARISON OF DIFFERENT TURBINE ARRANGEMENTS

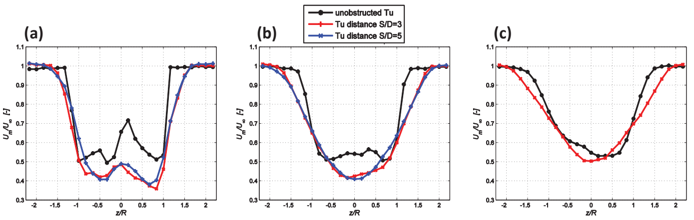


Fig. 5. Comparison of the normalized mean velocity U_M/U_∞ [-] behind one unobstructed turbine, two turbines separated *S/D=3* and two turbines separated *S/D=5*: (a) 1D downstream; (b) 3D downstream; (c) 5D downstream

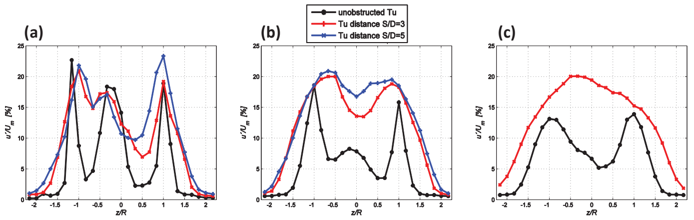


Fig. 6. Comparison of the turbulence intensity u'/U_M [%] behind one unobstructed turbine, two turbines separated *S/D=3* and two turbines separated *S/D=5*: (a) 1D downstream; (b) 3D downstream; (c) 5D downstream

5. CONCLUSIONS

- Evident asymmetries in mean velocity and turbulence intensity profiles in close distances behind the second turbine rotor
- More uniform and symmetrical flow field further downstream in the wake
- Significantly higher turbulence intensities behind two turbines than behind one unobstructed turbine
- Considerably higher velocity deficits in the near wake behind the second turbine compared to the wake behind one unobstructed turbine
- Hardly any influence of turbine separation distance *S/D* on velocity and turbulence profiles in the wake
- Velocity profile at five rotor diameters behind the second turbine is already very similar to the velocity distribution behind the first turbine
- Higher symmetry and uniformity in velocity and turbulence intensity profiles behind the second turbine than behind the first turbine

9th Deep Sea Offshore Wind R&D Seminar, 19-20 January 2012, Trondheim, Norway

NTNU
Norwegian University of Science and Technology

Active Power Control with Undead-Band Voltage&Frequency Droop for HVDC Converters in Large Meshed DC Grids

Til Kristian Vrana Olav Bjarte Fosso

Introduction
DC Voltage Control

HVDC Converter Control Requirements for Large Meshed DC Grids:
- High Reliability
- Integration of Uncontrolled Electrical Islands
- Distributed Balancing Control
- Plug and Play
- Robustness against Communication Faults
- Consideration of DC Voltage Drop
- Robustness against Manipulation
- AC Frequency Support

Known DC Voltage Control Methods
- Direct Voltage Control
- Voltage Margin Control
- Droop Control
- Dead-Band Droop Control

Control Method Overview

Control Method	Conv. 1		Conv. 2		Conv. 3	
	$D_{v,1}$	$D_{v,2}$	$D_{v,1}$	$D_{v,2}$	$D_{v,1}$	$D_{v,2}$
Direct Voltage	∞	∞	0	0	0	0
Voltage Margin	∞	0	0	∞	0	0
Droop	K_1	K_1	K_2	K_2	K_3	K_3
Dead-Band Droop	∞	K_1	0	K_2	0	K_3

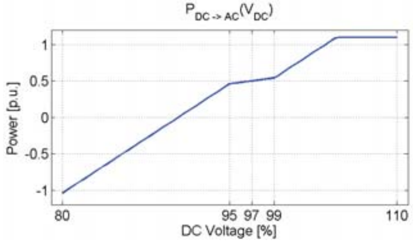
Undead-Band Droop Control
for Voltage and Frequency

Power, Voltage and Frequency Limitations

	Min.	Max.
Power limitation	-1,1	1,1
Power setpoint	-1,0	1,0
Voltage limitation	0,8	1,1
Voltage setpoint	0,9	1,0
Voltage tolerance	-2%	+2%

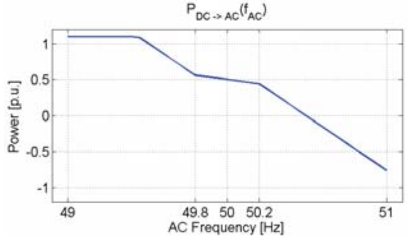
	Min.	Max.
Power limitation	-1,1	1,1
Power setpoint	-1,0	1,0
Frequency limitation	0,98	1,02
Frequency setpoint	1,0	
Frequency tolerance	-0,4%	+0,4%

Undead-Band Voltage Droop



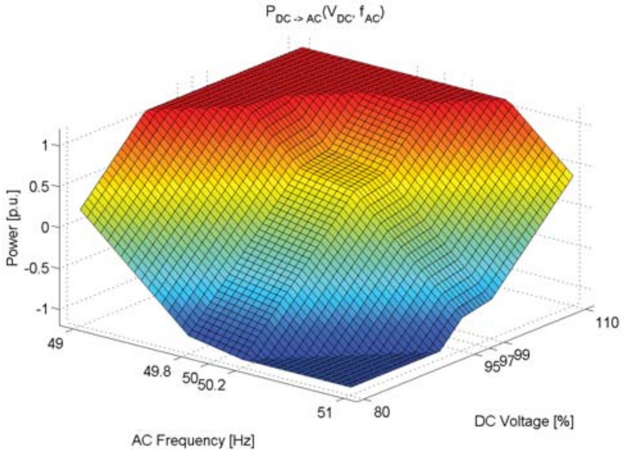
V_{set}	0.97
V_{norm}	0.97 ± 0.02
P_{set}	0.40
$D_{v,1}$	3
$D_{v,2}$	15

Undead-Band Frequency Droop



f_{set}	1.00
f_{norm}	1.00 ± 0.004
P_{set}	0.40
$D_{f,1}$	-15
$D_{f,2}$	-75

Combined Frequency&Voltage Droop
Concept and Advantages



Advantages:
- Wide definition, includes the other known control methods
- Avoiding zero and infinity as control parameter
- Combines advantages of the other methods
- Leaving room for individual optimisation
- Minimum of required communication
- Distributed balancing
- Self stabilising
- Robust against manipulation due to autonomous operation
- Automatic exchange of primary reserves
- Also suitable for storage units

Conclusion

Proposed control method has several conceptual advantages

Validation and verification via power system simulations is on its way

DTU Wind Energy
Department of Wind Energy

DTU

Fully Nonlinear Wave Forcing on an Offshore Wind Turbine. Structural Response and Fatigue.

S. Schløer, H. Bredmose, H. Bingham and T. Larsen

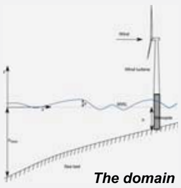
Model setup

The effect from fully nonlinear irregular wave forcing on the fatigue life of the monopile foundation and offshore wind turbine tower is investigated through aeroelastic calculations. Five representative sea states with increasing significant wave height are considered in a water depth of 40 m. The response is analysed for both linear and nonlinear wave forcing and the results are compared. The wind turbine is the NREL 5MW reference wind turbine.

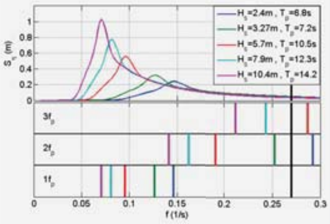
The fully nonlinear potential flow wave model of Engsig-Karup et al. (2009) is used to compute unidirectional irregular waves.

The dynamic behavior of the wind turbine and foundation is calculated in the aeroelastic code Flex5, Øye (1996).

Fatigue analysis is performed together with analysis of the sectional force in the bottom of the tower.



The domain



The spectra of the five sea states at the wave inlet (h=135m). Below the specta the three first harmonics of the sea states are indicated. The black line indicates the first eigenfrequency of the structure. The incident wave spectra are truncated at f=0.3 hz.

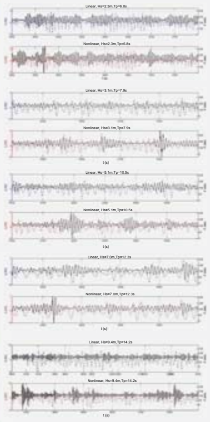
The wind speed in the aeroelastic computations are small, constant and equal for all five sea states. The effects of larger wind speeds and turbulence is discussed in column three.

H_s	T_p	W
m	(s)	(m/s)
2.3	6.8	5.0
3.1	7.9	5.0
5.1	10.5	5.0
7.0	12.3	5.0
9.4	14.2	5.0

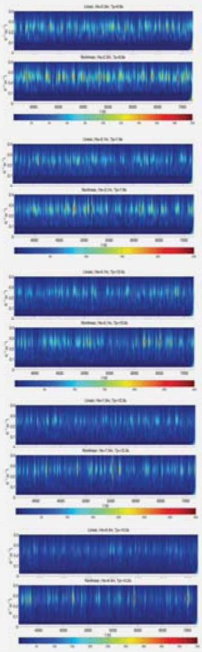
Wave and wind data

Response in bottom of tower

The sectional force in the bottom of the tower is very dependent on whether the waves are linear or nonlinear, cf. the figure in the next column. Excitation of the structural eigenmode in a ringing-type behavior is seen when steep waves hit the structure and almost only for nonlinear waves. The excitation is also seen for the smallest sea states.



The linear and nonlinear surface elevation and the corresponding sectional force in the bottom of the tower.



Left: Wavelet transformation of one hour time sequence of the sectional force in the bottom of the tower.

Equivalent load range

The equivalent load range, L_{eq}, represent one load value that for a certain number of cycles, N_{eq}, results in the same damage level as the history of fatigue loads which are investigated, here N_{eq} =7200

H_s	T_p	W	$\frac{L_{eq,NL}}{L_{eq,L}}$	$\frac{L_{eq,NL}}{L_{eq,L}}$
(m)	(s)	(m/s)	m=3	m=5
2.3	6.8	5.0	1.24	1.28
3.1	7.9	5.0	1.33	1.52
5.1	10.5	5.0	1.32	1.53
7.0	12.3	5.0	1.53	2.34
9.4	14.2	5.0	1.93	2.65

Ratio between the nonlinear and linear equivalent load range in the bottom of the tower for damage exponents m = 3 and m = 5.

It is clear that L_{eq} is largest in case of nonlinear waves and also that the ratio increases with increasing significant wave height.

Relative fatigue analysis

The fatigue analysis is based on the relative probability of occurrence

$$P_{i,rel} = \frac{P_i(H_s, T_p)}{\sum P_i(H_s, T_p)}, \quad i = 1, 2, \ldots, 5$$

The fatigue analysis states that for the linear waves the contribution from each sea state is close to the probability of occurrence. For the nonlinear waves the largest sea states contribute significantly to the relative fatigue damage, despite their low probability of occurrence.

H_s	T_p	W	$P_{i,rel}$	Linear		Nonlinear	
(m)	(s)	(m/s)	(%)	m=3	m=5	m=3	m=5
2.3	6.8	5.0	53	46.5	41.5	40.3	15.0
3.1	7.9	5.0	35	36.6	36.5	39.9	31.2
5.1	10.5	5.0	10	14.2	17.5	14.9	15.2
7.0	12.3	5.0	1.4	2.3	3.6	3.8	26.4
9.4	14.2	5.0	0.15	0.4	0.9	1.2	12.3

The relative contribution to the fatigue damage per sea state in the bottom of the tower for damage exponents m = 3 and m = 5.

Discussion

The analysis shown here indicate that the nonlinearity of the waves can change the response significantly. One example is the impulsive excitation of the force in the bottom of the tower for nonlinear waves. Also the equivalent loads are significant larger in case of nonlinear waves than in case of linear waves. Further, the largest sea states contribute significant to the fatigue damage level in case of nonlinear waves.

More realistic conditions may be obtained by incorporation of turbulent wind climates with speeds that better correspond to the sea states. Preliminary results of such computations show that the effect from nonlinear waves still exist. For this case, however, the aerodynamic damping is stronger and the ringing response is thus damped out faster. Further, interpretation is less clear, as the signal is overlaid with the response from the turbulent wind fluctuations.

The situation analysed here with a small wind velocity provides a clear base for analysis. For the case of a zero wind speed, the aerodynamic damping will be absent and the effects from wave nonlinearity are expected to be larger. This corresponds to the situation where the wind and wave direction are misaligned or a storm condition where the wind turbine is idled. As both situations are part of the design basis, the present results are highly relevant for practical design.

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Schløer, S., Bredmose, H. and Bingham , H. (2011). Irregular wave forces on monopile foundations. Effect of full nonlinearity and bed slope. In *In Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering.*
Øye, S. (1996). Flex4 simulation of wind turbine dynamics. In 28th *IEA Meeting of Experts Concerning State of the Art of Aeroelastic Codes for Wind Turbine Calculations* (available through International Energy Agency).

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Statkraft Ocean Energy Research Program

Statkraft NTNU Norwegian University of Science and Technology UPPSALA UNIVERSITET DTU Wind Energy Department of Wind Energy

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University of Stavanger

A panel vortex code for wind turbines implemented on a GPU

Lene Eliassen, University of Stavanger and Michael Muskulus, Norwegian University of Science and Technology

The aerodynamic loads acting on a wind turbine are typically implemented using the Beam Element Momentum (BEM) method. This method is valid within certain limits, e.g. as long as the flow is aligned perpendicular to the rotor plane. The main reason for the popularity of the BEM method is its efficiency and ease of implementation. However, the limitations of this method make it desirable to use a more general method for determining the aerodynamic loads acting on wind turbines. The vortex method is one such alternative, but it has not been extensively used due to its large computational cost. The purpose of the present study was to investigate the possibility of reducing the computational cost of the panel vortex method by implementing the code on a general purpose GPU.

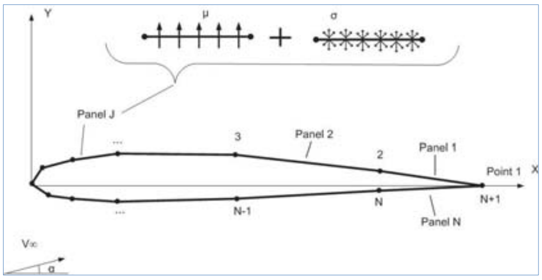
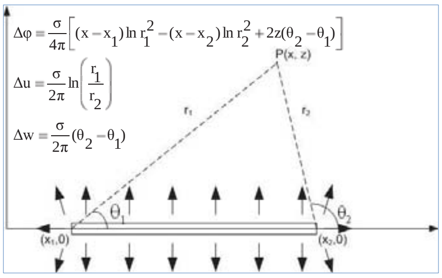


Figure 1: An illustration of the wing, with the surface divided into panel elements

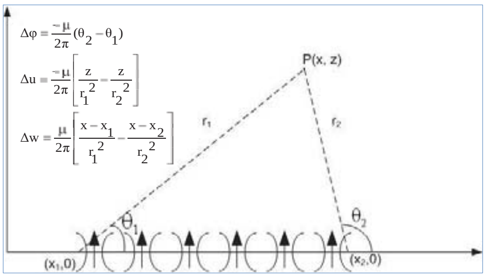


$$\Delta\varphi = \frac{\sigma}{4\pi}\left[(x - x_1)\ln r_1^2 - (x - x_2)\ln r_2^2 + 2z(\theta_2 - \theta_1)\right]$$

$$\Delta u = \frac{\sigma}{2\pi}\ln\left(\frac{r_1}{r_2}\right)$$

$$\Delta w = \frac{\sigma}{2\pi}(\theta_2 - \theta_1)$$

Figure 2: A two-dimensional constant strength source element



$$\Delta\varphi = \frac{-\mu}{2\pi}(\theta_2 - \theta_1)$$

$$\Delta u = \frac{-\mu}{2\pi}\left[\frac{z}{r_1^2} - \frac{z}{r_2^2}\right]$$

$$\Delta w = \frac{\mu}{2\pi}\left[\frac{x - x_1}{r_1^2} - \frac{x - x_2}{r_2^2}\right]$$

Figure 3: A two-dimensional constant strength doublet element

What is a GPU?

GPU is an abbreviation for Graphics Processing Unit and was originally developed for graphical applications. It has developed into a programmable processor unit that has a computing power exceeding those of multi-core CPUs [1]. A two-dimensional application with a combined GPU and CPU application has been validated, and the gain in computational speed relative to a pure CPU implementation has been evaluated [3]. The reduction in computational time is shown in figure 4.

The GPU implementation in [3] used the Thrust library [4] that allows for adapting a program to run parts of the code on the GPU with minimal changes in the code relative to the CPU version. This is not an optimal solution as the constant memory copying slows down the simulation. A code written in CUDA C, which would run completely on the GPU, would make the method faster. This implementation used a brute force algorithm, calculating all the interactions. An approximation algorithm (e.g. Barnes-Hut tree algorithm) is orders of magnitude faster. Still, it can be seen that even with this simple implementation the GPU is faster than the CPU if more than 1000 wake particles are used. In figure 4 one can see that the computational time saved increases as amount of wake particles increases.

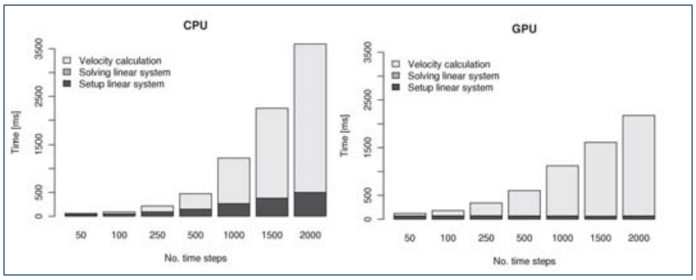


Figure 4: The computational times for a CPU, relative to a combined CPU and GPU for a two dimensional calculation [3]

Why do we need a faster vortex method?

The main analysis tool for aerodynamic loading is presently the Beam Element Momentum (BEM) method. This method is based upon a momentum approach, with the flow perpendicular to the rotor. Some of the situations modelled by the BEM method is out of its area of validity. At present, other tools such as computational fluid dynamic (CFD) and the vortex method have too high computational cost.

The vortex method is a more dynamic analysis tool. In its original form it is only for potential flow, which is an oversimplification. In reality there is vorticity in the flow. However, if one is aware of this, and uses the tool with caution one could calculate a more wide variety of load cases. At the moment the largest disadvantage using the vortex method is the large computational time. When this is reduced, the vortex method should be used as an aerodynamic analysis tool in addition to the BEM method.

What is the panel vortex method?

The vortex method is based on the assumption of potential flow. In the panel method the wing surface and the trailing wake are divided into panels. This is shown for a two-dimensional wing in figure 1. Each panel on the wing surface is given both a constant strength source and doublet element. If the strength of the elements are known, one can calculate the difference in potential or velocities due to the elements based on the distance, r, and angle, θ, see figures 2 and 3 [2].

The strength of the elements are established by applying two boundary conditions; the first is to set the flow across the elements to zero (Dirichlets boundary condition) and the second says that there should be no vortices at the trailing edge (Kutta condition).

Based on the equations included in figure 2 and 3, one can establish the velocity at any point in the fluid. The pressure can be computed based on these velocities using the Bernoulli's law, and thus the lift and drag forces can be established for the wing. The wake is also modelled as panels with doublet elements. Thus the shape and strength of the wake is included in the aerodynamic forces calculated by the vortex method. The main computational effort is spent in calculating the induced velocities, where all particles influence eachother.

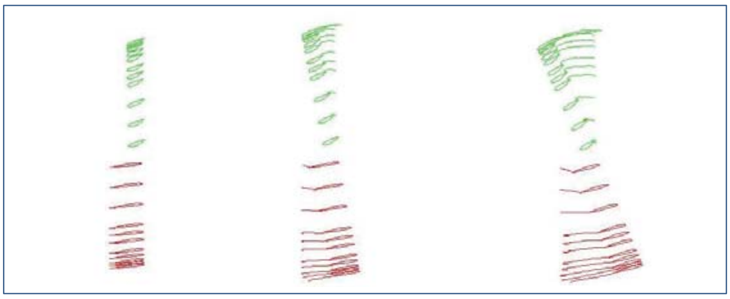


Figure 5: Two NACA 0012 wings rotating. The pitch angle is constant, and the illustration is showing the wake development at three different stages in time.

In figure 5 a three dimensional rotating wing is shown. Here the surface is divided into quadrilateral elements and the surface is given doublet and source strengths according to the incoming flow.

References:

[1] E. Lindholm, J. Nickolls, S. Oberman, J. Montryn. NVIDIA Tesla: A unified graphics and computing architecture. IEEE Computer Society, IEEE Micro, 28:39-55, 2008.
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[3] L. Eliassen and M. Muskulus. A study of the NACA 0012 using a parallel vortex method. 7th EAWE PhD Seminar on Wind Energy in Europe, Delft, Netherlands, 2011.
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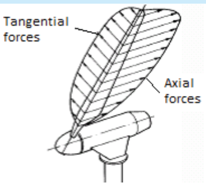
Yaw Moment of a three-bladed wind turbine with yaw error

Tania Bracchi, PhD student, Dept. of Energy and Process Engineering, NTNU

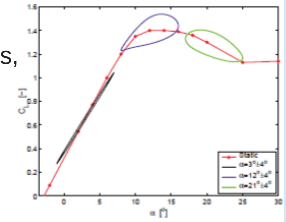
1.Introduction

Predicting yaw moments is a challenge, since the unsteady operating environment makes the flow behaviour difficult to predict. However a better understanding of the yaw behaviour could reduce operating/maintenance costs. In the present study the yaw moments of a 3-bladed HAWT are calculated with FAST. Finally they are compared with experimental results.

2.How yaw moments are generated?



- The blade loads vary during the rotation, due to the variation of angle of attack



- A dynamic variation of angle of attack causes hysteresis in the airfoil characteristics, contributing greatly to asymmetry, which increases yaw loads

3.Simulation assumptions

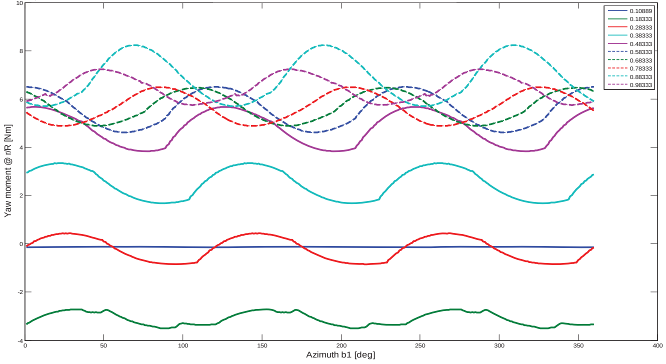
- The model geometry used for the simulation is the turbine tested in the wind tunnel at NTNU, for which large amount of data is available[1]
- Yaw moments are computed for fixed yaw angles of +10 and +20 in upwind and downwind configurations
- The aerodynamic model used to compute the blade loads is a Generalized Dynamic Wake model (GDW) and the Beddoes dynamic stall model is included[2]

4.Results

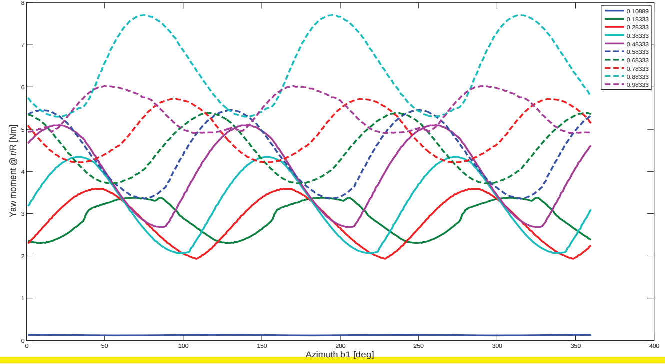
Convention used : Positive Yaw Moments return the rotor perpendicular to the wind.

Yaw Moments along the blade

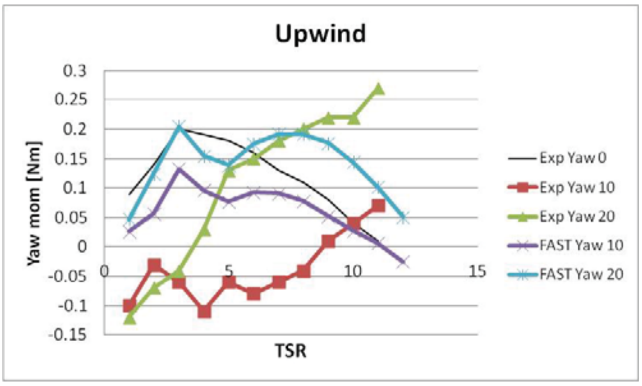
Upwind, TSR 4, Yaw 10

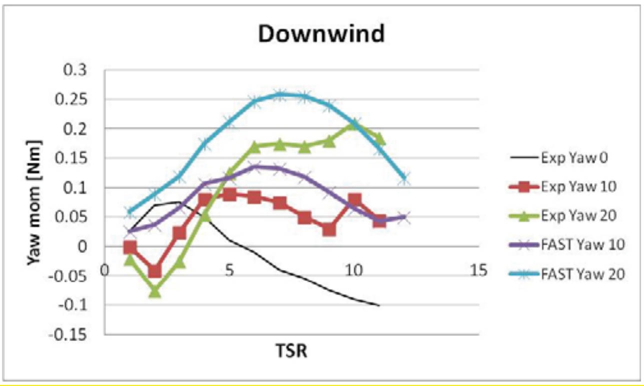


Downwind, TSR 4, Yaw 10



Comparison with experiment[3]





5.1. Discussion

Upwind: for r/R<30% the yaw moments give a negative contribution; for r/R>60% the yaw moments "pack" around 6e-3 Nm.

Downwind: the yaw moments are positive along the whole blade and less spread than for upwind.

5.2. Discussion

Upwind: the experimental results show an unstable behaviour up to TSR≈9 and 4 for Yaw = 10 and 20 deg respectively. Whereas it is prediced a stable behaviour for all the conditions unless at very high TSR, for Yaw=10 deg

Downwind: the experiment shows a unstable behaviour only at low TSR for both yaw angles.

The prediction seem more comparable with the experiment.

6.References

[1]Adaramola, M. and Krogstad, P-Å (2011). Experimental investigation of wake effects on wind turbine performance. Renewable Energy, 36, 2078-2086

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[3]Loland, M. K. (2011) *Wind turbine in yawed operation* (Master thesis, NTNU). Trondheim: NTNU.

Gain scheduled and robust $\mathcal{H}_\infty$ control above rated wind speed for wind turbines

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Abstract

Two different approaches for individual pitch control for wind turbines is investigated. The first one is a gain scheduled decentralised control design and the second one is a robust $\mathcal{H}_\infty$ loop shaping control design. Both controllers work well in the region above rated wind speed, exhibiting a response that is mostly independent of wind speed.

Introduction

For variable-speed wind turbines, the control regime is divided into an above-rated mode and a below-rated mode. Because of the increasing rotor size and the spatial load variations along the blade, it is necessary to react to turbulence in a more detailed way, with each blade separately controlled. The controllers designed in this paper are specifically designed to provide speed regulation above rated wind speed in order to reduce the blade flap motions.

The wind turbine model

The results presented in the poster correspond to the NREL 5 MW benchmark wind turbine.

Rating	5 MW
Rotor Configuration	Upwind, 3 blades
Rotor diameter, Hub height	126 m, 90 m
Rated wind speed, rated rotor speed	11.4 m/s, 12.1 rpm

Table 1: *Properties for the NREL 5MW benchmark wind turbine*

The dedicated software FAST, has been used for simulation and analysis of the wind turbine.

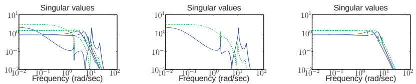
The wind turbine model has been Coleman transformed and the Coleman system and Coleman coordinates are used in the rest of the poster. The subscripts c, h, v are used for the collective, horizontal and vertical Coleman coordinates respectively. The model used is

$$\begin{bmatrix}\omega_g\\ f_h\\ f_v\end{bmatrix} = G\begin{bmatrix}\beta_c\\ \beta_h\\ \beta_v\end{bmatrix} \tag{1}$$

where G is the wind turbine model, ω_g is the generator speed, f is the individual blade flap motions, i.e. collective blade flap is not used, and β is the pitch input.

Linearization

The system has been linearized around different steady-state operating points above rated wind speed. The wind speed range under study is between 12.1 m/s and 26 m/s.



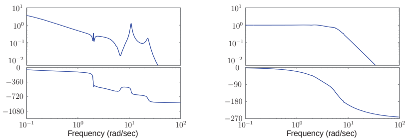
(a) Full system (b) Gen. speed (c) Ind. flap

Figure 1: *Singular values plot for the wind turbine model at two different wind speeds. 12.1 m/s (solid) and 26 m/s (dashed). Different outputs is used in each figure.*

It is clear that the linear systems response depends on the mean wind speed, and the difference is large for the system with the generator speed as output, but not very large when the flap motions are the outputs.

Design of a baseline controller

The linear model at 14 m/s has been used when designing a baseline controller. The Bode plot for the three control loops can be found in figure 2 (only one flap loop is shown but the other one is very similar).



(a) (b)

Figure 2: *Bode plots for the SISO loops at 14 m/s. a) The collective to generator speed loop, b) The individual pitch to individual flap loop.*

It is possible to use classical loop-shaping techniques on each loop. The collective pitch-generator speed loop uses a PI regulator and two notch filters with zeros at the poles of the high-frequency resonances. The same PI controller without the notch filters results in more vibrations in the drive train. The bandwidth of this loop is about 1 rad/s. A PID controller for the individual pitch-individual flap loops has been used resulting in a bandwidth of 10 rad/s.

The base line controller behaves well at wind speeds close to its design wind speed but behaves very badly at high wind speeds.

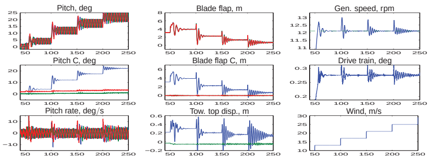


Figure 3: *The base line controller simulated in a wind field with steps in the uniform wind speed and with a vertical power law wind shear of 0.3. Note the large oscillating behavior at high wind speeds in all output signals.*

This can be fixed to some extent by using a slower controller but that would result in slow control at low wind speed which might not be satisfactory. A gain scheduled or more advanced robust controller might work better.

A Gain scheduled controller

A simple gain scheduling approach to nonlinearities is to design a continuous set of linear controllers, $K_\alpha(s)$, that is parametrized by a scheduling variables α. A scheduling variable is a variable that can be measured or calculated from measured signals that determine which operation point the system works at or works close to. The controller output is then calculated by first calculating the scheduling variable, α, and then using the controller $K_\alpha(s)$ to calculate the output.

This has been done for the wind turbine by using the collective pitch as scheduling variable and scheduling the gain of the baseline controller designed above. The controller used is thus

$$\beta_c^t = k(\beta_c^{t-1})K(s)y \tag{2}$$

where $K(s)$ is the baseline controller. The scheduling is only performed for the collective speed to generator speed loop. The function $k(\beta_c)$ is determined by first choosing new cross over frequencies for several wind speeds between 12.1 m/s and 26 m/s, followed by determining a new controller gain for each wind speed that achieves the chosen cross over frequency, and the last step is to fit a polynomial to the data points to get a continuous function. The new cross over frequencies are chosen to be lower than the cross over frequency for the base line controller below 14 m/s and the same as for the base line controller above 14 m/s. The reason for this is that the problem with the base line controller is due to a high system gain at high wind speeds and that the phase of the model is quite low at low wind speeds.

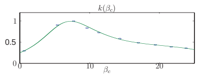
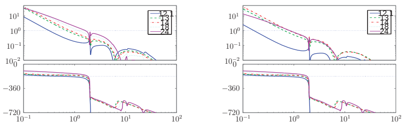


Figure 4: *The controller gain as a function of collective pitch. The circles show the gain for the operating points used in the calculation.*



(a) Base line (b) GS

Figure 5: *The loop transfer function from collective speed to generator speed when the baseline controller respectively the gain scheduling controller is used for the models at 12.1, 13, 14, 18 and 24m/s*

The gain scheduled based line controller works well in the whole region above rated wind speed.

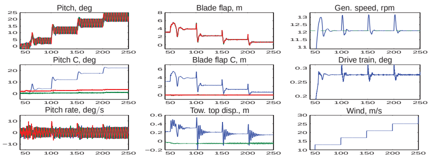
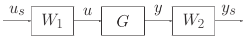


Figure 6: *The gain scheduled base line controller simulated in a wind field with steps in the uniform wind speed. Note that the behavior of the output signals do not depend much on the wind speed*

$\mathcal{H}_\infty$ loop shaping design

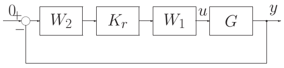
The gain scheduled diagonal controller designed above is simple to use but it might be difficult to achieve good closed-loop properties (such as high bandwidth and robustness). Another control method that has often resulted in good controllers is the $\mathcal{H}_\infty$ loop-shaping design proposed by Glover and McFarlane.

The first step is to shape the singular values of the loop transfer function $L_1 = W_2GW_1$, with the use of a pre-filter W_1 and a post-filter W_2.

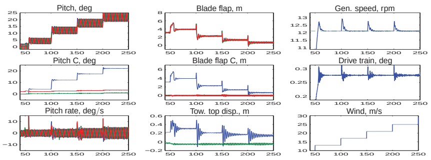


The loop transfer function L_1 is called the shaped plant. The goal of this step is to find filters W_1 and W_2 such that the shaped plant has a large magnitude where control is important, often at low frequencies, a crossover frequency that fits with the design, a roll-off-rate of about -1 around the crossover frequency to achieve stability, and enough roll-off at high frequencies to avoid problems with measurement noise and robustness.

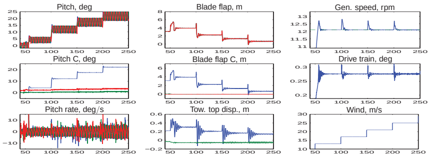
The second step is to robustly stabilize the loop transfer function L_1 by a second controller K_r. This step is completely automatic and the complete controller K is then given by $K = W_1K_rW_2$.



One possible design procedure is to design the pre-filter as a decentralized PID controller. This procedure is used in this work and the controllers that have been robustified are the baseline controller and a faster version of the baseline controller. Both controllers work well in the whole region above rated wind speed.



(a) The robust controller based on the baseline controller



(b) The robust controller based on a faster controller than the base line controller

Figure 9: *The $\mathcal{H}_\infty$ loop shaping controllers imulated in a wind field with steps in the uniform wind speed. Note that the behavior of the output signals do not depend much on the wind speed*

Conclusion

Two different individual pitch controllers that take into account the different behavior of a wind turbine at different wind speeds have been designed. The first one is a gain scheduled diagonal controller and the second one is a robust controller based on the $\mathcal{H}_\infty$ loop shaping design method. Both controllers work well in the whole region above rated wind speed. The gain scheduled controller is relatively easy to design, has a low order and the individual control loops are easy to understand. One possible drawback is that it is non linear. The $\mathcal{H}_\infty$ loop shaping controller is easy to design but it gives a controller of a large order where the individual loops is difficult to understand.

D Operation & maintenance

Distributed, hierarchical sensor network enabling park wide control of O&M on demand, Matthijs Leeuw, TNO

Occupational safety management in the offshore wind industry – status and challenges, Eirik Albrechtsen, SINTEF

Monitoring Offshore Wind Energy Use in Europe – Offshore WMEP,
Stefan Faulstich, Fraunhofer IWES

On the development of Condition based Maintenance Strategy for Offshore Wind Farm: Requirement Elicitation Phase, Idriss El-Thalji, VTT

Hywind: Two years in operation, what have we learnt and where are we going?
Sverre Trollnes, Statoil

Distributed, hierarchical sensor network enabling park wide control of O&M on demand:
a strategic research agenda

Picture: © Vattenfall, Horns Rev 1 owned by Vattenfall. Photographer Christian

Deepwind 2012

January 20th, 2012

Trondheim, Norway

,,

Matthijs W. Leeuw

Operation and Maintenance of Offshore Wind Parks (OMO)

Fraunhofer LBF	**Thilo Bein, project leader** **Andreas Friedmann** **Dirk Mayer**
Fraunhofer IWES	**Holger Huhn** **Hanno Schnars**
TNO	**Tom Basten** **Matthijs Leeuw** **Zoltan Papp**
VTT	**Erkki Jantunen** **Esa Peltola** **Idriss El-Thalji**
SINTEF	**Jorn Heggset** **Amund Skavhaug**

ERA NET - AERTOs

Nature

- ERA NET project: **A**ssociated **E**uropean **R**esearch and **T**echnology **O**rganisations
- Partners: European RTOs
- Duration: April 2008 - March 2012

Objectives

- Construction of a new, integrated pan-European RTO infrastructure
- Intended result is the alignments of the European Research Area by increasing coordination between national research programmes of a horizontal nature

Activities

- Systematically compare the activity profiles of the participating RTOs
- Identify those activities of common interest (full or variable geometry) which promise added value from greater cooperation
- **Implement first joint activities**
- Identify and develop joint governance mechanisms and structures

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Motivation for OMO

Contradicting/competing goals

- Maximize energy production
- Maximize availability
- Maximize lifetime
- Minimize maintenance

Complexity

- Individual wind turbine ➔ wind turbine park
- Onshore ➔ offshore installations

Unifying measure of success

- **Costs, costs, costs…**

Technology helps!

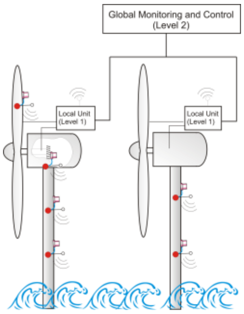
OMO's Vision

Utilization of **hierarchical, smart sensor and control networks** to reduce the overall life-cycle costs of off-shore wind farms

- **Level 1:** sensor network in single wind energy plant
- **Level 2:** Plant to plant interaction between the local sensor networks in the wind farm

Outside the scope of the project

- **Level 3:** Farm to farm interaction to optimize grid performance



OMO's Objectives

Objective

Definition of a **strategic research agenda (SRA)** for the development of a distributed, hierarchical sensor network

- for the control of the wind park operation
- for enabling (remote) maintenance-on-demand of offshore wind parks
- and to enable Predictive Health Monitoring (PHM) and Condition Based Maintenance (CBM) strategies

Approach

- Review of the state of the art (presented at the 1st OMO Workshop in 2010)
- Get views from the end users
- Identification of future research needs and gaps and definition of a joint research agenda
- Studies on representative problems

Topics considered within OMO

Level 1: Distributed sensor network in single wind energy plants

- Wireless communication
- Sensor / electronics development and sensor integration
- Smart structures for load control / fluid-structure interaction

- Load and condition monitoring
- Predictive health models
- Control and optimization concepts

Level 2: Plant to Plant interaction between local sensor networks

- Wireless communication

- Distributed monitoring and control architectures
- Distributed optimization and decision making

End-User's Point of View – Extract from the 1st OMO Workshop

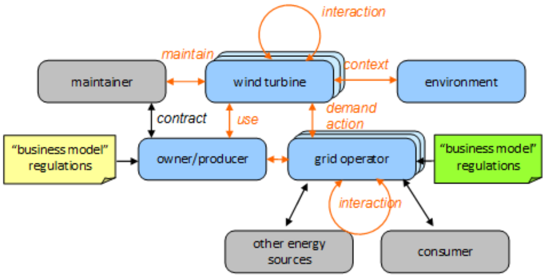
- Although only one maintenance visit per year is planned, seven or more unplanned maintenance visits per year are quite common
  - offshore wind turbines are typically not accessible by boat about 150 days/year and by helicopter about 20 days/year
  - a team of at least three mechanics is needed per visit
  - large spare parts require a vessel

- Monitoring systems are already used e.g. in the drive train or the rotor blades
  - about 150 sensors are currently applied
  - detection of large damages at the rotor blade, of unbalanced masses, of icing or lightning strikes
  - the applied systems are too complex with too much redundancy
  - only about 2% of the registered failures requires maintenance
  - a typical failure is loss of electrical contact

Research trajectories & milestones

Trajectory 1: Optimisation of control & operation	
2015	optimisation & control using advanced technologies on single wind turbine
2020	interaction between single wind turbines within wind parks (only operation)
2025	joint optimisation of operation & maintenance
Trajectory 2: Optimisation of maintenance	
2015	high quality data on wind turbines with respect to maintenance & failures (automatic collection)
2020	condition-based maintenance is the main strategy in wind turbine maintenance
2025	PHM is used in new wind parks
Trajectory 3: Integral approach	
2020	advanced monitoring (incl. remote inspection) on new installed wind turbines demonstrated
2025	new wind parks designed with park-wide control & PHM
2030	park-wide control & PHM fully implemented in all wind parks

Optimisation & Control: Challenges



Optimisation & Control: Challenges

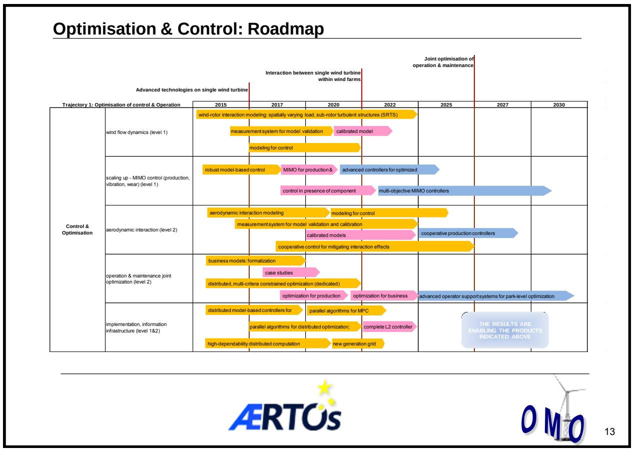
- Scaling up – turbine level
  - Non-uniform wind load
  - Sub-rotor size turbulence
  - Novel designs (structures, blades, turbines, inverters, etc.)

- Scaling up – wind parks
  - Aero-dynamical interactions among turbines
  - Wind flow dynamics

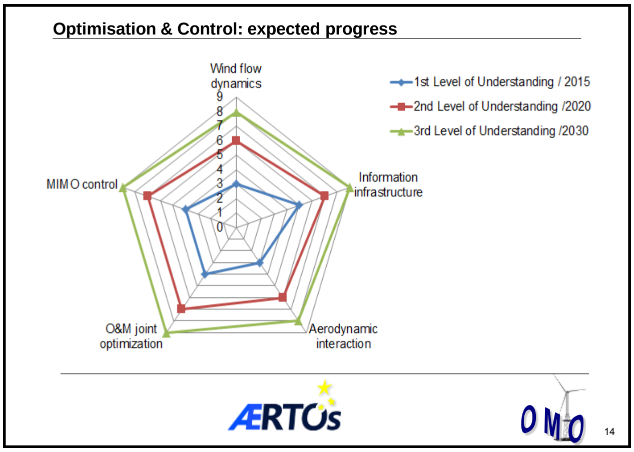
- Competitiveness, costs
  - Production uncertainties
  - Maintenance

Optimisation & Control: research needs

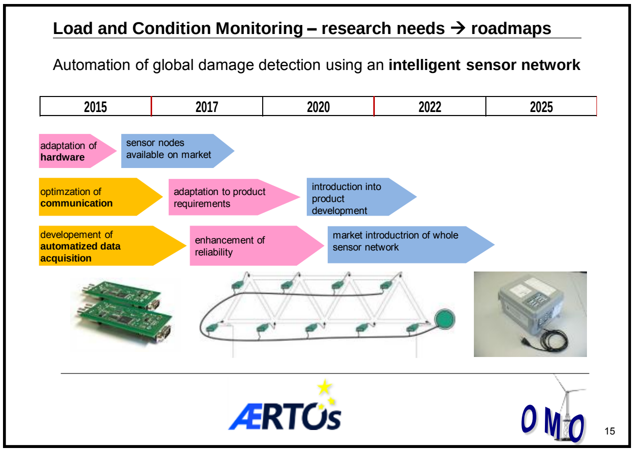
- Wind flow dynamics
  - Validated models for sub-rotor turbulent structures
  - Modeling for control
- Aerodynamic interaction
  - Validated interaction models, models for control
  - Cooperative control
- MIMO control (production, vibration, wear)
  - Robust model-based design
  - Multi-objective optimization
- Operation & maintenance joint optimization
  - Input from PHM!
  - Business model formalization
- Implementation, information infrastructure
  - Distributed/parallel algorithms, inherently fault tolerant algorithms



Optimisation & Control: Roadmap

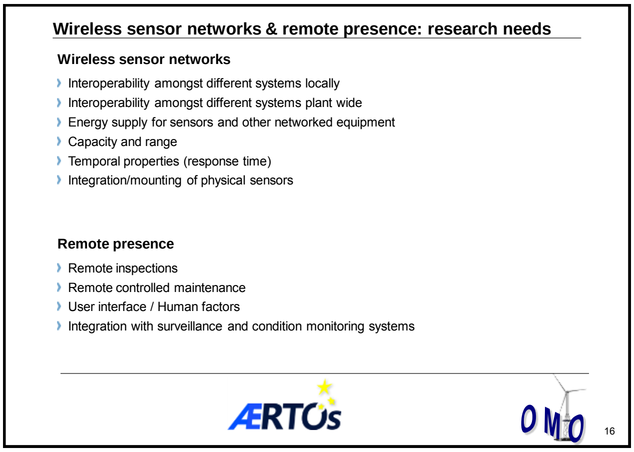


Optimisation & Control: expected progress



Load and Condition Monitoring – research needs → roadmaps

Automation of global damage detection using an **intelligent sensor network**



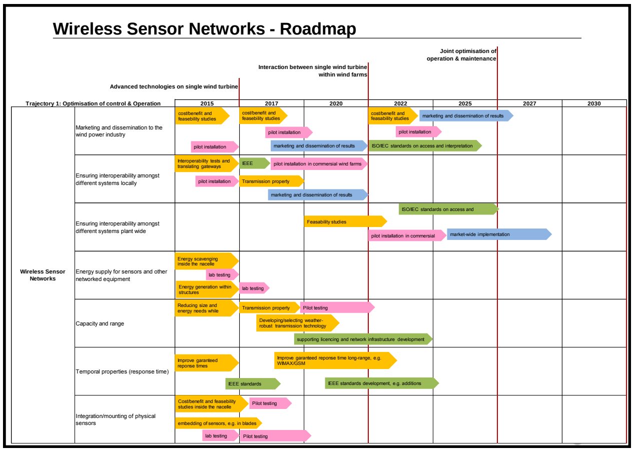
Wireless sensor networks & remote presence: research needs

Wireless sensor networks

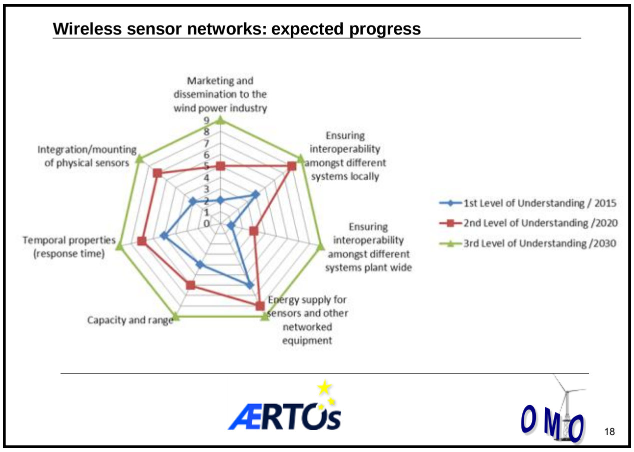
- Interoperability amongst different systems locally
- Interoperability amongst different systems plant wide
- Energy supply for sensors and other networked equipment
- Capacity and range
- Temporal properties (response time)
- Integration/mounting of physical sensors

Remote presence

- Remote inspections
- Remote controlled maintenance
- User interface / Human factors
- Integration with surveillance and condition monitoring systems

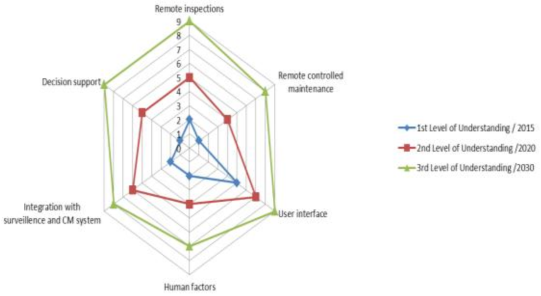


Wireless Sensor Networks - Roadmap



Wireless sensor networks: expected progress

Remote presence: expected progress

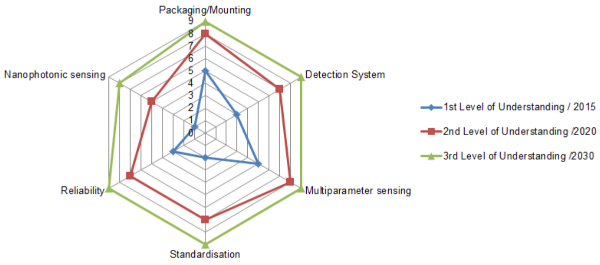


Sensor technologies: research demands

fibre optic sensor are one of the most promising sensor technologies for application in maintenance and control

- Packaging/mounting
  - Sensor should be part of system,
  - Embedding of optical fiber is crucial
- Detection system
  - Currently far too expensive, heavy/big, not always applicable for high sampling rates, high number of sensors.
  - Detection system needs attention
- Multi parameter sensing
- Standardisation
- Reliability
  - Self calibration/self assessment increase confidence
  - Repair strategies have to be developed
  - Reliable temperature compensation has to be available
- Nanophotonic sensing

Sensor technologies: expected progress



Impact of OMO technologies by 2030 compared to 2010

	Objectives	Measures / Indicators
Power generation	cost of energy production: - 40% power generation: +30%	availability >> 2010
		operational hours: + 20%
		park wide efficiency: +20%
Life-Cycle-Costs	life-cycle-costs: - 30%	life-time: + 50%
		# of spare parts: - 50%
Maintenance Costs	maintenance costs: - 70%	maintenance interval: < 1/year
		failures and false positive << 2010
		zero overloading
		prediction of failures / prognosis of wear
Lightweight Design	weight: - 20%	improved design
		operational loads: - 10%

Conclusion

- The presented SRA provides research gaps and needs harmonised between independent research providers
- New concepts are needed for wind parks and wind turbine operations for minimum energy cost over the life time while maintaining predefined level of availability, reliability and safety.
- Optimized maintenance strategies rely on Predictive Health Monitoring (PHM) and Condition Based Maintenance (CBM)
- Distributed sensor networks will play a critical role providing real-time information on operational conditions and the structural integrity of the asset.
- In 2030, offshore wind parks will possess a very high level of control authority on park level being controlled in any desired way such as
  - to highest efficiency,
  - to minimal costs,
  - longest life time,
  - needs of the electricity grid
- Research and development is needed in areas such as
  - control and optimisation,
  - predictive health monitoring,
  - load and condition monitoring,
  - wireless communication,
  - sensor technologies (particular fibre optic sensors) and
  - smart structures including self healing.


Thank you very much for your attention!

DeepWind, 19-20 January 2012

Occupational safety management in the offshore wind industry – status and challenges

Eirik Albrechtsen
SINTEF Technology and Society, dep of Safety Research, Trondheim, Norway

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Objectives and approach

- Purpose:
  - Show an overview of unwanted occupational incidents in the industry
  - Discuss status of safety management requirements to ensure that accidents, hazards and vulnerabilities are either avoided or dealt with
  - Identify some topics for further research.
- Approach:
  - Review of current research literature and mass media articles
  - Presentations at the European Offshore Wind Health and Safety Conference 2011 and a session on health and safety at the EWEA offshore 2011 conference.
- Delimited to studying occupational safety, i.e. personal accident prevention

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WELT ONLINE

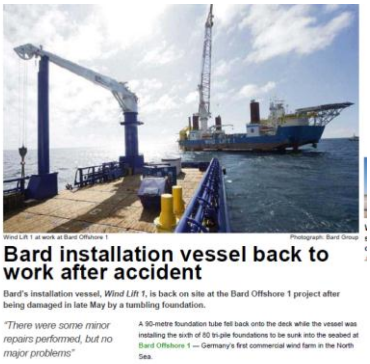
NORDSEE 27.11.2009 0

Schwerer Unfall in Offshore-Windpark

Ein Arbeiter in einer Offshore-Windpark-Anlage mitten im Meer bei Borkum hat sich bei einem Sturz schwerste Verletzungen zugezogen. Ein Schiff der Seenotretter konnte ihn wegen zu hoher Wellen nicht bergen. Ein Marine-Hubschrauber half.

Alpha Ventus, 2010:

A worker was working at a height of 15 metres when a fuse box fell onto him, leading to an occupational accident. Due to high waves (up to 3 metres) it was not possible to rescue him by boat. A naval helicopter rescued the man by dropping a wire from 50 metres, in what was characterised as "a spectacular manoeuvre".



Wind Lift 1 at work at Bard Offshore 1 Photograph: Bard Group

Bard installation vessel back to work after accident

Bard's installation vessel, *Wind Lift 1*, is back on site at the Bard Offshore 1 project after being damaged in late May by a tumbling foundation.

"There were some minor repairs performed, but no major problems"

A 90-metre foundation tube fell back onto the deck while the vessel was installing the sixth of 80 tri-pile foundations to be sunk into the seabed at Bard Offshore 1 — Germany's first commercial wind farm in the North Sea.

RECHARGE, 2010

Harwich and Manningtree Standard

Harwich: Tragedy at wind farm site

9:56am Friday 13th November 2009

By Andrea Collitt

A MAN has died and a woman has been injured after an accident on a vessel at a partly-constructed wind farm, 18 miles off Harwich.

It is thought the man was killed when a chain parted and he was struck on the vessel yesterday lunchtime.

Last night an investigation was under way as the vessel, a tug boat, was moored at Parkeston Quay.

Nishan Wijeratne, police spokesman said: "Essex Police is liasing with its Dutch counterparts following an incident in the North Sea in which a man was killed.

"Officers were called shortly after 12.30pm following reports a man had died and a woman was injured following the incident, at the Gabbard Wind farm, approximately 18 miles off the Essex coast.

"A Filipino and Dutch crew were on board a Dutch-registered vessel.

"Essex Police is currently carrying out enquiries into the circumstances surrounding the incident."

Keith Churchman, Harwich RNLI spokesman, said the people were onboard the tug vessel, Tycoon.

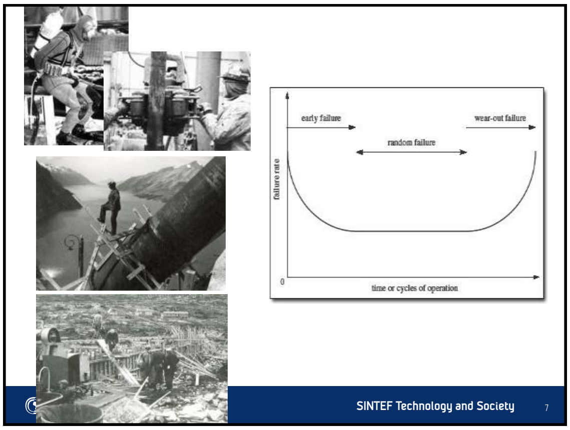
"It is believed a chain parted and that's what caused the fatality," he said.

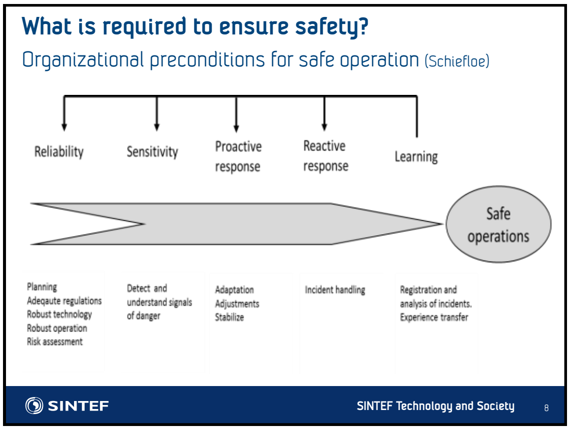
He said the woman had sustained a minor cut to her head and was treated by the vessel's onboard paramedic.

A spokesperson for Scottish and Southern Energy, which is project managing the construction of the windfarm, said: "Greater Gabbard Offshore Winds Limited (GGOWL) confirms there has been an incident on board a vessel in the North Sea operated by a sub-contractor working on the Greater Gabbard offshore wind farm."

Accidents in the offshore wind industry (Tveiten et al., 2011)

- The most frequent types of events seem to be:
  - related to lifting operations and falling objects during the installation of offshore wind farms, including two fatal accidents in the UK.
  - related to operation of jack-up construction vessels. It is reported 14 accidents in the period 1999-2008.
  - related to working in height
  - related to falling or moving objects
- Includes some fatal injuries
- Includes several severe near accidents
- Based on overviews of mass media articles
  - amount of information is limited
  - dark figures must be assumed
- These accidents have not happened on deep water





What is required to ensure safety?

Organizational preconditions for safe operation (Schiefloe)

Reliability

Sensitivity

Proactive response

Reactive response

Learning

Safe operations

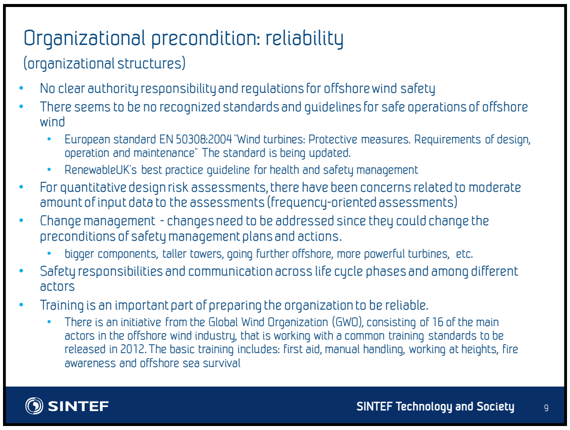
Planning
Adeqaute regulations
Robust technology
Robust operation
Risk assessment

Detect and understand signals of danger

Adaptation
Adjustments
Stabilize

Incident handling

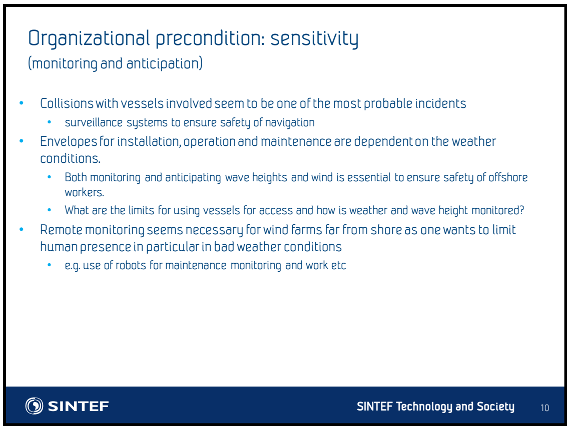
Registration and analysis of incidents.
Experience transfer



Organizational precondition: reliability

(organizational structures)

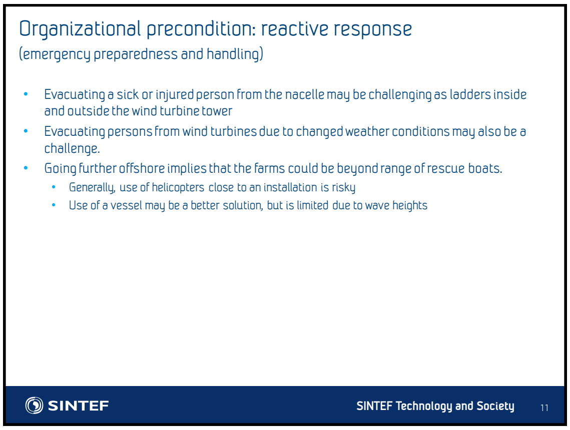
- No clear authority responsibility and regulations for offshore wind safety
- There seems to be no recognized standards and guidelines for safe operations of offshore wind
  - European standard EN 50308:2004 "Wind turbines: Protective measures. Requirements of design, operation and maintenance" The standard is being updated.
  - RenewableUK's best practice guideline for health and safety management
- For quantitative design risk assessments, there have been concerns related to moderate amount of input data to the assessments (frequency-oriented assessments)
- Change management - changes need to be addressed since they could change the preconditions of safety management plans and actions.
  - bigger components, taller towers, going further offshore, more powerful turbines, etc.
- Safety responsibilities and communication across life cycle phases and among different actors
- Training is an important part of preparing the organization to be reliable.
  - There is an initiative from the Global Wind Organization (GWO), consisting of 16 of the main actors in the offshore wind industry, that is working with a common training standards to be released in 2012. The basic training includes: first aid, manual handling, working at heights, fire awareness and offshore sea survival



Organizational precondition: sensitivity

(monitoring and anticipation)

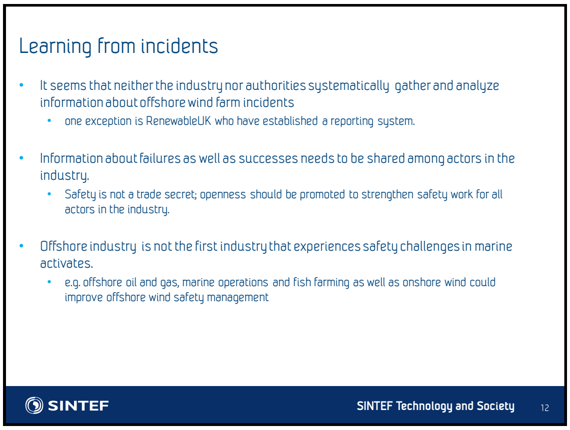
- Collisions with vessels involved seem to be one of the most probable incidents
  - surveillance systems to ensure safety of navigation
- Envelopes for installation, operation and maintenance are dependent on the weather conditions.
  - Both monitoring and anticipating wave heights and wind is essential to ensure safety of offshore workers.
  - What are the limits for using vessels for access and how is weather and wave height monitored?
- Remote monitoring seems necessary for wind farms far from shore as one wants to limit human presence in particular in bad weather conditions
  - e.g. use of robots for maintenance monitoring and work etc



Organizational precondition: reactive response

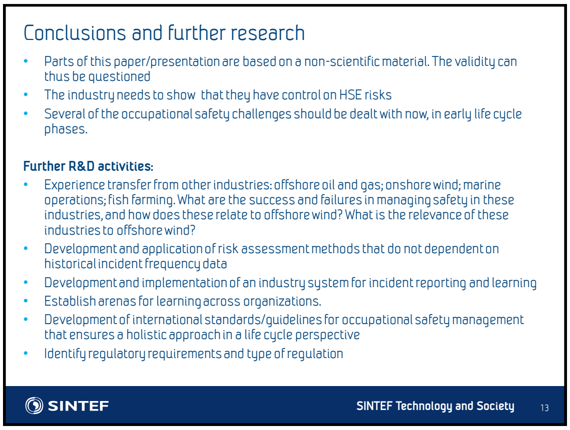
(emergency preparedness and handling)

- Evacuating a sick or injured person from the nacelle may be challenging as ladders inside and outside the wind turbine tower
- Evacuating persons from wind turbines due to changed weather conditions may also be a challenge.
- Going further offshore implies that the farms could be beyond range of rescue boats.
  - Generally, use of helicopters close to an installation is risky
  - Use of a vessel may be a better solution, but is limited due to wave heights



Learning from incidents

- It seems that neither the industry nor authorities systematically gather and analyze information about offshore wind farm incidents
  - one exception is RenewableUK who have established a reporting system.
- Information about failures as well as successes needs to be shared among actors in the industry.
  - Safety is not a trade secret; openness should be promoted to strengthen safety work for all actors in the industry.
- Offshore industry is not the first industry that experiences safety challenges in marine activates.
  - e.g. offshore oil and gas, marine operations and fish farming as well as onshore wind could improve offshore wind safety management



Conclusions and further research

- Parts of this paper/presentation are based on a non-scientific material. The validity can thus be questioned
- The industry needs to show that they have control on HSE risks
- Several of the occupational safety challenges should be dealt with now, in early life cycle phases.

Further R&D activities:

- Experience transfer from other industries: offshore oil and gas; onshore wind; marine operations; fish farming. What are the success and failures in managing safety in these industries, and how does these relate to offshore wind? What is the relevance of these industries to offshore wind?
- Development and application of risk assessment methods that do not dependent on historical incident frequency data
- Development and implementation of an industry system for incident reporting and learning
- Establish arenas for learning across organizations.
- Development of international standards/guidelines for occupational safety management that ensures a holistic approach in a life cycle perspective
- Identify regulatory requirements and type of regulation

Final remark

- Workshop on safety challenges and opportunities in the offshore wind industry to be arranged by NOWITECH in March- April
- If you are interested in participating: contact eirik.albrechtsen@sintef.no

Monitoring Offshore Wind Energy Use in Europe - Offshore~WMEP

ESTABLISHING A COMMON DATABASE FOR WIND TURBINE FAILURES

Stefan Faulstich, Paul Kühn, Sebastian Pfaffel, Philipp Lyding
Fraunhofer Institute for Wind Energy and Energy System Technology (IWES)

Monitoring Offshore Wind Energy Use in Europe - Offshore~WMEP

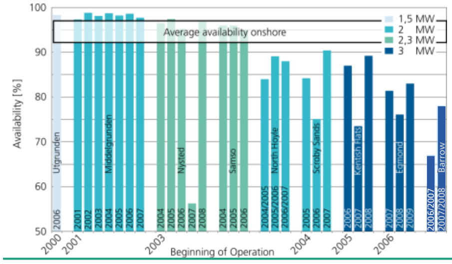
- Introduction
  - Motivation
  - WMEP
- Offshore~WMEP
  - Background
  - Different concepts
- Other activities
  - EVW-project
  - IEA-Task 33 "Reliability data"
- Conclusion & Outlook

Introduction
Motivation

Starting Point: Modern wind turbines achieve high availability

Number of faults cause unplanned downtimes ➔ high maintenance efforts and costs

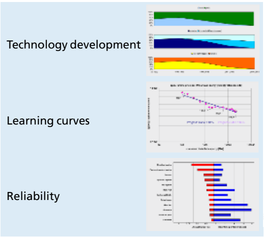
Offshore: drop of availability expected

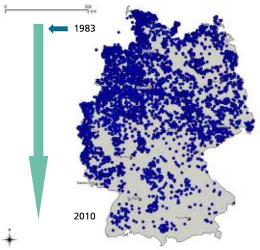


Introduction
WMEP

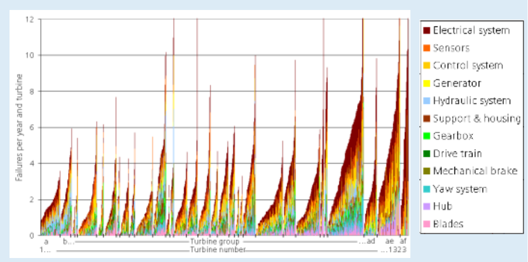
Scientific **M**easurement and **E**valuation **P**rogram („250 MW Wind" (1989-2006))

	193.000	monthly operation reports
and	64.000	Incident reports
from	1.500	wind turbines



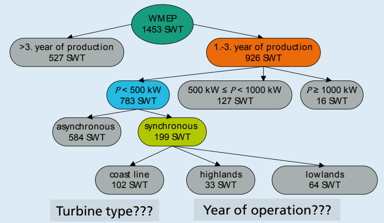


Introduction
WMEP



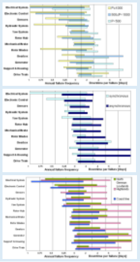
Introduction
WMEP

- For differential analysis distinctions regarding size, technical concepts, site conditions, etc. must be made

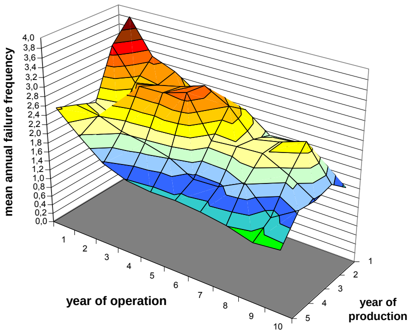


Turbine type???

Year of operation???

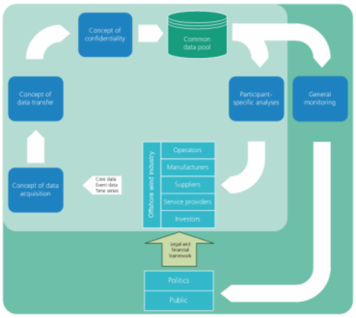


Introduction
WMEP



Offshore~WMEP
Concept

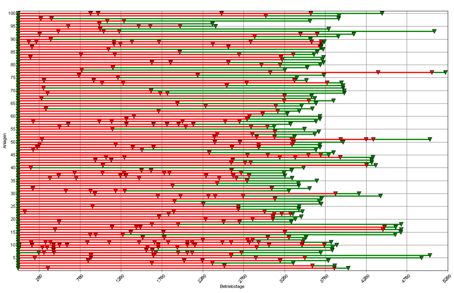
- The project is a follow-up project to the onshore wind energy monitoring program 'Scientific Measurement and Evaluation Program' (WMEP) and accompanies the offshore wind energy deployment in Germany
- Funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety



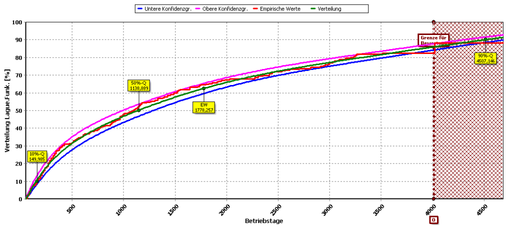
Offshore~WMEP
General monitoring

- Core issues
  - Site-specific offshore conditions
  - Installation
  - Energy output
  - Reliability
  - Availability
  - Facility concepts
  - Operation and maintenance concepts
  - Investment and operating costs

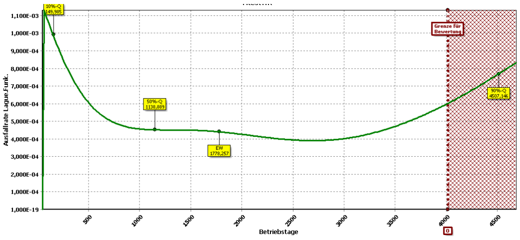
Offshore~WMEP
Participant specific analyses



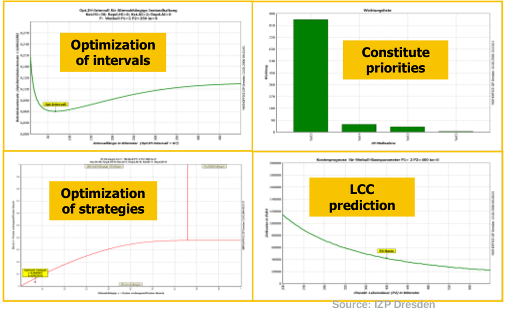
Offshore~WMEP
Participant specific analyses



Offshore~WMEP
Participant specific analyses

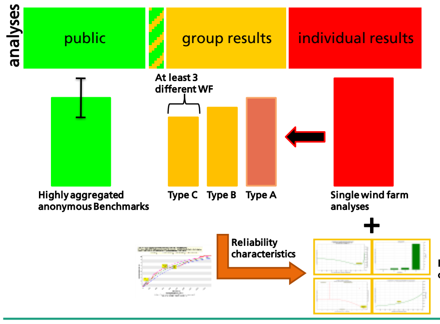


Offshore~WMEP
Participant specific analyses

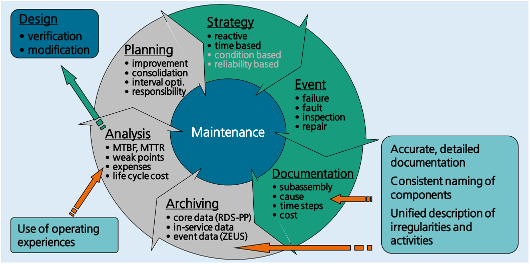


Source: IZP Dresden

Offshore~WMEP
Concept of confidentiality

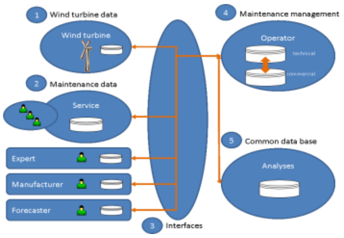


Offshore~WMEP
Concept of data acquisition



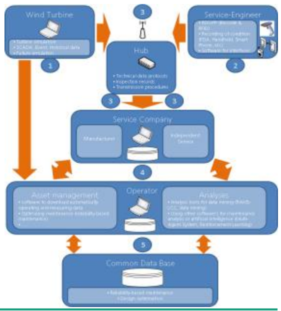
Other activities
EVW (Increasing availability of WTs)

- Funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
- Task: Knowledge management and maintenance optimization as methodical base for increasing the availability of wind power plants



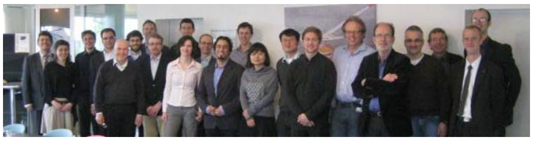
Other activities
EVW (Increasing availability of WTs)

- Developing a test and demonstration system
- Preparing recommended practices for reliability based maintenance
- Technical guidelines / standards (Federation of German Windpower)
- **Expand common database (onshore and offshore)**



Other activities
65th IEA Topical Expert Meeting TEM (IEA Wind Task 11)
International statistical analysis on wind turbine failures

- TEM in Kassel / Germany, March 2011: 23 experts from Denmark, Finland, GB, Germany, Netherlands, Norway, Sweden, USA; (16 presentations)
- It was decided to launch a new IEA Wind Task on *Databases for Wind Turbine Failures*
- Task Proposal was prepared by Fraunhofer IWES in cooperation with SINTEF, NTNU and Chalmers University of Technology



IEA Wind Task Proposal – Reliability Data
Future work and key questions

- Priorities for future work defined at the TEM:
  - Standardization of the structure databases (DB)
  - Definition of subassemblies and failures
  - Level of detail of the DB
  - Confidentiality and access to the DB
  - Harmonization of data analysis
- Key questions:
  - Which data are to be collected?
  - What data are needed for the different analyses?
  - How to implement a system to collect information in an appropriate, structured, detailed and strongly automated way?

IEA Wind Task Proposal – Reliability Data
Objectives

The objectives of the proposed IEA Task are threefold:

1. Provide an international, open platform for regular and continuous exchange of experience and progress from individual research projects and existing activities on failure statistics on wind turbines.
2. Development of *Recommended Practices for Reliability Data* during the course of the Task.
3. Identify areas for further research and development as well as standardization needs.

Conclusions & Outlook

- Potential for availability improvement and for reducing maintenance effort exists
- Common database needed due to parameter diversity
- Different concepts are necessary
  - Overall data structure
  - Standards and definitions
  - Accessibility of information
- Harmonization will take place in the new IEA-Task
- Offshore~WMEP is going from concept phase to the first implementation phase → database will be filled

alpha ventus picture library DOTI 2009/Matthias Ibeler

Fraunhofer IWES

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Stefan.faulstich@iwes.fraunhofer.de

Reliability & Maintenance strategies
R&D Division Energy Economy and Grid Operation

Fraunhofer Institute for Wind Energy and
Energy System Technology IWES
Königstor 59, 34119 Kassel

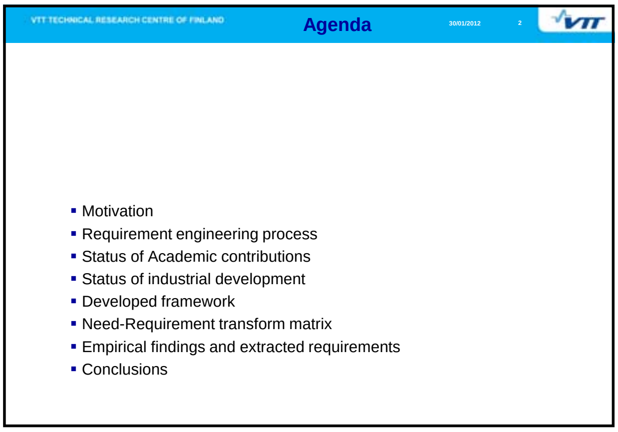
Business from technology

On Development of Condition Based Maintenance Strategy for Offshore Wind Farm:
Requirement Elicitation Process

Idriss El-Thalji and Erkki Jantunen

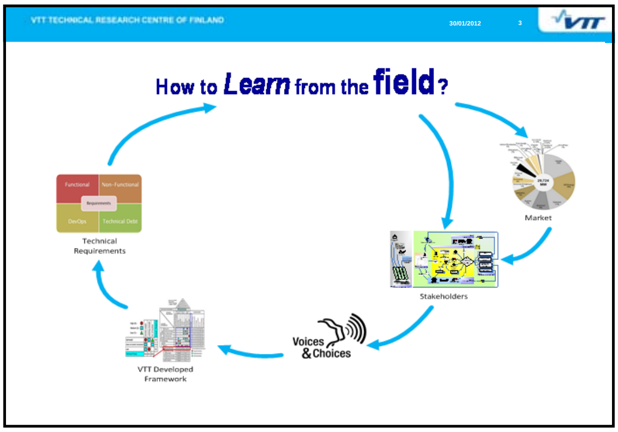
Industrial Systems,
VTT Technical Research Centre of Finland,

AERTOs Project and VTT-GS

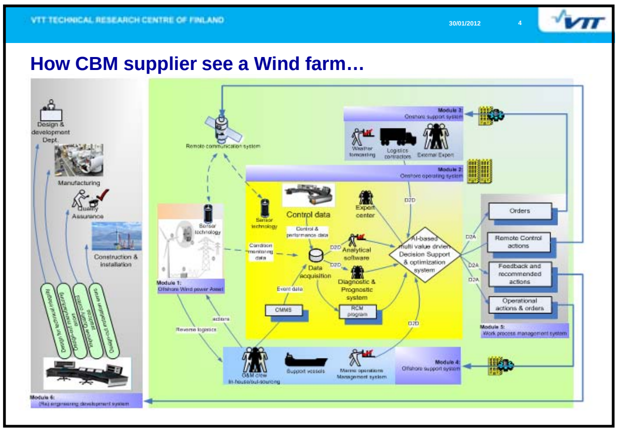


Agenda

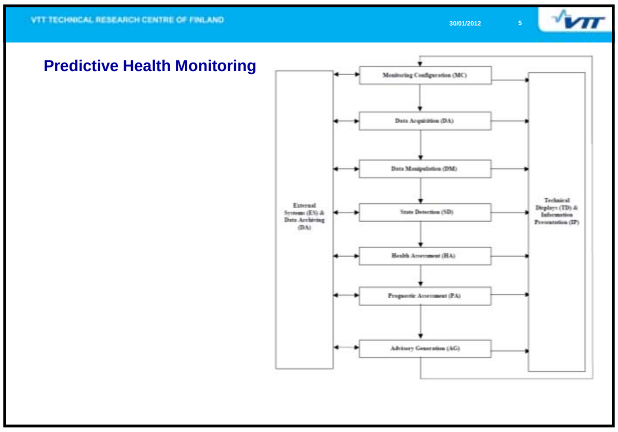
- Motivation
- Requirement engineering process
- Status of Academic contributions
- Status of industrial development
- Developed framework
- Need-Requirement transform matrix
- Empirical findings and extracted requirements
- Conclusions



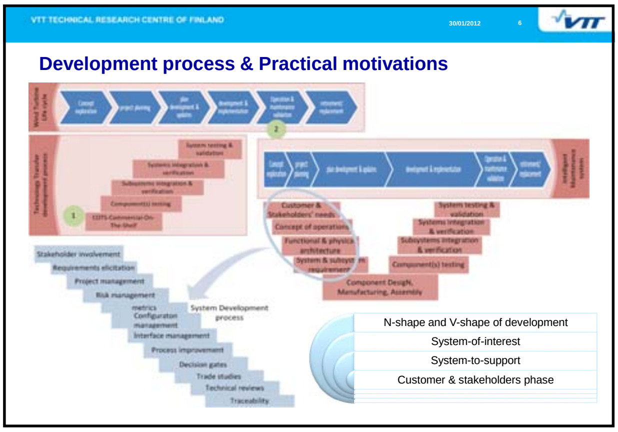
How to *Learn* from the **field**?



How CBM supplier see a Wind farm…

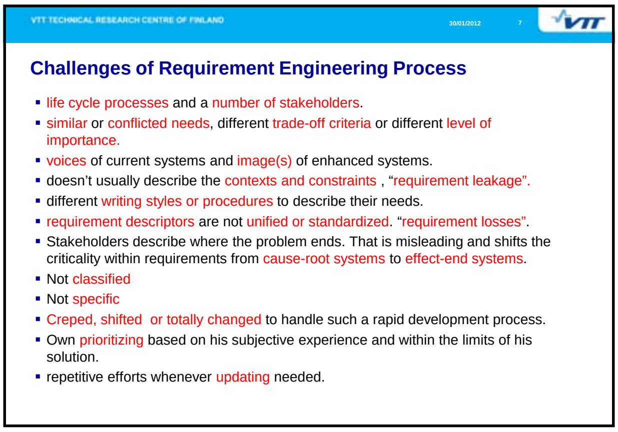


Predictive Health Monitoring



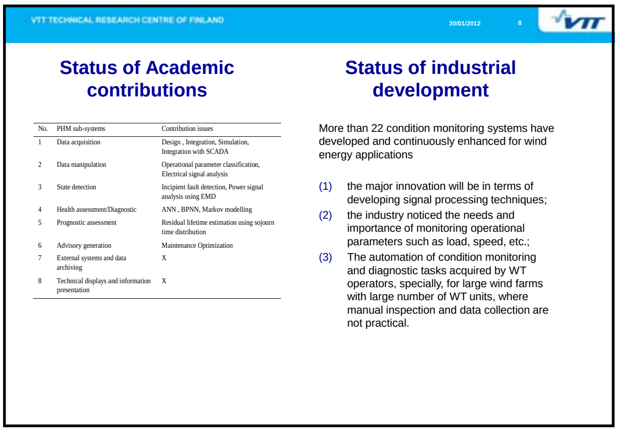
Development process & Practical motivations

N-shape and V-shape of development
System-of-interest
System-to-support
Customer & stakeholders phase



Challenges of Requirement Engineering Process

- life cycle processes and a number of stakeholders.
- similar or conflicted needs, different trade-off criteria or different level of importance.
- voices of current systems and image(s) of enhanced systems.
- doesn't usually describe the contexts and constraints , "requirement leakage".
- different writing styles or procedures to describe their needs.
- requirement descriptors are not unified or standardized. "requirement losses".
- Stakeholders describe where the problem ends. That is misleading and shifts the criticality within requirements from cause-root systems to effect-end systems.
- Not classified
- Not specific
- Creped, shifted or totally changed to handle such a rapid development process.
- Own prioritizing based on his subjective experience and within the limits of his solution.
- repetitive efforts whenever updating needed.



Status of Academic contributions

No.	PHM sub-systems	Contribution issues
1	Data acquisition	Design , Integration, Simulation, Integration with SCADA
2	Data manipulation	Operational parameter classification, Electrical signal analysis
3	State detection	Incipient fault detection, Power signal analysis using EMD
4	Health assessment/Diagnostic	ANN , BPNN, Markov modelling
5	Prognostic assessment	Residual lifetime estimation using sojourn time distribution
6	Advisory generation	Maintenance Optimization
7	External systems and data archiving	X
8	Technical displays and information presentation	X

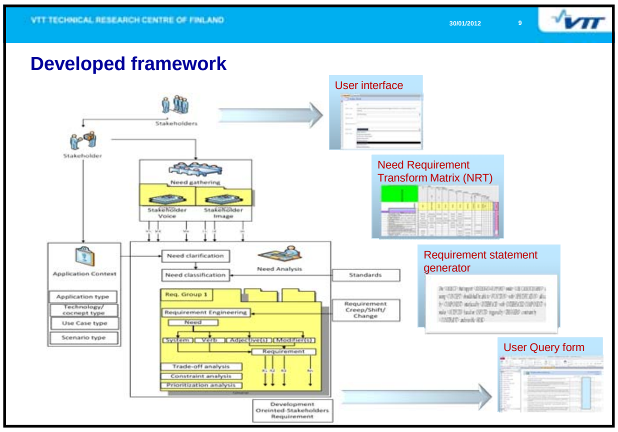
Status of industrial development

More than 22 condition monitoring systems have developed and continuously enhanced for wind energy applications

(1) the major innovation will be in terms of developing signal processing techniques;

(2) the industry noticed the needs and importance of monitoring operational parameters such as load, speed, etc.;

(3) The automation of condition monitoring and diagnostic tasks acquired by WT operators, specially, for large wind farms with large number of WT units, where manual inspection and data collection are not practical.



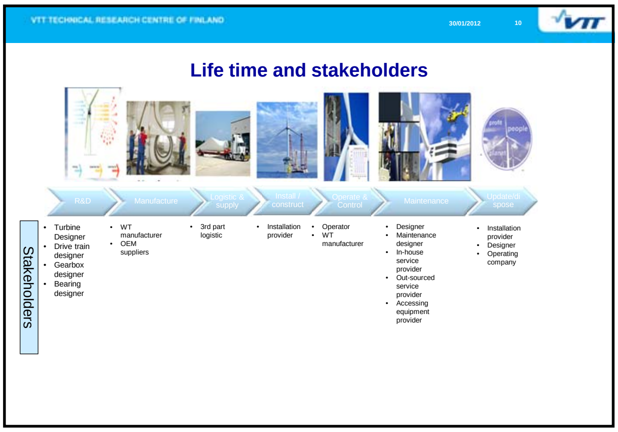
Developed framework

User interface

Need Requirement Transform Matrix (NRT)

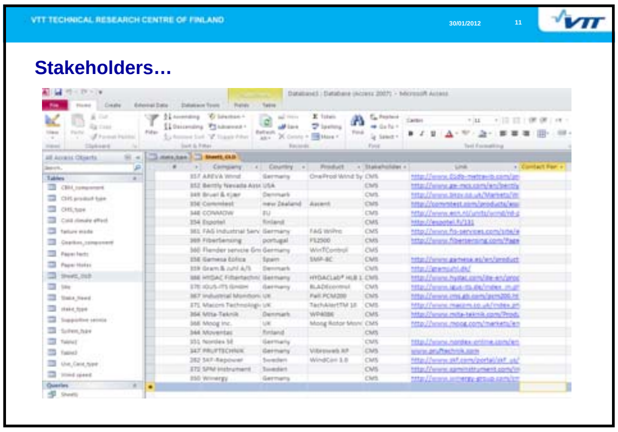
Requirement statement generator

User Query form

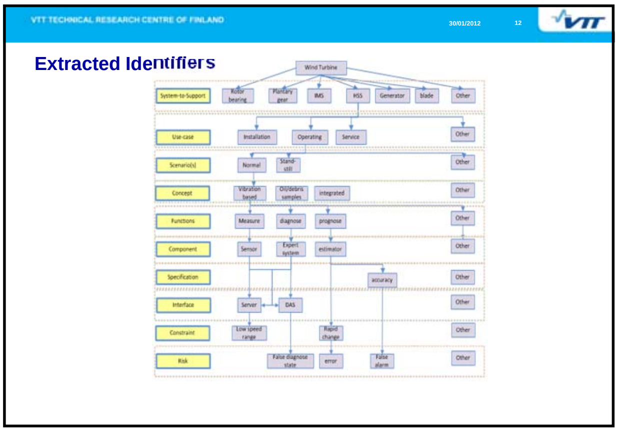


Life time and stakeholders

R&D	Manufacture	Logistic & supply	Install / construct	Operate & Control	Maintenance	Update/dispose
• Turbine Designer • Drive train designer • Gearbox designer • Bearing designer	• WT manufacturer • OEM suppliers	• 3rd part logistic	• Installation provider	• Operator • WT manufacturer	• Designer • Maintenance designer • In-house service provider • Out-sourced service provider • Accessing equipment provider	• Installation provider • Designer • Operating company

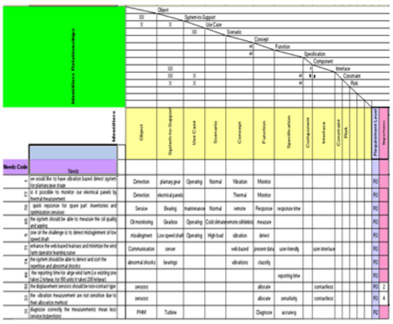


Stakeholders…



Extracted Identifiers

Need-Requirement Transform Matrix



Needs Code	Needs	Object	System-to-Support	Use Case	Scenario	Concept	Function	Specification	Component	Interface	Constraint	Risk	Requirement Level	Importance
[illegible]	we would like to have vibration based detect system for planetary gear stage	Detection	planetary gear	Operating	Normal	Vibration	Monitor						R0	
[illegible]	is it possible to monitor our electrical panels by thermal measurement	Detection	electrical panels			Thermal	Monitor						R0	
[illegible]	quick response for spare part inventories and optimization services	Service	Bearing	maintenance	Normal	remote	Response	response time					R0	
[illegible]	the system should be able to measure the oil quality and ageing	Oil monitoring	Gearbox	Operating	Cold climate	remote oil/debris	measure						R0	
[illegible]	one of the challenge is to detect misalignment of low speed shaft	misalignment	Low speed shaft	Operating	High load	vibration	detect						R0	
[illegible]	enhance the web-based features and minimize the wind farm operator learning curve	Communication	server			web-based	present data	user-friendly		user interface			R0	
[illegible]	the system should be able to detect and sort the repetitive and abnormal shocks	abnormal shocks	bearings			vibrations	classify						R0	
[illegible]	the reporting time for alrge wind farm (i.e existing one takes 2 hr/year, for 100 units it takes 200 hr/year)							reporting time					R0	
[illegible]	the displacement sensors should be non-contact type	sensors					allocate			contactless			R0	2
[illegible]	the vibration measurement are not sensitive due to their allocation method	sensors					allocate	sensitivity		contactless			R0	4
[illegible]	diagnose correctly the measurements mean less service inspections	PHM	Turbine				Diagnose	accuracy					R2	

(1) extract identifier(s)

(2) construct related requirements;

(3) classify requirements based on three levels (i.e. scope, high level and detailed level) and

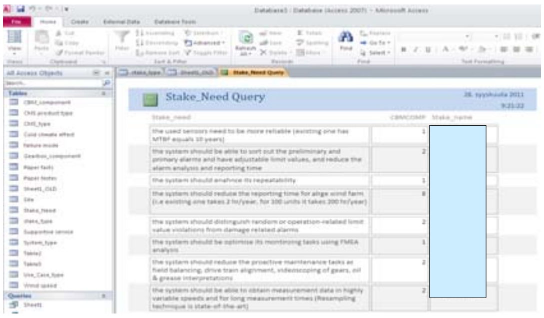
(4) assign the priority or importance of each requirement from different stakeholders' point of view.

Requirement statement generator

The generic statement is as follows:

The <OBJECT> that
support <SYSTEM-TO-SUPPORT>
under <USE CASE/SCENARIO> and
using <CONCEPT>
should/shall be able to <FUNCTION>
with <SPECIFICATION>
allocated by <COMPONENT>
interfaced by <INTERFACE>
with <INTERFACED COMPONENT>
that makes <OUTPUTS>
based on <INPUTS>
triggered by <TRIGGERS>
constraint by <CONSTRAINT> and
possible <RISK>

Some of PHM stakeholders' needs



Stake_Need Query

28. syyskuuta 2011
9:21:22

Stake_need	CBMCOMP	Stake_name
the used sensors need to be more reliable (existing one has MTBF equals 10 years)	1	[redacted]
the system should be able to sort out the preliminary and primary alarms and have adjustable limit values, and reduce the alarm analysis and reporting time	2	[redacted]
the system should enahnce its repeatability	1	[redacted]
the system should reduce the reporting time for alrge wind farm (i.e existing one takes 2 hr/year, for 100 units it takes 200 hr/year)	8	[redacted]
the system should distinguish random or operation-related limit value violations from damage related alarms	2	[redacted]
the system should be optimise its monitoring tasks using FMEA analysis	1	[redacted]
the system should reduce the proactive maintenance tasks as field balancing, drive train alignment, videoscoping of gears, oil & grease interpretations	2	[redacted]
the system should be able to obtain measurement data in highly variable speeds and for long measurement times (Resampling technique is state-of-the-art)	2	[redacted]

Empirical findings and extracted requirements

No.	PHM sub-systems	# of related requirements
1	Data acquisition	9
2	Data manipulation	8
3	State detection	27
4	Health assessment/Diagnostic	0
5	Prognostic assessment	0
6	Advisory generation	3
7	External systems and data archiving	10
8	Technical displays and information presentation	5
	Total	62

High-level requirements (PHM Concept)

- Integrated PHM for whole wind turbine, drive train, gearbox stages
- Site and seasonal disturbances and their impact on monitoring profiles
- Failure, symptoms and monitoring techniques analysis for different failure modes

Detailed requirements

- Physical system to support: rotor bearings, planetary gear, electrical panels, ring gear, LSS and HSS shafts and their bearings.
- Measurement type: temperature, lubricant temperature, rpm, load, oil age, vibrations. Detection object: wear, abnormal shocks, low rotational vibration, early damage states, imbalance, misalignment, ice.
- Sorting object: fault alarms, false alarms, damage alarms
- Data type: sampled signals, information, symptoms, and technicians' descriptors.
- Data processing: acquire, transfer, analyse, integrate, and visualize data
- Monitoring constraints: marginal conditions, pitching and rapid changes
- Data transfer: within turbine, within wind farm, with server, with service providers.
- Monitoring considerations: blade angle error, uneven rotor blade profile, blade damage, pitch error, external exciters, drive train misalignment, component scale, operational risks.
- Remote monitoring and acting: field balancing, alignment, lubrication interpretations
- Use cases and monitoring scenarios: stand still, idling, normal operating, extreme operating, braking, cut-off, etc.
- Specifications: scalability, time to response, integrity, user friendly, adaptive, remoteness, analysis performance, reporting performance, sampling intervals, allocation sensitivity, Mean time between failure, mean time to repair/replace, accuracy of detection, diagnosis, prognosis, data security.

Pros & Cons

Pros

- It grantee consider the whole life cycle stakeholders and not just one type or specific stakeholders
- It provide traceable relation between stakeholders and their needs
- It provide better requirements documentation and elicitation in order to avoid manual, incomplete, unclear and repeated data errors…
- It gives option for continuously updating the stakeholder needs

Cons

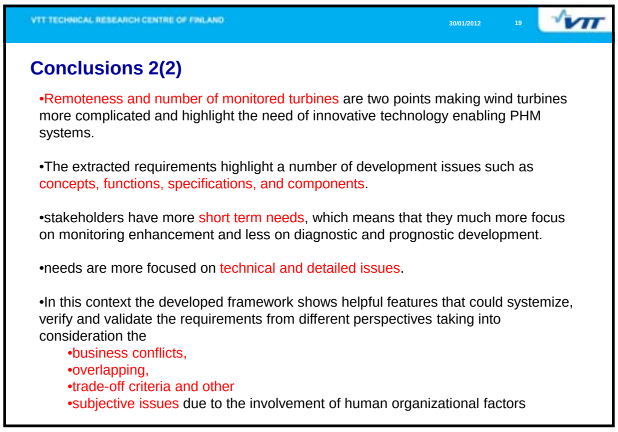
- Since wind energy quite new, thus, the stakeholder requirements will be important but not sufficient for define Strategic research demand
- Due to industrial stereotype, the industrial stakeholders have quite short strategic window
- Due to competitive market, the stakeholder will not completely provide their needs
- There are complex need conflicts, that required trade-off and balancing analysis
- Due to the rapid scaling up and development within wind energy sector, what is defined as 'need' today, it will be 'excellence' tomorrow and 'new generation' of needs will appear…

Conclusions 1(2)

- Requirement engineering process is more complicated in wind energy sector than other sectors due to a number of issues related to the
  - scale of wind turbines,
  - involvement of transfer technologies,
  - number of relevant stakeholders,
  - conflicts and trade-off criteria, responsibilities, and
  - lack of standards.
- Thus, the extracted requirements could be
  - ambiguous,
  - incomplete,
  - unverifiable,
  - inconsistent,
  - untraceable,
  - and ill-prioritized,

that tend to lead the further product development processes have more *pitfalls*.

- On basis of the state of the art study the academic contributions and research efforts are focused on shifting different techniques that have been successfully implemented in other industrial sectors as artificial intelligence.
- The expectation is to focus on an integrated monitoring system such as the stakeholders are talking about.



Conclusions 2(2)

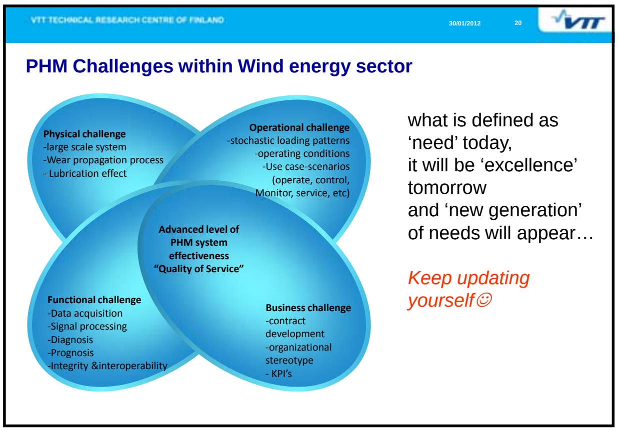
•Remoteness and number of monitored turbines are two points making wind turbines more complicated and highlight the need of innovative technology enabling PHM systems.

•The extracted requirements highlight a number of development issues such as concepts, functions, specifications, and components.

•stakeholders have more short term needs, which means that they much more focus on monitoring enhancement and less on diagnostic and prognostic development.

•needs are more focused on technical and detailed issues.

•In this context the developed framework shows helpful features that could systemize, verify and validate the requirements from different perspectives taking into consideration the
- •business conflicts,
- •overlapping,
- •trade-off criteria and other
- •subjective issues due to the involvement of human organizational factors



PHM Challenges within Wind energy sector

Physical challenge
-large scale system
-Wear propagation process
- Lubrication effect

Operational challenge
-stochastic loading patterns
-operating conditions
-Use case-scenarios
(operate, control,
Monitor, service, etc)

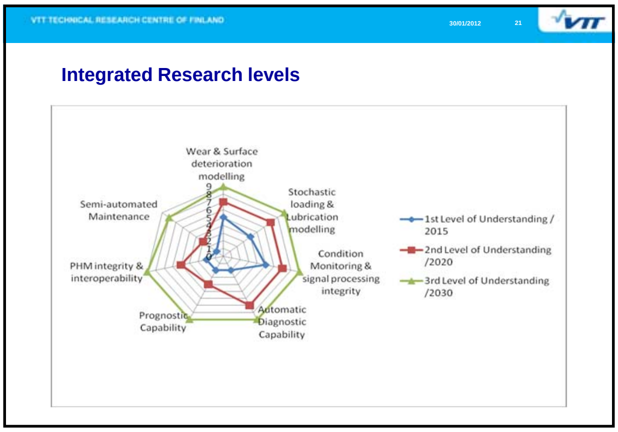
Advanced level of
PHM system
effectiveness
"Quality of Service"

Functional challenge
-Data acquisition
-Signal processing
-Diagnosis
-Prognosis
-Integrity &interoperability

Business challenge
-contract
development
-organizational
stereotype
- KPI's

what is defined as
'need' today,
it will be 'excellence'
tomorrow
and 'new generation'
of needs will appear…

Keep updating yourself☺



Integrated Research levels

AERTOs Project reports are available:

1. Offshore Wind farm Monitoring and Operation: Strategic Research Agenda
2. Predictive Health Monitoring: State-of-the-art

Hywind: Two years in operation, what have we learnt and where are we going?

Deep Sea Offshore Wind R&D Seminar
19th January 2012

The Hywind O&M Team
Morten Tufte **Thorbjørn Ulriksen**
Klaus K. Haglerød **Ørjan Haugen**
Anders Wikborg **Tom James**
Emil Orderud **Nenad Keseric**
Anne M. Hansen

Content

Offshore Wind Operation

Hywind Demo

Project opportunities

Principles for a Low Risk Operating Model

Maintenance is one of the largest controllable operating costs in capital intensive industries
Maintenance influence: Commercial risk; Production; Safety; Cost

Organisation	Contractual obligation must reflect organisational capabilities for both OEM's and Owner Both parties must recognize each others capabilities
Technology	Asset owner must take responsibility for technical integrity and increase internal knowhow of the systems
Cooperation	Force lean thinking, zero scrap and component reliability on the suppliers through new standards both in production and operation
OEM's	Work should be carried out in accordance with recognised standards with transparency at all levels Owner should have an active retrofit program

---

. . . will be used to develop a modern operating model for wind O&M

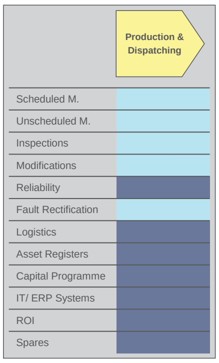
Critical Processes
Critical processes in control means good stability

Best Practice Work Processes
Controlling the value chain through best practice work processes

Performance Management
Structured measures on all levels increase performance

Organisational Development
Lean organisational structure based on principles in integrated operations

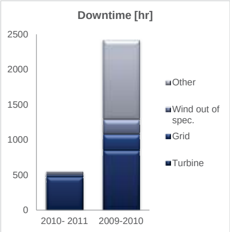
Decision Structure
Effective meeting structure for better and transparent decisions

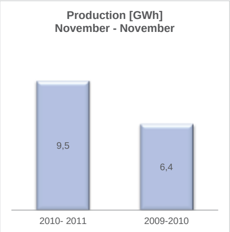


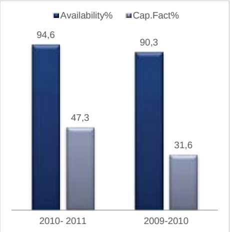
Hywind Demo - concept verified

- In operation from September 2009
- Actual movements confirmed simulation model
- Floater motions have no negative impact on turbine performance
- Capacity factor 50% in 2011
- Access and inspection confirmed to be satisfactory
- Technically verified

Hywind Performance







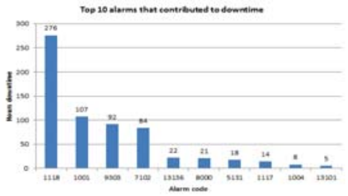
- Reduction of downtime with 1870 hr by better planning and quicker response
- Only one unscheduled stop in second operational year

- 50% production increase
- Average wind speed
  - 2nd year was 9,1 m/s, 3% below normal
  - 1st year was 12% below normal

- Overall availability 94,5 %
- Capacity factor at 47,3%
  - 4390 full load hours for 2011 (average in Norway ~2100)

Downtime

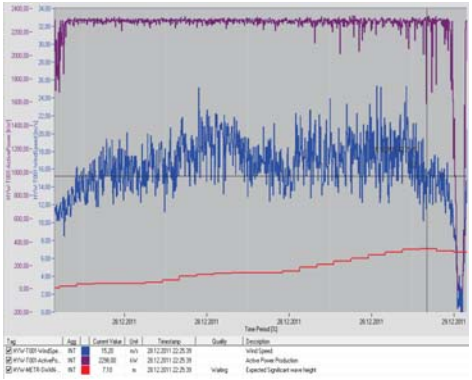
November 2010 – November 2011



Alarmcode	Alarm text	Alarm type
1118	Vibrations alarm by GS filt 4	1
1001	Manual stop	1
9303	Brakepressure too low	1
7102	Hyd oil temperature error	1
13136	Timeout DC-circuit charging	1
8000	Windspeed too high to operate	0
5131	Too many FRT activations	0
1117	Vibrations alarm by GS filt 3	1
1004	External stop	0
13101	Generator inverter tripped	1

- Vibration alarm was eliminated in Mars 2010, through effective root cause analysis
- Manuel stop is decided by owner and can be minimised by preventive maintenance
- The two other major losses left are related to increased pitching at extreme waive and wind conditions. Better cooling system will be installed to eliminate the loss.

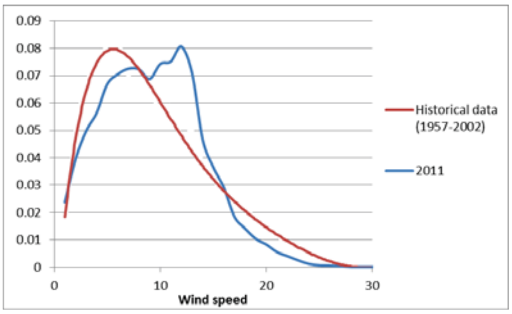
Production in heavy seas



Tag	Agg		Current Value	Unit	Timestamp	Quality	Description
☑ HYW-T001-WindSpe...	INT	🟦	15,20	m/s	28.12.2011 22:25:39		Wind Speed
☑ HYW-T001-ActivePo...	INT	🟪	2298,00	kW	28.12.2011 22:25:39		Active Power Production
☑ HYW-METR-SivMi...	INT	🟥	7,10	m	28.12.2011 22:25:39	Waleg	Expected Significant wave height

- 24 hour trendperiode during the «Dagmar» storm last Christmas.
- Avg. wind speed: 16 m/s
- Max wind speed: 28 m/s
- Avg. significant wave height: 4,7 m
- Max significant wave height:
- 7,1 m
- Power production for the periode: 96,7% of rated power.

Wind distribution. 2011 compared to histcast

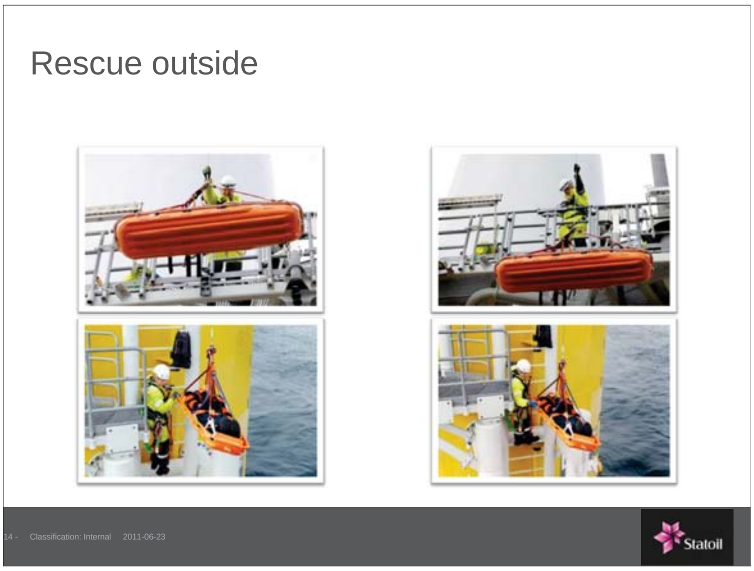


FOCUS ON HEALTH AND SAFETY (HSE)

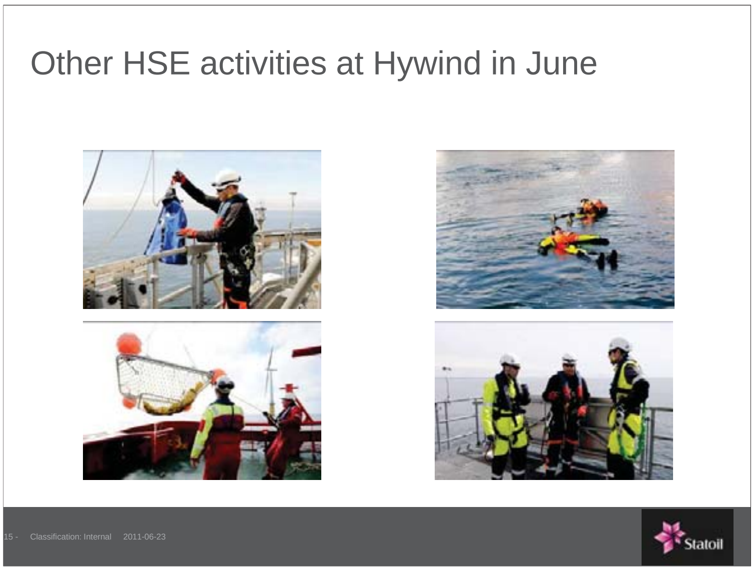
- Same HSE standard as on all Statoil installations
- Focus on:
  - Work permit system
  - Boat landing, access , egress and PPE
  - Lifting equipment
- No serious accidents
- Mitigating actions:
  - Hands-on follow-up of Statoil and Siemens equipment and procedure
  - Safety Job Analyses
  - Table top workshops - Defined situations of hazards and accidents (DSHA)
  - Safety training of personnel on-board Hywind

Rescue from hub
– use of milan and 2 metre rope

Rescue from nacelle – outside tower



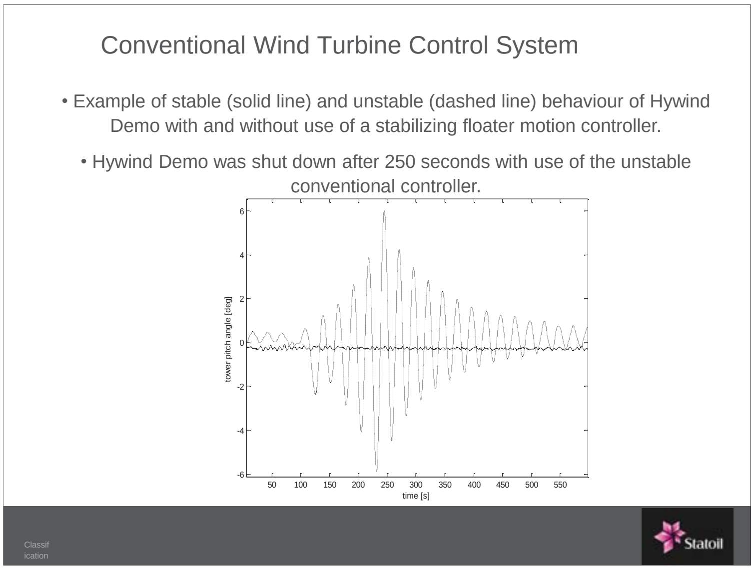
Rescue outside



Other HSE activities at Hywind in June

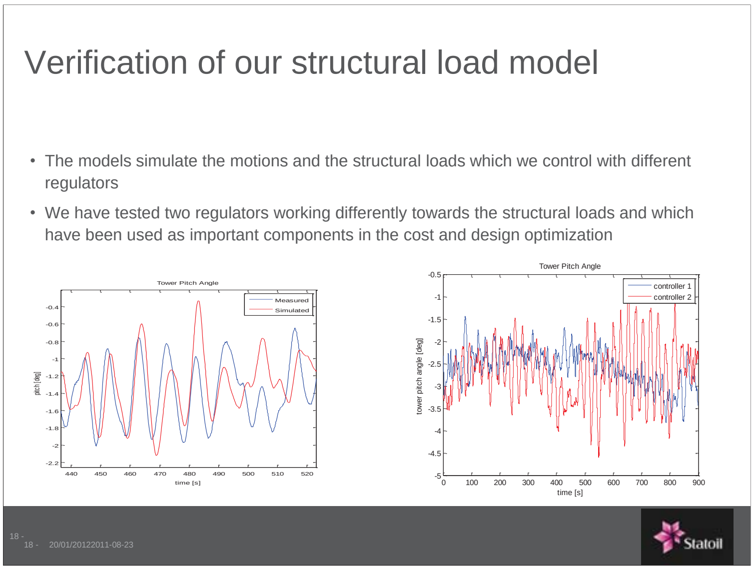
Observations and ideas - rescue from nacelle

- Inside rescue – challenges related to confined spaces and many movements of injured person
- Outside rescue – faster and easier due to less movements
- Attach Milan rescue kit to injured when possible
- Possible rescue time can be less than 1 hour for outside rescue
- Time from nacelle to boat based on speed with Milan Hub rescue is about <u>1:30min</u>
- Frequent training and exercises will reduce the rescue time
- Helicopter rescue will reduce transport time to hospital but not necessarily rescue time form nacelle
- Enable training on rescue tools, i.e. use of Milan rescue kit and fall arresters
- Develop training packages together with service provider
- Use Hywind for training purposes



Conventional Wind Turbine Control System

- Example of stable (solid line) and unstable (dashed line) behaviour of Hywind Demo with and without use of a stabilizing floater motion controller.
- Hywind Demo was shut down after 250 seconds with use of the unstable conventional controller.



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

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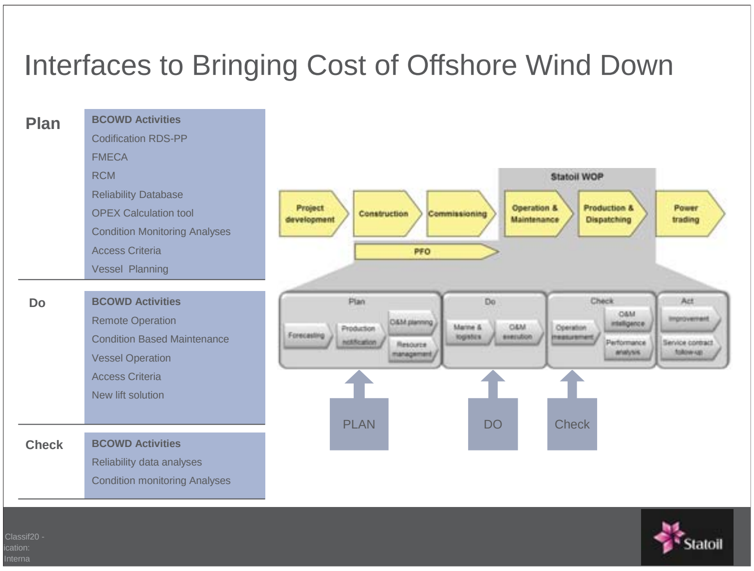
Conclusions

- It is demonstrated that a stabilizing floater motion controller is required for a floating wind turbine.
- Simulations and measurements are compared for wind speeds above rated wind speed. Good agreement is obtained in small as well as moderate sea states.
- Two different stabilizing controllers are compared by full scale testing. A significant difference in the response at resonance is observed. This difference is important to the fatigue life of the tower.
- The range of variation of typical wind turbine parameters like rotor speed, blade pitch angle and active power production are similar to what is observed for fixed foundation wind turbines.



Interfaces to Bringing Cost of Offshore Wind Down

Plan

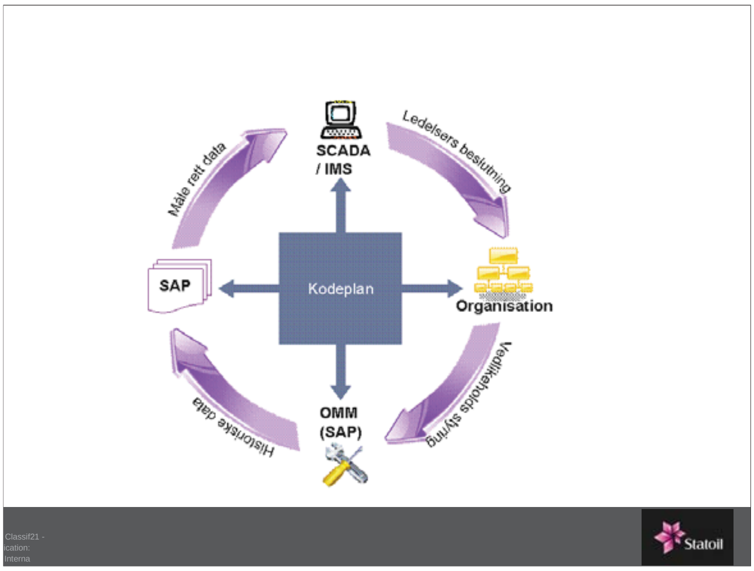
BCOWD Activities
- Codification RDS-PP
- FMECA
- RCM
- Reliability Database
- OPEX Calculation tool
- Condition Monitoring Analyses
- Access Criteria
- Vessel Planning

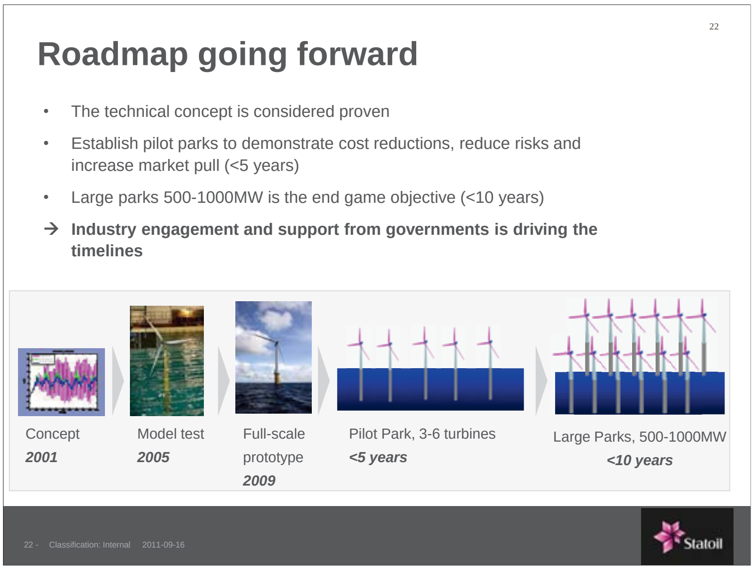
Do

BCOWD Activities
- Remote Operation
- Condition Based Maintenance
- Vessel Operation
- Access Criteria
- New lift solution

Check

BCOWD Activities
- Reliability data analyses
- Condition monitoring Analyses





Roadmap going forward

- The technical concept is considered proven
- Establish pilot parks to demonstrate cost reductions, reduce risks and increase market pull (<5 years)
- Large parks 500-1000MW is the end game objective (<10 years)

→ **Industry engagement and support from governments is driving the timelines**

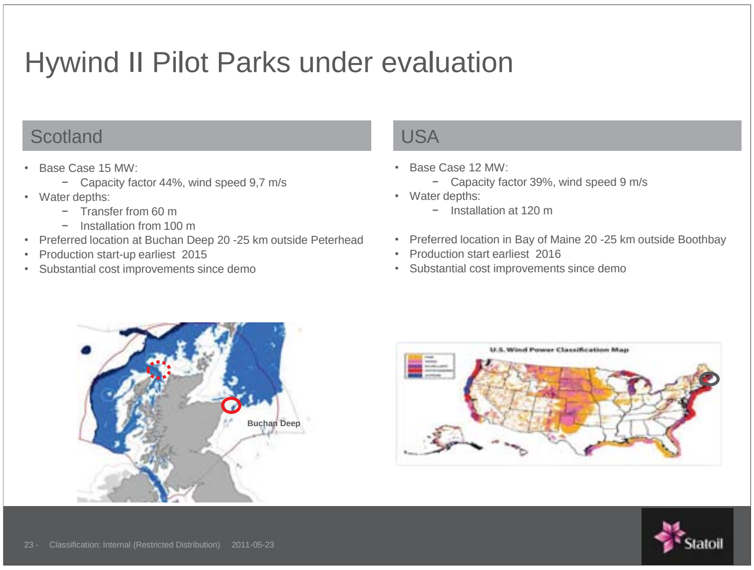
Concept *2001*

Model test *2005*

Full-scale prototype *2009*

Pilot Park, 3-6 turbines *<5 years*

Large Parks, 500-1000MW *<10 years*



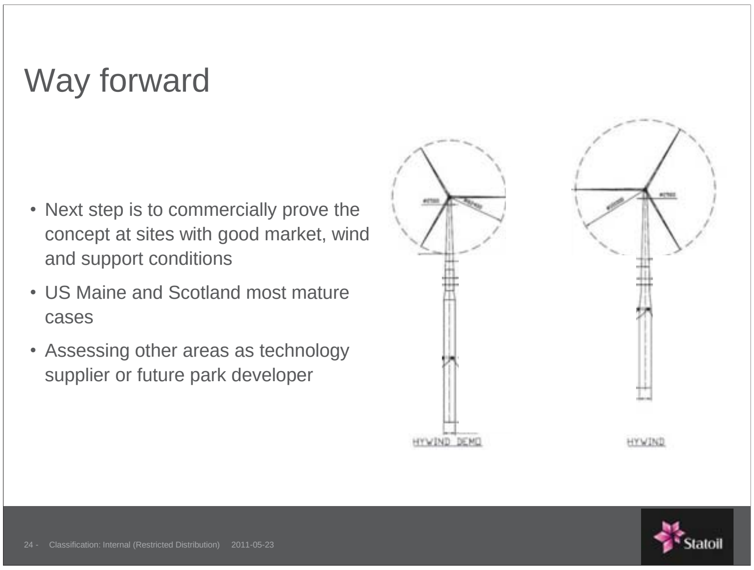
Hywind II Pilot Parks under evaluation

Scotland

- Base Case 15 MW:
  - Capacity factor 44%, wind speed 9,7 m/s
- Water depths:
  - Transfer from 60 m
  - Installation from 100 m
- Preferred location at Buchan Deep 20 -25 km outside Peterhead
- Production start-up earliest 2015
- Substantial cost improvements since demo

USA

- Base Case 12 MW:
  - Capacity factor 39%, wind speed 9 m/s
- Water depths:
  - Installation at 120 m
- Preferred location in Bay of Maine 20 -25 km outside Boothbay
- Production start earliest 2016
- Substantial cost improvements since demo



Way forward

- Next step is to commercially prove the concept at sites with good market, wind and support conditions
- US Maine and Scotland most mature cases
- Assessing other areas as technology supplier or future park developer

E Installation & sub-structures

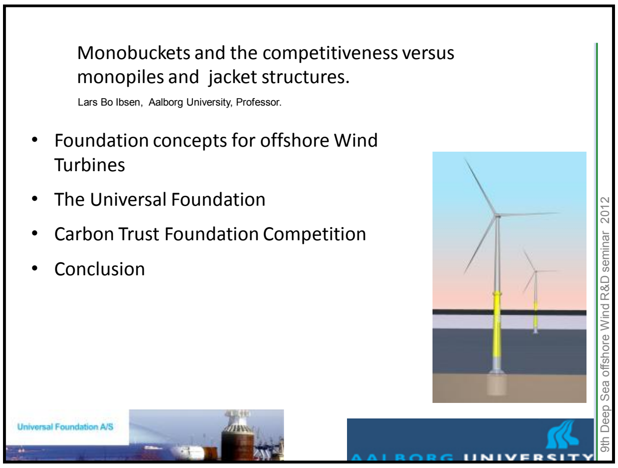
Monobuckets and the competitiveness versus monopiles and jacket structures, Prof Lars Bo Ibsen, Aalborg University

Feasibility of Application of Spar-type Wind Turbine in a Moderate Water Depth, Madjid Karimirad, Post Doc, NTNU

Effects of Hydrodynamic Modelling in Fully Coupled Simulations of a Semi-submersible Wind Turbine, Marit I. Kvittem, PhD stud, NTNU

Improving pile foundation models for use in bottom-fixed offshore wind turbine applications, Eric Van Buren, PhD stud, NTNU

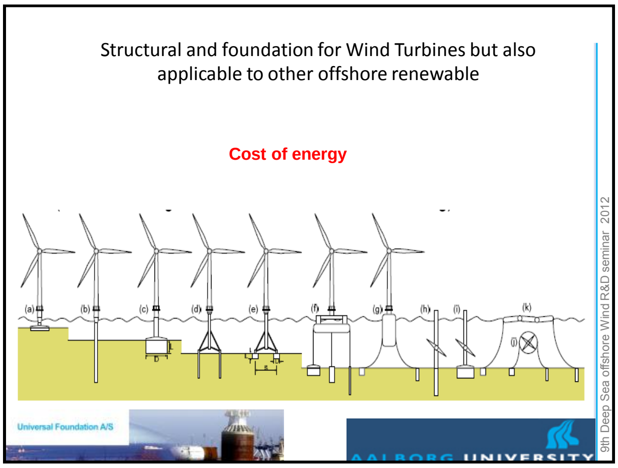
The full-height lattice tower concept, Prof Michael Muskulus, NTNU



Monobuckets and the competitiveness versus monopiles and jacket structures.

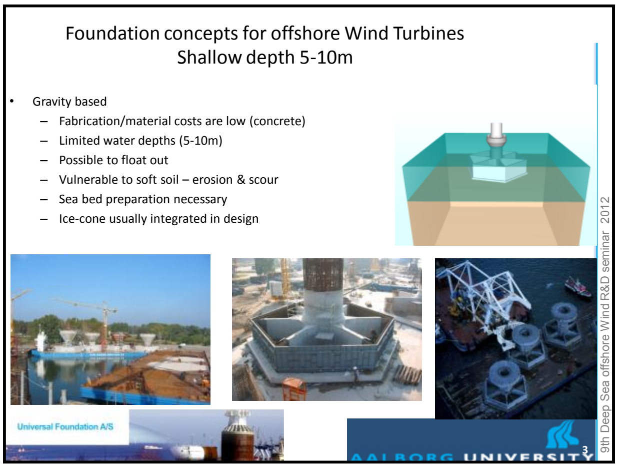
Lars Bo Ibsen, Aalborg University, Professor.

- Foundation concepts for offshore Wind Turbines
- The Universal Foundation
- Carbon Trust Foundation Competition
- Conclusion



Structural and foundation for Wind Turbines but also applicable to other offshore renewable

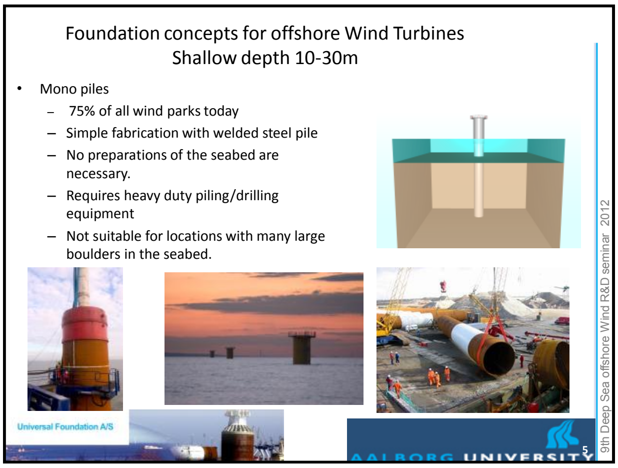
Cost of energy



Foundation concepts for offshore Wind Turbines
Shallow depth 5-10m

- Gravity based
  - Fabrication/material costs are low (concrete)
  - Limited water depths (5-10m)
  - Possible to float out
  - Vulnerable to soft soil – erosion & scour
  - Sea bed preparation necessary
  - Ice-cone usually integrated in design

Presently installing the "Rødsand-project"

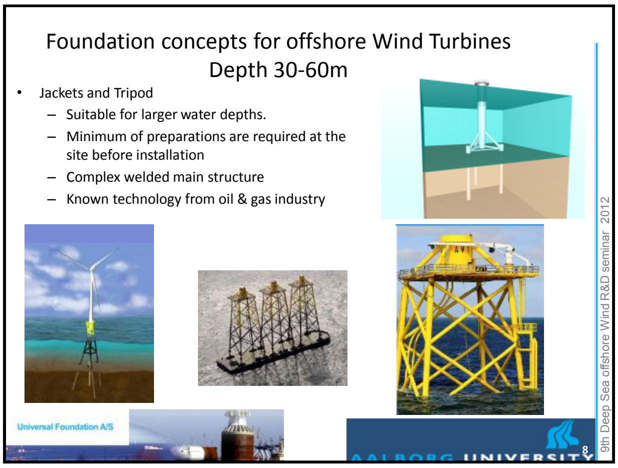


Foundation concepts for offshore Wind Turbines
Shallow depth 10-30m

- Mono piles
  - 75% of all wind parks today
  - Simple fabrication with welded steel pile
  - No preparations of the seabed are necessary.
  - Requires heavy duty piling/drilling equipment
  - Not suitable for locations with many large boulders in the seabed.

Noise

- The recommended requirements of maximum: 160 dB SEL and 190 dB Peak for underwater pile driving noise levels.
- So far, Germany is the only country having ratified the legislation, but the remaining EU countries are expected to follow Germany's example.

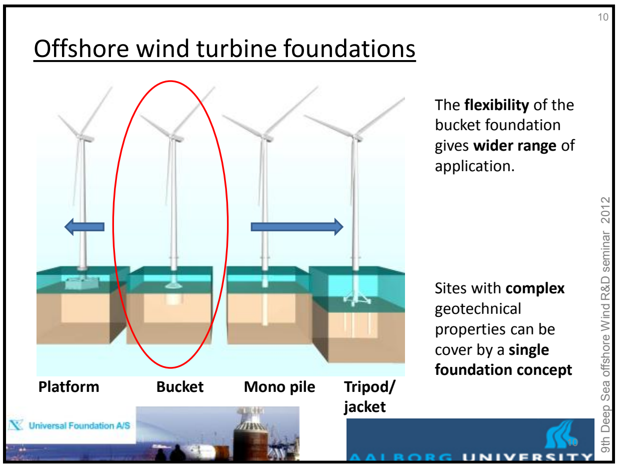


Foundation concepts for offshore Wind Turbines
Depth 30-60m

- Jackets and Tripod
  - Suitable for larger water depths.
  - Minimum of preparations are required at the site before installation
  - Complex welded main structure
  - Known technology from oil & gas industry

Foundation concepts for offshore Wind Turbines
Depth 30-60m

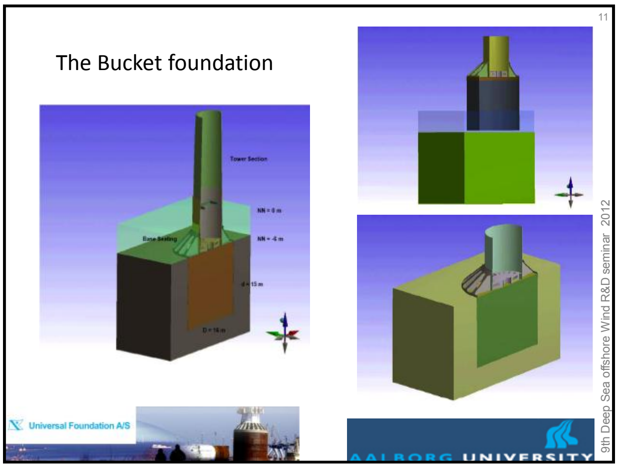
Tripod



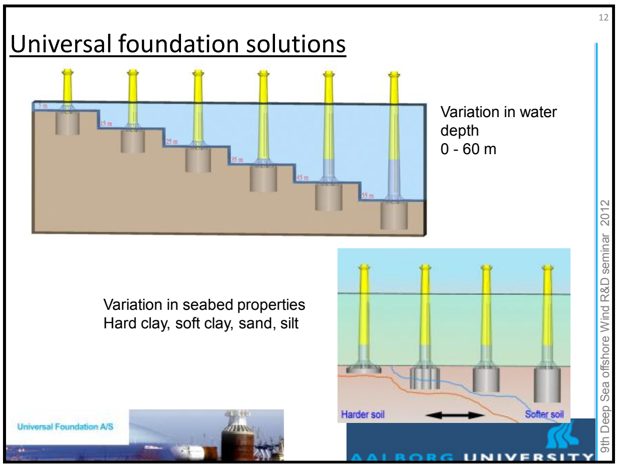
Offshore wind turbine foundations

The **flexibility** of the bucket foundation gives **wider range** of application.

Sites with **complex** geotechnical properties can be cover by a **single foundation concept**



The Bucket foundation

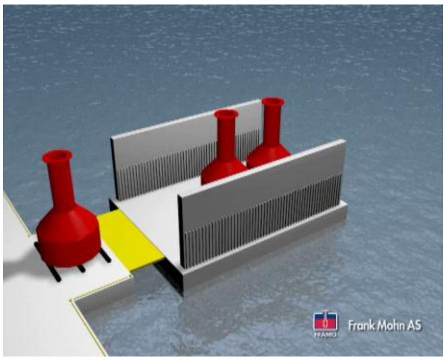


Universal foundation solutions

Variation in water depth
0 - 60 m

Variation in seabed properties
Hard clay, soft clay, sand, silt

Vision for Installation in 2001



Universal Foundation A/S

2011 - MBD Offshore Power A/S -> Universal Foundation A/S

Universal Foundations - Concept IP Holder

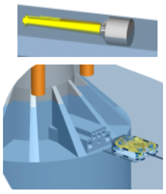
Universal Foundations – Solution Provider

- Fred.Olsen
- Dong Energi
- Novasion
- Aalborg University

Universal Foundation

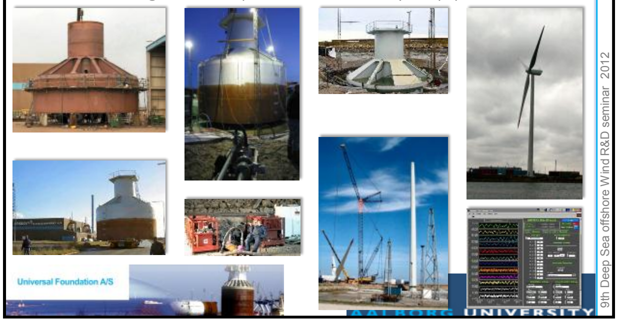
Transport / Installation

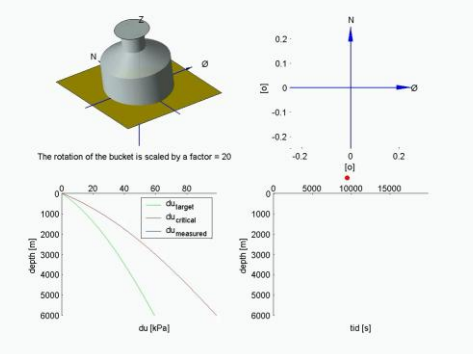
- **Buoyant** horizontal wet tow/ **vertical a/o horizontal** on jack-up or crane ship / **purpose build** vessel
- **Snap-on pump** unit interfacing the lid
- The structure is **upended** by ballast water or by crane
- Crane is hooked on to stabilize **touch down**
- After initial penetration, **suction** is applied
- Installation is finalized by void filling by injecting **cement slurry** under the lid if needed.



Reference 1: Pos. 1-Frederikshavn in operation 9 years

The Ø12x6 m prototype bucket foundation was designed for a Vestas V90 3MW turbine placed on 4 m of water. The design is certified by DNV. The bucket was installed in late 2002 and is in normal operation. The structure/soil interaction has been investigated with sophisticated modal analyse equipment.

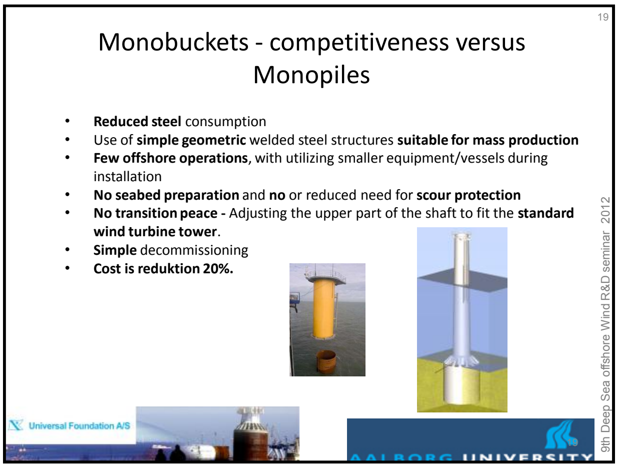




The bucket foundation technology

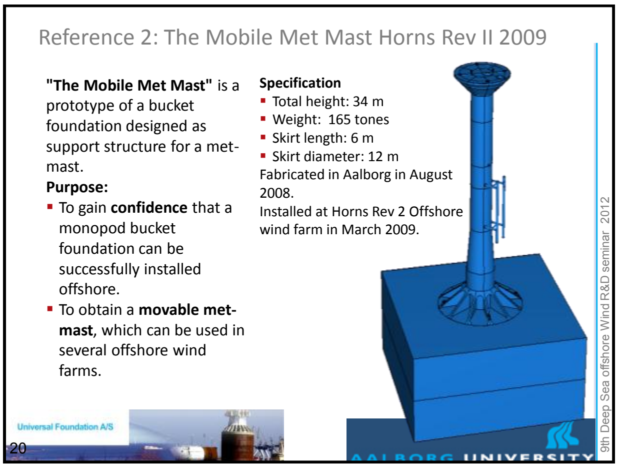
Installation advantages:

- **Minimum noise impact**. No pile driving hammers or drill drives are used
- **No grouted** connections
- **Minimum disturbance** to the existing seabed
- The use of excess material for **scour protection is reduced** or not necessary
- All steel materials can be recovered from the seabed and **reused / recycled** when the foundation is decommissioned



Monobuckets - competitiveness versus Monopiles

- **Reduced steel** consumption
- Use of **simple geometric** welded steel structures **suitable for mass production**
- **Few offshore operations**, with utilizing smaller equipment/vessels during installation
- **No seabed preparation** and **no** or reduced need for **scour protection**
- **No transition peace -** Adjusting the upper part of the shaft to fit the **standard wind turbine tower**.
- **Simple** decommissioning
- **Cost is redułktion 20%.**



Reference 2: The Mobile Met Mast Horns Rev II 2009

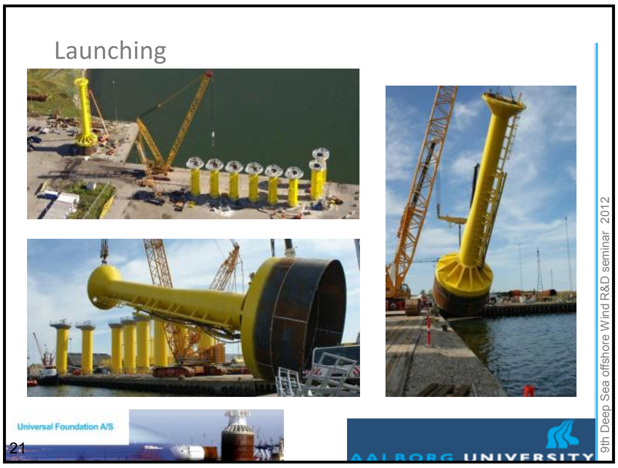
"The Mobile Met Mast" is a prototype of a bucket foundation designed as support structure for a met-mast.

Purpose:
- To gain **confidence** that a monopod bucket foundation can be successfully installed offshore.
- To obtain a **movable met-mast**, which can be used in several offshore wind farms.

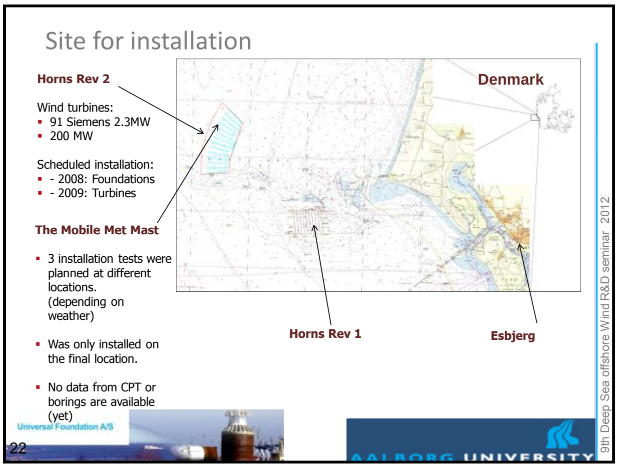
Specification
- Total height: 34 m
- Weight: 165 tones
- Skirt length: 6 m
- Skirt diameter: 12 m

Fabricated in Aalborg in August 2008.

Installed at Horns Rev 2 Offshore wind farm in March 2009.



Launching



Site for installation

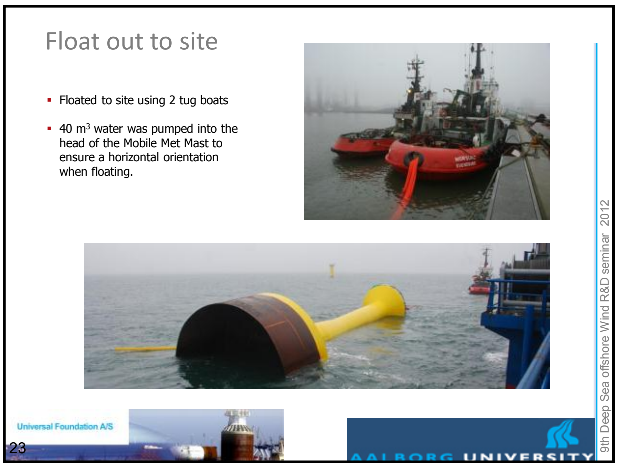
Horns Rev 2

Wind turbines:
- 91 Siemens 2.3MW
- 200 MW

Scheduled installation:
- - 2008: Foundations
- - 2009: Turbines

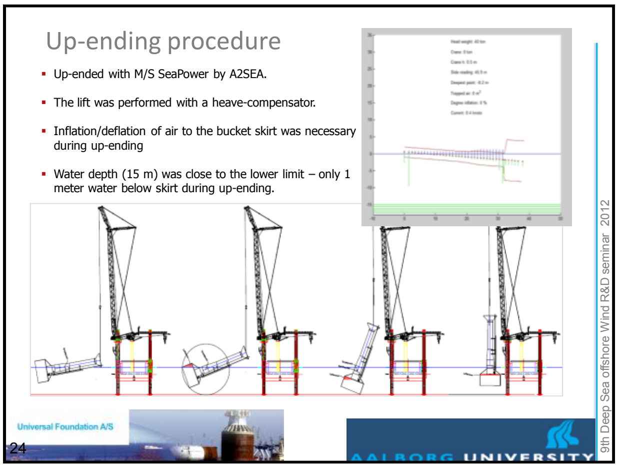
The Mobile Met Mast

- 3 installation tests were planned at different locations. (depending on weather)
- Was only installed on the final location.
- No data from CPT or borings are available (yet)



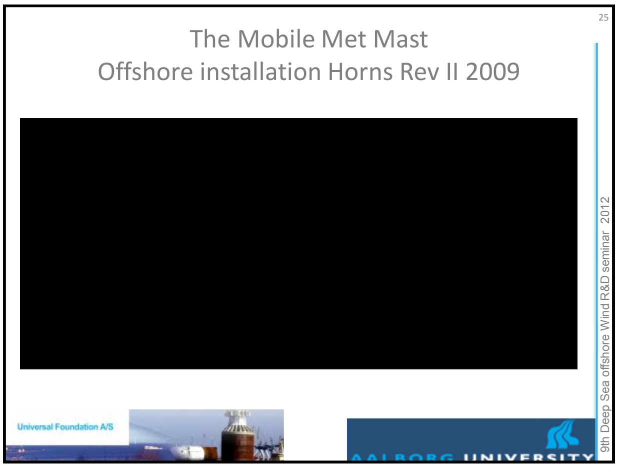
Float out to site

- Floated to site using 2 tug boats
- 40 m^3 water was pumped into the head of the Mobile Met Mast to ensure a horizontal orientation when floating.

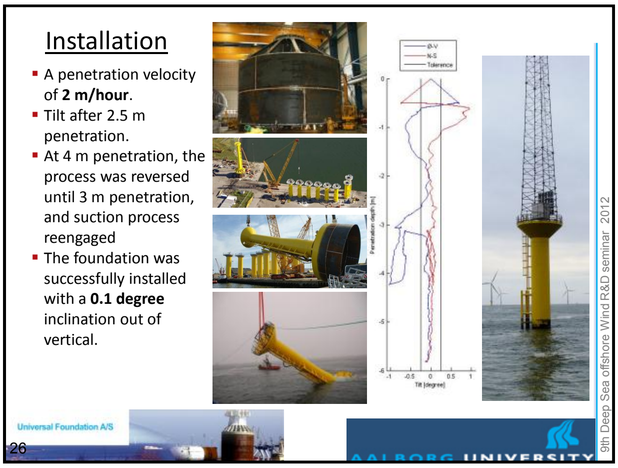


Up-ending procedure

- Up-ended with M/S SeaPower by A2SEA.
- The lift was performed with a heave-compensator.
- Inflation/deflation of air to the bucket skirt was necessary during up-ending
- Water depth (15 m) was close to the lower limit – only 1 meter water below skirt during up-ending.



The Mobile Met Mast
Offshore installation Horns Rev II 2009



Installation

- A penetration velocity of **2 m/hour**.
- Tilt after 2.5 m penetration.
- At 4 m penetration, the process was reversed until 3 m penetration, and suction process reengaged
- The foundation was successfully installed with a **0.1 degree** inclination out of vertical.

Offshore Wind Accelerator is a collaboration to reduce costs

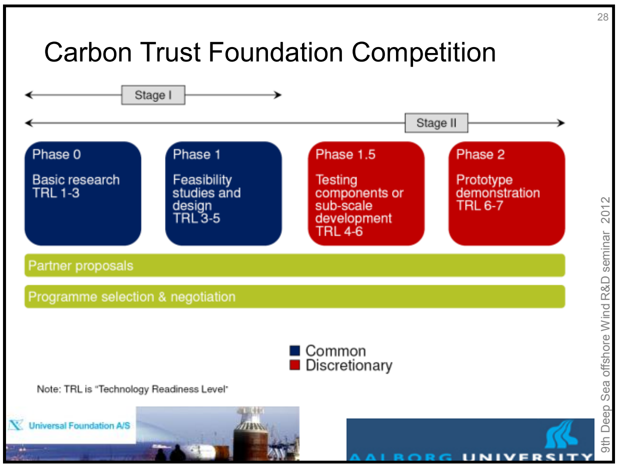
Objective: Reduce cost of energy by 10% through RD&D

Original partnership

CARBON TRUST
DONG energy
RWE The energy to lead
SCOTTISHPOWER RENEWABLES
SSE Renewables
Statoil

- **5 developers + Carbon Trust**
  - 46% of licensed capacity in UK waters (~22GW)
- **Initially 1.5 year commitment**
  - Launched Oct 2008
- **Focusing on identifying and developing technologies for**
  - Round 2 extensions
  - Round 3
  - Scottish Territorial Waters
- **Total budget of £1.5m for collaborative R&D**

Source: Carbon Trust



Carbon Trust Foundation Competition

Stage I
Stage II

Phase 0
Basic research
TRL 1-3

Phase 1
Feasibility studies and design
TRL 3-5

Phase 1.5
Testing components or sub-scale development
TRL 4-6

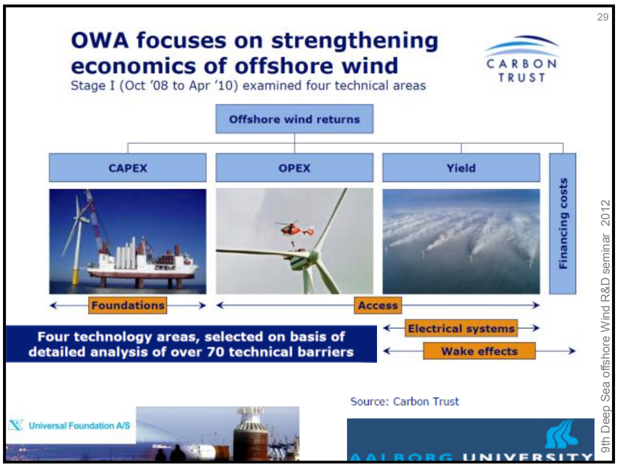
Phase 2
Prototype demonstration
TRL 6-7

Partner proposals

Programme selection & negotiation

🟦 Common
🟥 Discretionary

Note: TRL is "Technology Readiness Level"

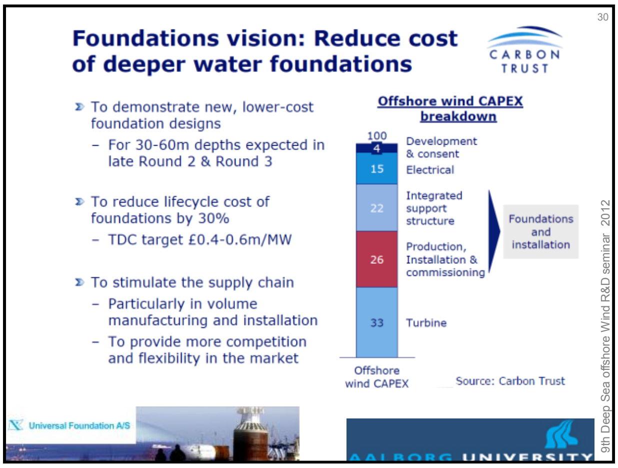


OWA focuses on strengthening economics of offshore wind

Stage I (Oct '08 to Apr '10) examined four technical areas

Four technology areas, selected on basis of detailed analysis of over 70 technical barriers

Source: Carbon Trust



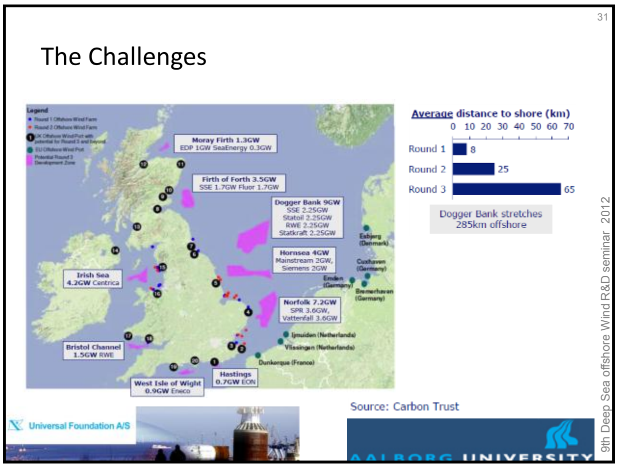
Foundations vision: Reduce cost of deeper water foundations

- To demonstrate new, lower-cost foundation designs
  - For 30-60m depths expected in late Round 2 & Round 3
- To reduce lifecycle cost of foundations by 30%
  - TDC target £0.4-0.6m/MW
- To stimulate the supply chain
  - Particularly in volume manufacturing and installation
  - To provide more competition and flexibility in the market

Offshore wind CAPEX breakdown

Offshore wind CAPEX (100)	
4	Development & consent
15	Electrical
22	Integrated support structure
26	Production, Installation & commissioning
33	Turbine

Source: Carbon Trust

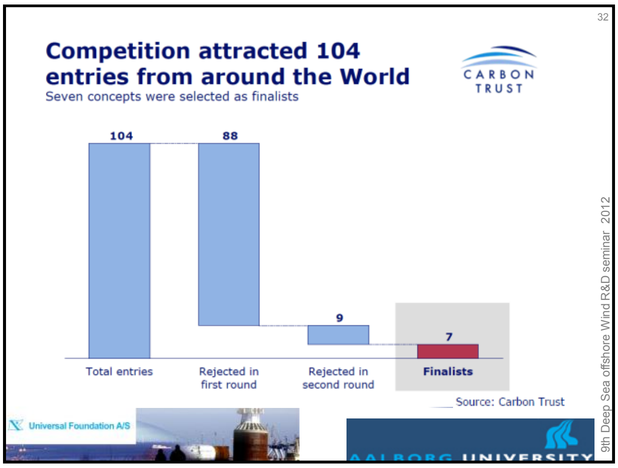


The Challenges

Average distance to shore (km)

Dogger Bank stretches 285km offshore

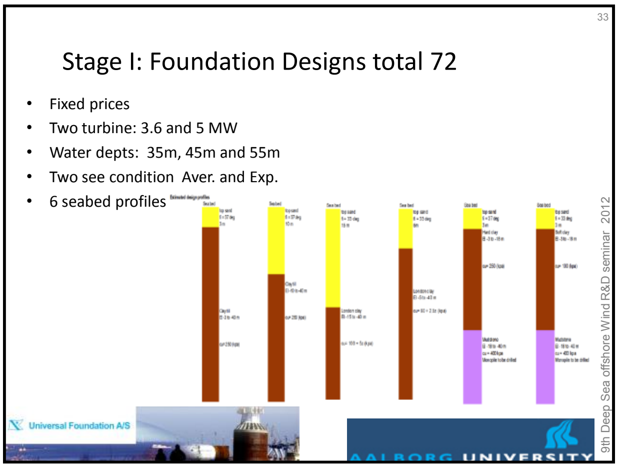
Source: Carbon Trust



Competition attracted 104 entries from around the World

Seven concepts were selected as finalists

Source: Carbon Trust



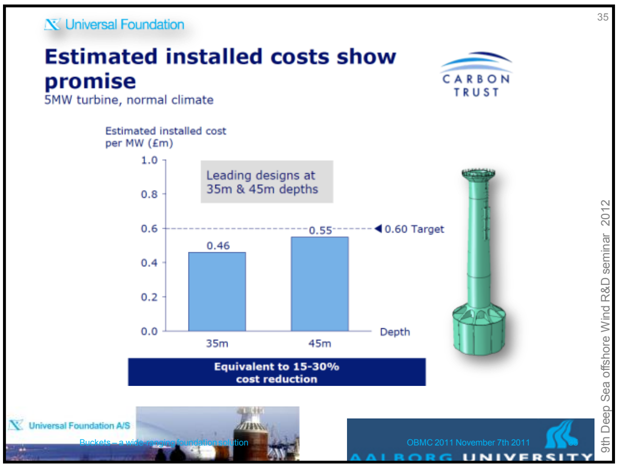
Stage I: Foundation Designs total 72

- Fixed prices
- Two turbine: 3.6 and 5 MW
- Water depts: 35m, 45m and 55m
- Two see condition Aver. and Exp.
- 6 seabed profiles

OWA has chosen four designs for further development

Selected based on expected installed cost on R3 sites

Source: Carbon Trust

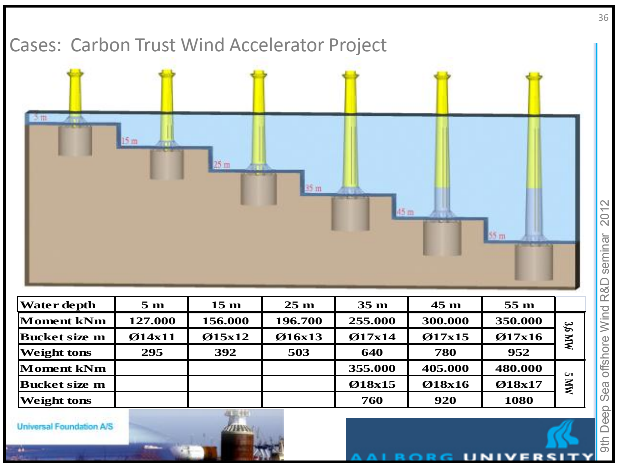


Universal Foundation

Estimated installed costs show promise

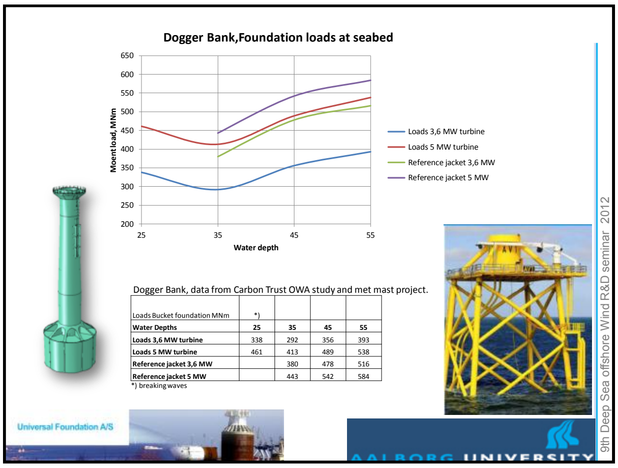
5MW turbine, normal climate

Equivalent to 15-30% cost reduction



Cases: Carbon Trust Wind Accelerator Project

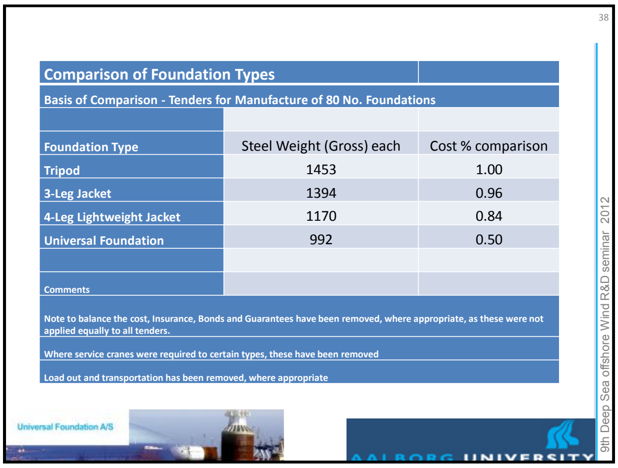
Water depth	5 m	15 m	25 m	35 m	45 m	55 m	
Moment kNm	127.000	156.000	196.700	255.000	300.000	350.000	3,6 MW
Bucket size m	Ø14x11	Ø15x12	Ø16x13	Ø17x14	Ø17x15	Ø17x16	
Weight tons	295	392	503	640	780	952	
Moment kNm				355.000	405.000	480.000	5 MW
Bucket size m				Ø18x15	Ø18x16	Ø18x17	
Weight tons				760	920	1080	



Dogger Bank, data from Carbon Trust OWA study and met mast project.

Loads Bucket foundation MNm	*)			
Water Depths	**25**	**35**	**45**	**55**
Loads 3,6 MW turbine	338	292	356	393
Loads 5 MW turbine	461	413	489	538
Reference jacket 3,6 MW		380	478	516
Reference jacket 5 MW		443	542	584

*) breaking waves



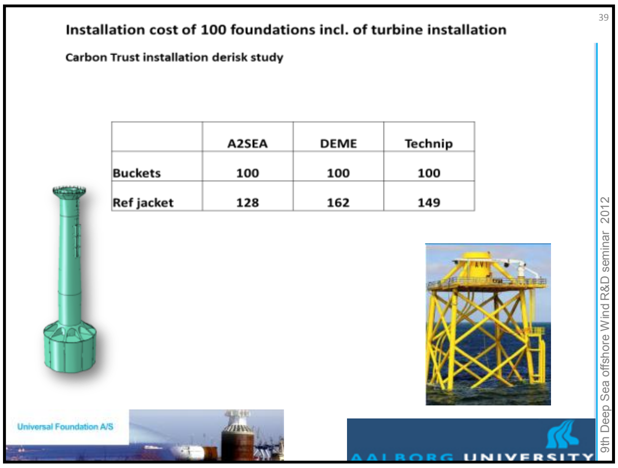
Comparison of Foundation Types	

Basis of Comparison - Tenders for Manufacture of 80 No. Foundations		
Foundation Type	Steel Weight (Gross) each	Cost % comparison
Tripod	1453	1.00
3-Leg Jacket	1394	0.96
4-Leg Lightweight Jacket	1170	0.84
Universal Foundation	992	0.50
Comments		

Note to balance the cost, Insurance, Bonds and Guarantees have been removed, where appropriate, as these were not applied equally to all tenders.

Where service cranes were required to certain types, these have been removed

Load out and transportation has been removed, where appropriate



Installation cost of 100 foundations incl. of turbine installation

Carbon Trust installation derisk study

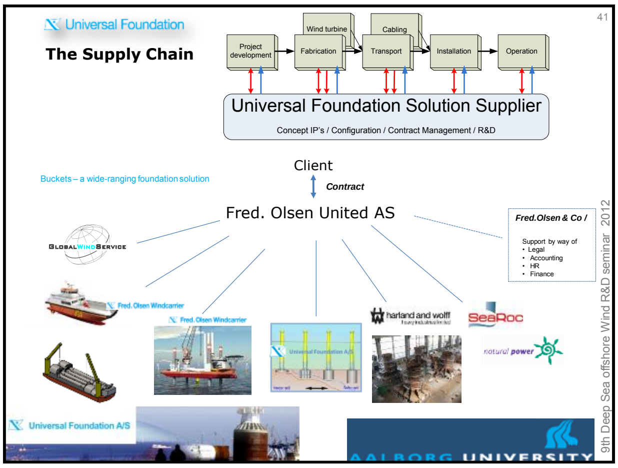
	A2SEA	DEME	Technip
Buckets	100	100	100
Ref jacket	128	162	149

We are now launching Offshore Wind Accelerator Stage II

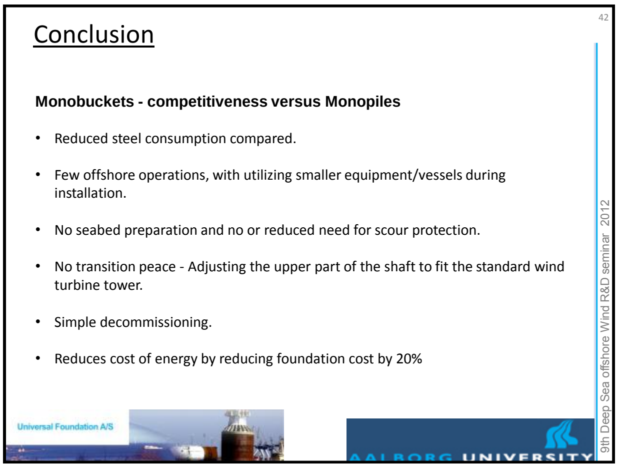
Objective: Reduce cost of energy by 10% through RD&D

- **4-year commitment**
- **Two new developers**
  - **Statkraft**
  - **Mainstream Renewable Power**
- **56% of licensed capacity in UK waters (~27GW)**
- **Total budget of £10m for collaborative R&D**
- **Up to £30m of demonstration projects**

Source: Carbon Trust



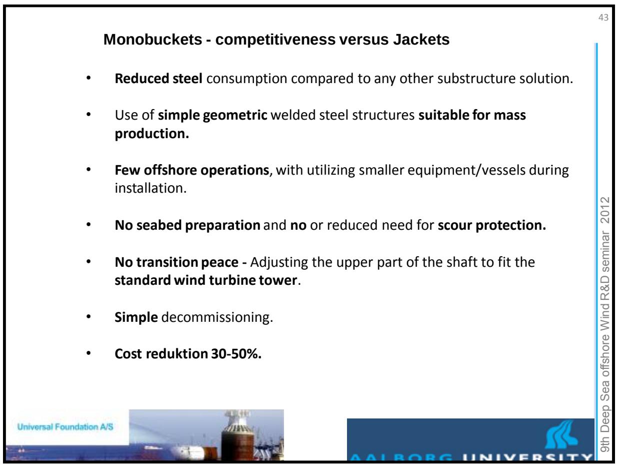
The Supply Chain



Conclusion

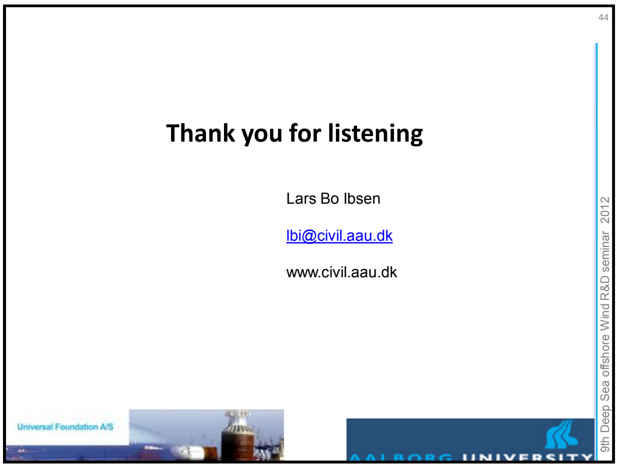
Monobuckets - competitiveness versus Monopiles

- Reduced steel consumption compared.
- Few offshore operations, with utilizing smaller equipment/vessels during installation.
- No seabed preparation and no or reduced need for scour protection.
- No transition peace - Adjusting the upper part of the shaft to fit the standard wind turbine tower.
- Simple decommissioning.
- Reduces cost of energy by reducing foundation cost by 20%



Monobuckets - competitiveness versus Jackets

- **Reduced steel** consumption compared to any other substructure solution.
- Use of **simple geometric** welded steel structures **suitable for mass production.**
- **Few offshore operations**, with utilizing smaller equipment/vessels during installation.
- **No seabed preparation** and **no** or reduced need for **scour protection.**
- **No transition peace -** Adjusting the upper part of the shaft to fit the **standard wind turbine tower**.
- **Simple** decommissioning.
- **Cost reduktion 30-50%.**



Thank you for listening

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Feasibility of Application of a Spar-type Wind Turbine at a Moderate Water Depth

Dr. Madjid Karimirad (CeSOS and Nowitech)
Prof. Torgeir Moan (CeSOS and Nowitech)

DeepWind, 19-20 January 2012, Trondheim, Norway

Outline

- Introduction
- Case studies
  - Wave only
  - Wave- and wind-induced cases
- Remarks and conclusions

Introduction

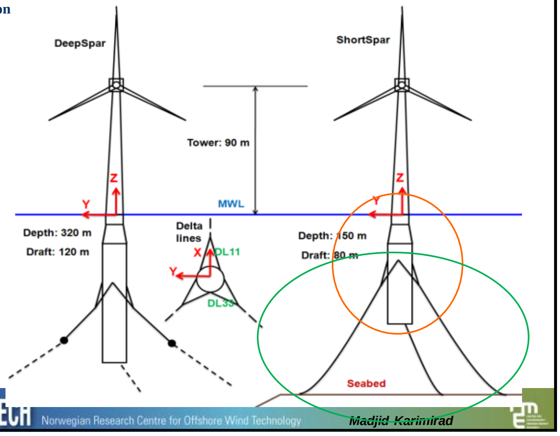


Table 2: Properties of the DeepSpar and ShortSpar offshore wind turbines.

Item	DeepSpar	ShortSpar
Turbine	NREL 5-MW	NREL 5-MW
Water depth (m)	320	150
Draft (m)	120	80
Displacement (m^3)	8016	5245
Centre of buoyancy (m)	-62	-42
Diameter at MWL (m)	6.5	6.5
Diameter at bottom (m)	9.4	9.4
Mass (ton)	8216	5376
Centre of gravity[1)] (m)	-78.5	-47.3
Mass moment of inertia, I_{XX} and I_{YY} ($ton*m^2$)	69.84 E+6	24.47 E+6
Mass moment of inertia, I_{ZZ} ($ton*m^2$)	16.78 E+4	77.62 E+3
Fairlead elevation (m)	-70	-30

GM, stability

1) Center of gravity of the floating wind turbine, including the rotor, nacelle, tower and spar (steel weight and ballast).

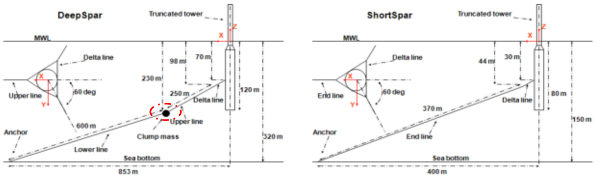
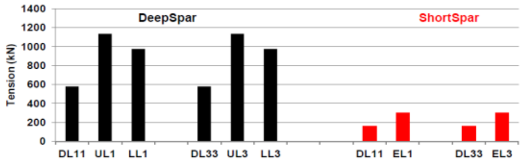


Figure 3: Schematic layout of the mooring system for DeepSpar and ShortSpar offshore wind turbines in deep and intermediate water depths (stress free configuration).



Hydrodynamic analysis

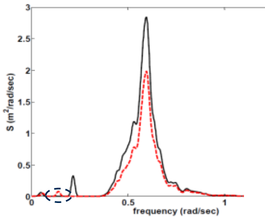


Figure 4: The spectrum of the surge response at 1-hour time-domain analysis under wave-o (Hs=4.2 m, Tp=10.5 sec).

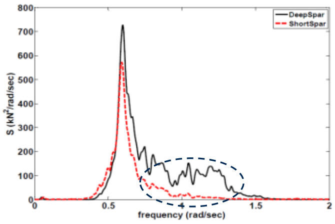
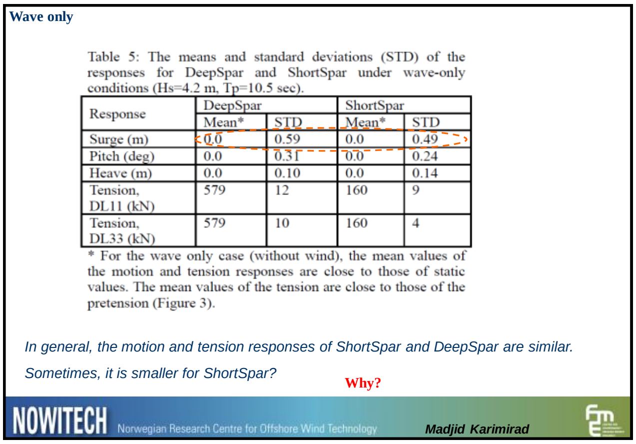


Figure 5: The spectrum of the tension response (DL11) based on 1-hour time domain analysis under wave-only conditions (Hs=4.2 m, Tp=10.5 sec).

Elastic modes of mooring system
Mooring line viscous damping helps



Wave only

Table 5: The means and standard deviations (STD) of the responses for DeepSpar and ShortSpar under wave-only conditions (Hs=4.2 m, Tp=10.5 sec).

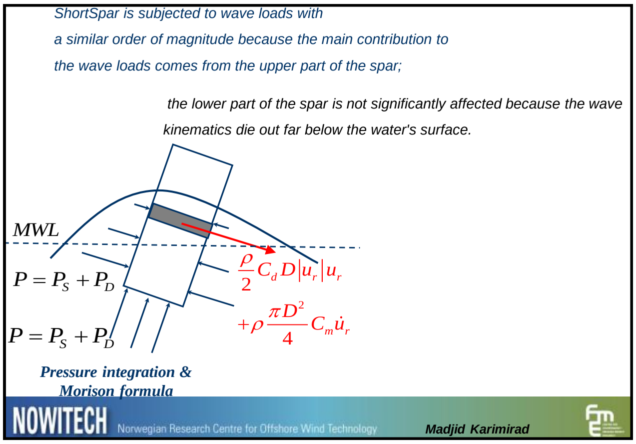
Response	DeepSpar		ShortSpar	
	Mean*	STD	Mean*	STD
Surge (m)	0.0	0.59	0.0	0.49
Pitch (deg)	0.0	0.31	0.0	0.24
Heave (m)	0.0	0.10	0.0	0.14
Tension, DL11 (kN)	579	12	160	9
Tension, DL33 (kN)	579	10	160	4

* For the wave only case (without wind), the mean values of the motion and tension responses are close to those of static values. The mean values of the tension are close to those of the pretension (Figure 3).

In general, the motion and tension responses of ShortSpar and DeepSpar are similar.

Sometimes, it is smaller for ShortSpar?

Why?



ShortSpar is subjected to wave loads with a similar order of magnitude because the main contribution to the wave loads comes from the upper part of the spar;

the lower part of the spar is not significantly affected because the wave kinematics die out far below the water's surface.

$$P = P_S + P_D$$

$$\frac{\rho}{2} C_d D |u_r| u_r$$

$$+\rho \frac{\pi D^2}{4} C_m \dot{u}_r$$

$$P = P_S + P_D$$

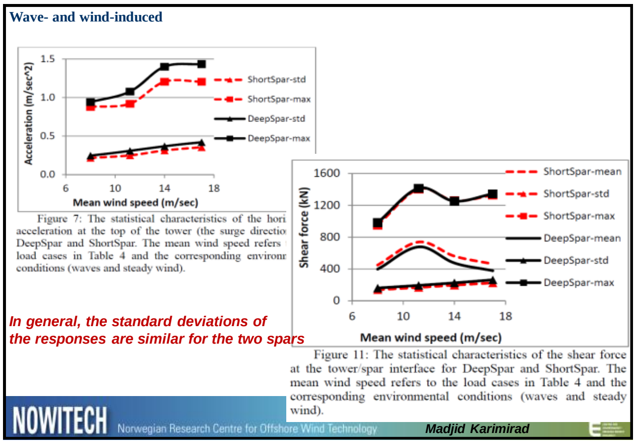
Pressure integration & Morison formula

The heave and pitch motions are mainly dominated by the heave and pitch resonant responses, respectively.

The resonant responses of DeepSpar and ShortSpar have the same order of magnitude.

Almost same hydro-damping

The wave frequency of the heave response is higher for ShortSpar because it has a smaller draft and its bottom experiences more wave loads and it weighs less.

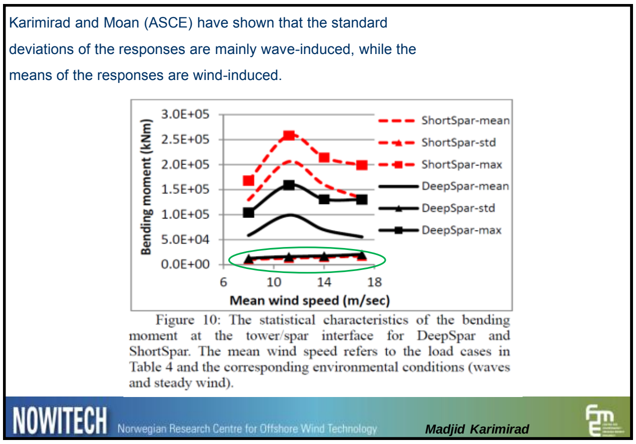


Wave- and wind-induced

Figure 7: The statistical characteristics of the hori acceleration at the top of the tower (the surge directio DeepSpar and ShortSpar. The mean wind speed refers load cases in Table 4 and the corresponding environr conditions (waves and steady wind).

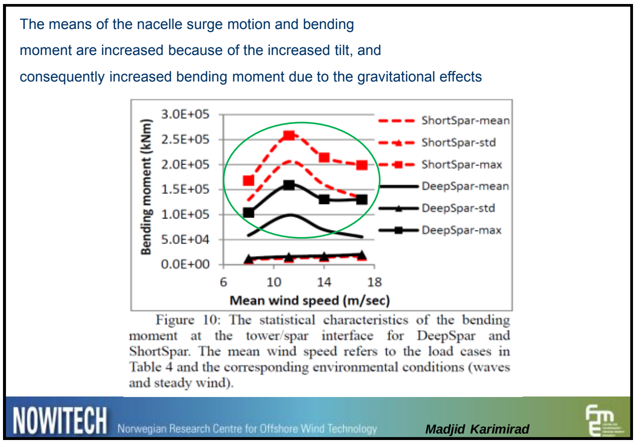
In general, the standard deviations of the responses are similar for the two spars

Figure 11: The statistical characteristics of the shear force at the tower/spar interface for DeepSpar and ShortSpar. The mean wind speed refers to the load cases in Table 4 and the corresponding environmental conditions (waves and steady wind).



Karimirad and Moan (ASCE) have shown that the standard deviations of the responses are mainly wave-induced, while the means of the responses are wind-induced.

Figure 10: The statistical characteristics of the bending moment at the tower/spar interface for DeepSpar and ShortSpar. The mean wind speed refers to the load cases in Table 4 and the corresponding environmental conditions (waves and steady wind).



The means of the nacelle surge motion and bending moment are increased because of the increased tilt, and consequently increased bending moment due to the gravitational effects

Figure 10: The statistical characteristics of the bending moment at the tower/spar interface for DeepSpar and ShortSpar. The mean wind speed refers to the load cases in Table 4 and the corresponding environmental conditions (waves and steady wind).

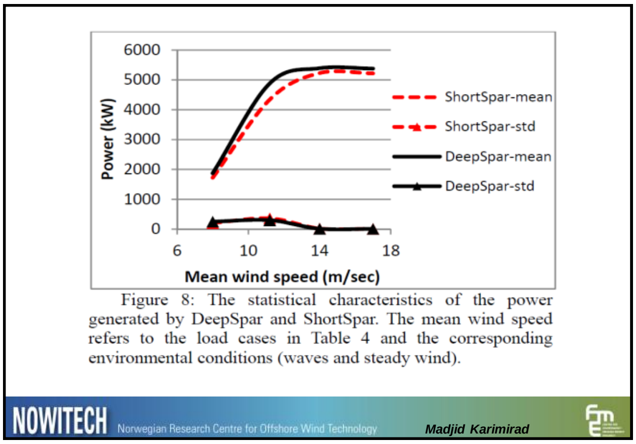


Figure 8: The statistical characteristics of the power generated by DeepSpar and ShortSpar. The mean wind speed refers to the load cases in Table 4 and the corresponding environmental conditions (waves and steady wind).

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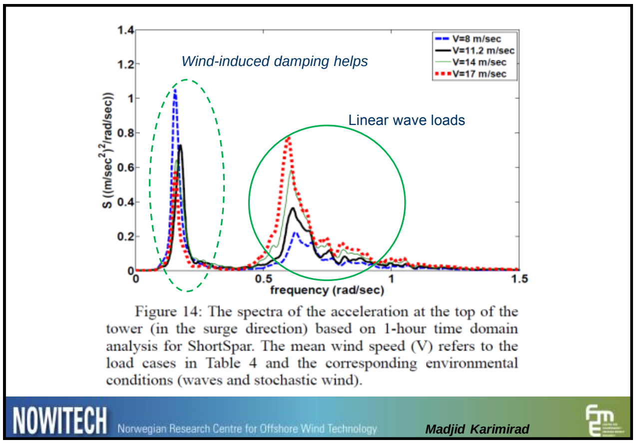

Wind-induced damping helps

Linear wave loads

Figure 14: The spectra of the acceleration at the top of the tower (in the surge direction) based on 1-hour time domain analysis for ShortSpar. The mean wind speed (V) refers to the load cases in Table 4 and the corresponding environmental conditions (waves and stochastic wind).

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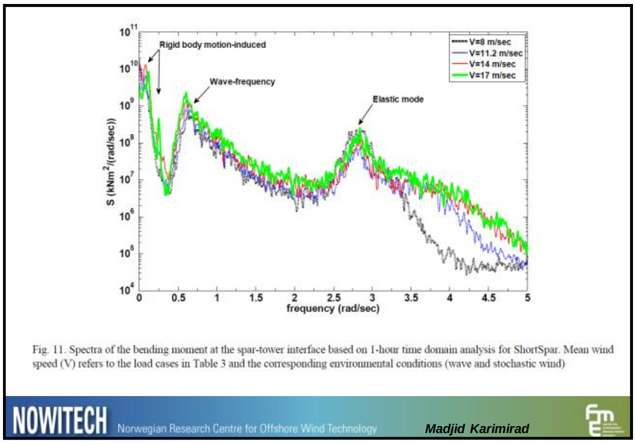

Fig. 11. Spectra of the bending moment at the spar-tower interface based on 1-hour time domain analysis for ShortSpar. Mean wind speed (V) refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

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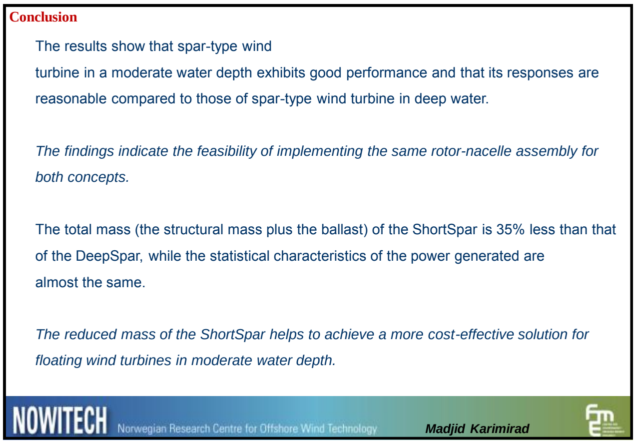

Conclusion

The results show that spar-type wind turbine in a moderate water depth exhibits good performance and that its responses are reasonable compared to those of spar-type wind turbine in deep water.

The findings indicate the feasibility of implementing the same rotor-nacelle assembly for both concepts.

The total mass (the structural mass plus the ballast) of the ShortSpar is 35% less than that of the DeepSpar, while the statistical characteristics of the power generated are almost the same.

The reduced mass of the ShortSpar helps to achieve a more cost-effective solution for floating wind turbines in moderate water depth.

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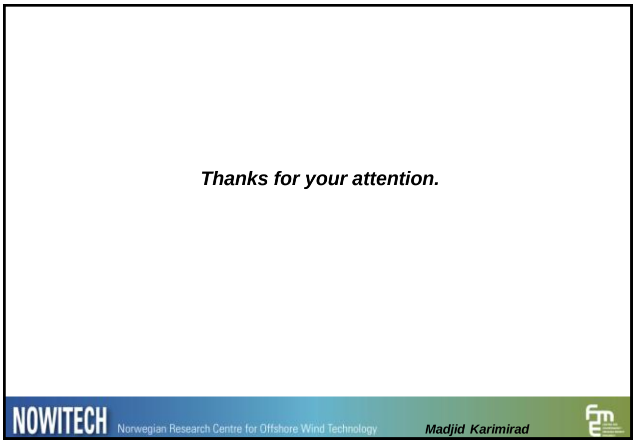

Thanks for your attention.

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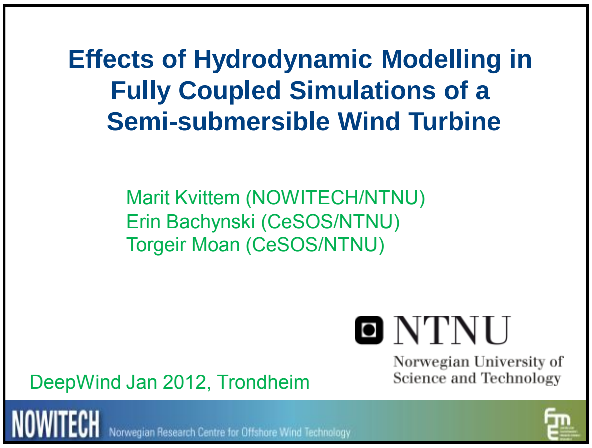
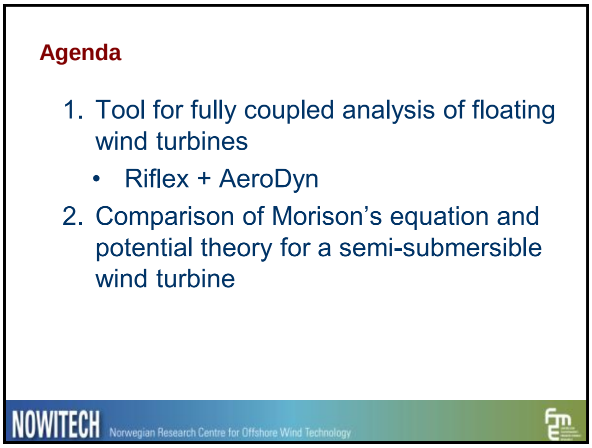


Effects of Hydrodynamic Modelling in Fully Coupled Simulations of a Semi-submersible Wind Turbine

Marit Kvittem (NOWITECH/NTNU)
Erin Bachynski (CeSOS/NTNU)
Torgeir Moan (CeSOS/NTNU)

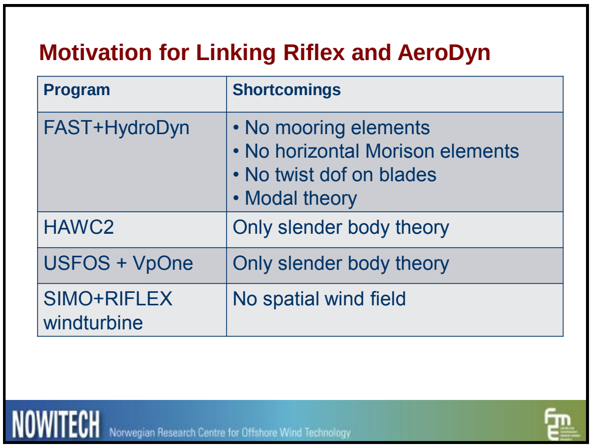
NTNU
Norwegian University of Science and Technology

DeepWind Jan 2012, Trondheim



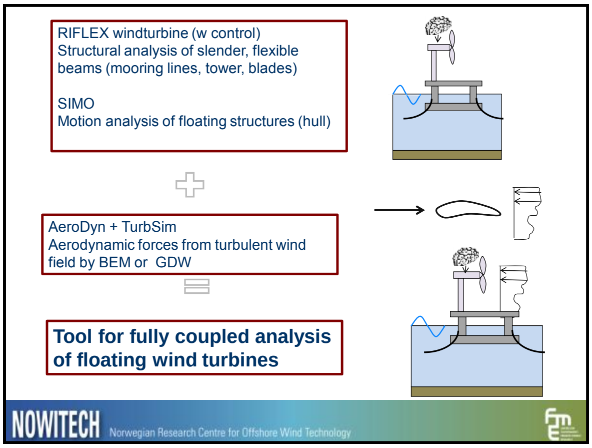
Agenda

1. Tool for fully coupled analysis of floating wind turbines
   - Riflex + AeroDyn
2. Comparison of Morison's equation and potential theory for a semi-submersible wind turbine



Motivation for Linking Riflex and AeroDyn

Program	Shortcomings
FAST+HydroDyn	• No mooring elements • No horizontal Morison elements • No twist dof on blades • Modal theory
HAWC2	Only slender body theory
USFOS + VpOne	Only slender body theory
SIMO+RIFLEX windturbine	No spatial wind field



RIFLEX windturbine (w control)
Structural analysis of slender, flexible beams (mooring lines, tower, blades)

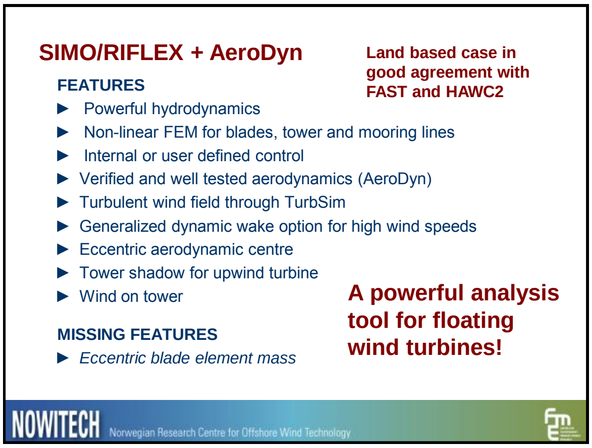
SIMO
Motion analysis of floating structures (hull)

+

AeroDyn + TurbSim
Aerodynamic forces from turbulent wind field by BEM or GDW

=

Tool for fully coupled analysis of floating wind turbines



SIMO/RIFLEX + AeroDyn

Land based case in good agreement with FAST and HAWC2

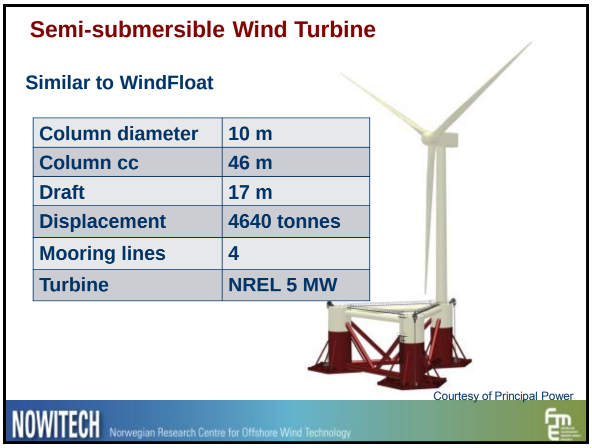
FEATURES

- ▶ Powerful hydrodynamics
- ▶ Non-linear FEM for blades, tower and mooring lines
- ▶ Internal or user defined control
- ▶ Verified and well tested aerodynamics (AeroDyn)
- ▶ Turbulent wind field through TurbSim
- ▶ Generalized dynamic wake option for high wind speeds
- ▶ Eccentric aerodynamic centre
- ▶ Tower shadow for upwind turbine
- ▶ Wind on tower

MISSING FEATURES

- ▶ *Eccentric blade element mass*

A powerful analysis tool for floating wind turbines!

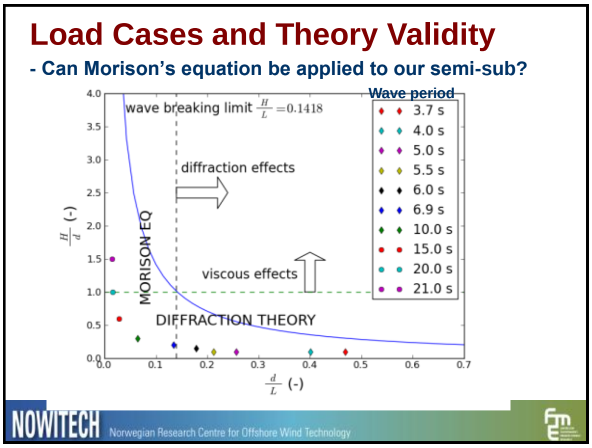


Semi-submersible Wind Turbine

Similar to WindFloat

Column diameter	**10 m**
Column cc	**46 m**
Draft	**17 m**
Displacement	**4640 tonnes**
Mooring lines	**4**
Turbine	**NREL 5 MW**

Courtesy of Principal Power



Load Cases and Theory Validity

- Can Morison's equation be applied to our semi-sub?

Morison vs Potential theory

For a single DOF system:

Diffraction for small wavelength-to-diameter ratios

Linear potential theory with quadratic drag

$$(M + A_{\infty})\,\ddot{x}(t) + \int_{-\infty}^{\infty} \kappa(t-\tau)\dot{x}(\tau)d\tau + Cx(t) + K\,(x(t)) = F^{FK} + F^{D} + C_q|u-\dot{x}|\,(u-\dot{x})$$

Morison

$$M\ddot{x}(t) + Cx(t) + K\,(x(t)) = (\rho_w V + m_a)a - m_a\ddot{x} + C_q|u-\dot{x}|\,(u-\dot{x})$$

***ma* is calculated based on A(ω) from potential theory, for columns and heave plates**

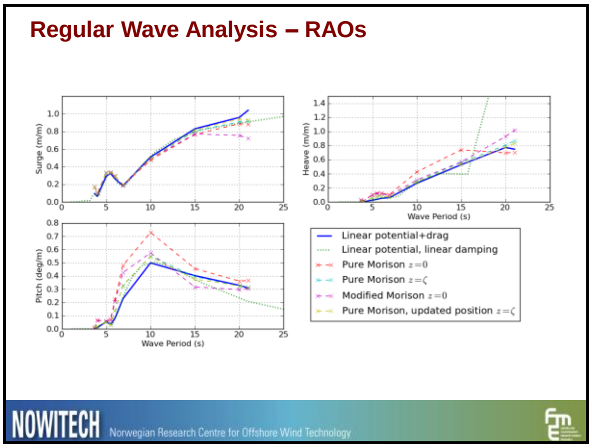
Morison vs Potential – Four models

Potential theory
- M, A(ω), B(ω), C and force transfer functions
- Quadratic drag

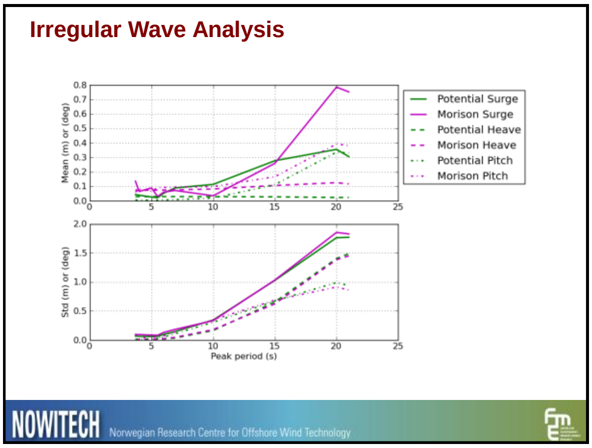
Pure Morison (z=ζ or z=0)
- Inertia terms
- Quadratic drag

Morison updated pos. (z=ζ)
- Inertia terms
- Quadratic drag elements
- Calculates forces in updated position of the platform

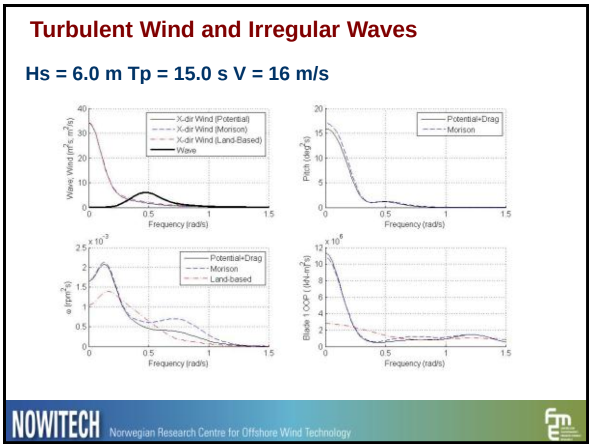
Morison with dynamic pressure (z=0)
- Inertia terms
- Quadratic drag
- Correction for dynamic pressure under columns



Regular Wave Analysis – RAOs



Irregular Wave Analysis



Turbulent Wind and Irregular Waves

Hs = 6.0 m Tp = 15.0 s V = 16 m/s

Turbulent Wind and Irregular Waves

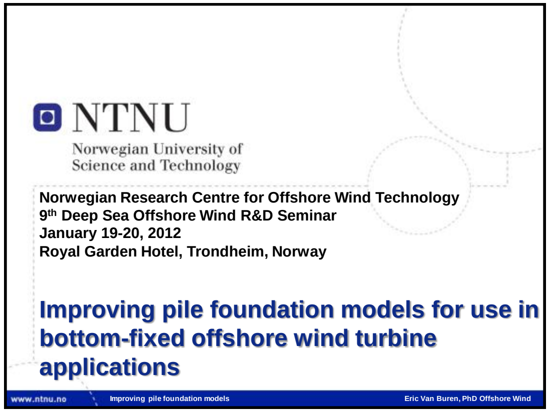
Hs = 6.0 m Tp = 15.0 s V = 16 m/s

	Land-Based		WF - Potential + Drag		WF - Morison	
	μ	σ	μ	σ	μ	σ
Electrical Power (kW)	4798	339	4767	384	4734	424.6
Generator Torque (kNm)	41.33	2.46	41.08	2.81	40.78	3.10
Blade Pitch (deg)	11.15	2.92	10.46	3.54	10.47	3.56
Rotor Speed (rpm)	12.10	0.25	12.09	0.27	12.09	0.30
Blade Root Out-Of-Plane Bending Moment (kNm)	5205	1645	5847	1850	5837	1900
Blade Root In-Plane Bending Moment (kNm)	1180	2621	1155	2524	1116	2510
Surge (m)	n/a	n/a	12.72	2.19	13.57	2.33
Heave (m)	n/a	n/a	-0.01	0.61	0.06	0.64
Pitch (deg)	n/a	n/a	7.18	1.87	7.37	1.96

Conclusions

- Diffraction effects are important for heave motions for wave periods below 7 s
- Morison can be applied for this structure, but stretching and coefficients must be chosen with care
- Effect of updated position is small
- Pitch motions are important to power production and blade root bending moment, so correct preditcion of motions is important


Thank you!



NTNU
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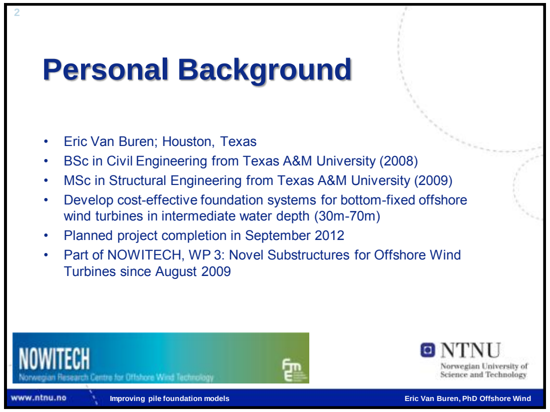
Norwegian Research Centre for Offshore Wind Technology
9th Deep Sea Offshore Wind R&D Seminar
January 19-20, 2012
Royal Garden Hotel, Trondheim, Norway

Improving pile foundation models for use in bottom-fixed offshore wind turbine applications



Personal Background

- Eric Van Buren; Houston, Texas
- BSc in Civil Engineering from Texas A&M University (2008)
- MSc in Structural Engineering from Texas A&M University (2009)
- Develop cost-effective foundation systems for bottom-fixed offshore wind turbines in intermediate water depth (30m-70m)
- Planned project completion in September 2012
- Part of NOWITECH, WP 3: Novel Substructures for Offshore Wind Turbines since August 2009

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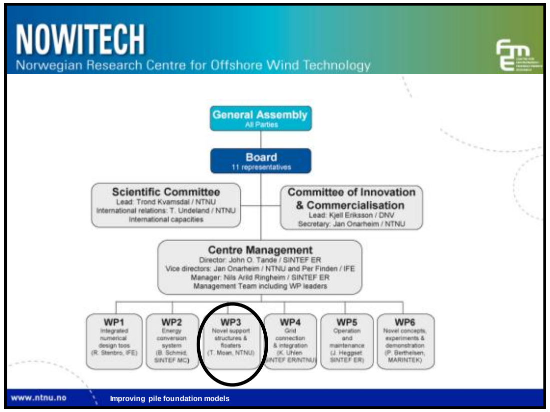

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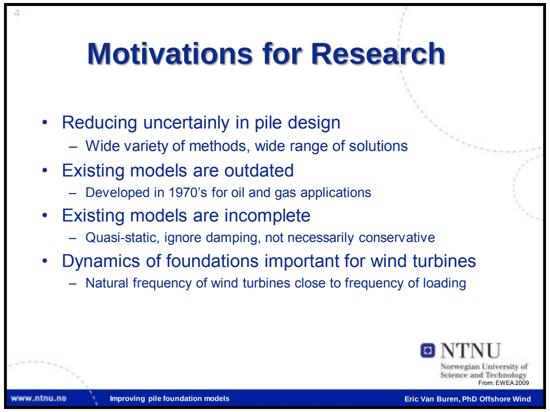
Management Team including WP leaders

WP1 Integrated numerical design toos (R. Stenbro, IFE)
WP2 Energy conversion system (B. Schmid, SINTEF MC)
WP3 Novel support structures & floaters (T. Moan, NTNU)
WP4 Grid connection & integration (K. Uhlen SINTEF ER/NTNU)
WP5 Operation and maintenance (J. Heggset SINTEF ER)
WP6 Novel concepts, experiments & demonstration (P. Berthelsen, MARINTEK)



Motivations for Research

- Reducing uncertainly in pile design
  - Wide variety of methods, wide range of solutions
- Existing models are outdated
  - Developed in 1970's for oil and gas applications
- Existing models are incomplete
  - Quasi-static, ignore damping, not necessarily conservative
- Dynamics of foundations important for wind turbines
  - Natural frequency of wind turbines close to frequency of loading

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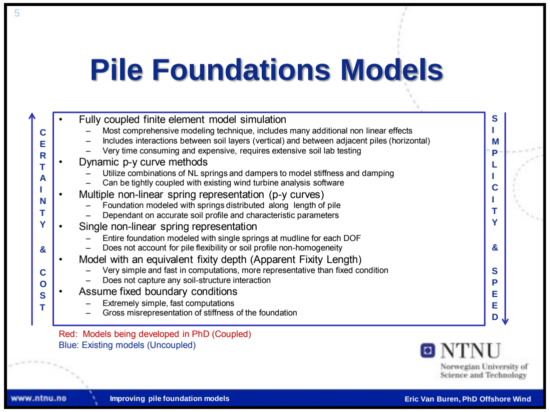
From: EWEA 2009



Pile Foundations Models

CERTAINTY & COST

- 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
- Dynamic p-y curve methods
  - Utilize combinations of NL springs and dampers to model stiffness and damping
  - Can be tightly coupled with existing wind turbine analysis software
- 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

SIMPLICITY & SPEED

Red: Models being developed in PhD (Coupled)
Blue: Existing models (Uncoupled)

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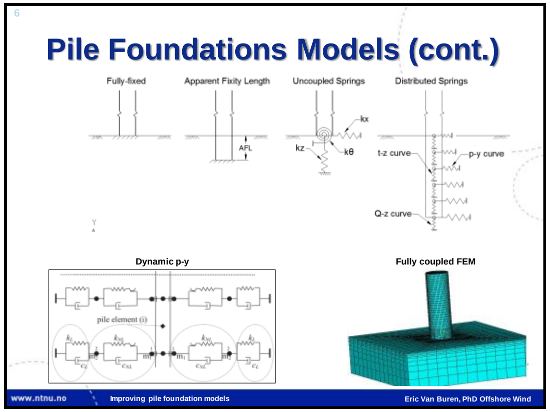
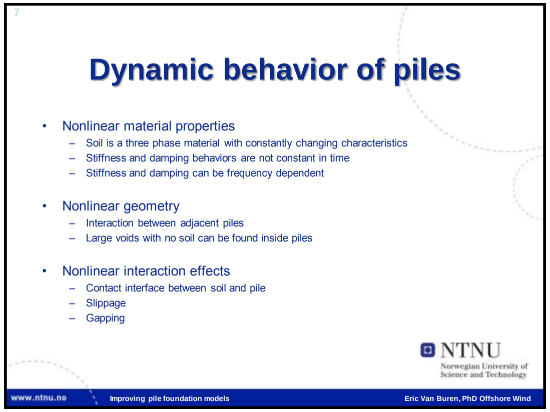


Pile Foundations Models (cont.)

Dynamic p-y

Fully coupled FEM



Dynamic behavior of piles

- Nonlinear material properties
  - Soil is a three phase material with constantly changing characteristics
  - Stiffness and damping behaviors are not constant in time
  - Stiffness and damping can be frequency dependent
- Nonlinear geometry
  - Interaction between adjacent piles
  - Large voids with no soil can be found inside piles
- Nonlinear interaction effects
  - Contact interface between soil and pile
  - Slippage
  - Gapping

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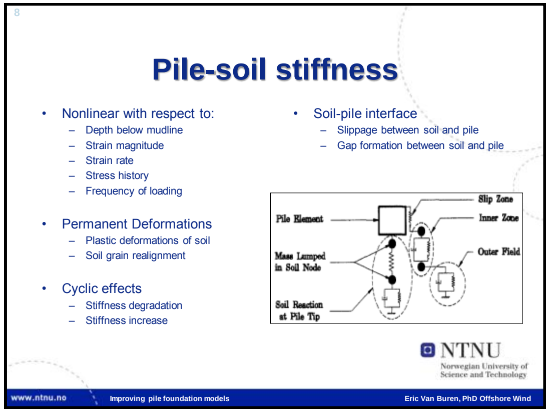

Pile-soil stiffness

- Nonlinear with respect to:
  - Depth below mudline
  - Strain magnitude
  - Strain rate
  - Stress history
  - Frequency of loading
- Permanent Deformations
  - Plastic deformations of soil
  - Soil grain realignment
- Cyclic effects
  - Stiffness degradation
  - Stiffness increase
- Soil-pile interface
  - Slippage between soil and pile
  - Gap formation between soil and pile

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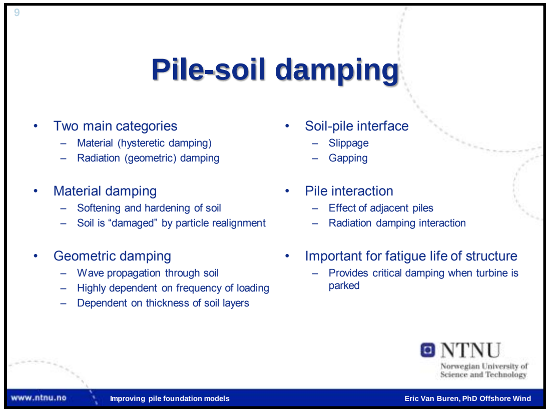

Pile-soil damping

- Two main categories
  - Material (hysteretic damping)
  - Radiation (geometric) damping
- Material damping
  - Softening and hardening of soil
  - Soil is "damaged" by particle realignment
- Geometric damping
  - Wave propagation through soil
  - Highly dependent on frequency of loading
  - Dependent on thickness of soil layers
- Soil-pile interface
  - Slippage
  - Gapping
- Pile interaction
  - Effect of adjacent piles
  - Radiation damping interaction
- Important for fatigue life of structure
  - Provides critical damping when turbine is parked

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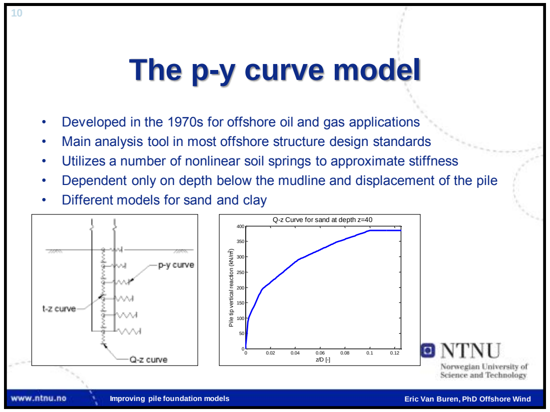

The p-y curve model

- Developed in the 1970s for offshore oil and gas applications
- Main analysis tool in most offshore structure design standards
- Utilizes a number of nonlinear soil springs to approximate stiffness
- Dependent only on depth below the mudline and displacement of the pile
- Different models for sand and clay

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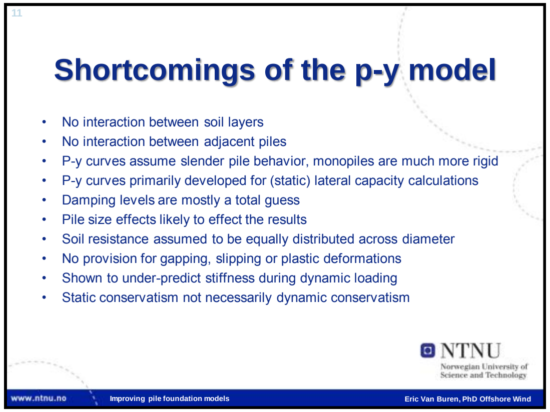

Shortcomings of the p-y model

- No interaction between soil layers
- No interaction between adjacent piles
- P-y curves assume slender pile behavior, monopiles are much more rigid
- P-y curves primarily developed for (static) lateral capacity calculations
- Damping levels are mostly a total guess
- Pile size effects likely to effect the results
- Soil resistance assumed to be equally distributed across diameter
- No provision for gapping, slipping or plastic deformations
- Shown to under-predict stiffness during dynamic loading
- Static conservatism not necessarily dynamic conservatism

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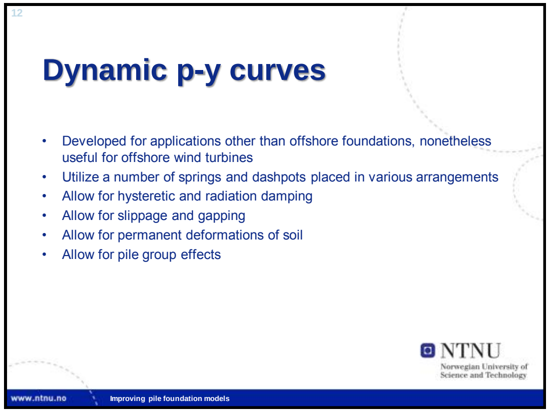

Dynamic p-y curves

- Developed for applications other than offshore foundations, nonetheless useful for offshore wind turbines
- Utilize a number of springs and dashpots placed in various arrangements
- Allow for hysteretic and radiation damping
- Allow for slippage and gapping
- Allow for permanent deformations of soil
- Allow for pile group effects

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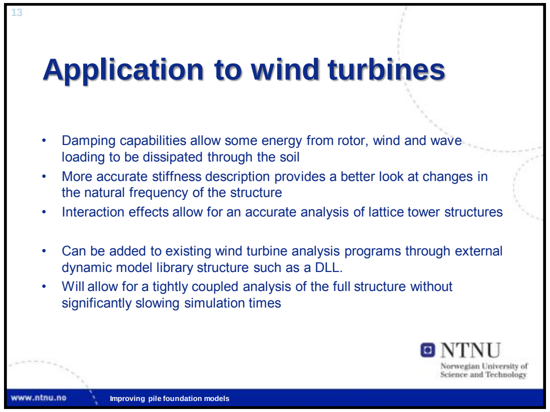

Application to wind turbines

- Damping capabilities allow some energy from rotor, wind and wave loading to be dissipated through the soil
- More accurate stiffness description provides a better look at changes in the natural frequency of the structure
- Interaction effects allow for an accurate analysis of lattice tower structures

- Can be added to existing wind turbine analysis programs through external dynamic model library structure such as a DLL.
- Will allow for a tightly coupled analysis of the full structure without significantly slowing simulation times

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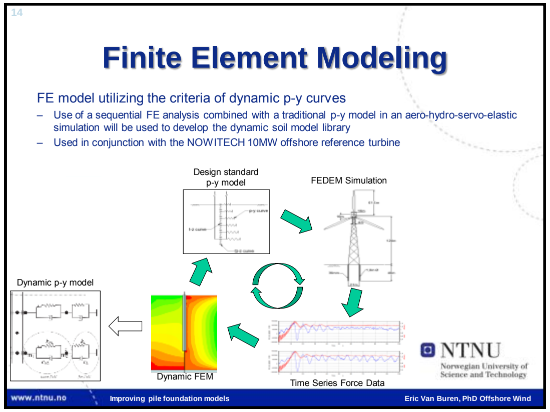

Finite Element Modeling

FE model utilizing the criteria of dynamic p-y curves
- Use of a sequential FE analysis combined with a traditional p-y model in an aero-hydro-servo-elastic simulation will be used to develop the dynamic soil model library
- Used in conjunction with the NOWITECH 10MW offshore reference turbine

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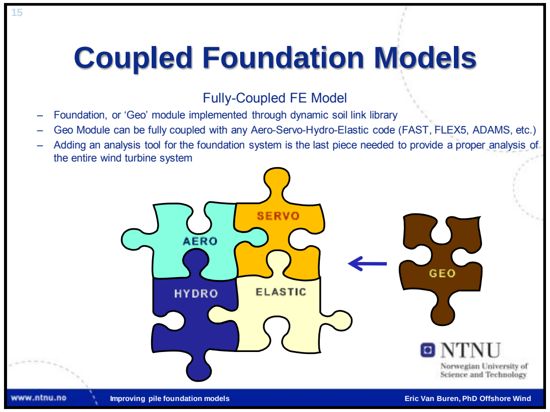

Coupled Foundation Models

Fully-Coupled FE Model
- Foundation, or 'Geo' module implemented through dynamic soil link library
- Geo Module can be fully coupled with any 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

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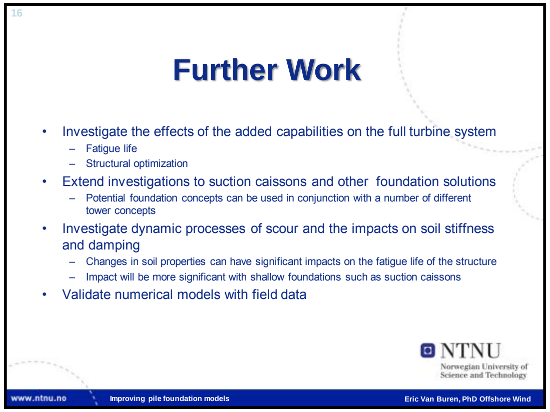

Further Work

- Investigate the effects of the added capabilities on the full turbine system
  - Fatigue life
  - Structural optimization
- Extend investigations to suction caissons and other foundation solutions
  - Potential foundation concepts can be used in conjunction with a number of different tower concepts
- 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
- Validate numerical models with field data

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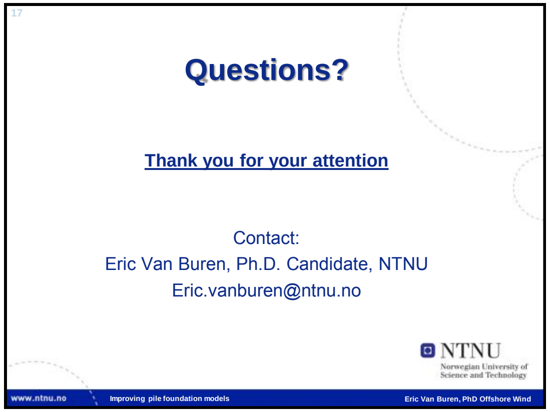

Questions?

Thank you for your attention

Contact:
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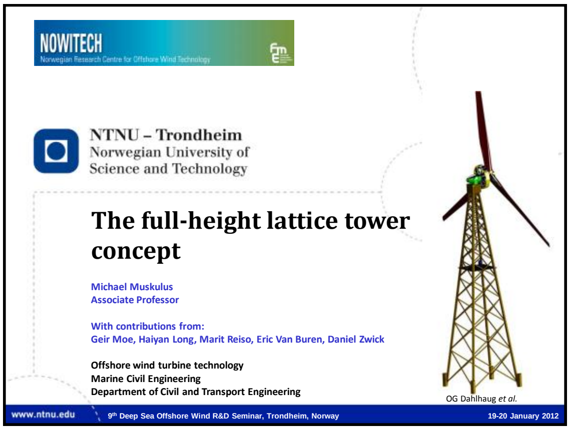

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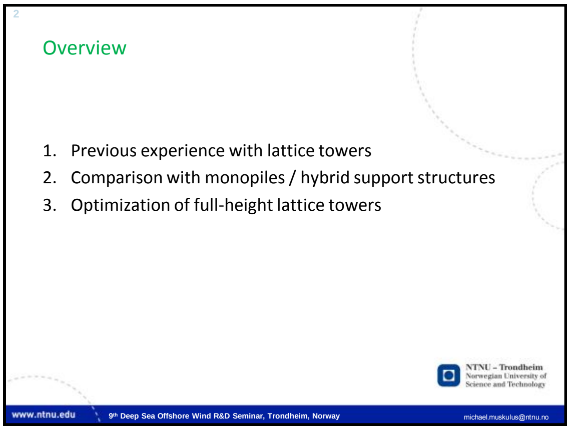
The full-height lattice tower concept

Michael Muskulus
Associate Professor

With contributions from:
Geir Moe, Haiyan Long, Marit Reiso, Eric Van Buren, Daniel Zwick

Offshore wind turbine technology
Marine Civil Engineering
Department of Civil and Transport Engineering

OG Dahlhaug *et al.*



Overview

1. Previous experience with lattice towers
2. Comparison with monopiles / hybrid support structures
3. Optimization of full-height lattice towers

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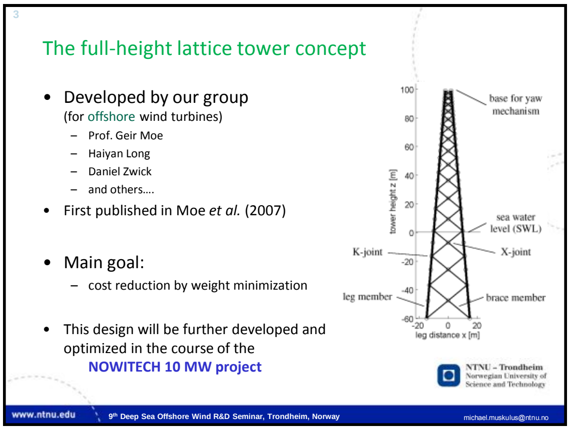

The full-height lattice tower concept

- Developed by our group
  (for offshore wind turbines)
  - Prof. Geir Moe
  - Haiyan Long
  - Daniel Zwick
  - and others….
- First published in Moe *et al.* (2007)
- Main goal:
  - cost reduction by weight minimization
- This design will be further developed and optimized in the course of the
  NOWITECH 10 MW project

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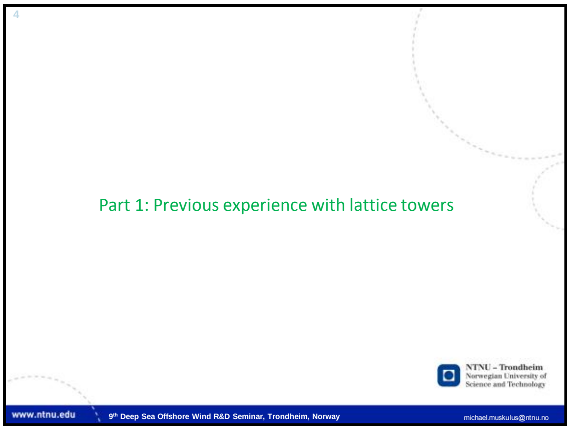

Part 1: Previous experience with lattice towers

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Previous experience with lattice towers 1/3

Figure 16.25. Wind park Qingdao in China with Nordex N62 wind turbines (Nordex)

Onshore:

- Predominant type of wind turbine support structure until late 80s
- Up to 750 kW (Zond Z750) in the US, 55m tall tower
- Difference of 5 percent of total cost compared to monopile (from 20-25 to 15 percent)

Figure 18.14. Assembly of a Vestas V-66 on a 117-m-high lattice tower, using a top crane extension

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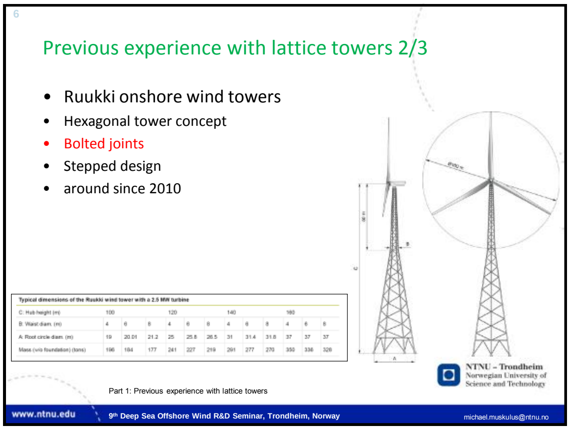
Part 1: Previous experience with lattice towers



Previous experience with lattice towers 2/3

- Ruukki onshore wind towers
- Hexagonal tower concept
- Bolted joints
- Stepped design
- around since 2010

Typical dimensions of the Ruukki wind tower with a 2.5 MW turbine

C: Hub height (m)	100			120			140			160		
B: Waist diam. (m)	4	6	8	4	6	8	4	6	8	4	6	8
A: Root circle diam. (m)	19	20.01	21.2	25	25.8	26.5	31	31.4	31.8	37	37	37
Mass (w/o foundation) (tons)	196	184	177	241	227	219	291	277	270	350	336	326

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Part 1: Previous experience with lattice towers

Previous experience with lattice towers 3/3

The Opti-OWECS support structures:

Gravity lattice tower

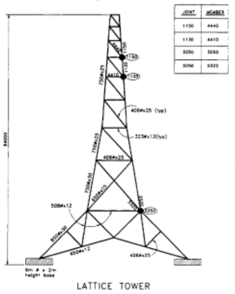
(Kühn 2001)

Developed for NL-5 site

- Wind V_{ave} = 10.1 m/s
- Mean sea level 25 m
- Sea state

  H_{max} = 15.4 m, T_p = 12.5 s
- Stiff design: ≈0.7 Hz first eigenfrequency

height	triangle edge length
- 23 m (MSL)	50 m
- 7 m (MSL)	18 m
21 m (MSL)	8.32 m
59 m (MSL)	3 m
total ballast 1000 t	

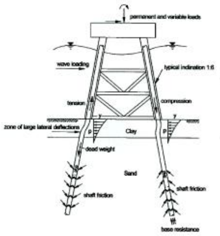


Part 1: Previous experience with lattice towers

Part 2: Comparison with monopiles and hybrid towers

Differences between monopiles and jackets

- Properties of lattice towers
  - Thrust force results mostly in axial forces in legs
  - Bending stiffness depends quadratically on leg bottom distance
  - Needs to be weighted against lengthening of the legs



Part 2: Comparison with other concepts

Differences between monopiles and jackets (for design purposes)

adapted from Marc Seidel (EWEA Offshore 2011)

Monopiles	Jackets
Excitation of *global vibration* by waves in fundamental mode	Stiff jacket structure prevents global vibrations
Misaligned waves cause large fatigue loads	Misalignment effects negligible?
Significant impact of *secondary structures* (e.g., boat landing)	
Soil data most important parameter	Soil has no significant influence?
Fatigue loads often *higher for idling turbine*: Reduced availability must be considered	100 percent availability is conservative

Jackets are easy to design?

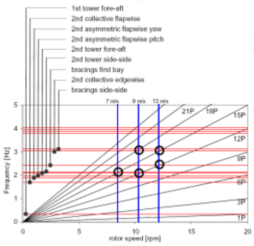
Part 2: Comparison with other concepts

Challenges for design optimization of lattice support structures

- Irregular and transient loads
- Uncertainty about soil conditions (scour)
- Fatigue-driven
- Importance of local vibrations

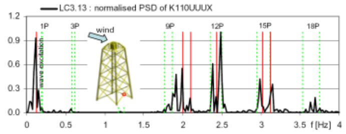
  (Böker 2009)

  Excitable from higher-order rotor modes

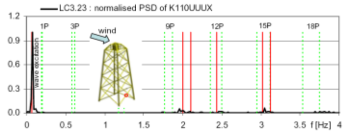


Part 2: Comparison with other concepts

Local vibrations



Irregular sea state
H_s = 1.5m
T_p = 5.5 s



Irregular sea state
H_s = 5.6m
T_p = 10.6 s

More severe sea state
Local vibrations less important

NB: normalized PSDs

Part 2: Comparison with other concepts

Summary

Monopiles

- Large diameter in deeper water: Problems for fabrication and pile-driving
- Problems with grouted connection
- Excitation of *global vibrations*
- *Soil uncertainty* critical design factor
- Secondary structure and wind-wave misalignment complicate the design
- Expensive transition piece
- Relatively large weight
- Protected space for access and maintenance (also: security, cold climates)

Jackets (half-height and full-height)

- Larger structures (esp. full-height tower): Problems for fabrication and installation
- Grouted connection unproblematic?
- *Local vibrations* of braces a potential problem
- Soil influence negligible (conservative)?
- Secondary structure negligible?

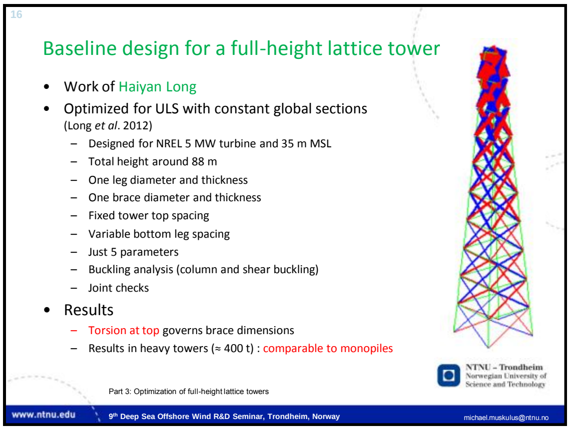
- More economical transition to yaw bearing
- Much lighter structure
- Access and maintenance not as straightforward and economical
- Many members and welds increase production time and cost
- Optimization of structures (different sites) not straightforward

> "if the combined cost of piling and access systems for the full-height lattice tower is significantly lower than the cost of the monopile foundation and transition piece, the full-height lattice tower is an interesting alternative"

Part 3: Optimization of full-height lattice towers

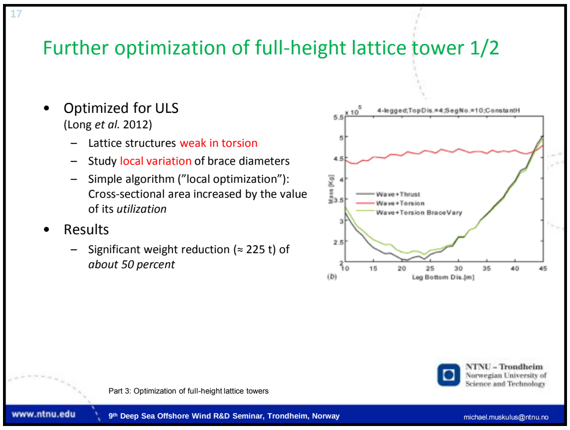
Assessment of fatigue damage

- For design optimization it is important
  - to obtain good approximations of lifetime fatigue damage
  - in a quick and efficient way (for many points in design space)
  - more or less **UNSOLVED PROBLEM**
- Available approaches
  - Short-term assessment of fatigue
    - Simplified fatigue assessment
    - Spectral assessment
    - Time-domain simulation (most accurate; expensive)
  - Long-term assessment of fatigue
    - Statistical lumping of load cases
    - Parametric load models?
  - (also see: API 2A WSD)



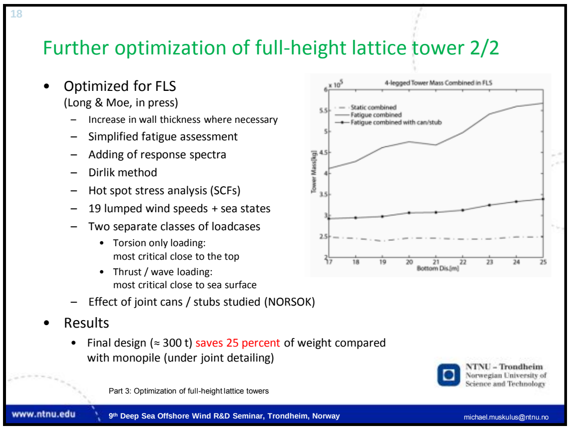
Baseline design for a full-height lattice tower

- Work of Haiyan Long
- Optimized for ULS with constant global sections (Long *et al*. 2012)
  - Designed for NREL 5 MW turbine and 35 m MSL
  - Total height around 88 m
  - One leg diameter and thickness
  - One brace diameter and thickness
  - Fixed tower top spacing
  - Variable bottom leg spacing
  - Just 5 parameters
  - Buckling analysis (column and shear buckling)
  - Joint checks
- Results
  - Torsion at top governs brace dimensions
  - Results in heavy towers (≈ 400 t) : comparable to monopiles



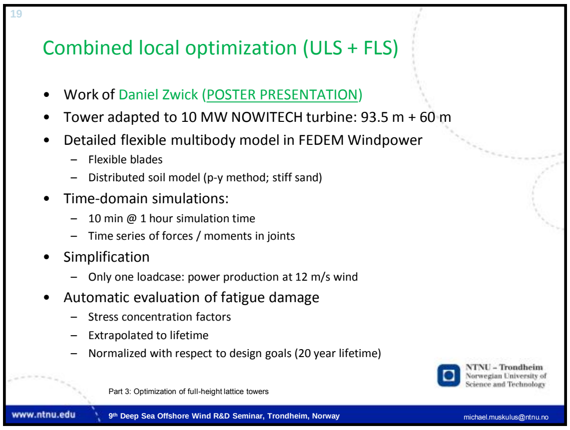
Further optimization of full-height lattice tower 1/2

- Optimized for ULS (Long *et al.* 2012)
  - Lattice structures weak in torsion
  - Study local variation of brace diameters
  - Simple algorithm ("local optimization"): Cross-sectional area increased by the value of its *utilization*
- Results
  - Significant weight reduction (≈ 225 t) of *about 50 percent*



Further optimization of full-height lattice tower 2/2

- Optimized for FLS (Long & Moe, in press)
  - Increase in wall thickness where necessary
  - Simplified fatigue assessment
  - Adding of response spectra
  - Dirlik method
  - Hot spot stress analysis (SCFs)
  - 19 lumped wind speeds + sea states
  - Two separate classes of loadcases
    - Torsion only loading: most critical close to the top
    - Thrust / wave loading: most critical close to sea surface
  - Effect of joint cans / stubs studied (NORSOK)
- Results
  - Final design (≈ 300 t) saves 25 percent of weight compared with monopile (under joint detailing)



Combined local optimization (ULS + FLS)

- Work of Daniel Zwick (POSTER PRESENTATION)
- Tower adapted to 10 MW NOWITECH turbine: 93.5 m + 60 m
- Detailed flexible multibody model in FEDEM Windpower
  - Flexible blades
  - Distributed soil model (p-y method; stiff sand)
- Time-domain simulations:
  - 10 min @ 1 hour simulation time
  - Time series of forces / moments in joints
- Simplification
  - Only one loadcase: power production at 12 m/s wind
- Automatic evaluation of fatigue damage
  - Stress concentration factors
  - Extrapolated to lifetime
  - Normalized with respect to design goals (20 year lifetime)

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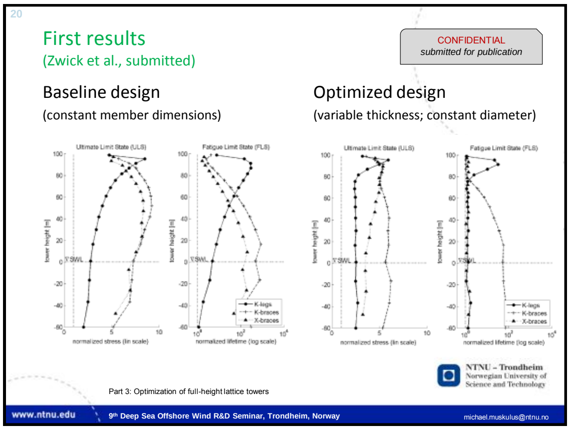

First results

(Zwick et al., submitted)

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submitted for publication

Baseline design

(constant member dimensions)

Optimized design

(variable thickness; constant diameter)

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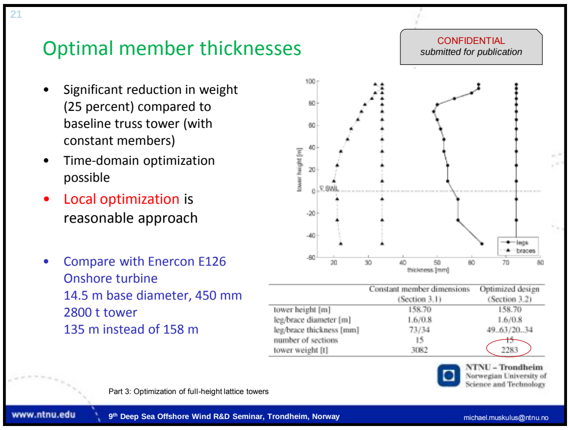

Optimal member thicknesses

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submitted for publication

- Significant reduction in weight (25 percent) compared to baseline truss tower (with constant members)
- Time-domain optimization possible
- Local optimization is reasonable approach

- Compare with Enercon E126 Onshore turbine
  14.5 m base diameter, 450 mm
  2800 t tower
  135 m instead of 158 m

	Constant member dimensions (Section 3.1)	Optimized design (Section 3.2)
tower height [m]	158.70	158.70
leg/brace diameter [m]	1.6/0.8	1.6/0.8
leg/brace thickness [mm]	73/34	49..63/20..34
number of sections	15	15
tower weight [t]	3082	2283

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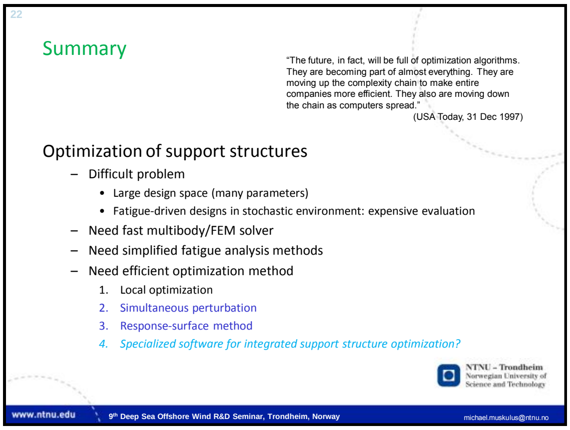

Summary

> "The future, in fact, will be full of optimization algorithms. They are becoming part of almost everything. They are moving up the complexity chain to make entire companies more efficient. They also are moving down the chain as computers spread."
> (USA Today, 31 Dec 1997)

Optimization of support structures

- Difficult problem
  - Large design space (many parameters)
  - Fatigue-driven designs in stochastic environment: expensive evaluation
- Need fast multibody/FEM solver
- Need simplified fatigue analysis methods
- Need efficient optimization method
  1. Local optimization
  2. Simultaneous perturbation
  3. Response-surface method
  4. *Specialized software for integrated support structure optimization?*

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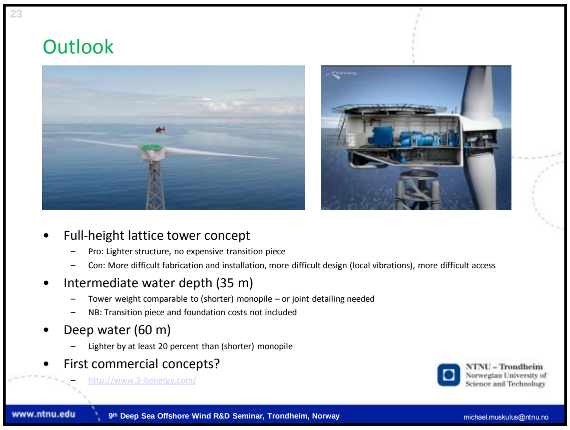

Outlook

- Full-height lattice tower concept
  - Pro: Lighter structure, no expensive transition piece
  - Con: More difficult fabrication and installation, more difficult design (local vibrations), more difficult access
- Intermediate water depth (35 m)
  - Tower weight comparable to (shorter) monopile – or joint detailing needed
  - NB: Transition piece and foundation costs not included
- Deep water (60 m)
  - Lighter by at least 20 percent than (shorter) monopile
- First commercial concepts?
  - http://www.2-benergy.com/

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Additional slides

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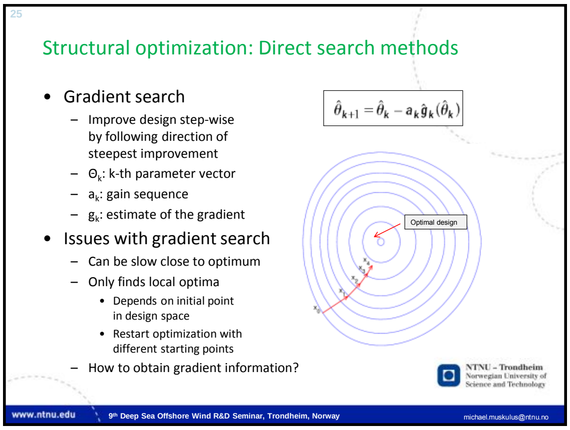

Structural optimization: Direct search methods

- Gradient search
  - Improve design step-wise by following direction of steepest improvement
  - Θ_k: k-th parameter vector
  - a_k: gain sequence
  - g_k: estimate of the gradient
- Issues with gradient search
  - Can be slow close to optimum
  - Only finds local optima
    - Depends on initial point in design space
    - Restart optimization with different starting points
  - How to obtain gradient information?

$$\hat{\theta}_{k+1} = \hat{\theta}_k - a_k \hat{g}_k(\hat{\theta}_k)$$

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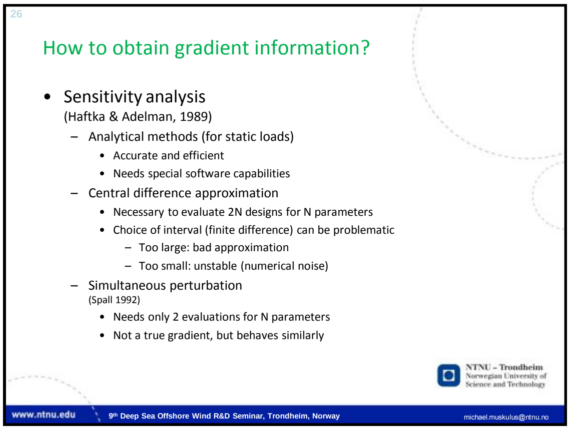

How to obtain gradient information?

- Sensitivity analysis
  (Haftka & Adelman, 1989)
  - Analytical methods (for static loads)
    - Accurate and efficient
    - Needs special software capabilities
  - Central difference approximation
    - Necessary to evaluate 2N designs for N parameters
    - Choice of interval (finite difference) can be problematic
      - Too large: bad approximation
      - Too small: unstable (numerical noise)
  - Simultaneous perturbation
    (Spall 1992)
    - Needs only 2 evaluations for N parameters
    - Not a true gradient, but behaves similarly

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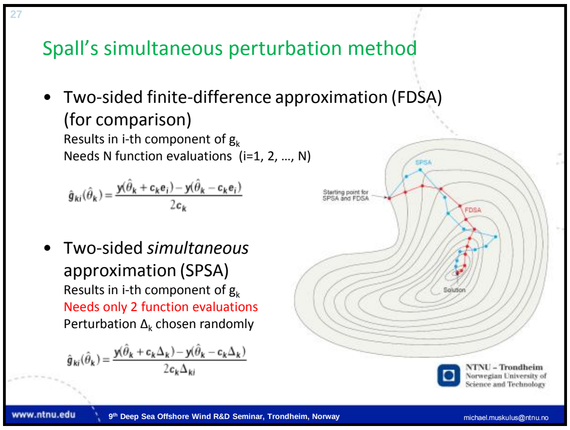

Spall’s simultaneous perturbation method

- Two-sided finite-difference approximation (FDSA) (for comparison)
  Results in i-th component of g_k
  Needs N function evaluations (i=1, 2, …, N)

$$\hat{g}_{ki}(\hat{\theta}_k) = \frac{y(\hat{\theta}_k + c_k e_i) - y(\hat{\theta}_k - c_k e_i)}{2c_k}$$

- Two-sided *simultaneous* approximation (SPSA)
  Results in i-th component of g_k
  Needs only 2 function evaluations
  Perturbation Δ_k chosen randomly

$$\hat{g}_{ki}(\hat{\theta}_k) = \frac{y(\hat{\theta}_k + c_k \Delta_k) - y(\hat{\theta}_k - c_k \Delta_k)}{2c_k \Delta_{ki}}$$

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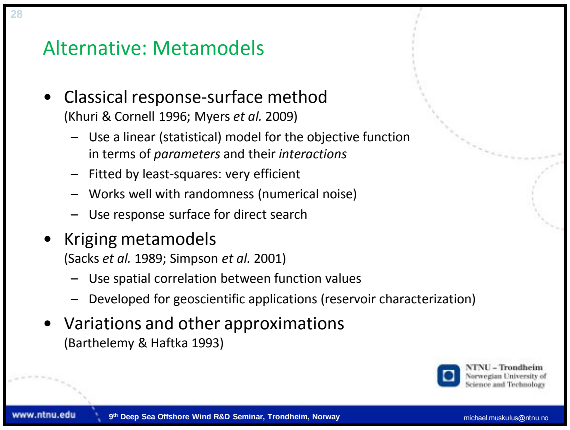

Alternative: Metamodels

- Classical response-surface method
  (Khuri & Cornell 1996; Myers *et al.* 2009)
  - Use a linear (statistical) model for the objective function in terms of *parameters* and their *interactions*
  - Fitted by least-squares: very efficient
  - Works well with randomness (numerical noise)
  - Use response surface for direct search
- Kriging metamodels
  (Sacks *et al.* 1989; Simpson *et al.* 2001)
  - Use spatial correlation between function values
  - Developed for geoscientific applications (reservoir characterization)
- Variations and other approximations
  (Barthelemy & Haftka 1993)

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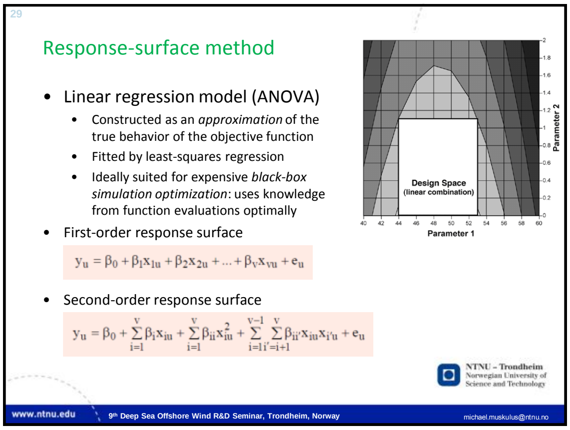

Response-surface method

- Linear regression model (ANOVA)
  - Constructed as an *approximation* of the true behavior of the objective function
  - Fitted by least-squares regression
  - Ideally suited for expensive *black-box simulation optimization*: uses knowledge from function evaluations optimally
- First-order response surface

$$y_u = \beta_0 + \beta_1 x_{1u} + \beta_2 x_{2u} + \ldots + \beta_v x_{vu} + e_u$$

- Second-order response surface

$$y_u = \beta_0 + \sum_{i=1}^{v} \beta_i x_{iu} + \sum_{i=1}^{v} \beta_{ii} x_{iu}^2 + \sum_{i=1}^{v-1} \sum_{i'=i+1}^{v} \beta_{ii'} x_{iu} x_{i'u} + e_u$$

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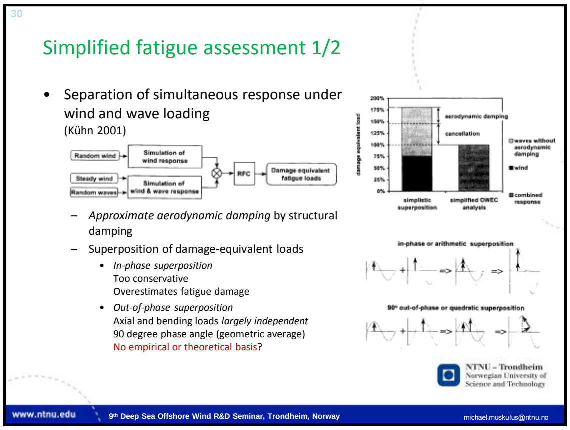

Simplified fatigue assessment 1/2

- Separation of simultaneous response under wind and wave loading
  (Kühn 2001)
  - *Approximate aerodynamic damping* by structural damping
  - Superposition of damage-equivalent loads
    - *In-phase superposition*
      Too conservative
      Overestimates fatigue damage
    - *Out-of-phase superposition*
      Axial and bending loads *largely independent*
      90 degree phase angle (geometric average)
      No empirical or theoretical basis?

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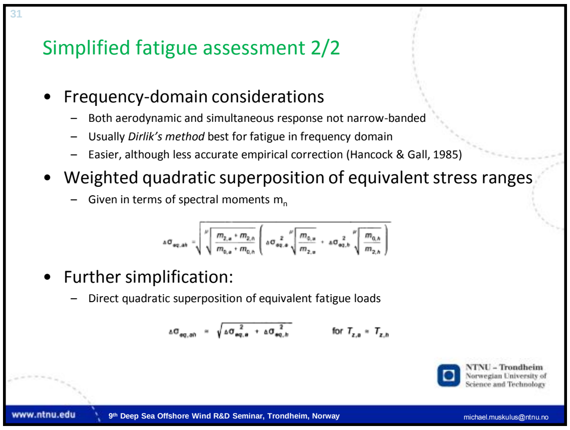

Simplified fatigue assessment 2/2

- Frequency-domain considerations
    - Both aerodynamic and simultaneous response not narrow-banded
    - Usually *Dirlik's method* best for fatigue in frequency domain
    - Easier, although less accurate empirical correction (Hancock & Gall, 1985)
- Weighted quadratic superposition of equivalent stress ranges
    - Given in terms of spectral moments m_n

$$\Delta\sigma_{eq,ah} = \sqrt{\sqrt[\mu]{\frac{m_{2,a} + m_{2,h}}{m_{0,a} + m_{0,h}}}\left(\Delta\sigma_{eq,a}^{2}\sqrt[\mu]{\frac{m_{0,a}}{m_{2,a}}} + \Delta\sigma_{eq,h}^{2}\sqrt[\mu]{\frac{m_{0,h}}{m_{2,h}}}\right)}$$

- Further simplification:
    - Direct quadratic superposition of equivalent fatigue loads

$$\Delta\sigma_{eq,ah} = \sqrt{\Delta\sigma_{eq,a}^{2} + \Delta\sigma_{eq,h}^{2}} \qquad \text{for } T_{z,a} = T_{z,h}$$

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F Wind farm modelling

Experimental results of the NOWITECH/NORCOWE blind test, Pål Egil Eriksen, PhD stud, NTNU

Wind Turbine Wake Models, Stefan Ivanell, University of Gotland

Wake Modeling with the Actuator Disc concept, Arne Reidar Gravdahl, WindSim AS

Recent Advances in Modelling Wind Parks in STAR-CCM+, Steve Evans, CD-adapco

Offshore wind farm optimisation, Trygve Skjold, GexCon

Experimental results for the NOWITECH/NORCOWE blind test

Pål Egil Eriksen, Phd candidate, NOWITECH/NTNU

DeepWind, 19-20 January 2012, Trondheim

Contents

- Introduction to WP1 and the Blind Test.
- Description of experimental facilities and setup.
- Experimental results
- Conclusion
- Future work
- A small sample of the results from the workshop.

Introduction to WP1 and the Blind Test (1/2)

- Goal of WP1: “The goal is establishment of a set of proven tools for integrated design of deep-sea wind turbines, hereunder characterization and interaction of wind, wave and current”
- Future product: Integrated design tools
- Example: Wind farm planning
  - Large range of scales => Simplifications are needed
  - State of the art
- Offshore wind margins are small
  - Accuracy is important

Introduction to WP1 and the Blind Test (2/2)

- The Blind Test
  - Comparison between experimental results and numerical predictions for a model wind turbine.
    - Power and thrust coefficients
    - Force distribution on blades(comparison between numerical predictions only)
    - Wake velocity field
  - A test case has been defined and the setup is open to everyone.
  - Seven different numerical predictions were handed in.
  - Experimental investigations carried out at NTNU
  - Cooperation between NOWITECH and NORCOWE
  - Workshop held in Bergen, October 2011.

Experimental setup (1/2)

- Wind tunnel
  - 11.2 m x 1.8 m x 2.7 m
  - 0.3 % turbulence level
  - Automatic traverse
  - Six component balance
  - Closed loop tunnel

Fig 1: Upstream view of model wind turbine

Experimental setup (2/2)

- Model wind turbine:
  - Diameter: 0.9 m
  - Peak efficiency: 0.448
  - Instrumentation:
    - Torque sensor
    - Photo cell
    - Slip rings for strain gages
  - NREL S826
  - Large chord length => Increases Re (10^5)
  - Stiff blade made of aluminum
  - Well known performance characteristics
  - Positioned 4D from entrance
  - Area ratio: 12%

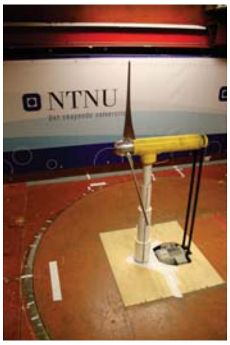
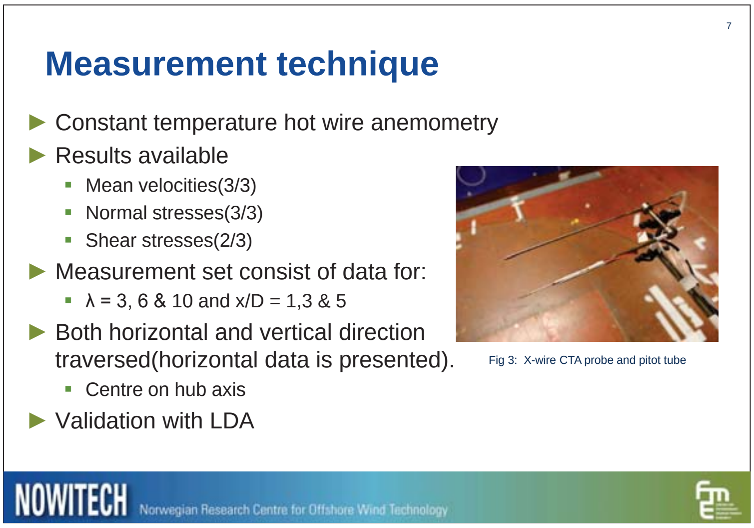


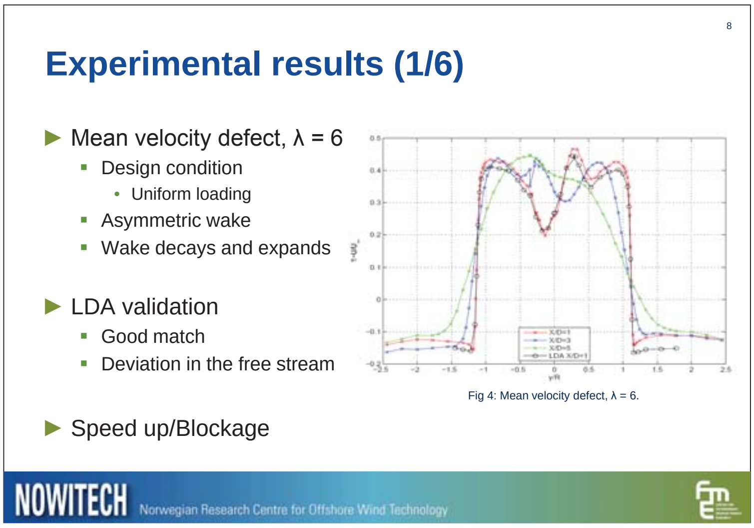
Fig 2: Model wind turbine in testsection



Measurement technique

- Constant temperature hot wire anemometry
- Results available
  - Mean velocities(3/3)
  - Normal stresses(3/3)
  - Shear stresses(2/3)
- Measurement set consist of data for:
  - λ = 3, 6 & 10 and x/D = 1,3 & 5
- Both horizontal and vertical direction traversed(horizontal data is presented).
  - Centre on hub axis
- Validation with LDA

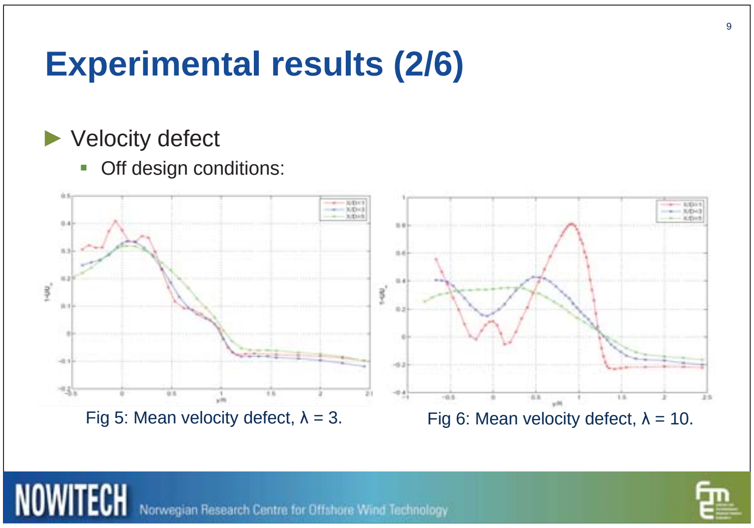
Fig 3: X-wire CTA probe and pitot tube



Experimental results (1/6)

- Mean velocity defect, λ = 6
  - Design condition
    - Uniform loading
  - Asymmetric wake
  - Wake decays and expands
- LDA validation
  - Good match
  - Deviation in the free stream
- Speed up/Blockage

Fig 4: Mean velocity defect, λ = 6.

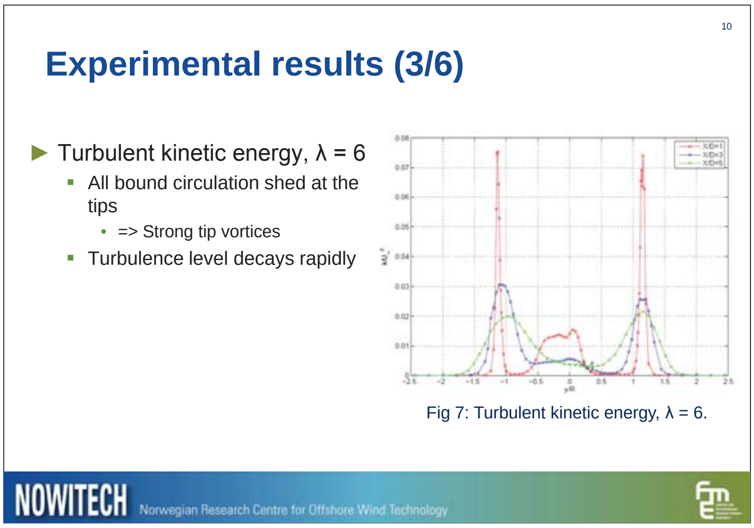


Experimental results (2/6)

- Velocity defect
  - Off design conditions:

Fig 5: Mean velocity defect, λ = 3.

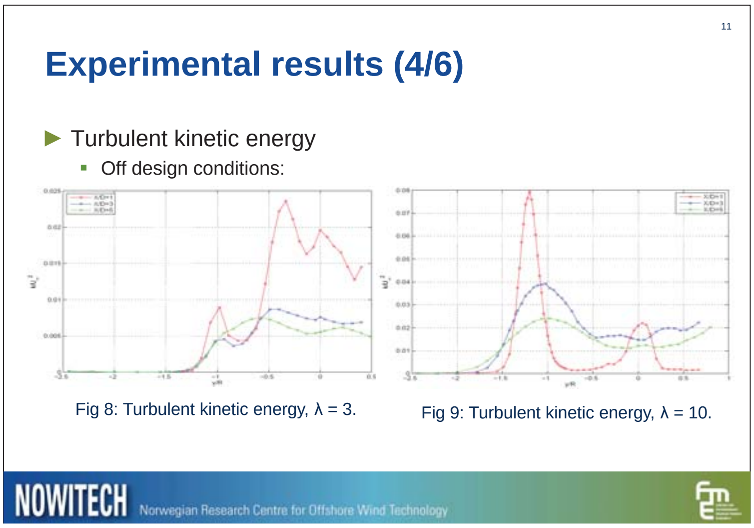
Fig 6: Mean velocity defect, λ = 10.



Experimental results (3/6)

- Turbulent kinetic energy, λ = 6
  - All bound circulation shed at the tips
    - => Strong tip vortices
  - Turbulence level decays rapidly

Fig 7: Turbulent kinetic energy, λ = 6.

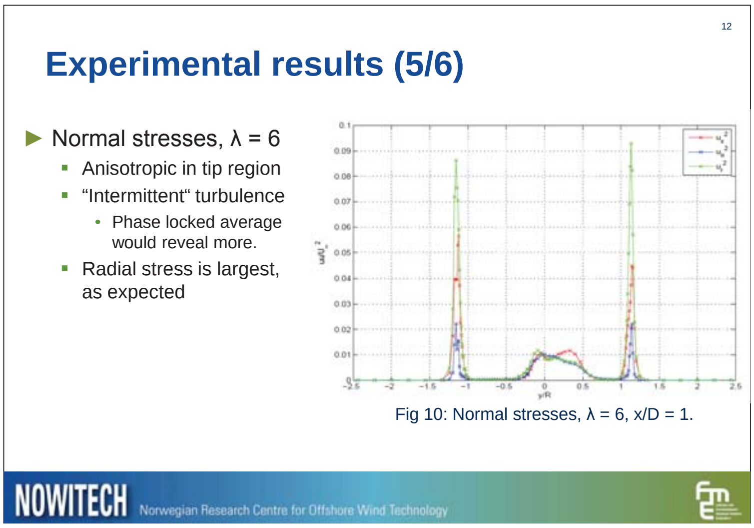


Experimental results (4/6)

- Turbulent kinetic energy
  - Off design conditions:

Fig 8: Turbulent kinetic energy, λ = 3.

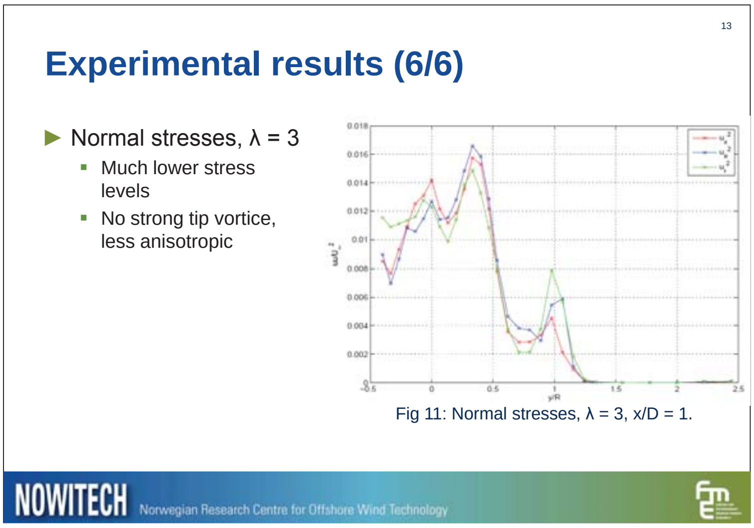
Fig 9: Turbulent kinetic energy, λ = 10.



Experimental results (5/6)

- Normal stresses, λ = 6
  - Anisotropic in tip region
  - “Intermittent“ turbulence
    - Phase locked average would reveal more.
  - Radial stress is largest, as expected

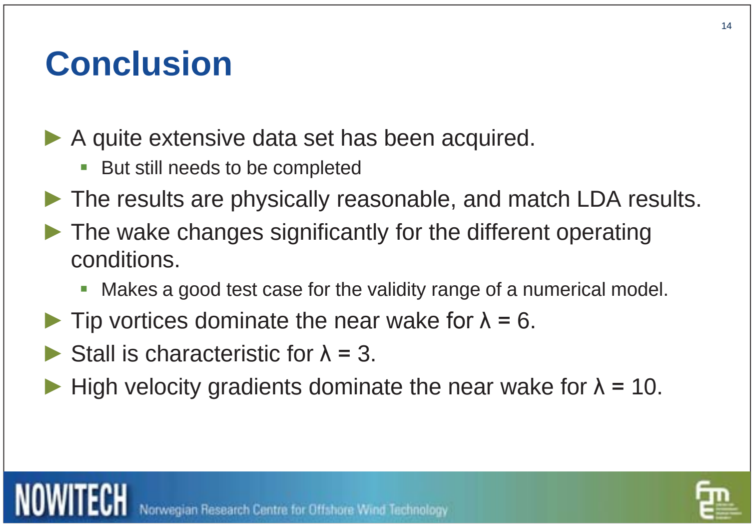
Fig 10: Normal stresses, λ = 6, x/D = 1.



Experimental results (6/6)

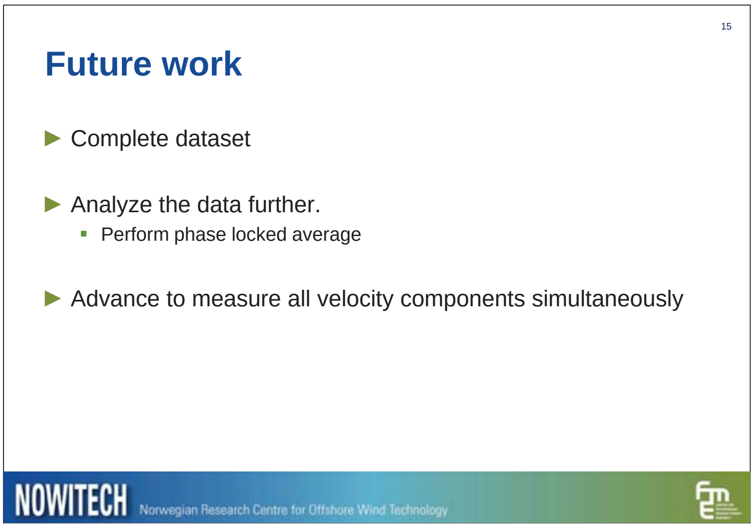
- Normal stresses, λ = 3
  - Much lower stress levels
  - No strong tip vortice, less anisotropic

Fig 11: Normal stresses, λ = 3, x/D = 1.



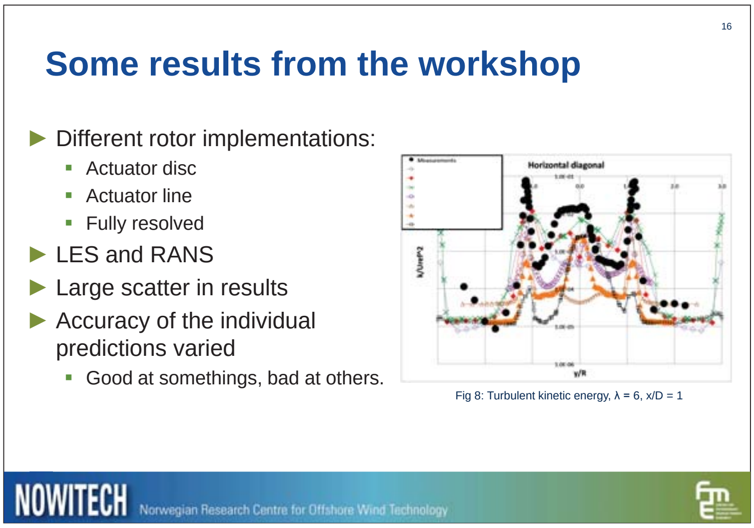
Conclusion

- A quite extensive data set has been acquired.
  - But still needs to be completed
- The results are physically reasonable, and match LDA results.
- The wake changes significantly for the different operating conditions.
  - Makes a good test case for the validity range of a numerical model.
- Tip vortices dominate the near wake for λ = 6.
- Stall is characteristic for λ = 3.
- High velocity gradients dominate the near wake for λ = 10.



Future work

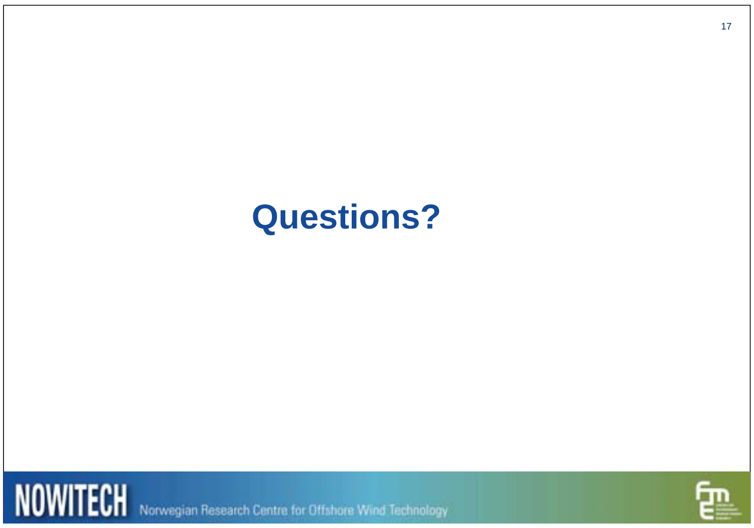
- Complete dataset
- Analyze the data further.
  - Perform phase locked average
- Advance to measure all velocity components simultaneously



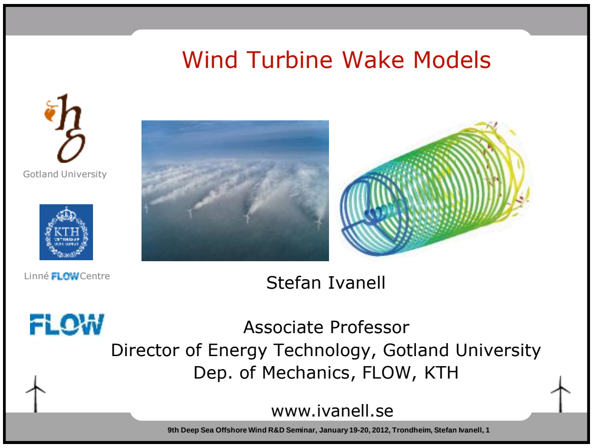
Some results from the workshop

- Different rotor implementations:
  - Actuator disc
  - Actuator line
  - Fully resolved
- LES and RANS
- Large scatter in results
- Accuracy of the individual predictions varied
  - Good at somethings, bad at others.

Fig 8: Turbulent kinetic energy, λ = 6, x/D = 1



Questions?



Wind Turbine Wake Models

Gotland University

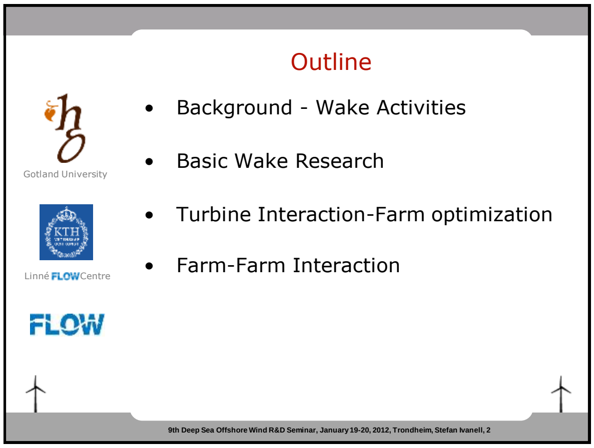
Linné FLOW Centre

FLOW

Stefan Ivanell

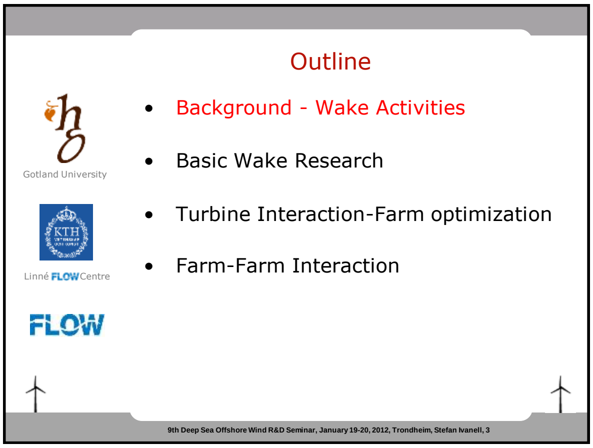
Associate Professor
Director of Energy Technology, Gotland University
Dep. of Mechanics, FLOW, KTH

www.ivanell.se



Outline

- Background - Wake Activities
- Basic Wake Research
- Turbine Interaction-Farm optimization
- Farm-Farm Interaction



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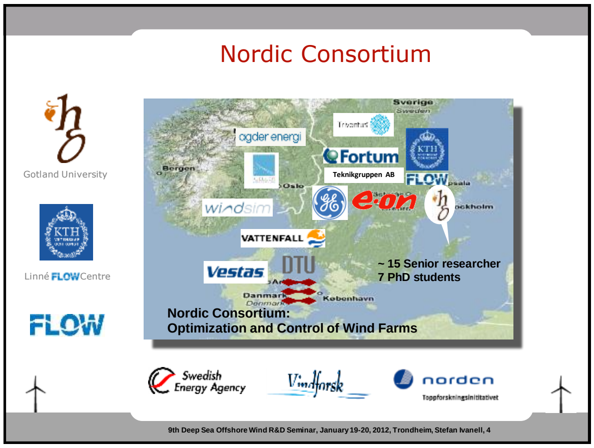


Nordic Consortium

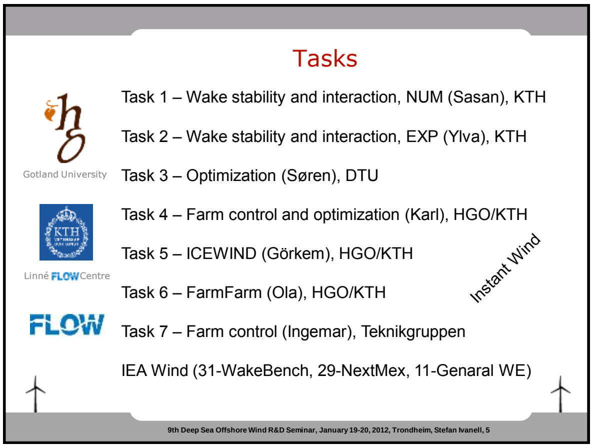
~ 15 Senior researcher
7 PhD students

Nordic Consortium:
Optimization and Control of Wind Farms

Swedish Energy Agency

Vindforsk

norden Toppforskningsinitiativet



Tasks

Task 1 – Wake stability and interaction, NUM (Sasan), KTH

Task 2 – Wake stability and interaction, EXP (Ylva), KTH

Task 3 – Optimization (Søren), DTU

Task 4 – Farm control and optimization (Karl), HGO/KTH

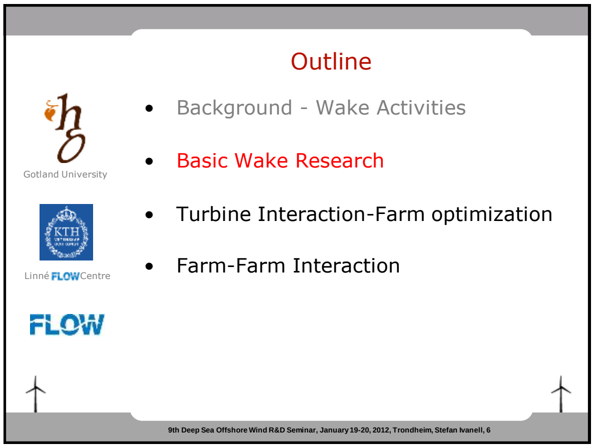
Task 5 – ICEWIND (Görkem), HGO/KTH

Task 6 – FarmFarm (Ola), HGO/KTH

Instant Wind

Task 7 – Farm control (Ingemar), Teknikgruppen

IEA Wind (31-WakeBench, 29-NextMex, 11-Genaral WE)



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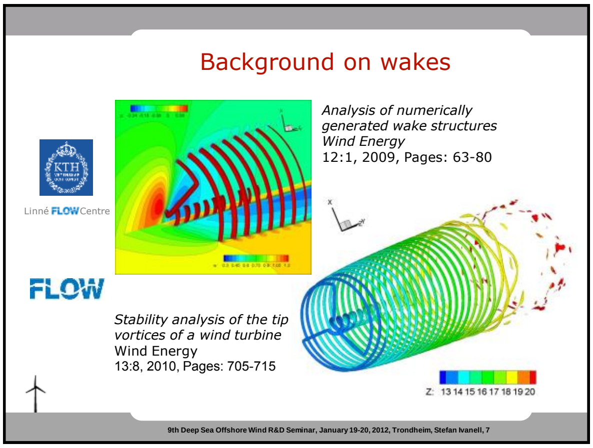
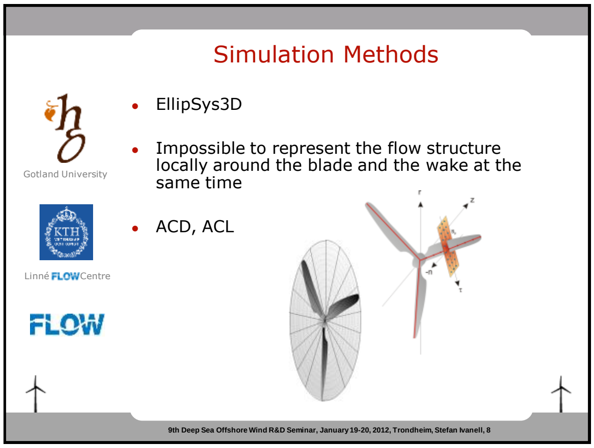


Background on wakes

Analysis of numerically generated wake structures
Wind Energy
12:1, 2009, Pages: 63-80

Stability analysis of the tip vortices of a wind turbine
Wind Energy
13:8, 2010, Pages: 705-715

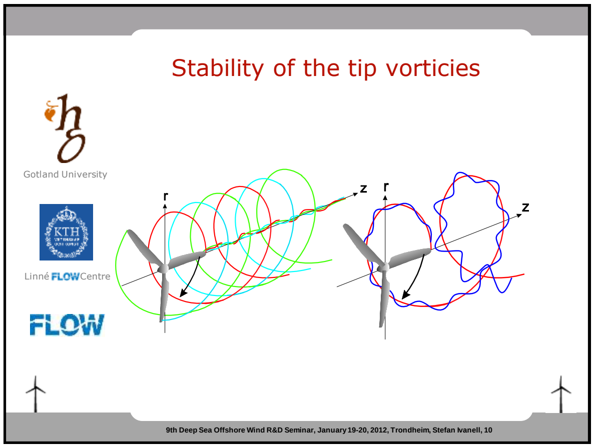


Simulation Methods

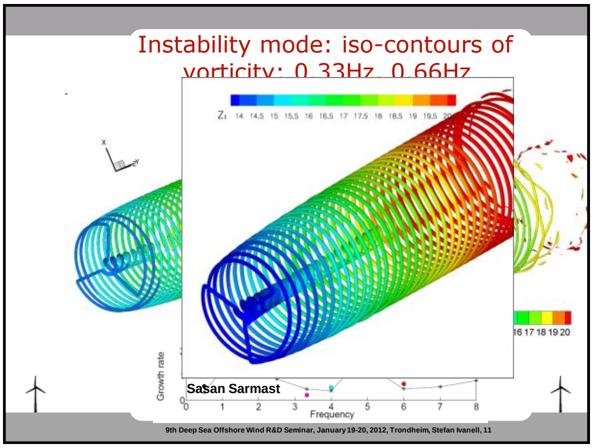
- EllipSys3D
- Impossible to represent the flow structure locally around the blade and the wake at the same time
- ACD, ACL

Wake structure

[Montgomerie, Dahlberg]

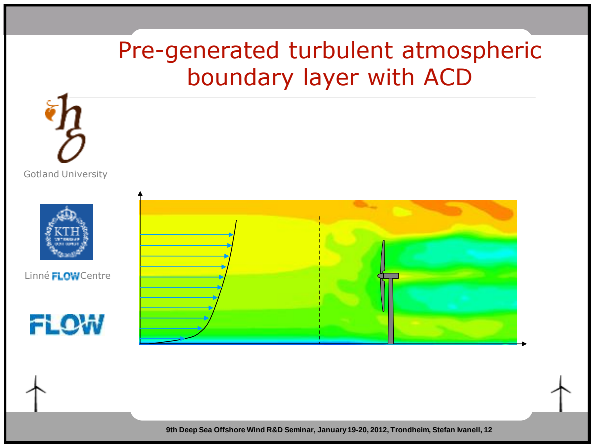


Stability of the tip vorticies



Instability mode: iso-contours of vorticity: 0.33Hz, 0.66Hz

Sasan Sarmast

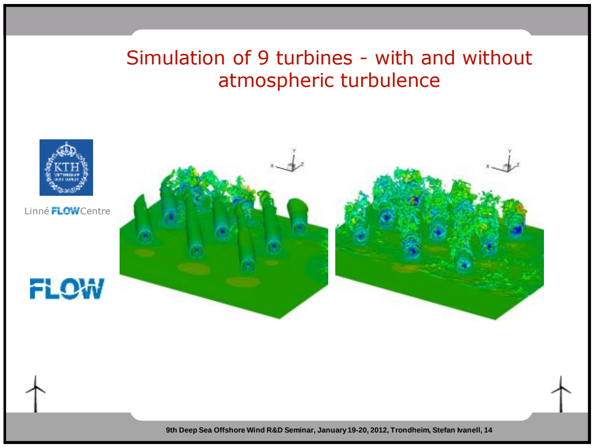


Pre-generated turbulent atmospheric boundary layer with ACD

Gotland University

Linné FLOW Centre

FLOW



Simulation of 9 turbines - with and without atmospheric turbulence

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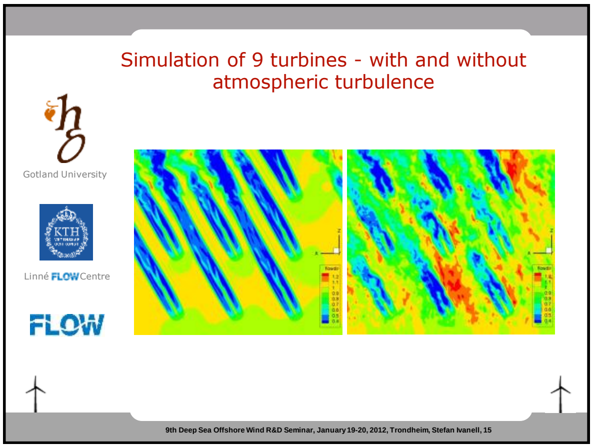

Simulation of 9 turbines - with and without atmospheric turbulence

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Outline

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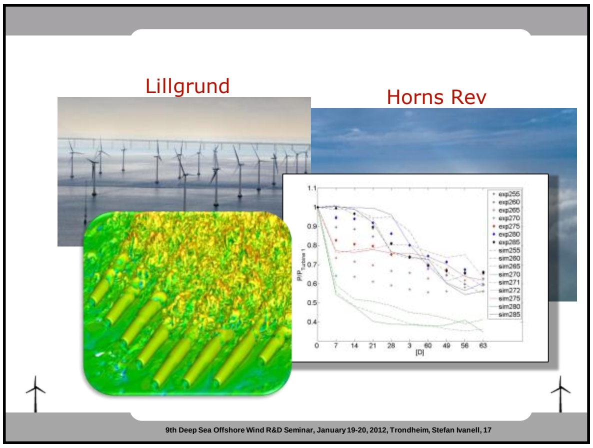
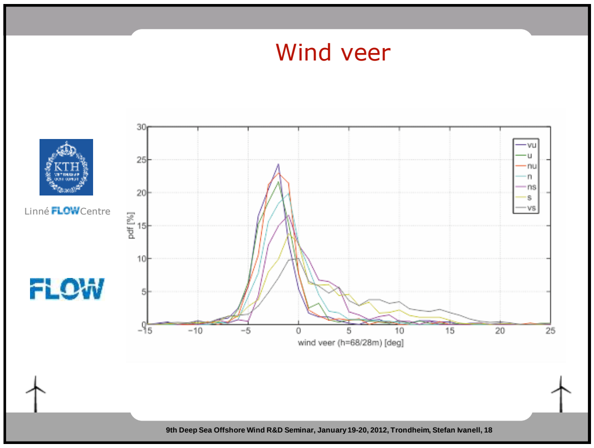


Lillgrund

Horns Rev



Wind veer

Linné FLOW Centre

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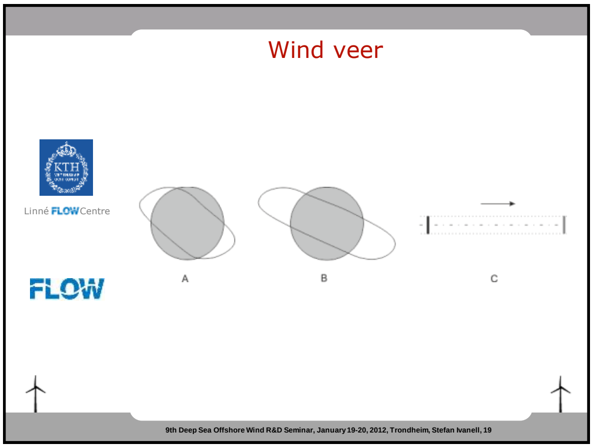
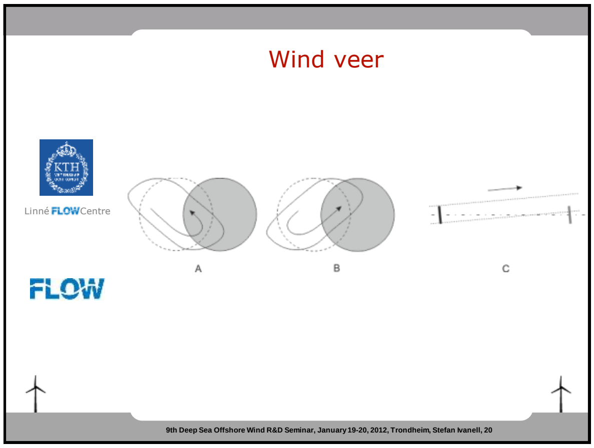


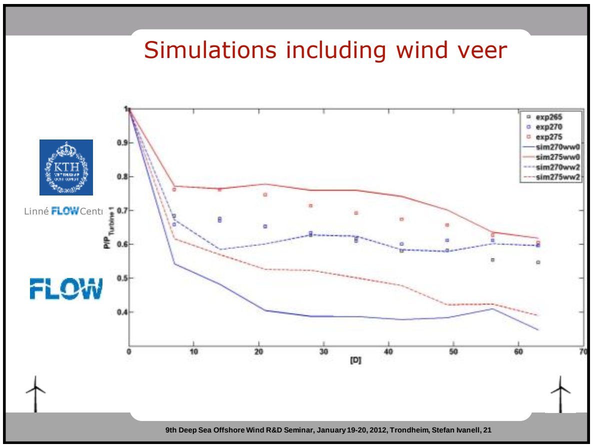
Wind veer

9th Deep Sea Offshore Wind R&D Seminar, January 19-20, 2012, Trondheim, Stefan Ivanell, 19



Wind veer

9th Deep Sea Offshore Wind R&D Seminar, January 19-20, 2012, Trondheim, Stefan Ivanell, 20



Simulations including wind veer

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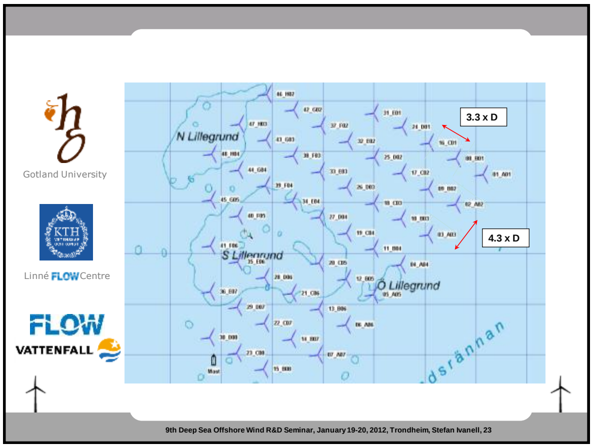

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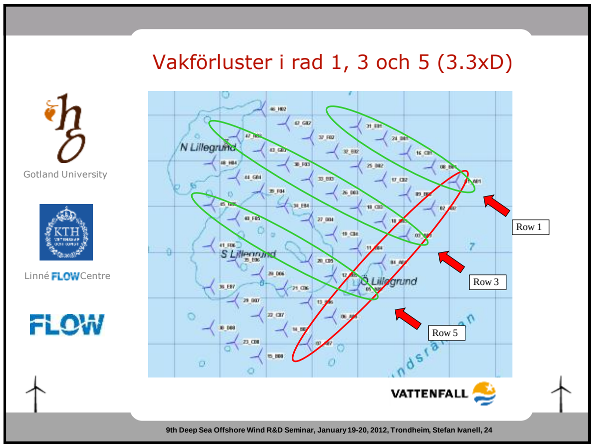

Vakförluster i rad 1, 3 och 5 (3.3xD)

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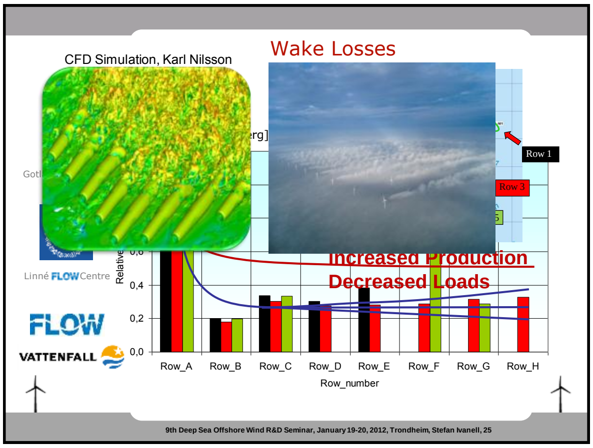
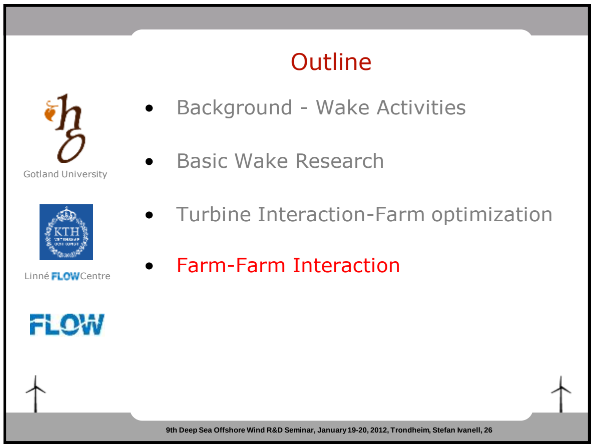


Wake Losses

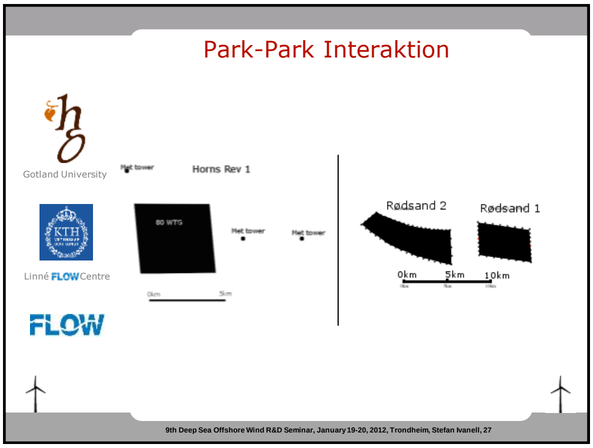
CFD Simulation, Karl Nilsson

Increased Production
Decreased Loads



Outline

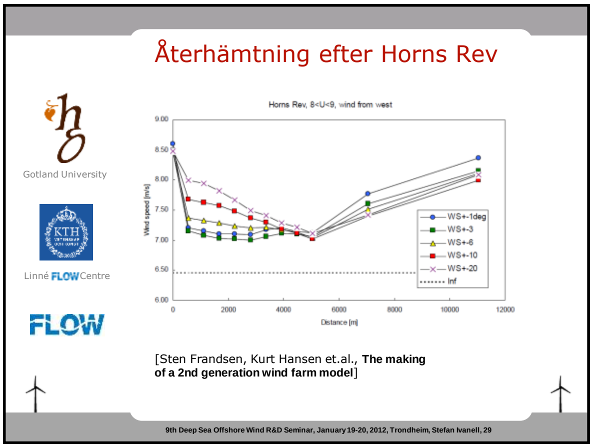
- Background - Wake Activities
- Basic Wake Research
- Turbine Interaction-Farm optimization
- Farm-Farm Interaction



Park-Park Interaktion

Park vak bakom Horns rev

[Sten Frandsen, Kurt Hansen et.al., **The making of a 2nd generation wind farm model**]

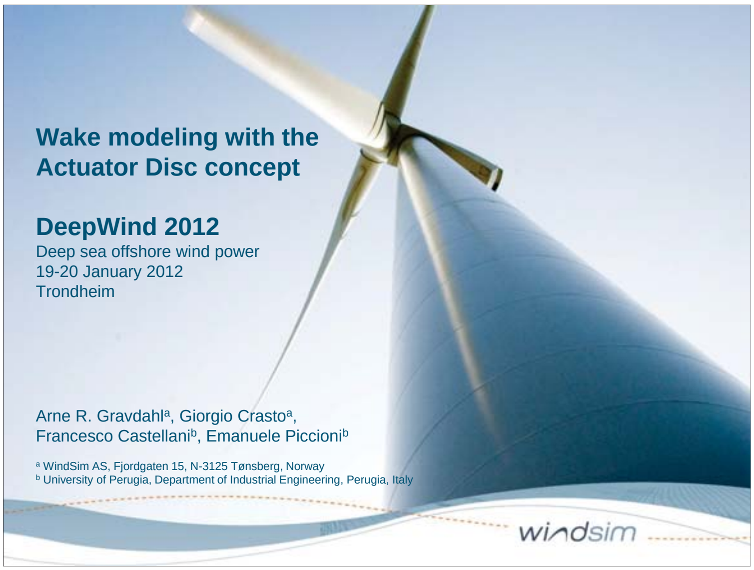


Återhämtning efter Horns Rev

[Sten Frandsen, Kurt Hansen et.al., **The making of a 2nd generation wind farm model**]

Thank you for your attention!

www.ivanell.se
stefan.ivanell@hgo.se



Wake modeling with the Actuator Disc concept

DeepWind 2012

Deep sea offshore wind power
19-20 January 2012
Trondheim

Arne R. Gravdahl[a], Giorgio Crasto[a],
Francesco Castellani[b], Emanuele Piccioni[b]

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[b] University of Perugia, Department of Industrial Engineering, Perugia, Italy

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Content

- WindSim AS
- Motivation
- Analytical wake models
- The Actuator Disc Concept
  - Modelling principles
  - Single wake validations
  - Wind farm validations
- Summary

WindSim AS

WindSim AS develops the software WindSim

WindSim is a CFD (Computational Fluid Dynamics) based Wind Farm Design Tool used to optimize energy production and reduce turbine loads

WindSim AS has been within the wind sector since 1997 offering the WindSim software and consulting services

WindSim HQ in Tønsberg, Norway

WindSim offices and distributors

Motivation – wake modelling

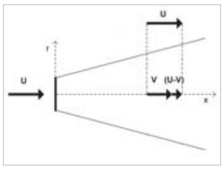
Wind farms get bigger and bigger. It has been a trend for several years and future offshore projects will most likely strengthen this trend for cost efficiency reasons.

Optimizing the cost efficiency for large wind farms is a indeed a challenge, where conflicting criteria within areal and resource planning have to be balanced.

In particular the reduced wind speeds and increased loading due to the wakes generated by each wind turbine is an important parameter in this respect.

Wake models – velocity deficit laws

Traditionally the wake models used within the wind industry have been based on so-called velocity deficit laws. These models reproduces reasonably well the reduced velocity in the wake region after one single wind turbine. However, when it comes to large wind farms the wake-wake interaction become important, which is not handled by these models.



Wind deficit: $\delta u(x) = U - V$

The Velocity deficit laws are computational inexpensive, suitable for optimization purposes investigating many layouts

---

Wake models – velocity deficit laws

1) Jensen model (Park model)

Oldest and simplest, often said to work well. The wake is supposed to expand like a cone, and the opening of the cone depends on the roughness-length at the turbine location.

2) Larsen model

More complex. It is obtained by integrating the momentum and continuity equations with a mixing-length turbulence model.

3) Ishihara et al. model

It was derived to model a wide range of situations, in theory to model sites with very low (offshore) and very high (complex terrains) turbulent intensities. It seems that the model has only partially achieved this goal, it normally estimates a higher wind deficit than the other two models.

Multiple wakes models

1. Linear sum of wake deficits (LS)

$$\delta u = \delta u_1 + \delta u_2 + \ldots + \delta u_n$$

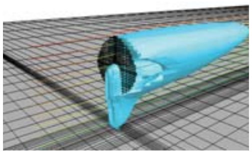
2. Root square of sum of squares of wake deficits (RSS)

$$\delta u = \sqrt{\delta u_1^2 + \delta u_2^2 + \ldots + \delta u_n^2}$$

Where the wake deficits on the RHS of the equations are computed with single wake models.

Wake models – Actuator Disc Concept

Various new modelling techniques based on Computational Fluid Dynamics (CFD) is under development. We present a wake model based on the Actuator Disc Concept, aimed towards capturing the wake losses in large wind farms. Likewise, wake losses in complex terrain will benefit from this new approach with improved handling of the wake-terrain interactions.

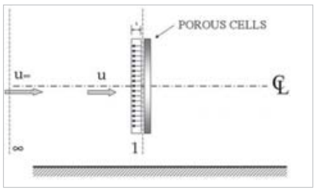


Actuator Disc Concept handles:
- wake-wake interaction
- wake-terrain interaction
- thermal effects

Perspective view of the actuator disc, streamlines and iso surface of turbulent kinetic energy (1,4 m^2/s^2, U_e 10 m/s at 500m a.g.l.)

Actuator Disc Concept – Our first attempt in 2008

The thrust, momentum sink for the axial flow, is supposed evenly distributed on the swept area (uniform pressure drop)



$$t = T / A = C_T \frac{1}{2} \rho u_\infty^2$$

$$T \approx \sum_i t_i = \sum_i \left(C_T \frac{1}{2} \rho u_{\infty i}^2 area_i \right)$$

$$t_i = C_{T,i}(u_{1,i}) \frac{1}{2} \rho \left(\frac{u_{1,i}}{1 - a_i(u_{1,i})} \right)^2 area_i$$

Axial induction factor:

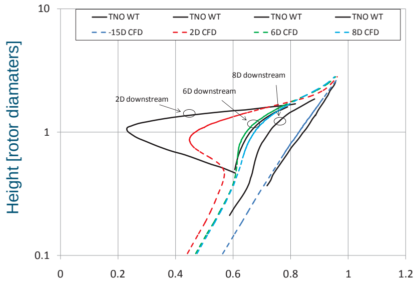
$$a_i = \frac{u_\infty - u_1}{u_\infty}$$

By definition

$$a = \frac{1}{2}\left(1 - \sqrt{1 - C_T}\right) \quad \textit{Betz's theory}$$

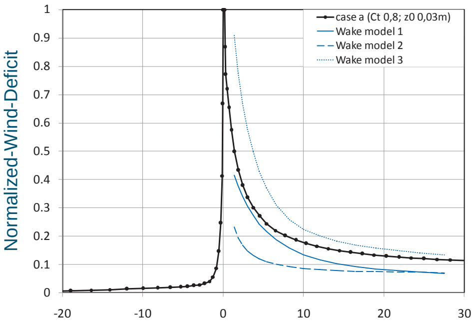
Singel wake; comparisons with Wind Tunnel runs

Vertical profiles of normalized velocity from TNO Wind Tunnel tests (solid black lines), from Vermeer *et al.*, predicted by the actuator disc CFD model (coloured lines).



Singel wake; Comparisons with analytical models

Case a: C_T = 0,80; z_0 = 0,03 m (onshore)



Actuator Disc Concept – Status in 2008

- An actuator disc concept was applied to model a wind turbine in RANS simulations of a single WECS wake

- A uniform pressure drop was applied on the disc; the value of the pressure drop was calculated from the thrust coefficient and axial induction factor.

- Comparison with wind tunnel tests show that the wind deficit predicted by the CFD simulations is under predicted in the near wake at 2D diameters downstream, the level of wind deficit is correctly predicted at 6D downstream while in the far wake the wind deficit is overestimated.

- When comparing the presented actuator disc to some analytical models the best match is found with the *Jensen* Model.

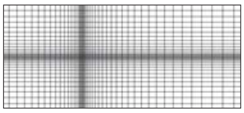
Actuator Disc Concept – Tasks post 2008

Automatization of the process:
- Reading the wind farm layout from the layout (.ows) file
- Automatic generation of the grid
- Reading of the thrust curve from the power curve (.pws) file

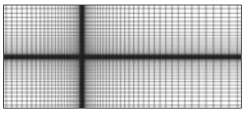
Investigation of:
- Introduction of turbulence sources over the swept area
- Radial distribution of axial forces
- Methods for power extraction
- Rotational effects (swirling wake)
- Stability
- Nesting technique to improve the grid design

Single turbine: neutral cases, grid sensitivity

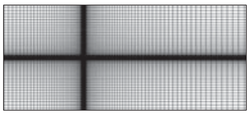
A grid sensitivity study is performed with 20, 10, 5 and 4 meters cell resolution in the turbine region, which in terms of rotor diameters are D/4, D/8, D/16 and D/20



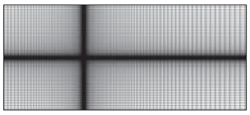
Resolution 20 meters, D/4



Resolution 10 meters, D/8

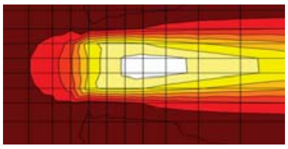


Resolution 5 meters, D/16

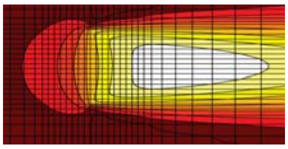


Resolution 4 meters, D/20

Single turbine: neutral cases, grid sensitivity

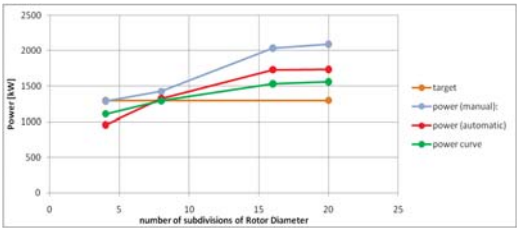


Wind speed, resolution 20 meters, D/4



Wind speed, resolution 5 meters, D/16

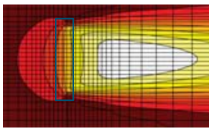
Single turbine: neutral cases, grid sensitivity



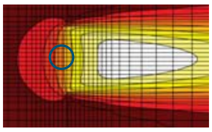
Conclusions of the grid sensitivity study:

1. A good level of grid dependency is reached with 16 subdivisions of the rotor diameter (in this case 5m);
2. There is a significant sensitivity on the method used to compute the power extracted by the disc.

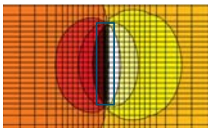
Power extraction method – pressure



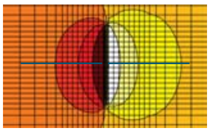
$\bar{u}$ is the bulk velocity over the swept area



$\bar{u}$ is the velocity at the hub



Δp is the max pressure drop over the swept area

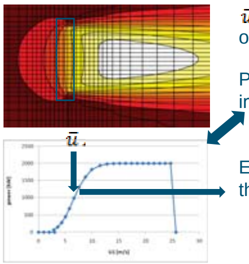


Δp is the max pressure drop along the centerline

$Power \approx \bar{u}\, A_s\, \Delta p$

where A_s is the swept area

Power extraction method – power curve

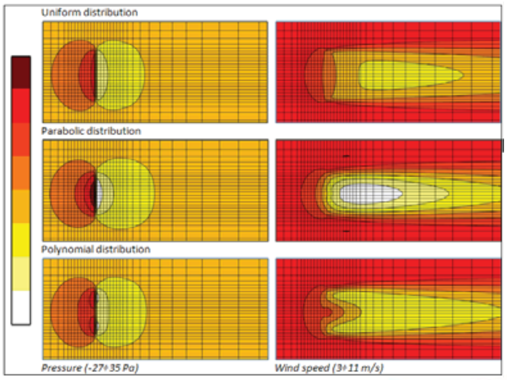


$\bar{u}$ is the bulk velocity over the swept area

Power curve corrected with axial-induction factor and Betz's theory

Evaluate the power entering in the corrected power curve

Radial distribution of axial forces



Pressure and wind speeds for various radial distribution of axial forces

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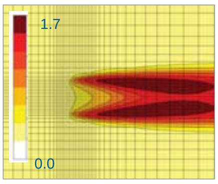
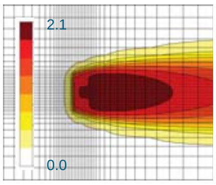
Generation of turbulence over swept area

Turbulent Kinetic Energy contour map at hub height [m^2/s^2]



Without source of turbulence (Ck = 0.0)



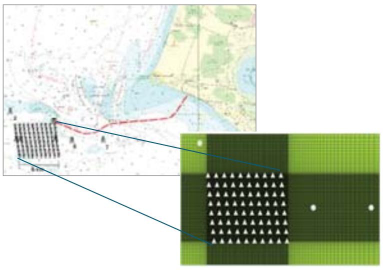
With source of turbulence (Ck = 0.01)

$$S \approx \sum_i s_i \ \ [\mathrm{W}]$$

$$s_i = C_k \ \rho \left| u_{1,i} \right|^3 area_i$$

Validation case: Horns Rev – Model

Horns Rev is an offshore wind farm located 13 km from the Danish coastline consisting of 80 wind turbines (Vestas V80)



Computational characteristics:

Resolution	D/4 (20 meter)
# cells	1.5 M
RAM	2-3 GB
Computational time	2 hrs

Note: Grid resolution D/4 does not give grid independent solutions

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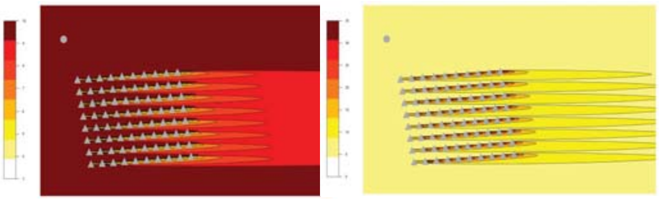
Validation case: Horns Rev – Results 274°



Wind speed left (m/s) and turbulent inensity right (%) for case with income wind from 274° and wind speed of 10 m/s and TI of 6% at hub height

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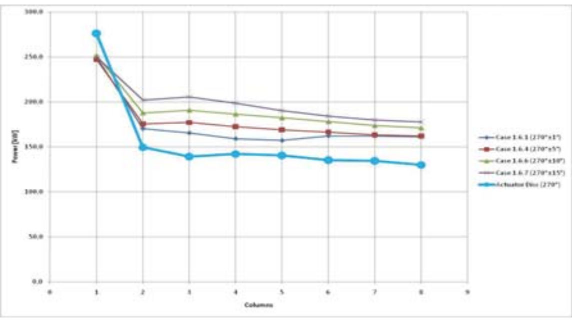
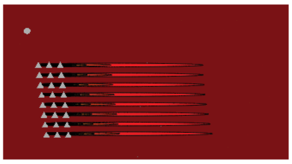
Validation case: Horns Rev – Results 270°



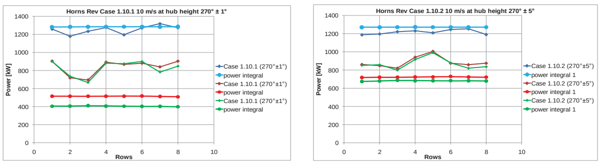
Average production for all eight turbines in each column for case with income wind from 270° and wind speed of 6 m/s at hub height.

Validation case: Horns Rev – Model (3 columns)



Computational characteristics:

Resolution	D/10 (8 meter)
# cells	5.0 M

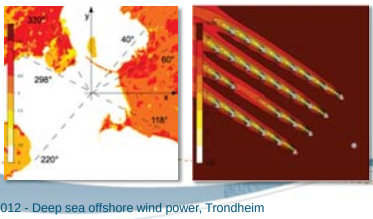


Production for all eight turbines in each three first columns for case with income wind from 270° and wind speed of 10 m/s at hub height. Variability due to sector division.

Validation case: Lillgrund

Lillgrund is an offshore wind farm located in Øresund consisting of 48 wind turbines (Siemens SWT-2.3-93)

The presence of shallow waters caused the layout of the wind farm to have regular array with missing turbines (recovery holes).
- Very close inter-row spacing
- Onshore effects
- Interesting wind farm for wake simulations



Raphaël Désilets-Aubé. *Developing boundary conditions using the nesting technique on simple terrain.* Thesis, Gotland University, Visby, Sweden, 2011

Summary

- Tests on single wakes
  - Neutral cases (grid sensitivity study)
  - Sensitivity to roughness (onshore/offshore)
  - Stable case (Monin-Obukhov length 100m)
  - Turbulence source at the rotor
- Tests on Horns Rev
  - Good behaviour in predicting the power ratio for the wide sectors
  - Meandering is not included in the simulations
  - Resolution issues - too coarse model (Resolution 20 meters, D/4)
- The actuator disc approach is promising – still more basic studies will be performed to adjust model constants

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Acknowledgements

This research has been supported by:

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Wind energy optimization by numerical wind modelling

eurostars™

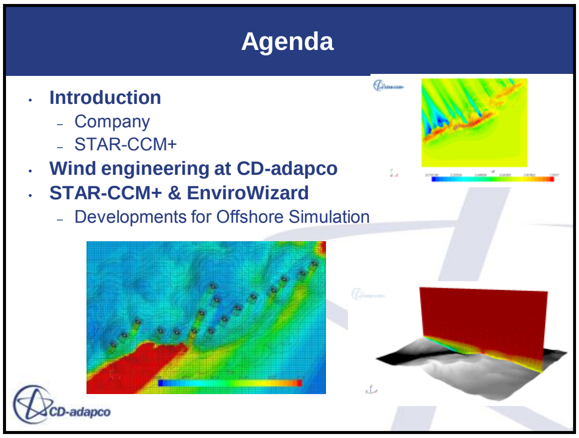
Carbon Trust Contract No C0910067;
Offshore Wind Accelerator Wake Effects Work Stream Phase 1

CARBON TRUST

CD-adapco

Recent Advances in Modelling Wind Parks in STAR-CCM+

Steve Evans



Agenda

- **Introduction**
  - Company
  - STAR-CCM+
- **Wind engineering at CD-adapco**
- **STAR-CCM+ & EnviroWizard**
  - Developments for Offshore Simulation

CD-adapco

CD-adapco: *Engineering Success*

We are a growing and *successful* engineering simulation company

- 20%+ growth in FY2011 global software sales
- $130m End User Spend in FY2011
- >560 employees in ~25 offices
- 40% of employees involved in Research and Development activities
- >9000 users worldwide

Our purpose is to ensure the customer's *success* through the use of engineering simulation

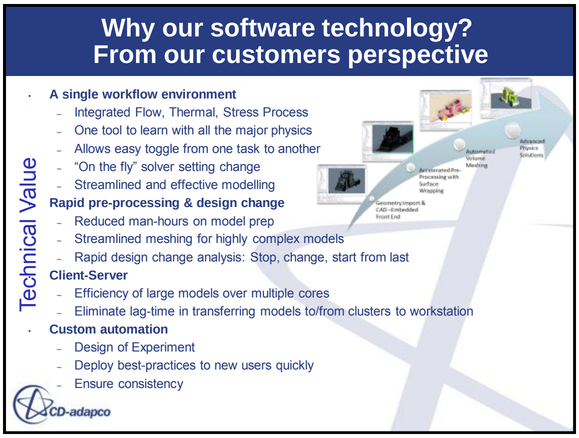
- Enable & inspire innovation
- Reduce engineering time & costs

We provide *successful* engineering simulation solutions

- Software products like STAR-CCM+ that are accurate, efficient, and easy to use
- **Flow**, **Thermal** and **Stress** simulation in a single tool.
- Local dedicated support
- Engineering services: technology transfer, burst engineering resources, custom software tools

Our independence breeds *engineering success*

- Largest independent CAE/CFD provider
- Heavily invest in employees
- Continuously invest in development of new technology



Why our software technology? From our customers perspective

Technical Value

- **A single workflow environment**
  - Integrated Flow, Thermal, Stress Process
  - One tool to learn with all the major physics
  - Allows easy toggle from one task to another
  - "On the fly" solver setting change
  - Streamlined and effective modelling
- **Rapid pre-processing & design change**
  - Reduced man-hours on model prep
  - Streamlined meshing for highly complex models
  - Rapid design change analysis: Stop, change, start from last
- **Client-Server**
  - Efficiency of large models over multiple cores
  - Eliminate lag-time in transferring models to/from clusters to workstation
- **Custom automation**
  - Design of Experiment
  - Deploy best-practices to new users quickly
  - Ensure consistency

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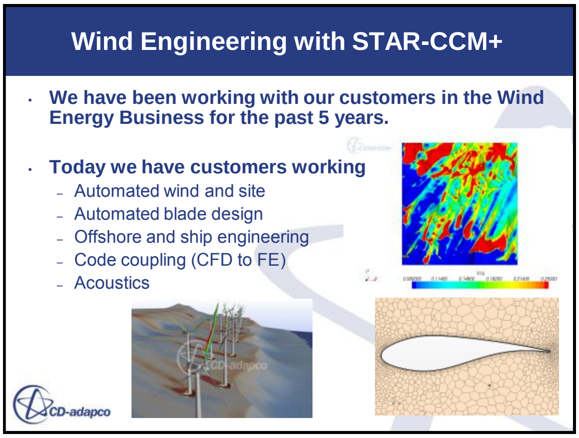

Wind Engineering with STAR-CCM+

- **We have been working with our customers in the Wind Energy Business for the past 5 years.**
- **Today we have customers working**
  - Automated wind and site
  - Automated blade design
  - Offshore and ship engineering
  - Code coupling (CFD to FE)
  - Acoustics

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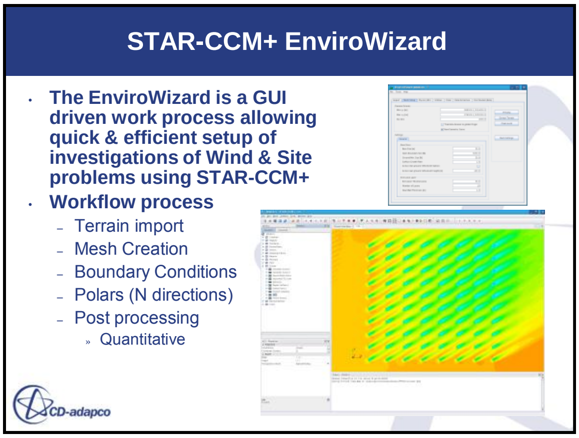


STAR-CCM+ EnviroWizard

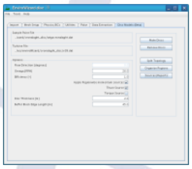
- **The EnviroWizard is a GUI driven work process allowing quick & efficient setup of investigations of Wind & Site problems using STAR-CCM+**
- **Workflow process**
  - Terrain import
  - Mesh Creation
  - Boundary Conditions
  - Polars (N directions)
  - Post processing
    - Quantitative

CD-adapco

Wake Interactions

- **Modelling the turbine interaction problem can generally be split into two problems**
  - Near Wake Effects
    - 3D & tip effects, stall
      - High fidelity models BEM/CFD required
  - Far wake (Wind Park Level) including
    - Wake interaction, turbulence & terrain
      - Lower fidelity model such as actuator discs can be used
- **EnviroWizard allows the User to investigate wake interactions**
  - Automatic setup of mesh and actuator functions

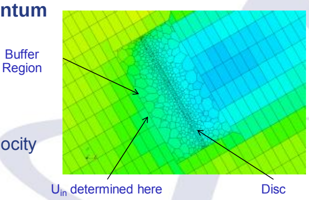

NASA AMES Wind Tunnel

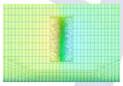


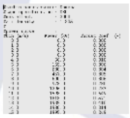
Wake Interactions

- **Each turbine is modelled individually as a momentum source.**
  - Torque $= \frac{V}{2\rho\omega}Q$
  - Thrust $= 0.5\rho C_T A U_{in}^2$
    - User can choose
  - U_{in} is area averaged velocity upstream of the disc
  - Embedded meshing
    - Hexahedral dominant mesh in main region
    - Polyhedral disc & buffer region

270 degrees, flow aligned grid







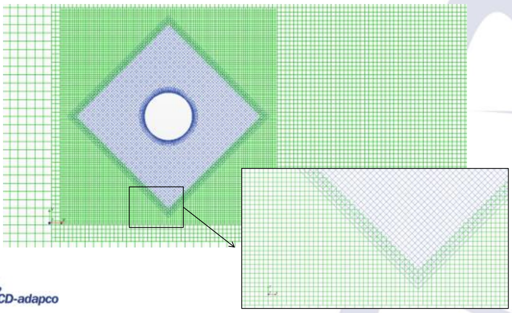
EnviroWizard Developments

- **While this automatic wake methodology works, the setup requires remeshing for each wind direction.**
- **In STAR-CCM+ 7.02 (end Feb 2012), CD-adapco will release a version containing the Overset method,**
  - This has the possibility to simplify the array problem
    - No remesh.
    - Just change the wind direction and disc orientation.
- **The EnviroWizard will be released at the same time incorporating this functionality.**

Overset Methodology

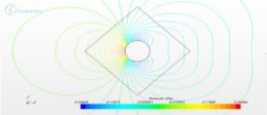
- **Cells are marked according to three types:**
  - active, inactive, and acceptor.
- **Active cells**
    - regular discretized equations are solved.
    - Donor for the interpolation.
- **Inactive cells**
  - no equation is solved – they are temporarily de-activated.
  - Need to be surrounded by acceptor cells.
- **Acceptor cells**
  - discretized equations are replaced by interpolation equations which express cell-centre value of a variable as a linear combination of values at another grid.

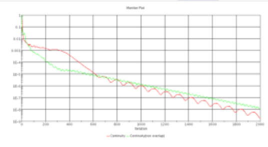
Overset Methodology

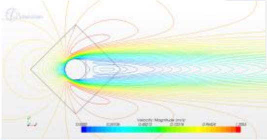


Overset Validation

- **Steady State Re=50 cross flow cylinder, 24K elements**

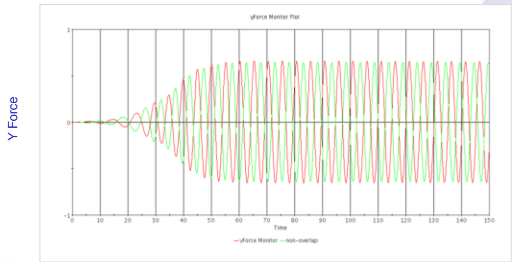

Steady State Pressure


Continuity Residuals
Red – overset
Green – no overset


Steady State Velocity

Overset Validation

- **Transient Re=200 cross flow cylinder, 24K elements**



Time 0 – 150s

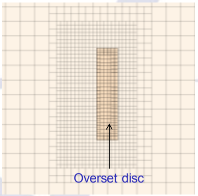
Overset Features

- **Release features for v702 (end Feb 2012)**
  - Any number of overlaps, restricted to:
    - Not overlapping each other
    - Not overlapping any solid body or exit background mesh
  - Physics / Solver
    - Steady, moving, or sliding grid.
    - Parallel
    - VOF, cavitation etc.
    - Not particle tracking, liquid film

EnviroWizard with Overset

- **New option in the Disc Models**
  - Setup of N turbines in array is performed with the Wizard.

Buffer Block Cross Section Edge Length [m] 120.0
Upstream Distance Factor [-] 0.5
Downstream Distance Factor [-] 0.5
Wake Refinement length [m] 1000.0
Overset Methodology ☑



- **Test against a known case, Hornsref**

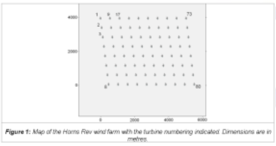
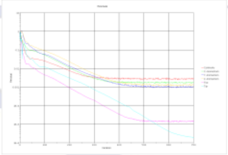


Figure 1: Map of the Horns Rev wind farm with the turbine numbering indicated. Dimensions are in metres.

The author wishes to acknowledge Elkraft who provided this production data and the owners of the array, Dong Energy and Vattenfall.

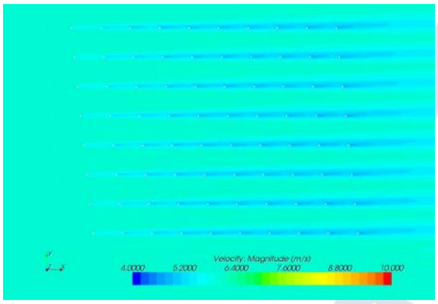
EnviroWizard with Overset

- **Computational requirements**
  - Approximate timings for 5.9M cells
    - 1 background mesh with 80 overset regions
  - Test machine 2*4 core Intel Xeon X5560 2.8GHz
  - Setup & mesh
    - 15m
  - Solver
    - elapsed time on 8 cpus = 38 s/iter
  - Peak memory (coupled solver)
    - ~40 G



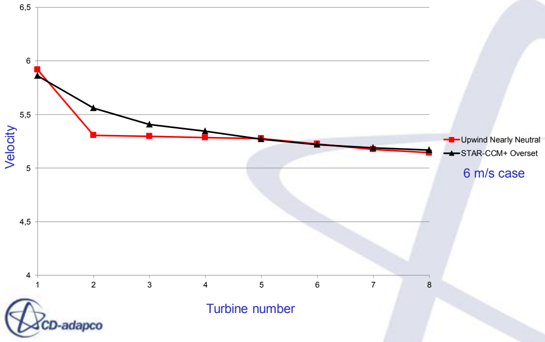
Convergence

EnviroWizard with Overset

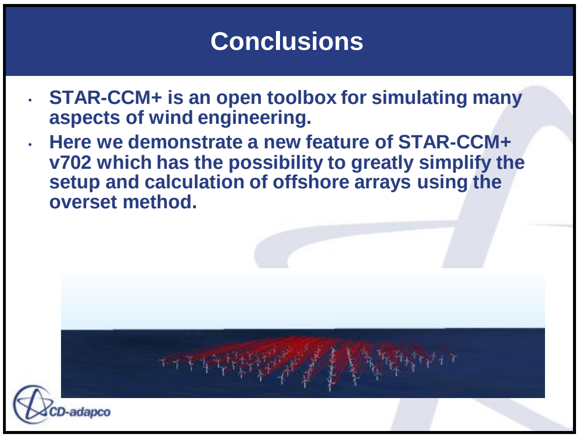


6 m/s case

EnviroWizard with Overset



6 m/s case



Conclusions

- STAR-CCM+ is an open toolbox for simulating many aspects of wind engineering.
- Here we demonstrate a new feature of STAR-CCM+ v702 which has the possibility to greatly simplify the setup and calculation of offshore arrays using the overset method.

Offshore Wind Farm Optimisation

Ninth Deep Sea Offshore Wind R&D Seminar
Royal Garden Hotel, Trondheim
19-20 January 2012

Trygve Skjold

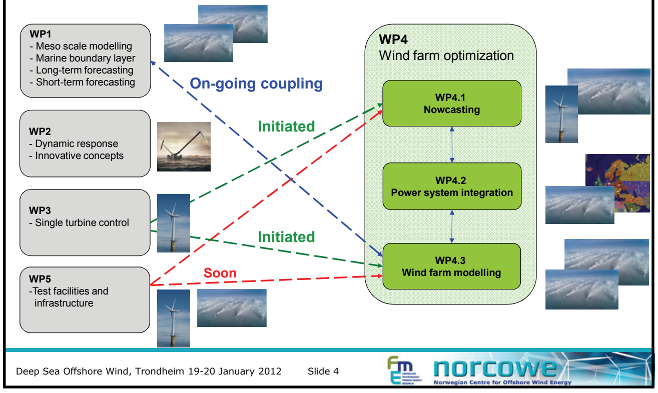
Manager GexCon R&D and WP4 Manager NORCOWE

Outline

- WP4 in NORCOWE
- Vision for WP4
- Challenges
- Modelling
- FLACS-Wind
- Activities 2012
- Reflections
- Questions?

NORCOWE WP4

NORCOWE: WP4 and other WPs



WP1
- Meso scale modelling
- Marine boundary layer
- Long-term forecasting
- Short-term forecasting

WP2
- Dynamic response
- Innovative concepts

WP3
- Single turbine control

WP5
-Test facilities and infrastructure

On-going coupling

Initiated

Initiated

Soon

WP4
Wind farm optimization

WP4.1
Nowcasting

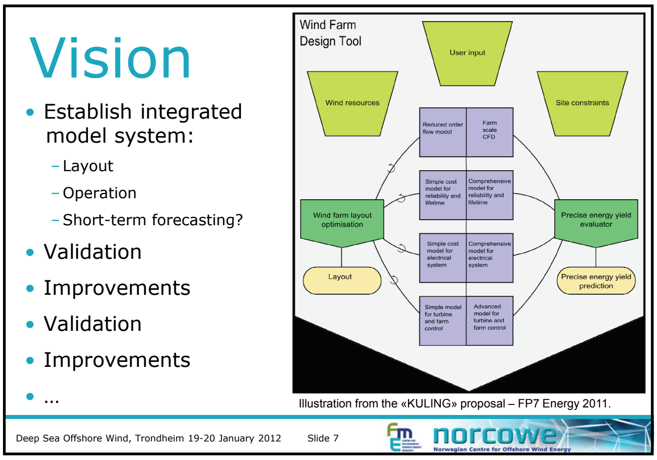
WP4.2
Power system integration

WP4.3
Wind farm modelling

Vision

Vision NORCOWE WP4

- Develop a fully integrated model system for optimising the layout of (offshore) wind farms!
  - CFD code(s) with subgrid models validated against experiments and/or more detailed CFD simulations!
  - One-way coupling to relevant meso-scale models (from WP1)!
  - Run manager that can incorporate weather and wave statistics, as well as other site-specific constrains: depth, bottom conditions, shipping lanes, environmental constraints, …
  - Models for electrical system and network integration: cable length, AC vs. DC, transformers, …
  - Integrated optimisation scheme for farm layout that takes advantage of parameter reduction and/or artificial neural networks (ANN)
  - Updated documentation to support users and investment decisions!



Vision

- Establish integrated model system:
  - Layout
  - Operation
  - Short-term forecasting?
- Validation
- Improvements
- Validation
- Improvements
- …

Wind Farm
Design Tool

User input

Wind resources

Site constraints

Reduced order flow model

Farm scale CFD

Simple cost model for reliability and lifetime

Comprehensive model for reliability and lifetime

Wind farm layout optimisation

Precise energy yield evaluator

Simple cost model for electrical system

Comprehensive model for electrical system

Layout

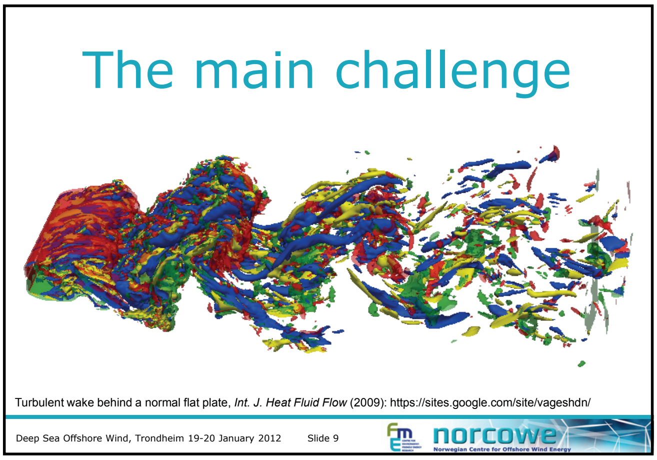
Precise energy yield prediction

Simple model for turbine and farm control

Advanced model for turbine and farm control

Illustration from the «KULING» proposal – FP7 Energy 2011.

Challenges



The main challenge

Turbulent wake behind a normal flat plate, *Int. J. Heat Fluid Flow* (2009): https://sites.google.com/site/vageshdn/

Turbulence

"My favourite definition of turbulence is that it is the general solution of the Navier-Stokes equations."

"Turbulence: The Chief Outstanding Difficulty of our Subject"
Bradshaw, P. (1994). *Experiments in Fluids*, **16**: 203-216

Governing equations

Conservation of Mass:

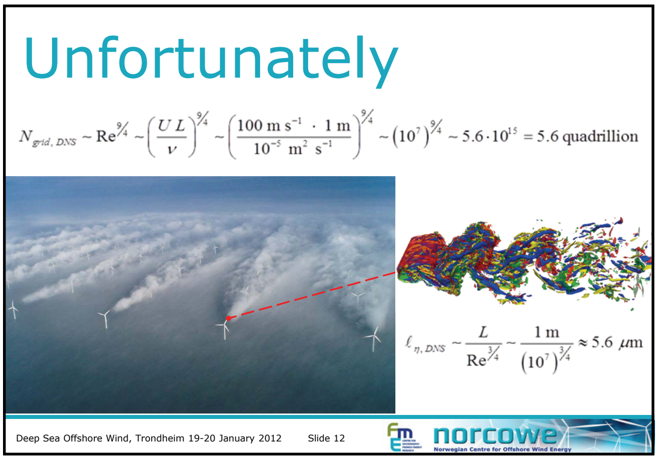
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0$$

Conservation of Momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\underbrace{\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \left(\mu_B - \frac{2}{3}\mu\right)\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)}_{\tau_{ij}} + \rho a_i$$

Conservation of Energy:

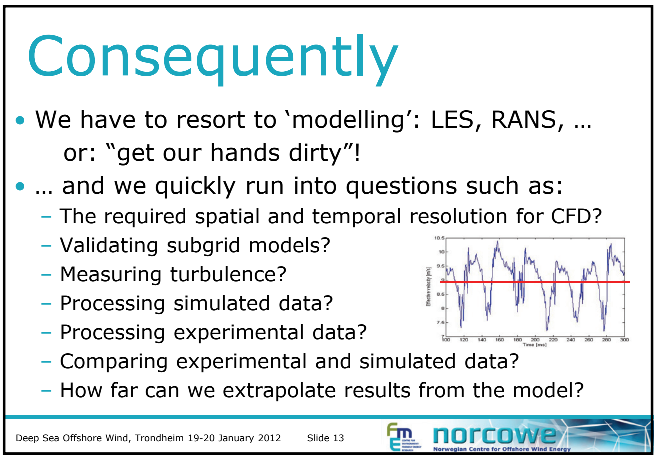
$$\underbrace{\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}\left(\rho h u_j\right)}_{\rho\frac{Dh}{Dt}} = \underbrace{\frac{\partial p}{\partial t} + u_j\frac{\partial p}{\partial x_j}}_{\frac{Dp}{Dt}} + \frac{\partial}{\partial x_j}\left(J_{h,j}\right) + S_h$$



Unfortunately

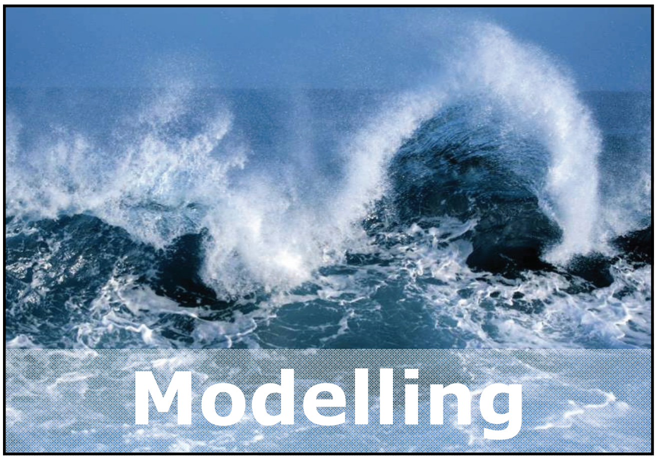
$$N_{grid,\,DNS} \sim \mathrm{Re}^{9/4} \sim \left(\frac{U\,L}{\nu}\right)^{9/4} \sim \left(\frac{100\ \mathrm{m\,s^{-1}}\ \cdot\ 1\ \mathrm{m}}{10^{-5}\ \mathrm{m^2\ s^{-1}}}\right)^{9/4} \sim \left(10^7\right)^{9/4} \sim 5.6\cdot 10^{15} = 5.6\ \text{quadrillion}$$

$$\ell_{\eta,\,DNS} \sim \frac{L}{\mathrm{Re}^{3/4}} \sim \frac{1\ \mathrm{m}}{\left(10^7\right)^{3/4}} \approx 5.6\ \mu\mathrm{m}$$



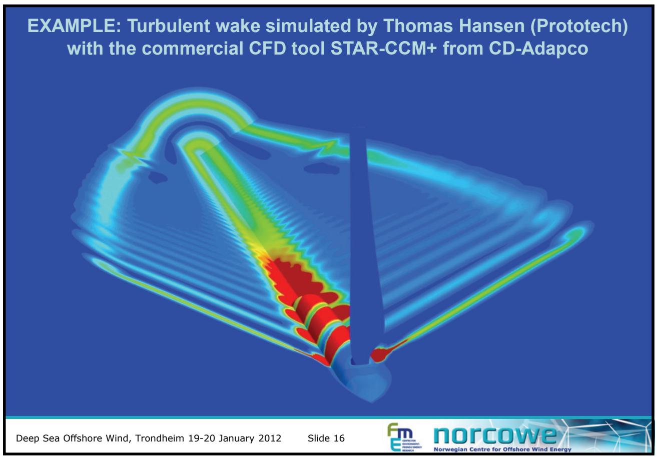
Consequently

- We have to resort to ‘modelling’: LES, RANS, …
  or: “get our hands dirty”!
- … and we quickly run into questions such as:
  - The required spatial and temporal resolution for CFD?
  - Validating subgrid models?
  - Measuring turbulence?
  - Processing simulated data?
  - Processing experimental data?
  - Comparing experimental and simulated data?
  - How far can we extrapolate results from the model?

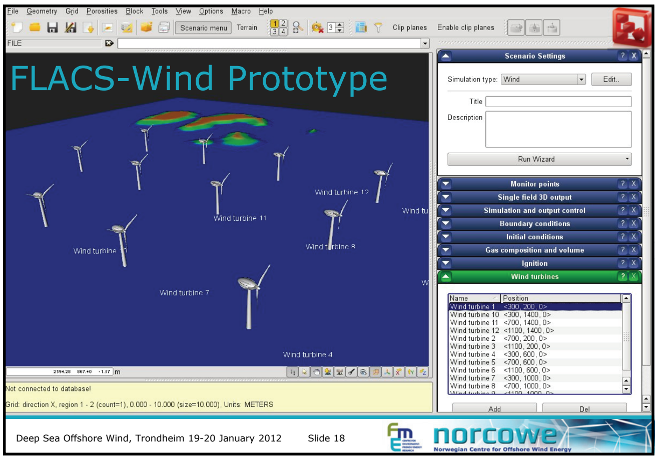


Modelling in NORCOWE WP4

- **Prototech**:
  - Relatively detailed wake modelling with a *k*-ω Shear Stress Transport (SST) formulation in the commercial CFD solver **STAR-CCM+** from CD-Adapco.
- **StormGeo/UiS & Uni Research**:
  - RANS / LES modelling in the open source CFD solver **OpenFOAM** (GNU GPL), with focus on turbulent wakes, coupling, effect of swell on MBL, etc.
- **GexCon**:
  - RANS modelling in the commercial CFD solver **FLACS-Wind**
- **CMR Computing**
  - Model reduction techniques in combination with CFD, in order to reduce calculation time …
- **Uni Research**
  - Artificial intelligence (AI) and Artificial Neural Networks (ANN), in order to avoid solving the Navier Stokes equations …



EXAMPLE: Turbulent wake simulated by Thomas Hansen (Prototech) with the commercial CFD tool STAR-CCM+ from CD-Adapco



FLACS-Wind Prototype

Simulation type: Wind

Title

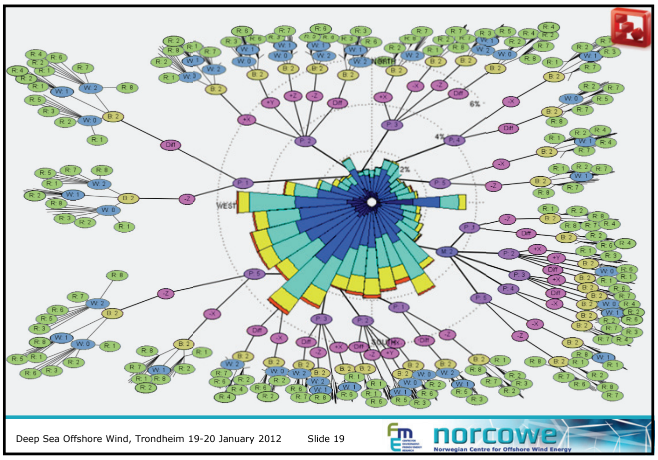
Description

Name	Position
Wind turbine 1	<300, 200, 0>
Wind turbine 10	<300, 1400, 0>
Wind turbine 11	<700, 1400, 0>
Wind turbine 12	<1100, 1400, 0>
Wind turbine 2	<700, 200, 0>
Wind turbine 3	<1100, 200, 0>
Wind turbine 4	<300, 600, 0>
Wind turbine 5	<700, 600, 0>
Wind turbine 6	<1100, 600, 0>
Wind turbine 7	<300, 1000, 0>
Wind turbine 8	<700, 1000, 0>

2594.28 867.40 -1.37 m

Not connected to database!

Grid: direction X, region 1 - 2 (count=1), 0.000 - 10.000 (size=10.000), Units: METERS



Activities 2012

NOWITECH

Norwegian Research Centre for Offshore Wind Technology

Third Joint NOWITECH / NORCOWE Workshop on

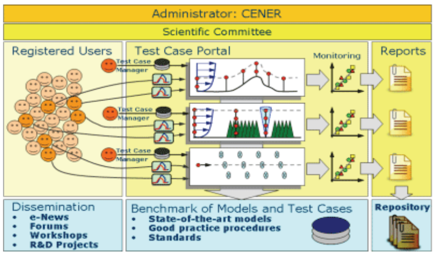
Wind & Wake Modelling

Coming autumn 2012

Contact NOWITECH: Prof. Lars Sætran E-mail: lars.satran@ntnu.no
Contact NORCOWE: Dr. Lene Sælen E-mail: lene@gexcon.com

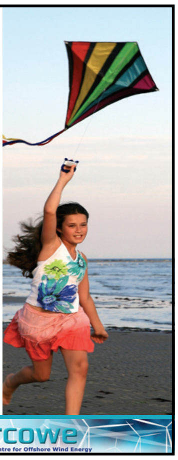
norcowe
Norwegian Centre for Offshore Wind Energy

IEA Wind Task 31 WakeBench



Further details: www.ieawind.org/Summary_Page_31.html
Contact point in Norway: www.windsim.com

Reflections



- Approach to research / engineering
  - Blade ⇨ Turbine ⇨ Near Wake ⇨ Far wake ⇨ Wind farm ⇨
  - … or jump to full scale wind farm and tune the model?
- Urgent need for validation data
  - Limited access to data from full-scale wind farms!
  - Uncertainty / variation in site-specific data?
- Sources of uncertainty
  - Model uncertainties vs. weather predictions!
  - Downscaling from meso scale: 3-30 km ⇨ 1-10 m
  - Marine boundary layer: wind-wave interactions!
- Importance vs. urgency
  - It takes time to develop a complex model system!
  - Attempts at boosting the funding for the modelling work have thus far proven unsuccessful.

Questions?

Closing session

Considerations when designing large wind turbines, Torolf Pettersen, Blaaster
(no presentation available)

A floating multi-turbine platform, Marc Lefranc, WindSea

Innovations in Offshore Wind Technology the We@Sea programme,
Jos Beurskens, ECN

WINDSEA

A floating multi-turbines platform

WindSea AS, January 2012

MARC LEFRANC

The Company

WINDSEA

- Norwegian company based in Sandvika
- Established in 2008
- Fixed and floating foundations for offshore wind
- Owned by NLI and FORCE Technology

NLI

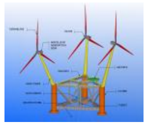
•Norwegian company
•Engineering, fabrication, and technology
•Offshore oil & gas, and hydropower
•2000 employees
•50% owner in WindSea

FORCE TECHNOLOGY

•Norwegian/Danish company
•Engineering, material technology and Inspection
•Offshore oil & gas, and wind power
•1200 employees
•50% owner in WindSea

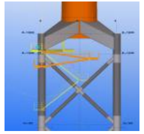
WindSea's solutions

Floating platform



✓Semi-submersible platform
✓Applicable from 45 meters to very deep water
✓Carries three full size (5MW+) turbines
✓Some R&D work still needed

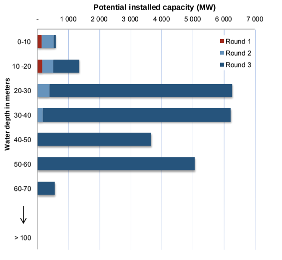
Fixed jacket structure



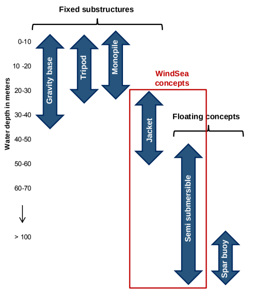
✓Simple jacket structure
✓Applicable from 20-50 meters
✓Cost effective fabrication and installation
✓Concept is ready for commercial projects

The market for the WindSea's foundations

Largest growth in water depth > 30m



Water depth for use of technology



Source: Crown Estate 2009, edp (The WindFloat Project, May 2010) and WindSea

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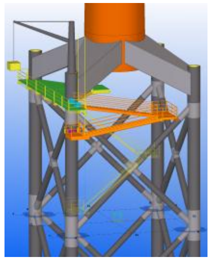
WindSea's jacket concept - cost effective fabrication, transport and installation

The WindSea jacket



Key facts

Design	▪ Vertical legs ▪ Modular design ▪ Piling through legs
Turbines	▪ All commercial offshore turbines
Water depth:	▪ 20-50 meters
Access system	▪ Effective and secure boat landing and staircase system
Status	▪ Concept ready for commercial use

WindSea Floater: Key Facts

•Semi-submersible platform

• Three columns

•Three turbines

• Mooring system connected by a "turret".

•Self orientation against the wind

• Inclined towers

Key Facts

- Build complete platform at yard
- Tow with commissioned turbines
- Pre-installed anchor system
- Platform self oriented to the wind
- Easy connection to mooring system
- Optimum power production
- Based on proven technology
- Easy access by helicopter or boat
- Large deck area: allow for maintenance
- May be easily towed back to yard for major repair and inspection

Wake Effect / Turbulence

Wake Effect / Turbulence

- Reduction of power production at the rear turbine
- No turbulence effect from the up wind turbines on the rear turbine
- Inclined towers result in less interaction with the rotor blades

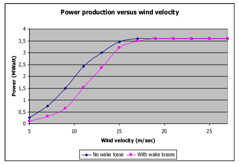
Power production

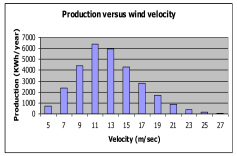
Based on a specific field data, a specific turbine type.

- Total power production of 3 standing alone turbines:
- 44,5 GWh/year

Rear turbine power reduction: 25 %

- Total power production for Windsea: 41,4 GWh/year
- 93% of the theoretical



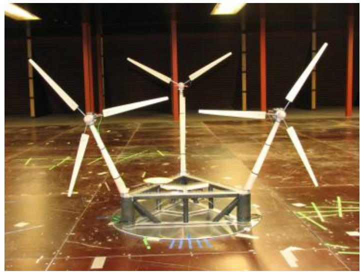


Model Test: Validation of the concept

- Validate the main principles of the concept and prove its physical feasibility.
- Verify interaction between turbines.
- Verify effect of turbines on vessel motion.
- Verify effect of vessel motion on power production.
- Verify the self-orientation property.

Model Test: Wind Tunnel

- Aerodynamic interaction in-between the turbines. Scale 1:150



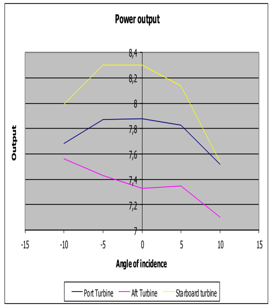
Model Test: Wind Tunnel

WINDSEA

•One wind velocity, 5 directions

•The power of the aft turbine was reduced to 89% of the average of port and starboard turbine power.

•The forward turbines were only marginally affected by one another or by the aft turbine.



Model Test: Wave Basin

WINDSEA

- Interaction between Wave and wind induced motion. Scale 1:64

Model Test: Wave Basin

WINDSEA

Maximum Motion

Hs	Heave		Pitch	
	Without turbine	With turbine	Without turbine	With turbine
2,5 m	0,4 m	0,3 m	0,6°	1°
5,5 m	1,8m	1,6 m	2,2°	3,1°
13,8 m	8,5 m	8,7 m	1,8°	3,4°

Standard deviation

Hs	Heave		Pitch	
	Without turbine	With turbine	Without turbine	With turbine
2,5 m	0,1 m	0,08 m	0,17°	0,2°
5,5 m	0,4m	0,38 m	0,38°	0,75° *
13,8 m	2,5 m	2,5 m	0,74°	0,76°

* This high value is due to operational problems during the test.
A more refined analysis of the time history is required.
Value around 0,3 is most likely.

Model Test: Wave Basin

WINDSEA

Power production

Hs	Turbine 1	Turbine 2	Aft Turbine
0 m	3,0	3,0	1,4
2,5 m	3,0	3,0	1,2
5,5 m	3,1	3,3	1,4
13,8 m	3,5	3,0	1,3

Model Test: Conclusions

WINDSEA

- Results in accordance with calculations
- No interaction between the two up-wind turbines
- Reduction of power production for the rear turbine
- Heave motion identical for both conditions: with and without turbines
- Pitch motion slightly increased when turbines are in action (Hs 5,5 m; 2,2˚ to 3,1˚)
- Power production almost independent of the sea state

CONCLUSION

WINDSEA

- WindSea Concept has been proven to be feasible.
- WindSea has a wide range of application area.
- WindSea reduces the cost of installation.
- WindSea reduces the maintenance cost.
- Economic analysis shows that the cost per MW is at lower bound of today's solutions.
- Further optimisation / tests will bring the cost lower.

WINDSEA

Thank You for Your attention

Innovations in offshore wind technology; the We@Sea programme

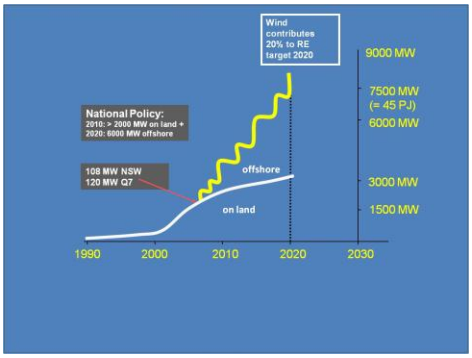
Jos Beurskens
We@Sea
(former ECN Wind Energy
Petten-NL)

9-th Deep Sea Offshore Wind R&D Seminar
Trondheim, 20 January 2012

The We@Sea project

- Project defined in 2002-2003
- Started in 2004
- Concluded 2010
- Total budget: M€ 26

National targets at launch of programme



Participants We@Sea consortium

R&D Establishments
- ECN
- TNO
- TU-Delft
- WMC BV

Environment, nature & safety
- IMARES
- Bureau Waardenburg
- TNO
- Greenpeace
- Stichting.Noordzee
- University Twente

Wind turbine manufacturers
- GE wind energy
- Vestas
- XEMC Darwind

Offshore technology
- Ballast Nedam
- Fabricom
- Fugro Engineers BV
- GustoMSC
- Lloyd's Register NL

Project developers
- E-connection,
- Evelop
- Shell Wind Energy BV

Wind energy technology
- Smulders Group
- Siemens

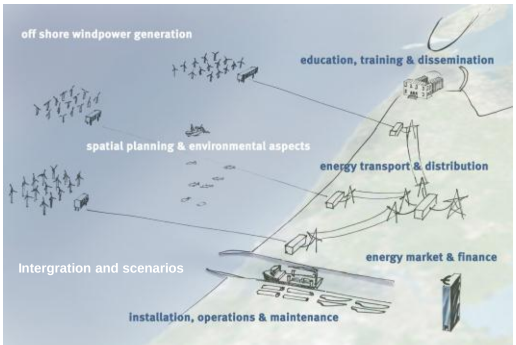
Energy consultants:
- Kema Power
- Ecofys

Energy sector
- Delta
- ENECO
- Nuon/vattenfall
- Statkraft
- TenneT

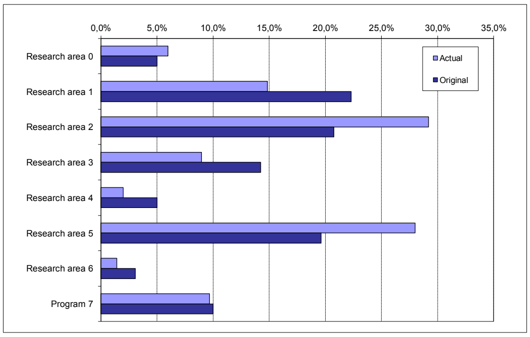
Logistics and harbour development
- STC BV

Financiers
- NIBC

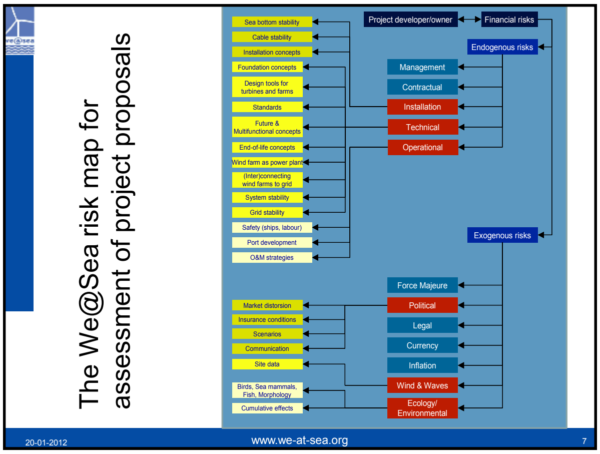
Research areas We@Sea



Budgets and spending per research area

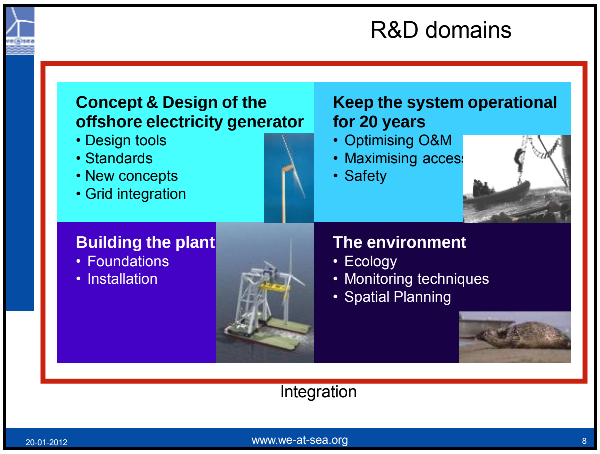


RA0: Integration, scenarios
RA1: Offshore wind power technology
RA2: Spatial planning and ecology
RA3: Energy transport & integration
RA4: Energy market
RA5: Installation, O&M, dismantling
RA6: Education & dissemination



The We@Sea risk map for assessment of project proposals

- Project developer/owner ↔ Financial risks
- Endogenous risks
  - Management
  - Contractual
  - Installation
    - Sea bottom stability
    - Cable stability
    - Installation concepts
  - Technical
    - Foundation concepts
    - Design tools for turbines and farms
    - Standards
    - Future & Multifunctional concepts
    - End-of-life concepts
    - Wind farm as power plant
    - (Inter)connecting wind farms to grid
    - System stability
    - Grid stability
  - Operational
    - Safety (ships, labour)
    - Port development
    - O&M strategies
- Exogenous risks
  - Force Majeure
  - Political
    - Market distorsion
    - Insurance conditions
    - Scenarios
    - Communication
  - Legal
  - Currency
  - Inflation
  - Wind & Waves
    - Site data
  - Ecology/ Environmental
    - Birds, Sea mammals, Fish, Morphology
    - Cumulative effects



R&D domains

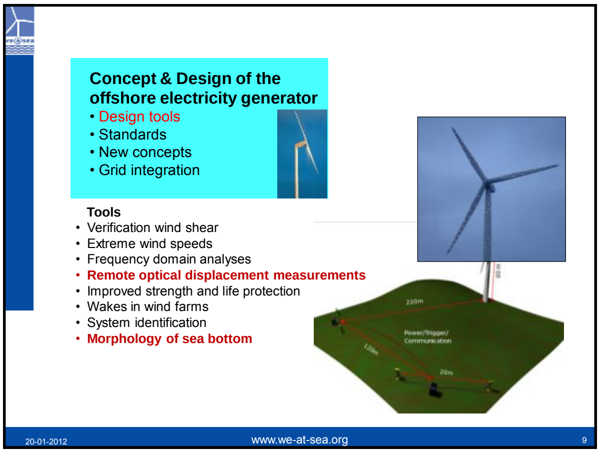
Concept & Design of the offshore electricity generator
- Design tools
- Standards
- New concepts
- Grid integration

Keep the system operational for 20 years
- Optimising O&M
- Maximising access
- Safety

Building the plant
- Foundations
- Installation

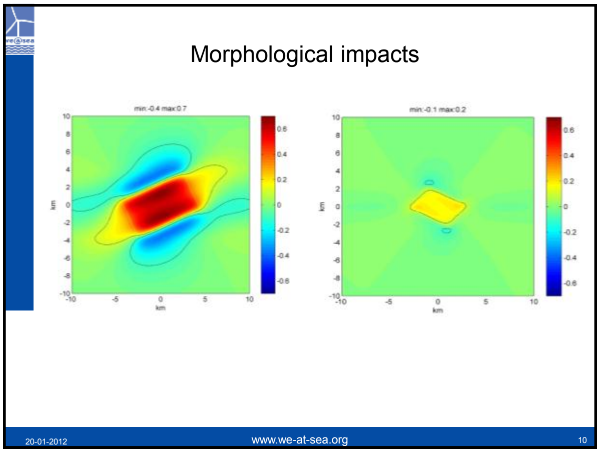
The environment
- Ecology
- Monitoring techniques
- Spatial Planning

Integration

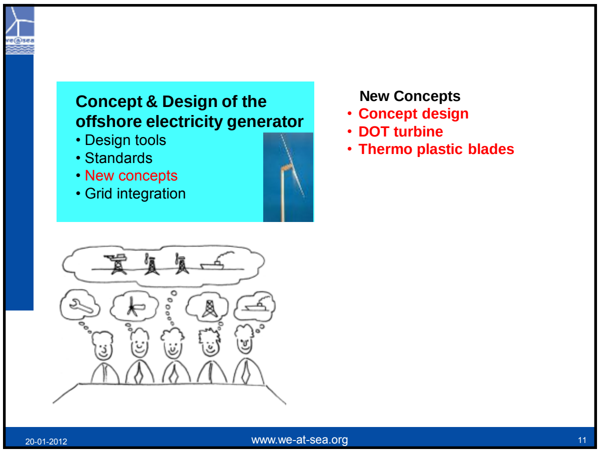


Concept & Design of the offshore electricity generator
- Design tools
- Standards
- New concepts
- Grid integration

Tools
- Verification wind shear
- Extreme wind speeds
- Frequency domain analyses
- **Remote optical displacement measurements**
- Improved strength and life protection
- Wakes in wind farms
- System identification
- **Morphology of sea bottom**



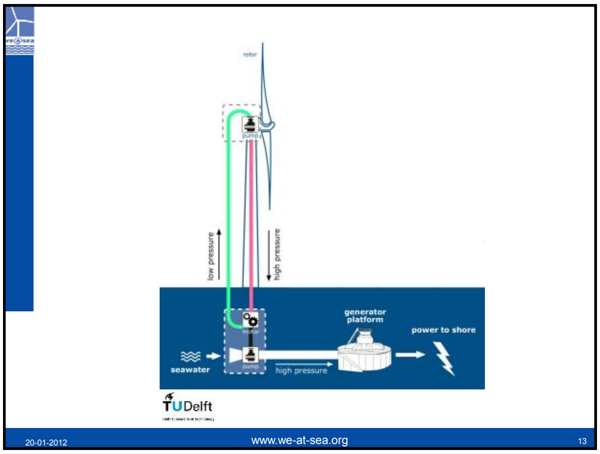
Morphological impacts



Concept & Design of the offshore electricity generator
- Design tools
- Standards
- New concepts
- Grid integration

New Concepts
- **Concept design**
- **DOT turbine**
- **Thermo plastic blades**

Requirement	Solution	Concepts
Up scaling (Full blade pitch becomes ineffective due to large variations in the wind field in the rotor plane)	Distributed blade control with advanced (LIDAR based) control systems	UpWind
Reliability	Reduced number of components (central conversion unit in wind farm, direct drive generators, passive yawing)	Lagerwey DOT Hydraulic conversion
Weight reduction	Two bladed rotor (reduces rotor weight and increases rotor speed, which leeds to reduced drive train weight)	2B-Energy Stork Ultimate turbine
Integrated operations and design	Transport of floating components. Self erecting and installing systems	Deep Wind Seilsam-Sea Sway
Servicebility	Access technology	Z Technologies Ampelmann
Maintainability	Floating cantilever structures	Lagerwey
Wind farm efficiency	Movable foundations Non conventional wind farm lay outs	Ideol (movable foundations) Topfarm



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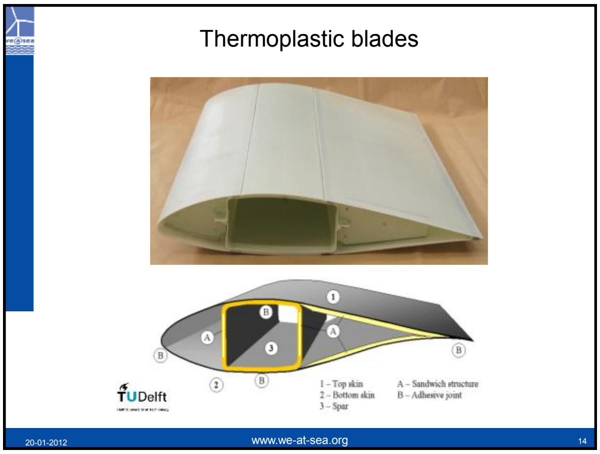

Thermoplastic blades

1 – Top skin
2 – Bottom skin
3 – Spar

A – Sandwich structure
B – Adhesive joint

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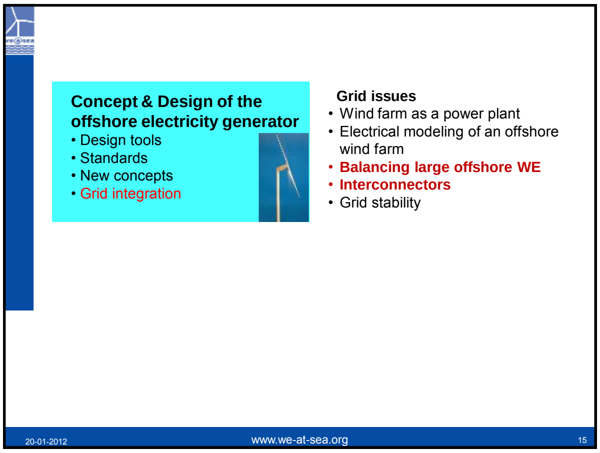

Concept & Design of the offshore electricity generator
- Design tools
- Standards
- New concepts
- Grid integration

Grid issues
- Wind farm as a power plant
- Electrical modeling of an offshore wind farm
- **Balancing large offshore WE**
- **Interconnectors**
- Grid stability

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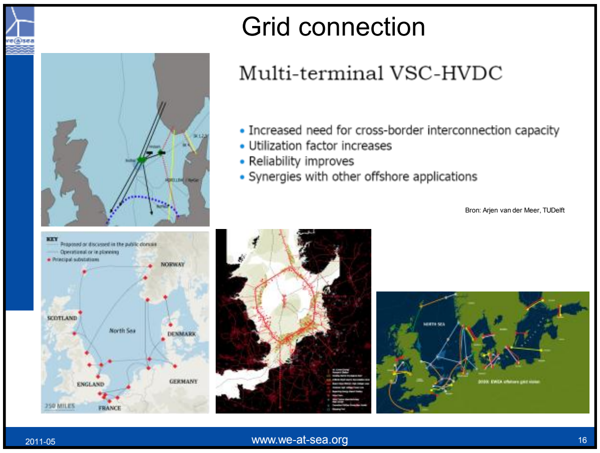

Grid connection

Multi-terminal VSC-HVDC

- Increased need for cross-border interconnection capacity
- Utilization factor increases
- Reliability improves
- Synergies with other offshore applications

Bron: Arjen van der Meer, TUDelft

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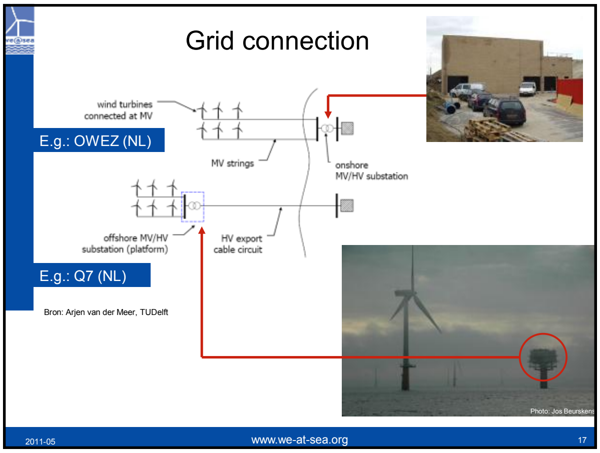

Grid connection

E.g.: OWEZ (NL)

E.g.: Q7 (NL)

Bron: Arjen van der Meer, TUDelft

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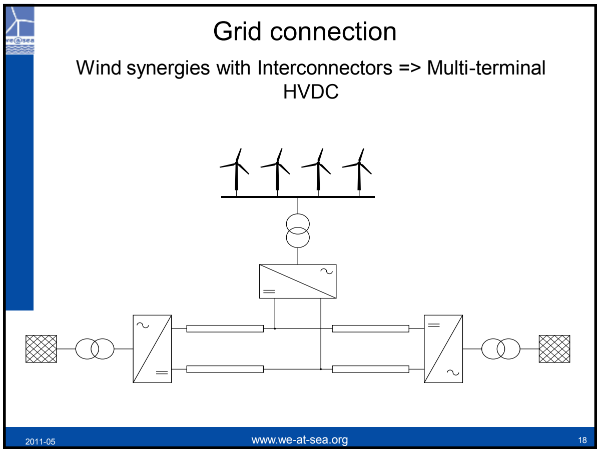

Grid connection

Wind synergies with Interconnectors => Multi-terminal HVDC

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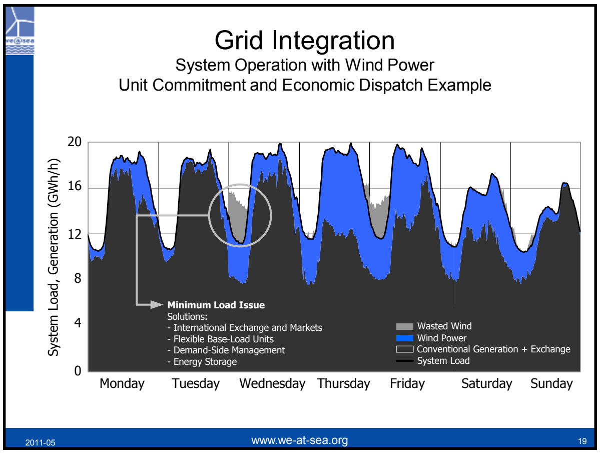
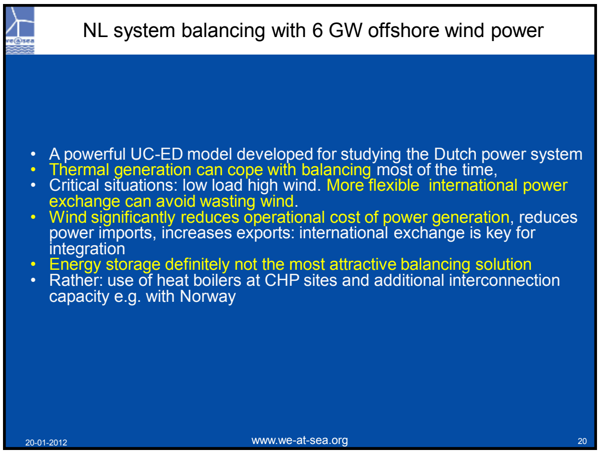


Grid Integration

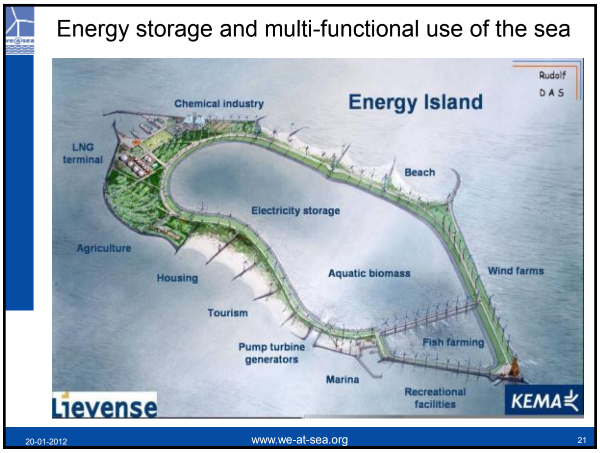
System Operation with Wind Power
Unit Commitment and Economic Dispatch Example

Minimum Load Issue
Solutions:
- International Exchange and Markets
- Flexible Base-Load Units
- Demand-Side Management
- Energy Storage



NL system balancing with 6 GW offshore wind power

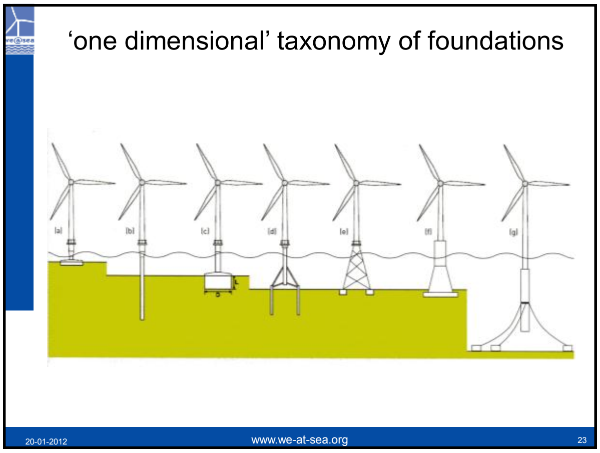
- A powerful UC-ED model developed for studying the Dutch power system
- Thermal generation can cope with balancing most of the time,
- Critical situations: low load high wind. More flexible international power exchange can avoid wasting wind.
- Wind significantly reduces operational cost of power generation, reduces power imports, increases exports: international exchange is key for integration
- Energy storage definitely not the most attractive balancing solution
- Rather: use of heat boilers at CHP sites and additional interconnection capacity e.g. with Norway



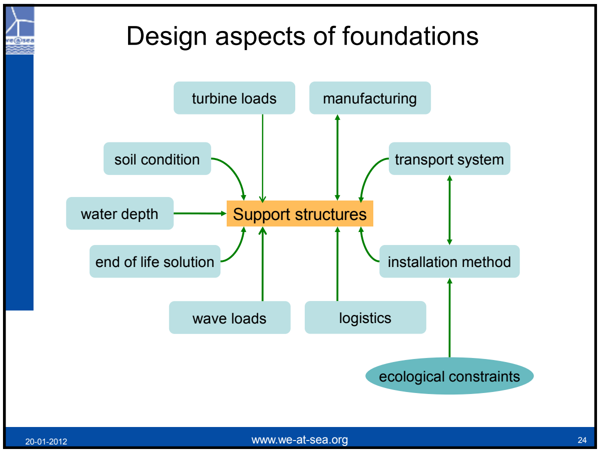
Energy storage and multi-functional use of the sea

Building the plant
- Foundations
- Installation

Installation & Foundation
- Integration of foundations and installation and efficiency of installation
- Site and environmentally specific.



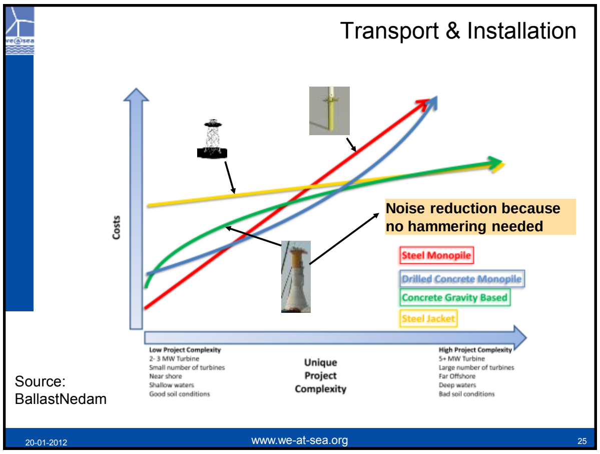
‘one dimensional’ taxonomy of foundations



Design aspects of foundations

Support structures

turbine loads
manufacturing
soil condition
transport system
water depth
end of life solution
installation method
wave loads
logistics
ecological constraints



Transport & Installation

Noise reduction because no hammering needed

Source: BallastNedam

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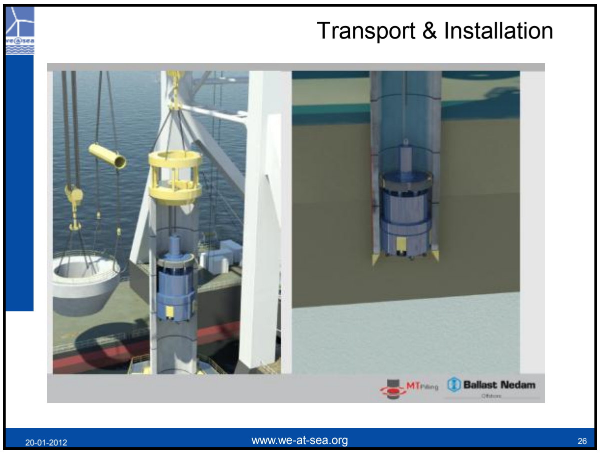

Transport & Installation

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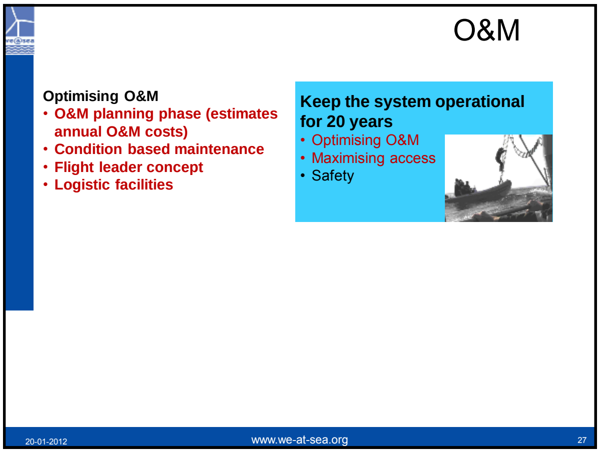

O&M

Optimising O&M

- O&M planning phase (estimates annual O&M costs)
- Condition based maintenance
- Flight leader concept
- Logistic facilities

Keep the system operational for 20 years

- Optimising O&M
- Maximising access
- Safety

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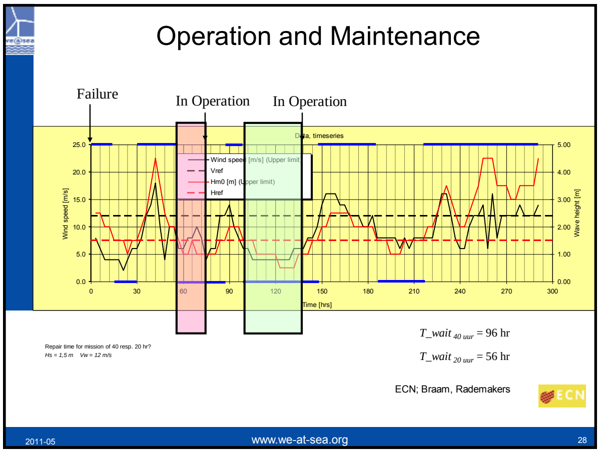

Operation and Maintenance

Repair time for mission of 40 resp. 20 hr?
Hs = 1,5 m Vw = 12 m/s

$T\_wait_{40\ uur} = 96$ hr

$T\_wait_{20\ uur} = 56$ hr

ECN; Braam, Rademakers

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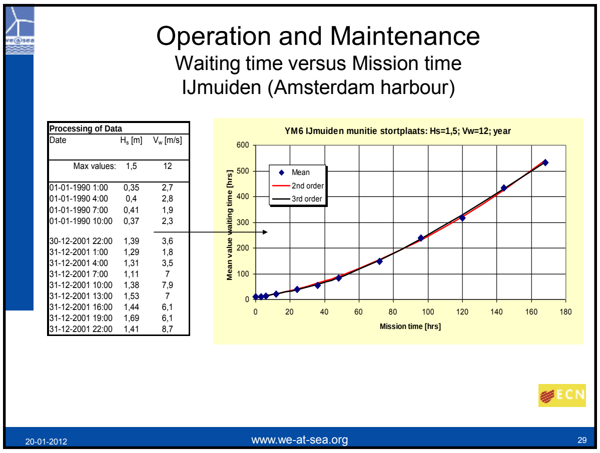

Operation and Maintenance

Waiting time versus Mission time
IJmuiden (Amsterdam harbour)

Processing of Data		
Date	H_s [m]	V_w [m/s]
Max values:	1,5	12
01-01-1990 1:00	0,35	2,7
01-01-1990 4:00	0,4	2,8
01-01-1990 7:00	0,41	1,9
01-01-1990 10:00	0,37	2,3
30-12-2001 22:00	1,39	3,6
31-12-2001 1:00	1,29	1,8
31-12-2001 4:00	1,31	3,5
31-12-2001 7:00	1,11	7
31-12-2001 10:00	1,38	7,9
31-12-2001 13:00	1,53	7
31-12-2001 16:00	1,44	6,1
31-12-2001 19:00	1,69	6,1
31-12-2001 22:00	1,41	8,7

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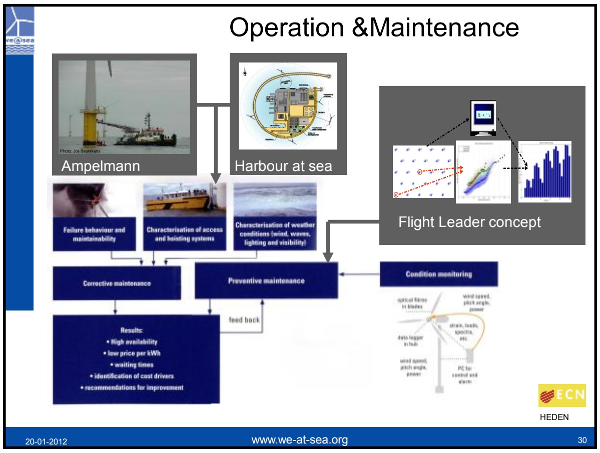

Operation &Maintenance

Ampelmann

Photo: Jos Beurskens

Harbour at sea

Flight Leader concept

Failure behaviour and maintainability

Characterisation of access and hoisting systems

Characterisation of weather conditions (wind, waves, lighting and visibility)

Corrective maintenance

Preventive maintenance

Condition monitoring

feed back

Results:
- High availability
- low price per kWh
- waiting times
- identification of cost drivers
- recommendations for improvement

HEDEN

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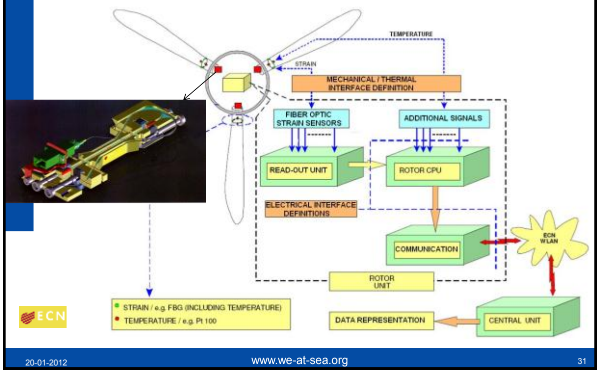
Layout of blade monitoring system

based on optical sensors for strain measurements



Darwind XEMC

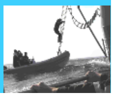
Access

- **Ampelmann concept tested**

(First applications in oil & gas sector!)

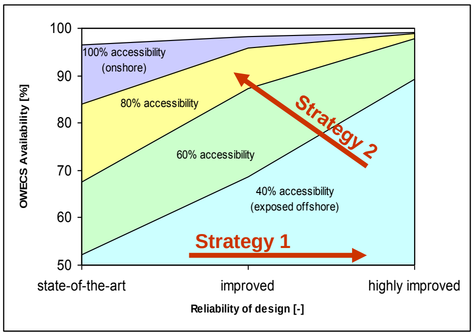
Keep the system operational for 20 years

- Optimising O&M
- Maximising access
- Safety



Access

Availability = *f* (reliability, accessibility)

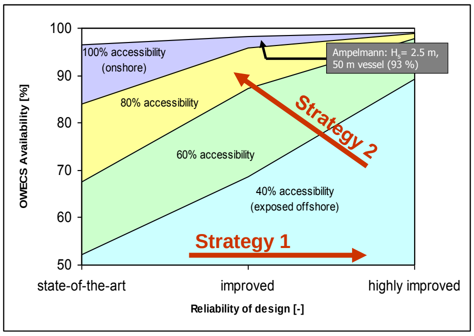


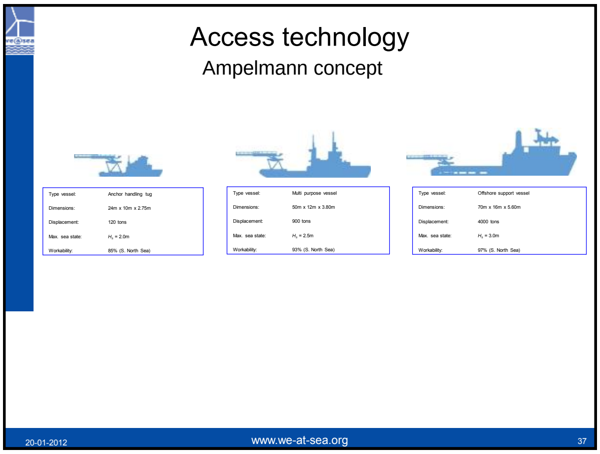
Access technology

Ampelmann concept

Access

Availability = *f* (reliability, accessibility)





Access technology

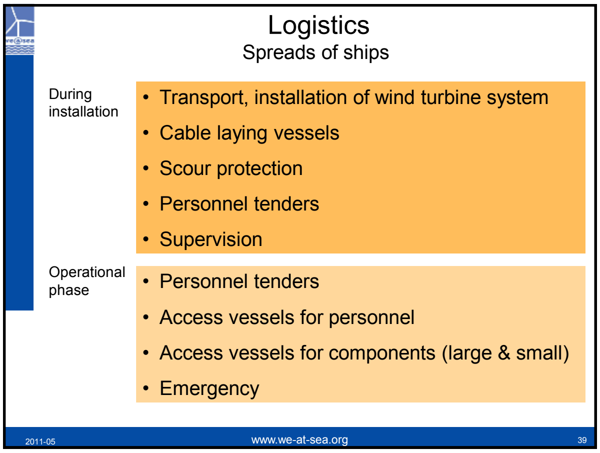
Ampelmann concept

Type vessel:	Anchor handling tug
Dimensions:	24m x 10m x 2.75m
Displacement:	120 tons
Max. sea state:	H_s = 2.0m
Workability:	85% (S. North Sea)

Type vessel:	Multi purpose vessel
Dimensions:	50m x 12m x 3.80m
Displacement:	900 tons
Max. sea state:	H_s = 2.5m
Workability:	93% (S. North Sea)

Type vessel:	Offshore support vessel
Dimensions:	70m x 16m x 5.60m
Displacement:	4000 tons
Max. sea state:	H_s = 3.0m
Workability:	97% (S. North Sea)

Working harbours



Logistics

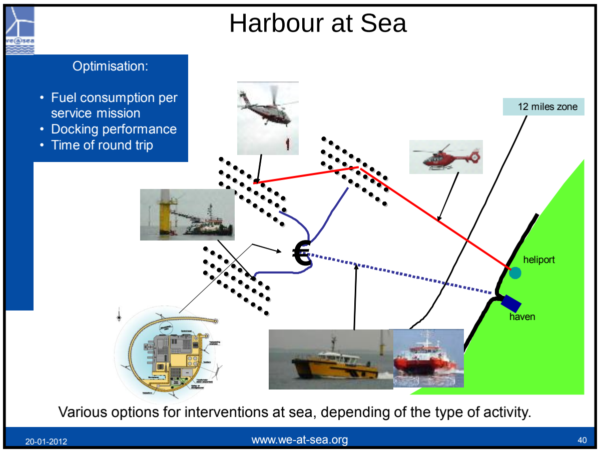
Spreads of ships

During installation

- Transport, installation of wind turbine system
- Cable laying vessels
- Scour protection
- Personnel tenders
- Supervision

Operational phase

- Personnel tenders
- Access vessels for personnel
- Access vessels for components (large & small)
- Emergency

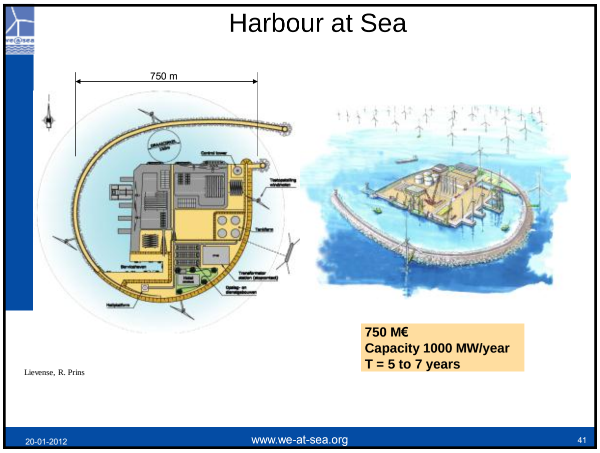


Harbour at Sea

Optimisation:

- Fuel consumption per service mission
- Docking performance
- Time of round trip

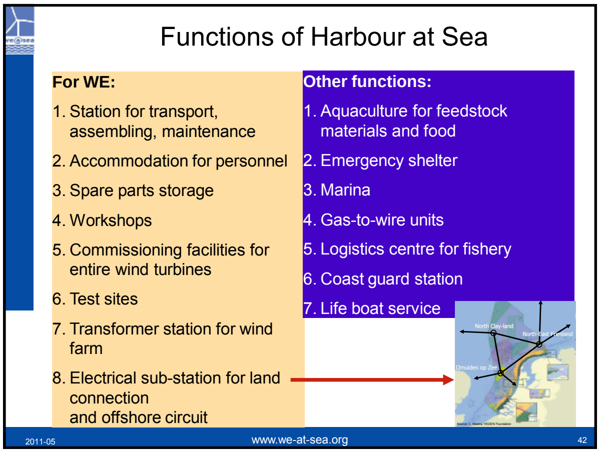
Various options for interventions at sea, depending of the type of activity.



Harbour at Sea

750 M€
Capacity 1000 MW/year
T = 5 to 7 years

Lievense, R. Prins



Functions of Harbour at Sea

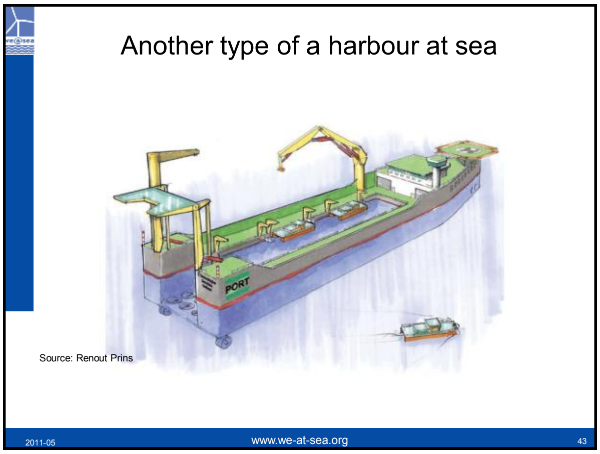
For WE:

1. Station for transport, assembling, maintenance
2. Accommodation for personnel
3. Spare parts storage
4. Workshops
5. Commissioning facilities for entire wind turbines
6. Test sites
7. Transformer station for wind farm
8. Electrical sub-station for land connection and offshore circuit

Other functions:

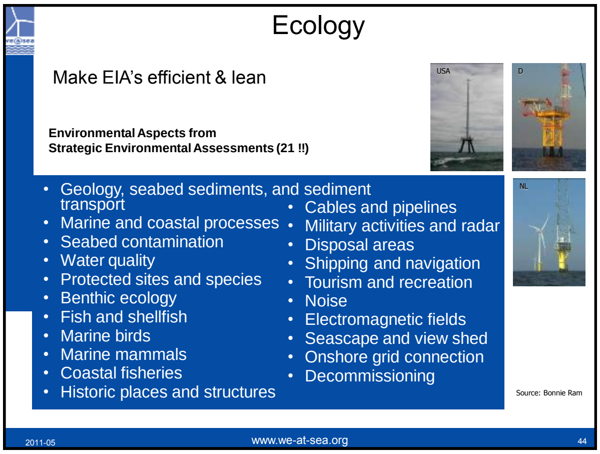
1. Aquaculture for feedstock materials and food
2. Emergency shelter
3. Marina
4. Gas-to-wire units
5. Logistics centre for fishery
6. Coast guard station
7. Life boat service

Source: C. Westra, HEDEN Foundation



Another type of a harbour at sea

Source: Renout Prins



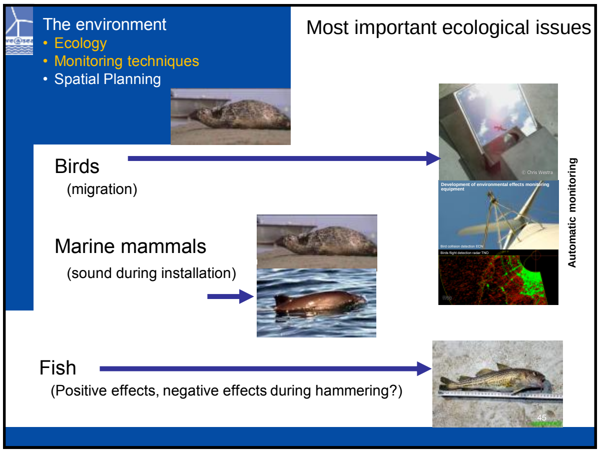
Ecology

Make EIA's efficient & lean

Environmental Aspects from Strategic Environmental Assessments (21 !!)

- Geology, seabed sediments, and sediment transport
- Marine and coastal processes
- Seabed contamination
- Water quality
- Protected sites and species
- Benthic ecology
- Fish and shellfish
- Marine birds
- Marine mammals
- Coastal fisheries
- Historic places and structures
- Cables and pipelines
- Military activities and radar
- Disposal areas
- Shipping and navigation
- Tourism and recreation
- Noise
- Electromagnetic fields
- Seascape and view shed
- Onshore grid connection
- Decommissioning

Source: Bonnie Ram



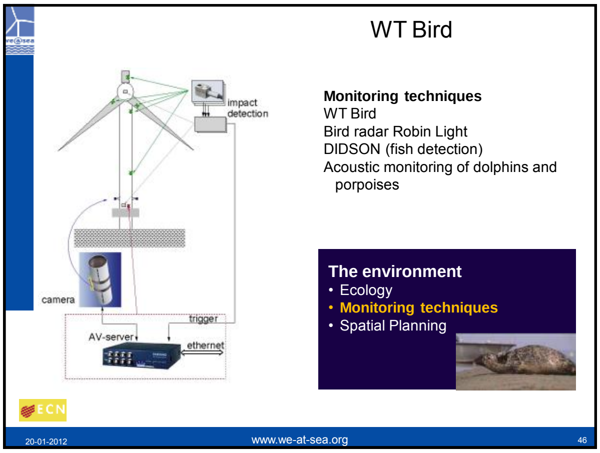
The environment
- Ecology
- Monitoring techniques
- Spatial Planning

Most important ecological issues

Birds
(migration)

Marine mammals
(sound during installation)

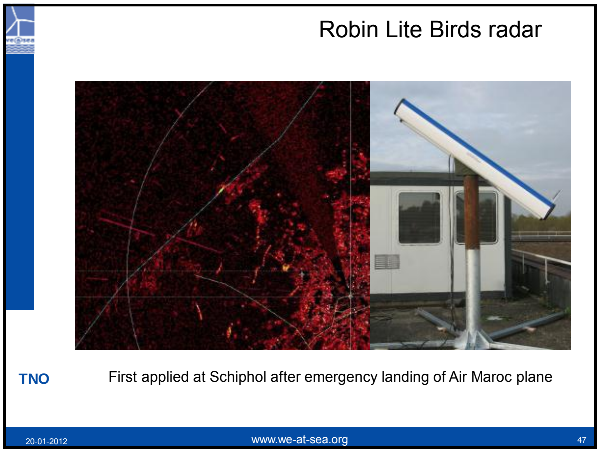
Fish
(Positive effects, negative effects during hammering?)



WT Bird

Monitoring techniques
WT Bird
Bird radar Robin Light
DIDSON (fish detection)
Acoustic monitoring of dolphins and porpoises

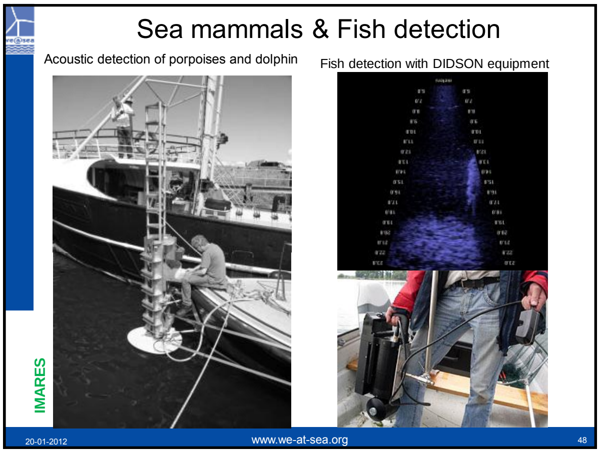
The environment
- Ecology
- **Monitoring techniques**
- Spatial Planning



Robin Lite Birds radar

TNO

First applied at Schiphol after emergency landing of Air Maroc plane



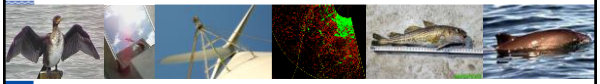
Sea mammals & Fish detection

Acoustic detection of porpoises and dolphin

Fish detection with DIDSON equipment

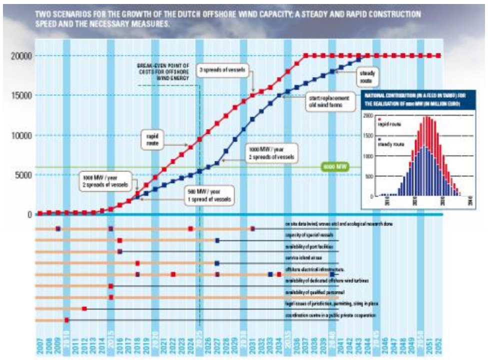
IMARES

Ecological issues

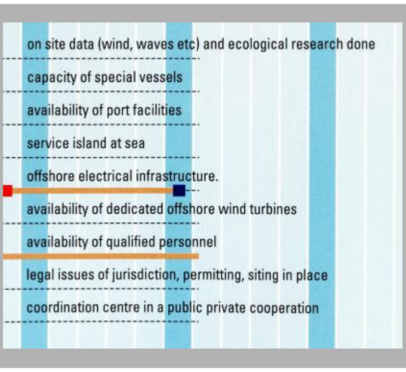


- The more research is conducted …..
- the less anticipated problems appear to be real ones,
- the more mitigating measures appear possible and effective,
- However, cumulative effects are still unknown

NL Policy master plan



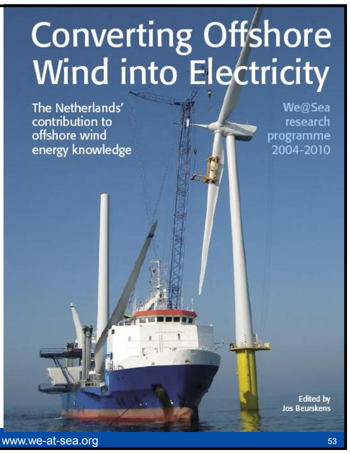
Master plan



on site data (wind, waves etc) and ecological research done
capacity of special vessels
availability of port facilities
service island at sea
offshore electrical infrastructure.
availability of dedicated offshore wind turbines
availability of qualified personnel
legal issues of jurisdiction, permitting, siting in place
coordination centre in a public private cooperation

Concluding remarks
Potential Obstacles towards LS offshore WE

- How to enter in the overall learning curve? (All projects are unique, lack of sharing operational & planning experience, lack of standardisation, …..)
- Lack of dedicated transport, installation, access vessels, logistic centres (harbour facilities (at sea))
- Support structures manufacturing critical
- For the far future: dedicated offshore wind turbines, including full set of design tools are needed
- Spatial plan at sea lagging behind to actual developments
- Coherence of spatial plans between bordering countries needed
- Grid at sea requires international spatial planning based on ecological considerations and claims of other users of the sea
- Cumulative effects on ecosystem unknown
- Electrical infrastructure at sea not available in time; broad concept and standards needed
- Experts and trained personnel not available in time



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The Netherlands' contribution to offshore wind energy knowledge

We@Sea research programme 2004-2010

Edited by Jos Beurskens

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