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Wind Power R&D seminar - Deep Sea Offshore Wind

John Olav Tande

SINTEF Energy Research

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TECHNICAL REPORT

SINTEF

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CONTRIBUTOR(S)

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CLIENT(S)

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RESULT (summary)

Targets are set for a massive installation of offshore wind. In Europe alone the industry suggests 40 GW by 2020 and 150 GW by 2030 as viable. The development is ongoing, but in an early stage. Only approx. 2 GW of offshore wind have so far been installed in Europe, and all relatively close to shore using what can be called onshore wind technology.

The topic of this seminar is deep sea offshore wind technology, i.e. technology for water depths excess of 30 meters, both bottom-fixed and floating. Bottom-fixed wind farms, and mainly at shallow waters, are expected to dominate the near term development, whereas large-scale deployment of deep offshore (floating) wind farms are expected after 2020.

The high targets for offshore wind (150 GW by 2030) are only viable provided that costs can be reduced to a competitive level. This requires long-term efforts to develop offshore-specific turbine technology, sub-structures, grid connection and O&M schemes. The seminar addresses the R&D status and results on these topics through a mix of invited presentations by industry, research institutes and universities. Special emphasis is put on presenting developments in Norway having started strong research programmes on offshore wind power (NOWITECH and NORCOWE), and with industry parties being active both in demonstration programmes and as commercial developers. Examples are the floating wind turbine concept HyWind being tested at the west-coast of Norway, supplies of sub-structures to the Alpha-Ventus wind farm in German waters, and engagements in developing commercial wind farms in UK.

This seminar has been arranged every year since 2004, and has been established as an important venue for the wind power sector in Norway. News for this year are that all presentations will be in English allowing for more international participation, poster presentations by PhD students and a strong focus on deep sea offshore wind technology.

KEYWORDS		
SELECTED BY AUTHOR(S)	Offshore wind power	Power system integration
	Wind turbine technology	Sub-structures

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21-22 January 2010, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY

	Thursday 21 January	
09.00	Registration & coffee	
	Opening session – offshore wind opportunities Chairs: John Olav Tande, SINTEF/NOWITECH and Kristin Guldbrandsen Frøysa, CMR/NORCOWE	
09.30	Opening and welcome by chair	
09.40	*Offshore wind – a golden opportunity for Norwegian industry* Åslaug Haga, Federation of Norwegian Industries	
10.10	*Norwegian hydro as the European energy battery – potential and challenges* Thomas Trötscher, SINTEF	
10.30	*Development of offshore wind farms* Bjørn Drangsholt, Statkraft	
11.00	*HyWind experiences and potential for large-scale deployment* Sjur Bratland, Statoil	
11.30	*The need for a Norwegian test and demonstration programme on offshore wind* John Olav Giæver Tande, SINTEF / NOWITECH	
11.50	Summary and discussions by chair	
12.00	Lunch	
	Parallel sessions	
	A1) New turbine technology Chairs: A Strand, CMR, BW Tveiten, SINTEF	**B1) Power system integration** Chairs: Prof Tore Undeland, Prof K Uhlen, NTNU
13.00	Introduction by Chair	Introduction by Chair
13.10	*A quantitative comparison of three floating wind turbines*, Jason Jonkman, NREL	*Prospects for new cross-border connectors* Kjartan Hauglum, Statnett
13.30	*Long blades for offshore turbines* Jørg Høyland, PhD student NTNU	*Optimal design of a North-Sea offshore grid* Thomas Trötscher, SINTEF
13.50	*VAWT for offshore – pros and cons* Dr Olimpo Anaya-Lara and Prof Bill Leithead, University of Strathclyde	*Power market analysis of large-scale offshore wind* Magnus Korpås, SINTEF
14.10	*HyWind modelling and validation* Bjørn Skaare, Statoil	*Power fluctuations from offshore wind farms* Prof Poul Sørensen, Risø DTU
14.30	*Floating wind turbine. Wave induced loads.* Ivar Fylling, MARINTEK	*Cost of balancing large-scale wind generation* Prof Lennart Söder, KTH
15.00	Refreshments	
	A2) New generator technology Chairs: A Strand, CMR, BW Tveiten, SINTEF	**B2) Grid connection** Chairs: Prof Tore Undeland, Prof K Uhlen, NTNU
15.30	Introduction by Chair	Introduction by Chair
15.35	*Light-weight gear and generator technology* Bo Rohde Jensen, Senior Specialist, Vestas Wind Systems A/S	*From power markets to voltages and currents* Prof Kjetil Uhlen, NTNU
15.55	*Direct-drive generator and converter system* Prof Robert Nilssen, NTNU	*Sub-stations for offshore wind farms* Steve Aughton, Siemens T&D Limited
16.15	*New gearbox technology* Lars Raunholt, Angle Wind AS	*New converter topologies for offshore wind farms* Prof Marta Molinas, NTNU
16.35	*Potential top-mass reduction by hydraulic transmission*, Prof Ole G Dahlhaug, NTNU	*Power quality measurements from wind farms* Trond Toftevaag and Tarjei Solvang, SINTEF
16.55	Closing by Chair	Closing by Chair
17.00	**Poster Session with refreshments and presentation of PhD students on offshore wind**	
19.00	Dinner	

Wind Power R&D seminar – deep sea offshore wind **21-22 January 2010, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY**		
	Friday 22 January	
	Parallel sessions	
	C) Met-ocean conditions, operations and maintenance Chairs: Prof J Reuder, UiB, J Heggset, SINTEF	**D) Installation and sub-structures** Chairs: Prof I Langen, UiS, Prof G Moe, NTNU
09.00	Introduction by Chair	Introduction by Chair
09.05	*North-Sea wind database - NORSEWInD* Erik Berge, Kjeller Vindteknikk / IFE	*Research at Alpha Ventus: RAVE and GIGAWIND* Prof. Dr.-Ing. habil. Raimund Rolfes, ForWind, Leibniz University Hannover
09.25	*Oceanic wind profile, turbulence and boundary layer characteristics* Prof Idar Barstad, UniResearch	*Hydrodynamic effects on bottom-fixed offshore wind turbines*, Karl O. Merz, PhD student NTNU, Prof G Moe, NTNU, Prof Ove T. Gudmestad, Univ. of Stavanger
09.45	*Transfer of methods and experience on O&M in other industries to offshore wind farms* Erik Dyrkoren, MARINTEK	*Supply of jackets to the Alpha-Ventus wind farm* Jørgen Jorde, NorWind
10.05	*Corrosion protection of offshore wind turbines*, OØ Knudsen, A. Bjørgum, SINTEF	*Cost comparison of sub-structures* Daniel Zwick and Haiyan Long, PhD students NTNU
10.25	Closing by Chair	Closing by Chair
10.30	Refreshments	
	Closing session – expert panel on R&D needs for developing offshore wind farms Chairs: John Olav Tande, SINTEF/NOWITECH and Kristin Guldbrandsen Frøysa, CMR/NORCOWE	
11.00	Introduction by Chair	
11.05	*The European research agenda on offshore wind*, Beate Kristiansen, Research Council of Norway	
11.25	*State-of-the-art design practices for offshore wind farms*, Peter Hauge Madsen, Risø DTU	
11.45	*Panel debate on R&D needs for developing offshore wind farms* Dr habil Hans-Gerd Busmann, Head of Fraunhofer IWES Peter Hauge Madsen, Head of Wind Energy Division, Risø DTU Dr Olimpo Anaya-Lara, University of Strathclyde Finn Gunnar Nielsen, Chief Scientist, Statoil Bo Rohde Jensen, Senior Specialist, Vestas Wind Systems A/S Terje Gjengedal, R&D director, Statnett	
12.45	Closing and Summary by Chair	
13.00	Lunch	

List of participants
Offshore Wind R&D Seminar, 21. – 22. January 2010

Name	Company
Aakervik, Anne-Lise	Mediekompaniet I Ilsvika
Abrahamsen, Odd Henning	Lyse Produksjon AS
Adaramola, Muyiwa	NTNU
Aigner, Tobias	NTNU (student)
Åkervik, Espen	Kjeller Vindteknikk
Almås, Geir A.	Teekay Shipping Norway
Anders Arvesen	NTNU (student)
Andersson, Janne Grete Endal	Segel AS
Anthonippillai Antonarulrajah	NTNU
Armendáriz, José Azcona	CENER
Aughton, Steve	Siemens T&D Limited
Barstad, Idar	UNI – Bjerknes Centre for Climate Research
Berg, Bjørn	Rolls-Royce Marine as, Foundry Bergen
Berg, Jon Trygve	Sarsia Seed Management AS
Berge, Erik	Kjeller Vindteknikk
Bergseth, Roger	Segel AS
Berland, Jostein	Vest Kran Wind Power
Berthelsen, Petter Andreas	MARINTEK
Bjørgum, Astrid	SINTEF Materials and Chemistry
Bjørlo, Alfred	Måløy Vekst
Bøen, Endre	Teekay Shipping
Bracchi, Tania	NTNU
Bratland, Sjur	Statoil
Bredmose, Henrik	DTU Mechanical Engineering
Brovold, Heidi	DNV
Bull-Berg, Heidi	SINTEF Teknologi og Samfunn
Busmann, Hans-Gerd	Fraunhofer IWES
Byrkjedal, Øyvind	Kjeller Vindteknikk
Christophersen, Espen Borgir	Enova SF
Dahl, Bergny	Innovasjon Norge
Dahlhaug, Ole Gunnar	NTNU
Dong, Wenbin	NTNU (student)
Drangsholt, Bjørn	Statkraft
Dyrkoren, Erik	MARINTEK
Echarri, Xabier Munduate	CENER
Eek, Jarle	SINTEF Energi AS
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Ertsgaard, Aage	Det Norske Veritas
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Finden, Per	IFE
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Frøysa, Kristin Gulbrandsen	NORCOWE / CMR
Fuglseth, Thomas	NTNU (student)
Fylling, Ivar	MARINTEK
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Gjengedal, Terje	Statnett
Gjerde, Sverre	NTNU (student)
Gjertdsen, Tor	Lutelandet Offshore AS
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Graczyk, Mateusz	MARINTEK
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Gundersen, Joakim	Nordnorsk Havkraft AS
Haarberg, Per Olav	ChapDrive AS
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Hanssen, Jan Erik	1-Tech s.p.r.l.
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Heggset, Jørn	SINTEF Energi AS
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Henjesand, Rune	Innovasjon Norge
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Holmøy, Vidar	Norsetek AS
Høyland, Jørg	NTNU
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Imafidon, Oliver	NTNU (student)
Jafar, Muhammad	NTNU (student)
Jakobsen, Tomas Frithjof	EDR AS
Jensen, Bo Rohde	Vestas Wind Systems AS
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Johnsen, Roy	NTNU
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Jorde, Jørgen	NorWind
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Karimirad, Madjid	CeSOS / NTNU (student)
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Knudsen, Ole Øystein	SINTEF Materials and Chemistry
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Kristensen, Jonas	Vestas Technology R&D
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Kristiansen, Øyvind	Statkraft
Krokstad, Jørgen Ranum	Statkraft Development AS
Kupen, Frode	Sikkerhetssenteret i Måløy
Kvalbein, Ådne	Bryne Mekanikk AS
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Låte, Leiv	Fedem Technology AS
Laukhammer, Vegard	Vecon

Lijuan Dai	NTNU (student)
Liland, Tommy Andre	Depro AS
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Madsen, Petter Hauge	Risø DTU
Malvik, Inger Marie	Fugro OCEANOR
Mathisen, Jan-Petter	Fugro OCEANOR
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Merz, Karl O.	NTNU
Mikkelsen, Hans Jørgen	FORCE Technology Norway AS
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Moan, Torgeir	NTNU /CeSOS
Moe, Geir	NTNU
Molinas, Molinas	NTNU
Muskulus, Michael	NTNU
Myhr, Anders	University of Life Sciences (UMB)
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Nakken, Torgeir	Statoil
Naustdal, Ainor Fristad	Lutelandet Utvikling AS
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Niedzwecki, John	Texas A&M University
Nielsen, Finn Gunnar	Statoil
Nilssen, Robert	NTNU
Nonås, Lars Magne	MARINTEK
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Nysveen, Arne	NTNU
Olimpo Anaya-Lara	University of Strathclyde
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Onarheim, Jan	NTNU
Ottesen, Stein-Arne	Lutelandet Utvikling AS
Øyen, Rune	Depro AS
Peddie, David	Christian Michelsen Research AS
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Pellet, Laure	EDF R&D
Pettersson, Hans	Teknova
Pleym, Anngjerd	SINTEF Energi AS
Pramayon, Pierre	EDF R&D
Quesnel, Louis	Fraunhofer IWES
Radan, Damir	IRIS - International Research Institute of
Rådberg, Carolin	GE Wind Energy
Raunholt, Lars	Angle Wind AS
Reiso, Marit	NTNU (student)
Reuder, Joachim	University of Bergen
Ringheim, Nils Arild	SINTEF Energi AS
Rolfes, Raimund	Leibniz Universität Hannover
Røset, Einar	Siemens AS
Rui, Øyvind	Statnett
Sætern, Arnt Inge	TrønderEnergi Kraft AS
Sætrevik, Torleif	Statkraft Development
Sandquist, Fredrik	NTNU (student)
Sandvik, Håkon	Vestavind Kraft AS
Sarkar, Arunjyoti	University of Stavanger
Schmid, Bernd	SINTEF Materials and Chemistry

Skaare, Bjørn	Statoil
Skånøy, Thomas	Siemens AS
Skare, Eirik	SmartMotor AS
Skipenes, Anders	Sparebanken Sogn og Fjordane
Skjølsvik, Kjell Olav	Enova SF
Söder, Lennart	KTH
Soloot, Amir Hayati	NTNU (student)
Solvang, Tarjei	SINTEF Energi AS
Sørensen, Poul	Risoe DTU
Sørheim, Hans-Roar	Christian Michelsen Research AS
Steen, Hans Chr.	TrønderEnergi Invest AS
Stenbro, Roy	IFE
Stickler, Morten	Statkraft
Støa, Petter	SINTEF Energi AS
Strand, A.	CMR
Stranden, Øystein	Fedem Technology AS
Straume, Harald	Bergen Group Rosenberg AS
Sung-Woo Im	RIST
Svendgård, Ole	VIVA Testsenter
Svendsen, Harald	SINTEF Energi AS
Svendsen, Trine	SWECO
Tande, John Olav	SINTEF Energi AS / NOWITECH
Tande, Jørgen	NTNU (student)
Tasar, Gursu	NTNU (student)
Thomassen, Paul	NTNU
Thomsen, Knud Erik	ChapDrive AS
Toftevaag, Trond	SINTEF Energi AS
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Tørset, John	Hägglunds Drives AS
Trötscher, Thomas	SINTEF Energi AS
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Undeland, Tore	NTNU
Undem, Linn Silje	Norwegian Water Resources and Energy
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Valibeigloo, Mahmoud	NTNU (student)
van Buren, Eric	NTNU (student)
van Wingerde, Arno	Fraunhofer IWES
Vrana, Til Kristian	NTNU (student)
Weider, Pia	Lyse Produksjon AS
Welde, Håkon	TrønderEnergi Invest AS
Wik, Fredrik	WindSim AS
Wold, Erik	NTNU Technology Transfer as
Zhen Gao	NTNU / CeSOS
Zwick, Daniel	NTNU

Opening session – offshore wind opportunities

Offshore wind – a golden opportunity for Norwegian industry (no presentation available), Åslaug Haga, Federation of Norwegian Industries

Norwegian hydro as the European energy battery – potential and challenges, Thomas Trötscher, SINTEF

Development of offshore wind farms, Bjørn Drangsholt, Statkraft

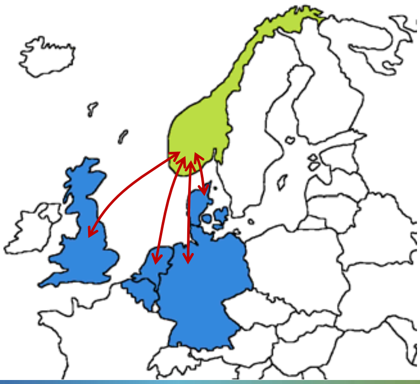
HyWind experiences and potential for large-scale deployment,
Sjur Bratland, Statoil

The need for a Norwegian test and demonstration programme on offshore wind
John Olav Giæver Tande, SINTEF / NOWITECH

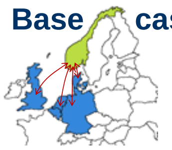
Norwegian hydro as the European energy battery – potential and challenges

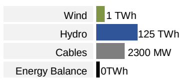
Thomas Trötscher
Magnus Korpås
John Olav Tande
SINTEF Energy Research

Area



Base case scenario





Key figures "Europe"

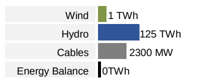
Installed wind power: 111 GW
Wind power penetration: 34%
Load: 1052 TWh/p.a.
Wind power production: 358 TWh/p.a.
All other power is thermal

Key figures Norway

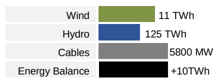
Installed wind power: 280 MW
Wind power penetration: <1%
Max stored hydro gen.: 23000 MW
Max run-of-river gen.: 7000 MW
Pumping power: 1335 MW
Min hydro gen.: 5000 MW
Available winter capacity: ~24500 MW
Load: 126TWh/p.a.
Median hydro production: 125 TWh/p.a.
Wind power production: 1 TWh/p.a.

Cases

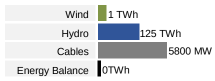
- Base Case



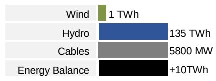
- Base Case +3500MW +10TWh wind power



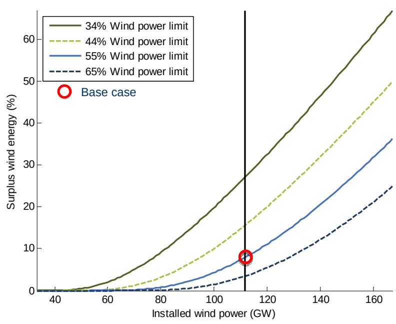
- Base Case +3500MW exchange capacity



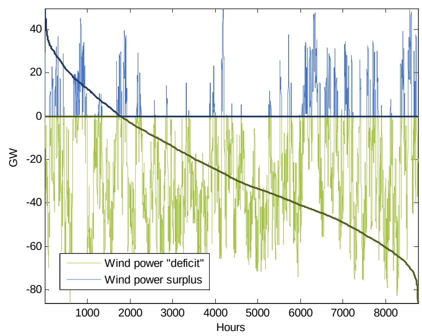
- Base Case +3500MW +10TWh run-of-river hydro power



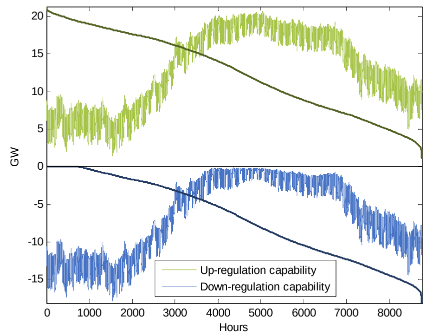
Installed wind power in Europe



European power surplus and "deficit"

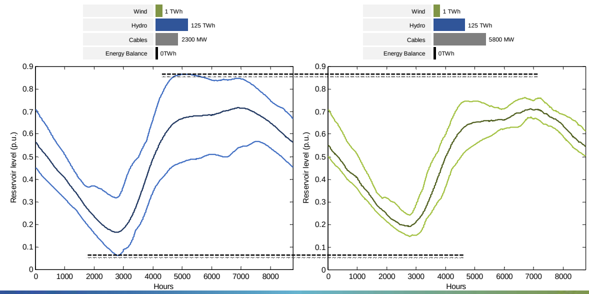


Norwegian hydro balancing capabilities

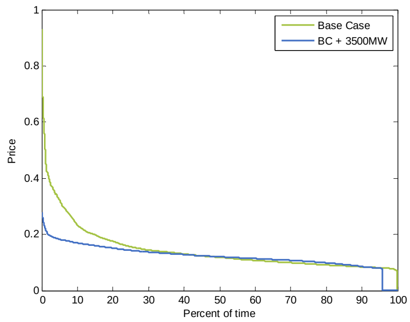


Norwegian hydro reservoir level

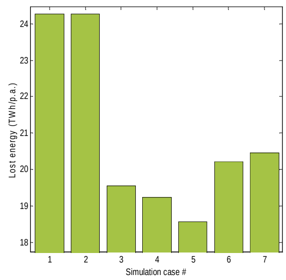
Base Case | **Base Case +3500MW**



Prices in Norway



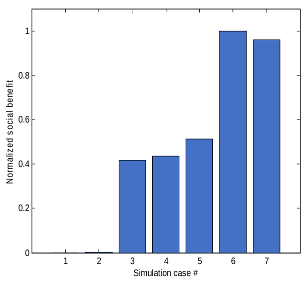
Lost/unused renewable energy



Simulation cases

1. Base Case (BC)
2. BC **+1000MW pumping**
3. BC **+3500MW exchange capacity**
4. BC +3500MW exchange capacity **+1000MW pumping**
5. BC + **4500MW exchange capacity**
6. BC + 3500MW exchange capacity + **10TWh wind**
7. BC + 3500MW exchange capacity + **10TWh run-of-river hydro**

Relative social economic cost



Simulation cases

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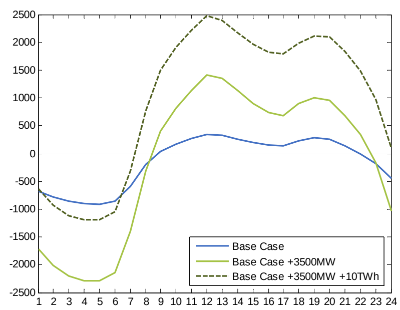
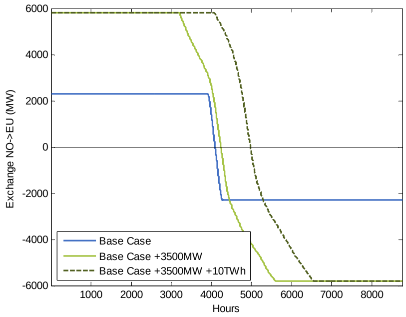
7. BC + 3500MW exchange capacity + **10TWh run-of-river hydro**

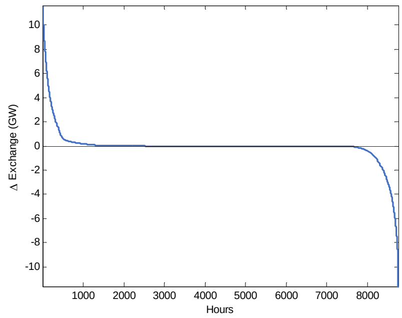
Diurnal exchange pattern



Utilization of exchange capacity



Hour-to-hour change in export



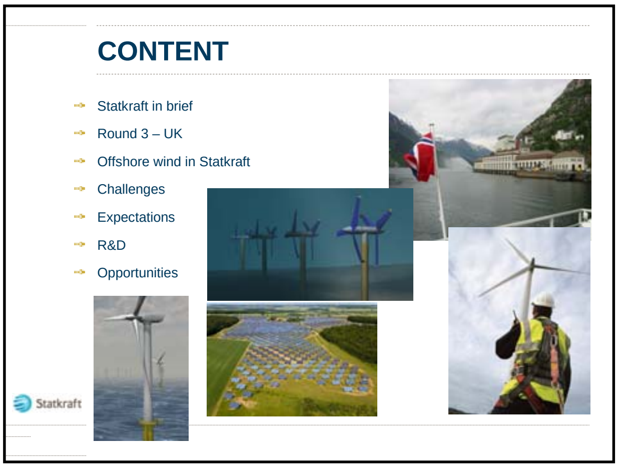
Discussion

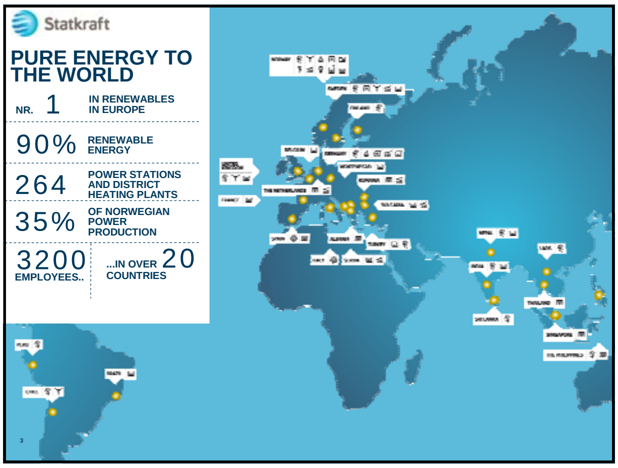
- **Internal grid bottlenecks**
- **Limitations on water flow**
- **Capacity upgrade and reserve requirements**

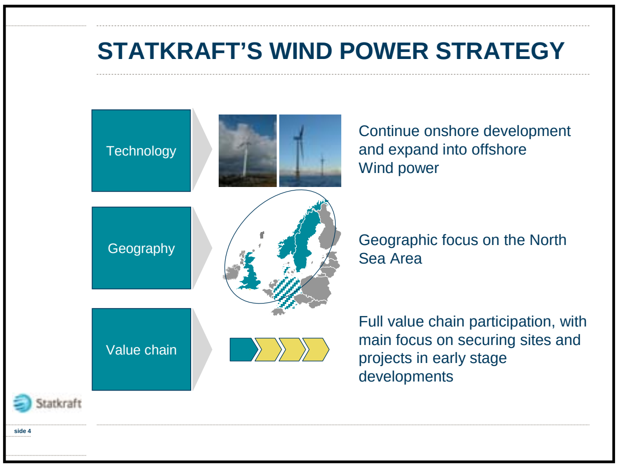
Conclusions

- Norway can act both as a net exporter of renewable electricity and as a ”battery” for Europe
  - Provided the exchange capacity is suitably expanded
- Norway can help Europe meet its balancing needs
- Norwegian hydro reservoirs have sufficient capacity
  - Down-regulation capability is limited by little pumping capacity during the spring thaw
  - Up-regulation capability is less of an issue, but is somewhat limited in the winter time
- We should not fear to ”import” European prices
  - As long as the planned amount of wind power is built in the North Sea region, prices in Norway will likely fall slightly and stabilize
  - Prices will be less influenced by the annual changes in inflow

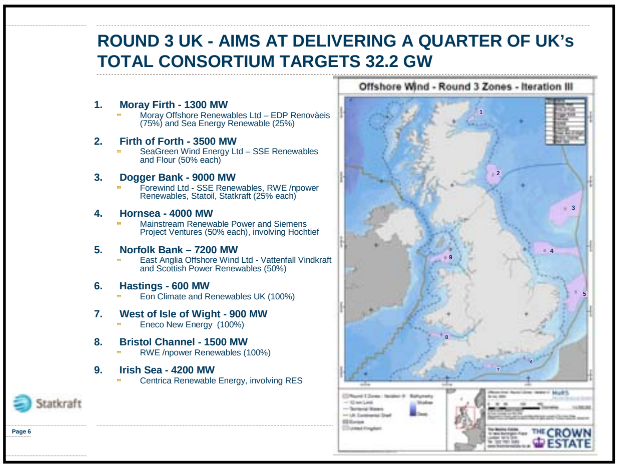

Development of
Offshore Wind Farms
Bjørn Drangsholt, Vice President
Wind Power R&D Seminar
Royal Garden, Trondheim, 21st January 2010
Statkraft
PURE ENERGY


CONTENT
Statkraft in brief
Round 3 – UK
Offshore wind in Statkraft
Challenges
Expectations
R&D
Opportunities
Statkraft

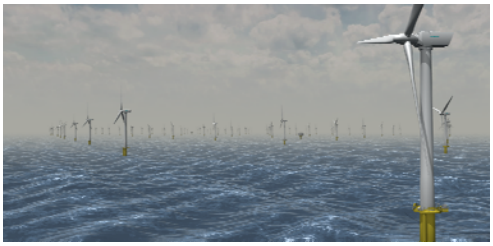

Statkraft
PURE ENERGY TO THE WORLD
NR. 1 IN RENEWABLES IN EUROPE
90% RENEWABLE ENERGY
264 POWER STATIONS AND DISTRICT HEATING PLANTS
35% OF NORWEGIAN POWER PRODUCTION
3200 EMPLOYEES..
...IN OVER 20 COUNTRIES


STATKRAFT'S WIND POWER STRATEGY
Technology
Continue onshore development and expand into offshore Wind power
Geography
Geographic focus on the North Sea Area
Value chain
Full value chain participation, with main focus on securing sites and projects in early stage developments
Statkraft
side 4


ROUND 3 – PREFERED BIDDER ANNOUNCED
Announcement of the successful bidders by Prime Minister Gordon Brown 8th January 2010
Møller for milliarder
The big new projects
Wind is the revolution needed in this country
£100bn wind farm plan heralds green energy era
Kan bli industri-eventyr
The revolution starts here - but foreign firms gain most from wind power deals
£75bn on energy bills to fund 'dash for wind power'
Giant wind farms will need £100bn and 'super-grid'
U.K. widens efforts to tap wind energy
U.K. bets on wind power and jobs it would create
Statkraft


ROUND 3 UK - AIMS AT DELIVERING A QUARTER OF UK's TOTAL CONSORTIUM TARGETS 32.2 GW
1. Moray Firth - 1300 MW
Moray Offshore Renewables Ltd – EDP Renovàeis (75%) and Sea Energy Renewable (25%)
2. Firth of Forth - 3500 MW
SeaGreen Wind Energy Ltd – SSE Renewables and Flour (50% each)
3. Dogger Bank - 9000 MW
Forewind Ltd - SSE Renewables, RWE /npower Renewables, Statoil, Statkraft (25% each)
4. Hornsea - 4000 MW
Mainstream Renewable Power and Siemens Project Ventures (50% each), involving Hochtief
5. Norfolk Bank – 7200 MW
East Anglia Offshore Wind Ltd - Vattenfall Vindkraft and Scottish Power Renewables (50%)
6. Hastings - 600 MW
Eon Climate and Renewables UK (100%)
7. West of Isle of Wight - 900 MW
Eneco New Energy (100%)
8. Bristol Channel - 1500 MW
RWE /npower Renewables (100%)
9. Irish Sea - 4200 MW
Centrica Renewable Energy, involving RES
Offshore Wind - Round 3 Zones - Iteration III
THE CROWN ESTATE
Statkraft
Page 6

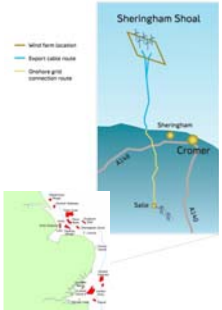
SCIRA OFFSHORE ENERGY LTD
SHERINGHAM SHOAL OWF



Statkraft Statoil

7

SHERINGHAM SHOAL OWF

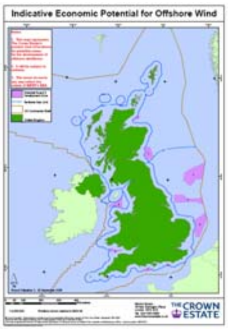


- Offshore wind farm located in the Greater Wash, about 20 km off the coast of Norfolk
- The Owner is Scira Offshore Energy Ltd (50/50 Statoil / Statkraft)
- 315 MW installed capacity, annual production of 1.1 TWh
- 88 turbines, Siemens 3.6 MW
- Other main contracts; MT Højgaard, Areva, Nexans, Master Marine, Visser & Smith
- Constructions started onshore 2009, generation from 2011
- Total investment of NOK 10 BillionNOK

Statoil Statkraft

ROUND 3 UK – WHAT COULD IT MEAN

- 9 zones, 32.200 MW @ 102 SSOWF's
- Governmental aspiration was 25 GW by 2020, new zone target is set to 32,2 GW which could involve:
  - ~5000 – 6000 large turbines and foundations or ~9000 SSOWF 3,6 MW turbines
  - ~150 - 250 offshore substations
  - ~30-40 next generation installation vessels (for turbines & foundations)
  - Large amounts of offshore cable and electrical infrastructure onshore
  - Large amount of survey vessels, cable laying vessels, various O&M vessels
  - Government assumption 75 BGBP investments



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FOREWIND
DELIVERING YOUR ENERGY FUTURE

Forewind Offshore Wind Projects

Round 3

SSE Statkraft RWE Statoil

Crown Estate: Key facts on zone 3-Dogger Bank

The Dogger Bank zone is located off the east coast of Yorkshire between 125 and 195 kilometres offshore.

- It extends over approximately 8,660 km² with its outer limit aligned to UK continental shelf limit as defined by the UK Hydrographic Office
- Equivalent in size to North Yorkshire or Vest Agder in Norway
- This is the largest zone in Round 3
- The water depth ranges from 18–63 metres

Statkraft

side 11

EXPECTATIONS

FOREWIND

- Forewind is obliged to complete a working plan that bring the projects to the point of concession. Extensive surveys, assessments and planning for the consenting process. The consortium's commitment is to secure all the necessary consents for the construction and development of Dogger Bank, up to the point of an investment decision, which is anticipated around late 2014.
- Forewind has agreed with The Crown Estate a target installed capacity of 9GW, though the zone has a potential for approximately 13GW, which equates to around 10 per cent of the total projected UK electricity requirements.
- Our 25% share is estimated to cost Statkraft 350 MNOK up to 2014 / 2015
- The owners are building a project organization through the Forewind Ltd company
- Dogger Bank will be divided into several projects.
- If developed it is likely to be the world's largest offshore wind project.

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DOGGER BANK DEVELOPMENT

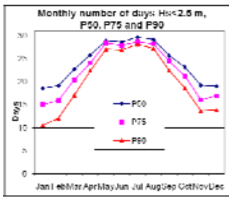
Tentative development plan:

- Joint organisation being established in Reading, UK
- Environmental Impact Assessment (EIA)
- Supply chain development

Statkraft

DOGGER BANK – SOME OF THE CHALLENGES

- Economy (capex, opex, ROC's)
- Distance from shore
- Water depth
- Wave climate
  - Limiting installation
  - Limiting access for maintenance
- Grid connection, grid capacity, OFTO regime
- Capacity limitation throughout the supply chain
- Availability of competent personnel
- New consenting Process (IPC)
- New O&M Philosophy



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DOGGER BANK – SOME EXPECTATIONS

- Larger turbines, 5-6MW +
- Focus on simplicity and reliability (minimum intervention), condition monitoring
- Offshore accommodation and installation in the operational phase (fixed or floating)
- Improved means of access
- Economy of scale (serial production/ installation)
- More optimized design
- New vessels and installation methods – larger capacities and less weather sensitive
- HVDC transmission
- New development of harbour facilities

KeppelFels design

Statkraft

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STATKRAFT SUPPORTS R&D WITHIN OFFSHORE WIND

- Statkraft
  - Is industrial partner in the two CEERs (FME) on offshore wind: NOWITECH and NORCOWE
  - Initiated the Ocean Energy Research Programme: contains many projects within offshore wind, wave- and tidal power at NTNU, DTU and University of Uppsala
  - Supports individual R&D projects which are also supported by the Norwegian Research Council
- For Statkraft, R&D is a tool for reaching our targets, i.e. developing, constructing and operating profitable offshore wind farms.
- To ensure this, good cooperation is needed
  - Between national and international R&D initiatives
  - Between industry and research institutions

Statkraft

Huge opportunities for the International Wind Industry, As well as for the Norwegian Industry – But it won't come easy

The future offshore wind business will be a challenge not only for the developer, but also for the supply- and contractor industry.

- It will demand new and smart solutions
- Equipment needs to be improved
- Risks needs to be understood and managed
- Ability to handle large scale and complex projects a prerequisite
- A long list of Stakeholders will have conflicting interests
- Cost needs to get down to make Round 3 happen

Competition with Global Players

Ocean Services, Marintek, Sintef, Nexans, Aker Verdal AS, NorWind, Storm, NGI, Force Technology, Parker, Kjeller, DNV

Examples of "Norwegian" Companies that can supply services

Statkraft

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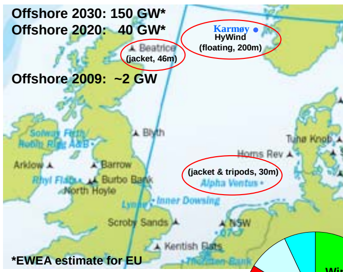
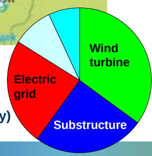
The need for a Norwegian test and demonstration programme on offshore wind

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

A huge international market

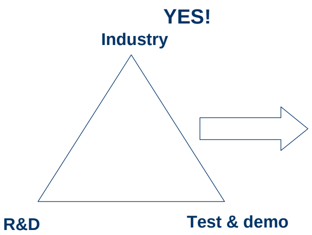




CAPEX distribution
offshore wind farm (DTI study)

- Norwegian industry are taking part as wind farm developers and suppliers of goods and services
- This demonstrates ability to compete, BUT the question is how to secure future large supplies?

The golden triangle for success



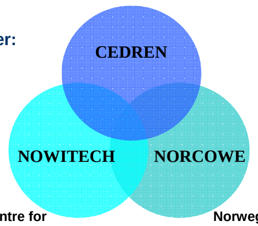
- Supply to international market
- Improved and proven technology and know-how
- Lower cost per kWh from offshore wind farms

Needs to be developed!

A strong cluster on offshore wind R&D

Total budget for the cluster:
~800 MNOK / 8 years

Centre for Environmental Design of Renewable Energy



Norwegian Research Centre for Offshore Wind Technology

Norwegian Centre for Offshore Wind Energy

NOWITECH - in brief

- Objective:
  Pre-competitive research laying a foundation for industrial value creation and cost-effective offshore wind farms. Emphasis on deep sea (+30 m).
- R&D partners: SINTEF, IFE, NTNU + associates: Risø DTU (DK), NREL & MIT (US), Fraunhofer IWES (DE), University of Strathclyde (UK)
- Industry partners: Statkraft, Statoil, Vestavind Kraft, Dong Energy, Lyse, Statnett, Aker Solutions, SmartMotor, NTE, DNV, Vestas, Fugro Oceanor, Devold AMT, TrønderEnergi + associates: Innovation Norway, Enova, NORWEA, NVE, Energy Norway, Navitas Network
- Work packages:
  1. Numerical design tools (including wind and hydrodynamics)
  2. Energy conversion system (new materials for lightweight blades & generators)
  3. Novel substructures (bottom-fixed and floaters)
  4. Grid connection and system integration
  5. Operation and maintenance
  6. Concept validation, experiments and demonstration
- Total budget (2009-2017): +NOK 320 millions including 25 PhD/post docs

NORCOWE - in brief

- Vision:
  Combine Norwegian offshore technology and Danish wind energy competence + Create innovative and cost effective solutions for deep waters and demanding offshore conditions
- R&D partners: CMR, UNI Research, University of Bergen, University of Agder, University of Stavanger, Aalborg University (DK)
- Industry partners: Statkraft, Vestavind Offshore AS, Agder Energi, Statoil, Lyse, Aker MH, National Oilwell Norway, Origo Engineering, Norwind
- Work packages:
  1. Wind and ocean
  2. Offshore wind technology and innovative concepts
  3. Marine operations and maintenance
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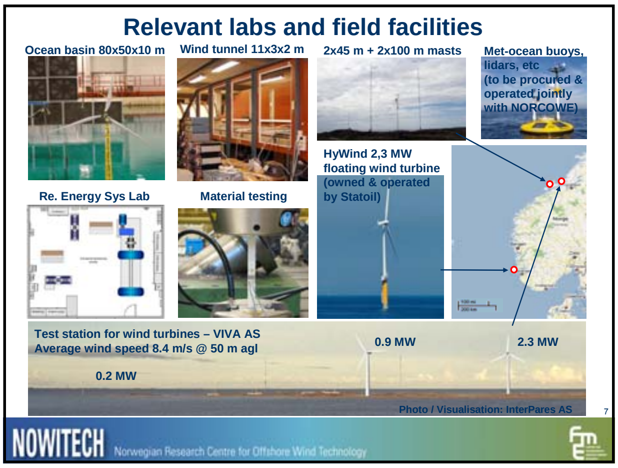
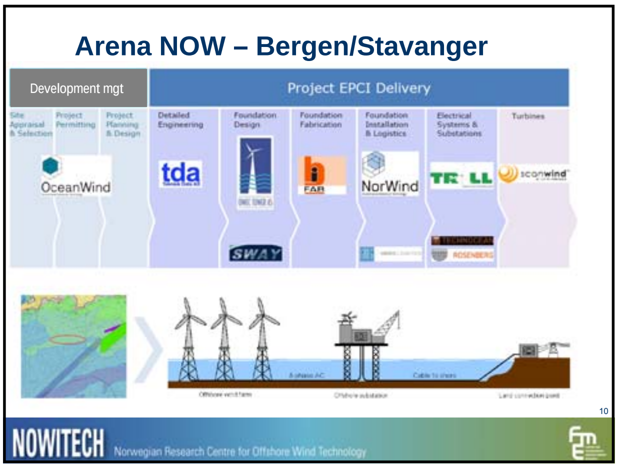
  5. Common topics: Education, Security, Environment, Test facilities and infrastructure
- Total budget (2009-2017): NOK 240 millions including ~20 PhD/post docs





Rationale for test & demo programme

- One of the main goals for the Norwegian offshore wind industry is to establish demonstration areas for:

1. Demonstrating new and existing technologies and products in order to acquire references for Norwegian suppliers
2. Testing new technologies for R&D purpose
3. Building competency and track record

- with the ultimate aim to strengthen Norwegian offshore wind competitive capabilities.

- Arena NOW, Arena Vindenergi, Norcowe, and Nowitech have agreed to take a common approach as to define a national plan for an offshore wind demonstration programme.

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NOWITECH Norwegian Research Centre for Offshore Wind Technology

Business case

There is a need for the Norwegian offshore wind industry to:

1. Have domestic facilities for testing of new Norwegian offshore wind related technologies and products
2. Build Norwegian competency and partnerships in order to strengthen competitive capabilities towards foreign competitors in commercial markets
3. Create Norwegian reference projects that can be used to win projects and contracts externally/commercially
4. Create show-cases on various offshore wind technologies to the Norwegian government

- The above will be achieved through the realisation of a coordinated national offshore wind test and demonstration programme.

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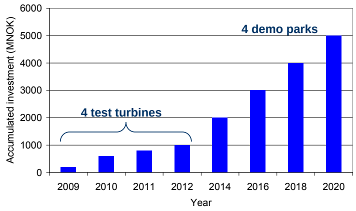
NOWITECH Norwegian Research Centre for Offshore Wind Technology

How to bridge the gap between R&D and large scale deployment of deep sea offshore wind?

► **Suggestion: A NOK 5 billion test & demo programme**
a necessary step between R&D and large scale deployment

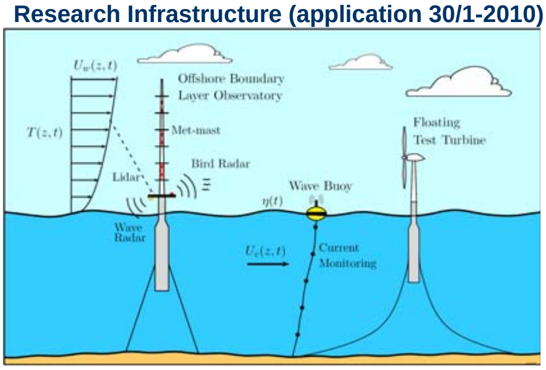


- ► Test and Demonstrate deep sea technology (bottom fixed & floaters)
- ► Utilize R&D results & gain new knowledge
- ► Qualify suppliers
- ► Kick-off offshore wind farm development
- ► Create new industry and employment

Example elements of a test & demo programme

- ► **Small scale (200 kW) test turbine for open experimental research (infrastructure application due 30/1-2010 by NORCOWE, NOWITECH and CEDREN)**
- ► **Prototypes, possibly in scale, of various new turbine concepts and technologies (bottom-fixed and floaters)**
- ► **Demonstration wind farms of semi-commercial nature, showcasing planning, installation, new technology, operation, access, grid connection, ..**
- ► **Open programme; significant state funding; locations and applications for test and demo are decided by developers; funding based on rational criteria**

NOWERI – Norwegian Offshore Wind Energy Research Infrastructure (application 30/1-2010)



Rounding up

- ► Remarkable results are already achieved by industry and R&D institutes on deep offshore wind
- ► Technology still in an early phase – Big potential provided technical development and bringing cost down to a competitive level
- ► NOWITECH and NORCOWE plays a significant role in providing new knowledge as basis for industrial development of cost-effective offshore wind farms at deep sea (still need for continued increased R&D efforts)
- ► The industry is well positioned, but to secure their competitive capabilities a strong domestic test and demonstration programme is urgently needed!

The need for a Norwegian test and demonstration programme on offshore wind

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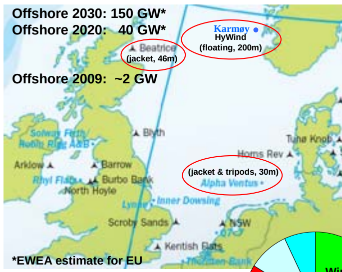

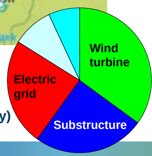

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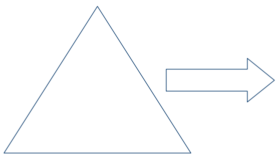

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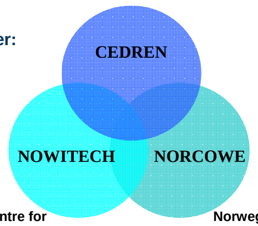

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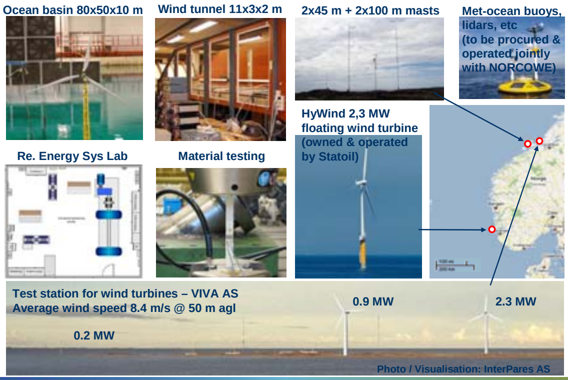
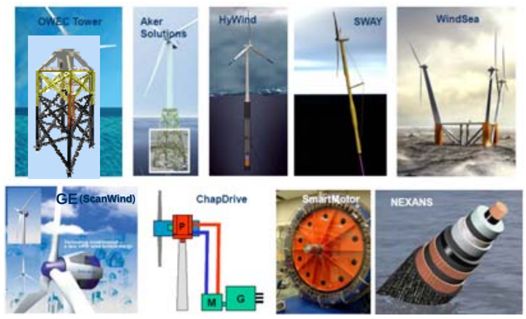
Relevant labs and field facilities

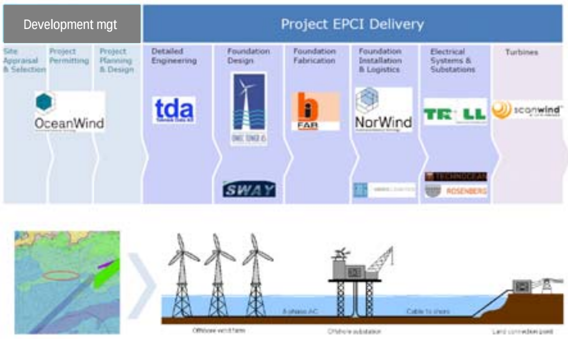


Norway is developing offshore wind technology



Arena - Wind energy (Mid-Norway) ”Building Norway’s Bremerhaven”

Arena NOW – Bergen/Stavanger



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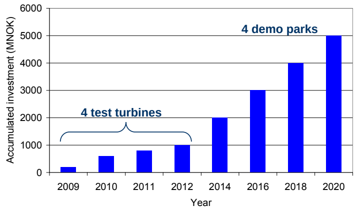

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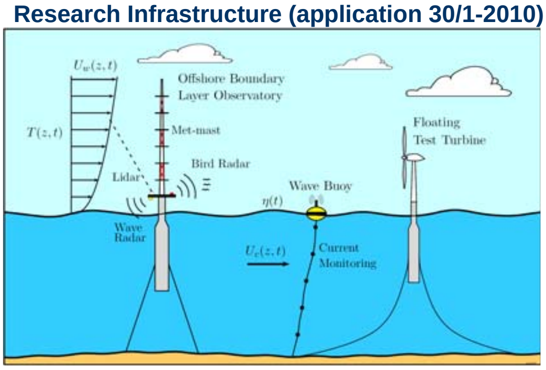

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A1 New turbine technology

A quantitative comparison of three floating wind turbines, Jason Jonkman, NREL

Long blades for offshore turbines, Jørg Høyland, PhD student NTNU

VAWT for offshore – pros and cons, Dr Olimpo Anaya-Lara and Prof Bill Leithead, University of Strathclyde

HyWind modelling and validation, Bjørn Skaare, Statoil

Floating wind turbine. Wave induced loads, Ivar Fylling, MARINTEK

A Quantitative Comparison of Three Floating Wind Turbines

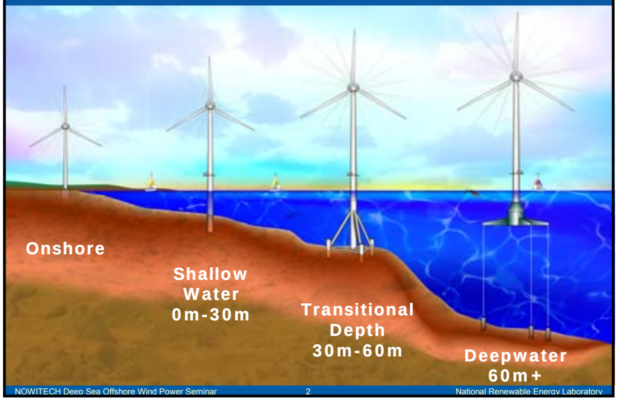
NOWITECH Deep Sea Offshore Wind Power Seminar

January 21-22, 2009

Jason Jonkman, Ph.D.

Operated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy by Midwest Research Institute • Battelle

Offshore Wind Technology



Floating Wind Turbine Pioneers



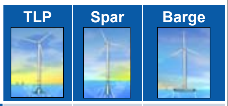

Developer	• StatoilHydro, Norway	• Blue H, Netherlands	• Principle Power, USA	• SWAY, Norway
Platform	• "Hywind" spar buoy with catenary moorings	• Tension-leg concept with gravity anchor	• "WindFloat" semi-submersible with catenary moorings	• Spar buoy with single taut tether
Wind Turbine	• Siemens 2.3-MW upwind, 3-bladed	• Gamma 2-bladed, teetering, yaw-regulated	• Coordinating with suppliers for 5-MW+ units	• Swivels downwind • Partnering with Multibrid
Status	• $78M demonstration project in North Sea • First PoC installed in Summer 2009 • Plans to license technology	• Deployed PoC system with 80-kW turbine in Italy in summer 2007 • Receiving funding from ETI for UK-based projects	• Extensive numerical modeling • Tested in wave tank • Planning demonstration projects	• Extensive numerical modeling • Planning demonstration projects

Floating Wind Turbine Concepts

Design Challenges

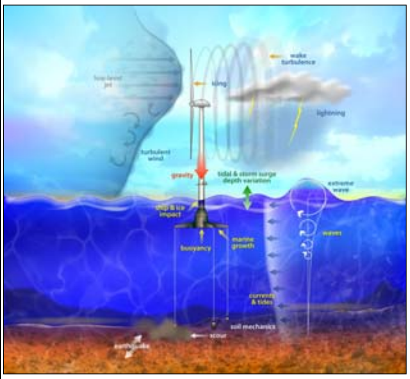
- Low frequency modes:
  - Influence on aerodynamic damping & stability
- Large platform motions:
  - Coupling with turbine
- Complicated shape:
  - Radiation & diffraction
- Moorings, cables, & anchors
- Construction, installation & O&M

+ relative advantage
0 neutral
– relative disvantage



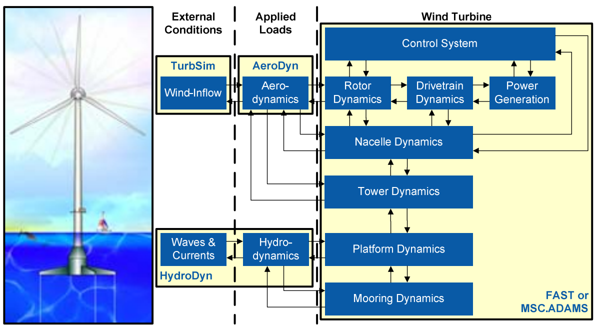
	TLP	Spar	Barge
Pitch Stability	Mooring	Ballast	Buoyancy
Natural Periods	+	0	–
Coupled Motion	+	0	–
Wave Sensitivity	0	+	–
Turbine Weight	0	–	+
Moorings	+	–	–
Anchors	–	+	+
Construction & Installation	–	–	+
O&M	+	0	–

Modeling Requirements



- Coupled aero-hydro-servo-elastic interaction
- Wind-inflow:
  - Discrete events
  - Turbulence
- Waves:
  - Regular
  - Irregular
- Aerodynamics:
  - Induction
  - Rotational augmentation
  - Skewed wake
  - Dynamic stall
- Hydrodynamics:
  - Diffraction
  - Radiation
  - Hydrostatics
- Structural dynamics:
  - Gravity / inertia
  - Elasticity
  - Foundations / moorings
- Control system:
  - Yaw, torque, pitch

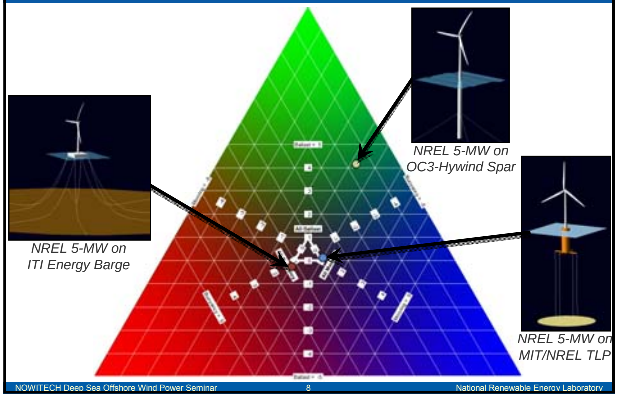
Coupled Aero-Hydro-Servo-Elastics



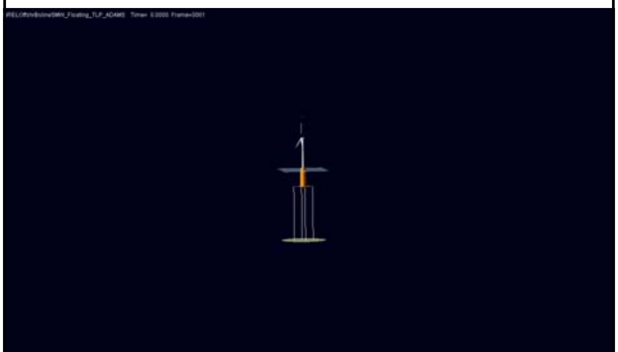
Floating Concept Analysis Process

1) Use same NREL 5-MW turbine & environmental conditions for all
2) Design floater:
   - Platform
   - Mooring system
   - Modify tower (if needed)
   - Modify baseline controller (if needed)
3) Create FAST / AeroDyn / HydroDyn model
4) Check model by comparing frequency & time domain:
   - RAOs
   - PDFs
5) Run IEC-style load cases:
   - Identify ultimate loads
   - Identify fatigue loads
   - Identify instabilities
6) Compare concepts against each other & to onshore
7) Iterate on design:
   - Limit-state analysis
   - MIMO state-space control
8) Evaluate system economics
9) Identify hybrid features that will potentially provide the best overall characteristics

Three Concepts Analyzed



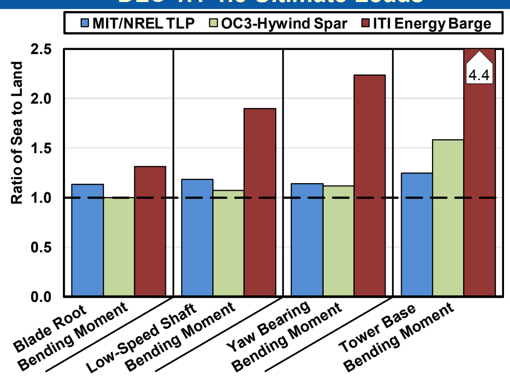
Sample MIT/NREL TLP Response



Design Load Case Table

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

Normal Operation:
DLC 1.1-1.5 Ultimate Loads



Floating Platform Analysis Summary

MIT/NREL TLP
+ Behaves essentially like a land-based turbine
+ Only slight increase in ultimate & fatigue loads
− Expensive anchor system

OC3-Hywind Spar Buoy
+ Only slight increase in blade loads
0 Moderate increase in tower loads; needs strengthening
− Difficult manufacturing & installation at many sites

ITI Enery Barge
− High increase in loads; needs strengthening
− Likely applicable only at sheltered sites
+ Simple & inexpensive installation

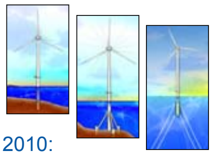
Ongoing Work & Future Plans

- Assess role of advanced control
- Resolve system instabilities
- Optimize system designs
- Evaluate system economics
- Analyze other floating concepts:
  - Platform configuration
  - Vary turbine size, weight, & configuration
- Verify under IEA OC3
- Validate simulations with test data
- Improve simulation capabilities
- Develop design guidelines / standards

Semi-Submersible Concept

Model Verification through IEA OC3

- The IEA "Offshore Code Comparison Collaboration" (OC3) is as an international forum for OWT dynamics model verification
- OC3 ran from 2005 to 2009:
  - Phase I – Monopile + Rigid Foundation
  - Phase II – Monopile + Flexible Foundation
  - Phase III – Tripod
  - Phase IV – Floating Spar Buoy
- Follow-on project to be started in April, 2010:
  - Phase V – Jacket
  - Phase VI – Floating semi submersible



NREL RISØ cener Leibniz Universität Hannover GARRAD HASSAN SIEMENS MARINTEK Fraunhofer IWES IFE Universität Stuttgart acciona NTNU

OC3 Activities & Objectives

Activities

- Discussing modeling strategies
- Developing a suite of benchmark models & simulations
- Running the simulations & processing the results
- Comparing & discussing the results

Objectives

- Assessing the accuracy & reliability of simulations to establish confidence in their predictive capabilities
- Training new analysts how to run & apply codes correctly
- Investigating the capabilities / limitations of implemented theories
- Refining applied analysis methodologies
- Identifying further R&D needs

NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Thank You for Your Attention

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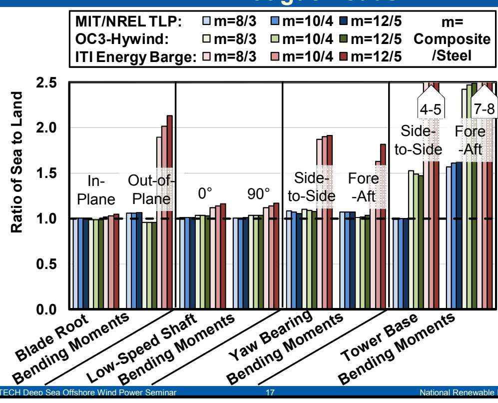
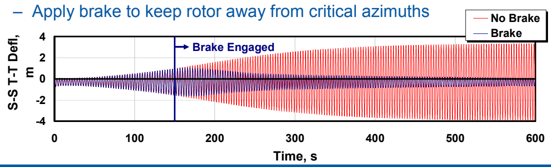
Operated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy by Midwest Research Institute • Battelle

Normal Operation:
DLC 1.2 Fatigue Loads



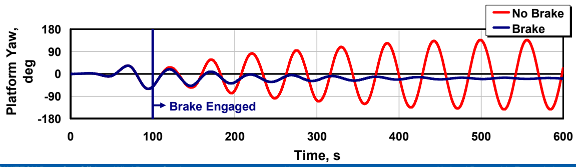
Idling:
DLC 6.2a Side-to-Side Instability

- Aero-elastic interaction causes negative damping in a coupled blade-edge, tower-S-S, & platform-roll & -yaw mode
- Conditions:
  - 50-yr wind event for TLP, spar, & land-based turbine
  - Idling + loss of grid; all blades = 90°; nacelle yaw error = ±(20° to 40°)
  - Instability diminished in barge by wave radiation
- Possible solutions:
  - Modify airfoils to reduce energy absorption
  - Allow slip of yaw drive
  - Apply brake to keep rotor away from critical azimuths



Idling:
DLC 2.1 & 7.1a Yaw Instability

- Aero-elastic interaction causes negative damping in a mode that couples rotor azimuth with platform yaw
- Conditions:
  - Normal or 1-yr wind & wave events
  - Idling + fault; blade pitch = 0º (seized), 90º, 90º
  - Instability in TLP & barge, not in spar or land-based turbine
- Possible solutions:
  - Reduce fully feathered pitch to allow slow roll while idling
  - Apply brake to stop rotor



Technology shift for large wind turbine blades

PhD-stud

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NTNU

Supervisors: Andreas Echtermeyer
Nils Petter Vedvik

Start: April 2004
Finish: April 2010

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Currently employed at SmartMotor AS

Development of permanent magnet synchronous machines

- Customized
- Compact
- High torque
- High efficiency
- Suitable for demanding environments

SmartMotor
Energy Efficient Technology

NTNU

A doubling of blade length will quadruple the blade weight

Product/ Rotor diameter (m)	V15	V17	V19	V20	V25	V27	V39	V44	V47	V52	V66	V80	V82	V90	V90
Year of installation	1981	1984	1986	1987	1988	1989	1991	1995	1997	2000	1999	2001	2003	2004	2002
Capacity (kW)	55	75	90	100	200	225	500	600	660	850	1,750	1,800	1,650	1,800	3,000

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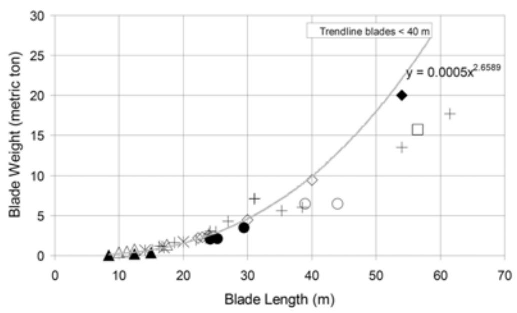
Blade mass



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Installation cost offshore

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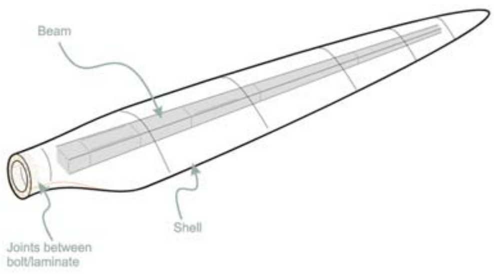
Blade construction



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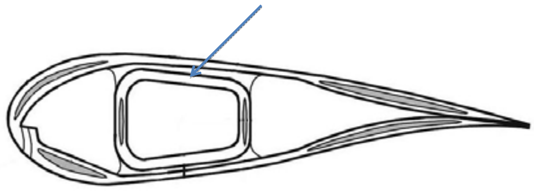
Blade construction

Focus on flanges in main spar



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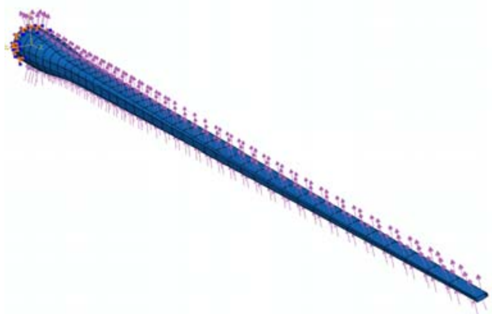
Computer analysis of 100m spar



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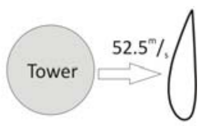
Extreme load cases for blades with pitch control

50-year gust

1-year gust



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Material choices

- Glass fiber
- Carbon fiber
- Carbon and glass

How does material choice affect price and weight?

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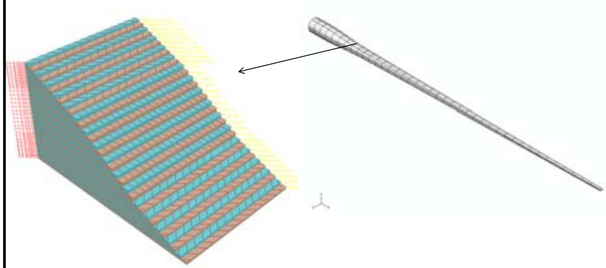
Define materials in FEM model



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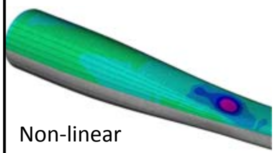
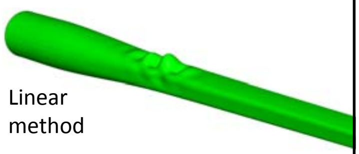
Stress/strain analyses

Buckling



Non-linear method



Linear method

100m spar results

Material	Weight [tonn]	Price [Euro]
Carbon	40.2	932 000
Carbon/glass	65.5	476 000
Glass	75.6	171 000

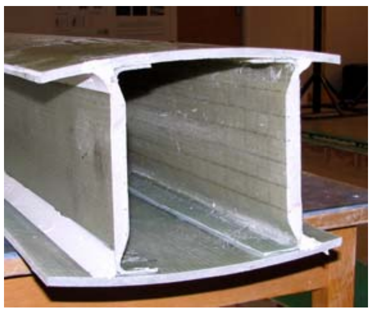
FEM model

=

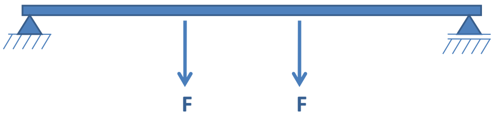
Reality?

6m glass fiber spar manufactured at NTNU

Cross section of 6m spar



4-point bending test of spar



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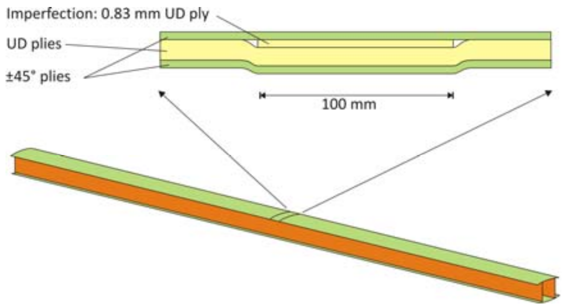
Manufacturing "defect"



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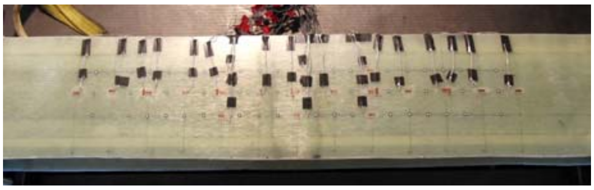
Strain gages and optical measuring points



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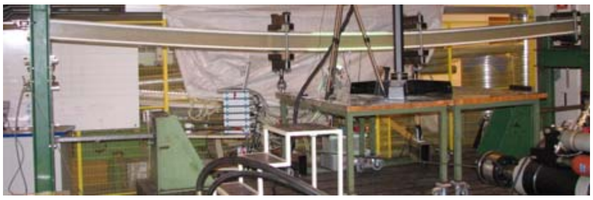
Test of 6m beam at IPM/SINTEF fatigue laboratory



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Spar failure

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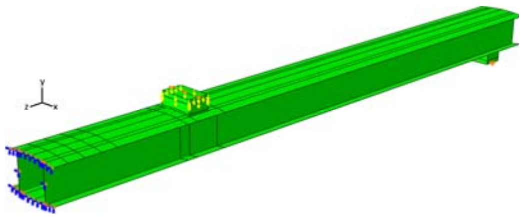
Computer model of spar



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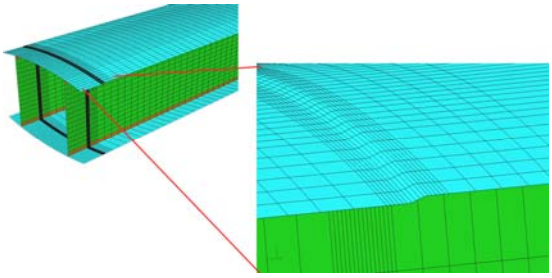
Include imperfection in FEM model



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FEM analysis results

- Spar deflections are accurately predicted
- Strains measured during testing are reproduced in FEM analysis.

The FEM model can be used as a tool for optimization of the composite materials in the spar.

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Thank you for your attention ☺

Questions?

NTNU

University of Strathclyde Engineering

VAWTs for Offshore – Pros and Cons

Bill Leithead
Olimpo Anaya-Lara

Outline

- Introduction – VAWTs Early Development
- Pros and cons
- Conclusion
- Future requirements

Evolution of VAWTs

The earliest VAWTs were drag devices.

Their direct descendent is the Savonius rotor.

Modern Development

Development of machines based on lift force started by Darrieus in the 1920's. Further developed in the US, but today common consensus is that they are not economical for large machines.

Modern Development

Darrieus rotor

Modern Development

Derivatives of the Darreius rotor:
Giromill Gorlov helical turbine

VAWTs for offshore

- For offshore wind turbines need to be Multi-Watt, bigger 5MW.
  - Additional costs support structures
  - Subsea cables to shore
- Argument that VAWTs will scale more easily than HAWTs so may be provide cheaper very large machines ~10MW

Costs

Cost of sub-system as %age of total 5MW HAWT cost:

- Rotor 18%
- Tower 16%
- Yaw gear 3%
- Gearbox 17%
- Main bearing 3%
- Generator 7%

Total cost of sub-systems 64%

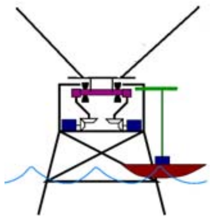
If cost of rotor, main bearing and generator (assuming direct-drive) is less than this then VAWT would look competitive.

Pros

- Machinery near to sea level so easier access
- Less space and weight restrictions on sub-systems
- Simpler so might be more reliable so easier to get high availability
- Lower centre of thrust so reduced loading on support structure

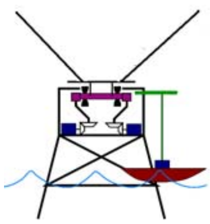
Machinery near to sea level

- Assists installation of WT
- By modularisation, weight of individual drive-train components can be kept to around 10tonnes
- Standard supply vessels with light lift capability are sufficient for most O&M tasks
- Hoist easily incorporated into nacelle

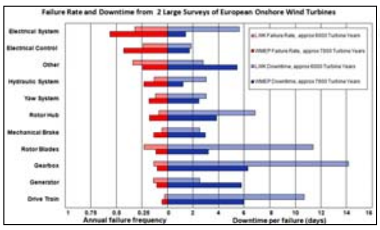


Less space and weight restrictions on sub-systems

- Easy to accommodate large multi-pole generators in direct drive-train – cost comes down as diameter increased – doubling the size roughly halves the cost.
- Easy to accommodate large mechanical brakes – doubling the diameter roughly halves the number of callipers required.
- More space makes maintenance easier.



Simpler so might be more reliable so easier to get high availability



- In simplest form might consist of only a rotor, main bearing and multi-pole generator.
- Many sub-systems with high failure rate eliminated.

Lower centre of thrust so reduced loading on support structure

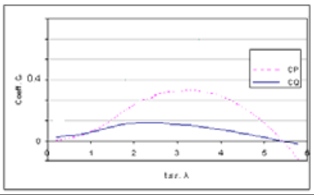
- As size increases the savings on support structure costs become more marked.
- Enables floating structures in shallower seas (60m)

Cons

- Low Cp-max and low max tip speed ratio
- Rotor diameter is large and rotor speed low
- Very large loads
- Cyclic loading on drive-train
- Poor aerodynamic behaviour in high wind speeds

Low Cp-max and low max tip speed ratio

- Aerodynamics are less efficient
- Maximum Cp is attained at a tip-speed ratio of roughly half that of a HAWT
- Highest possible Cp-max is 0.35~0.4

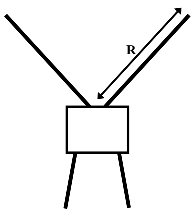


Rotor diameter is large and rotor speed low

- Lower aerodynamic efficiency
- Lower swept area

⇒Large rotor diameter

⇒ Low rotor speed ~ 5rpm



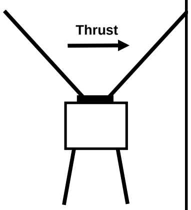
Swept area is ~ R^2

Very large loads

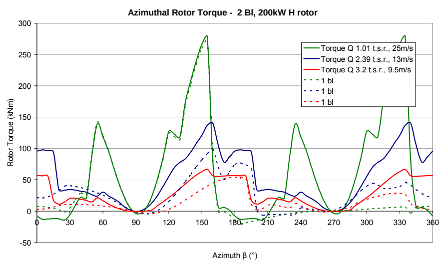
- Low rotor speed ⇒ high drive-train torques

  ⇒ high drive-train cost
- Direct-drive becomes very costly
- Very large over-turning moment

  ⇒ very large loads on main bearing

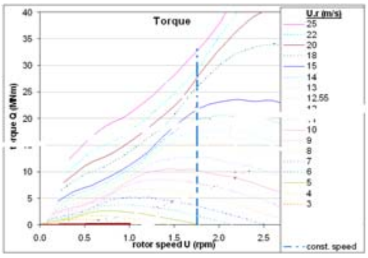


Cyclic loading on drive-train



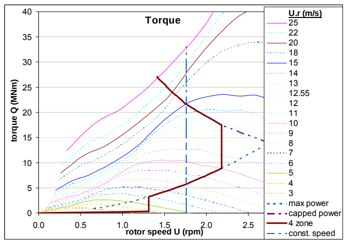
- Peak loads per revolution are much higher than average
- Reduced by inertia as propagates through drive-train
- Sub-systems must accommodate peak loads

Poor aerodynamic behaviour in high wind speeds



- Due to dynamic stall effects, power can not be limited by stalling

Poor aerodynamic behaviour in high wind speeds



- Need to keep close to stall region, when stall regulated

Poor aerodynamic behaviour in high wind speeds

- Aerodynamic control would enable better performance and higher capacity factor
- Aerodynamic control not straightforward for VAWT

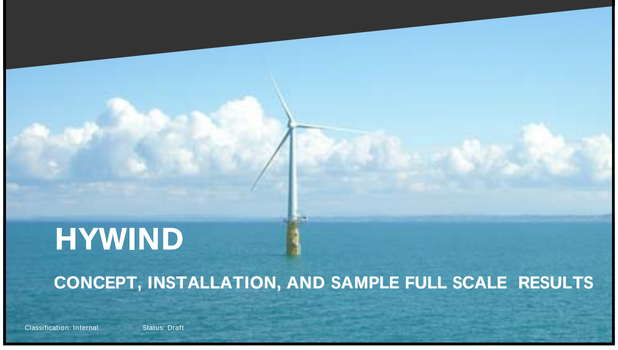
Conclusion

- **New design approaches required**

- Sails cancel over-turning moment
- Main bearing requirements much reduced
- Loads on support structures much reduced

energy technologies institute

NOVA



HYWIND

CONCEPT, INSTALLATION, AND SAMPLE FULL SCALE RESULTS

Classification: Internal Status: Draft

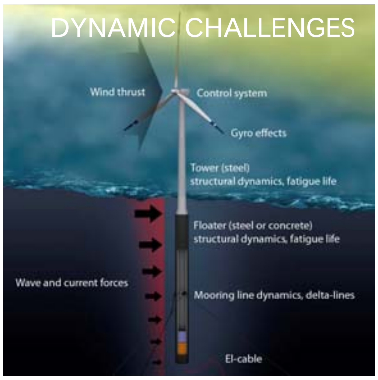
THE HYWIND CONCEPT

Main particulars for HYWIND Demo

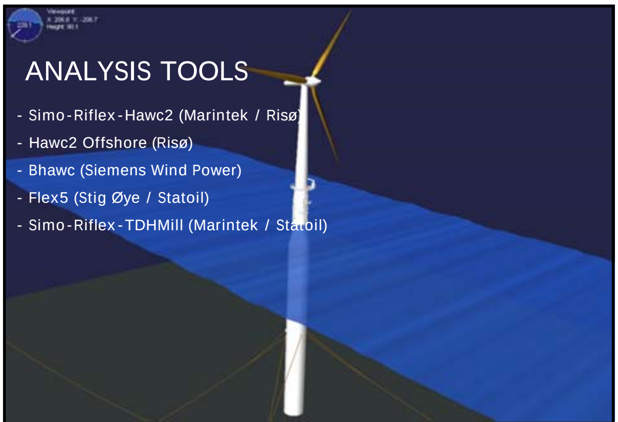
Turbine power	:	2.3 MW
Turbine weight	:	138 tons
Draft hull	:	100 m
Nacelle height	:	65 m
Rotor diameter	:	82.4 m
Water depth	:	150–700 m
Displacement	:	5300 t
Mooring	:	3 lines
Diameter at water line:		6 m
Diam. submerged body:		8,3 m

Classification: Internal Status: Draft

DYNAMIC CHALLENGES



Classification: Internal Status: Draft

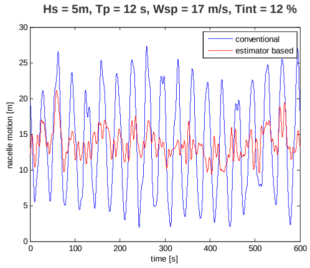


ANALYSIS TOOLS

- Simo-Riflex-Hawc2 (Marintek / Risø)
- Hawc2 Offshore (Risø)
- Bhawc (Siemens Wind Power)
- Flex5 (Stig Øye / Statoil)
- Simo-Riflex-TDHMill (Marintek / Statoil)

Classification: Internal Status: Draft

SIMULATION EXAMPLE



Relative Damage on Tower	
Reference Case: Waves	1
Conventional Only Control Strategy	16,7
Estimator Based Control Strategy	2,4

Classification: Internal Status: Draft

INSTALLATION OF HYWIND DEMO

Classification: Internal Status: Draft

INSTALLATION OF HYWIND DEMO

Classification: Internal Status: Draft

INSTALLATION OF HYWIND DEMO

Classification: Internal Status: Draft

INSTALLATION OF HYWIND DEMO

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Classification: Internal Status: Draft

INSTALLATION OF HYWIND DEMO

Classification: Internal Status: Draft

INSTALLATION OF HYWIND DEMO

Classification: Internal Status: Draft

TEST PROGRAM

- Main Objective:
  - Verify the overall behaviour of the Hywind concept in harsh environment.
  - Identify areas of improvements, either with respect to cost reduction or improved functionality
- Test Cases
  - A variety of test cases has been defined to observe the behaviour of Hywind Demo under various environmental loadings and control strategies.

Classification: Internal Status: Draft

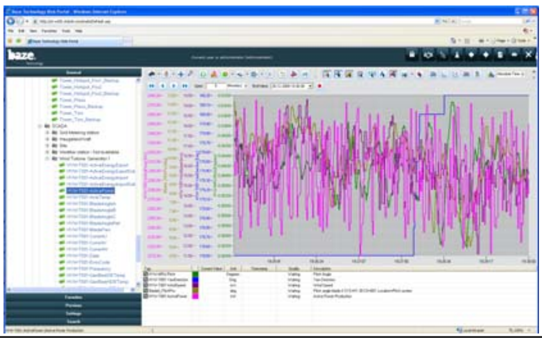
SENSORS

Hywind Demo is equipped with more than 200 sensors, including

- Tower motion
- Mooring line tension
- Strain in tower and substructure
- Metocean data (wind, waves and current)
- Typical conventional wind turbine measurements like active power production, rotor speed, etc.

Classification: Internal Status: Draft

DATABASE SYSTEM



Classification: Internal Status: Draft

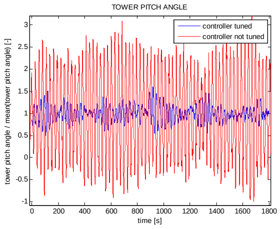
OPERATIONS

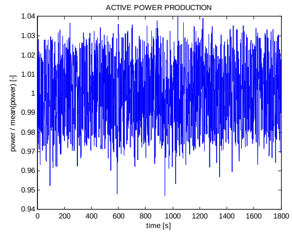
- The first 2-3 months of operation can be considered as a start-up phase where the turbine has been through a type testing procedure
- The turbine has only been operated during online monitoring from the Hywind Operations Rooom during this start-up phase .
- Since December 23rd 2009, Hywind Demo has been on automatic operating mode at its rated power (2.3 MW) for average wind speeds up to 18 m/s.
- Since January 15th 2010, Hywind Demo has been on automatic operating mode for all wind speeds.

Classification: Internal Status: Draft

SAMPLE FULL SCALE MEASUREMENTS

- Tower Motions & Power Production

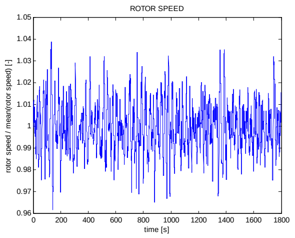


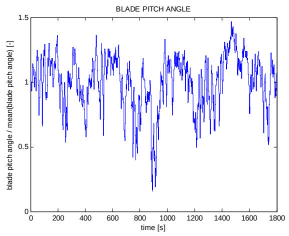


Classification: Internal Status: Draft

SAMPLE FULL SCALE MEASUREMENTS

- Rotor Speed & Blade Pitch Angle





Classification: Internal Status: Draft

FURTHER WORK

- The test program continues until October 2011.
- Systematic and detailed analysis of measurements with comparisons to corresponding dynamic simulations.
- Testing and analysis of different floater motion controllers.
- Optimization of the Hywind substructure.

Classification: Internal Status: Draft

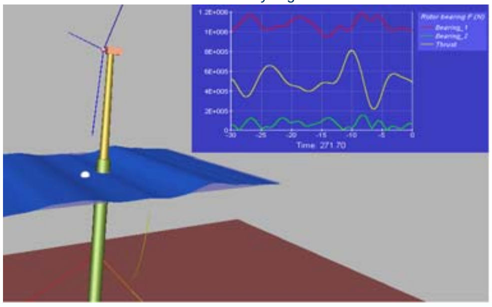
Classification: Internal Status: Draft

MARINTEK SINTEF

Floating wind turbine
Wave induced motions and loads

Wind Power R&D seminar – deep sea offshore wind 21-22 Jan 2010, Trondheim, Norway

Ivar Fylling MARINTEK



MARINTEK SINTEF

Case study

- SIMO as floating wind turbine analysis tool based on resources and experience from the offshore industry.
- Implementation of a wind turbine module in a multi-body simulation model has provided a tool for efficient analysis of motions, support forces and power conversion potential, as influenced by waves, wind, and current.
- Some results from simulation of a 5 MW turbine on an 8000 t spar buoy are presented.
- Tower support forces and rotor thrust forces, as well as rotor power statistics for a range of wind and wave conditions are shown.

MARINTEK SINTEF

Test case – IEA Annex23 Benchmark

Table 1 Rotor, nacelle and tower data.

Rotor diameter	m	126.
Rotor mass	t	110.
Hub height	m	89.6.
Nacelle mass	t	240.0
Yaw bearing elevation	m	87.6
Tower mass	t	249.7
Elevation of tower mass centre	m	43.45
Elevation of tower base	m	10.0

Table 2 Spar buoy platform data.

Depth to platform base	m	120
Water plane diameter	m	6.5
Diameter of main part	m	9.4
Volume	m^3	8030
Position of mass centre	m	-89.92
Position of buoyancy centre	m	-62.14
Platform mass, including ballast	t	7303
Platform radius of gyration in pitch	m	24

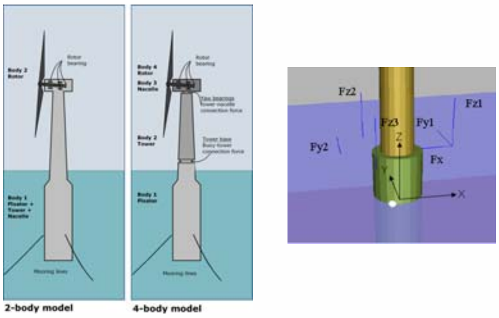
MARINTEK SINTEF

Simo

- SIMO is a general-purpose program for simulating motions of arbitrarily shaped floating structures, including interconnected multi-body systems. The force models comprise:
- *Hydrodynamic forces*: Linear and quadratic potential forces, hydrodynamic coupling effects, Morison-type force models, lumped, and distributed on slender elements.
- *Wind forces*: Drag force due to gusty wind.
- *Mechanical forces*: Mooring line forces, a range of body-to-body coupling force models, control forces (DP system), variable mass.
- *Inertia- and gravity forces.*
- User specified arbitrary 'External Force'.

MARINTEK SINTEF

Modelling to calculate rotor bearing forces and tower support forces



MARINTEK SINTEF

Aerodynamic rotor forces

- The blade element momentum (BEM) method is used for calculation of rotor blade forces. In the rigid-body model in SIMO the *sum* of all blade element forces, a 6-component vector, is used as external load on a rotating body (Rotor).
- The Rotor is coupled to the support structure (Support) by means of two radial bearings and one thrust bearing. The torque generated by the power take-off system is transferred directly from the Rotor to the Support.
- The applied BEM code will give correct time-series results for rotor and blade loads under conditions of changing blade pitch angle, wind speed and direction, and tower motion.
- The implementation allows more than one rotor on the same floating structure. No modification to the modelling or analysis features in SIMO has been done as part of this development.

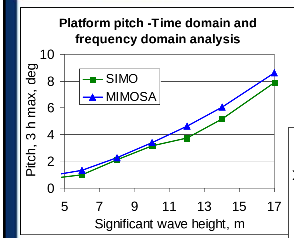
MARINTEK SINTEF

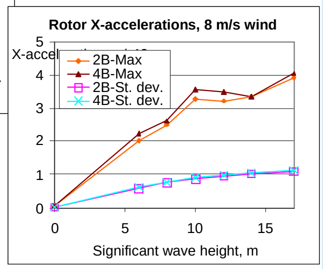
Hydrodynamic forces

1. The hydrodynamic loads comprise:
2. Linear potential forces. Frequency dependent excitation, added mass, and damping.
3. Slow drift, 2nd order potential forces, as frequency dependent drift force coefficients.
4. Viscous drag forces on the spar buoy, proportional with relative velocity squared.
5. Linear damping coefficients in surge, sway, heave, and yaw.
6. The two first items were calculated by the panel program WAMIT

MARINTEK SINTEF

Simulation model testing





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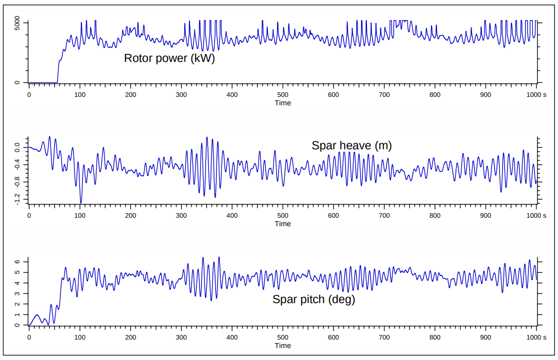
Sample of time series of power and motion



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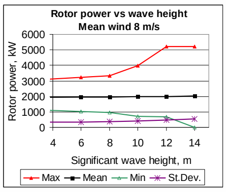

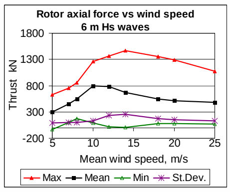

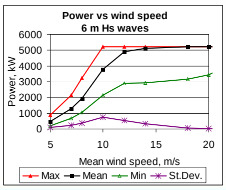

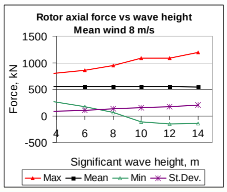

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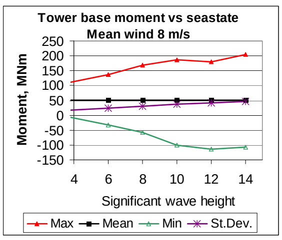
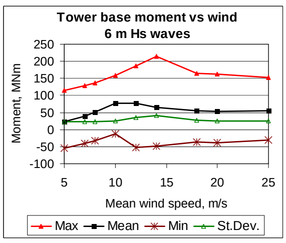




MARINTEK SINTEF

Conclusions

Parameter variation analysis results for the test case indicate that

- The power production is weakly dependent on the seastate, except that power fluctuation increases with increasing wave height.
- The maximum bearing forces and tower support forces are mainly governed by wave induced pitch motions of the tower.
- The wave induced motions will have a dominating effect on rotor bearing forces and on tower support forces, but relatively small effect on the wind power absorption performance.
- It is the pitch motion of the spar buoy that appears to be the greatest challenge to the turbine bearing- and support structure design in this case. Accelerations in the range 0.3 -0.4 g, angles up to 8 deg in extreme waves.

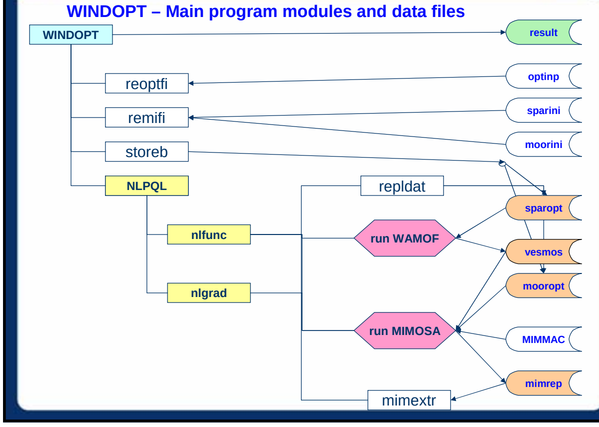
MARINTEK SINTEF

Ongoing activities for improvement of design tools

- Finalising implementation of turbine model in RIFLEX, to facilitate elastic response analyses of mooring lines, tower and rotor blades. (Final part of KMB-project Deepsea Offshore Wind)
- WINDOPT – Optimization tool for minimum cost specification of floating support structure and mooring system for a wind turbine (NOWITECH activity for completing of pilot project initiated as part of KMB Deepsea Offshore Wind.)

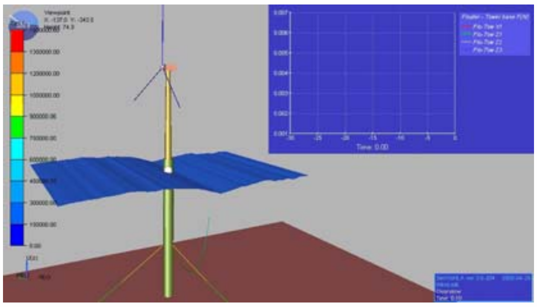
MARINTEK SINTEF

WINDOPT – Main program modules and data files



MARINTEK SINTEF

Thanks for your attention !



A2 New generator technology

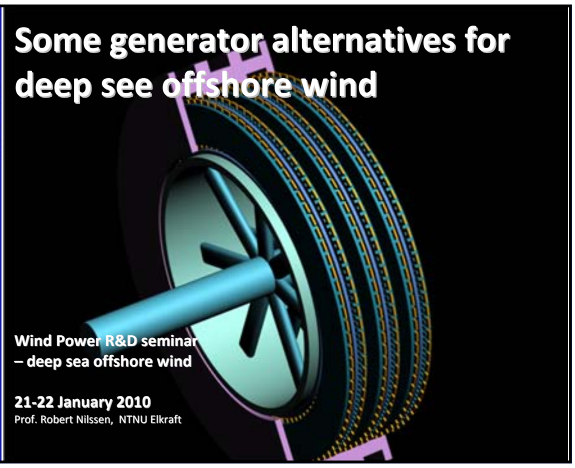
Light-weight gear and generator technology (no presentation available).
Bo Rohde Jensen, Senior Specialist, Vestas Wind Systems A/S

Direct-drive generator and converter system, Prof Robert Nilssen, NTNU

New gearbox technology, Lars Raunholt, Angle Wind AS

Potential top-mass reduction by hydraulic transmission, Prof Ole G Dahlhaug, NTNU

NTNU



Some generator alternatives for deep see offshore wind

Wind Power R&D seminar
– deep sea offshore wind

21-22 January 2010

Prof. Robert Nilssen, NTNU Elkraft

1

NTNU

Plan for this presentation

- PM-machines vs Induction machines in general
- Direct driven vs Geared systems
- Converters close to the generator
- Functional requirements important for choises
- Drives for research

2

NTNU

Why focus on new PM-machine technology?

- **Lower PM costs @**
- **Higher temperatures** T >> 160
- **Powerful magnetization**
- **For high efficiency**
- **High compactness– kW/m3**
- **Design flexibility – high pole numbers, low speed, large air gaps, lower tolerances**
- **Induction machines are more costly to produce than PM machines!**

3

NTNU

Induction machines more expansive than PM-machines??

- For the same speed and power
- **PM cost 63% of Induction machines**
  - Not proven claim
  - For volume production
  - Not in the marked today
  - Based on material and labor cost evaluation
  - Ref: Among several, ABB-designers focusing PM machines in the paper mill industry.

4

NTNU

Is this reasonabel: Look at low cost pump applications

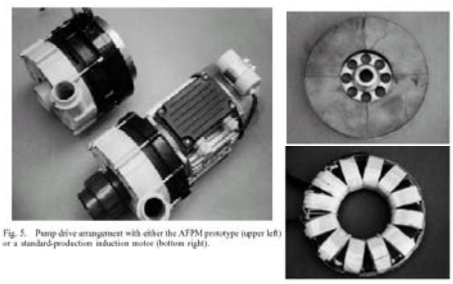


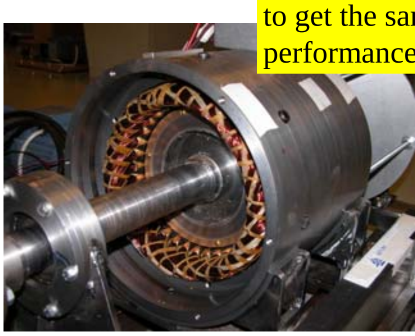
Fig. 5. Pump drive arrangement with either the AFPM prototype (upper left) or a standard-production induction motor (bottom right).

5

NTNU

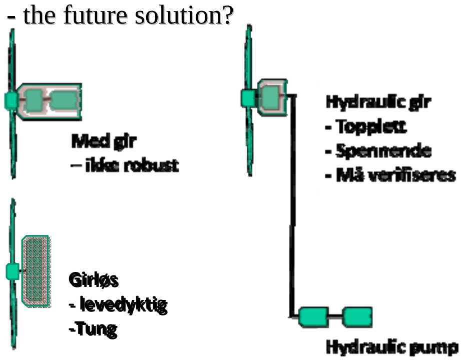
NTNU research

Use half the length to get the same performance



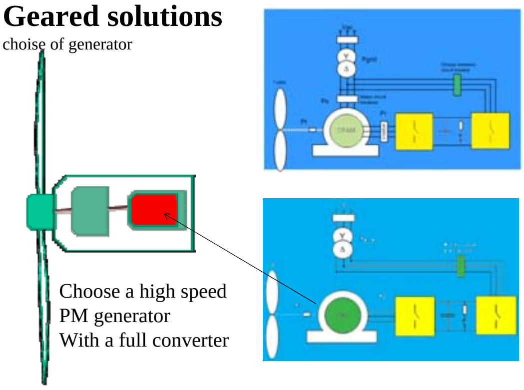
6

Nacellekoncepts
- the future solution?



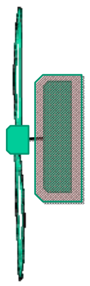
7

Geared solutions
choise of generator



8

Direct driven Generators



Low speed requires synchronous machines
With hig pole numbers
- -Field winding in Rotor, large diamter, High cost
- -PM magnetization, Less cost

Why direct drive:
- - gear problems above 4 MW
- - less maintenance

Why not:
- - High investment costs and weight

9

Intermediat solutions with less gir ratio may also come?

10

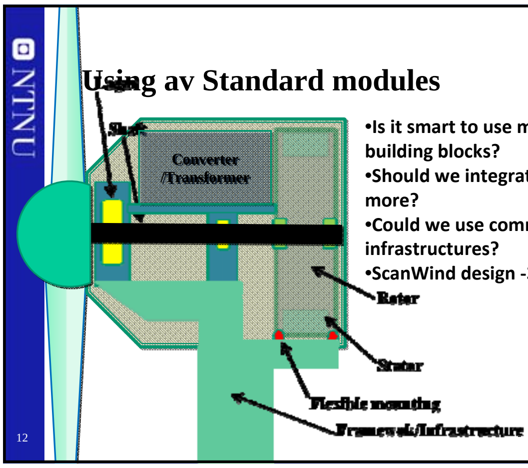
Design philosophy

- Standard generator
  - Supplier competition
  - "Long shaft"
  - Minimize rotor and stator diameter (important cost driver)
  - Technology: Radial flux machines, Superconductive machines.
- Integrated design
  - Minimize common infrastructure
  - Remove shaft and hub
  - Larger diameter, New bearing concepts
  - Direct cost control on supplier
  - New standards?
  - Technology: Radial or Axial, Composite materials,

11

Using av Standard modules

- •Is it smart to use modlar building blocks?
- •Should we integrate more?
- •Could we use common infrastructures?
- •ScanWind design -3.5MW



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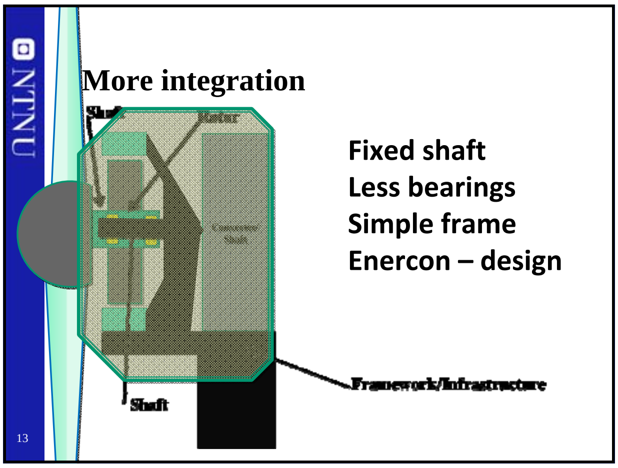
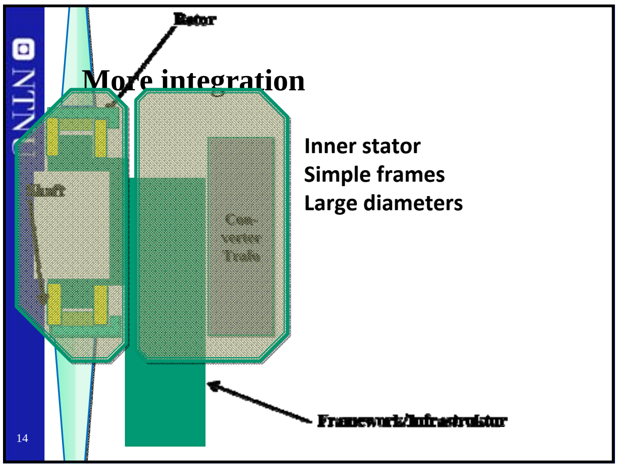
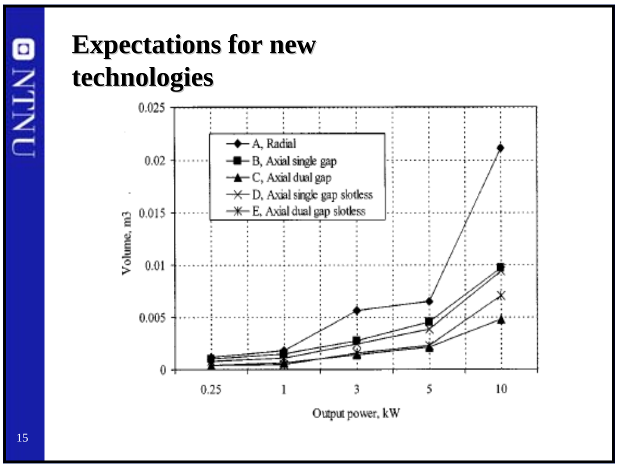
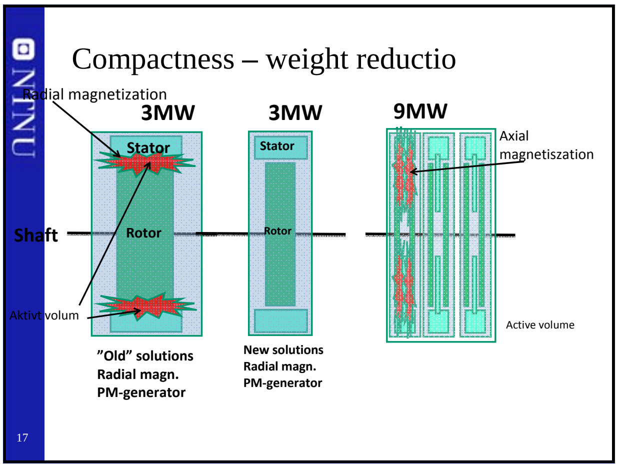
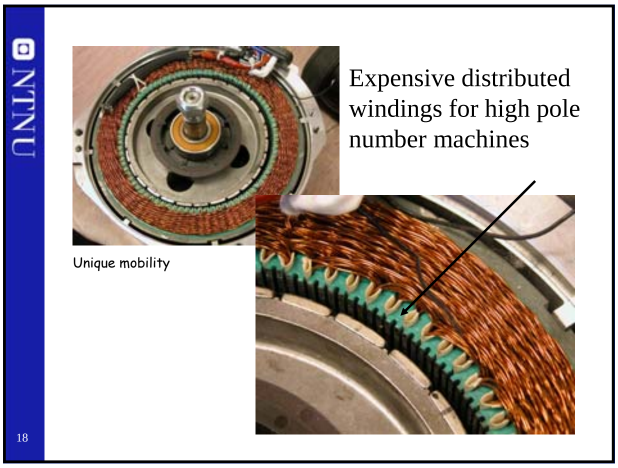

NTNU
More integration
Shaft
Rotor
Fixed shaft
Less bearings
Simple frame
Enercon – design
Framework/Infrastructure
Shaft
13


NTNU
Rotor
More integration
Shaft
Con-
verter
Trafo
Inner stator
Simple frames
Large diameters
Framework/Infrastruktur
14

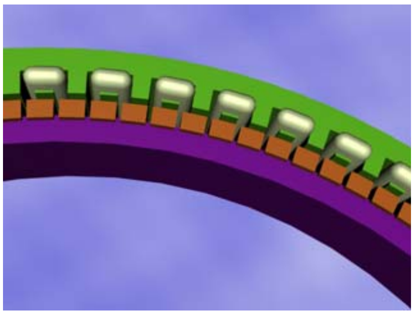

NTNU
Expectations for new technologies
A, Radial
B, Axial single gap
C, Axial dual gap
D, Axial single gap slotless
E, Axial dual gap slotless
Volume, m3
0.025
0.02
0.015
0.01
0.005
0
0.25
1
3
5
10
Output power, kW
15


NTNU
Multidisc machines – the future high torque motor??!!
Fra NTNUs verksted
16


NTNU
Compactness – weight reductio
Radial magnetization
3MW
3MW
9MW
Stator
Stator
Axial magnetiszation
Shaft
Rotor
Rotor
Aktivt volum
Active volume
"Old" solutions
Radial magn.
PM-generator
New solutions
Radial magn.
PM-generator
17


NTNU
Expensive distributed windings for high pole number machines
Unique mobility
18

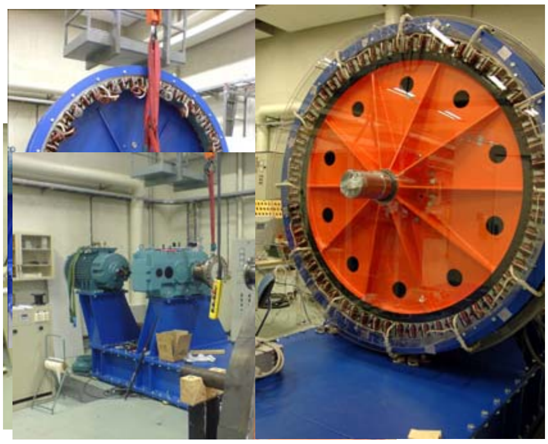
Permanent magnets are used to reduce volume and cost



19

Concentrated and fractional slot winding with q less than 1/3 result in simpler designs

20



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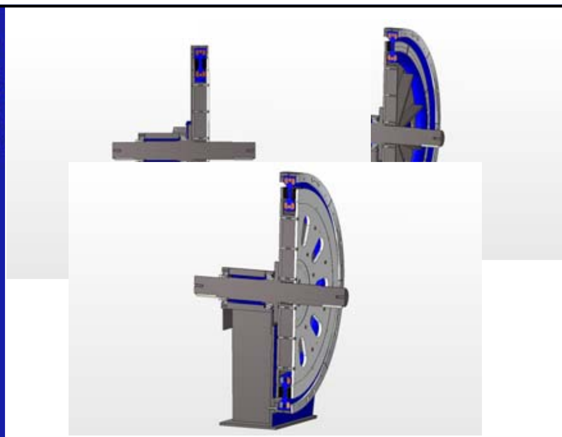
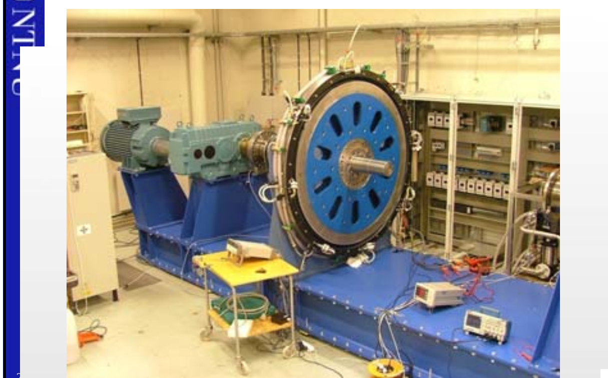


22

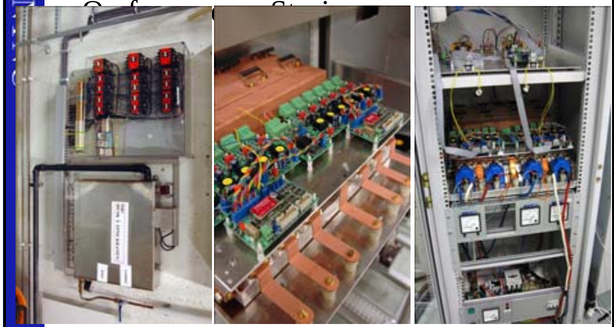
AFPM – Built and tested



23

NTNU and Sefas – Wind Lab.

24



Water cooled power electronics

25

New Mechanical Gearbox and Drive Train for Wind Turbines

Wind Power R&D Seminar, Trondheim, 21. January 2010

Lars Raunholt, CEO

Gearbox and Drive-Train for a new generation wind turbines

What is unique?

Competitive advantages

Lower investment cost:
- Lower weight of nacelle (250 tons reduction for 5 MW) by moving generator and equipment to sea level
  - Less steel in tower
  - Reduced cost of foundations

Lower O&M cost:
- High reliability Gearbox
  - Few movable parts
  - Torque overload protection
- Easier access and maintenance when generator is placed at ground/sea level

Additionally: Future requirements for "improved work place environment" may become favourable for AW technology

Between 3 and 10 % lower cost of energy

2

Drive Train and Gearbox technology

Drive Train animation

- The Drive-Train transforms the rotor torque to electric current
  - High transmission gearbox
  - Bevel gear connected to vertical mechanical shaft
  - Vertical standard generator

Eccentric gearbox

- High reliability gearbox
  - Few movable parts
  - Large transmission ratio in one step
  - Torque overload protection
  - Integrated bearings
  - Noise reduction ?
  - Lower gearbox weight ?

3

Experienced organization

Owners

SåkornInvest II AS	Seed capital	37,6%
Per Olav Haughom	Co-founder	21,9%
Lars Raunholt	Co-founder	21,9%
Lyse Produksjon AS	Energy company	18,6%
		100,0%

Organization

Lars Raunholt (44) – Founder & CEO
- 10 years experience in R&D management
- M.Sc. in Offshore Engineering and MBA
- 6 years marine structures

Per Olav Haughom (66) – Founder & Technical Director
- Inventor of Gearbox & Drive Train
- Inventor of several commercialized products
- M.Sc. in Mechanical Engineering
- 35 years of experience in the energy industry

Øyvind Tjølsen (47) – CTO

Nils Erik Faulhaber (40) – Senior Mech. Engineer

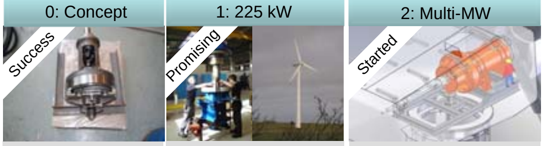
Dagfinn Nygaard (33) – Business Dev. Manager

Jon Risdal (31) – In-house Mech. Eng. consultant

+ Gearbox specialist consultant

4

Gearbox and Drive-Train development phases

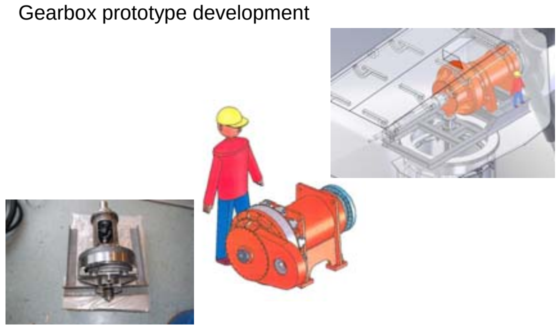


0: Concept	1: 225 kW	2: Multi-MW
Success	Promising	Started

• Q1 08 – Q2 08
• Concept drawings, patenting, freedom-to-operate, animations
• 3. party concept evaluation, Det norske Veritas
• Cost of NOKm 0,4
• Financed by Innovation Norway (0,2) and AW
	• Manufacturing and workshop test (Q2 08 – Q1 10)
	  • Budget of NOKm 8
	  • Already financed by Lyse (1,9), Innovation Norway (1,9), AW (3,2) and Skattefunn (1,0)
	• Fieldtest wind turbine (Q2 10 – Q4 10)
	  • Second hand turbine already purchased, financed by IRIS/NFR (NOKm 3)
	  • Site location approved
		• Design, M.fact. and 3rd party test of Gearbox (Q1 10 – Q2 11)
		  • Budget of NOKm 18,6
		  • NOKm 6,5 granted from Norwegian Research Council's RENERGI programme
		  • Planning for IFU-contract
		• Fieldtest wind turbine (Q3 11)
		  • Budget of NOKm 55
		  • Private placement of NOKm 25+
		  • Planned supported by industrial partner and Enova

5

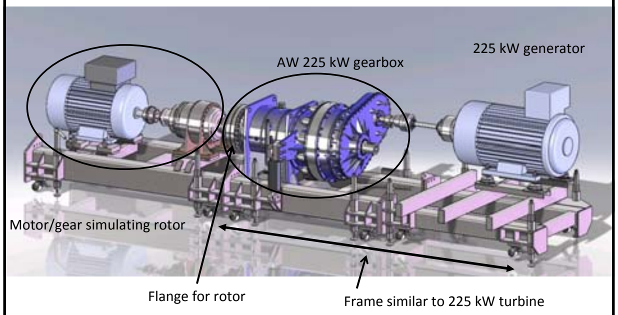
Gearbox prototype development



Small model (2008) | 225 kW (2009-2010) | Multi-MW (3 MW) (2010-2011)

6

AW 225 kW Gearbox in-house test setup



Phase 1: 225 kW gearbox (IFU), Results

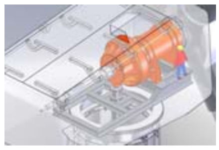
- Objective:
  - FAT test of 225 kW eccentric gearbox before field test in wind turbine
- Test results
  - "Torsional Vibrations Measurements" by DnV, performed in order to determine the torsional natural frequencies of the gear, and to tune DnV's torsional calculations model.
  - "Field balancing of the gear" by DNV, to verify calculations regarding eccentric weights.
  - Temparature rise logged to verify efficiency estimations.
  - Vibrations logged with SKF Windcon.
  - Low noise levels observed
  - All tests performed with good and promising results.
  - One third party test to be performed before installation in 225 kW turbine

Field test of gearbox in IRIS 225 kW turbine

9

Phase 2: Multi-MW gearbox (RENERGI)

- Upscale study 3, 6 and 8 MW
- Optimization, simulations, FMECA
- Manufacture, assembly and workshop function test of 3 MW gearbox (Norway)
- 3. party 2-week full-power test (International)
- Supported by the Norwegian Research Councils RENERGI programme



10

3 MW demonstration with strategic industrial partner

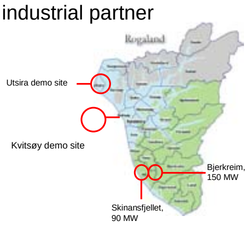
Lyse Energy

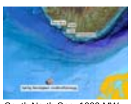
- Energy company in Rogaland
  - Revenue 2008, NOKm 4 395
  - Operating profit 2008, NOKm 2 445
- Planned wind projects:
  - Kvitsøy, Utsira and other demo sites
  - Partner in Skinansfjellet (90 MW) and Bjerkreim (150 MW)
  - Utsira, 280 MW deep offshore
  - South North-Sea, 1000 MW, offshore

3 MW turbine demo

- Lyse Energy is applying NVE
- AW to submit application to Enova
- 3 MW gearbox field test planned for Q3

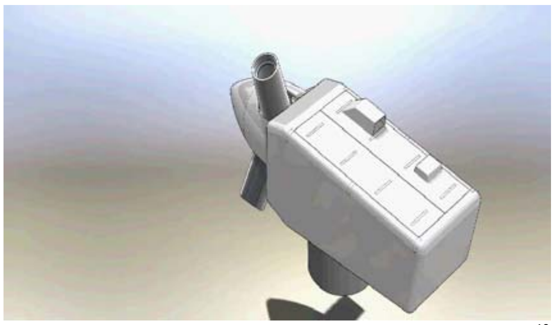
11




South North-Sea, 1000 MW

11

Animation of eccentric gearbox in 225 kW turbine



www.anglewind.no

12

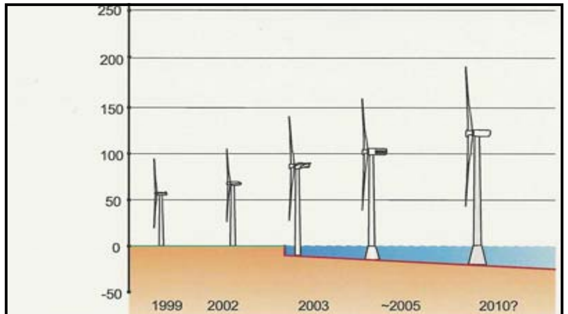
1

Potential top-mass reduction by hydraulic transmission

By
Ole Gunnar Dahlhaug
The Norwegian University of Science and Technology

Wind Power R&D seminar
Trondheim, 21st – 22nd January 2010

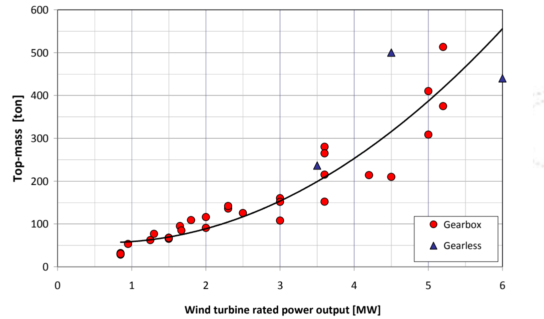
NTNU



		1999	2002	2003	~2005	2010?	
CAPACITY	P	1	2	3	5	10	MW
HUB HEIGHT	H	60	70	90	100	120	m
ROTOR	D	60	70	90	120	160	m
SPEED	n	20	17	13	5 – 15	3 – 10	rpm

3

Wind Turbine Top-Mass Development



Ref: Wind Turbine Market 2008
Todays Energy Solutions (tes.texterity.com)

4

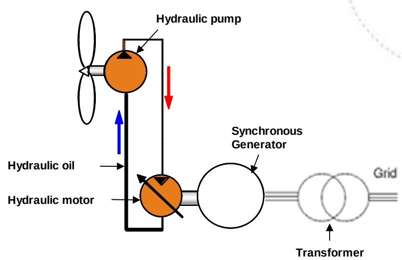
Wind Turbine Technology is changing

High top weight → Low top weight
Induction Generator → Synchronous generator
Mechanical Gearbox → Gearless

	Standard Gearbox	Direct drive	Hybrid 1:10 gear + "Direct drive"	Hybrid Gearbox + Hydraulic	Hydraulic transmission
Commercial	Yes	Yes	Yes	Yes	No
Market share	84 %	15%	< 1%	< 1 %	-
Top weight, 5MW	> 350 ton	> 500 ton	310 ton	-	< 200 ton
Eliminates gearbox	No	Yes	Partly	No	Yes
Generator	Induction	Synchronous	Synchronous	Synchronous	Synchronous
Leading Suppliers	Vestas, GE, Gamesa, Suzlon,	Enercon	Multibrid	DeWind	ChapDrive

5

Hydraulic Transmission

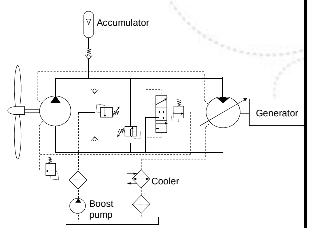


NTNU

6

Hydraulic Transmission Features

- Low top-mass weight
- Variable speed on the Turbine shaft
- Constant speed on the Generator shaft
- Dampened torque fluctuation on the generator shaft
- Hydraulic brake
- Control system

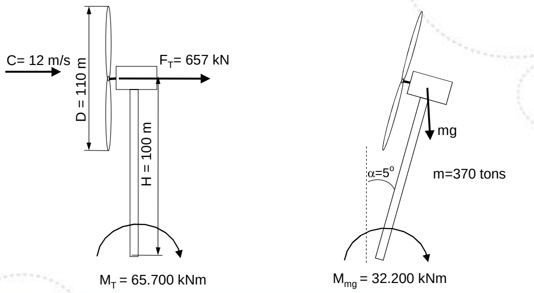


NTNU

7

Example on Thrust force

Power output = 5 MW



8

ChapDrive Turbines at Viva's test facilities at Valsnes

225 kW

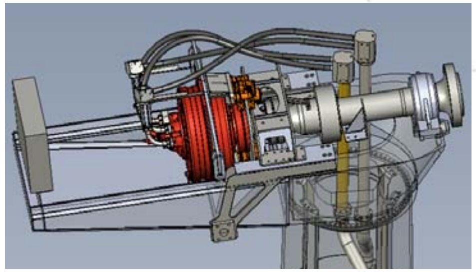
Vestas V27

900 kW

Vestas NM 52/900

9

ChapDrive 900 kW Nacelle



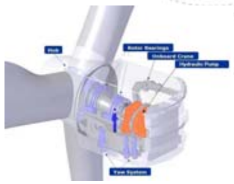
ChapDrive 900 kW laboratory nacelle

10

ChapDrive 5 MW Nacelle

RePower Nacelle

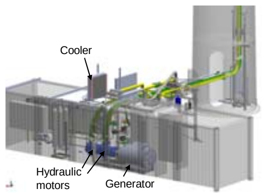
ChapDrive Nacelle



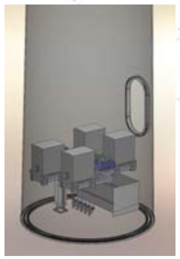
11

ChapDrive Power Unit

Today's 900 kW Power Unit Laboratory



5 MW Power unit inside the tower



12

ChapDrive Hydraulic transmission

ChapDrive's solution creates savings by: (approx. figures)

- Reducing top weight by 50 %
- Reducing cost of installation, tower and foundation by 30 %

=> Reduced capital expenditure:

- Onshore 5 %
- Offshore 10%
- Offshore floating 20%

=> Reduced operation and maintenance cost by 30 %

Lower annual production by 5 %

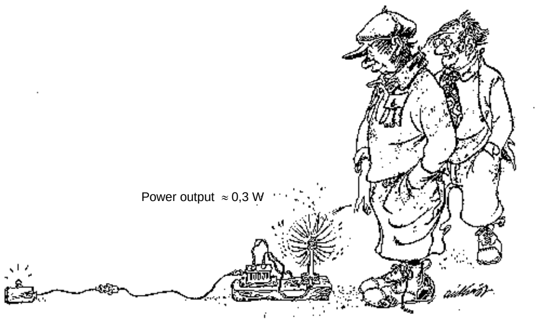
13

ChapDrive Top-Mass Reduction

Item	RePower 5 MW	ChapDrive 5 MW
Rotor	120 ton	No change
Rotor main shaft	27 ton	No change
Yaw	16 ton	No change
Main frame	89 ton	Reduced weight
Gearbox	63 ton	Not present
Generator	17 ton	Not present
Converter	5.5 ton	Not present
Transformer	13 ton	Not present
Nacelle housing	11 ton	Reduced weight
Other	68.5 ton	Reduced weight
Total top mass	**410 ton**	**ca. 200 ton**

The weights of the RePower turbine are approximate figures.
The total weight are given at: www.repower.de

14



B1 Power System integration

Prospects for new cross-border connectors, Kjartan Hauglum, Statnett

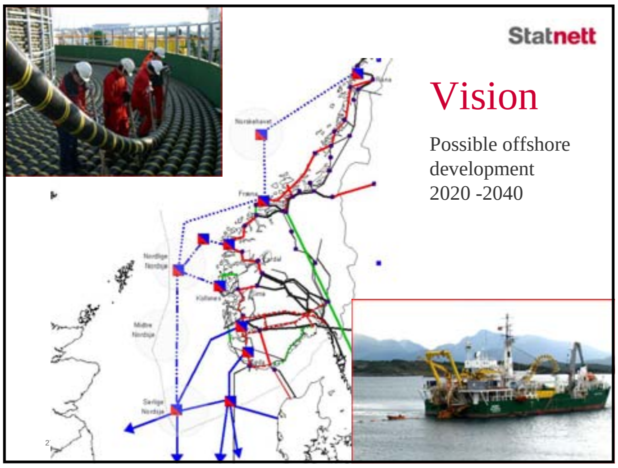
Optimal design of a North-Sea offshore grid, Thomas Trötscher, SINTEF

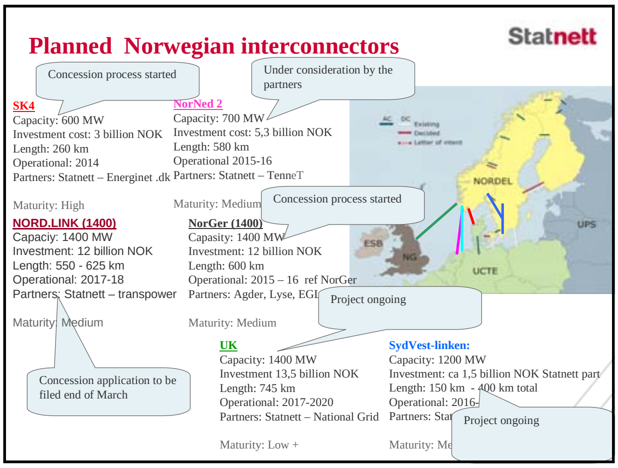
Power market analysis of large-scale offshore wind, Magnus Korpås, SINTEF

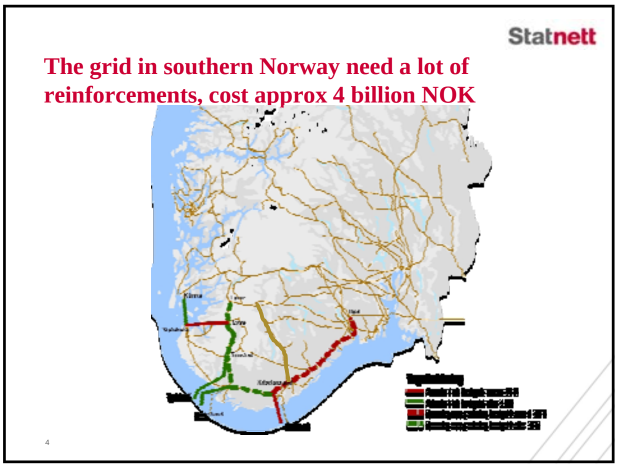
Power fluctuations from offshore wind farms, Prof Poul Sørensen, Risø DTU

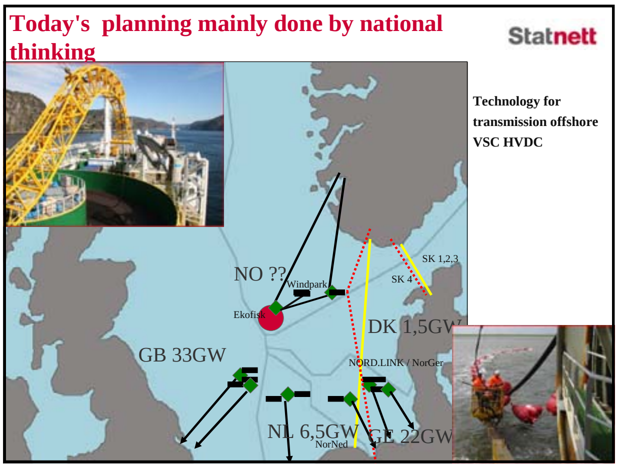
Cost of balancing large-scale wind generation, Prof Lennart Söder, KTH

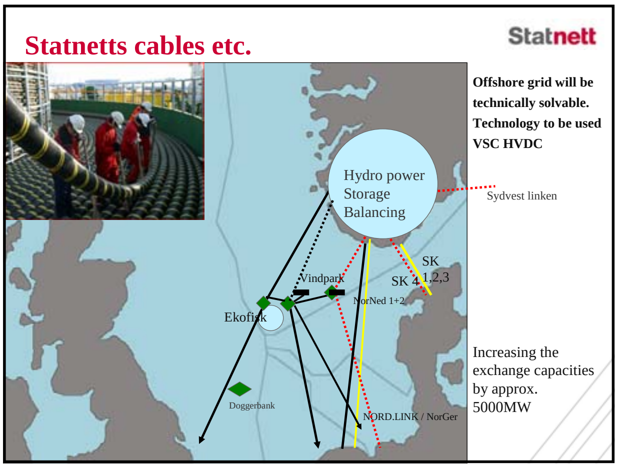

Statnett
Prospects for new cross-border connectors
Kjartan Hauglum, Statnett


Statnett
Vision
Possible offshore development 2020 -2040


Planned Norwegian interconnectors
Statnett
Concession process started
Under consideration by the partners
SK4
Capacity: 600 MW
Investment cost: 3 billion NOK
Length: 260 km
Operational: 2014
Partners: Statnett – Energinet .dk
Maturity: High
NorNed 2
Capacity: 700 MW
Investment cost: 5,3 billion NOK
Length: 580 km
Operational 2015-16
Partners: Statnett – TenneT
Maturity: Medium
Concession process started
NORD.LINK (1400)
Capaciy: 1400 MW
Investment: 12 billion NOK
Length: 550 - 625 km
Operational: 2017-18
Partners: Statnett – transpower
Maturity: Medium
NorGer (1400)
Capasity: 1400 MW
Investment: 12 billion NOK
Length: 600 km
Operational: 2015 – 16 ref NorGer
Partners: Agder, Lyse, EGL
Maturity: Medium
Project ongoing
Concession application to be filed end of March
UK
Capacity: 1400 MW
Investment 13,5 billion NOK
Length: 745 km
Operational: 2017-2020
Partners: Statnett – National Grid
Maturity: Low +
SydVest-linken:
Capacity: 1200 MW
Investment: ca 1,5 billion NOK Statnett part
Length: 150 km - 400 km total
Operational: 2016-
Partners: Stat
Maturity: Me
Project ongoing
NORDEL
UPS
ESB
NG
UCTE

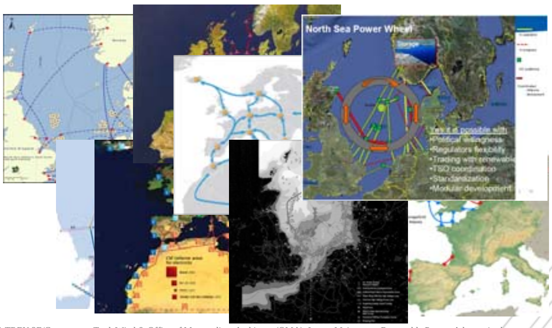

Statnett
The grid in southern Norway need a lot of reinforcements, cost approx 4 billion NOK


Today's planning mainly done by national thinking
Statnett
Technology for transmission offshore VSC HVDC
NO ??
Windpark
Ekofisk
SK 1,2,3
SK 4
DK 1,5GW
GB 33GW
NORD.LINK / NorGer
NL 6,5GW
NorNed
GE 22GW


Statnetts cables etc.
Statnett
Offshore grid will be technically solvable. Technology to be used VSC HVDC
Hydro power
Storage
Balancing
Sydvest linken
SK 1,2,3
SK 4
Windpark
NorNed 1+2
Ekofisk
Doggerbank
NORD.LINK / NorGer
Increasing the exchange capacities by approx. 5000MW

Statnett

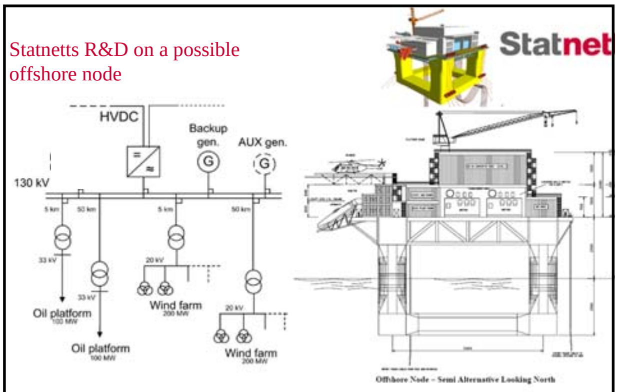
What offshore grid/"supergrid"?



Sources: DG-TREN,3E/Greenpeace, TradeWind & Office of Metropolitan Architects (OMA), Imera, Mainstream Renewable Power, Adamowitsch, Supersmartgrid.net, Desertec

Statnett

Statnetts R&D on a possible offshore node



Studiecase node 400 MW – kraftsystem

Studiecase node 400 MW – plattform (Aker Solutions layout, basert på mål og vekt for HV-utstyr fra ABB, Siemens, Areva)

Statnett

Development of interconnectors and a possible future grid

- TSO cooperation thru ENTSO-E, flexible regulators and political willingness
  - A possible grid will emerge as modules from national wind clusters and or new interconnectors
- Interconnector technology
  - VSC HVDC, recommended solution, supplier interface needed
  - Voltage level, to be agreed
  - CIGRE to develop standards
- R&D development needed
  - Multi-terminals, DC breakers
  - Increased capacity and reduced losses
- Trading and balancing
  - European trading with renewables
  - European balancing and storage

Statnett

Offshore development in Norway as seen from the TSO

- Legal framework for offshore wind not yet approved, seems promising
  - Dedicated areas to be selected for wind production offshore
  - Interconnector routing may be located close to selected areas
  - Stepwise development
- Technology and standards need development
- Offshore wind, very limited development before 2020 in Norwegian sector
- Electrification of offshore oil and gas installations may be a driver
- Norway have not yet nominated an offshore TSO
  - May hamper overall planning and development offshore and coordination with onshore

Statnett

Main message

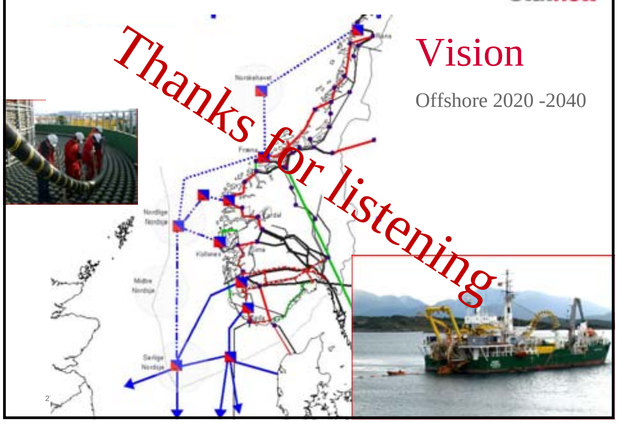
- Statnett has knowledge and experience to take an active role in development of interconnectors and a possible future offshore grid in the North Sea
- VSC HVDC gives flexibility for the future, but more R&D is needed
- Offshore wind is not a driving force for a grid in Norwegian sector
- The value of flexible Norwegian hydropower for balancing and storage will increase with more interconnectors
- **Norway has a large potential for onshore and offshore renewables if the market is willing to pay the cost, subsidies included**
  - **Develop wind and small hydro onshore first**

Statnett will by 2020 have the 5 planned interconnectors in operation

Statnett

Vision

Offshore 2020 -2040

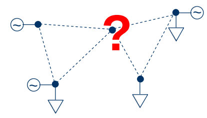


NOWITECH
Norwegian Research Centre for Offshore Wind Technology

Optimal design of a subsea power grid in the North Sea

T. Trötscher, M. Korpås
SINTEF Energy Research AS

General problem description



- How to connect nodes with transmission lines to achieve optimal social benefit?

Problem: Connect off-shore wind farms to the on-shore grid and build interconnectors between countries

Objective: Maximize social economic benefit

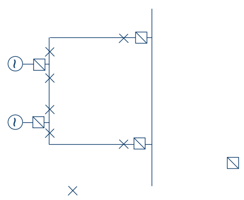
Exogenous variables: Capacity and location of offshore wind power clusters, possible land connection points, statistical description of wind and power prices, onshore grid equivalent, cost scenarios for grid infrastructure.

Unknowns: Where to build cables and with what power rating

Problem type: This is a mixed integer problem which can be solved with a branch and bound algorithm

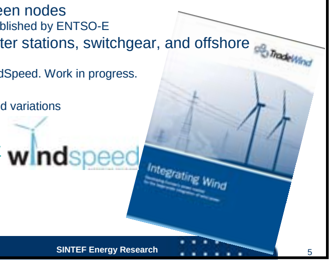
Node configuration

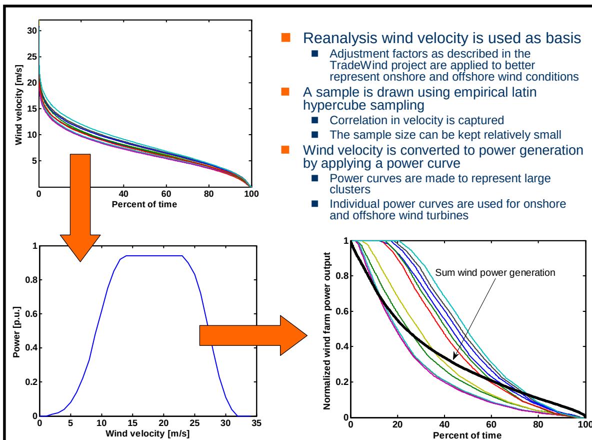
Example



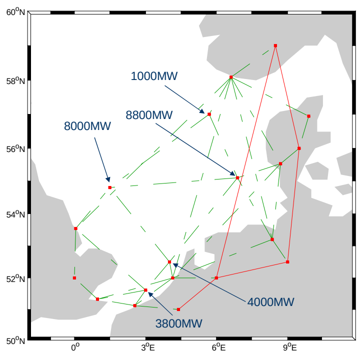
Input data assumptions

- Land connection nodes in relevant countries as latitude-longitude pairs
  - Selected relevant connection points from the TradeWind project
- Marginal cost of generation, generation capacities and time series of load.
  - Official ENTSO-E scenarios, same as in TradeWind
- Capacity and location of offshore wind power clusters
  - Selected a few large clusters as identified in the TradeWind project
- Existing exchange capacity between nodes
  - Used the net transfer capacities as published by ENTSO-E
- Cost scenarios for cables, converter stations, switchgear, and offshore platforms
  - Adapted from the EU-IEE project WindSpeed. Work in progress.
- Wind data
  - Interpolated reanalysis data with added variations
- Sources
  - TradeWind http://www.trade-wind.eu/
  - WindSpeed http://www.windspeed.eu/



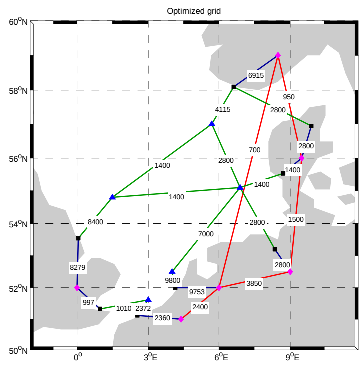


- Reanalysis wind velocity is used as basis
  - Adjustment factors as described in the TradeWind project are applied to better represent onshore and offshore wind conditions
- A sample is drawn using empirical latin hypercube sampling
  - Correlation in velocity is captured
  - The sample size can be kept relatively small
- Wind velocity is converted to power generation by applying a power curve
  - Power curves are made to represent large clusters
  - Individual power curves are used for onshore and offshore wind turbines



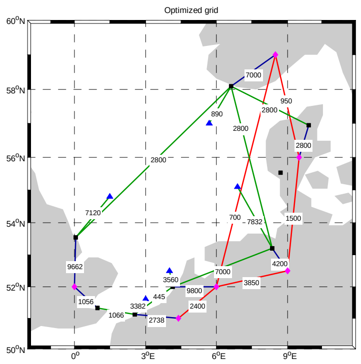
All considered interconnectors

- 33 considered projects
  - Leads to 1e25 possible configurations
  - Impossible to enumerate
- Onshore wind, TradeWind "2030 medium wind" scenario
  - Norway: 4980MW
  - Denmark: 7291MW
  - Germany: 45444MW
  - Netherlands: 3050MW
  - Belgium: 1183MW
  - UK: 10136MW



An example of an optimized grid...

Red lines	Existing connections
Green lines	New optimized connections
Black lines	Symbolic onshore connection to load centre
Pink dot	Load centre
Blue triangle	Wind farm cluster
Black square	Onshore connection point

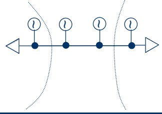


Locked to radial connections only...

- Investement in grid infrastructure 6.5 – 13.5 billion. €
  - Depending on cost scenario
- Savings by allowing a meshed grid: ~2 billion €
- Better reliability for wind farms with a meshed grid
- Meshed grid is more complex to operate
- Uncertain costs of t-offs/circuit breakers

Conclusions

- Meshed grids give better economic benefit for the EU as a whole than do radial connections
  - Steps should be taken to reduce regulatory barriers
  - Potential of savings of around 25% of investment cost
- Meshed grid have a higher utilization rate than do radial wind farm connections (~70% vs ~45%)
- Cost of VSC HVDC T-offs/circuit breakers as opposed to distance to shore will influence optimal grid structure
  - Higher costs short distance → radial + bilateral interconnectors
  - Lower costs long distance → meshed grid
- Meshed grids also...
  - ... Improves reliability of grid connection for wind farms
  - ... Makes it viable to connect wind farms further offshore



Challenges

A grid solution that is cost effective for the society must be attractive for the developers!

- Sharing of costs and benefits between TSOs
  - Construction costs, losses, congestion rent, operation costs
- Support for wind power is different around the North Sea
- Different legalisation for
  - Permissions, system operation, grid codes, system operation
- Market integration and balancing of wind power

Joint "North Sea TSO"
Harmonized support schemes for wind power

Sources:
•An analysis of Offshore Grid connection at Kriegers Flak in the Baltic Sea By Energinet.dk Svenska Kraftnät Vattenfall Europe Transmission
•Pentalateral Energy Forum : Working plan proposal on offshore electricity infrastructure

Further work

- Stepwise building
  - Current model optimizes the grid all at once
  - Better assumption: The grid is built in steps to accomodate more wind power. Costs fall.
  - Can be achieved with dynamic programming
- Generator marginal costs from TradeWind don't give rise to price variations as experienced in the market
  - Result: value of grid is underestimated
  - Use actual prices with a sesitivity to power infeed or...
  - Construct better/more realistic MC curves

Power market analysis of large-scale offshore wind

Magnus Korpås, Daniel Huertas Hernando, Harald Svendsen, Leif Warland

SINTEF Energy Research

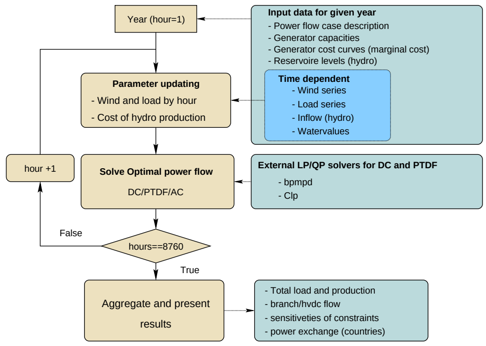
Outline

- PSST - Power System Simulation Tool
- Case-study of North Sea offshore wind
  - Offshore grid vs. Radial grid
  - Based on offshore grid structures as identified in the previous presentation
  - Grid bottlenecks, constrained wind, hydro utilization, power flows
- The presented material is based on results from:
  - EU-IEE project TradeWind
  - KMB project Deep Sea Offshore Wind
  - NOWITECH Work Package 4

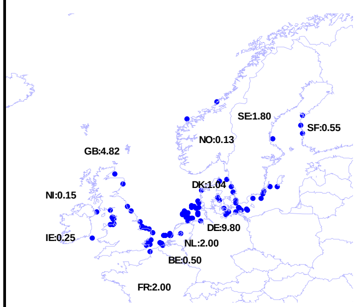
Power System Simulation Tool

- ***Time series simulation model*** of main transmission, generation and load (for years 2007, 2010, 2015, 2020, 2030 combined with +3 wind variants)
- ***Input*** time series of wind speed & load demand (1 hour resolution)
- ***Market model*** to compute power balances and prices. Simple marginal costs of generation. Water values from the EMPS model.
- ***Network model:*** DC power flow with 1380 nodes, 2220 branches, 525 generators + wind farms

Power System Simulation Tool

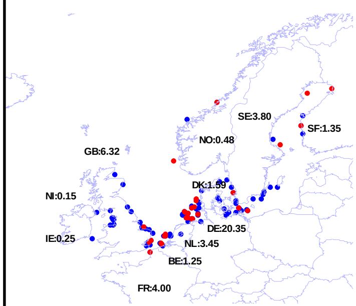


TradeWind Scenarios 2015



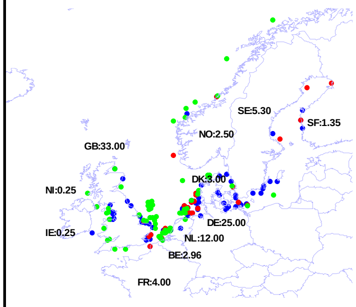
Scenario	L	M	H
sum (GW)	15.00	**23.04**	32.23

TradeWind Scenarios 2020



Scenario	L	M	H
sum (GW)	21.25	**42.86**	55.67

TradeWind Scenarios 2030



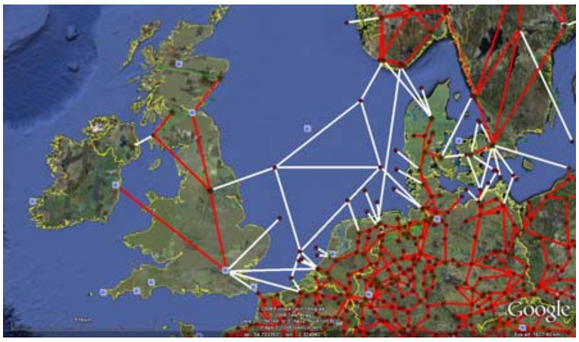
Scenario	L	M	H
sum (GW)	35.72	**89.61**	124.26

PSST Simulation case study

- Two North Sea grid structures are studied
  - "Radial grid": Radial connections of offshore wind farms and point-to-point HVDC connections between countries
  - "Offshore grid": Inclusion of offshore nodes
  - Nodes and cable capacities are determined by the Grid Optimization tool
- Input data on generation capacity, load, NTCs and wind speeds as in the Grid Optimization tool
- No demand increase : Motivated by EC's New Energy Policy scenario
- TradeWind scenario 2030 "medium" for offshore and onshore wind
  - Total 302 GW …
  - …gives 818 TWh/year (25 % wind energy penetration)

Radial grid

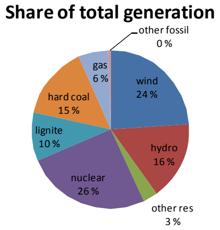
Offshore grid



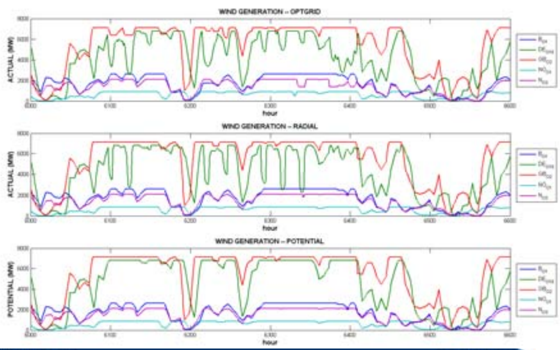
Comparison of grid alternatives

	Operational costs (Mill € /year)	Investment costs (Mill €)	Benefit PSST* (Mill €)	Benefit Net-Op* (Mill €)
Radial grid	74550,8	8283,2		
Optimal grid	74443,6	7279,4		
Difference	107,2	1003,8	**2651,7**	**1287,7**
*30 years, 5 % discount rate				

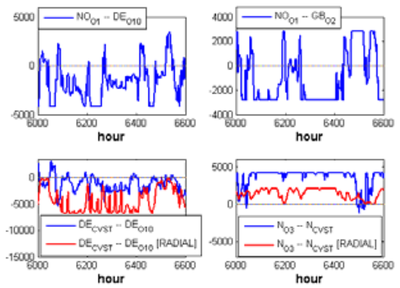
	Marginal costs (€/MWh)
wind	0
hydro	24*
other res	51
nuclear	11
lignite	44
hard coal	39
gas	56
other fossil	91-106
*avg. water value	



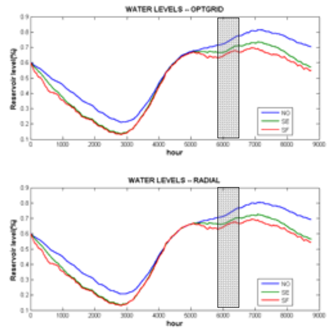
Mainland bottlenecks put constraints on offshore wind power output



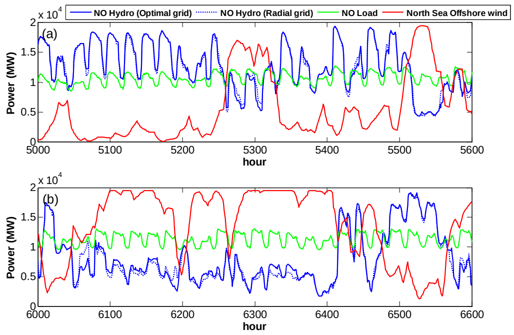
The offshore grid facilitates export of excess wind power



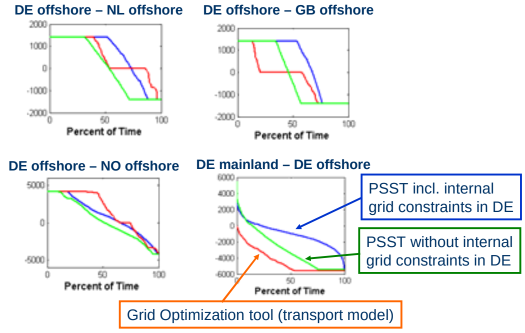
Hydro reservoir development



Hydro power generation is influenced by the new interconnectors



Grid modelling detail level influence the simulated utilization of offshore cables



Summary

- Building an offshore grid instead of radial wind farm connections and point-to-point interconnectors have positive effects on the power market:
  - Facilitates export of offshore wind directly to the most optimal market area -> lower total power system operating costs
  - Bottlenecks in the mainland grid can be avoided
  - Higher utilization of installed subsea cables
  - Facilitates trade between countries when wind generation is low
- Onshore grid modelling detail influences the simulated utilization of the subsea cables
  - An offshore grid building strategy must reflect the plans and opportunities for onshore grid upgrades
  - Must also take into account the expected continued growth in onshore wind development
- Norwegian hydro power will not only be used as buffer for offshore wind
  - The power exchange to/from Norway is also determined by variations in demand and onshore wind generation at the continent

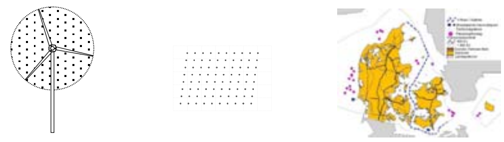
Power Fluctuations from Offshore Wind Farms

Poul Sørensen
Nicolaos Cutululis
Søren Larsen
Risø DTU - Wind Energy Division

Risø DTU
National Laboratory for Sustainable Energy

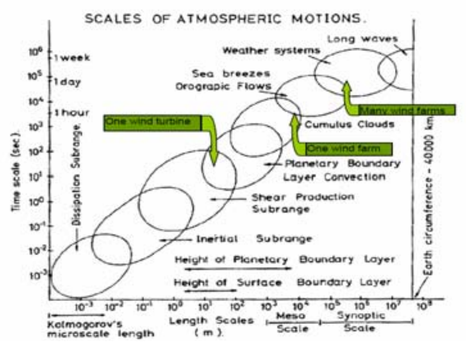
Wind power fluctuation models

2002 2007 2009

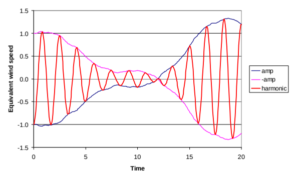


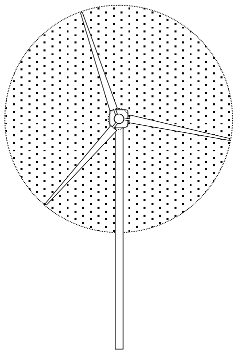
Wind turbine(s) Wind farm Power system area

Time scales and space scales

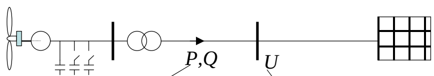


Rotor wind variability



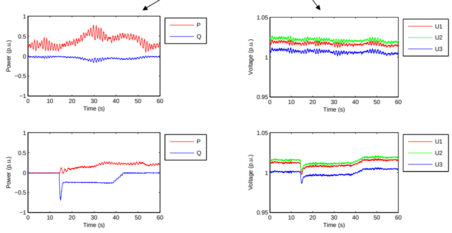


Single wind turbine power fluctuations

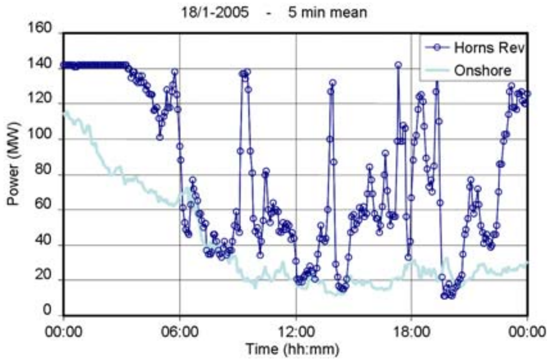


continuous

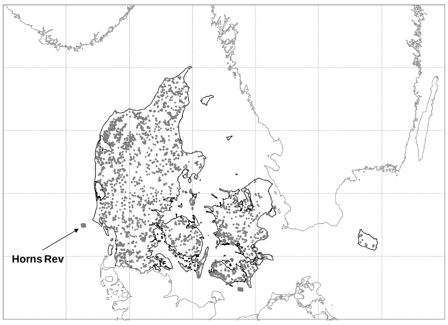
startup



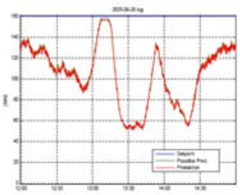
Power fluctuation offshore – on land



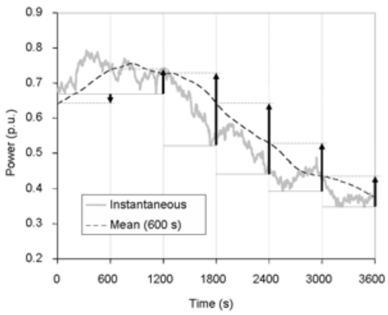
Wind turbine sites in Denmark



Rain clouds – a suspicion



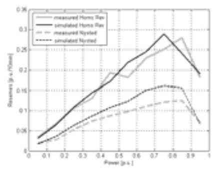
Reserve requirements



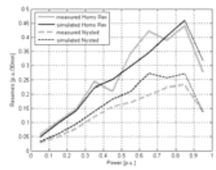
$$P_{res}(n) = P_{mean}(n) - P_{min}(n+1)$$

Validation – 1% percentiles reserves

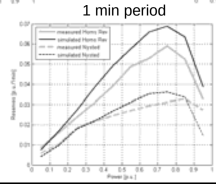
10 min period



30 min period

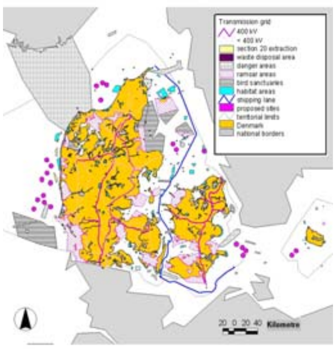


1 min period

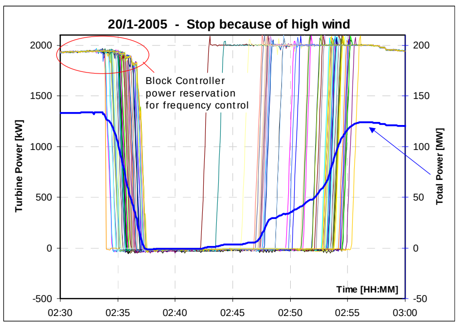


Plans for future offshore wind farms

- Report on future Offshore sites
- Update of action plan from 1997
- 23 Sites each 44 km2 for a capacity of 4600 MW Wind Power
- Production 18 TWh, or just over 8% of total energy consumption in Denmark or approximately 50% of Danish electricity consumption
- http://www.ens.dk/graphics/Publikationer/Havvindmoeller/Fremtidens_%20havvindm_UKsummery_aug07.pdf

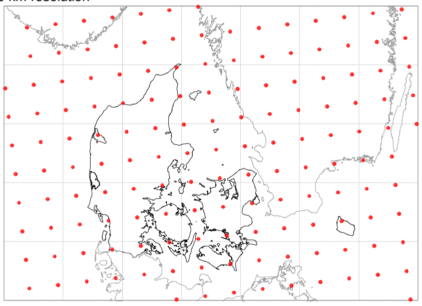


Storm passages

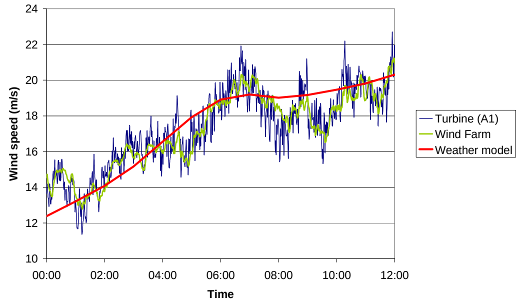


Climate model resolution

Supplied by MaxPlank Germany
25 years of data
1 hour 50 km resolution

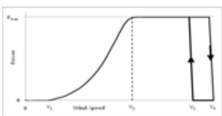


Simulated wind speeds - smoothing

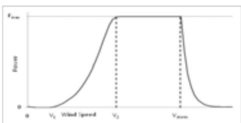


Storm Control

- Tradidionally wind turbines disconnect in storms to reduce mechanical loads (20 – 25 m/s)
- There is a patent on a simple alternative based on power curve (SST to the right)
- Alternative soft solutions will appear in the future

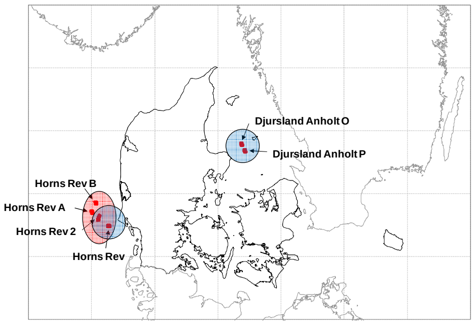


Hard storm transition (HST) here with hysteresis



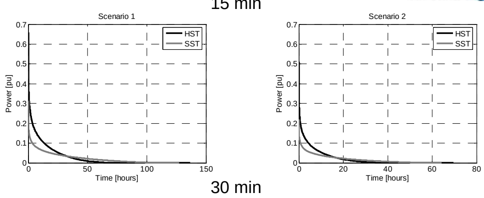
Soft storm Transition (SST)

Study cases

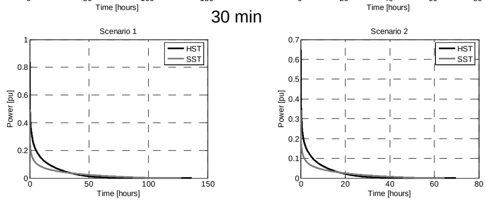


Reserve requirements - storm

15 min



30 min



Conclusions / remarks

- Time scales of relevant power fluctuations depends on geographical spreading (dispersion)
  - Single wind turbines
    - Fixed speed impact voltage fluctuations and flicker locally (time scales from 0.1 s and larger)
    - Variable speed (time scales from 5-10 s and larger)
  - Large offshore wind farms have an impact on the area control at power system level, only little dependency on technology (time scales from minutes and larger)
  - Simulation tool developed and validated on wind farm level (Horns Rev and Nysted data)
  - Wind farm power fluctuations can be quantified in terms of reserve requirement to balance the fluctuations
  - Wind farm power fluctuations can also be seen as reliability issue (e.g. reliability indeces like frequency and duration of storms)
  - Planned large scale offshore development will require new solutions to handle storms in a secure way (to be demonstrated in TWENTIES).

Cost of balancing large-scale wind generation

Wind Power R&D seminar – deep sea offshore wind

Lennart Söder
Professor in Electric Power Systems, KTH
21-22 January 2010, Trondheim

Renewable energy systems

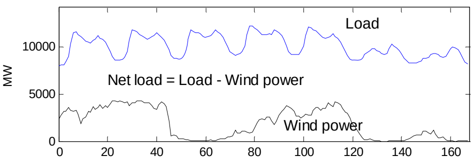
- Energy is "produced" where the resource is
- The energy has to be transported to consumption center
- The energy inflow varies, which requires storage and/or flexible system solutions
- This is valid for hydro power, **wind power**, solar power

Example

- Nordic hydro inflow can vary 86 TWh between different years (1996, 2001)
- Transport from north Sweden to south Sweden
- Energy **balancing** with thermal power in Da+Fi+Ge+EE+Pl+NL

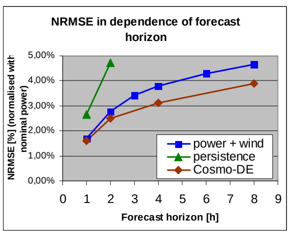
Wind power – basics - 1

- The production in wind power varies continuously:



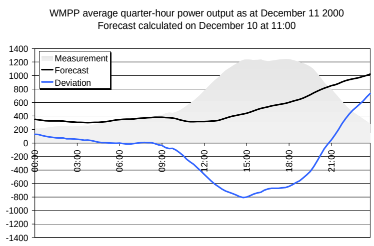
Wind power – basics - 2

- The production in wind power can be forecasted...



Wind power – basics - 3

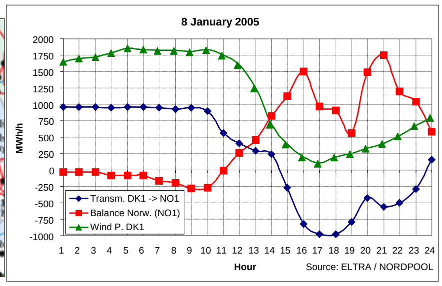
- ... but the forecasts are not always close to real production.



Danish example: Foreign **balancing** through transmission

- W Den-Nor: 1000 MW
- W Den-Swe:740 MW
- W Den-Ger: 1200 MW
- ➔ Denmark - neighbors: ~ 2940 MW

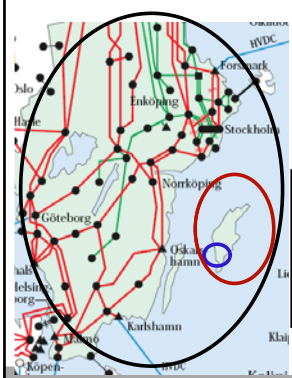
Danish example: Foreign **balancing** through transmission



Balancing summary

- Not only one part (region, country) of the system should be considered
- A system wide **balancing** is economically **efficient**
- A system wide **balancing** is what we will get in a future with large amount of wind power

➔ Consider the whole **power system**



Possibilities of external **balancing**

An illustration

Region	Wind power	Share of local load energy	Maximal share of wind power
Näsudden	50 MW	169 %	48%
Gotland	90 MW	19 %	40 %
Sweden	339 MW	0.4 %	1.5 %

Definition of ”**penetration level**”

$$\textit{Maximal share of wind power} = \frac{\textit{Maximal wind power}}{\textit{Lowest consumption} + \textit{possible exchange}}$$

Region	Wind power	Share of local load energy	Maximal share of wind power
Näsudden (on Gotland)	50 MW	169 %	48%
Gotland	90 MW	19 %	40 %
West Denmark	2380 MW	21 %	58 %
Schleswig-Holstein	2275 MW	33 %	44 %

Examples of **penetration levels**

Source:
- IEA Annex 25
- Final report, Phase one 2006-08
- **“Design and operation of power systems with large amounts of wind power”**

Region / case study	% of peak load	% of gross demand	% of (min load + interconn)
West Denmark 2008	64 %	24 %	58 %
Denmark 2025 a)	90 %	53 %	83 %
Denmark 2025 b)	90 %	53 %	69 %
Nordic /VTT	27 %	12 %	67 %
Nordic+Germany/Greennet	37 %	12 %	80 %
Finland /VTT	52 %	18 %	89 %
Germany 2015 / dena	46 %	14 %	71 %
Ireland / ESBNG	54 %	27 %	140 %
Ireland / SEI	28 %	13 %	58 %
Ireland 2020/All island	63 %	35 %	178 %
Netherlands	40 %	28 %	61 %

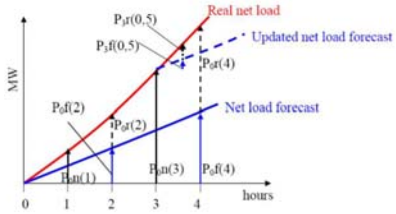
Balancing services - 1

Separate between:

- Scheduled **balancing services** for known **variations** of net load (= load minus wind power) ➔ required **flexibility**
- Scheduled **balancing services** for net load **forecast errors** ➔ required **reserves**

Balancing services - 2

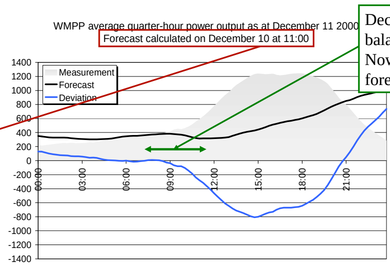
- Some net load **variation** that can **not** be **fore-casted** ➔ required **reserves** in other power plants



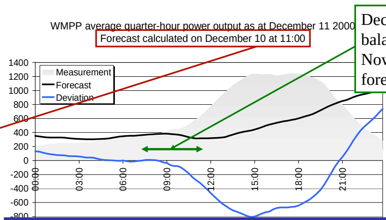
Balancing services - 3

- **Reserves** is a part of required **flexibility**
- The largest requirements of **reserves** is at high wind power production ➔ other units are not operated so much ➔ they can act as reserves.
- ➔ Larger requirements of **reserves** does not necessarily leads to requirement of new "reserve plants"
- Higher ramp rates and fast start-up may become an important issue ➔ better acceptance of not perfect forecasts

Balancing services - 4



Balancing services - 5

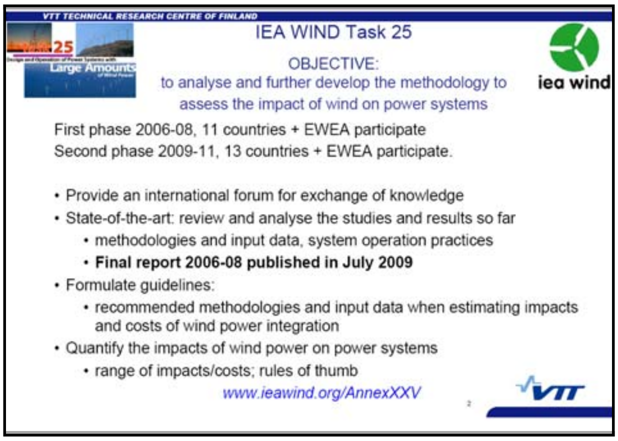


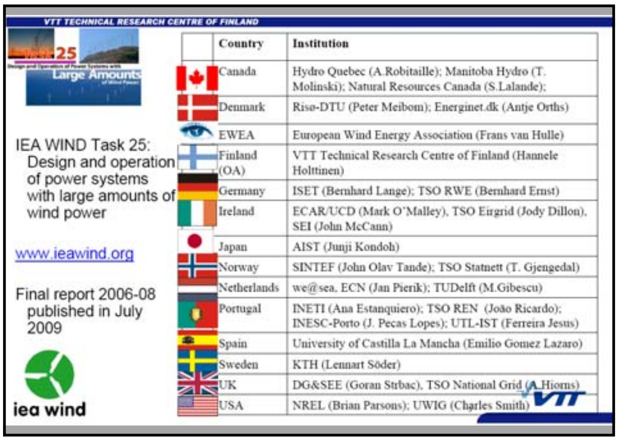
Requires flexible intraday markets!
= "Balancing service"?

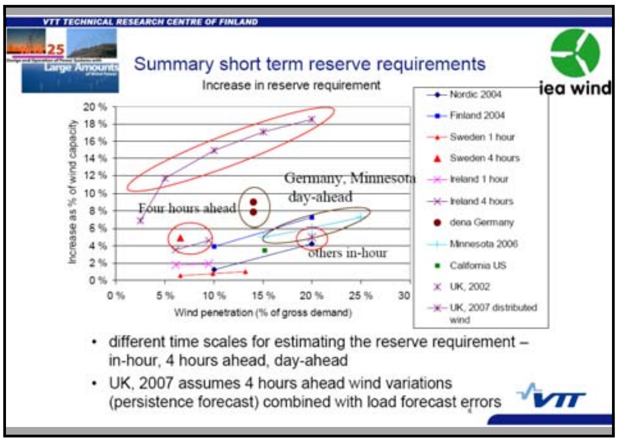
Balancing services example- 9

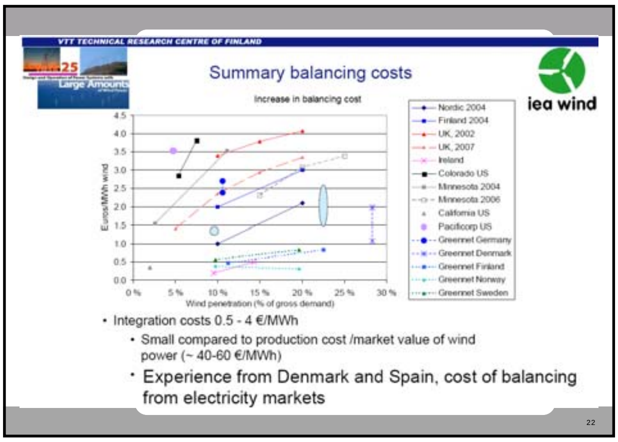
Nordic regulating market:

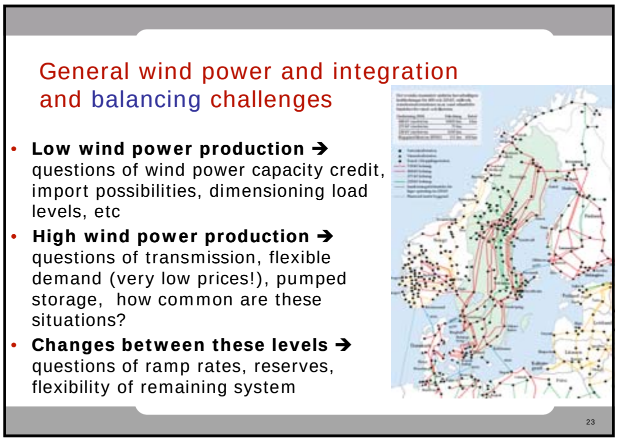
- No AGC (except Dk-W)!
- Assume that wind power decreases in Denmark with 100 MW
- The bids to the regulating market (tertiary control – up-regulation in 15 minutes) are coordinated in the Nordic system
- If an up-regulating bid from northern Finland is the cheapest and transmission limits are not violated, then this one is used!
- Distance: ~1400 km

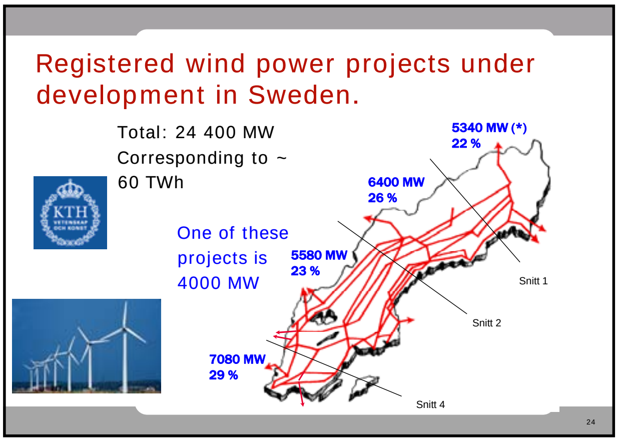

VTT TECHNICAL RESEARCH CENTRE OF FINLAND
IEA WIND Task 25
OBJECTIVE:
to analyse and further develop the methodology to assess the impact of wind on power systems
iea wind
First phase 2006-08, 11 countries + EWEA participate
Second phase 2009-11, 13 countries + EWEA participate.
• Provide an international forum for exchange of knowledge
• State-of-the-art: review and analyse the studies and results so far
• methodologies and input data, system operation practices
• Final report 2006-08 published in July 2009
• Formulate guidelines:
• recommended methodologies and input data when estimating impacts and costs of wind power integration
• Quantify the impacts of wind power on power systems
• range of impacts/costs; rules of thumb
www.ieawind.org/AnnexXXV
VTT


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
IEA WIND Task 25:
Design and operation of power systems with large amounts of wind power
www.ieawind.org
Final report 2006-08 published in July 2009
iea wind
Country | Institution
Canada | Hydro Quebec (A.Robitaille); Manitoba Hydro (T. Molinski); Natural Resources Canada (S.Lalande);
Denmark | Risø-DTU (Peter Meibom); Energinet.dk (Antje Orths)
EWEA | European Wind Energy Association (Frans van Hulle)
Finland (OA) | VTT Technical Research Centre of Finland (Hannele Holttinen)
Germany | ISET (Bernhard Lange); TSO RWE (Bernhard Ernst)
Ireland | ECAR/UCD (Mark O'Malley), TSO Eirgrid (Jody Dillon), SEI (John McCann)
Japan | AIST (Junji Kondoh)
Norway | SINTEF (John Olav Tande); TSO Statnett (T. Gjengedal)
Netherlands | we@sea, ECN (Jan Pierik); TUDelft (M.Gibescu)
Portugal | INETI (Ana Estanquiero); TSO REN (João Ricardo); INESC-Porto (J. Pecas Lopes); UTL-IST (Ferreira Jesus)
Spain | University of Castilla La Mancha (Emilio Gomez Lazaro)
Sweden | KTH (Lennart Söder)
UK | DG&SEE (Goran Strbac), TSO National Grid (A.Hiorns)
USA | NREL (Brian Parsons); UWIG (Charles Smith)
VTT


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
Summary short term reserve requirements
iea wind
Increase in reserve requirement
Increase as % of wind capacity
Wind penetration (% of gross demand)
Germany, Minnesota day-ahead
Four hours ahead
others in-hour
Nordic 2004
Finland 2004
Sweden 1 hour
Sweden 4 hours
Ireland 1 hour
Ireland 4 hours
dena Germany
Minnesota 2006
California US
UK, 2002
UK, 2007 distributed wind
• different time scales for estimating the reserve requirement – in-hour, 4 hours ahead, day-ahead
• UK, 2007 assumes 4 hours ahead wind variations (persistence forecast) combined with load forecast errors
VTT


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
Summary balancing costs
iea wind
Increase in balancing cost
• Integration costs 0.5 - 4 €/MWh
• Small compared to production cost /market value of wind power (~ 40-60 €/MWh)
• Experience from Denmark and Spain, cost of balancing from electricity markets
22


General wind power and integration and balancing challenges
• Low wind power production →
questions of wind power capacity credit, import possibilities, dimensioning load levels, etc
• High wind power production →
questions of transmission, flexible demand (very low prices!), pumped storage, how common are these situations?
• Changes between these levels →
questions of ramp rates, reserves, flexibility of remaining system
23


Registered wind power projects under development in Sweden.
Total: 24 400 MW
Corresponding to ~ 60 TWh
One of these projects is 4000 MW
5340 MW (*)
22 %
6400 MW
26 %
5580 MW
23 %
7080 MW
29 %
Snitt 1
Snitt 2
Snitt 4
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B2 Grid connection

From power markets to voltages and currents, Prof Kjetil Uhlen, NTNU

Sub-stations for offshore wind farms, Steve Aughton, Siemens T&D Limited

New converter topologies for offshore wind farms, Prof Marta Molinas, NTNU

Power quality measurements from wind farms, Trond Toftevaag and
Tarjei Solvang, SINTEF

NTNU

Wind Power R&D seminar – deep sea offshore wind
21-22 January 2010, Royal Garden Hotel, Trondheim, NORWAY

Grid connection of offshore wind

From power markets to voltages and currents

Kjetil Uhlen
Temesgen Haileselassie
Electrical Power Engineering Department
NTNU

NOWITECH Norwegian Research Centre for Offshore Wind Technology

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Outline

- The system integration and power market challenges
- Operation: The various control stages.
- New possibilities and challenges with an offshore HVDC grid.
- Example from ongoing research:
  - Primary Control of Multi-terminal HVDC Transmission for Offshore Wind Energy

NOWITECH Norwegian Research Centre for Offshore Wind Technology

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Power markets

- Purpose:
  - Establish a planned power balance
  - Optimal use of resources (mainly generation)
  - Price and scheduled exchanges
  - Congestion management
- Challenges with an offshore grid and large amounts of offshore wind:
  - Variable generation → More power flow variations and faster ramp rates
  - More interconnections → Stronger coupling between market areas
- How should the markets be adapted?
  - To deal with the changes
  - To make optimal use of the new possibilities

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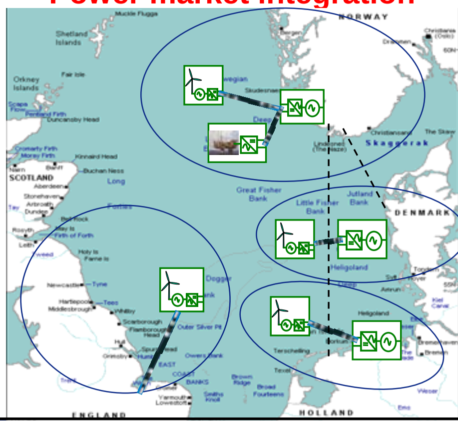
Power market integration



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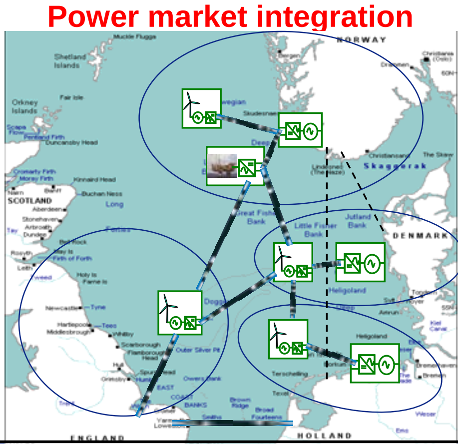
Power market integration



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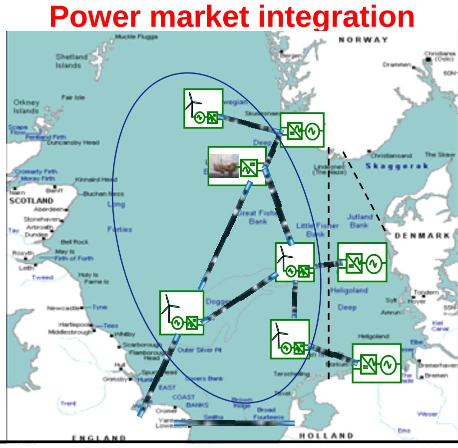
Power market integration



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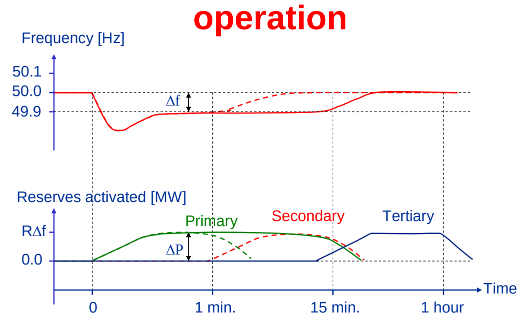
Control stages in power system operation

The power system must be in balance at any time:

- Long-term balance (hours and beyond):
  - Power markets (day-ahead and intra-day markets)
- Short-term balance and management of deviations from plans/forecasts:
  - Primary control - Automatic control
  - Secondary control - LFC/AGC (market based?)
  - Tertiary control - Manually activated (balancing markets)

Control stages in power system operation



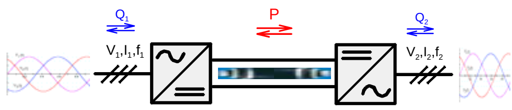
System frequency response: **R** = $\frac{\Delta P}{\Delta f}$ [MW/Hz]

Main challenges in operation and control

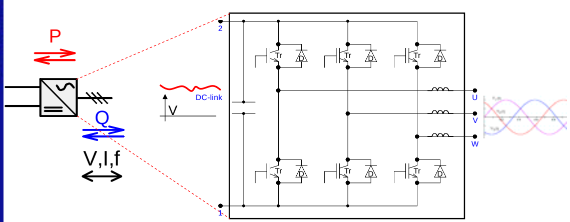
- Primary control:
  - Less primary reserves if new generation provide less frequency response
- Secondary control:
  - More need for secondary reserves with more variable generation
- Tertiary control:
  - Benefits with larger control areas and exchange of reserves.
- **New possibilities with an offshore Multi-terminal HVDC grid!**

New possibilities and challenges with an offshore HVDC grid.

- **Increased controllability:**
  - More complex control systems
  - New possibilities
- **Fast fault detection and protection needed**
  - IGBT control and AC breakers used



Two-level AC/DC "Voltage Source Converter" (2L-VSC)



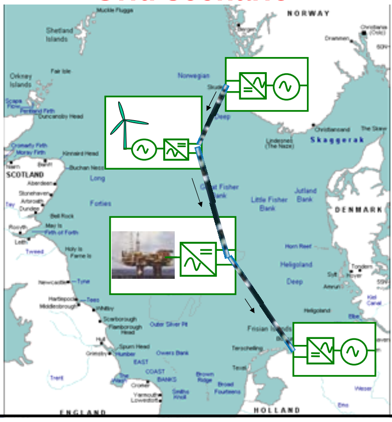
Properties:

- Fast dynamic control of active and reactive power
- Fast dynamic control of current, voltage and frequency
- Very fast (close to instantaneous) current limitations during faults

Source: SINTEF Energy Research

Control of Multiterminal HVDC Transmission for Offshore Wind Energy

Grid scenario



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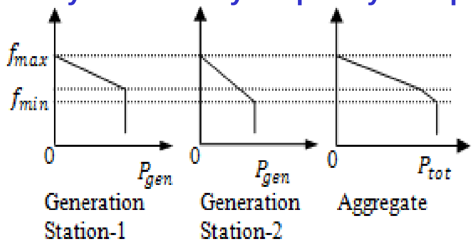
To begin with…

Power balance control in AC grids:

Normally achieved by frequency droop



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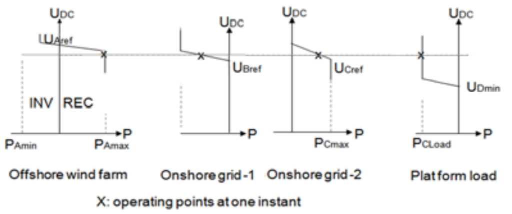
DC voltage droop configuration for the model MTDC



- No need for communication between terminals
- Many converter terminals contribute to DC voltage regulation
- DC analogy to distributed *frequency droop control* in AC systems

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Remarks

- Robust control of MTDC was achieved by DC voltage droop characteristics
- But, the DC control system does not account for the loading level of the AC grids (i.e. The DC and AC grid power controls remain decoupled)
- In worst case this may cause frequency instability in the AC grids connected to the MTDC system
- Hence the MTDC should also have capability for primary frequency support in case of need

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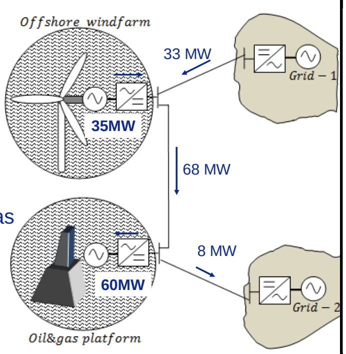
Primary frequency support by MTDC

4 terminal MTDC model developed in PSCAD

Model adjustments:

- 2 isolated AC grids
- AC grids modelled as simple equivalents with sync. gen. and load
- New control loops



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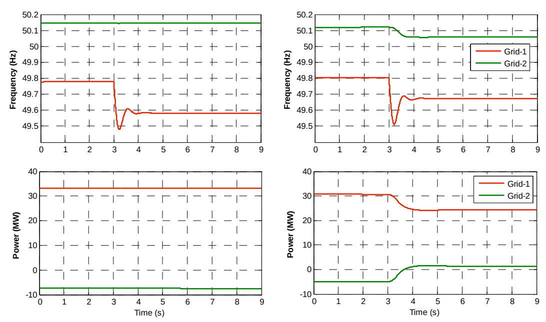
Frequency support Simulation results



a. Before

b. After

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Control strategy attributes

- Robust control of MTDC was achieved by DC voltage droop characteristics
- No need for fast communication between terminals
- The system can also contribute to primary frequency support

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Concluding remarks

- Great possibilities and challenges with an offshore transmission grid based on VSC HVDC
- Market solutions must be adapted to the new possibilities (to make optimal use of the controllability of HVDC and the increased complexity of the grid)
- Technical and market based solutions must be developed to realise the potential for exchanging balancing power (in particular to utilise the flexibility of Norwegian hydro power)
- Technical solutions can be developed for exchanging primary reserves between different synchronous systems (and contribute to primary frequency support)

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Thank you.

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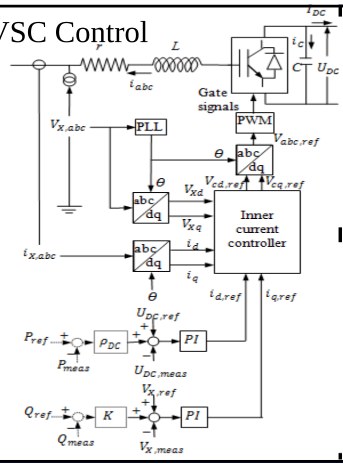
Generalized VSC Control Structure



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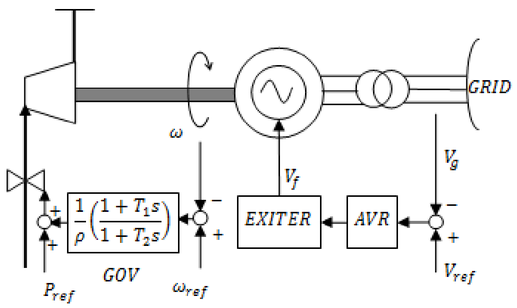
Frequency control implementation at generator station



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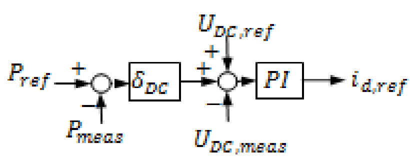
DC droop control implementation at converter station



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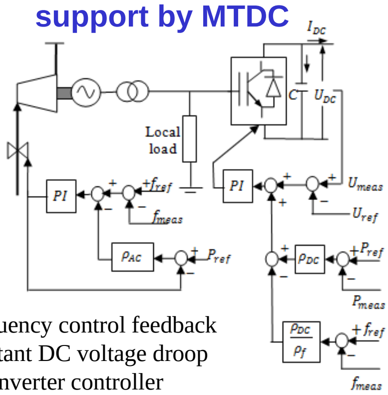
Control scheme for frequency support by MTDC



- Add frequency control feedback of a constant DC voltage droop on the converter controller

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Sub-stations for offshore wind farms

Technology and issues for offshore wind projects

Steve Aughton, Business Development Mgr.
Siemens Transmission and Distribution Ltd.

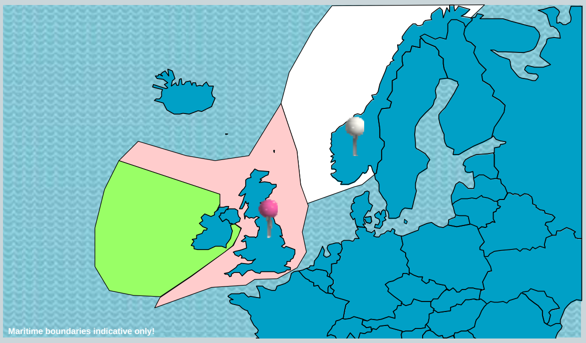
Wind Power R&D seminar – deep sea offshore wind
21-22 January 2010, Royal Garden Hotel, Trondheim

24th September 2009 07:00 near Hartlepool
IG SUB 500MW, 2,100 tonnes, C£50M
The worlds first interconnected offshore substation sails out

..Only another 299 like this to go by 2030 (in Europe alone)

SIEMENS

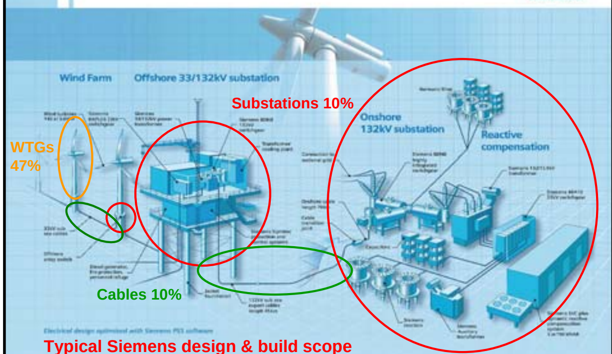
Europe needs renewable energy
Norway, (Ireland), & UK own the windy parts of the sea



Elements of an offshore wind farm & grid connection

designed by Siemens Transmission and Distribution Limited

SIEMENS



Typical Siemens design & build scope

Typical %CAPEX figures from Ernst & Young study for UK Government

SIEMENS

Challenges for offshore Electrical Power Transmission

- Supply Chain
- Costs
- Technology
- Market
- Service & Operation

- Standardisation, economies of scale – lower costs
- Steady ramp up of market v tidal wave – give supply chain a chance
- Incentivisation – creating the market conditions
- R&D, best practice sharing – improve reliability and find solutions

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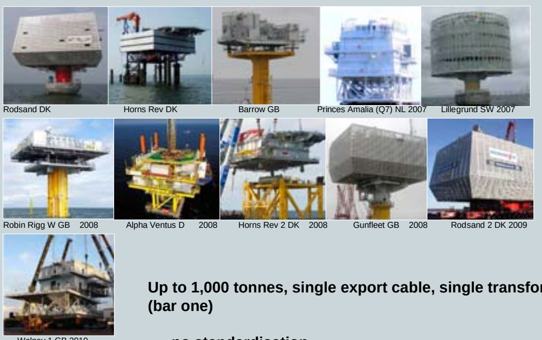
The story so far…..
'1st generation' offshore substations



Up to 1,000 tonnes, single export cable, single transformer (bar one)

…..no standardisation…

The next steps…..
’2nd generation’ offshore substations

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Sheringham 2010

1,500 tonnes plus, multiple export cable, multiple transformers

…..still no standard solution….

AREVA

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What have we learned so far?
Grid connection optimisation

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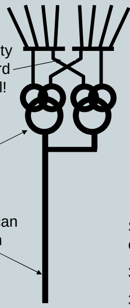
As much flexibility as you can afford watch fault level!

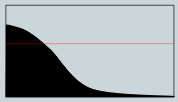
Two is better than one

As few as you can get away with



Value of availability vs. capex
Many factors
- Electrical
- Practical
- Supply chain etc.

Some rules of thumb have emerged



Size the wind farm to optimise the connection

33kV collection works OK

330 MW and 500 MW block sizes

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What have we learned so far?
Critical Design Phase – 6 months

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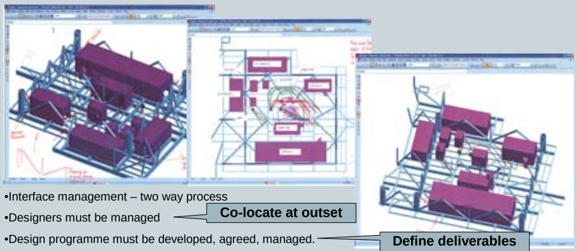

- •Interface management – two way process
- •Designers must be managed — **Co-locate at outset**
- •Design programme must be developed, agreed, managed. — **Define deliverables**
- •Cause and effect of delays / change — **Update & add events**
- •Define Level of detail required by fabricator – loadings, location, fixings, cable schedules, transits etc
- •End date does not change

All changes cost, when they change dictate actual cost, design, fabrication+, painting++, Offshore+++

Page 9 January 2010

What does this mean for costs?

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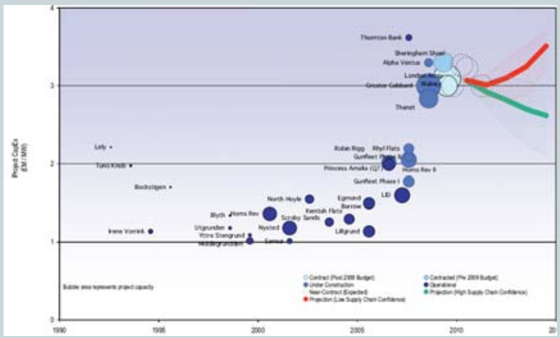

Source BWEA: UK Offshore Wind - Charting the Right Course

Page 10 January 2010 Steve Aughton

Technology – future developments
HVDC plus

SIEMENS

AC systems have limits

DC systems are needed for high power long distance transmission

- Moyle (UK)
- Storebaelt (DK)
- Brit-Ned (UK/NL)

Classic ‘Line Commutated’ HVDC requires a strong AC network at each end, not suitable for offshore wind

Siemens HVDCplus launched 2008
- Unique conversion system
- Many benefits for offshore wind
- HVDC Plus from Siemens

Page 11 January 2010 Steve Aughton

Technology – future developments
Self installing / floating platforms & larger zones

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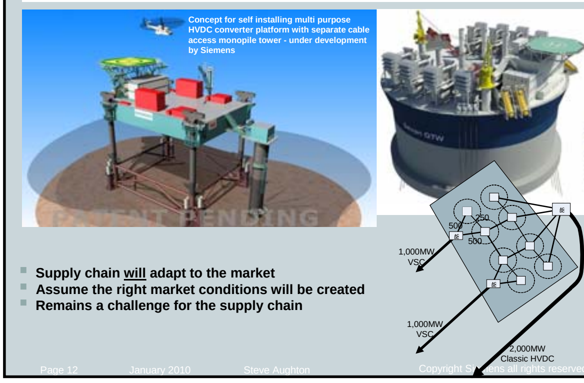
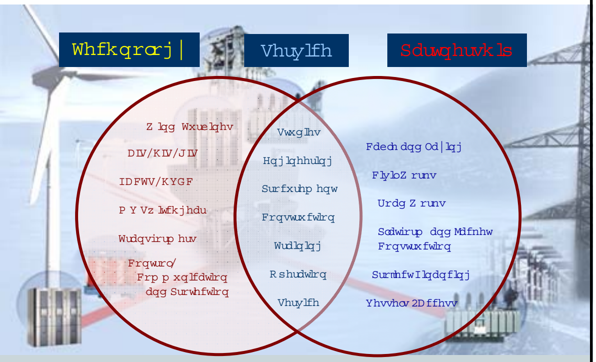


- **Supply chain will adapt to the market**
- **Assume the right market conditions will be created**
- **Remains a challenge for the supply chain**

Page 12 January 2010 Steve Aughton

Siemens Energy
Solutions for off shore wind farms

SIEMENS



There are two futures for offshore wind

SIEMENS

Virtuous (positive) spiral	Death (negative) spiral
Steady ramp up of projects allows supply chain to invest	All wait until costs come down
Innovation, standardisation, economies of scale	Projects come along in ones
Costs fall, reinforcing the above	Suppliers don't invest
Offshore wind fulfils potential	Costs stay high
	Offshore wind dies in Europe

Conclusions

Europe's Energy Revolution is underway
Norway should be a key part of it.

Suppliers are developing new equipment and ways to deliver

Significant investment is needed to meet the challenge and bring unit costs down

Mixing electricity with water has never been so exciting

steve.aughton@siemens.com

The opportunity……

SIEMENS

- 'Standard' building blocks solutions for AC connections
- Standardisation and repeatability – biggest impact on reducing cost
- Economies of scale will also help reduce costs
- Interconnection will create economies of scale
- Alternative – pressure on supply chain will force up costs
- Key is investment in supply chain to meet the challenge
- Where will the investment go ?
  - Not to the country with the biggest eventual programme
  - To the place where the conditions are right first
  - A steady market, where customers and suppliers can form long term relationships
- Incentives will help - but only if there is a market there to serve

NEW CONVERTER TOPOLOGIES FOR OFFSHORE WIND FARMS:

STATE OF THE RESEARCH

Marta Molinas
NTNU – Jan. 21, 201

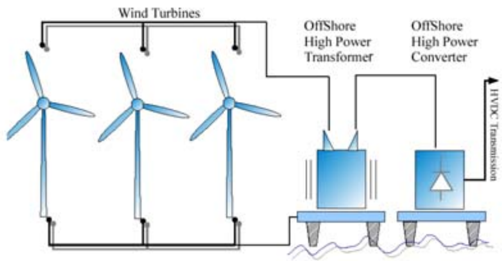
Wind Power R&D Seminar:
Deep sea offshore wind

NTNU 100 skapende år

Offshore Challenges

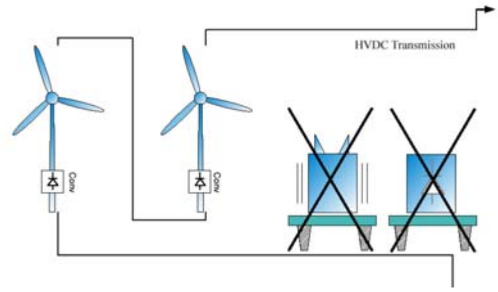
- Reliability and efficiency
  - Reduced number of components and conversion stages
  - Modularity of the conversion system
- Weight reduction in the nacelle
  - High power density: compact solutions: HF transformers
  - HF will give high switching losses in converters
- Component oriented optimization is conflictive with global optimization
  - Generator – converters – transformer – park - transmission
- Optimal design targeting two objectives:
  - Maximize efficiency (identify frequency for best operation of overall system)
  - Maximize power density of conversion system (Minimize weight for a given power)

Parallel connection



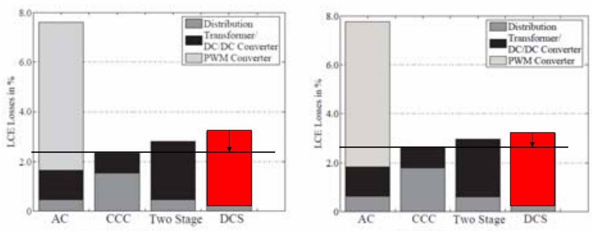
Losses? Reliability? MPP ?

Series connection



Losses? Reliability? MPP ?

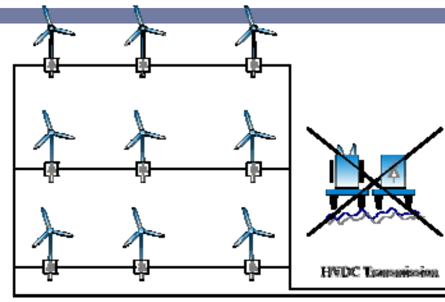
The starting point: motivation (1)



(a) 500 MW wind farm (b) 1000 MW wind farm

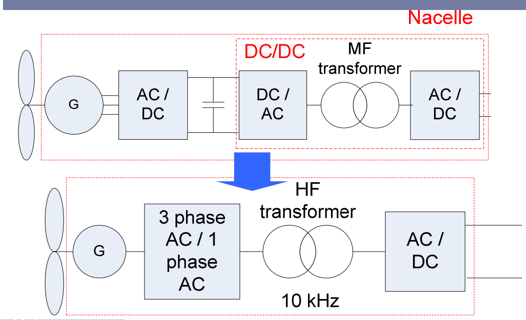
C. Meyer, "Key components for future offshore DC grids," PhD dissertation, Rheinisch-Westfallischen Technischen Hochschule Aachen, Germany, 2007

The wind park system



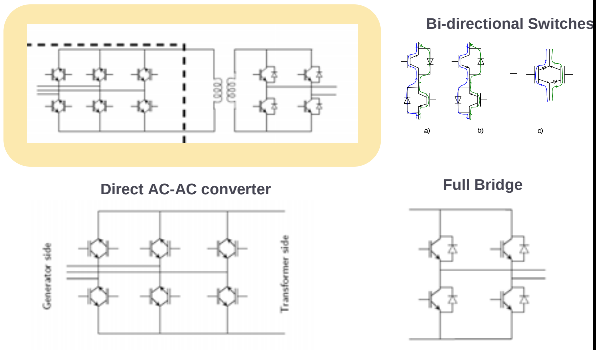
S. Lundberg, Wind farm configuration and energy efficiency studies - series dc versus ac layouts. Lic. of Eng. thesis, Chalmers University of technology, Goteborg, Sweden, 2006.

Reducing the number of conversion stages

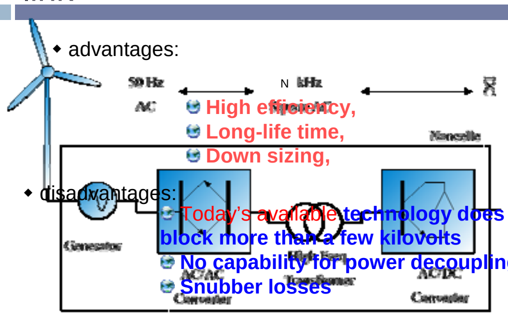


Marta Molinas
NTNU – Nov. 19, 2010

Reduced number of switches



The conversion system: Direct AC link



- advantages:
  - High efficiency,
  - Long-life time,
  - Down sizing,
- disadvantages:
  - Today's available technology does not block more than a few kilovolts
  - No capability for power decoupling
  - Snubber losses

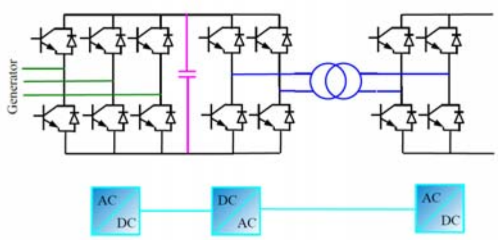
Marta Molinas
NTNU – Jan. 21, 2010

Comparative Investigation

1	Back to Back Converter ⇐ **Reference for comparison**
2	Reduced Matrix Converter with Full Bridge

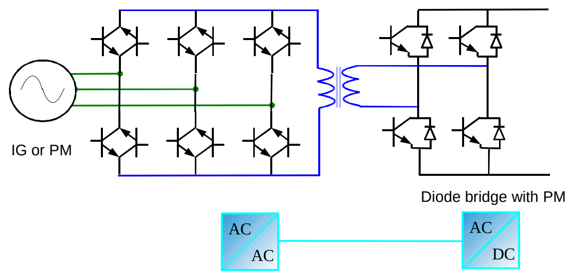
Marta Molinas
NTNU – Jan. 21, 2010

Topology 1: Back to back converter (ref)



S. Lundberg, Wind farm configuration and energy efficiency studies - series dc versus ac layouts. Lic. of Eng. thesis, Chalmers University of technology, Goteborg, Sweden, 2006.
R. L. Steigerwald, R. W. De Doncker, M. H . Kheraluwala, "A Comparison of High-Power DC-DC Soft-Switched Converter Topologies," IEEE Trans. on Industry Aplications, vol. 32, no. 5, Sept. 1996

Topology 2: Reduced Matrix Converter with Full Bridge

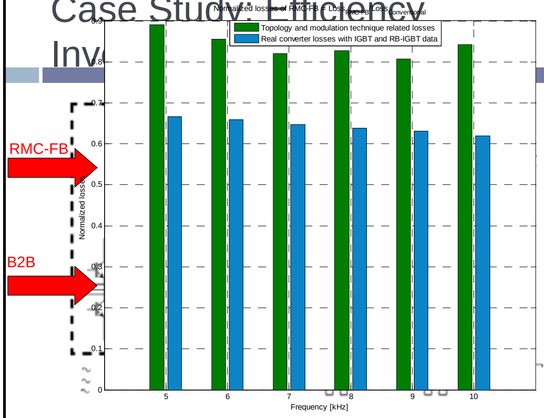


A. Mogstad, M. Molinas, P. Olsen, and R. Nilsen, A power conversion system for offshore wind parks, in Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, Nov. 2008, pp. 2106-2112.
A. Mogstad, M. Molinas, "Power collection and integration on the electric grid from offshore wind parks," In proc. NORPIE 2008, June 2008, pp. 21062112.

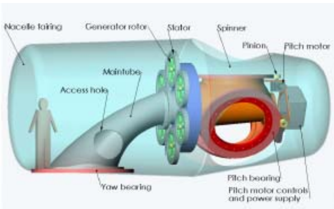
Summary of compared topologies

Topology	Components	Switches	Total	HF-Trafo
B2B	$AC_3/DC+C+DC/AC_1$ HF-T_1+AC_1/DC	14 IGBT 14 Diode	28	Single-Ph
RMC-FB	AC_3/AC_1 HF-T_1+AC_1/DC	12 RB-IGBT 4 IGBT 4 Diodes	20	Single-Ph

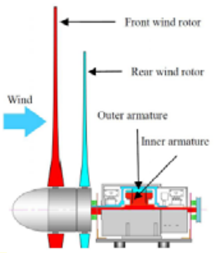
Case Study: Efficiency Inv



Potential applications



J. Cotrell, A preliminary evaluation of a Multiple-generator drivetrain configuration for wind turbines. National renewable energy laboratory. Colorado 2002



K. Kubo, Development of intelligent wind turbine unit with tandem wind rotors and double rotational armatures. Journal of fluid science and technology. Nov 2008

The Liberty 2.5 MW

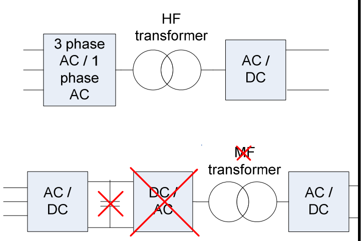
2.5 MW with 4 conventional high speed PM generators of 660kW each.

Observations

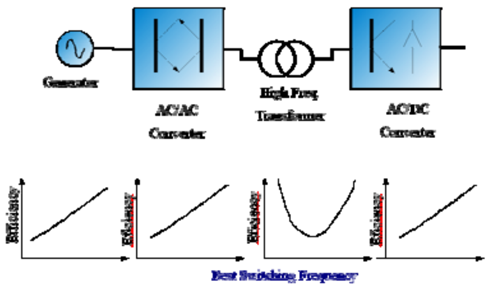
- Conversion stages
- Converter losses
- Capacitor
- Transformer

Several barriers remain

- High voltage blocking
- Snubber losses
- Not self energized



The final objective (PhD-study)



Highest efficiency
Maximum power density

Next Steps in this Research

- Losses comparison in the studied topologies
  - impact of modulation and operation principle
  - loss model extraction
- Transient studies:
  - On-shore three phase fault: use of kinetic energy in the turbine
  - Loss of one wind turbine (by pass, reconfiguration)
  - HVDC line fault
  - Operation at reduced AC voltage
- Implementation of Bi-directional switches with higher voltage blocking capability for MW units or multi-generator turbine (modular approach)
- Multi-domain design approach for high power density and high efficiency
- Laboratory tests of RMC

Challenges today!

- Protective devices (DC circuit breaker, bypass, insulation)
- Electronic transformers
- Collection and conversion plaforms
- High frequency transformers
- MW scale converters

Common denominator:

Utilization of power electronics…

Concluding Remarks

- Wind power encompasses several disciplines within electrical engineering
- In each of them the challenges related to integration are different…..and can be conflictive
- It is necessary to take distance and look at the challenges from a system perspective

Questions?

For further details

http://www.elkraft.ntnu.no/eno/

Follow the link to "Publications"

marta.molinas@elkraft.ntnu.no

Speak to me for more recent work...

Marta Molinas
Department of Electrical Power Engineering, Energy Conversion Group
Norwegian University of Science and Technology
Trondheim, Norway

Power Quality Measurements from Wind Farms

Wind Power R&D seminar – Deep Sea Offshore Wind
21-22 January 2010, Royal Garden Hotel, Trondheim, NORWAY

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Tarjei Solvang tarjei.solvang@sintef.no
SINTEF Energy Research

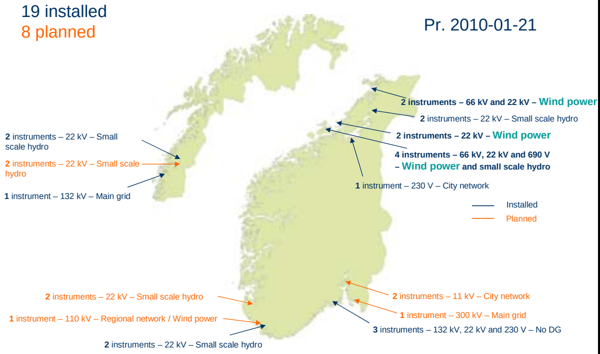
Contents

- Ongoing measurement campaign (SINTEF Energy Research)
- About the measurements
- Motivation for PQ-measurements in wind farms
- Case 1 Description/Overview
- Case 1 Results
- Case 2 Grid Topology
- Case 2 Description/Overview
- Case 2 Results
- Conclusions

Measurement campaign - overview

19 installed
8 planned

Pr. 2010-01-21



About the measurements

- Recognized power quality measurement instruments
- The Elspec Blackbox is used due to the unique data compression and storage system
  - Stores all sampled fundamental frequency periods (5 to 30 GB/year).
  - No trigger settings necessary, only measurement accuracy
- The instrument measures the following:
  - Three phase currents
  - Three phase voltages
  - Sample rate 25,6 kHz (512 samples per fundamental period)
- The Instrument stores instantaneous values for all (3) currents and voltages
- Communication with database at SINTEF Energy Research
- The instrument calculates :
  - Active power
  - Reactive power
  - Flicker intensity
  - THD

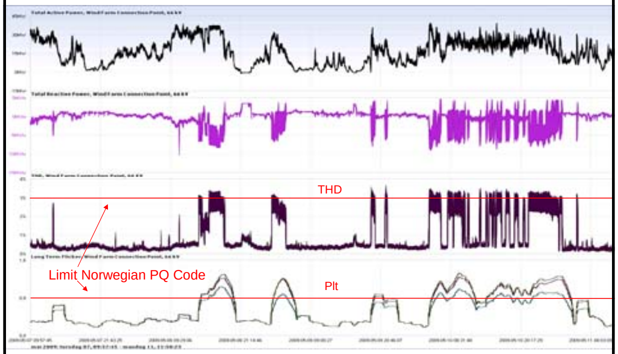
PQ-measurements in wind farms

- **Main motivation**:
  - to create a realistic basis for the validation of existing simulation models for different technologies of wind turbine generators
  - the models are used in power system analysis tools (dynamic analyses)

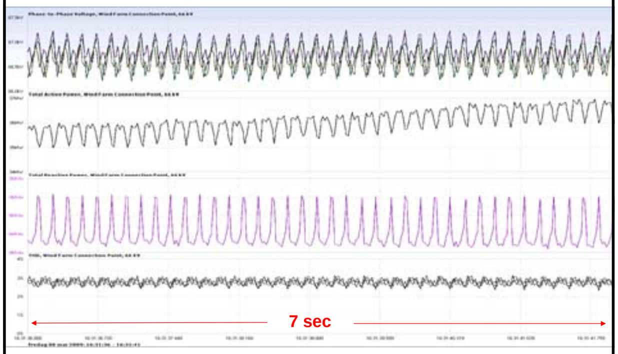
Case 1 – Description/Overview

- Wind farm 1
  - 17 wind turbines
  - 15 equipped with series connected power electronic converter
  - Main transformer 60 MVA
- Measurements
  - On one wind turbine (3,5 MVA, 22 kV level)
  - On main transformer (60 MVA, 66 kV)

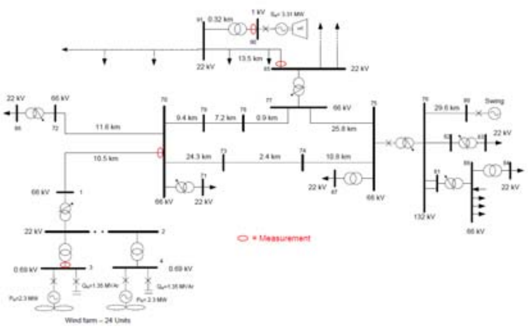
Case 1 – Measurements (1)



Case 1 – Measurements (2)



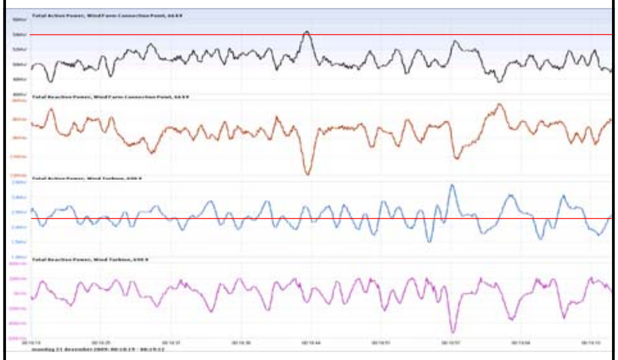
Case 2 – Grid topology



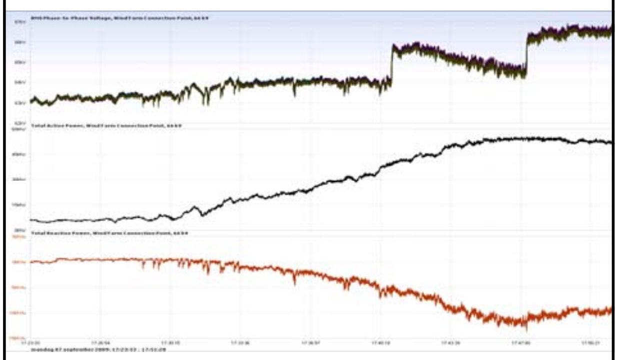
Case 2 – Description/Overview

- Wind farm 2
  - 24 wind turbines rated 2,3 MW
  - Induction generator with local reactive compensation
  - Main transformer 56 MVA
- Measurements
  - On one wind turbine (2.3 MW, 0.69 kV level)
  - On main feeder to wind farm (66 kV level)

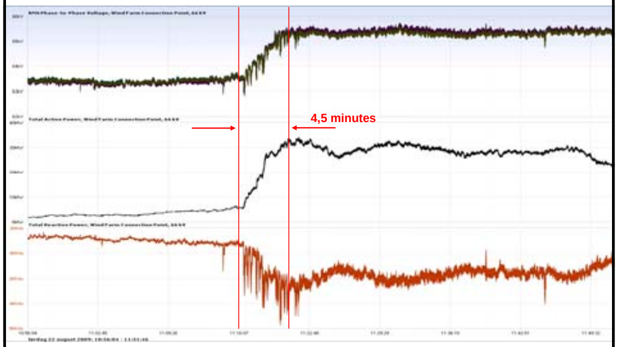
Case 2 – Measurements (1)



Case 2 – Measurements (2)



Case 2 – Measurements (3)



Conclusions/status – so far

- The measurement results (so far) have given valuable information to the owners of the wind farms, windmill manufacturers and grid owners
- Observed phenomena
  - Considerable voltage variations
  - Stability problems (related to controllers)
  - Increased rate of operation for transformer tap-changers
- The measurements will continue in 2010
- Validation of simulation models in progress, with main focus on dynamic behaviour of wind farms during grid faults

Poster session PhD students on offshore wind

Hybrid HVDC for Offshore Wind Applications, Raymundo Torres Oleguin

Maintenance Optimization of Offshore Wind Farms from Design to Operation, Zafar Hameed

Fatigue Reliability Analysis of Jacket-type Offshore Wind Turbine Considering Inspection and Repair, Wenbin Dong

Experimental Study of Two Model Horizontal-Axis Wind Turbines in Tandem Arrangement, Muyiwa Adaramola

Reduced Matric Converter for Off-shore Wind Farm Applications, Alejandro Garces

Industrial Ecology Perspective of Offshore Wind Power Industry,
Anders Arvesen

Full Scale Wind Measurements Relevant for Offshore Wind Power, Gursu Tasar

Evaluation of the Dimensioning Dynamic Forces on Large Floating Wind Turbines, Lars Frøyd

RAMS Engineering in the Development of Offshore Wind Power Production System, Lijuan Dai

Dynamic Response of Spar Type Floating Wind Turbine in Extreme Environmental Conditions, Madjid Karimirad

A Simplified Approach to Wave Loading for Fatigue Damage Analysis of Monotowers, Paul Thomassen

Grid Integration of Offshore Wind Farms and Offshore Loads using Multiterminal HVDC, Temesgen Haileselassie

Modelling and Control of Floating Wind turbines, Thomas Fuglseth

Condition Monitoring and Maintenance Optimization of Offshore Wind Farms, Mahmoud Valibeigloo

Individual Pitch Control for Horizontal Axis Wind Turbines, Fredrik Sandquist

Analysis of Switching Transients in Wind Park with Focus on Prevention of Destructive Effects, Amir Hayati Soloot

Hybrid HVDC using in a Offshore Wind Farm Applications

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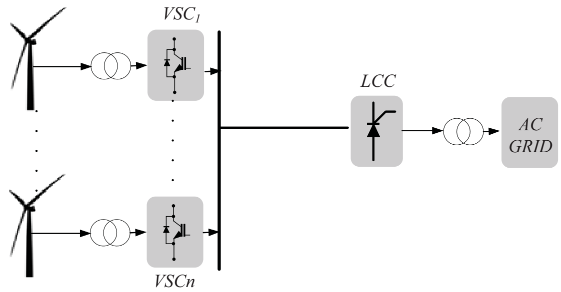
Statkraft Ocean Energy Research Program

Introduction

There are two different HVDC transmission technologies, i.e. Voltage Source Converter (VSC), using controllable switches like Insulated-gate bipolar transistors (IGBT), and Current Source Converter (CSC) or Line-Commutated Converter (LCC), using controllable switches like thyristors.
The Hybrid HVDC option is aimed at combining advantages of both HVDC technologies and compensating their drawbacks.

Figure 1: Hybrid HVDC for Offshore Wind Farms Applications

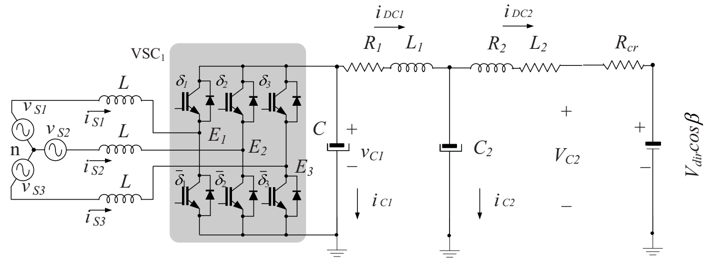


VSCs, connected at the wind turbine, regulate the active and reactive power using a d-q synchronous reference frame controller while the LCC,connected to the main grid, maintains the DC voltage using a PI controller.(In Figure 3 and Figure 4 is shown the proposed controller)

LCC, VSC and Hybrid HVDC

HVDC	Advantages	Disavantages
LCC	▶ Feasibility for very high power levels ▶Less power losses	▶ Some difficulties to operate with weak grids
VSC	▶ Active and reactive power exchange can be controlled independently ▶ No commutation failure problem ▶ No communications required between two stations	▶More losses compared with LCC ▶Defenseless against DC faults
Hybrid	▶Combining advantages of both HVDC	▶ Power flow in one direction

Figure 2: Equivalent Scheme of the Hybrid HVDC



System Description of the Hybrid HVDC

According Figure 2, the dynamic of the VSC can be represent by the following model

$$L\frac{d}{dt}\mathbf{i}_{Sdq} = \boldsymbol{\vartheta}_{dq} - \mathbf{v}_{Sdq} - \omega L\mathbf{J}\mathbf{i}_{Sdq} \quad (1)$$

$$Cv_{C1}\frac{d}{dt}v_{C1} = v_{C1}i_{DC1} - \boldsymbol{\vartheta}_{dq}{}^{\top}i_{Sdq} \quad (2)$$

where $\mathbf{i}_{Sdq} = [i_{Sd}, i_{Sq}]^{\top}$, $\mathbf{v}_{Sdq} = [v_{Sd}, v_{Sq}]^{\top}$, $\boldsymbol{\vartheta}_{dq} = [\vartheta_d, \vartheta_q]^{\top}$ represent the line current, AC voltage and duty vector in dq coordinates. v_{C1} is the DC voltage in the DC link and i_{DC1} is the DC current in the DC link. The dynamic of the LCC can be expressed by the following model

$$v_{C2} = \frac{3\sqrt{2}}{\pi}v_{LL}cos\beta - i_{DC2}\frac{3}{\pi}\omega L_c \quad (3)$$

where v_{C2} is the DC voltage in the DC link, β is the ignition advance angle, i_{DC2} is the DC current in the DC link, v_{LL} represents the line-to-line voltage in the AC side, L_c is the inductance in the AC side and ω is the angular frequency in the AC side.

Figure 3: Block diagram of the proposed controller for the VSC

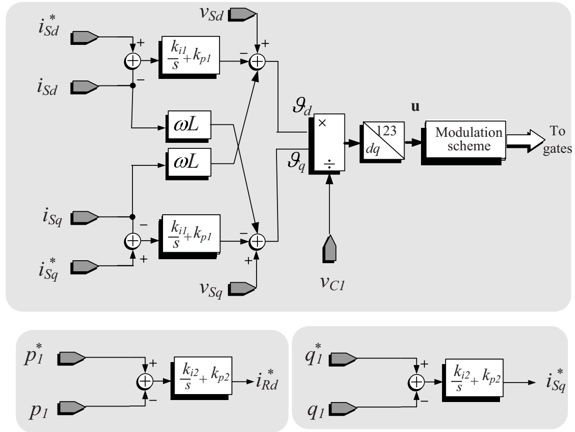


Figure 4: Block diagram of the proposed controller for the LCC

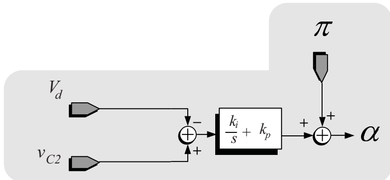
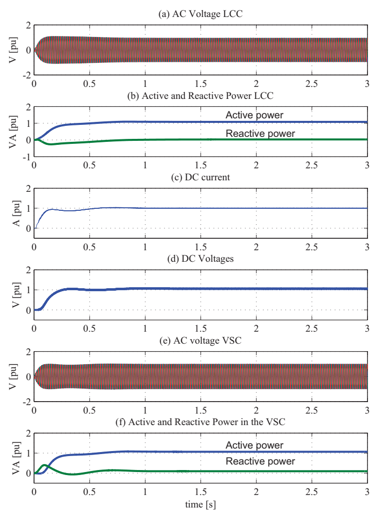
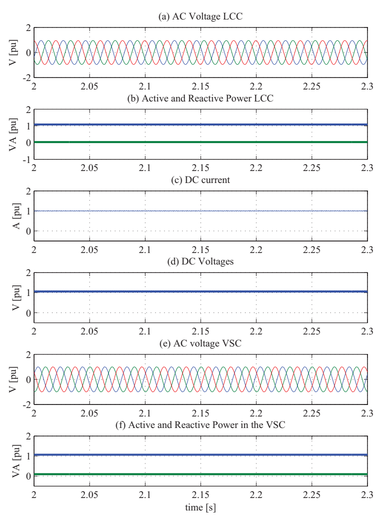


Figure 5: Simulation Results



(a)Start up hybrid HVDC



(b)Steady State up hybrid HVDC

(From top to bottom) AC voltage in the rectifier, Active and reactive power in the rectifier, DC current, DC voltage, AC voltage in the inverter, Active and Reactive power in the inverter.

Maintenance Optimization of Offshore Wind Farms from Design to Operation

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About the PhD Fellowship

- Started in October 2009
- Funded by NOWITECH : NOWITECH is part of the Centre for Environment friendly Energy Research (CEER) scheme co-funded by the Research Council of Norway (Forskningsrådet)
- Part of NOWITECH Work package 5: Development of **Operation and Maintenance** (O&M) strategies and technologies. The goal is to develop a scientific foundation for implementation of cost-effective O&M strategies and technologies for offshore wind farms

Challenges, Strategies, and Goals

Being an environment friendly, Renewable energy is the future of energy industry. Wind energy is the one form of renewable source of power. Wind farms are available both on Onshore and Offshore sites.

The trend has been shifting from Onshore to Offshore due to social and political reasons. Due to this change of trend, new challenges have been emerged which are coupled with Offshore Wind Farms like installation, transportation, operation, and maintenance.

In the operation of Wind farms, main challenges are related with sudden failures and downtimes. Due to difficulties involved in the accessibility, remote location of these farms from onshore and depot, high production losses due to far locations from onshore due to sudden breakdown, high costs of corrective maintenance, and tough maritime environment are playing crucial role in the formulation of maintenance strategies for Offshore Wind Farms.

Among the maintenance strategies, preventive and predictive ones are suitable for implementation in offshore wind turbines. The primary focus of this research is to optimize the maintenance intervals for preventive and predictive maintenance choices. Artificial Intelligence (AI) approaches like Artificial Neural Network, Genetic Algorithm, and Support Vector Machines could be used for having an optimum maintenance interval for such kind of maintenance tools.

Condition monitoring (CM) based technologies, such as dynamic load characteristics, oil analysis, strain measurements, physical condition of the materials, acoustic monitoring, performance monitoring etc, are quite helpful for monitoring of wind turbines. In this research we will also focus on the condition monitoring of wind turbine and CM data will be used for deciding about the maintenance. To define the deterioration models by using CM data and then formulation of the mathematical models based on that data is also one of the core objectives this research.

Operational and Maintenance (O&M) cost reduction coupled with less downtimes is the underpinning of this research. Due to Offshore Wind Farm locations, new challenges will emerge which may pose hindrances in reducing the O &M costs. Another core objective of this research will be to overcome such challenges to minimize the O& M expenditure.

It is highly expected that Optimization of maintenance interval using AI techniques coupled with Condition Based Maintenance strategies will give promising results.

Fatigue reliability analysis of Jacket-type offshore wind turbine considering inspection and repair

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Norwegian University of Science and Technology

Norwegian Centre of Excellence

Abstract

Offshore wind turbines (OWTS) are subjected to the severe environmental loads and are less in accessible than land-based turbines. Generally, the operation of OWTS is above five to ten times more expensive than work on land. Considering these issues, reliability of OWTS is crucial. Methods for reliability of OWTS are therefore needed.

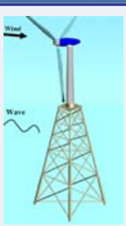
The present paper focuses on fatigue reliability prediction analysis of tubular joints of a fixed jacket offshore wind turbine designed for a North Sea site in a water depth of 70 m. For fatigue analysis, one of the most important parts is the calculation of long term statistical response of structures. The response analysis of OWTS must take account for the dynamic coupling between the support structure platform motions and turbine motions, and this is a challenge now. The present paper uses a simplified method to model the Jacket-type offshore wind turbine and calculates the load effect. Wind load is obtained in HAWC2 well known software for simulation of wind turbine response in time domain, and dynamic response of whole structure is obtained in USFOS well known software for dynamic response analysis of space frame structures.

In order to quantify the effect fo inspection depending upon its quality for a given inspection strategy and optimize the inspection scheme at the design stage, a reliability based fracture mechanics (FM) which depends on the quality of inspection in terms of probability of crack detection curves is presented in this paper . The long term statistical distribution of stress ranges of tubular joints is obtained by combination of time domain simulation for representative sea states and SN-Miner-Palmgren approach. Target safety levels are taken from SN-Miner-Palmgren approach with no effect of inspection.

Objectives

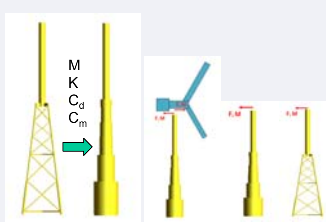
- Determine the fatigue reliability of tubular joints at the design stage based on design information
- Quantify the effect of inspection for a given inspection strategy at the design stage
- Optimize the inspection scheme for tubular joints at the design stage
- Decide on the allowable cumulative damage Δ_d (Δ_d is the design Miner's sum at failure) depending upon the inspection scheme

Methods

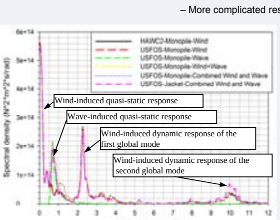


- Design information
  - Jacket structure (partly based on information from Aker Solution)
    - Water depth: 70 m
    - Jacket height: 92 m
    - Soil data (Ekofisk)
  - Wind turbine
    - 5MW NREL wind turbine
    - Tower height:67 m; Weight:210 tonnes
    - Nacelle weight: 295 tonnes
    - Blade weight: 115 tonnes; Diameter: 126 m
    - V: rated=12m/s, cutin=5m/s, cutout=25m/s
    - Automatic controller: Risø Nat. Lab.

- Simplified method to model the Jacket-type offshore wind turbine
  - HAWC2
    - Beam, simple structure (monopile)
    - Wind force (dominating)
    - Operational / parked conditions
  - USFOS
    - Imported nodal force from HAWC2
    - Wave and current forces
    - More complicated response analysis (jacket)



Jacket structure | Equivalent monopile structure | HAWC2 analysis | USFOS analysis



Overturning moment in the operational condition

- Dynamic response analysis
  - Excited second global mode contributes to fatigue damage most
  - Long-term response analysis : wind response + wave response
  - Long-term statistical distribution of stress ranges of turbular joints fits weibull distribution

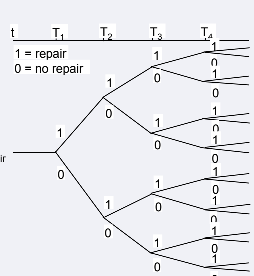
- Fatigue reliability calculation considering the effect of inspection and repair
  - Safety margin for failure before time t

$$M(t) = \int_{a_0}^{a_c} \frac{da}{\left(\gamma_Y Y \sqrt{\pi a}\right)^m} - C\nu_0 (t - T_0) A^m \Gamma(1 + \frac{m}{B})$$
M(t) > 0, safety; M(t) < 0, failure

  - Event margin for inspection

$$H = \int_{a_0}^{a_D} \frac{da}{\left(\gamma_Y Y \sqrt{\pi a}\right)^m} - C\nu_0 (T_1 - T_0) A^m \Gamma\left(1 + \frac{m}{B}\right)$$
H > 0, crack is not detected,no repair; H < 0, crack is detected, repair

  - Fatigue reliability calculation
    - Failure probability considering inspection and repair : $P_f = P\left[M \le 0 \mid H > 0 or H < 0\right]$
    - Reliability calculation : $\Re = 1 - P_f$
  - Method
    - FORM method (First Order Reliability Method)
    - software: DNV Proban



Inspection scheme

Results

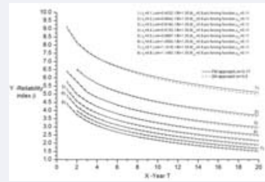


Fig.1 Reliability index for welded joints in jackets as a function of time. No inspection and repair

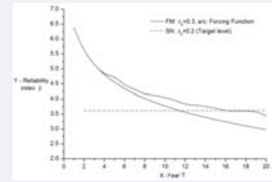


Fig. 2 Reliability index for welded joints in jackets as a function of time. The target level is given by Δ_d = 0.2 and no use of inspection and repair, corresponding to a_0=0.11 mm.The inspection and repair scheme is characterized by 4 inspections, a_D=2.0 mm and a_R=0.11 mm.

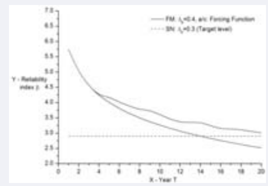


Fig. 3 Reliability index for welded joints in jackets as a function of time. The target level is given by Δ_d = 0.3 and no use of inspection and repair, corresponding to a_0=0.11 mm.The inspection and repair scheme is characterized by 4 inspections, a_D=2.0 mm and a_R=0.11 mm.

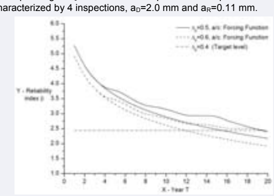


Fig. 4 Reliability index for welded joints in jackets as a function of time. The target level is given by Δ_d = 0.4 and no use of inspection and repair, corresponding to a_0=0.11 mm.The inspection and repair scheme is characterized by 3 inspections for Δd = 0.5 and 4 inspections for Δd = 0.6, a_D=2.0 mm and a_R=0.11 mm.

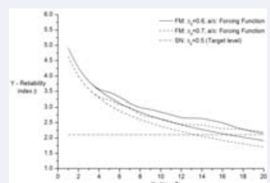


Fig. 5 Reliability index for welded joints in jackets as a function of time. The target level is given by Δ_d = 0.5 and no use of inspection and repair, corresponding to a_0=0.11 mm.The inspection and repair scheme is characterized by 3 inspections for Δd = 0.6 and 4 inspections for Δd = 0.7, a_D=2.0 mm and a_R=0.11 mm.

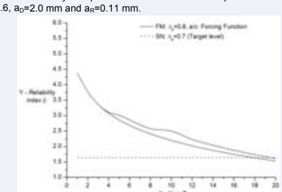


Fig. 6 Reliability index for welded joints in jackets as a function of time. The target level is given by Δ_d = 0.7 and no use of inspection and repair, corresponding to a_0=0.11 mm.The inspection and repair scheme is characterized by 2 inspections, a_D=2.0 mm and a_R=0.11 mm.

(Note: β is reliability index ($\beta(t) = -\Phi^{-1}(P_F(t))$, Φ is standard normal probability distribution function) ; a_0 is the initial crack size; a_D is the detectable crack size which is assumed given by the POD curve; a_R is the initial crack size after repair; a/c is the crack aspect ratio ; M_{red} is a parameter representing effects due to local weld toe smoothing, which is used in the local stress intensity magnification factor.)

Conclusions

In present paper the effect of inspection depending upon its quality for a given inspection strategy for welded tubular joints in jacket-type offshore wind turbine structures has been quantified by using probabilistic methods. The conclusions are taken from the following assumptions: welded joints in North Sea structures, 4 year inspection interval, mean crack size after repair $\mu_{a_R} = 0.11$ mm and mean detectable crack size $\mu_{a_D} = 2.0$ mm .

Based on the OWTS model used in present paper, for tubular joints, loaded by bending and tensile stresses with a bending-tension stress ratio of 4.0, the allowable cumulative damage ,when no inspection and repair is implemented, is assumed to be 0.2,0.3,0.4,0.5 and 0.7 respectively. For the case of Δ_d=0.2, it may not be relaxed, when inspection scheme as described above is considered, as shown in Fig. 2 ; for the case of Δ_d=0.3, it may be relaxed to 0.4, as shown in Fig. 3; for the case of Δ_d=0.4, it may be relaxed to 0.5-0.6,as shown in Fig. 4; for the case of Δ_d=0.5, it may be relaxed to 0.6-0.7, as shown in Fig. 5; for the case of Δ_d=0.7, it may be relaxed to 0.8, and only 2 inspections may be implemented, as shown in Fig. 6 .

Based on the experience in offshore oil and gas industry in North sea, the inspection reliability is rather ambitious, especially for tubular joints in jackets, therefore, the relaxation in design criteria shown represents a maximum effect of inspection on design criteria.

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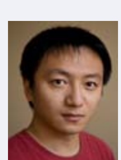

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Experimental Study of Two Model Wind Turbines in Tandem Arrangement

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INTRODUCTION AND OBJECTIVES

In a wind farm, space and economic constraints make it impossible to locate turbines sufficiently apart to prevent interactions between them. The effect of these interactions may have severe implications on the downstream turbines which are located in the wake of the upstream turbine. The power losses from the downstream turbine due to velocity deficit depends, among other factors, on the performance characteristics of the upstream turbine and distance between the turbines. Despite the practical importance of this flow, experimental information on the performance of a turbine under the effect of wake interference are difficult to come by in open literature. This poster presents the performance characteristics of a model wind turbine operating in the wake of another turbine. The effects of distance of separation between the turbines and the operating condition of the upstream turbine on performance of the downstream turbine were investigated.

EXPERIMENTAL SET-UP

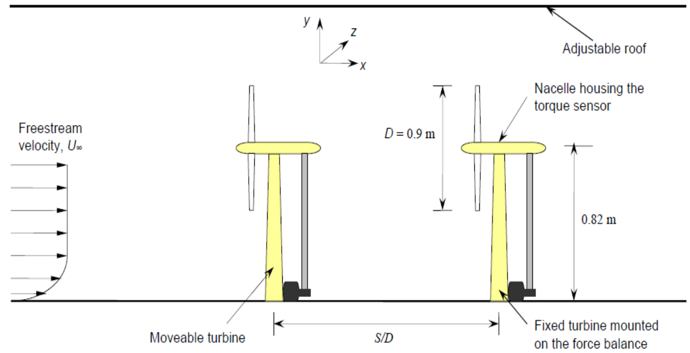

Figure 1: Schematic diagram of the experimental set-up.

RESULTS

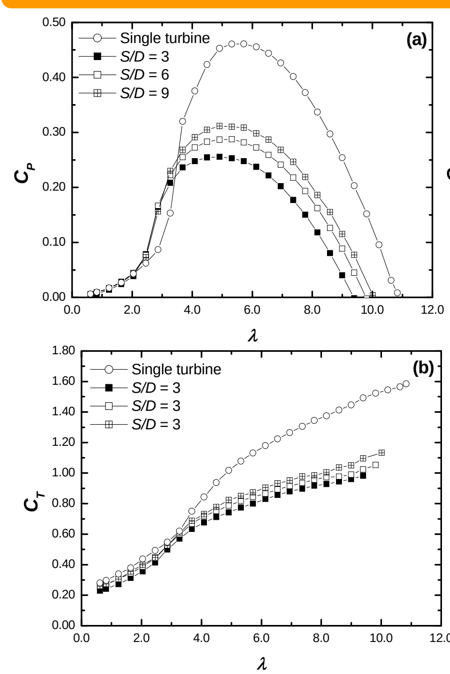

Figure 2: Wake interference effect on the downstream model turbine performance at different S/D locations (a) power coefficient and (b) thrust coefficient.

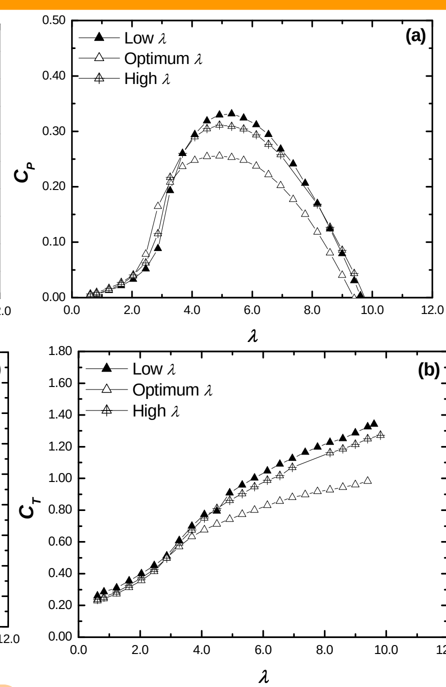

Figure 3: Wake interference effect on the downstream turbine performance at different upstream operating condition (a) power coefficient and (b) thrust coefficient.

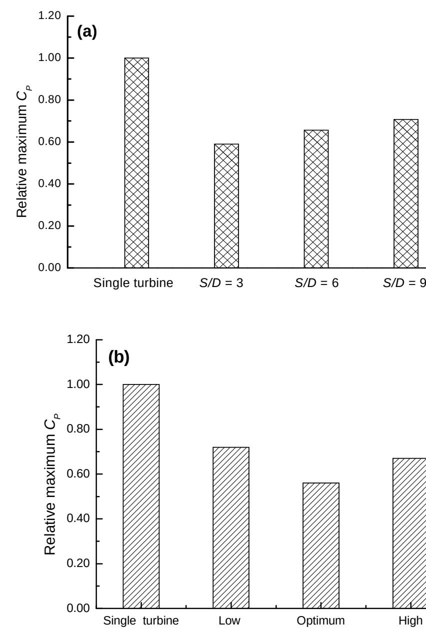

Figure 4: The relative maximum power coefficient (a) downstream distance effect and (b) upstream turbine operating at different tip speed ratios.

Conclusions

The results presented in this poster shows that the power losses for a turbine operating in the wake of another is significant. In this study, it was observed that the loss in maximum power coefficient varies between about 29 and 45% depending on the distance between the turbines and the operating tip speed ratio of the upstream turbine. Compared with the unobstructed turbine, the thrust of the downstream turbine is generally lower. The reduction in power coefficient and thrust coefficient from the downstream turbine is as a result of the velocity deficit in the wake so that the downstream turbine sees a considerably lower freestream velocity than the upstream turbine and thus, less energy is available in the air stream.

However, by adjusting the operating condition of the upstream turbine, the power output from the downstream turbine can be substantially enhanced. When the upstream turbine was operating at different tip speed ratios, the highest and lowest loss in maximum power coefficient occured when the upstream turbine was operating at low tip speed and optimum tip speed ratios, respectively. This is because at low and high tip speed ratios, less energy is extracted from the air stream by the upstream turbine compared with when it is operating at optimum tip speed ratio and this leads to relatively higher wind speed in the wake of the upstream turbine. This results in increased power and thrust coeffcients of the downstream turbine.

PRESENTED AT: WIND POWER R&D SEMINAR – DEEP SEA OFFSHORE WIND POWER, 21-22 JANUARY 2010, TRONDHEIM, NORWAY

Reduced Matrix Converter for Off-Shore Wind Farm Applications

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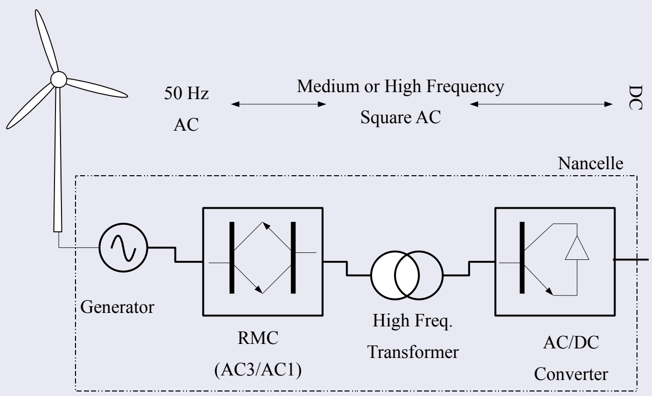
Introduction

Off-Shore wind energy is a promising alternative for electrical power generation because of its well known environmental advantages over conventional technologies. Long distances are expected in real off shore wind farms since the longer the distance to shore the higher and more constant the power is. HVAC is not a feasible alternative and HVDC lines must be used. New conversion topologies should be studied to increase the efficiency and reliability and reduce the size and weight of the converter. Matrix converter fulfills these requirements.

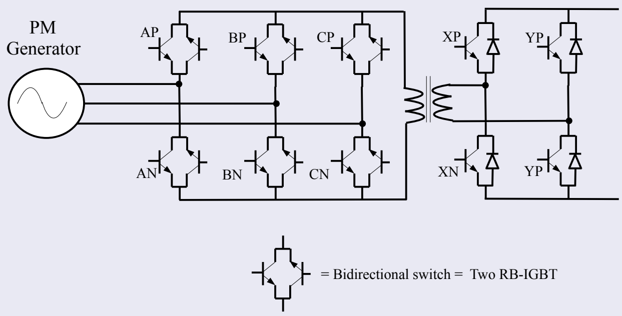
Figure 1: Propose energy conversion system



Energy Conversion System

Fig 1 shows the general concept of the proposed high frequency link. Each nacelle of each turbine has asynchronous generators or permanent magnet synchronous generators connected to a reduced matrix converter. A high frequency high power transformer is suggested to electrically isolate the generator and to raise the voltage. High frequency is used to reduced the weight of the transformer and to reduce the harmonic distortion. It is specially important for offshore wind farms since the investment costs could be reduced. Electrolytic capacitor is not required, therefore, reliability is increased. Efficiency is also increased since less conversion stages are required.

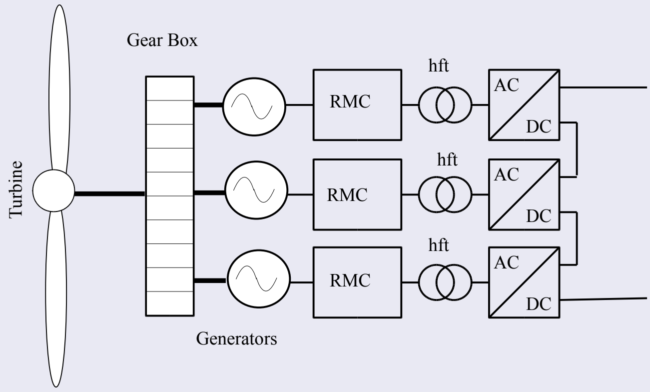
Figure 2: RMC built with RB-IGBTs



Reduced matrix converter and RB-IGBT

The Reduced Matrix converter (RMC) requires bi-directional switches which can be built using reverse-blocking IGBTs. These RB-IGBTs can form a bidirectional switch without the use of additional diodes, resulting in an efficiency increase compared to a conventional devices. In spite that conventional IGBTs are theoretically able to block reverse voltages, in practice, due to construction constrains,it is necessary an external diode. However, the new reverse-blocking IGBT has an intrinsic diode that leads to a reduction of the forward conduction state voltage drop of the switch. Figure 2 shows in detail the converter.

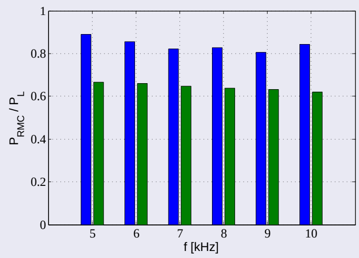
Figure 3: Series connection inside of each turbine



Modular approach

The proposed topology can be used also as a modular solution with multiple generator per turbine as shown in Fig 3. The concept of this type configuration has been studied by Cotrell [1] from the mechanical point of view. This kind of topology presents some advantages over the conventional one, like increasing of reliability and efficiency as well as decreasing of gear box mass.

Figure 4: Simulation results



Preliminary results

A conventional back to back topology and the proposed one were compared according to the losses. Three kind of simulations were done: First, losses in the conventional topology were calculated for different frequencies. It was used an IGBT SEMiX 151GD066HDs. Next, losses in the reduced matrix converter were calculated using data for a RB-IGBT (600 V/200A). Finally, the conventional topology was tested again using an equivalent IGBT with the same parameters of the RB-IGBT. Results are shown in Fig 4.

Discussion

In all cases, losses in the reduced matrix converter are almost **20%** less than the losses in the conventional one. This inprovment in the efficienty is caused by the topology itselft and not by the semicondutor used, since in both cases, parameters in the IGBTs are equivalent. On the other hand, the green plot, shows the relation of losses between the two converterts using an IGBT in the conventional one (SEMiX 151GD066HDs) and a RB-IGBT in the reduced matrix converter. In this case, the losses are decreased in almost **40%**. This relation shows how the efficiency is improved not only due to the topology itself but also due to the use of reverse blocking IGBTs.

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Industrial ecology perspective of offshore wind power industry

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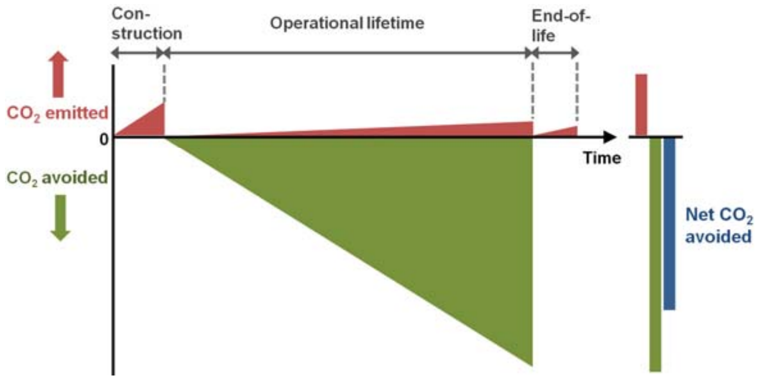
The absence of in-plant combustion in wind turbines does not in itself justify claims of wind power as a "clean" technology. This is because emissions and resource use occur in the life-cycle of wind energy systems. A systematic evaluation of life-cycle environmental impacts is important to document the technology's superiority over competing options. Also, life-cycle assessments can help in identifying system designs and strategies for maximizing the environmental benefits of wind power.

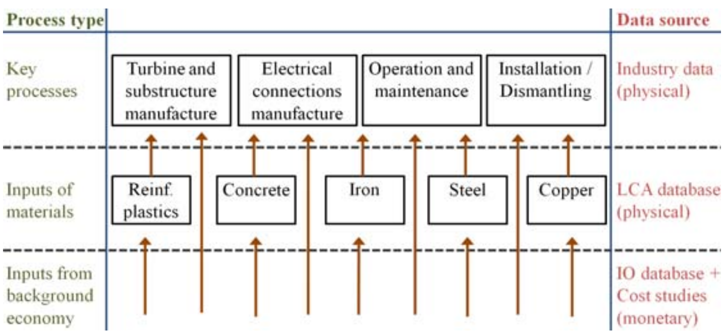


Objectives

Our primary objective is to quantify and assess life-cycle resource use and emissions of wind energy systems. A secondary objective is to illuminate how different economic sectors contribute to wind power development. Unit-based findings should be aggregated to study economy-wide implications of existing projections for wind power.

Methods

At its core, our research method is based on life-cycle assessment (LCA) and economic input-output analysis (IOA). Combining LCA and IOA in a common framework serves two purposes. First, it ensures complete system coverage. Second, it facilitates the simultaneous modeling of environmental and economic impacts.

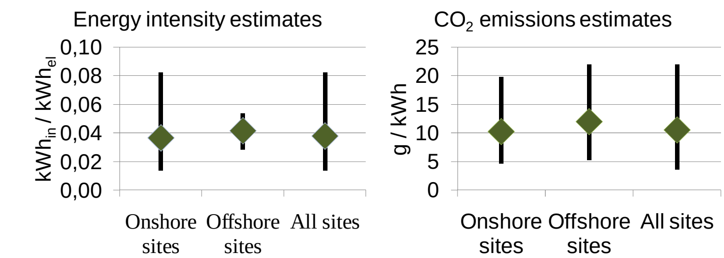


Current status

Work done so far comprises a survey-based review of existing LCA studies, and preliminary IOA calculations for offshore wind power. Results from improved calculations are expected to be produced soon.

Review of existing LCA studies

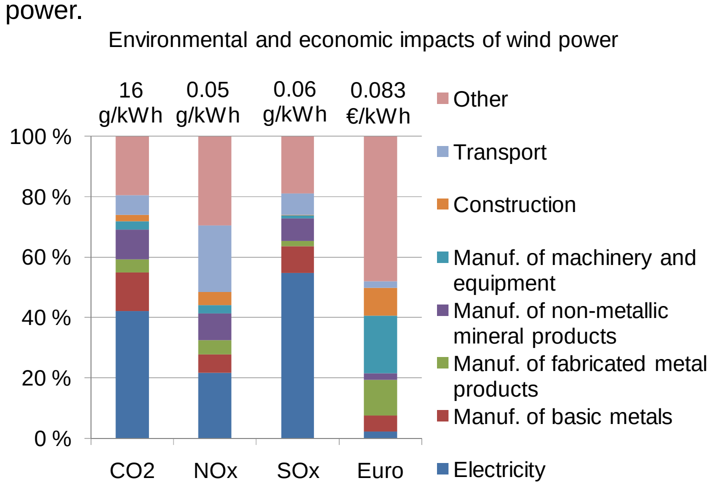
- 28 estimates (8 for offshore) from 18 studies
- Energy intensity average: 0.04 kWh_{in}/kWh_{el}
- CO_2 average: 11 g CO_2-eq/kWh
- Offshore sites: Improved wind conditions outweighs increased resource requirements



By comparison, life-cycle emissions of a modern natural gas combined cycle power plant is about 420 g CO_2/kWh (Ecoinvent database).

Preliminary results from own calculations

Purely monetary assessment, based on input-output database for Europe and cost studies for offshore wind power.



Full Scale Wind Measurements Relevant For Offshore Wind Power

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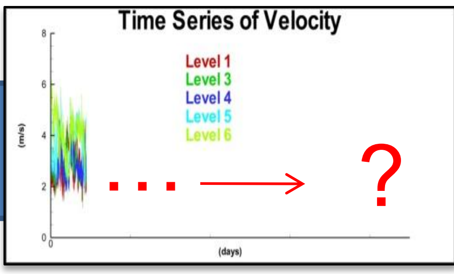
1. SKIPHEIA

Skipheia **is wind measuring station** in Titran, Frøya, run by **NTNU** which is located on the south west tip of **Frøya** (Sør Trøndelag). The station is 200 km away from Trondheim and NTNU. It is highly exposed to ocean winds.



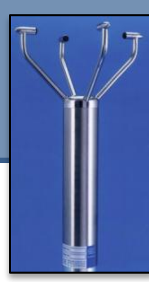
2. OBJECTIVES

•**Analyzing Wind Characteristics:** Full scale measurements: wind mean and turbulent characteristics; temperature of Atmospheric Boundary Layer.

•**Data for Wind Energy industry**: estimation of dynamic loads, wind farm producibility.

3. FACILITIES

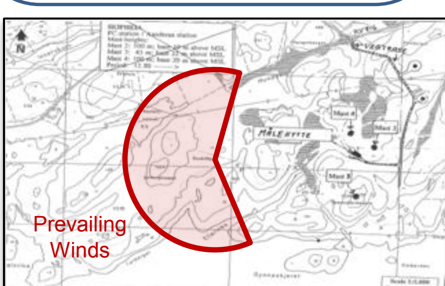
- Three masts: 2 x **100m** , 1 x **45m**
- **400 kW** test Wind Turbine
- Additional Mast (45m) in nearby island
- Measurement cottage
- **Ultrasonic** Gill Anemometers
  - _Range_ 0 – 65 m/s
  - _Accuracy_ ±2 % @ 12 m/s
  - _Resolution_ 0.01 m/s
  - _Offset_ ±0.01 m/s



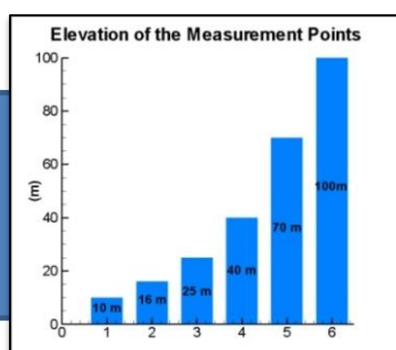
Anemometers

The two 100m masts

Instrumentation Cottage



Gale force maritime wind. The Froya data base. Part 1: Sites and instrumentation. Review of the data base, Odd Jan Andersen, Jørgen Lovseth.



4. CURRENT ACTIVITY

- **Dec 2009:** Mast 2 equipped with 12 sonic anemometers and 7 RTDs.
- **6** Levels with Log height distribution
- Acquiring Data with a sampling rate of **1 Hz.**

5. FUTURE WORK

- Further measurements
- Analyzing data: correlations
- Equipping other masts
- Papers and conference attendance

Statkraft

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Evaluation of the Dimensioning Dynamic Forces on Large Floating Wind Turbines

PhD programme: NOWITECH (NTNU/SINTEF/IFE) Candidate: Lars Frøyd

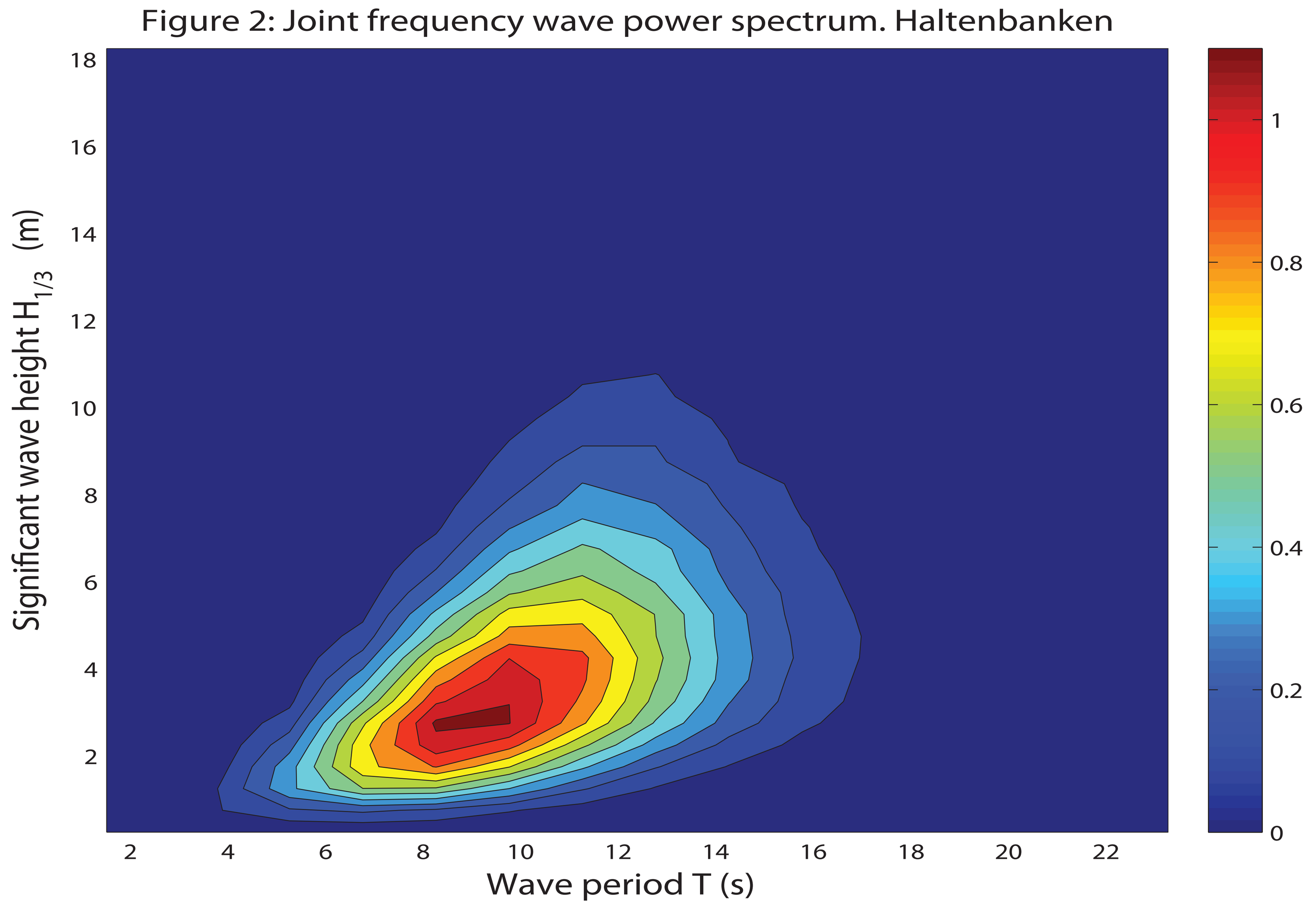
About the PhD fellowship

- Startup: August 2009
- Duration: 3 years
- Advisor: Professor Ole Gunnar Dahlhaug
- Co-advisors: None. Suggestions are welcome!

- Funded by NOWITECH. NOWITECH is part of the Centre for Environment-friendly Energy Research (CEER) scheme co-funded by the Research Council of Norway (Forskningsrådet).

- Part of NOWITECH Work Package 1: *Development of integrated numerical design tools for novel offshore wind energy concepts*. The goal of WP1 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

Figure 2: Joint frequency wave power spectrum. Haltenbanken



Possible research areas of interest

- **Investigation of relevant load cases (LC's) for FWT:**
Onshore wind fatigue LC's use 600 s turbulent simulations. Still they are quite time consuming. For FWT's, the number of possibly relevant LC's are much larger: Combined wind, wave height, wave frequency and current. What about wind, wave and current directions? Can you always be sure that aligned loads are more severe than misaligned loads? To reduce the numbers of LC's one needs to find out which are the *relevant* load combinations.

- **Measurement of offshore wind conditions** (Frøya or offshore location)
Possibly joint wind and wave measurements if there exist facilities to do so.

- **Verification of aero-elastic software for floating turbines:**
The aero-elastic software used today was created for onshore turbines. To check the compatibility with FWT, the IEA OC3 Phase IV has done benchmark tests, comparing the different codes. Comparison with a prototype floating turbine, i.e. Hywind test data, would be even more valuable.

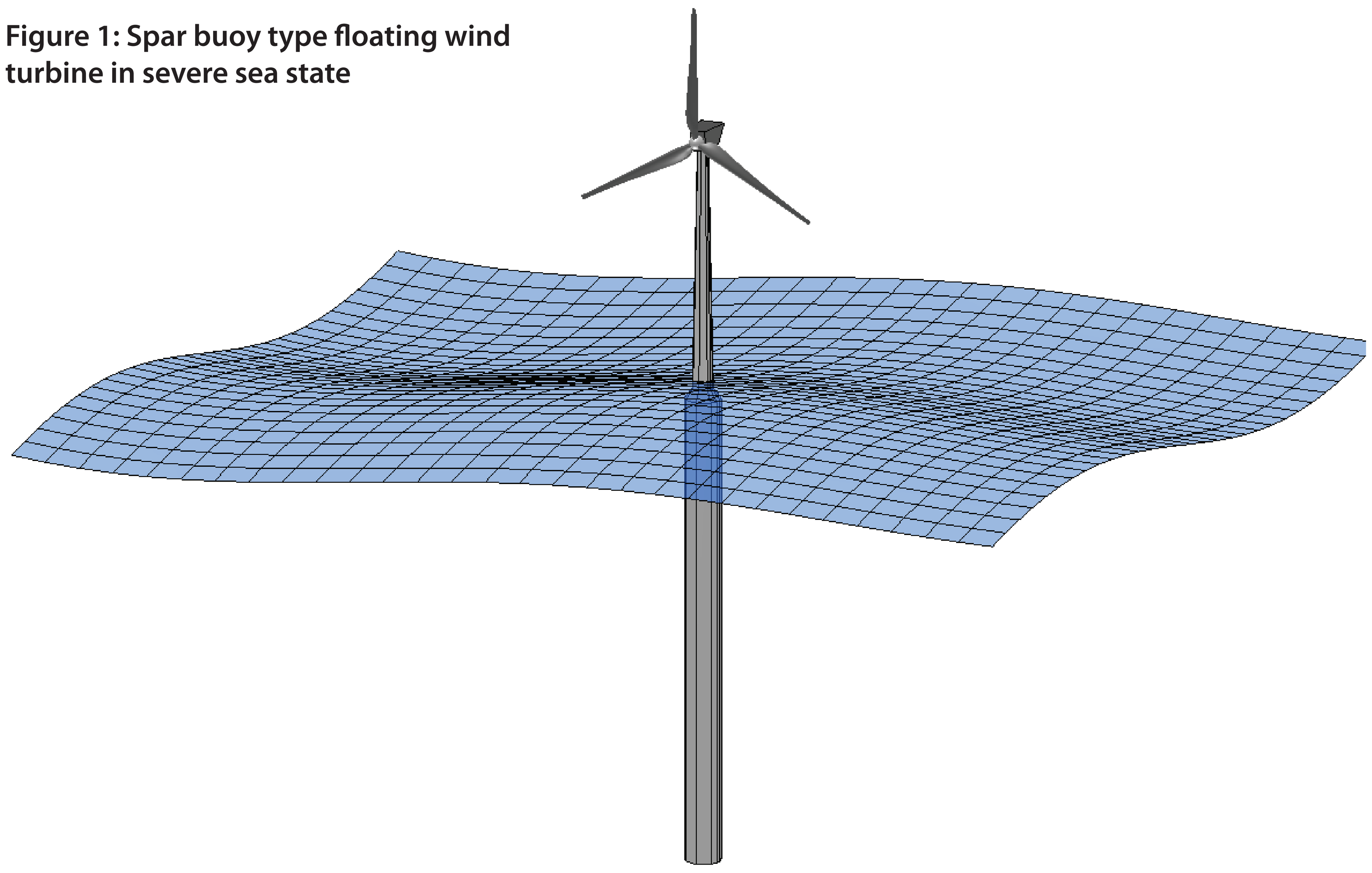
- **Investigation of control methods to reduce fatigue loading:**
Large FWT's might need state-of-the-art control methods for load reduction and to achieve good performance vs. fatigue characteristics.

- **Investigation of novel turbine concepts to reduce fatigue loading or top weight:** High speed downwind rotors can be made very lightweight and flexible to reduce the weight. With a strong flap/twist coupling it could be possible to reduce the loads even further.

- **Does every turbine have to be an advanced multi MW power plant?**
Maybe simpler and smaller (1-3 MW) turbines with inherent load reducing capabilities, two-blade tethering or flapping hubs can prove more economic?

- **Do you have suggestions of FWT related areas that need research?**
Please tell me, I am very open for suggestions and discussions!

Figure 1: Spar buoy type floating wind turbine in severe sea state



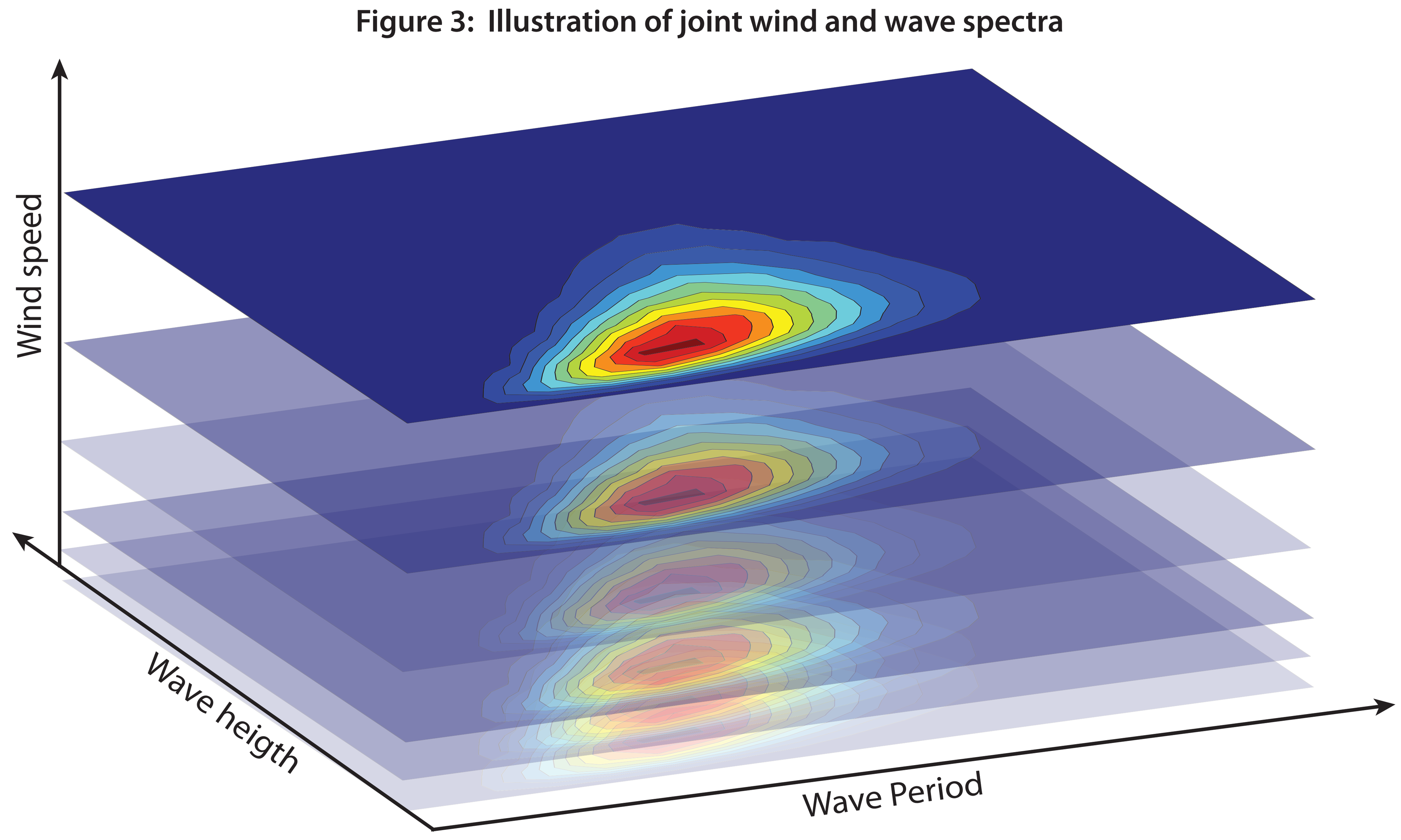
Background

To facilitate safe and economic design of floating wind turbines (FWT) it is necessary to have a good description of the physical environment that the wind turbine is subject to. This includes knowledge of which loads and load combinations are relevant for design of the different components of the wind turbine.

For land based and bottom fixed wind turbines there exist standards that define these load cases, but none exist at the present for floating wind turbines. It is believed that the existing standards are not sufficient, as the influence of waves and current will have relatively larger influence on the floating turbine.

For calculations of the fatigue loading, it is customary to use aero-elastic simulation codes. For wind turbines, the averaging time is 10 min, whereas the mean sea-state period usually is 1-3 hours. Is there a need for different approaches to keep calculation cost at a reasonable level?

Figure 3: Illustration of joint wind and wave spectra



About me

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RAMS Engineering in the Development of Offshore Wind Power Production Systems

NTNU
Norwegian University of Science and Technology

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1 Introduction

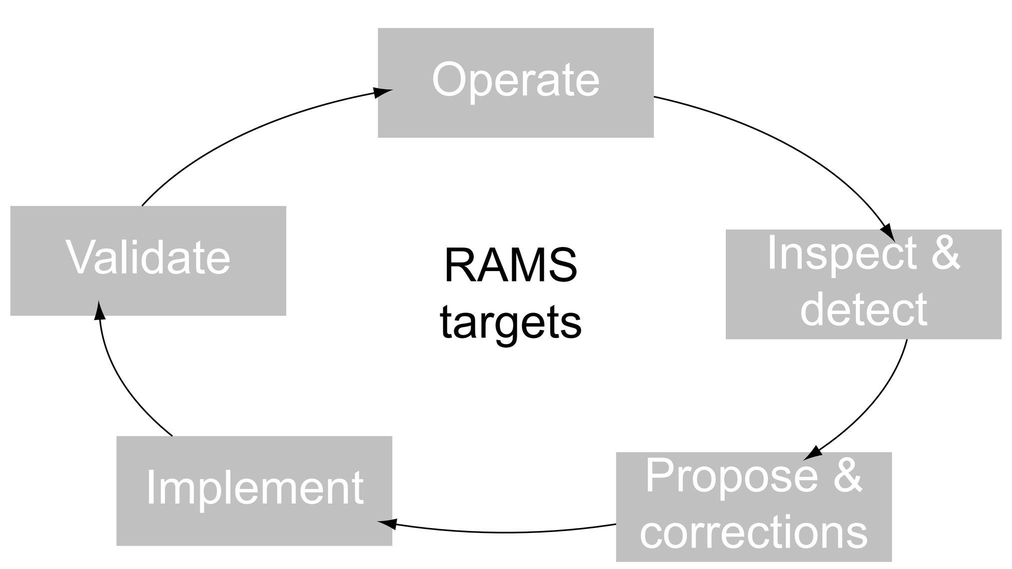
Deep sea environment and unique features of wind turbine structures bring considerable challenges to the development of offshore wind power production systems, such as increased corrosion risk, reduced accessibility and harsh operating environment for maintenance, greatly affecting the actual availability of offshore wind power [1]. The availability of a wind farm, defined as the percentage of time it is able to produce electricity, is a function of the reliability, maintainability and serviceability of the hard- and software used in the whole system [2]. Operation and maintenance of offshore wind turbines are more difficult and expensive than equivalent onshore wind turbines, which impact substantially on costs of offshore wind turbine systems, and influence optimum scale for minimum cost of energy.

RAMS engineering is an engineering discipline which focuses on how technical systems should be designed and managed with emphasized attributes of reliability, availability, maintainability and safety. In the development and operation of offshore wind turbines, RAMS requirements imply that the offshore wind turbine system must have high reliability to secure few failures and a long time in service; the system must have a good maintainability and be equipped with adequate condition monitoring systems to facilitate efficient preventive maintenance; and the system must be safe and prevent damage to people, the environment, and material assets. As stated above, these requirements are essential for the success of offshore wind turbines, and proper integration of RAMS engineering is pivotal in the development.

2 Objectives

The main objective of this presentation is to outline how RAMS engineering can be integrated into the development program of offshore wind power production systems - and to discuss what analyses and management approaches that should be included in the various phases of the development.

A new approach for integrating reliability engineering into product or system development has recently been developed in the book "Product Reliability; Specification and Performance" [3] and a similar approach to integrating safety aspect into product or system development has been proposed in an article in Safety Science by Rausand and Utne [4]. This presentation is built on and extend these approaches. It serves as a framework of the writers' ongoing PhD project. And a paper on the same topic will be presented in the 10th International Probabilistic Safety Assessment & Management Conference (PSAM 10) in June 2010.



Phase 1:

Establishment and negotiation of RAMS requirements, in parallel with consideration for technological and commercial viability.

- To develop a RAMS policy, which states the management commitments to RAMS principles, and outlines the main strategy for achieving the RAMS policy;
- To make a RAMS management plan, which describes all RAMS related activities in each life cycle phase, and identifies persons, departments and organizations responsible for the different phases and tasks of OWTS development;
- To establish RAMS controlling documents that include procedures, work processes, tools, and methods that address RAMS aspects and the requirements according to related standards.

Phase 2:

Allocation of the overall RAMS requirements, and transformation of the desired performance from phase 1 into a physical characteristics.

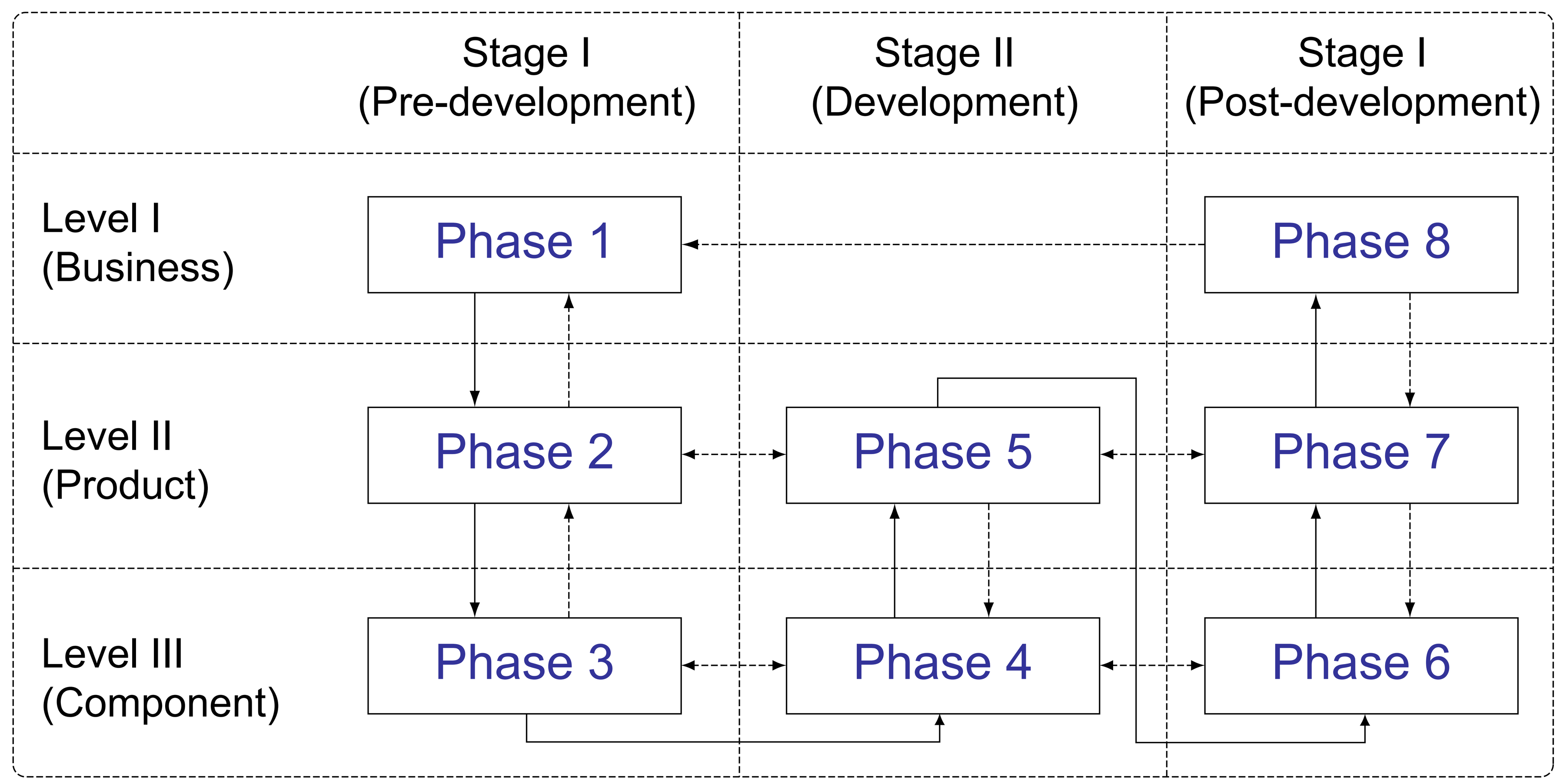
- To develop a preliminary description of the system, its sub-systems, and components;
- To make a design review during the various activities in the operational phase, i.e. installation, operation, maintenance, disposal;
- To perform reliability, availability, maintainability and safety analysis, in order to obtain the RAMS specification, and the critical items and hazards list;
- To update the RAMS specification and transform into requirement before proceeding to the next phase.

Phase 3:

Implementation of RAMS requirements by detailed design, and preparation of initial system construction and testing.

- To develop design specifications for components, specify and prepare for interfaces with other systems, e.g. the energy distribution system;
- To follow-up subcontractors, and verify that the components get the desired RAMS performance;
- To update the reliability analysis, availability, and maintainability analyses from phase 2, with new information on component failure rates and characteristics;
- To update the system design specification and transform into requirement before proceeding to the next phase.

3 Development process in line with the life cycle model



Phase 4:

Prototype qualification in controlled environments, including construction, integration, and testing.

- To verify that the specified procedures, work practises, and tools are adhered to so that the systematic failures are avoided, revealed and followed up;
- To perform function testing of prototype components, taking into account the desired RAMS performance;
- To review and update the reliability and availability analyses with new information and data;
- To update and follow up the critical items and hazards list.

Phase 5:

Prototype qualification in operating environments, in order to assess field performance and to make design changes, if necessary.

- To perform operational testing under various operational and environmental conditions;
- To record and classify all non-conformities, and allocate responsibilities for their follow-up;
- To update and follow up the critical items and hazards list.

Phase 6:

Final construction and preparation for operation.

- To ensure quality control and construction process;
- To perform safety analyses of scheduled activities in phase 7 that may expose humans or environment to risk, e.g. activities related to operation, testing, maintenance, and disposal;
- To update and finalize operator and maintenance instruction manuals;
- To update and finalize maintenance support preparation.

Phase 7:

Operation and follow-up of RAMS performance.

- Data collection and evaluation of the system performance;
- Regular inspection, function testing and maintenance;
- Making decisions regarding "adequate" RAMS performance;
- Updating critical items and hazards list and RAMS controlling documents.

Phase 8:

Evaluation and learning from experience for future developments.

4 Conclusion

This presentation illustrates the integration of RAMS aspects with the development of offshore wind power production system, by the application of the life cycle model of Murthy et al. [3], which includes all phases from "cradle to grave". It is shown to be an efficient approach for obtaining a holistic development process of the systems, especially focussing on the essential attributes for the successful exploitation offshore wind power.

5 References

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Wind Power R&D seminar - Deep sea offshore wind power
21-22 January 2010, Trondheim, NORWAY

EXTREME STRUCTURAL DYNAMIC RESPONSE OF A SPAR TYPE WIND TURBINE

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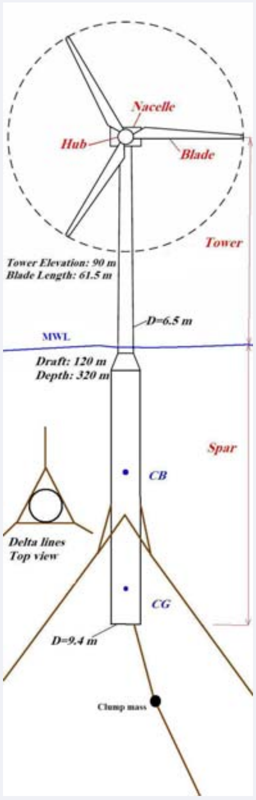
Abstract

Proper performance of structures requires among other things that its failure probability is sufficiently small. This would imply design for survival in extreme conditions. The failure of a system can occur when the ultimate strength is exceeded (Ultimate Limit State) or fatigue limit (Fatigue Limit State) is passed. The focus in this paper is on the determination of extreme responses for ULS design checks. The present paper deals with coupled wave and wind induced motion and structural response in harsh condition up to 14.4 (m) significant wave height and 49 (m/sec) 10-min average wind speed (at top of tower, 90 m) for a parked floating wind turbine. In survival condition the wind induced resonant responses (mainly pitch resonance) are dominant. Due to resonant motion responses the structural responses are close to Gaussian. The dynamic structural responses show that the process is wide banded. The critical structural responses are determined by coupled aero-hydro-elastic time domain simulation. Based on different simulations (20 1-hour, 20 2-hours, 20 3-hours and 20 5-hours) the mean up-crossing rate has been found in order to predict the extreme structural responses. The most probable maximum and bending moment for up-crossing level of 0.0001 for present study are very close. The minimum total simulation time in order to get accurate results is highly correlated to the needed up-crossing level. The 1-hour and 2-hours original values cannot provide any information for 0.0001 up-crossing level. Comparison of different simulation periods shows that the 20 1-hour simulations can be used in order to investigate the 3-hours extreme bending moment if the proper extrapolation of up-crossing rate used.

Theory

While analytical models are used for determining the linear response, the distribution of nonlinear response in general need to be treated in a semi-empirical manner by modeling the distribution of the response peaks or up-crossing rates.

Extreme value statistics for 1 or 3 hours period can be obtained taking into account the regularity of the tail region of the mean up-crossing rate. The mean up-crossing rate is instrumental in obtaining statistics of extremes. As the up-crossing of high levels are statistically independent event, we can assume a Poisson distribution for extreme bending moment.



Catenary Moored Deep Spar Floating Wind Turbine

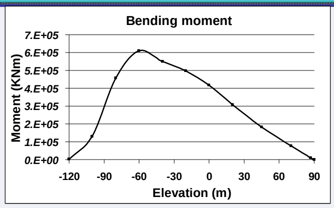
To limit the computational efforts to determine the 100-year extreme response value a contour surface method is applied based on a joint distribution of wind speed, significant wave height and wave period. The 100-years return period environmental condition has been set in order to get 100-years response of the floating wind turbine in harsh environmental condition. A systematic study for choosing the turbulent wind intensity and scaling the mean wind velocity has been carried out.

Model

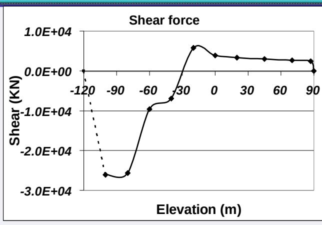
Floating Wind Turbine Properties (CMS)

Total Draft	120 m
Diameter Above Taper	6.5 m
Diameter Below Taper	9.4 m
Spar Mass, Including Ballast	7593,000 kg
Total Mass	8329,230 kg
Centre of Gravity, CG	-78.61 m
Pitch Inertia about CG	2.20E+10 kg•m^2
Yaw Inertia about Centerline	1.68E+08 kg•m^2
Rating	5 MW
Rotor Configuration	3 Blades
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg

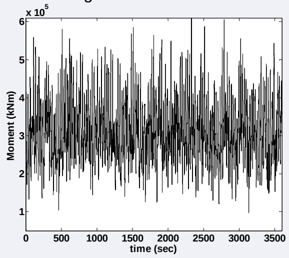
Results



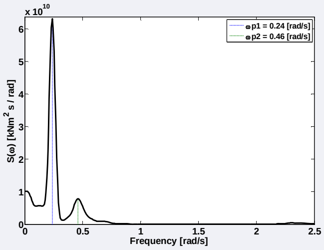
Maximum bending moment in each section along the structure in 1-hour analysis



Maximum shear force in each section along the structure in 1-hour analysis



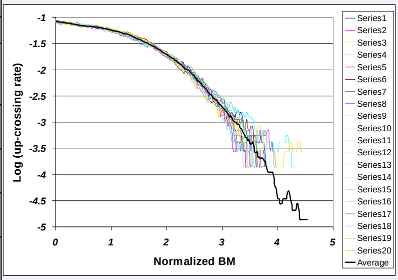
Bending moment time history at z= -60 m



Bending moment spectrum at z= -60 m

Dynamic response Statistics (1-hour simulation)

Response	Mean	STD	Skewness	Kurtosis
Nacelle Surge (m)	78.64	10.69	0.002	2.63
Pitch (deg)	12.35	3.23	-0.116	2.32
BM at interface (kNm)	2.18e+5	6.14e+4	-0.026	2.98
BM at tower top (kNm)	1.90e+3	2.24e+3	0.039	3.04
BM at blade root (kNm)	-1.24e+4	2.30e+3	-0.260	3.19
Shear at interface (kN)	1.32e+3	674.9	-0.120	3.10
Shear at tower top (kN)	1.05e+3	405.7	-0.002	3.12
Shear at blade root (kN)	436.53	78.29	0.260	3.20



Up-crossing rate for 20 2-hours simulations and the average up-crossing rate (40 hours)

Conclusions

Extreme values for severe environmental conditions have been obtained based on 20 1-hour, 20 2-hours, 20 3-hours and 20 5-hours simulations. Since the response is governed by resonance the response is close to Gaussian. The process is wide banded. The up-crossing rates based on time series have been obtained.

The minimum total simulation time (number of simulations multiply by simulations period) in order to get accurate results is highly correlated to the needed up-crossing level. The 1-hour and 2-hours original values cannot provide any information at the 0.0001 up-crossing level. The extrapolation of 1-hour period in order to capture the up-crossing level of 0.0001 can be used. The Naess approach gives more reasonable results. If up-crossing of higher levels is needed the total simulation time should be increased. The most probable maximum and bending moment for up-crossing level of 0.0001 for present study are very close. Comparison of different simulation periods show that the 20 1-hour simulations are sufficient for predicting the 3-hours extreme bending moment if the up-crossing rate is based on reasonable extrapolation.

Acknowledgement

The first author would like to thank Drs. Zhen Gao and Nilanjan Saha from CeSOS/ NTNU for discussion about hydrodynamic and stochastic analysis, Profs. Sverre Haver and Finn Gunnar Nielsen from Statoil for discussion about environmental conditions and floating wind turbine concepts. We also thank Prof. Jakob Mann, Torben J. Larsen and Dr. Anders Melchior Hansen regarding discussion about the HAWC2 code developed at Risø DTU. Finally we would like to acknowledge the financial support from the Norwegian Research Council which has been granted through the Center for Ships and Ocean Structures (CeSOS).

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A Simplified Approach to Wave Loading for Fatigue Damage Analysis of Monotowers

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Introduction

The monotower is the dominating substructure concept used for offshore wind turbines. Offshore wind farms have so far been built at a depth of up to 24m. As the importance of wave loads increase when deeper waters (30-60m) are considered for wind farms, it becomes increasingly important to correctly and efficiently include wave loading in structural analysis. Also, for deeper waters monotowers are expected to gradually become less economical compared to alternative substructure concepts (e.g. truss towers), and wave loading is important to rate different alternatives.

The fatigue limit state is generally assumed to be very important for offshore wind turbines. Here, wave loading on a monotower is discussed in the context of fatigue loading.

Typically, wind loading will dominate over wave loading, and must, of course, be taken into account in design of a real structure. However, wind loading is ignored to allow a broader discussion of wave loading. Likewise, dynamic effects are ignored.

A (Rational) Scatter Diagram

For several reasons it is of interest to make a simplified evaluation of the wave climate and the accompanying wave forces, e.g.:

- Wind turbine substructure concepts can be evaluated and compared independent of a specific site
- In situ wave measurements in particular, but also computer simulations are resource demanding. Thus, a simplified approach is very useful in an initial phase of a project
- Using a simplified method gives an improved understanding of the nature and influence of wave climate and loading.

Thus, a scatter diagram based on a limited number of key parameters that is both easy to construct and not directly connected to a specific site can be useful in structural design as a (partial) description of the wave climate.

Ref: Carter, D.,1982."Prediction of wave height and period for a constant wind velocity using JONSWAP results". Ocean Engineering, 9(1), pp. 17-33

Børresen, J. A., 1987. "Vindatlas for Nordsjøen og Norskehavet".

SMB curve

E.g. Carter (1982):

Duration limited:

- $Hs=0.0146D[h]^{5/7}U_{10}^{9/7}$
- $Tp=0.540D[h]^{3/7}U_{10}^{4/7}$

Fetch limited:

- $Hs=0.0163F[km]^{1/2}U_{10}$
- $Tp=0.566F[km]^{0.3}U_{10}^{0.4}$

Fully developed:

- $Hs=0.0246U_{10}^{2}$
- $Tp=0.785U_{10}$

Fetch

50km / 500km

Storm duration

(Børresen, 1987)

Wind Speed [m/s]	Mean Duration
10.8-13.8	20-25h
13.9-17.1	ca.15h
17.2-20.7	ca. 12h

Scatter diagram

Hs[m] / Tp[s]	0.5	1.0	1.5	2.0	2.5
2.5	8.3/0				
3.0					
3.5	8.3/0	1.2/0			
4.0					
4.5		0/14.5			
5.0		24.8/0	1.2/0		
5.5			9.6/10		
6.0			0/15	2.0/0	
6.5					
7.0					0/10.3
7.5					0/5.7

Wind Distribution

- Weibull (2-param.)
- Shape: 1.9, scale: 10.0
- 50-year: 35 m/s
- 1-year: 28 m/s
- $U_{10,mean}$= 8.9 m/s

Effect of Shallow water

d=30m / 50m

U_{10} = 7.5m/s - 22.5m/s

Wave Loads

The Keuligan-Carpenter KC number and the slenderness relationship are typically used to classify wave loading on a vertical bottom mounted cylinder. As the KC number is small, drag can be neglected and the mudline moment amplitude can be found analytically by integrating the wave load over the depth:

$$M_{Mudline} = \frac{1}{4}\rho\pi D^2\omega^2 H\left[\frac{d(1-e^{-kd})}{k} - \frac{1-e^{-kd}-kde^{-kd}}{k^2}\right]$$

Scatter diagram

Monotower: D=6 m

Potential theory

Morison's eq.

→ Keulegan-Carpenter $KC \approx \frac{\pi H}{D} < 1.3$

→ Slenderness λ/D=2 - 13

→

- Inertia dominated (no drag)
- Potential theory, C_M=2
- (Possibly diffraction)

Fatigue Damage

The structure is assumed to be quasi-static and each seastate is assumed to consist of regular waves with wave height H=Hs and wave period T=Tp.

As regular waves are assumed, the stress history of a seastate will be sinusoidal with the period of the waves. The critical fatigue detail is assumed to be located at the mudline cross-section. SN curve G is assumed to get reasonable values for fatigue life.

Ref: OC3 baseline. www.ieawind.org/annex_xxiii.html

DNV, 2005. "Fatigue design of offshore structures. Recommended practice DNV-RP-C203.

Scatter diagram and Wave spectrum

Monotower (OC3 baseline) D=6 m, t=60 mm

Depth: 50 m

Relative fatigue damage at mudline (fetch 50km/500km)

Hs[m] / Tp[s]	0.5	1.0	1.5	2.0	2.5
2.5	1/0				
3.0					
3.5	0.4/0	2/0			
4.0					
4.5		0/3			
5.0		19/0	7/0		
5.5			43/9		
6.0			0/10	29/0	
6.5					
7.0					0/55
7.5					0/23

Wave loads at mudline

Time domain analysis for each seastate

SN-curve: G DNV(2005)

Conclusions

A rational and efficient approach to constructing a scatter diagram based on SMB curves, fetch, the effect of shallow water, the duration of winds, and wind distribution is presented. The approach is recommended for use both in addition to and in the absence of more resource demanding alternatives.

Fatigue life at mudline

Fetch\ Depth	30 m	50 m
50 km	857 year	37year
500 km	239 year	8 year

The fatigue damage of the monopile at the mud line has been found considering only wave loads. The minimum fatigue life for 30m and 50m depth was 239 year and 8 year, respectively. When wind loads are also included wave loads are expected to be important due to the exponential nature of fatigue damage.

STATKRAFT OCEAN ENERGY RESEARCH PROGRAM

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Grid Integration of Offshore Windfarms and Offshore Loads Using Multiterminal HVDC

TEMESGEN M. HAILESELASSIE, *NTNU*   KJETIL UHLEN, *NTNU*   TORE UNDELAND, *NTNU*

***Abstract*—The use of multiterminal HVDC (MTDC) system as a prospective technology for integrating of offshore wind farms and offshore loads has been investigated in this work. A robust power flow control method, based upon DC bus voltage droop measurements, was proposed for the MTDC system. For testing the proposed control strategy, a four terminal HVDC simulation model consisting of an offshore windfarm, offshore oil/gas platform load and two onshore grid connections was modeled in PSCAD simulation software.**

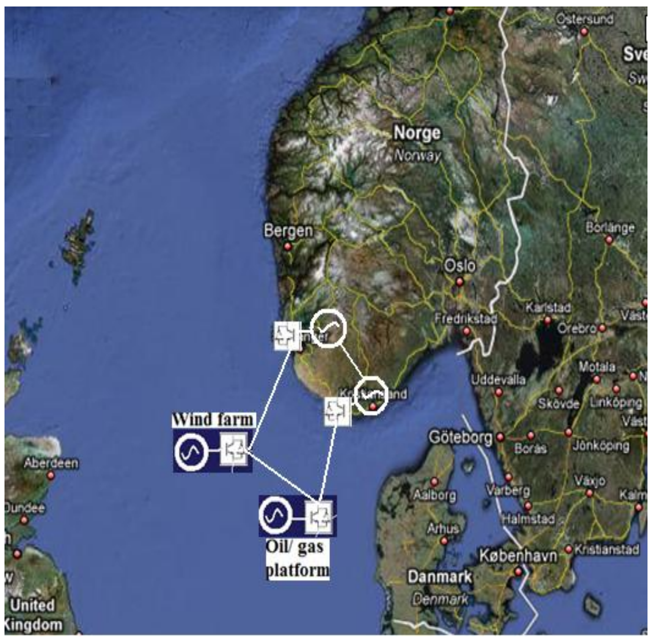


Figure 1: Early stage scenario of multiterminal HVDC in the North Sea

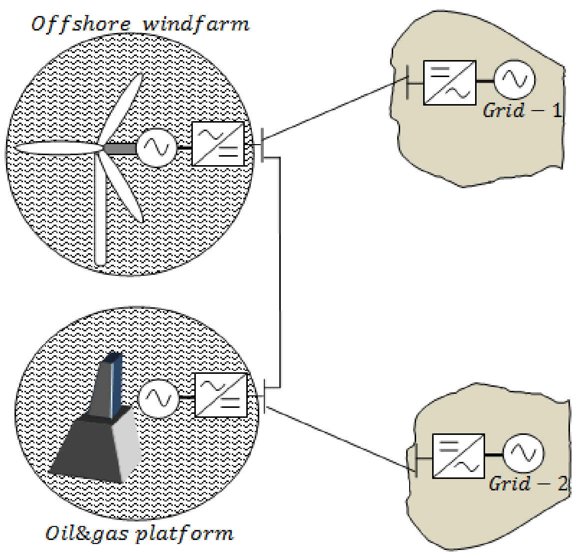


Figure 2: A four terminal HVDC model used for simulation

The four HVDC converter terminals were assigned the dc droop characteristics as shown in Figure 2.

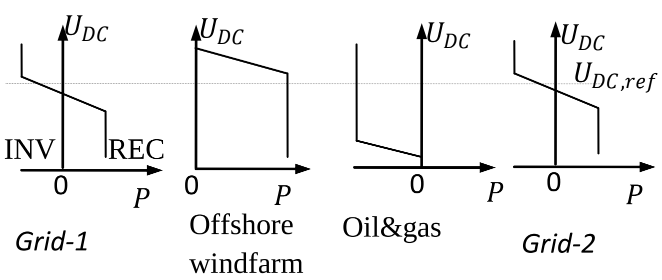


Figure 3: Assigned DC droop characteristics for the HVDC terminals

Advantages of MTDC control with the DC droop control

- No need for communication between terminals
- Many converter terminals contribute to DC voltage regulation
- DC analogy to distributed *frequency droop control* in AC systems

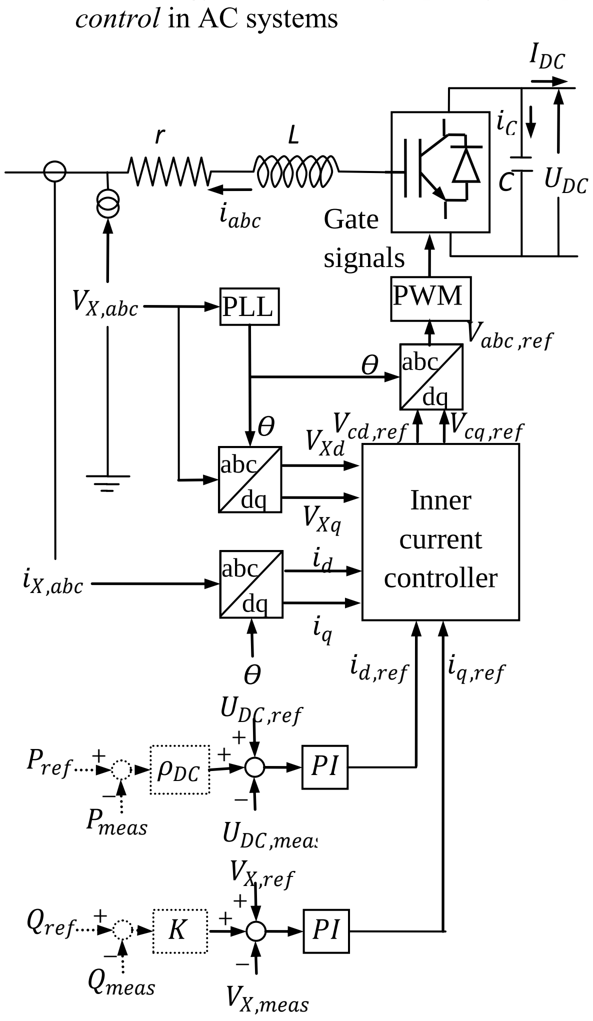


Figure 4: Complete VSC control structure including outer controllers

Mathematical model of the voltage source converter

$$\frac{d}{dt}\begin{pmatrix}i_d\\ i_q\end{pmatrix}=\frac{1}{L}\left\{\begin{pmatrix}0 & \omega L-r\\ -\omega L & -r\end{pmatrix}\begin{pmatrix}i_d\\ i_q\end{pmatrix}-U_{DC}\begin{pmatrix}m_d\\ m_q\end{pmatrix}+\begin{pmatrix}V_{Xd}\\ 0\end{pmatrix}\right\}$$

ω – *Line frequency (rad / s)*

L, r – *Line inductance (H) & resistance (Ω)*

V_{Xd} – *Measured voltage at PCC*

m – *modulation index*

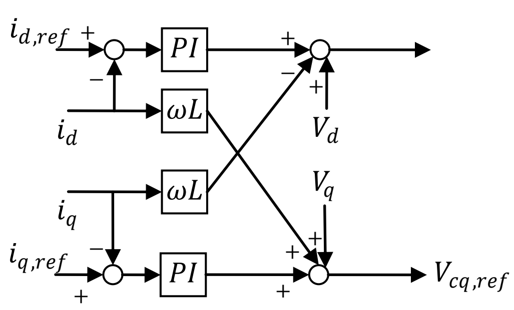


Figure 5 : Inner current control loop

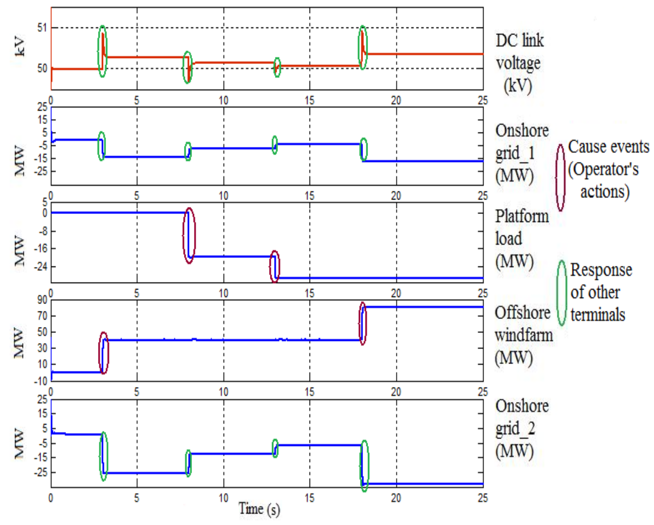


Figure 6: DC voltage droop control responses

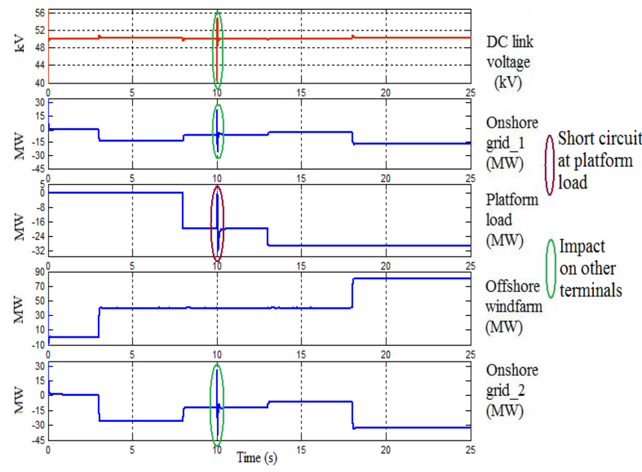


Figure 7: Impact of three phase short circuit fault occurring at oil/gas platform load

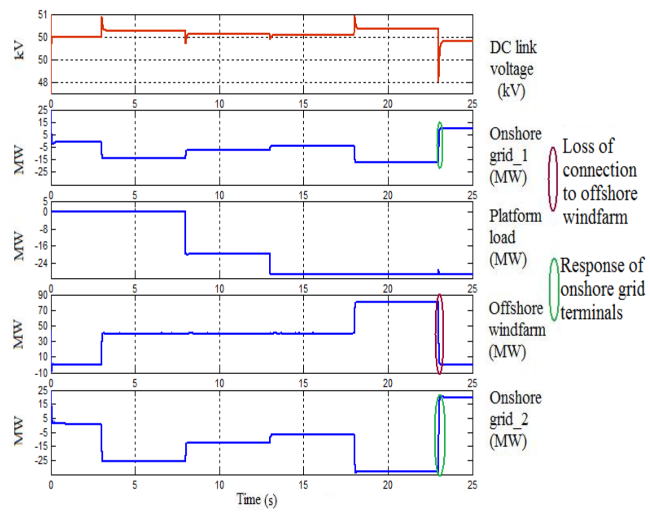


Figure 8: Loss of generation from the offshore wind farm

Conclusions

- Robust control of MTDC was achieved by DC voltage droop characteristics
- No need of fast communication between terminals for operation under disturbances
- System is little affected by short duration AC fault occurrences
- Readily expandable without any change of the existing system needed

NTNU   NOWITECH Norwegian Research Centre for Offshore Wind Technology

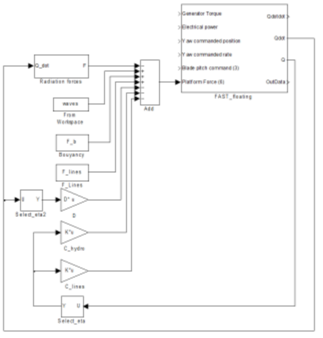
Modelling and control of floating wind turbines

NTNU[99]
Norwegian University of Science and Technology

Thomas Fuglseth
PhD-student, Dept. of Electrical Power Engineering, NTNU

Tools

Wind turbine simulation code FAST coupled with modular hydrodynamics model in Simulink. FAST has been modified to accept a 6 DOF vector of hydrodynamic forces computed in Simulink. Equations of motion are solved by FAST



- •Hydrodynamic/hydrostatic data from WAMIT
- •Linear restoring forces (hydrostatic and mooring)
- •Linear damper based on data from Statoil
- •State-space model of frequency-dependent forces found using system identification methods

$$(\mathbf{M}+\mathbf{A})\ddot{\mathbf{q}} = \mathbf{f}_{grav} + \mathbf{f}_b + \mathbf{f}_{lines} - \mathbf{C}_{hydro}\cdot\mathbf{q} - \mathbf{C}_{lines}\cdot\mathbf{q} - \ldots$$
$$\ldots \mathbf{D}\cdot\dot{\mathbf{q}} + \mathbf{f}_{rad}(t) + \mathbf{f}_{wave}(t)$$

Constant added mass ($\mathbf{A}$); Weight ($\mathbf{f}_{grav}$); Bouyancy ($\mathbf{f}_b$); Constant mooring tension ($\mathbf{f}_{lines}$); Hydrostatic stiffness ($\mathbf{C}_{hydro}$); Mooring stiffness ($\mathbf{C}_{lines}$); Damping term ($\mathbf{D}\cdot\dot{\mathbf{q}}$); Radiation forces ($\mathbf{f}_{rad}(t)$); Wave forces ($\mathbf{f}_{wave}(t)$)

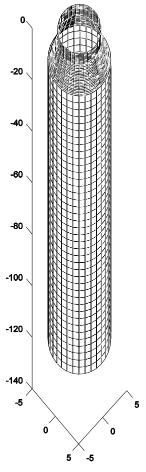
Radiation forces are computed by linear state space models running in parallel. State space models found from frequency-dependent WAMIT data using system identification techniques.

Wave excitation calculated by numerical convolution of wave amplitude times series and wave excitation response function

$$f^{i}_{wave}(t) = H_i(t) * \eta(t)$$

Wave amplitude time series ($\eta(t)$)

Wave excitation transfer function (found from WAMIT) ($H_i(t)$)



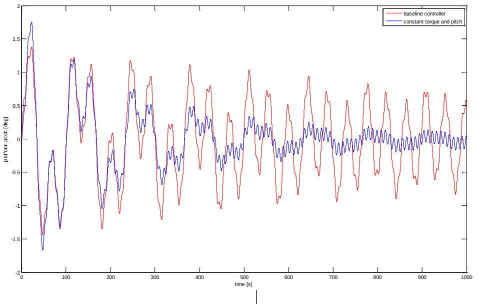
Model

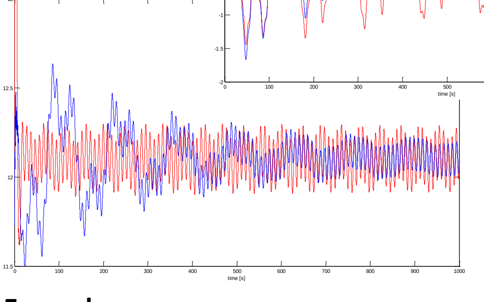
- •Platform model based on HyWind 5 MW design
  - •Cylindrical platform, 120 m draft and 9.4 m diameter tapered towards the top.
  - •7500 ton mass
  - •Platform modeled in WAMIT
- •Turbine model: NREL offshore baseline
  - •5MW reference design based on several industrial designs

Control issues

Conventional constant-power (above rated wind speed) control algorithms can cause negative damping of platform pitch motion.

- •Platform pitching will periodically increase and decrease the wind speed experienced by the turbine.
- •Rotor blade pitch control decreases rotor thrust when wind speed increases and vice versa.
- •Platform pitches forwards → reduced thrust
- •Platform pitches backwards → increased thrust





Example

- •17 m/s constant wind speed
- •2.26 m wave height, period of 9.57 seconds
- •Standard blade pitch controller for the NREL offshore baseline compared with constant torque and blade pitch

Changing controller type can significantly damp out platform pitch movement. However, this requires knowledge of true windspeed, unaffected by platform movements. Anemometers at the rear of the nacelle are problematic, as the measurement is delayed as well as affected by the rotor.

- •Observer/state estimator can be used to filter out wave motions and estimate true wind speed → solution used by Statoil.
- •New wind speed measurement such as spinner-mounted pitot tubes or forward-looking LIDAR can be advantageous.

Condition Monitoring and Maintenance Optimization of Offshore Wind Farms

Department of Production and Quality Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Mahmoud Vlibeiglou holds a Master of Science degree in maintenance management. Mahmoud has over 6 years of work experience related to railway industry, particular in fleet maintenance.
As a researcher, he has specialized in maintenance management, maintenance optimization, condition monitoring and their implementation on offshore wind farms industry.

Started PhD in 2009 **Supervisor: Professor Jørn Vatn** **Cooperating business: Statcraft**

Renewable energy has a vital role in the future of energy industry. Wind farms are one of the main sources for producing electric power. As offshorewind farms are more advantageous, so these are commonly used now-a-days.

Main challenges in operation of wind farms are maintenance, sudden failures and downtimes. Difficult accessibility, too far from onshore and depot, high production losses, significant cost of corrective maintenance, hard maritime environment are playing vital role in maintenance affaires of offshore wind farms.

Among the maintenance strategies, preventive and predictive ones are suitable for implementation in offshore wind turbines. Condition monitoring (CM) technologies, such as vibration analysis, oil analysis, thermography, crack measurement … are very useful for monitoring of wind turbines. In this research we focus on the condition monitoring of wind turbine and use of CM data for making decision of maintenance. To define the deterioration models by using CM data and match them with mathematical models is one of the main objectives of this research.

In economic aspect, reducing the maintenance cost without compromising the quality of maintenance is more demanding for companies. Maintenance optimization is the golden key for this success. Maintenance optimization helps the managers defining the cost equations, grouping maintenance activity, suitable inspection interval, overhaul interval, and preventive maintenance interval in reducing the maintenance cost and increasing system productivity.

Finally this research is looking for proper combination between Condition Base Maintenance and Maintenance Optimization to maintain offshore wind farms by using mathematical models and existing data.

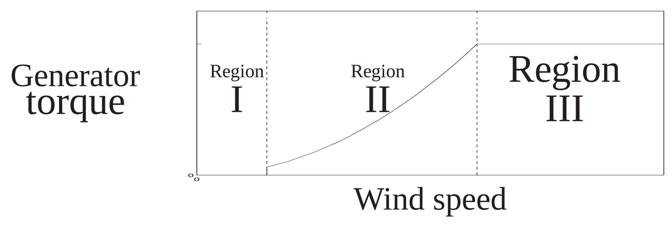
High availability and reliability with low cost are our ideal.

Individual Pitch Control for Horizontal Axis Wind Turbines

Fredrik Sandquist, PhD student NTNU fredrik.sandquist@ntnu.no

Introduction

- Operation Regions
  - Region1, 2 and 3



- Region 2: Maximum power
  - Constant tip speed ratio
  - Collective pitch constant
  - Variable torque
- Region 3: Constant speed and power
  - Variable Pitch
  - "Constant" torque

Inputs

- Control inputs
  - Blade pitch angle for each blade
  - Turbine torque

Goal

- Load reduction
  - Drive train
  - Blade load, mostly flap
  - Tower
- Loading
  - Gravity
  - Wind
- Periodic loading
  - Gravity
  - Wind shear
- Almost periodic loading
  - Wind gusts

Collective vs Individual Pitch Control

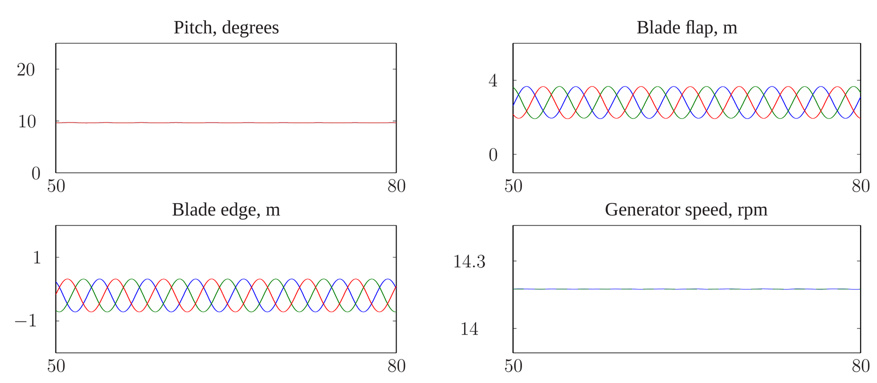


Figure 1: Simulation in a steady wind field with a vertical wind shear with collective pitch

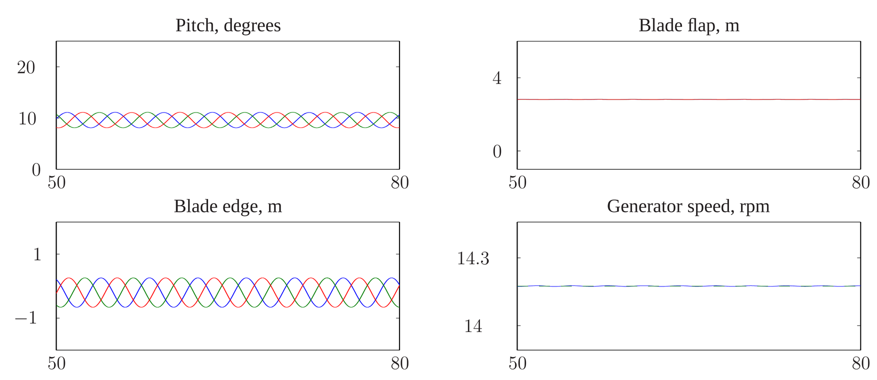


Figure 2: Simulation in a steady wind field with a vertical wind shear with individual pitch

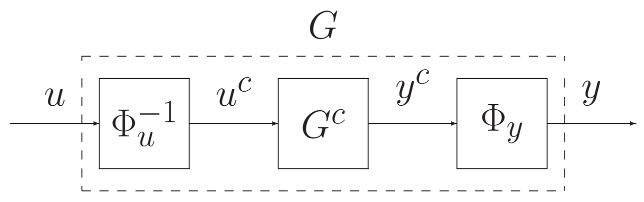
- It is possibly to get rid of the flap motion with individual pitch.

Method

- Nonlinear aero elastic dynamic model of the entire turbine
  - FAST, Bladed, HAWK2, flex5 and others
- Determine an operation trajectory for a given wind speed, generator speed and generator torque
  - Constant pitch angle
  - An azimuth depending trajectory for blade motions
- Linearize the model around the trajectory
  - A linear system for each azimuth angle
- Change the states, inputs and outputs for each system with the Coleman transformation
  - (Almost) the same linear model for all azimuth angles
- Take the mean of all system matrixes and call the corresponding system the Coleman turbine.
- The Coleman turbine "almost" time (azimuth) invariant

The Coleman Wind Turbine

- The turbine model is a time (azimuth) invariant system, turbine Coleman, enclosed by time (azimuth) varying Coleman transformations
- The Coleman turbine can be approximated by a linear system
- It is good representation of the turbine



, where G is the turbine, G^c is the Coleman turbine and Φ_u and Φ_y are the Coleman transformation of the inputs and outputs.

The Coleman Transform

- The Coleman transform is a transform from individual blade coordinates, $\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$ to rotor disk coordinates $\begin{bmatrix} q_c^c \\ q_h^c \\ q_v^c \end{bmatrix}$.
  - q_c^c is the collective coordinate
  - q_h^c is the horizontal coordinate
  - q_v^c is the vertical coordinate

The Coleman transformation is given by

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} 1 & \sin(\Psi) & \cos(\Psi) \\ 1 & \sin(\Psi + 2\pi/3) & \cos(\Psi + 2\pi/3) \\ 1 & \sin(\Psi + 4\pi/3) & \cos(\Psi + 4\pi/3) \end{bmatrix} \begin{bmatrix} q_c^c \\ q_h^c \\ q_v^c \end{bmatrix}$$

, where Ψ is the azimuth angle, $\Psi = 0$ when blade 1 is straight up.

$$q = \Phi q^c$$

Modeling of the Wind

- Wind shear is easily modeled in Coleman coordinates
  - Collective=mean wind
  - Vertical=vertical linear wind shear
  - Horizontal=horizontal linear wind shear
- Time varying wind fields can be seen as change in wind shear to some extent.

The Linear Model

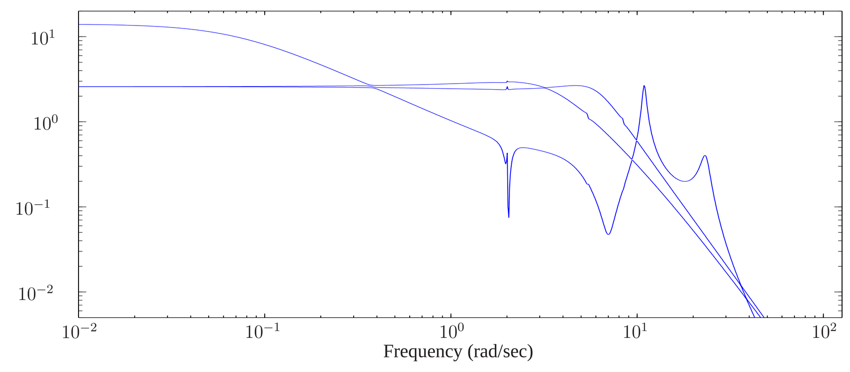


Figure 3: Singular value plot from pitch to generator speed and individual flap

- The singular value plot shows the gains in the system
- The notch and gain at 2 rad/sec is due to the tower
- The peak at 10.8 rad/s is due to large resonances in the drive train and blade edge motion.
- The peak at 22.9 rad/s is due to resonance in the drive train and blade edge motion.

Bode magnitude plots for the linear system

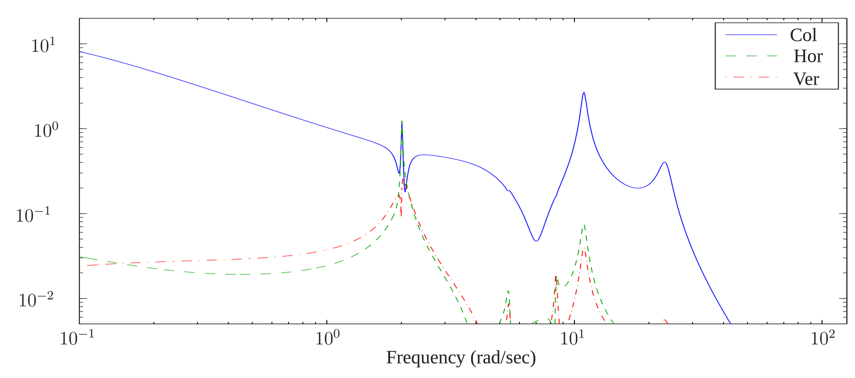


Figure 4: Generator speed from Collective, Horizontal and Vertical pitch

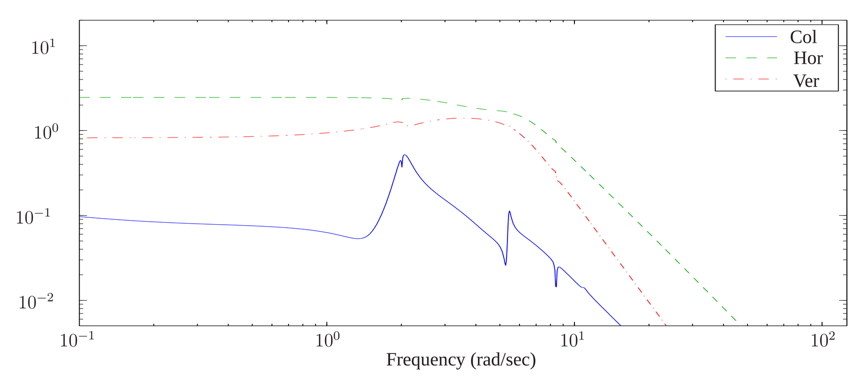


Figure 5: Horizontal flap from Collective, Horizontal and Vertical pitch

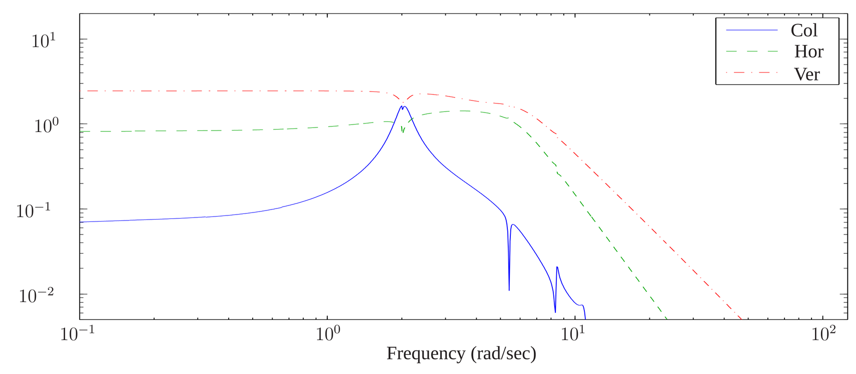


Figure 6: Vertical flap from Collective, Horizontal and Vertical pitch

Interactions

- Not much interaction between generator speed and individual pitch
- Not much interaction between individual flap and collective pitch
- Some interactions between the two individual channels
- There are interactions between all signals at 2 rad/s, this is due to the tower
- A diagonal controller can be good

Control Analysis and Design Diagonal PID Controller

- Measure generator speed and individual flap (2 signals)
- Control inputs collective and individual pitch

Controller

- The individual flap is easy to control with a PID controller
- The generator speed is more difficult to control
  - Zeros in the right half plane
  - Low phase
  - Resonant peaks at high frequency
- A PI regulator and notch filters at the resonant peaks works good
- This controller works good but it is possibly to achieve better performance with other controllers.

Simulations

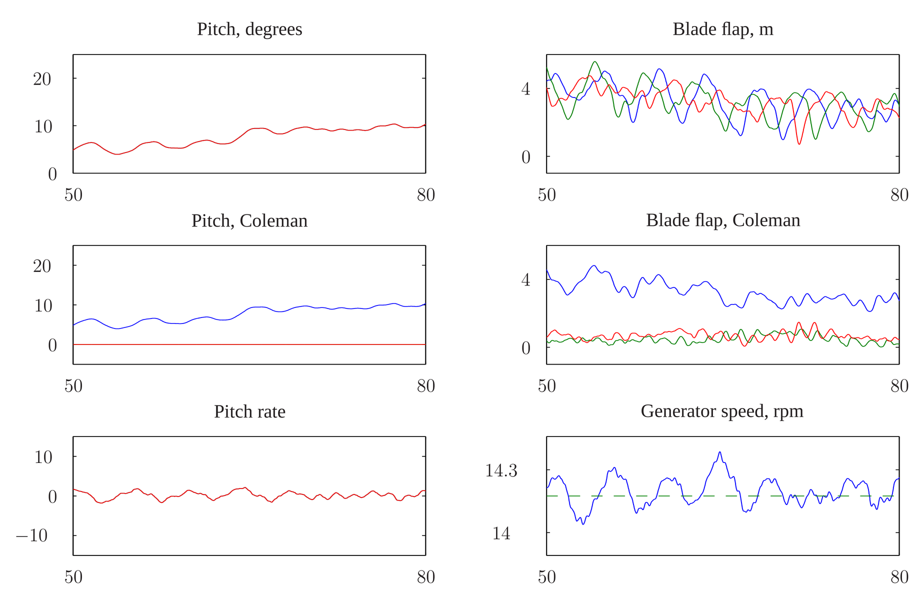


Figure 7: Collective pitch

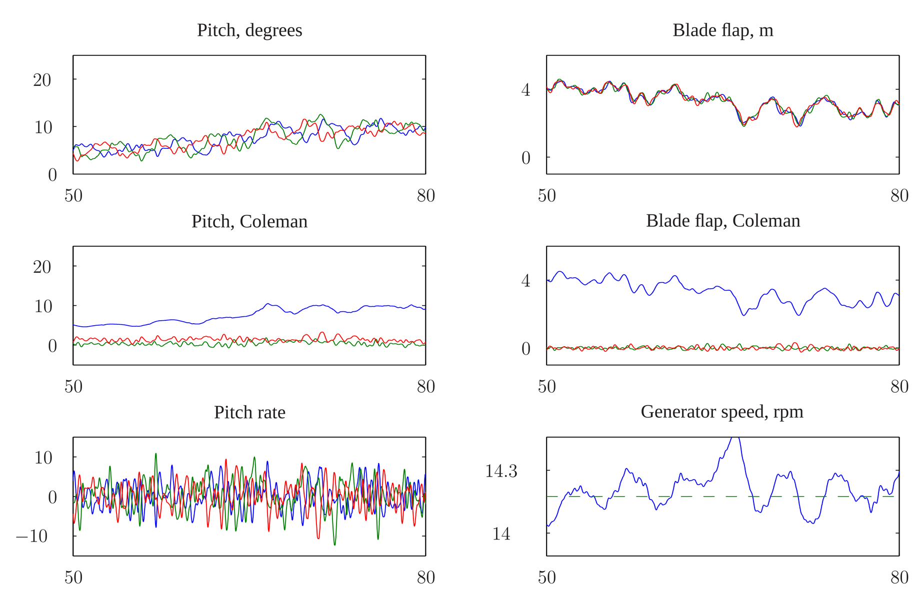


Figure 8: Individual pitch with the diagonal controller

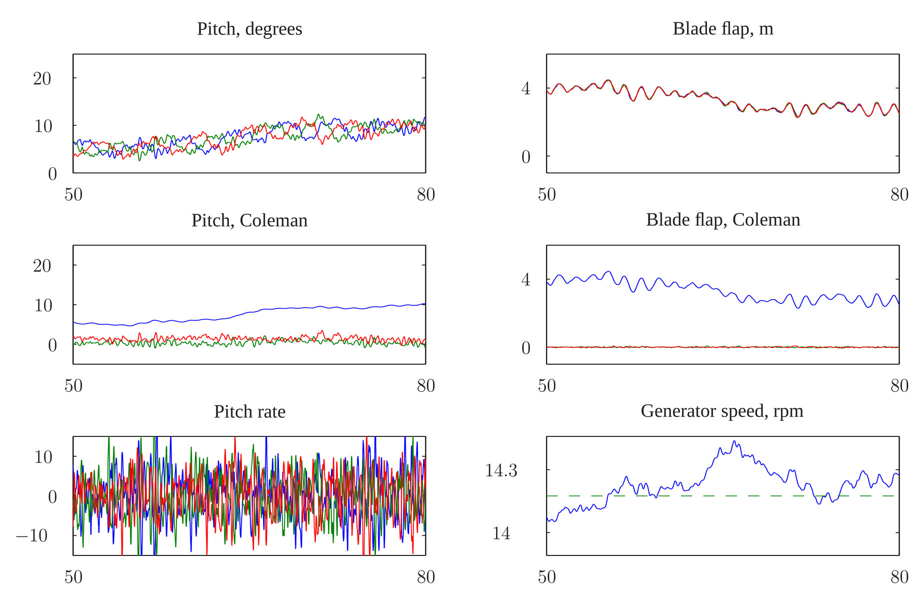


Figure 9: Individual pitch with a more advance controller

Analysis of Switching Transients in Offshore Wind Parks with Focus on Prevention of Destructive Effects(NOWITECH WP4 project)

AMIR HAYATI SOLOOT, HANS KRISTIAN HØIDALEN
Electric Power Technology Group, Electric Power Department, IME Faculty, NTNU

Introduction

According to environmental consideration, the renewable energy resources such as wind power are focused in Research and Development (R&D) centers. For two main reasons, offshore wind farms are investigated more in recent years; 1- The speed and power of winds in ocean area are more than those in shore or land area, 2- The noise inconveniences and area occupation of wind farm in land areas.
Cumulative offshore wind capacity installed in Europe, amounting to 770MW at the end of 2005, will grow to about 8300MW at the end of 2009, according to some estimates [1]. The average size of the wind parks (WPs) is increasing as well [2]. Some of the WPs planned during 2005 in England have total installed power higher than 500MW, which is larger than, for instance, many electrical installations in industrial plants[3].
There is a similarity between Wind Parks (WP) and industrial Medium Voltage (MV) networks in this regard as both use Vacuum Circuit Breaker (VCB) as switching device and consists of a cable network. The use of a cable network and VCB in MV networks could be a source of insulation failure and result in large financial losses [4] due to the Transient Over Voltages (TOVs) after energization and the fast voltage transients caused by multiple re-strikes of VCB[5]. Therefore the severity and destructive effects of switching overvoltages in offshore wind farms should be considered as great importance and investigated to improve the future designs.

PhD project aim: started at October 2009- scheduled termination October 2013
- ❖Analysis of transients in wind parks to improve the future design and insulation coordination
- ❖Discover critical cases and incompatibilities in switching phenomenon and recommend remedies (solutions) in order to develop competence in wind park design.

PhD Project Motivations:
- ➢Industry motivation :
  - ➢Failures in wind parks have been reported.
  - ➢Switching over voltages should be considered in the design of wind park system.
- ➢Academic motivation:
  - ➢Synthesis (development) of models for cable / transformer/ VCB for transient studies in offshore wind park.

PhD Project Approach:
Modeling
- Transformers:
  - compare models and develop the appropriate one:
    1. Multi Transmission Line (MTL) model or RLC ladder model (based on design information) [6]
    2. Black box model (based on terminal measurements) [7], [8]
    3. Topological Hybrid model (Test reports + Design key parameters) [8]
- Generators:
  Black box model (based on terminal measurements)
- Cables:
  - compare models and develop the appropriate one
    1. Analytical model (based on design parameters)
    2. Finite Element method with UFIELD software (based on design parameters) [9]
    3. Frequency response model (based on measurements)
    4. PSCAD phase domain model (based on vector fitting[10])
- Vacuum Circuit breaker:
  The model should consider over voltages due to current chopping and multiple reignition.

Experiments
- Wind park transient recording (expand ongoing power quality recordings)
- Live tests (energization, de-energization)
- Laboratory setups (CB, cable, transformer, generator)
- Black box Characterization of transformers (oil, dry type), generators and cables




Measurements in NYSTED Offshore Wind Farm[11]

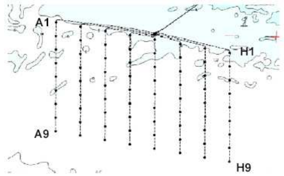


Fig 1: NYSTED Offshore Wind Farm

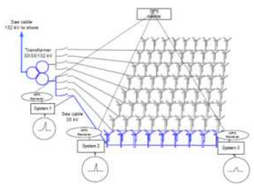


Fig 2:Measuring points in the wind farms, first and last WT of the first row and the

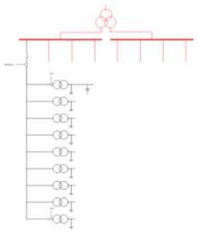


Fig 3: Case study- Energization of row A in Nysted offshore wind farm

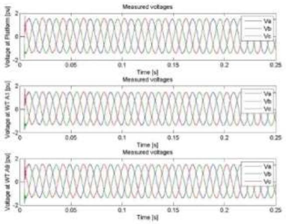


Fig 4:Voltage at different measuring

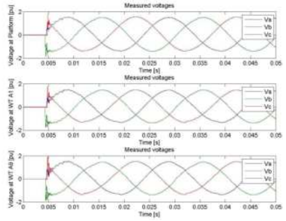


Fig 5:Voltage at different measuring

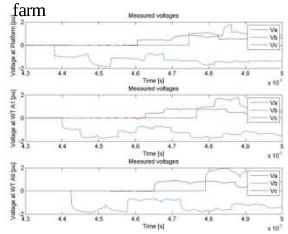


Fig 6:Voltage at different measuring

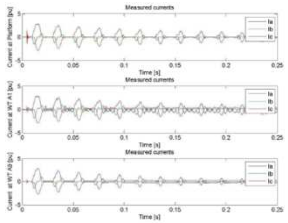


Fig 7: Current at different measuring points in Row A: 0-250 ms

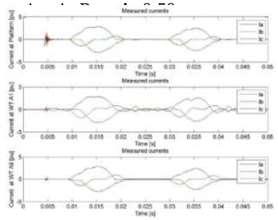


Fig 8: Current at different measuring points in Row A: 0-50 ms

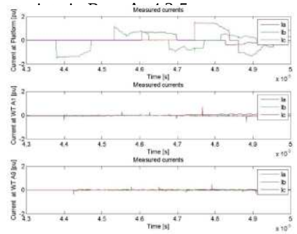


Fig 9: Current at different measuring points in Row A: 4.3-5 ms

References

[1] Madsen BT. , Emerging offshore wind power markets—conditions, quantities and timetable. *Copenhagen Offshore Wind Conference, Copenhagen, 26–28 October 2005.*
[2] L. Liljestrand, A. Sannino, H.Breder and S. Thorburn, "*Transients in Collection Grids of Large Offshore Wind Parks*", Wiley Interscience , Wind Energ. 2008; **11:45–61.**
[3] List of projects in planning, from UK Wind Energy Database UKWED. [Online]. Available: http://www.bwea.org. (accessed 18 December 2005)
[4] D. Chapman, "The Cost of Poor Power Quality", Power Quality Application Guide, Section 2.1, Copper Development Association of UK, November 2001.
[5] Abey Daniel & Samson Gebre, "Analysis of Transients in Wind Parks: Modeling of System Components and Experimental Verification", MSc. Thesis, Chalmers University of Technology, Sweden, 2008.
[6] S. M. H. Hosseini, M. Vakilian, and G. B. Gharehpetian, " Comparison of Transformer Detailed Models for Fast and Very Fast Transient Studies", *IEEE Trans. On Power Delivery , Vol. 23,pp. 733-741, No. 2, April 2008.*
[7] B. Gustavsen, "Wide band modeling of power transformers," *IEEE Trans. Power Del., vol. 19, no. 1, pp. 414–422, Jan. 2004.*
[8] G. B. Gharehpetian, H. Mohseni, and K. Möller, "Hybrid modeling of inhomogeneous transformer windings for very fast transient overvoltage studies," *IEEE Trans. Power Delivery, Vol. 13, pp. 157–163, Jan. 1998.*
[9] B. Gustavsen, A.Bruaset, J. J. Bremnes, and Arild Hassel, "A Finite-Element Approach for Calculating Electrical Parameters of Umbilical Cables" , *IEEE Trans. On Power Delivery, Vol. 24, No. 4, October 2009.*
[10] B. Gustavsen, A. Semlyen, "Rational Approximation of Frequency Domain Responses by Vector Fitting", *IEEE Trans. On Power Delivery, Vol. 14, No. 3, July 1999.*
[11] I. Arana Aristi, "Modeling of Switching Transients in Nysted Offshore Wind Farm and a Comparison with Measurements " , MSc. Thesis, Technical University of Denmark, June 2008.

C Met-ocean conditions, operations and maintenance

North-Sea wind database – NORSEWIND, Erik Berge,
Kjeller Vindteknikk / IFE

Oceanic wind profile, turbulence and boundary layer characteristics,
Prof Idar Barstad, UniResearch

Transfer of methods and experience on O&M in other industries to offshore wind farms, Erik Dyrkoren, MARINTEK

Corrosion protection of offshore wind turbines, OØ Knudsen, A. Bjørgum, SINTEF

KJELLER VINDTEKNIKK

NORSEWiND data base

Wind Power R&D seminar - deep sea offshore wind

Trondheim 21-22 January 2010

by

Erik Berge

Kjeller Vindteknikk AS / IFE

What is NORSEWiND?

- 7'th framework EU R&D project. Project period Aug 2008 – Aug 2012
- Northern Seas Wind Index Data base (NORSEWiND).

KJELLER

Partners:

Oldbaum Services (coordinator)	DanishTechnical University IMM
Garrad Hassan & Partners	INETI
ISET	Kjeller Vindteknikk
RISOE DTU	University of Strathclyde
WINDTEST Kaiser Wilhelm Koog	Scottish Enterprise
DONG Energy	Nautilus Associates
Statoil	3E
CLS	

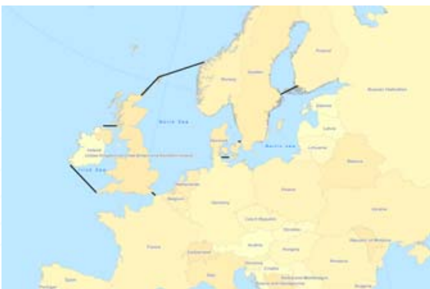
KJELLER

Main objectives:

- Deliver high quality offshore wind atlases at hub-height for the Irish Sea, the North Sea and the Baltic Sea
- Develop an offshore wind database and the associated wind atlases based on real data acquired offshore
- Develop a set of techniques to provide cost effective data anywhere offshore
- Promotion and acceptance of remote sensing within the wind industry
- Validate the wind atlas methodology

KJELLER

Geographical areas covered are the Irish Sea, the North Sea and the Baltic Sea



KJELLER

Wind atlas methodology

- Set up measurement points and collect wind data
- Collect and process satellite data wind data
- Develop vertical profile modeling to "lift" satellite data from 10m up to hub-height
- Generate meso-scale model data to complement and validate satellite data, and to fill inn gaps of missing data.
- Combine the data sources to an optimal wind atlas.
- Apply long-term corrections to the wind atlas quantities

KJELLER

KVT's main tasks in NORSEWiND

- Task leader for the aggregation of the data sources into the wind atlases
- Meso-scale modelling
- Verical profile analysis and modelling
- Long-term data analysis and correction
- Operate, maintain and analyse the data from the Statoil wind cube at Utsira.

Parameters of the wind atlas

- Annual average wind speed maps (long-term corrected)
- Monthly average wind speed maps (long-term corrected)
- Standard deviation of annual averages
- Weibull-distribution
- Wind direction distributions
- Turbulence intensity
- Wind shear (maps of the wind shear coefficient)
- Temperature and static stability
- Mixing height
- Uncertainty level of each physical parameter

The reference height is 100 m

Data source 1: Measurements (Windtest, ISET)

Public available Lidar and met.mast data

Overview observations:

Public available data:

3 Lidars (Zephir)	Irish Sea, Finnish Bay, West of Portugal
Meteorological Masts, Fino 1, 2 and 3	North Sea and Baltic Sea
1 Sodar	Coast of Latvia

Pluss oil rig data

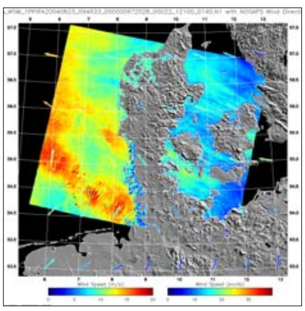
Confidential data with restricted usage:

12 Lidars

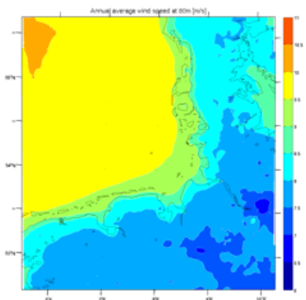
7 Meteorological masts

All measeurements are entered into a database

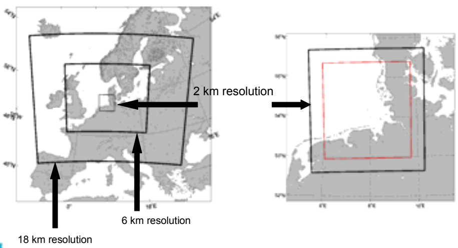
Data source 2: Satellite data (RISØ DTU)



Data source 3: Meso-scale model data (KVT)

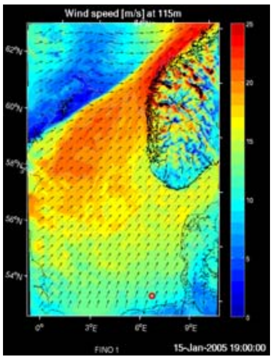


Meso-scale model – WRF Weather Research and forecast model set-up:

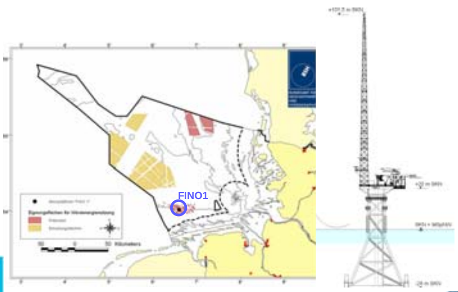


Meso-scale model set-up (continued):

- Global NCEP boundary data every 3 hour
- WRF-runs for 27 hours covering 1 day
- Model runs for all three domains for four complete years (2004-2007)
- Data stored hourly in every grid-point for all model layers

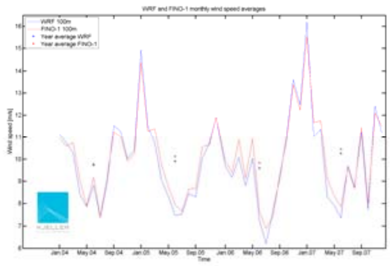


Measurements from the FINO 1 plattform



Mast data corrected by Lidar data

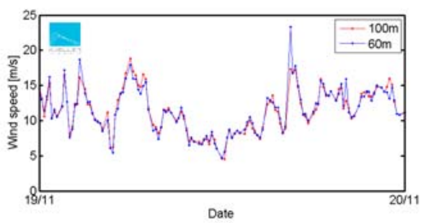
Annual and monthly averages:



WRF yields ~ 0.1 m/s lower annual average

Hourly correlation is ~ 0.92

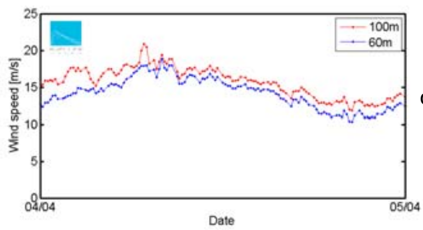
Large wind variability and low wind shear at FINO 1 – convective case (10 min averages):



$\alpha \sim 0$

19.11.2004

Low wind variability and high wind shear at FINO 1 – stable case:



$\alpha \sim 0.15\text{-}0.35$

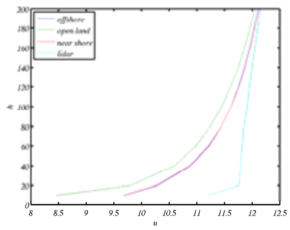
04.04.2004

■ **Data source 4: Vertical modeling (RISØ DTU, KVT)**

Statoil Lidar at Utsira, view toward SSV

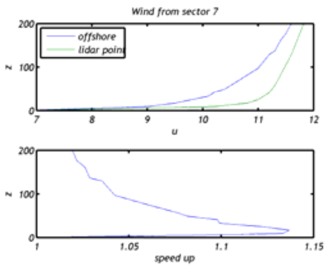
■ **Examples of vertical wind profiles from WAsP**

Wind profiles from WAsP



Utsira island

■ **Vertical wind profile modeling**



Wind profile for sector S based on WAsP

First focus areas - high resolution data:

■ **Horns Rev and German Bight:** North Sea

Summary of NORSEWiND activities

- An offshore measurement data base are being established based on both public data and restricted data.
- Satellite data are presently retrieved and processed
- Meso-scale model data are also generated for large offshore areas
- The vertical modeling has started, but still some time to wait for measurements to be available
- The wind atlas methodology will be developed and tested for the focus area 1 Horns Rev and German Bight during 2010.
- Future high quality wind assessment/wind atlases can be developed for any offshore area depending on the needs of the industry and decision makers.

Bjerknes Centre for Climate Research

Controlling factors for the Planetary Boundary Layer (PBL)

Idar Barstad
Head of Research - Ocean wind energy

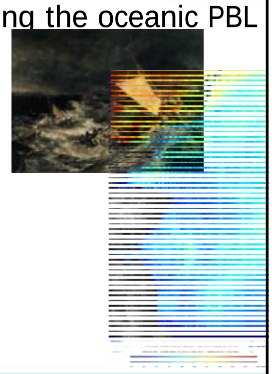
Alastair Jenkins & Anna Fitch

Bjerknes Centre for Climate Research / UniResearch

norcowe
Norwegian Centre for Offshore Wind Energy

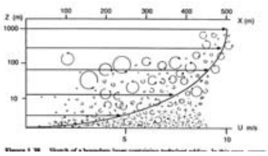
External Factors controlling the oceanic PBL

- Ocean roughness
- The proximity of mountains
- Installation of wind farms



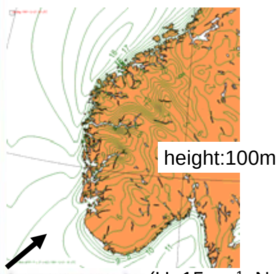
PBL-height and exchange of momentum

Boundary layer height =>
a competition between
wind shear and *stability*

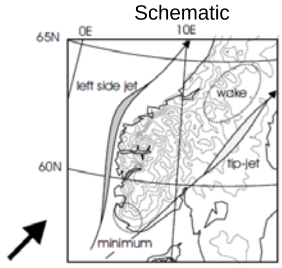


Mountain disturbances

Ideal atmosphere- real terrain



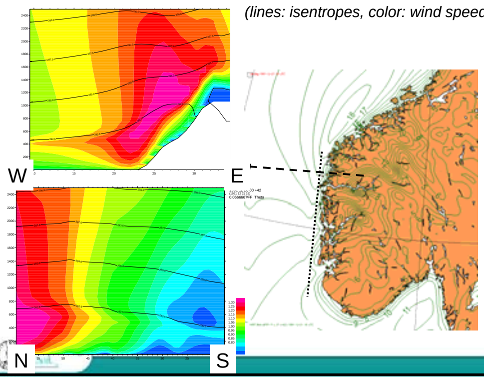
Schematic



(U=15ms^{-1}, N=0.012s^{-1}) Barstad (2002)

Mountains' influence on PBL

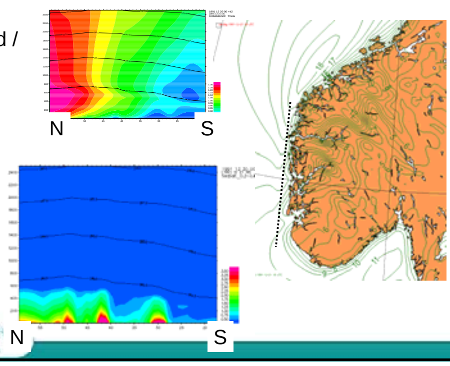
(lines: isentropes, color: wind speed)



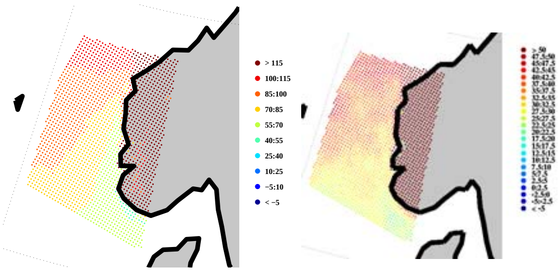
Mountains' influence on PBL

wind speed / isentropes

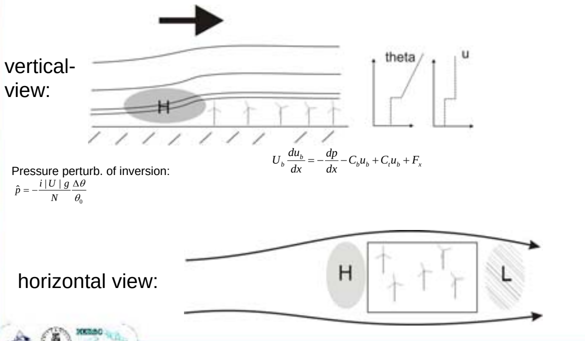
TKE / isentropes



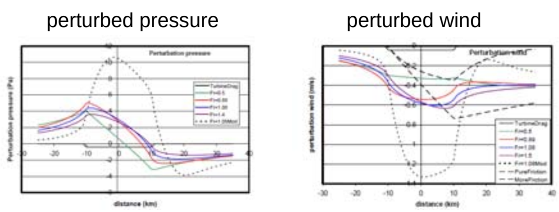
SW-direction



Self-induced disturbances from wind farms

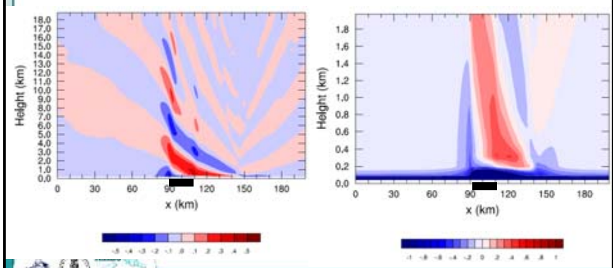


U ⟶



Smith (2009)

Model simulations



Thanks!

Email: Idar.Barstad@uni.no

Extract of paper for EWEC

TRANSFER OF METHODS AND EXPERIENCES FROM OPERATION AND MAINTENANCE IN OTHER INDUSTRIES TO DEEP SEA OFFSHORE WIND FARMS

Erik Dyrkoren
Co-authors: Jørn Heggset, Anders Valland, Jørn Vatn

Wind Power R&D seminar
Royal Garden 22nd January 2010

1

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Summary of paper

- Operations and maintenance philosophies and practices as applied in comparable, mature industries
- Success stories
- Failure stories
- Applicability to deep sea offshore wind farms

2

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Some comparable industries

- Oil and gas industry in the North Sea
- Electric power networks industry in Norway
- Ship management
- Operations of the International Space Station

3

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Comparable equipment

- Rotating equipment
- High voltage power lines
- Floating structures
- Rough and corrosive environment
- Remote systems and remote operations
- Accessibility problems
- Systems with a great number of identical units.

4

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Questions to answer

- How have they adapted to their respective rough environments and lack of accessibility?
- How do they manage O&M?
- What are best practices?
- What are the major differences between O&M of shallow and deep water offshore wind farms?
- What are typical mistakes and startup problems?
- How can these experiences be used and adapted for the deep sea offshore wind industry?

5

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Example: Offshore subsea remote area operations

- Challenges for operation and maintenance
  - Access to infrastructure, i.e. supply bases
  - Intervention logistics
  - Long lead-times for interventions
  - Safety issues may require use of multiple vessels in remote areas
- Solutions
  - Extensive use of redundancy in critical components and systems
  - Systems designed for reduced intervention opportunities
    - Take advantage of reservoir characteristics to allow shutdown of producers without loss of total production
  - Automated monitoring of systems

6

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Example cont.: Offshore subsea remote area operations

- Business specific operational measures
  - Specialised vessel for dedicated intervention tasks (i.e. inspection, light well intervention, coil tubing, hot stab etc.)
- Safety / HMS aspects
  - Remote area operations requires vessel autonomy with regard to
    - Medical staff, capability for light surgery
    - Firefighting
    - Handling of spills
- What can be transferred to Offshore wind?
  - Use of redundancy,
  - Robust design
  - Use of dedicated instrumentation for condition monitoring
  - System design with intrinsic robustness towrads extended downtime of single producers
  - Component and system design for operation reliability
    - Modular systems to allow easy replacement of defective components (plug-and-play)

7

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Example: Electric power networks (overhead lines)

- Industry challenges within O&M
  - Geographically dispersed components
  - Limited/difficult accessibility due to mountains, fjord crossings, rough climate, etc.
  - Many components near end of life (old)
  - Difficult to make group of identical components for statistical analyses (mainly due to large climatic variations)
- Technical solutions,
  - Redundancy (N-1 criterion: The system will handle the loss of one component)
  - Cross-linked polyethylene (XLPE) covered conductors,
  - Earth cables
- Operational solutions
  - Condition monitoring and degradation models to calculate remaining life (independent of age)
  - Condition monitoring handbooks with specified condition criteria makes it possible to collect data in a uniform way

8

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Example: Electric power networks (overhead lines)

- Typical O&M methods and strategies
  - Risk based methods (RCM and variations on this)
  - Shift from Time based to Condition based maintenance
  - "Safety based" maintenance (safety is often the triggering factor for maintenance and renewal)
- Industry unique operational measures
  - Inspection from helicopter and drones (unmanned micro helicopters)
- Failure stories
  - Nord-Salten: Up to 1 week interruption because the reserve line was not maintained to take over the load during breakdown of the primary line. Impossible to get access to the failed components due to very bad weather.
- What can be transferred to Offshore wind?
  - Use of probabilistic methods to calculate risk
  - Well-defined condition criteria and failure models
  - Helicopter / drone inspections??

9

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Lessons learned from FPSO

- How to unite a whole industry in doing things differently
- The importance of viewing maintenance as an enabler and not as a cost
- Accept for thinking two thoughts simulataneously, RAM:
  - Regularity and Availability vs.
  - Maintainability
  - Maintenance as a mean to achieve regularity

10

NOWITECH Norwegian Research Centre for Offshore Wind Technology

ewec 2010 WARSAW Europe's premier wind energy event

Featuring Polish Day Conference 2010

TRANSFER OF METHODS AND EXPERIENCES FROM OPERATION AND MAINTENANCE IN OTHER INDUSTRIES TO DEEP SEA OFFSHORE WIND FARMS

www.ewec2010.info

11

NOWITECH Norwegian Research Centre for Offshore Wind Technology

Corrosion protection of offshore wind turbines

Astrid Bjørgum and Ole Øystein Knudsen

Wind Power R&D seminar – deep sea offshore wind,
Trondheim, 21-22 January 2010

Offshore wind turbines – Challenges

- High corrosivity (marine environment)
- Erosion impacts due to salt particles and water droplets
- Mechanical loads due to floating ice
- Mechanical loads due to biofouling in submerged zone

- Variation in weather conditions
  - Wind
  - Waves
- Reduced accessibility
- Long and irregular inspection intervals
- High maintenance and repair costs

Hywind – www.statoil.com

Corrosion protection – necessary from the very beginning

- Safety reasons
- Regularity in energy production

Environmental conditions:
- Atmospheric zone
- Splash zone
- Sub-merged zone
- Inside the tower

Design of the structure:
- Rotor blades
- Nacelle
- Tower
- Sub-structure
- Mooring

www.statoil.com

How can the turbine be protected?

Application of protective coating systems

- Steel tower
  - Sub-structure
    - Cathodic protection
  - Inside the tower
    - Keeping the internal environment dry
- Blades
  - Corrosion resistant composite materials
- Nacelle
  - Corrosion resistant materials
  - Keeping the internal environment dry

www.statoil.com

Rules and regulations

- International standards
  - IEC 61400 developed to ensure safety for systems and components
  - DNV DNV-OS-J101 is based on existing oil & gas standards/ experience; synchronised with IEC
- National standards
  - Denmark
  - Germany

Standards/Guidelines		Year
IEC 61400-1	Wind Turbines, Part 1 Design requirements:	1999/
IEC 61400-3	Wind Turbines, Part 3: Design requirements for offshore wind turbines	1999/ 2005
Germanische Lloyd - GL Rules and Regulations, II Materials and Welding.	Part 1 Metallic Materials	1998
Germanische Lloyd - GL Rules for Classification and Construction, III Offshore Technology	Guideline for Certification of Offshore Wind Turbines	2003/ 2005
The Danish Energy Agency's Approval Scheme for Wind Turbine	Recommendations for Technical Approval of Offshore Wind Turbines	2001
DNV-OS-J101 (Det Norske Veritas)	Design of Offshore Wind Turbine Structure	2004/ 2007
EU-Project RECOFF. Contract No. ENK-CT-2000-00322	Recommendations for Design of Offshore Wind Turbines	

Protective coatings – offshore oil & gas experience

- NORSOK M-501 specifies
  - Pre-treatment quality
  - Generic type of coatings
  - Film thickness and number of coats
  - Inspection during construction and service
- Experience indicates shorter lifetime of coatings recommended for the atmospheric zone than the 20 years designed life for offshore wind turbines

Exposure conditions	Typical coating system	Lifetime expectancy
→ Atmospheric zone	Zinc epoxy 60 µm Epoxy barrier coat 150 µm UV resistant topcoat 70 µm	Time to first major maintenance is normally about 10 years
Submerged zone	2-coats epoxy Mean dry film thickness 350 µm	According to design life. Degradation of the coating is compensated by sacrificial anodes.
Splash zone	2-coats polyester Mean dry film thickness > 1000 µm	Lifetime of 20 years or more is usually achieved

Are extended coating lifetimes possible?

- To ensure a lifetime corresponding to design life with a minimum maintenance requirement, DNV recommends
  - Use coating systems with documented performance
    - Operational experience
    - Prequalification (NORSOK M-501)
  - Control that specified surface preparation and application conditions are followed

Exposure conditions	Typical coating system	Dry film thickness (DFT)
Atmospheric zone	A coating system according to ISO 12944-5, category C5-M (very high corrosivity): - zinc rich epoxy primer - intermediate epoxy - epoxy or polyurethane topcoat, polyurethane if a colour or gloss retention is required	Minimum 320 µm
Splash zone	- Glass flake reinforced epoxy or polyurethane or - Thermally sprayed aluminium with a silicon sealer	Minimum 1.5 mm Minimum 200 µm
Submerged zone	- Multilayer two component epoxy and cathodic protection - Alternatively cathodic protection only	Minimum 450 µm No coating

SINTEF Materials and Chemistry 7

Challenges for offshore wind turbines

- Keep costs low
- Higher energy output
  - Improved foundation technology
  - Enlarged wind turbines
- Steel foundations seem to be competitive to concrete
- 50 years design lifetime is possible for steel structures
- What about the corrosion protection?


www.energy.siemens.com

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Coating systems in use

Offshore wind parks [1]

- Outside
  - Zinc duplex systems
    - Thermally sprayed zinc-TSZ [2]
    - Paint system
- Inside
  - Mainly paint alone
  - TZS specified in splash zone on some towers
- Generally limited information on coatings and coating performance

Windpark	Operation year	Protection system outside		Protection system inside	
		Coating [1]	DFT (µm)	Coating	DFT (µm)
Tunø Knob	1995	Metallization Epoxy Epoxy Polyurethane topcoat	80 µm 100 µm 100 µm 50 µm	Zinc epoxy Epoxy	40 µm 2x 140 µm
Vindeby 11 turbines installed	1991	Metallization Epoxy Epoxy Polyurethane topcoat	120 µm 100 µm 100 µm 50 µm	Epoxy Epoxy	75 µm 150 µm
Utgrunden 7 turbines installed	2000	Zinc epoxy Epoxy Polyurethane topcoat	75 µm 2 x 110 µm 50 µm	Zinc epoxy Epoxy	70 µm 150 µm
Middelgrunden 20 turbines installed	2001	Metallization Epoxy Epoxy Polyurethane topcoat	100 µm 120 µm 100 µm 50 µm	Metallization Epoxy Epoxy	80 µm 100 µm 100 µm
Horns Rev 80 turbines installed	2002	Metallization Epoxy Epoxy Polyurethane topcoat	100 µm 100 µm 120 µm 50 µm	Metallization Epoxy Epoxy	80 µm 100 µm 100 µm
Samsø	2003	Metallization Epoxy Epoxy Polyurethane topcoat	80 µm 120 µm 100 µm 50 µm	First 10 m: Metallization Epoxy Above 10 m: Zinc epoxy Epoxy	 60 µm 200 µm 50 µm 100 µm

[1]: Reported by Hempel
[2]: Mainly Zinc/Al - TSZA (85/15)

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Corrosion protection on new projects

Hywind

- Coating systems on substructure based on
  - NORSOK M-501
  - Statoils experiences from offshore oil & gas
- Standard tower/turbine
  - Not known, but probably according to ISO 12944, class C5-M
- Tower and nacelle
  - Climate inside controlled by dehumidifiers

Sharingham Shoal wind park

- Substructure
  - Paints according to NORSOK M-501 in/above splash zone
  - Cathodic protection (sacrificial anodes) only in submerged zone
- Tower
  - ISO 12944, class C5-M
- Below the air-tight deck
  - No coating applied inside
  - 6 mm corrosion allowance added

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Corrosion protecting coating systems for offshore wind turbines

Demands

- Rapid production
- Low investments costs
- Low costs in service
- Long lifetime compared to lifetime experienced for offshore oil & gas installations

↓

- Maintenance-free coating systems

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Alternative protection systems today

Conventional coating system

- Experiences from offshore oil and gas installations
  - First maintenance after 8-0 years
- According to Hempel
  - Existing NORSOK M-501 qualified coating systems has 20-25 years lifetime
  - A minor increase in the dry film thickness may increase the lifetime to 25 - 30 years

Including metallization

- Already used on offshore wind turbines
- Used by the Norwegian Public Roads Administration since 1965
  - Rombak bridge showed no corrosion after 40 years
  - Coating system
    - Thermally sprayed zinc (TSZ)
    - Corrosion protecting paint


Rombak Bridge, www.Wikipedia.com

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Our recommendations – existing coatings

- Recently, a life cycle cost analysis has been performed for
  - Conventional three-coats system
  - TSZ duplex systems
- Metallization
  - 30-50% cost increase in construction
  - 30% LCC saved by avoiding maintenance

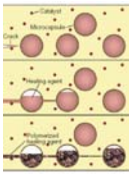
We recommend

- TSZ duplex system
  - Atmospheric and splash zone
- Combined cathodic protection and epoxy coating in submerged zone

- Reduced application costs
  - Automation of coating application
  - Reduce the number of paint coats

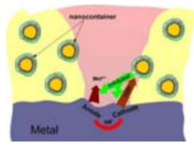
New coating technology

- Self repairing coatings may improve corrosion performance of a coating system
  - Healing agents release from microcapsules
  - Chemical inhibiting species release in connection to coating damages



Picture from publication of W. Schott

- Before such coatings can be used on offshore wind turbines we need further
  - Evaluation
  - Optimization



Thank you for your attention!

D Installation and sub-structures

Research at Alpha Ventus: RAVE and GIGAWIND,
Prof. Dr.-Ing. habil. Raimund Rolfes, ForWind, Leibniz University Hannover

Hydrodynamic effects on bottom-fixed offshore wind turbines, Karl O. Merz, PhD student NTNU, Prof G Moe, NTNU, Prof Ove T. Gudmestad, Univ. of Stavanger

Supply of jackets to the Alpha-Ventus wind farm, Jørgen Jorde, NorWind

Cost comparison of sub-structures, Daniel Zwick and Haiyan Long,
PhD students NTNU

Research at Alpha Ventus:
RAVE and GIGAWIND

RAVE
RESEARCH AT ALPHA VENTUS
Eine Forschungsinitiative des Bundesumweltministeriums

Raimund Rolfes, P. Schaumann, T. Schlurmann, L. Lohaus, M. Achmus, G. Haake (Leibniz Universität Hannover), H. Huhn, M. Durstewitz (Fraunhofer-IWES)

Outline

- Policy – Germanys offshore wind strategy
- about alpha ventus offshore wind farm
- The RAVE research initiative
- GIGAWIND *alpha ventus* Research on support structures


alpha ventus in Nov 09

German offshore strategy

Achievement of
- ~25 GW offshore capacity until 2030,
- profound offshore technology know how
- Independence from energy imports from other countries (nuclear, oil and gas)

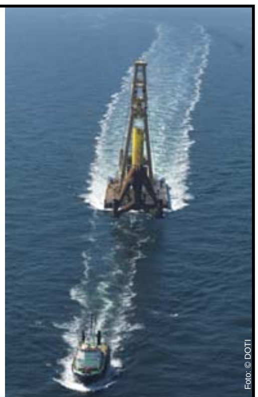
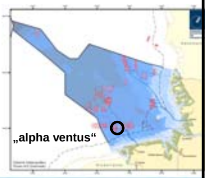


Foto: © DOTI

About alpha ventus

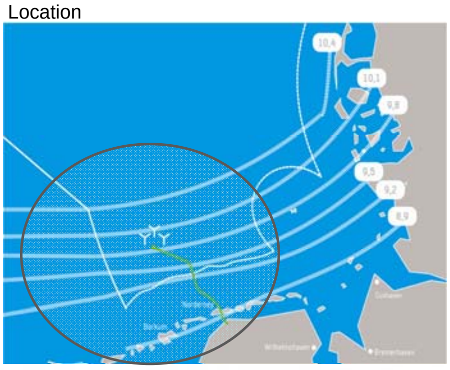

2nd installation phase 2009

- 1st German offshore wind farm
- 12 OWEC á 5MW (Multibrid / REpower)
- operator: DOTI
- distance from coast: 45km
- water depth: 30m
- planning: since 2006
- installation: 2008 – 2009
- Research: RAVE

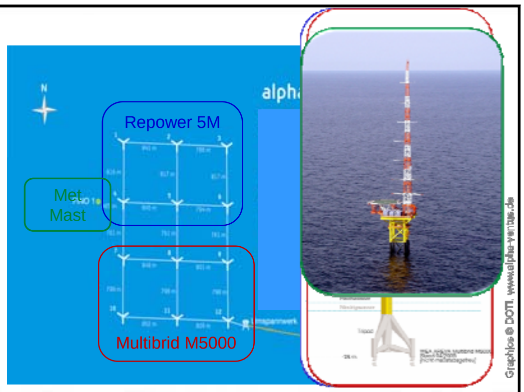


About alpha ventus

Location


Graphics © DOTI www.alpha-ventus.de

Layout of alpha ventus



Graphics © DOTI www.alpha-ventus.de

Initiative of Government (BMU)

- Support of accompanying research in at alpha ventus
- Budget: ~50 M€ within five years
- 2009: 25 projects approved, budget ~35 M€

targets

- Validation of offshore performance capability of 5 MW turbines
- Further development of offshore technology
- Study important issues of offshore wind energy use
- Expansion of Germanys research potential

Overview research initiative RAVE

RAVE-research initiative

- 25 individual projects
- 15 single or joint research projects
- 9 coordinating entities
- 40+ project partners
- measurements with ~ 1,200 sensors (available to accredited reseachers)

RAVE – research consortium

- Operation, Coordination, Measurements
  - Development and construction of alpha ventus (DOTI)
  - RAVE Coordination (IWES)
  - Realization of the RAVE measurements and data management (BSH)

RAVE coordination committee

- Foundation and support structures
  - GIGAWIND alpha ventus - Holistic design concept for offshore WT support structures on the base of measurements at the offshore test field alpha ventus (LUH)
  - Cyclic loads at offshore foundations (BAM)

RAVE – thematic research topics (1)

- Turbine Technology and Monitoring
  - Optimization of components (REpower)
  - Performance-optimized and cost-efficient rotor blade (REpower)
  - Further development, construction and test of the M5000 turbine in offshore conditions (Multibrid)
  - LIDAR wind measuring techniques (Uni Stuttgart)
  - „OWEA" - Verification of offshore turbine designs (Uni Stuttgart)
  - "Offshore WMEP" - Monitoring of the offshore wind energy deployment in Germany Monitoring (IWES)

Simulation of wind turbine rotor aerodynamics with computer fluid dynamics (CFD)

RAVE – thematic research topics (1)

- Grid Integration
  - Grid integration of offshore wind energy (IWES)
- Ecology and Environment
  - Operating noises and sound propagation between tower and water (Fh Flensburg)
  - Ecologic research - Evaluation of StUK 3 (BSH)
  - Sonar transponders for offshore wind energy converters (LUH)
  - "Hydrosound" – Research and testing of a little bubble curtain in the test field alpha ventus (LUH)
  - Geology (BSH)

Little Bubble Curtain as protection for maritime marmals

RAVE – thematic research topics (2)

"Holistic Design Concept for OWEC Support Structures on the base of measurements at the offshore test field alpha ventus"

GIGAWIND *alpha ventus*

BMU project (Coordination: LUH)
3 Mio. €

RAVE – 50 Mio. € (member in)

GIGAWIND project Leibniz Universität Hannover (75%)

GIGAWIND project Fraunhofer-Gesellschaft IWES (25%)

cooperation partners with supporting function (Multibrid GmbH, REpower Systems AG)

own funding

GIGAWIND alpha ventus

GIGAWIND *alpha ventus*

Institut für Stahlbau
deputy coordination

ISD Institut für Statik und Dynamik
coordination

Fraunhofer IWES

ForWind
Leibniz Universität Hannover

IfB Institut für Baustoffe

Cooperation Partners:

AREVA MULTIBRID

Franzius-Institut für Wasserbau und Küsteningenieurwesen

IGBE

REpower Systems

associated project in: RAVE Research at alpha ventus

funded by: PtJ Projektträger Jülich

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

GIGAWIND alpha ventus consortium

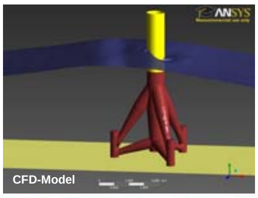
RAVE Research at alpha ventus

Targets:

- Reduction of the cost for OWEC support structures (tower, substructure and foundation)
  - lighter support structures (material cost)
  - optimised design process (personnel cost)
- Integration of separate computational tools into an easy operable simulation and design package with common interfaces
  ➔ holistic design concept
- Cooperation with industry
  ➔ research according to need
- Validation with measurement data from the test site "alpha ventus"

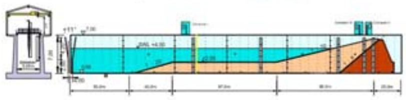
Targets of GIGAWIND

- Objective: Optimisation of wave load models
  Method: Parameter analysis (labour, CFD) => model => validation
- Physical testing
  Analysis of specific parameters and effects under labour conditions, Franzius Institute, January to March 2010 in "large wave flume"
- Measurement data from alpha ventus
  Comparison of measurement data of water pressure in circumferential direction labour with data from alpha ventus (February 2010).
- Numerical simulation
  Calibration of CFD Models with labour data and alpha ventus data for simulation of non-breaking and breaking waves.



Wave load models

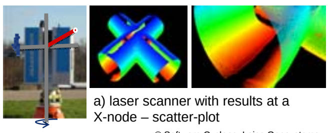
ForschungsZentrumKüste (FZK)
Gemeinsame zentrale Einrichtungen der LUH und der TU BS



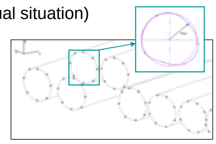
World biggest wave flume in Hannover (324m x 7m x 5m)

Laboratory testing

- Influence of manufacturing aspects on fatigue resistance
  - Measurement of node geometries (actual situation) with laser scanner und tachymeter



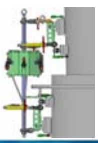
a) laser scanner with results at a X-node – scatter-plot



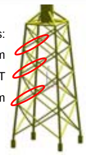
b) tachymeter - results tubes in store, out-of-roundness (raised)

© Software Cyclone, Leica Geosystems

- Relative displacement at Grouted Joint
  - Inductive measurement of displacement (3 directions)
  - flexible installation



Analysis of fatigue resistance

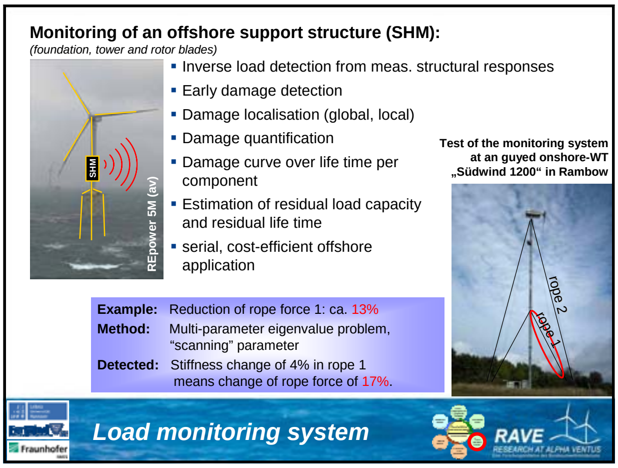


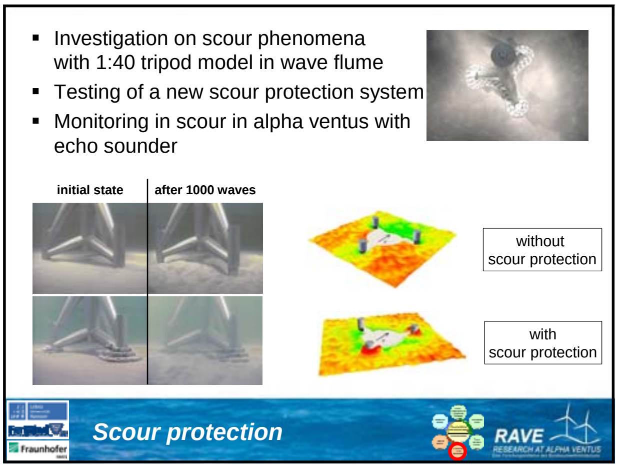
Example: Mineral corrosion protection system

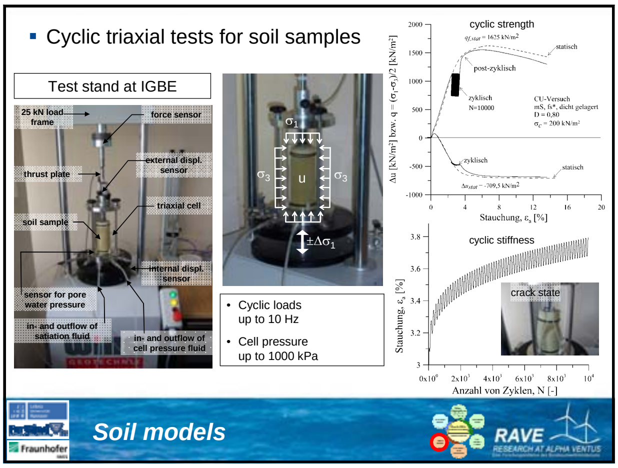
Installed coupons on the jacket

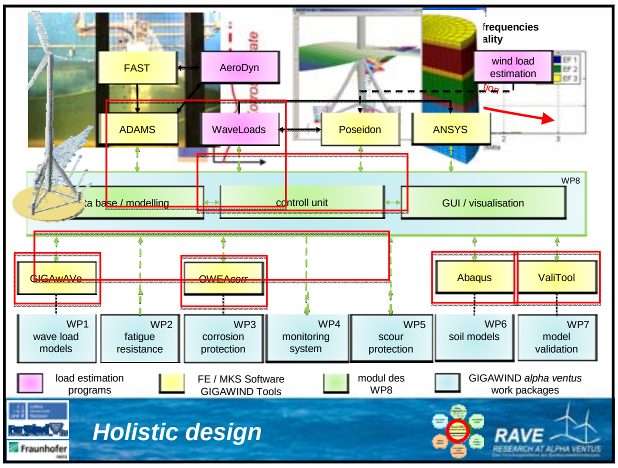
Online monitoring of corrosion (ISO 20340)
Paints and varnishes – performance requirements for protective paint systems for offshore and related structures.
After 6 / 27 cycles

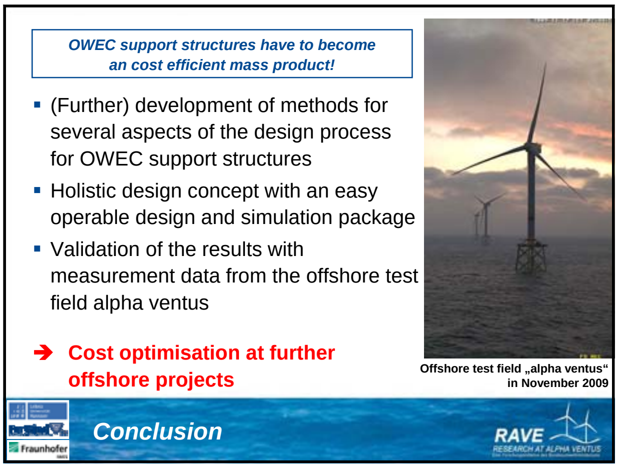
Corrosion protection


Monitoring of an offshore support structure (SHM):
(foundation, tower and rotor blades)
Inverse load detection from meas. structural responses
Early damage detection
Damage localisation (global, local)
Damage quantification
Damage curve over life time per component
Estimation of residual load capacity and residual life time
serial, cost-efficient offshore application
SHM
REpower 5M (av)
Test of the monitoring system at an guyed onshore-WT „Südwind 1200" in Rambow
rope 2
rope 1
Example: Reduction of rope force 1: ca. 13%
Method: Multi-parameter eigenvalue problem, "scanning" parameter
Detected: Stiffness change of 4% in rope 1 means change of rope force of 17%.
Load monitoring system
RAVE


Investigation on scour phenomena with 1:40 tripod model in wave flume
Testing of a new scour protection system
Monitoring in scour in alpha ventus with echo sounder
initial state
after 1000 waves
without scour protection
with scour protection
Scour protection
RAVE


Cyclic triaxial tests for soil samples
Test stand at IGBE
25 kN load frame
force sensor
thrust plate
external displ. sensor
triaxial cell
soil sample
internal displ. sensor
sensor for pore water pressure
in- and outflow of satiation fluid
in- and outflow of cell pressure fluid
Cyclic loads up to 10 Hz
Cell pressure up to 1000 kPa
cyclic strength
cyclic stiffness
crack state
Stauchung, ε_1 [%]
Anzahl von Zyklen, N [-]
Soil models
RAVE


FAST
AeroDyn
ADAMS
WaveLoads
Poseidon
ANSYS
wind load estimation
frequencies
GUI / visualisation
controll unit
WP8
GIGAWAVe
OWEAcorr
Abaqus
ValiTool
WP1 wave load models
WP2 fatigue resistance
WP3 corrosion protection
WP4 monitoring system
WP5 scour protection
WP6 soil models
WP7 model validation
load estimation programs
FE / MKS Software GIGAWIND Tools
modul des WP8
GIGAWIND alpha ventus work packages
Holistic design
RAVE


OWEC support structures have to become an cost efficient mass product!
(Further) development of methods for several aspects of the design process for OWEC support structures
Holistic design concept with an easy operable design and simulation package
Validation of the results with measurement data from the offshore test field alpha ventus
➔ Cost optimisation at further offshore projects
Offshore test field „alpha ventus" in November 2009
Conclusion
RAVE

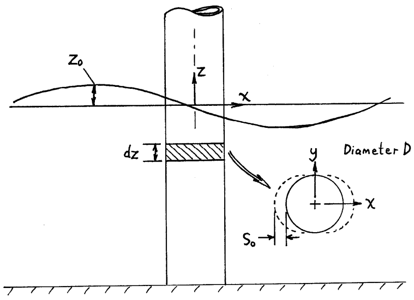

Thank you for your attention!
www.gigawind.de
www.rave-offshore.de
www.alpha-ventus.de
www.forwind.de
Fatigue resistance / manufacturing aspects
Load modelling for waves
Corrosion protection
Holistic design concept
Model validation
Soil modelling
Load monitoring systems
scour protection / scour monitoring
Loads
Durability
Foundations
RAVE
GIGAWIND alpha ventus


RAVE
RESEARCH AT ALPHA VENTUS
Fraunhofer

A Review of the Morison Equation for Calculating Hydrodynamic Loads on Vertically-Oriented Cylinders

Karl Merz
Department of Civil Engineering
Norwegian University of Science and Technology (NTNU)
January 22, 2010

A Definition of the Problem



Find the net force of the fluid on the structure, *F(z,t)*.

Key Points

The loads on the structure are a function of **several flow processes** (waves, current, structural motion) which act simultaneously and interact nonlinearly.

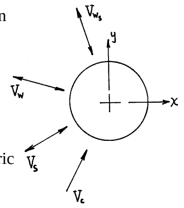
Calculation of loads is heavily empirical. There is a lot of laboratory data at flow parameters (like Reynolds number) that are not representative of full-scale structures. There have been field measurements on full-scale structures, but here the flow parameters are somewhat uncertain. Connecting the two is not easy; design values should not be considered "final" or broadly applicable.

The value used for **fluid damping should be calibrated independently of the primary drag coefficient** C_D, and should be guided by full-scale data.

There are several important, outstanding issues that are not considered in this presentation:
- free surface effects, run-up, draw-down, impact (slamming), and ringing ("burst motions")
- negative damping, "lock-in", the interaction of vortex shedding and structural vibration
- forces on members at an angle to the oncoming flow, or parallel to the free surface

Flow Processes

It is convenient to think about the hydrodynamic loading in terms of flow processes. Multiple processes – wind-generated waves, remote swell, current, and structural motion – are active simultaneously, and their (nonlinear) interaction results in the fluid force on the structure.



(For the present discussion, we shall assume that each process can be described by a single dominant trigonometric term; in reality, multiple harmonics are involved.)

The net flow velocity vector may exhibit large fluctuations in both direction and magnitude. If the flow separates, forming a wake of shed vortices, then there is a ``memory effect"; the pressure about the structure is a function not only of the instantaneous flow velocity vector, but also its time history.

$$\begin{aligned} V = &V_{w0}\sin(2\pi f_w t + \psi_w)(\cos\theta_w \mathbf{i} + \sin\theta_w \mathbf{j}) \\ &+ V_{w0,s}\sin(2\pi f_{ws} t + \psi_{ws})(\cos\theta_{ws} \mathbf{i} + \sin\theta_{ws} \mathbf{j}) \\ &+ \dot{s}_0 \sin(2\pi f_s t + \psi_s)(\cos\theta_s \mathbf{i} + \sin\theta_s \mathbf{j}) \\ &+ |V_c|(\cos\theta_c \mathbf{i} + \sin\theta_c \mathbf{j}) \end{aligned}$$

Morison Equation

How do we predict loads on the structure? For large-volume structures (Kc = $V_{w0}/f_w D$ < 1 or 2), potential theory is used to calculate the wave forces, with an empirical drag force (the second term in the equation below) superposed to account for a steady current.

Typical ocean wavelengths are over 40 m, therefore wind turbine towers will typically be considered small-volume structures. In this case, the Morison equation is used. This equation is a little bit of theory combined with a lot of empiricism:

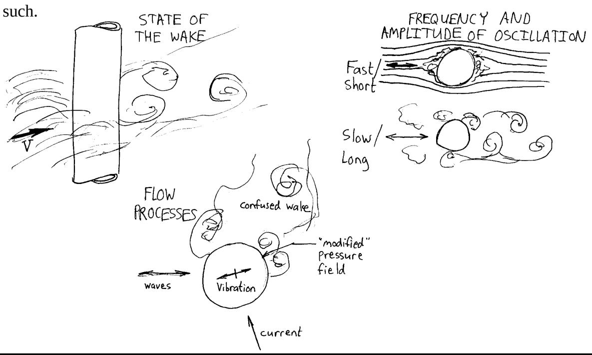
$$dF = \rho \frac{\pi D^2}{4}\ dz\ C_M\ \dot{V} + \frac{1}{2}\rho D\ dz\ C_D\ |V|\ V$$

The Morison equation states that the fluid force is a superposition of a term in phase with the acceleration of the flow (inertia), and a term whose dominant component is in phase with the velocity of the flow (drag). It accounts for some flow nonlinearity, by way of the drag term.

The Morison equation is deterministic. In itself it does not account for the history of the flow (the state of the wake), the frequency with which the flow oscillates back and forth, nor the fact that the instantaneous velocity vector *V* arises as a superposition of several flow processes.

Morison Equation: Empirical Coefficients

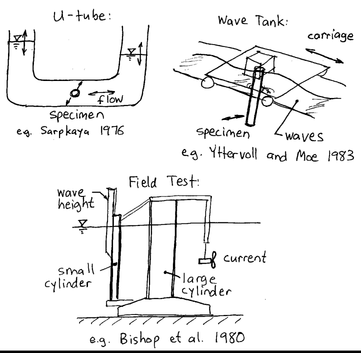
The effect of the history of the flow on the fluid force *dF* must be accounted for entirely by the coefficients C_M and C_D. In other words, the coefficients are a function of the state of the wake, the flow processes which are active, the frequency of flow oscillation, and such.



Morison Equation: Empirical Coefficients

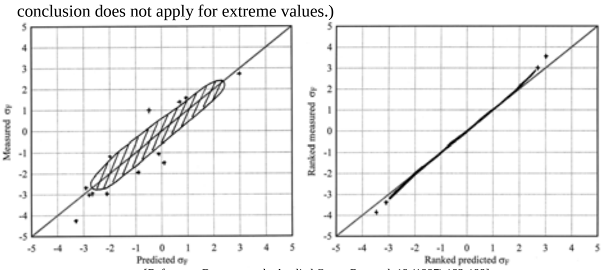
Coefficients are determined by either a laboratory experiment or measurements on a field test rig mounted in the ocean.

Flow conditions in the laboratory are controlled, while in the field there is always some uncertainty as to the local flow conditions. However, the results of laboratory experiments are seldom directly applicable to the design of full-scale structures; typically, the Reynolds number is much too low.



Morison Equation: Empirical Coefficients

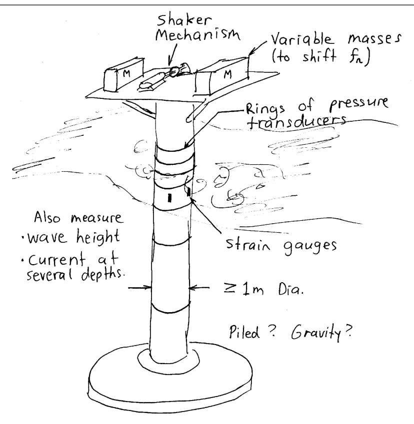
When an experiment is performed, and the coefficients in the Morison equation are calibrated to the experiment, then a good correlation is obtained, particularly if experimental and calculated load cycles are ranked lowest to highest. (This conclusion does not apply for extreme values.)



[Reference: Burrows et al., Applied Ocean Research 19 (1997) 183-199]

There is a need for further *field measurements* regarding the interaction between fluid flow and structural motion, particularly the appropriate value of C_D with which to calculate fluid damping of structural motion, under various flow conditions.

An Experiment I Would Like to See



Morison Equation: Multiple Flow Processes

Write the Morison equation such that the multiple flow processes are explicit:(1)

$$dF = \rho \frac{\pi D^2}{4}\ dz\ a_w + \rho \frac{\pi D^2}{4}\ dz\ (C_M - 1)\ (a_w - \ddot{s})$$

$$+ \frac{1}{2}\rho D\ dz\ C_D\ |u_w + u_c - \dot{s}|\ (u_w + u_c - \dot{s})$$

But, each process is acting with its own amplitude, frequency, and phase. Why should we be able to describe the effects of the simultaneous wave, current, and structural motion processes through just one drag coefficient and one added mass coefficient? Propose:

$$dF = \rho \frac{\pi D^2}{4}\ dz\ C_{M1}\ a_w - \rho \frac{\pi D^2}{4}\ dz\ (C_{M2} - 1)\ \ddot{s}$$

$$+ \frac{1}{2}\rho D\ dz\ |c_{d0} u_c + c_{d1} u_w - c_{d2}\dot{s}|\ (c_{d0} u_c + c_{d1} u_w - c_{d2}\dot{s})$$

This equation says that the processes interact, but they do so with different strengths.

(1): Swell and wind-generated waves have been combined into one "wave" term.

Morison Equation: Multiple Flow Processes

Attempting to derive firm values for all those empirical coefficients would be clumsy and difficult. Is the separate-coefficient form of the Morison equation useful for anything?

Yes. Consider a case in which the amplitude of the structural velocity is small in comparison with the combined amplitude of the wave and current velocities, say, $s_0 < 0.2\ (u_{w0} + u_{c0})$. Then, neglecting terms of $O(s^2)$, the drag term of the separate-coefficient Morison equation can be written as:

$$dF_D = \frac{1}{2}\rho D\ dz$$

$$\times \left[|c_{d0} u_c + c_{d1} u_w|\ (c_{d0} u_c + c_{d1} u_w) - 2 |c_{d0} u_c + c_{d1} u_w|\ (c_{d2}\dot{s}) \right]$$

If we assume (following current practice) that we can derive a single drag coefficient C_D that is representative of the combined effects of c_{d0} and c_{d1}, then we can write the drag term:

$$dF_D = \frac{1}{2}\rho D\ dz\ \left[\ C_D\ |u_c + u_w|\ (u_c + u_w) - 2C_{D2}\ |u_c + u_w|\ \dot{s} \right]$$

Damping

$$dF_D = \frac{1}{2}\rho D\ dz\ \left[\ C_D\ |u_c + u_w|\ (u_c + u_w) - 2C_{D2}\ |u_c + u_w|\ \dot{s} \right]$$

This equation is useful, because it gives us the means to – and, in fact, says that we should – calibrate our structural damping independently from the calibration of the primary loading. This has been corroborated by experiment, for example Yttervoll and Moe (1983).

Because the loading associated with the $|u_c + u_w|\ (u_c + u_w)$ term may be several times the magnitude of the loading associated with the $|u_c + u_w|\ (ds/dt)$ term, it is advisable to determine, or at least validate, the value of C_{D2} based upon damping measurements, rather than a least-squares fit to force data.

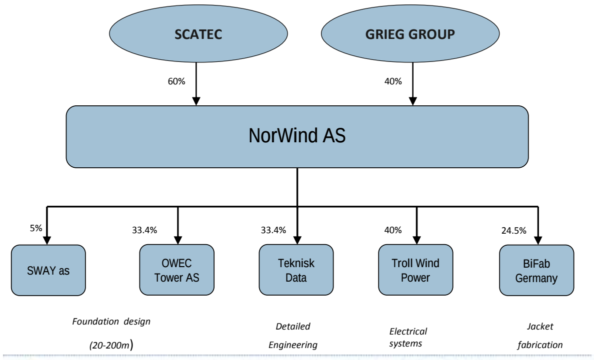
Alpha Ventus Jacket Installations

22. January 2010

www.norwind.no

NorWind

Company overview



NorWind

Alpha Ventus Offshore Wind Project based on pre-piling of Jacket foundations

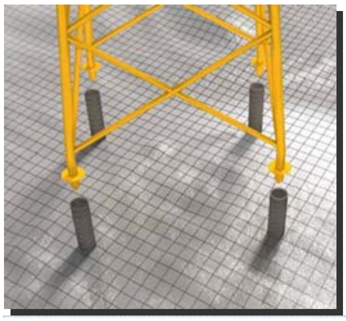
PROJECT: ALPHA VENTUS

- Location: Borkum Island, Germany
- Customer: DOTI (Vattenfall, E.On, EWE)
- Contractor: NorWind
- Scope: Engineering, Procurement, Construction and Installation of 6 jacket foundations
- Jacket: 6 off/500 T/60 m/ 20x20m
- Pile: 24 off/75 T/35-40m/OD: 72'
- Depth: 28 m
- Soil: Sand

NorWind

Photographs courtesy of: Doti, OWEC Tower, BiFab, NorWind

Short introduction to the installation methodology



- Pre-piling decided – tight tolerances on pile installation
- First: Drive piles: Piling vessel, hammer, pile frame, verification
- Second: Install jacket: Installation vessel, grouting vessel

NorWind

Piling frame and template

- A centre template (TMP) is used to secure position on seabed, designed: IHC SeaSteel.
- A IHC SeaSteel piling frame (72SLOT) is moved around the centre template for the 4 pile locations.
- This method is verified to ensure correct x y positions of the piles including inclination.

NorWind

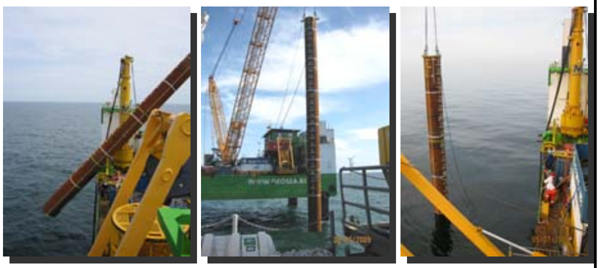
Piling vessel

- Buzzard – owned by GeoSea
- Jack-up rig with no propulsion
- Deck space very confined
- Limited carrying capacity
- Crawler crane
- No helideck

NorWind

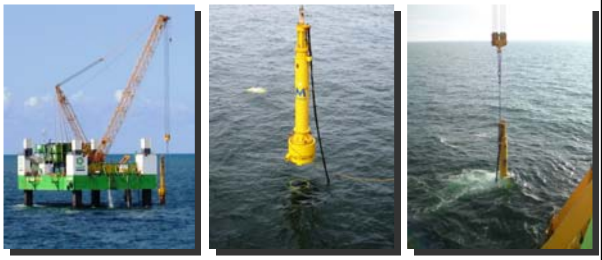
Pile installation

- Piles are loaded onboard and up-ended in an up-ending tool prior to lifting the piles into the slot on the seabed.



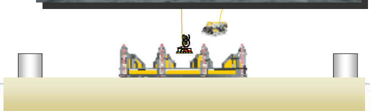
Pile driving

- Piles are driven/ hammered down using a sub sea hammer from Menck, monitored by ROV and measurement equipment from NGI



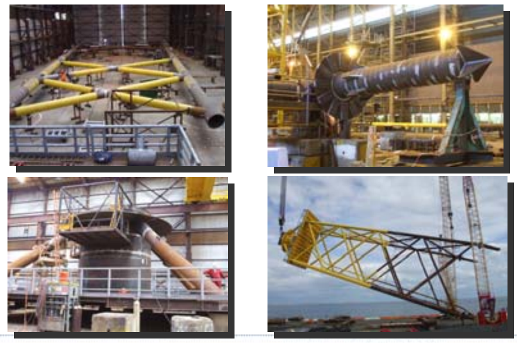
ROV operations

- Oceaneering WROV was used for all underwater operations including:
  - hook on/off
  - position verifications
  - pile measurements
  - pile excavation
- Underwater visibility of only 1 - 2 meters and current up to 3 knots



Jacket fabrication

•OWEC Tower Quattropods fabricated at BiFab (Scotland)



Jacket transportation

Jacket transportation

Installation of Jackets

Jacket installation

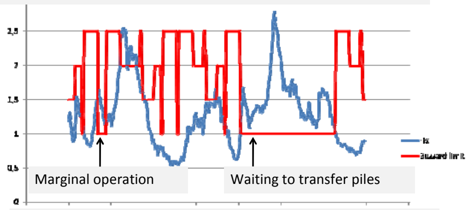
•Heerema's Thialf DP crane vessel (15 000 tonnes capacity)

Grouting of jacket (subsea)

•Grouting Vessel – Toisa Valiant, owned by Sealion
•Grouting contractor – ULO/Miles Offshore
•ROV contractor – Fugro Offshore Survey

Comparison: Operations modelled in real weather data

Time series of Significant wave height, from Alpha Ventus June 2009, installations at three sites (12 piles)



Jack-up operations
Rapid sequencing → shorter ops period than weather changes!

New concept – pile and jacket installation vessel

NorWind and partners have designed a new vessel concept for installation of piles and jackets. The vessel is based upon the following:

- Experience gained from the Alpha Ventus project
- Experience from the oil and gas, and from the maritime industry
- The following companies are involved in our project
  - Maritime Projects – project manger
  - Marintek – vessel simulations/model testing
  - Rolls Royce & Kongsberg – dynamic positioning system
  - TTS Marine – cranes & lifting equipment
  - DnV – 3. party verification

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Cost comparison of support structures

Department of Civil and Transport Engineering
Daniel Zwick, Haiyan Long, Geir Moe

Overview

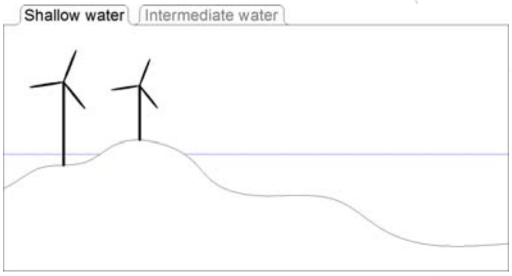
- Development of offshore wind energy
- Selection of concepts for support structures
- Cost comparison
- Other aspects of the support structure design
- Summary

From shallow to intermediate water

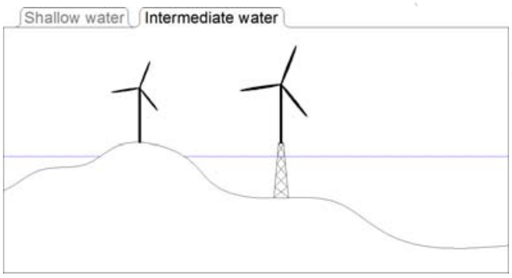
Horns Rev, 6-14m water depth, 2002

Alpha Ventus, 30m water depth, 2009

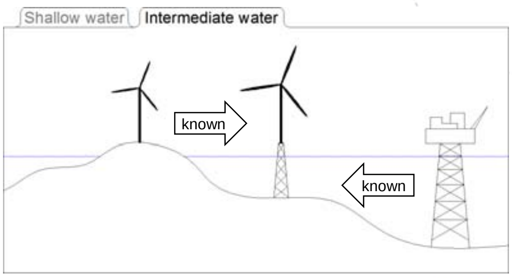
Development of support structures



Development of support structures



Development of support structures



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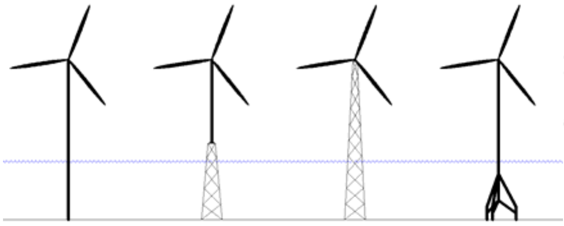
Different concepts



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Driving force for selection

- **Costs**
  - material
  - fabrication
  - transport
  - installation
- **Consequences for total concept**
  - rotor configuration
  - lifetime of the structure
  - maintenance

Beatrice Project, 45m water depth, 2007

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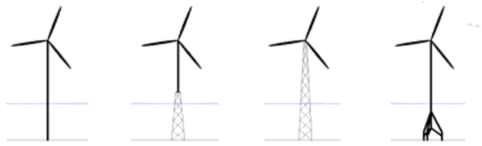
Weight comparison of concepts



fully tubular	lattice-tubular	fully lattice		tripod-tubular
	4-legs	3-legs	4-legs	
1000t	710t *	700t	540t	800t *

(weights of substructure and tower, * from www.alpha-ventus.de)

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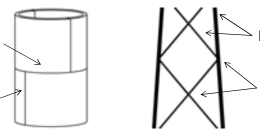
Fabrication of support structures



		Number of welds	Tube diameter	Wall thickness
fully tubular		140	3,9-7,3m	19-88mm
fully lattice			legs / bracings	legs / bracings
	3-legs	250	1,1m / 0,39m	56mm / 19mm
	4-legs	330	0,9m / 0,36m	35mm / 14mm

Tower design for 30m water depth, tower height 120m.

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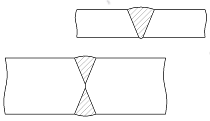
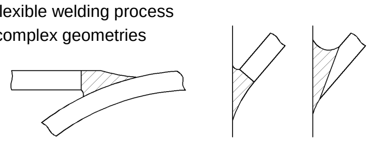
Welding of support structures

- **Submerged arc welding (SAW)**
  - effective welding process
  - suitable for large wall thickness
  - simple geometries
- **Flux core arc welding (FCAW)**
  - flexible welding process
  - complex geometries





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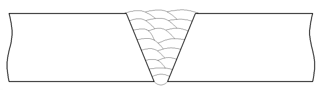
Important parameters

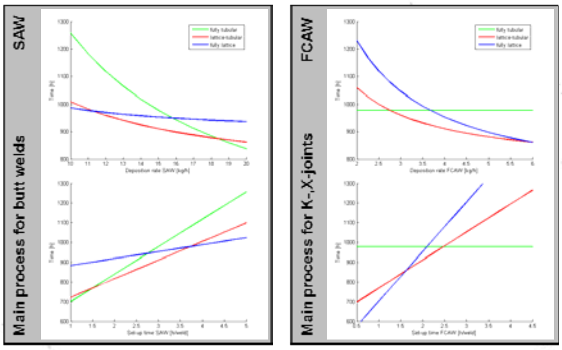
- **Deposition rate [kg/h]**
  - for calculation of the net welding time
- **Set-up time [h/weld]**
  - preparation
  - inspection

SAW	FCAW
typical 10-15kg/h	typical 3-5kg/h

Depends mainly on:
- size and geometry of the joint
- fabrication facilities

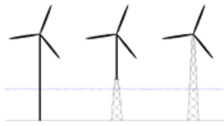


Comparison of fabrication costs



Comparison of fabrication costs

- no big difference in net welding time inclusive joint set-up
- most steel used for fully tubular tower, least for fully lattice tower



- Not considered...
  - complexity of fabrication of the whole structure
  - tubes are more expensive than plates

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Other aspects

transparency | downwind | tower wake | service

transparency of lattice towers to waves and winds

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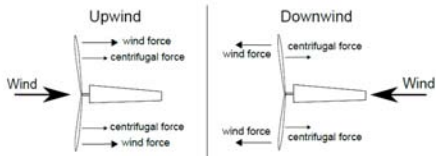
Other aspects

transparency | **downwind** | tower wake | service



possible use of downwind rotors
- blade coning can keep blades away from tower
- may generate less torsion of the tower

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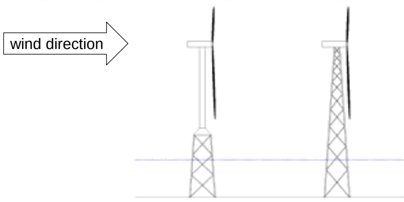
Other aspects

transparency | downwind | **tower wake** | service



influence of tower wake effects to the blades

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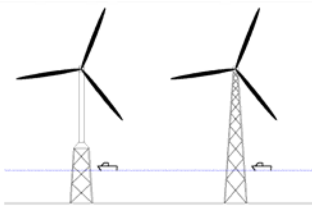
Other aspects

transparency | downwind | tower wake | **service**



access for service and maintenance

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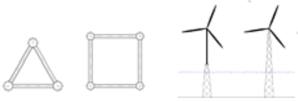
3- vs. 4-legs / hybrid vs. fully lattice



- tower mass
- number of welds
  weld metal mass
- fabrication complexity

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Summary

- fully tubular not suitable for intermediate water depth
- lattice-tubular and fully lattice as competitive concepts
- key figures are the fabrication facilities and methods
- transparency of lattice towers to waves and winds

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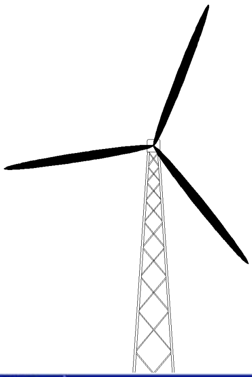

...questions?

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Closing session – expert panel on R&D needs for developing offshore wind farms

The European research agenda on offshore wind, Beate Kristiansen, Research Council of Norway

State-of-the-art design practices for offshore wind farms, Peter Hauge Madsen, Risø DTU

Panel debate on R&D needs for developing offshore wind farms

Dr habil Hans-Gerd Busmann, Head of Fraunhofer IWES
Peter Hauge Madsen, Head of Wind Energy Division, Risø DTU
Dr Olimpo Anaya-Lara, University of Strathclyde
Finn Gunnar Nielsen, Chief Scientist, Statoil
Bo Rohde Jensen, Senior Specialist, Vestas Wind Systems A/S
Terje Gjengedal, R&D director, Statnett

The European research agenda on offshore wind

Beate Kristiansen, Special Adviser / EU NCP Energy

Drivers for the R&D

The climate and energy targets for 2020:

- **20 % renewable energy**
- **20 % energy efficiency/saving**
- **20 % GHG reduction**

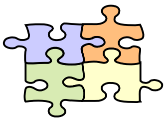
Three pillars:

➔Competitiveness
➔Energy security
➔GHG

Strategic Energy Technology (SET) Plan

- The technology pillar of the EU's energy & climate policy

➔Cooperation!



- **Member States**: *Steering Group*
  - Strategic planning and implementation; Reinforce the coherence between nation.
  - Lead by the EC
- **Industry**: *European Industrial Initiatives (EII)*
  - Strengthen industrial energy research and innovation
  - Promising technologies where barriers, investment and risk better tackled collectively.
    - Grid, **Wind,** Sun, CCS, Bio, Cities/efficiency, nuclear fission
- **Research institutes**: *European Energy Research Alliance (EERA)*
  - Cooperate – excising activities

SET-plan Roadmaps

- **Action plan, targets, activities:**
  1. R&D programmes: basic and applied, pilot, test facilities
  2. Demonstration programmes
  3. Market replication measures
- **Resources needed:**
  - From 3 to 8 bill euro per year
    ~ 50 bill Euro the next 10 years
- **Org. & instruments/funding:**
  - Ongoing
    - Programme cooperation, ERA-NET+, JTI...
    - EEPR, EU ETS, EIB, FP7, MS programmes....
  - Variable geometry (voluntary)

EWI, Industrial Wind Initiative

- **Industrial sector objective:**
  enable 20 % share wind in EU electricity by 2020
- **Roadmap:**
  - ***What:*** reduce costs, move offshore and resolve grid integration
  - ***How*:**
    1. New turbines & components
    2. Offshore technology
    3. Grid integration
    4. Resource assessment
  - ***Cost:*** 6bn€

Roadmap actions (I)

1) **New turbines/components:** lower investment, O&M costs:

- **R&D programme:** new turbine designs, materials and comp.; on- and offshore applications; demo. programme on large scale turbine prototype (10-20MW).
- **Network** of 5-10 European **testing facilities:** efficiency & reliability of turbine systems.
- **EU cross-industrial cooperation and demo. programme:** mass production of wind systems: increased component and system reliability, advanced manufacturing techniques, and offshore turbines. 5–10 demo. projects.

Roadmap actions (II)

2) Offshore technology: structures for large-scale turbines and deep waters (>30 m).

- **Dev. and demo. programme:** new structures; distant from shore; different water depths.

  At least 4 structure concepts developed & tested under different conditions.
- **Demonstration programme:** advanced mass-manufacturing processes of offshore structures.

Roadmap actions (III)

3) Grid integration, large-scale penetration of variable electricity supply.

A programme on wind farms management as "virtual power plants", demonstrate at **industrial-scale**:

- Offshore wind farms interconnected to at least two countries and use of different grid interconnection techniques.
- Long distance High Voltage Direct Current.
- Controllable multi-terminal offshore solutions with multiple converters and cable suppliers.

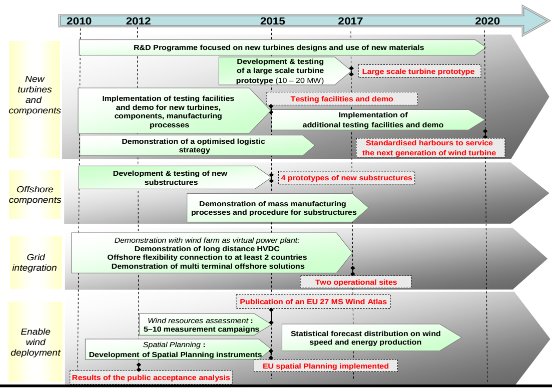
Roadmap actions (IV)

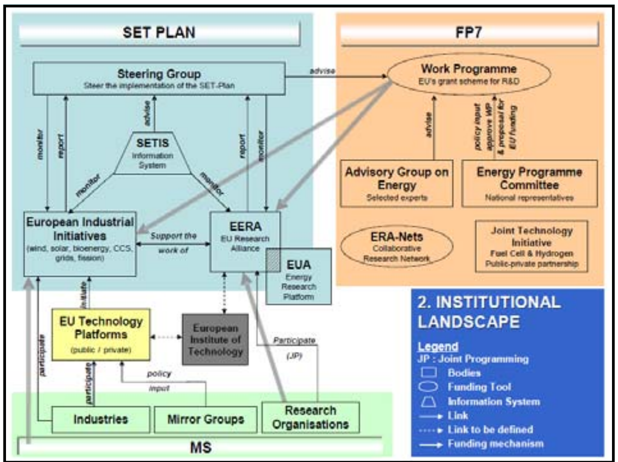
4) Resource assessment and **spatial planning** to support wind energy deployment.

A R&D programme for forecasting distribution of wind speeds and energy production that includes:

- Wind measurement campaigns.
- Database on wind data, environmental and other constrains.
- Spatial planning tools and methodologies for improved designs & production

WIND - Technology Roadmap 2010-2020





Thank you for your attention!

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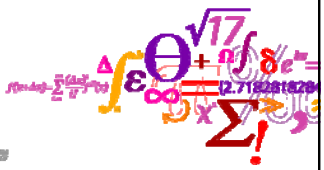
SET-plan:
ec.europa.eu/energy/technology/


Facing big challenges
calls for more / better cooperation!
Cross: themes, disciplines, sectors, industries, nations…
➔ Which parts of the RD&D
▪ at national level?
▪ at EU level?
➔ Researchers as links between disciplines and sectors?
➔ Funding instruments for R&D to promote cooperation?
(when “common pot” is not possible…)

State-of-the-art design practices for offshore wind farms

Peter Hauge Madsen
Head of Wind Energy Division

Presented at the
Wind Power R&D seminar – deeep sea offshore wind
21-22 Jan 2010 – Trondheim Norway



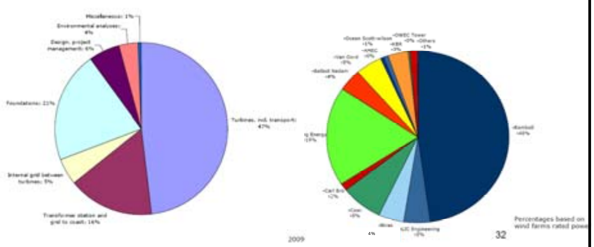
Risø DTU
National Laboratory for Sustainable Energy

Offshore wind turbine installation – a series-produced machine or a custom built structure

Wind turbine generator system ~ Wind turbine structure

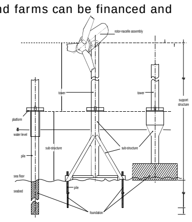
A selection of offshore wind concepts

Offshore wind investment cost (IEA 2008) and foundation design marketshares



Design of offshore wind turbines

- Offshore wind turbines are not onshore wind turbines!
  - hydrodynamic loads, sea ice, long periods at standby
- Offshore wind turbines are not oil rigs!
  - wind loads, shallow water, dynamics, unmanned
- Marriage of expertise from wind power and offshore engineering industries
- Technology Risks
  - Improve confidence with which offshore wind farms can be financed and implemented



Why Offshore Wind Differs from Traditional Offshore

Beatrice Offshore Wind Turbine - UK

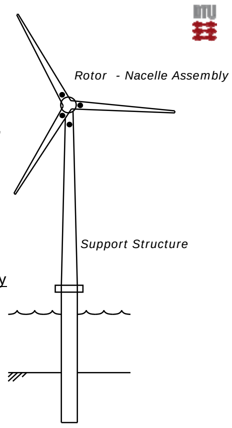
- Offshore Wind Turbines Characteristics
  - Highly dynamic response
  - Strict eigen frequency requirements
  - Actively controlled load response
  - Wind and wake effects
- Design Considerations
  - 50-year return period on extreme event
  - Wind load dominated (shallow water)
  - Overall fatigue driven (incl. low cycle)
- Traditional Offshore Structures:
  - Passive in their load response
  - 100-year wave load dominated
  - Built-in structural redundancy

Standards for Offshore Wind Turbines

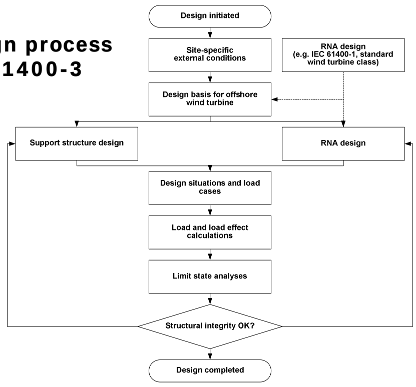
- Onshore wind turbines
  - IEC 61400-1, Edition 3
- Offshore wind turbines
  - IEC 61400-3
  - GL Regulations for Offshore WECS, 1995
  - DNV, Design of Offshore Wind Turbine Structures, OS-J101, 2007
  - GL Wind, Guideline for the Certification of Offshore Wind Turbines, 2005
- Offshore structures – petroleum and natural gas industries
  - ISO 19900, General Requirements for Offshore Structures, 2002
  - ISO 19901, Specific Requirements for Offshore Structures, 2003
  - ISO 19902, Fixed Steel Offshore Structures, 2004 (DIS)
  - ISO 19903, Fixed Concrete Offshore Structures, 2004 (DIS)

IEC 61400-3 Design Requirements for offshore wind turbines

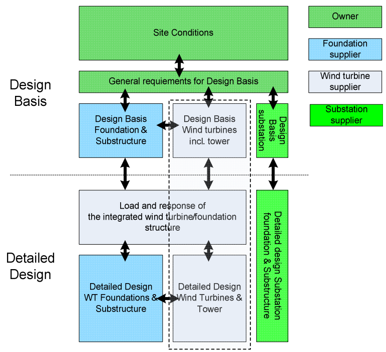
- A wind turbine is considered "offshore" if the support structure is subject to hydrodynamic loading
- Support structure design must be based on "site-specific" conditions
- Design of rotor - nacelle assembly may be based on:
  - site-specific conditions, or,
  - generic conditions, e.g. from 61400-1. In this case the structural integrity of RNA must be demonstrated based on site-specific conditions



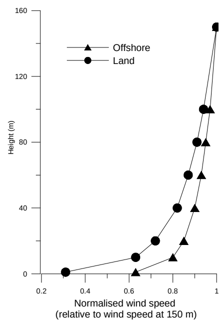
Design process IEC 61400-3



Design steps and documentation

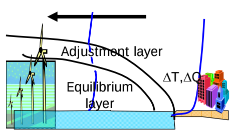


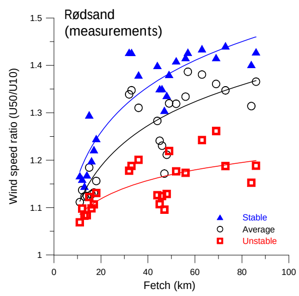
General concept based on lower roughness offshore



- Higher wind speeds/lower turbulence/lower wind shear
- Stability important: Complex u profiles/further wake propagation
- Higher wind speeds, more frequent, persist for longer periods offshore
- Statistically, coastal zone >20 km

Complexity of winds in the coastal zone (~50 km)

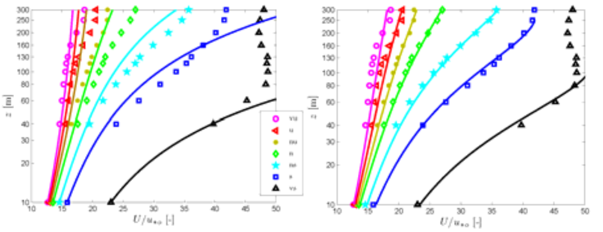




Wind Profile - Høvsøre cup/lidar to 300 m

Lines show logarithmic wind profile.
Symbols show data.
Notice good correspondance only at <40 m height.

Lines show mixing-length profile *using boundary layer height.*
Symbols show data.
Notice good correspondance at all heights in the boundary layer.

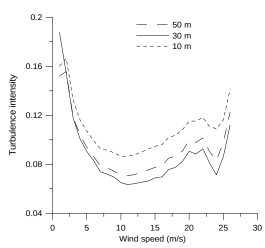


Colours: atmospheric stability - vu very unstable, n neutral, vs very stab

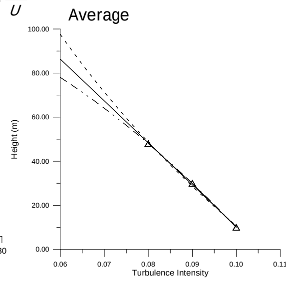
Turbulence

$T.I. = \frac{\sigma_U}{U}$

Rødsand



Average



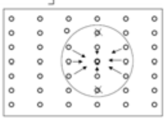
Decrease in T.I. Observed to 20 km from the coast

Assessment of turbulence intensity

In case of wakes:

$$I_{\mathrm{eff}} = \frac{\hat{\sigma}_{\mathrm{eff}}}{V_{\mathrm{hub}}} = \frac{1}{V_{\mathrm{hub}}}\left[(1 - N\,p_w)\hat{\sigma}^m + p_w \sum_{i=1}^{N} \hat{\sigma}_T^m(d_i)\right]^{\frac{1}{m}};\ p_w = 0{,}06$$

$$\hat{\sigma}_T = \sqrt{\frac{0{,}9V_{\mathrm{hub}}^2}{(1{,}5 + 0{,}3d_i\sqrt{V_{\mathrm{hub}}/c})^2} + \hat{\sigma}^2}$$



$$\sigma_1 \geq I_{\mathrm{eff}} \cdot V_{\mathrm{hub}} + 1{,}28\hat{\sigma}_\sigma$$

Marine environmental conditions

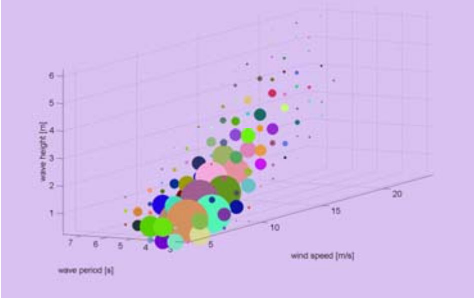
- Marine conditions
  - Waves
  - Currents
  - Water level
  - Sea ice
  - Marine growth
  - Scour and seabed movement
- Normal conditions – occur frequently during normal operation of wind turbine
- Extreme conditions – 1 year and 50 year recurrence period

Wind-Wave Response Interaction

Horns Rev Offshore Wind Farm - Denmark

- Increasingly Important in Deeper Waters
  - Relatively larger wave contributions
  - Less uni-directionality
- Combined Load Simulation Issues
  - Co-directionality of wind and waves
  - Damping characteristics
    - Only in-line aero-dynamic damping
    - Cross-vibrations due to waves
- Design Implications
  - Application of multi-directional simulation
  - Potential fatigue damage increase
  - Cross-vibrational damping
    - Characteristic soil damping
    - Wave damping

Scatter diagram – North Sea site



Loads and Load Cases

- Sources of load as for onshore turbines +
  - Hydrodynamic loads
  - Sea ice loads
  - Boat (+helicopter) impact
- Hydrodynamic loads affect RNA indirectly through vibration of support structure
  - Weak effect
- Normal design situations with normal or extreme external conditions
- Fault design situations with appropriate external conditions
- Transportation, installation, maintenance situations with appropriate external conditions
- Offshore turbines may experience long periods of non-production time

Example design load cases

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
1) Power production	1.1a	NTM $V_{in} < V_{hub} < V_{out}$ RNA	NSS $H_s=E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	For extrapolation of extreme loads on the RNA	U	N (1,25)
	1.1b	NTM $V_{in} < V_{hub} < V_{out}$ Support structure	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, UNI	NCM	NWLR	For extrapolation of extreme loads on the support structure	U	N (1,25)
	1.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$	NSS $H_s=E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
	1.4	ECD $V_{hub} = V_r - 2\ m/s, V_r, V_r + 2\ m/s$	NSS (or NWH) $H_s=E[H_s \| V_{hub}]$	MIS, wind direction change	NCM	MSL		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s=E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
	1.6a	NTM $V_{in} < V_{hub} < V_{out}$	SSS $H_s= H_{s,SSS}$	COD, UNI	NCM	NWLR		U	N
	1.6b	NTM $V_{in} < V_{hub} < V_{out}$	SWH $H = H_{SWH}$	COD, UNI	NCM	NWLR		U	N

Wind Turbine-Foundation Interaction

- Eigen-Frequency Envelope Requirement
  - Ensures the safety and the operational performance of the turbine
  - Is an essential foundation requirement
  - Is affected by the – per-location – specific cyclic stiffness and damping of the soil
- Offshore Wind Farm Considerations
  - Varying soil conditions in large areas
  - Varying water depths on sloping locations
- Design Implications
  - Ample site survey
  - Individual turbine assessment
  - Characteristic response
  - Fatigue Limit State critical

Conclusions

- Wind turbine and foundation design is integrated to a very limited extent
- Site conditions very complex – the site specific design conditions are derived in an ad-hoc and pragmatic way
- Foundations are designed to site specific conditions (waves, soil, depth ..) but with general, conservative interface loads from the turbine
- Integrated design tools exist but are primarily used to demonstrate conservatism of approach
- Limited validation of design loads and response
- Deep water (> 30 m) is a challenge

Some R&D challenges

- Condition Monitoring developments (highest reliability and lower OPEX)

  Significant developments are required in CM for transformers (e.g. DGA of oil, tap-changers), cables (Partial Discharge?, located where?), switchgear (gas pressure?), power electronic converter equipment (?).

1

Some R&D challenges

- Enhanced offshore transmission models for fast switching transients and harmonics analyses in power systems

  Over-voltages from switching transients and phenomena of this type may be very damaging on very extensive EHV submarine cable circuits. The insulation co-ordination requirements of the offshore substations needs to be evaluated.

2

Some R&D challenges

- There is also a requirement to define the duty that will be seen by the switchgear and other equipment.

- The effect of faults at various locations have to be investigated and the transient behaviour of the network simulated (using appropriate models)

3

Foundations for manufacturing and installation.

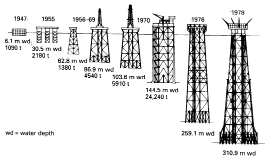
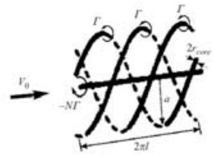


Figure 2.5 Evolution of deep water production capability (from Lee 1980)

How to approach Gordon Browns challenge: 30 – 40% cost reduction?

Time for evolution or step change?

From tip vorticity to wake



Sketch of the far-wake model proposed by Joukowski (1

Wake losses may jeopardise the park economy

Statnett

R&D Challenges

Terje Gjengedal

Statnett

Development of interconnectors and a possible future grid

- TSO cooperation thru ENTSO-E, flexible regulators and political willingness
  - A possible grid will emerge as modules from national wind clusters and or new interconnectors
- Interconnector technology
  - VSC HVDC, recommended solution, supplier interface needed
  - Voltage level, to be agreed
  - CIGRE to develop standards
- R&D development needed
  - Multi-terminals, DC breakers
  - Increased capacity and reduced losses
- Trading and balancing
  - European trading with renewables
  - European balancing and storage

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Offshore development in Norway as seen from the TSO

- Legal framework for offshore wind not yet approved, seems promising
  - Dedicated areas to be selected for wind production offshore
  - Interconnector routing may be located close to selected areas
  - Stepwise development
- Technology and standards need development
- Electrification of offshore oil and gas installations may be a driver
- Norway have not yet nominated an offshore TSO
  - May hamper overall planning and development offshore and coordination with onshore

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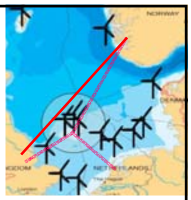
Is power trade *via* wind parks better than direct connections?



Technically feasible?

- ❖ Probably, but complicated
- ❖ Requires VSC HVDC to handle multi terminal solutions
- ❖ Unproven – several challenges

Will regulatory systems allow it?

- ❖ Hopefully
  - Need to overcome *national* focus
- ❖ Who pays and who gets the power?
  - Power flow in the right direction?

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Wind and market structure?

- ❖ Increasing amount of wind power will require new market instruments?
- ❖ How do we design the market to manage huge amounts of wind power?
- ❖ New market instruments and other products?
- ❖ How to design the market to include
  - Huge amounts of wind power
  - The need to manage flexibility
  - Congestion management and a flexible grid

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