NTNU – Trondheim
Norwegian University of Science and Technology

Cost reduction through better modeling and design

A perspective for offshore wind energy

www.nowitech.no

Michael Muskulus

Offshore wind turbine technology
Department of Civil and Transport Engineering
Norwegian University of Science and Technology

NOWITECH in brief

- a joint pre-competitive research effort
- focus on deep offshore wind technology (+30 m)
- budget (2009-2017) EUR 40 millions
- co-financed by the Research Council of Norway, industry and research partners
- 25 PhD/post doc grants
- Vision:
  - large scale deployment
  - internationally leading

Research partners:
- SINTEF (host)
- IFE
- NTNU

Industry partners:
- Devold AMT AS
- Det Norske Veritas
- DONG Energy Power
- EDF R&D
- Fedem Technology AS
- Fugro OCEANOR AS
- GE Wind Power AS
- Kværner Verdal
- NTE Holding AS
- SmartMotor AS
- Statkraft
- Statnett SF
- Statoil Petroleum AS
- Vestas
- Vestavind Offshore

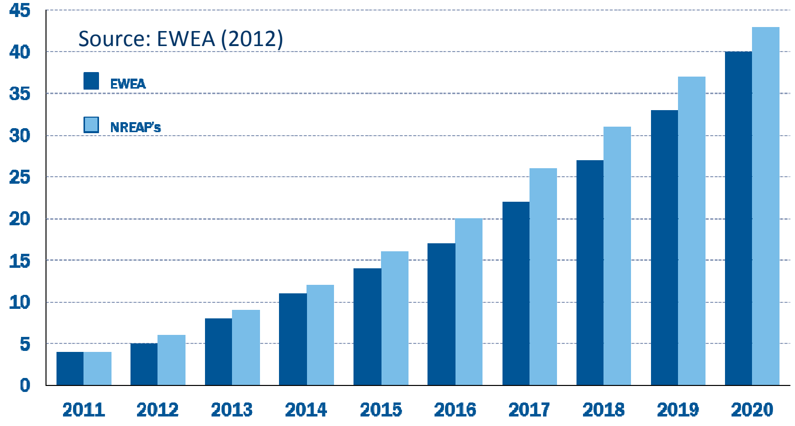
Associated research partners:
- DTU Wind Energy
- MIT
- NREL
- Fraunhofer IWES
- Uni. Strathclyde
- TU Delft
- Nanyang TU

Associated industry partners:
- Access Mid-Norway
- Energy Norway
- Enova
- Innovation Norway
- NCEI
- NORWEA
- NVE
- Wind Cluster Mid-Norway

Key issue: Innovations reducing cost of energy from offshore wind

A large growing global market

EU OFFSHORE WIND FORECAST INSTALLED CAPACITY (GW)



OFFSHORE WIND KEY INDICATORS

Key indicators	2010	2016
Capex (NOK)	26.6 bn NOK	92bn NOK
Capex (USD)	4.7 bn USD	16 bn USD
Added capacity	1 GW	3.6 GW
Turbines	370	975
Foundations	639	1,435
Cables	518 km	1,972 km
Installation vessels	21	45
PTVs	86	277

Source: Douglas-Westwood (2012)

- Firm European commitment to develop offshore wind
- EU offshore wind forecast 2020:
  - Total installed capacity 40 GW
  - Total investments EUR 65.9 billions
- EU offshore wind forecast 2030:
  - Total installed capacity 150 GW
  - Total investments EUR 145.2 billions
- Significant developments also in China, Japan, Korea and USA
- The near-term large commercial market is mainly for bottom-fixed wind farms at shallow to intermediate water depths (50 m)
- Significant interest in developing floating concepts expecting large volume after 2020
- Threat: International financial crisis / economic recession

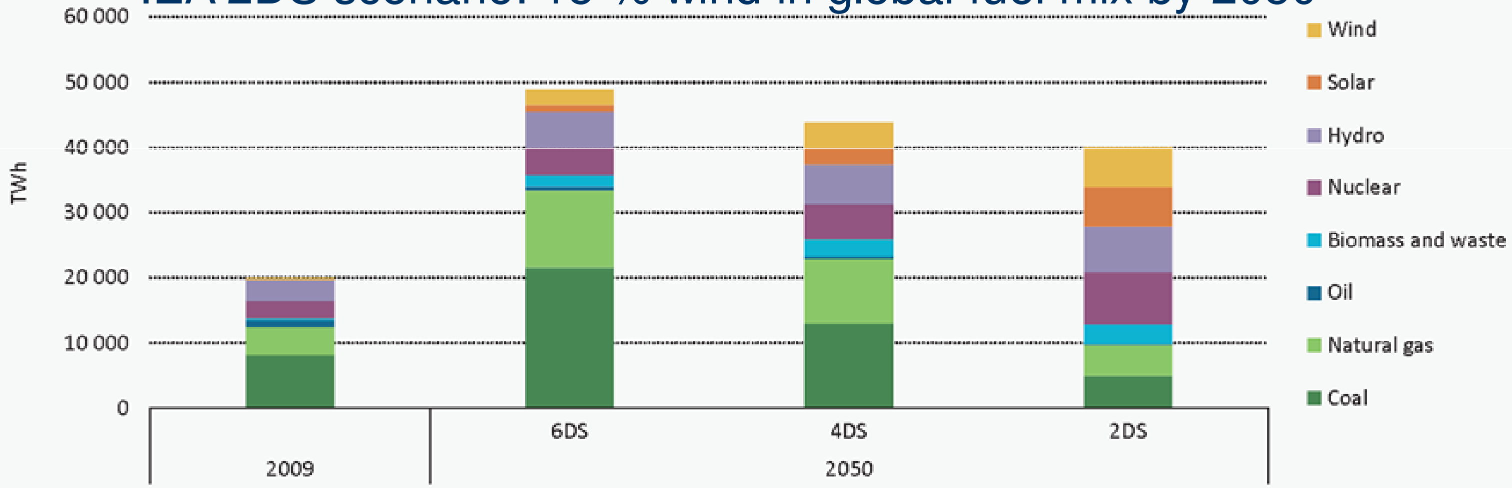
Main drivers

- Battle climate change
- Security of supply
- Industry value creation

Stern Review (2006):
..strong, early action on climate change far outweighs the costs of not acting.

Figure 1.10 Fuel mix in electricity generation, by scenario

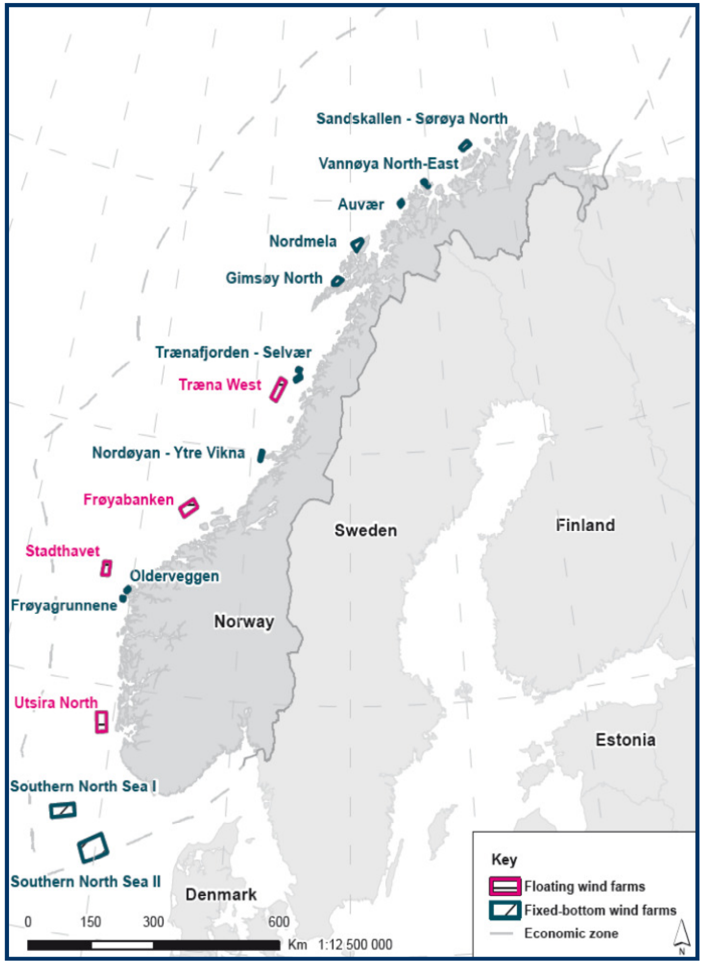
IEA 2DS scenario: 15 % wind in global fuel mix by 2050



Key point *Diversification of fuels and increased use of low-carbon sources in the 2DS achieves a high degree of decarbonisation in electricity generation by 2050.*

Copy from IEA Energy Technology Perspectives 2012

A possible Norwegian market, but uncertain



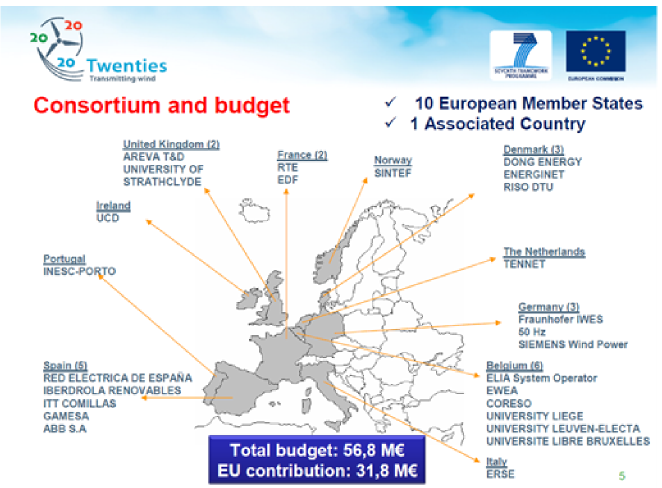
- NVE has identified 15 areas for development of offshore wind farms (total ~10 GW)
- Applying the petroleum taxation regime to offshore wind farms for supply to oil and gas installations may create a immediate Norwegian market (total ~100-1000 MW)
- A significant Norwegian market for onshore turbines are expected through green certificates, e.g. 6 TWh by 2020 (total market for green certificates in Norway and Sweden is 26 TWh).

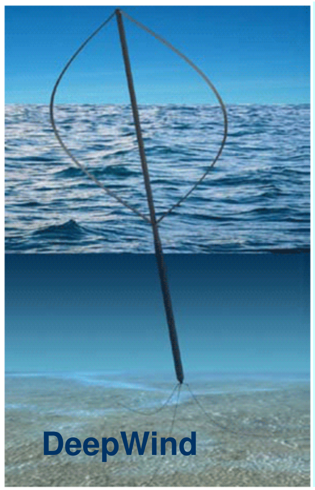
Relevant results giving basis for cost reduction and value creation

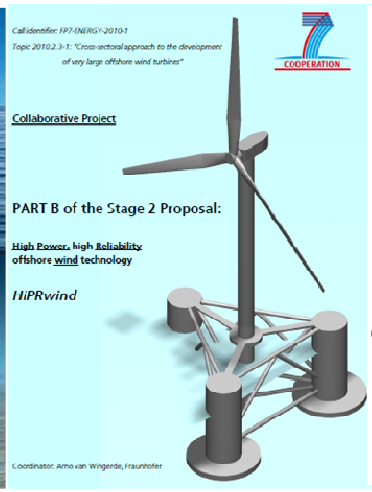
- Example industry oriented R&D results
  - **Fedem – model of generator, converter, control and grid connection**
  - **Improvements of NIRWANA (analysis tool for sub-structures)**
  - **NETOP (optimization of offshore grid topology)**
  - **WINDOPT (optimization of spar buoy)**
  - **3DFLOAT (integrated design tool)**
  - **LCP (life cycle profit for offshore wind farms)**
  - **NOWITECH reference turbine – sub-structure/tower**
  - **PSST (power system simulation tool: grid and market model)**
  - **Remote Presence (prototype, new business in preparation)**
  - **SmartMotor / PhD Sverre Gjerde (HVDC output from wind turbines)**
- Example partners having included results in their business
  - **Statoil, DNV, Fedem, …**

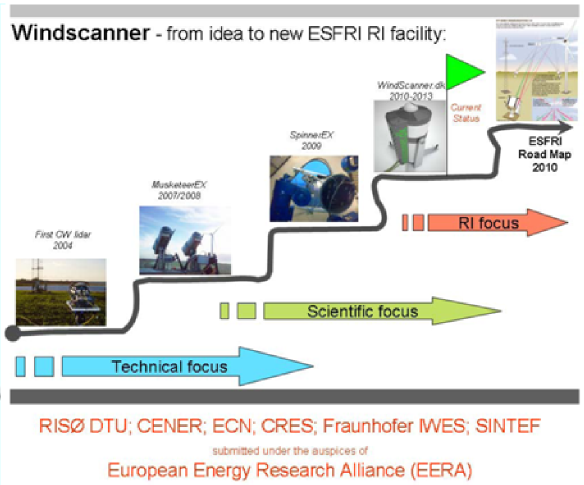
An attractive partner on the international scene

- Active in EERA, TPwind, EAWE, IEA, IEC
- Partner in EU projects, e.g.: Twenties (2009-), DeepWind (2010-), HiPRWind (2010-), EERA-DTOC (2012-), InnWind (2012-), LeanWind (application), EERA IRP wind (application)
- ESFRI WindScanner, http://cordis.europa.eu/esfri/









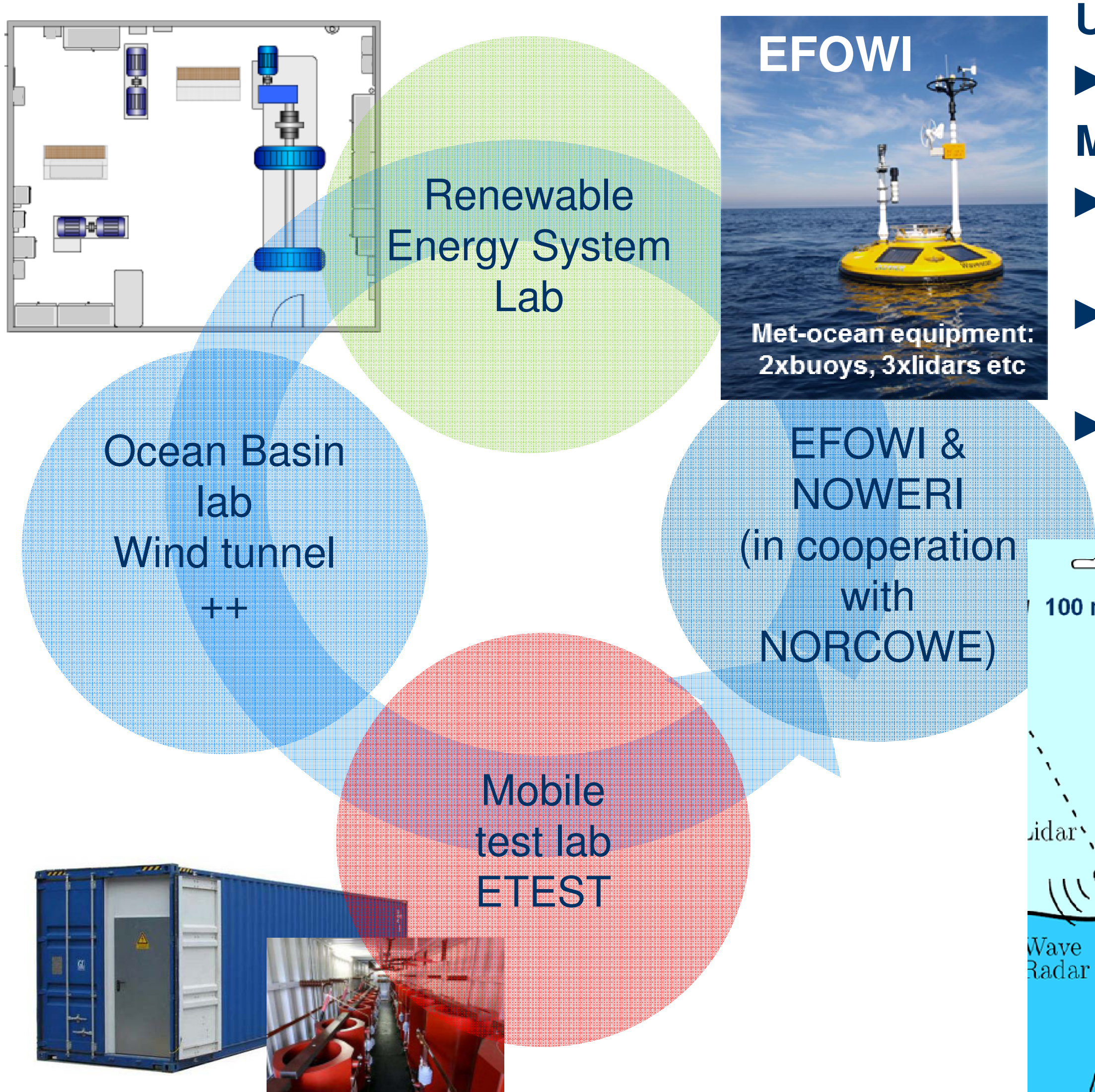
Research gives basis for industrial development

- Competence achieved through RCN projects have been critical for industrial development, e.g. ChapDrive, HyWind, SWAY

- NOWITECH CIC focus on relevance and helps commercialize ideas:
  - Development of TRL guideline (DNV)
  - Idea search and development of ideas (TTO)
  - Develop of business plan for "Remote presence" (Impello)

- Education is a key; 25 PhD and post doc students are granted by NOWITECH and +30 students are funded through other projects
- NTNU partner in Erasmus Mundus European Wind Energy Master

Strong research infrastructure in development

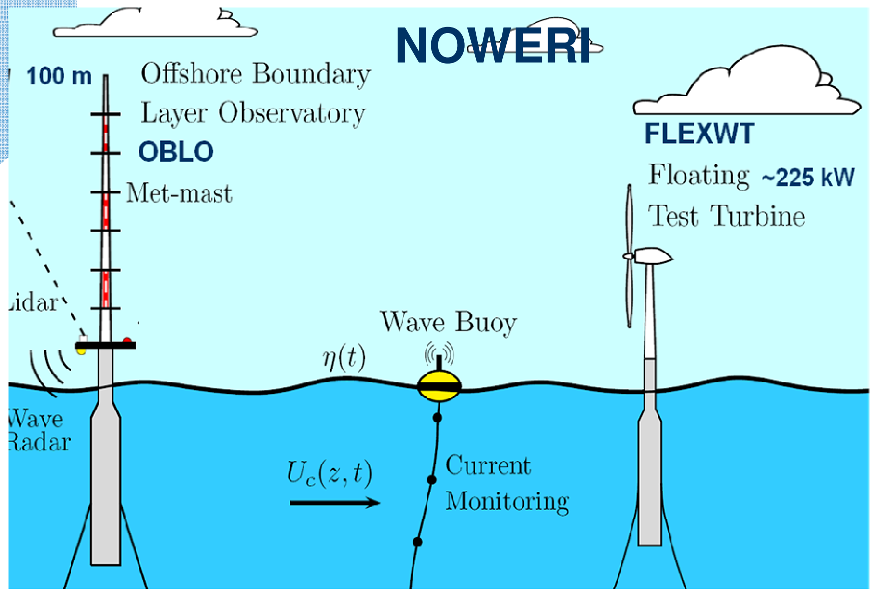


Users:

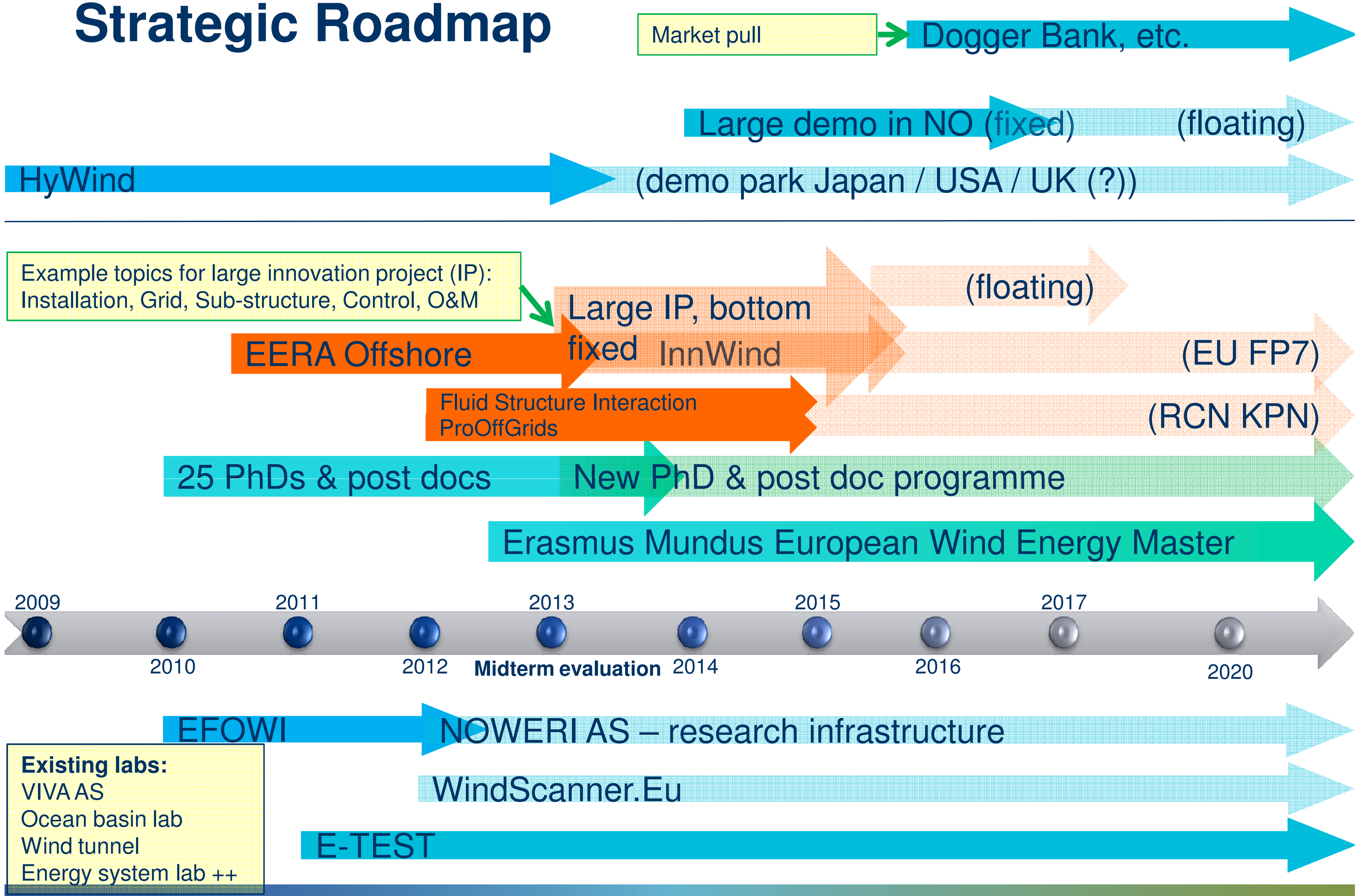
- Research & Industry

Main Objectives:

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



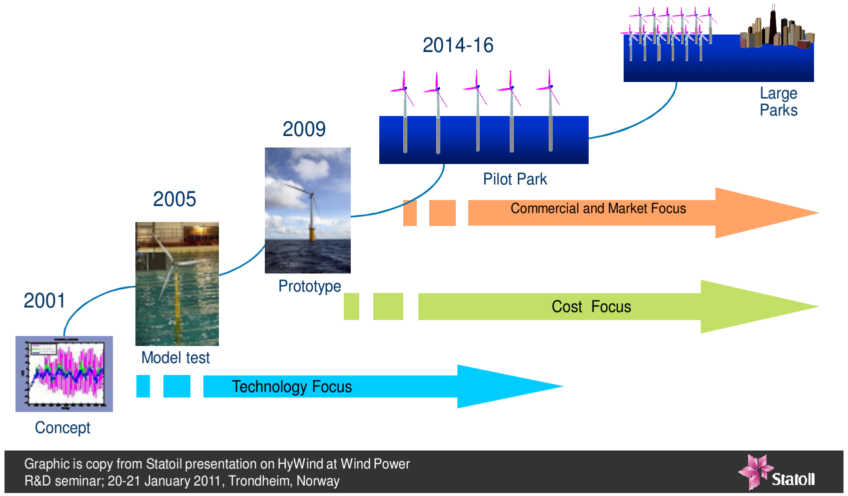
Strategic Roadmap



Demonstration

- Demonstration in large scale is vital for bringing research to the market
- Applying the petroleum taxation regime to offshore wind farms may create a opportunity for large scale demonstration wind farms in Norway
- NOWITECH should also follow up on opportunities for demo outside Norway
- Both bottom-fixed and floating concepts should be developed

From Idea to Commercial Deployment

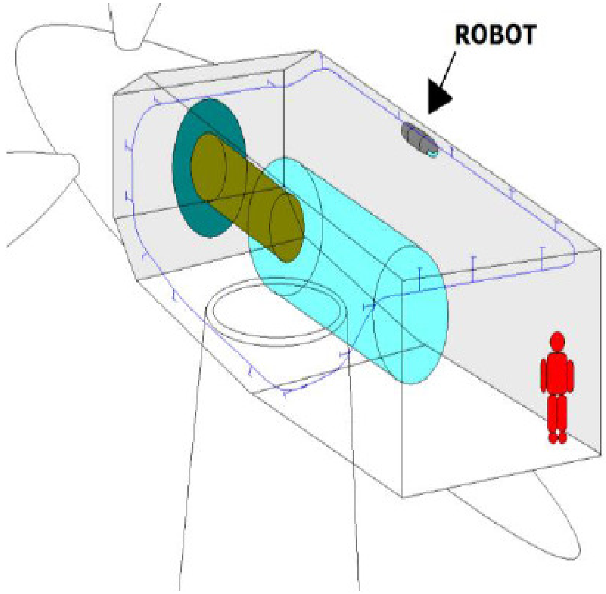


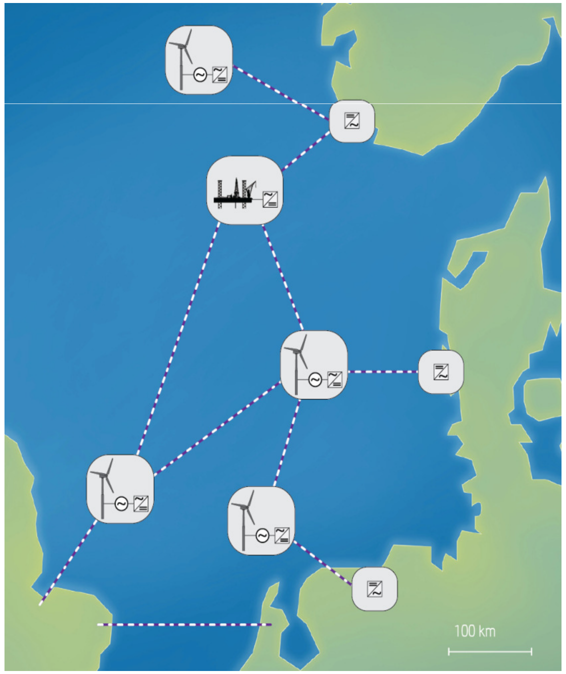
THE HAVSUL CONCEPT BY VESTAVIND OFFSHORE

- Norway's only granted license for a full scale offshore wind farm
- 350 MW installed capacity – estimated annual energy output 1-1,3 TWh
  - Floatable foundation solutions for bottom fixed offshore wind turbines
  - Inshore assembly of complete wind turbine including foundation
  - Offshore installation in one operation without need for special purpose vessels

Research

- Several results from NOWITECH are ready for a next stage development
- Key issues: Installation, Grid connection, Sub-structure, Control, O&M
- Follow up by EU / EERA, KPN, IPN and bilateral projects and strategic work to establish a large research programme linked to a offshore demonstration wind farm.





Education

- NOWITECH funds 25 PhD and post docs that will be finished in 2014
- Action to establish new PhD grants is required to keep up the momentum and secure continued flow of qualified candidates to industry and research. Budget ~75 MNOK
- This can be by a number of smaller projects (KPN, etc) or through a large research programme linked to a offshore demonstration wind farm similar to RAVE (Research at Alpha Ventus)

www.alpha-ventus.de

Rounding up

- **NOWITECH is about education, competence building and innovations reducing cost of energy from offshore wind**

- Remarkable results are already achieved
  - Strong master and PhD programme
  - Significant publications
  - Relevant R&D results
  - Strong infrastructure in development
  - Internationally attractive partners
  - Strategic positions in EU networks
  - Efficient dissemination of results
  - A high number of spin-off projects

- Outlook is demanding, but prosperous with a growing global market

- **Vision: large scale deployment & internationally leading**

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NOWITECH Norwegian Research Centre for Offshore Wind Technology

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

What is modeling? (1/4)

- Physical models
  - Only through experiments can we link our theories with reality
  - Example: scale models (Froude scaling)
  - However: Limited explanatory power themselves
  - Provide data for the development of other models

What is modeling? (2/4)

- Theoretical models
  - Equations that express the laws of nature
  - High explanatory power: reduction in complexity
  - Modern philosophy of science:
    Anti-realist attitude - Does the new model work better than previous ones in explaining the main features of interest?
  - Engineering approaches / models highly relevant

What is modeling? (3/4)

- Numerical models
  - In-between physical (experiments) and theoretical models
  - What are the consequences of theories and assumptions?
  - Implementation relies on theoretical models
  - Need care when interpreting results

What is modeling? (4/4)

- Relevance to marine and coastal engineering:
  - We need physical model tests to improve our understanding of the underlying phenomena
  - But: we also need to improve
    - our theoretical models, and
    - our numerical models
  - Knowledge gained through experiments needs
    - to be translated into theories, and also
    - to be implemented in software

Applied and Basic Science (1/3)

- More and more focus on applied research
  - Example: European collaborative projects
  - Funding for basic research: national open competitions
- Criterion?
  - Participation of private sector partners
  - Matching: public funding only in addition to private sector funding

Applied and Basic Science (2/3)

- Norwegian example
  - Knowledge-Building Projects (KPN) for Industry
  - Cash contribution of 20 percent from private sector required
  - Remaining 80 percent provided by Government (Research Council of Norway)
  - Popular?

Applied and Basic Science (3/3)

- The issue of relevance
  - Private sector is asked to comment on the relevance of proposed research projects
  - Typical manifestation: Letter of Interest
  - Often the difference between a successful research project – or one more idea in the drawer
  - Sometimes no commitments required – only interest!
  - Example: Recent Danish proposal

Key research questions (1/9)

- Main differences offshore vs. onshore wind energy
  - Presence of hydrodynamic phenomena and subsequent loads that need to be taken into account during design
  - Differences in support structure technology and geotechnical design
  - More complex and costly installation, operation & maintenance

Key research questions (2/9)

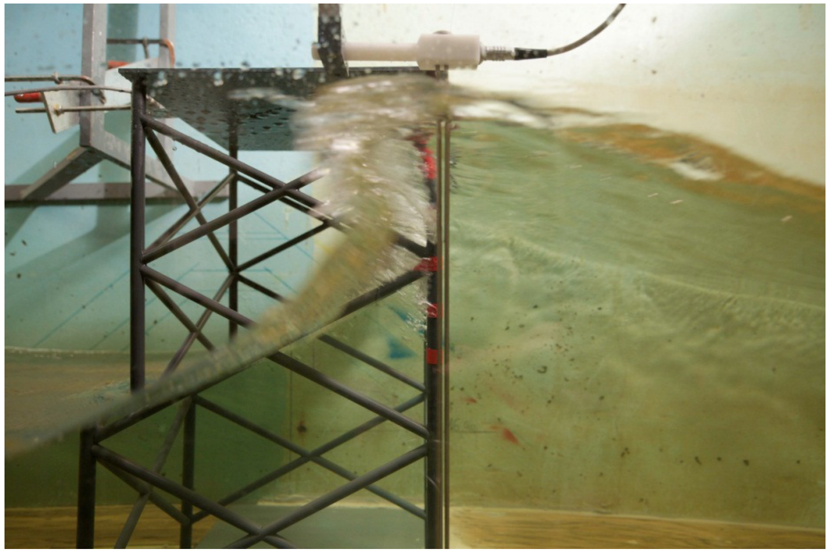
- Optimization of designs
  - Reducing uncertainty
  - Optimization of performance

Key research questions (3/9)

- Reducing uncertainty
  - Uncertainty (or: ignorance about physical reality) is undesirable – since it has to be dealt with (e.g., factors of safety)
  - Important: also refers to modeling methodology and numerical approximations that have been made

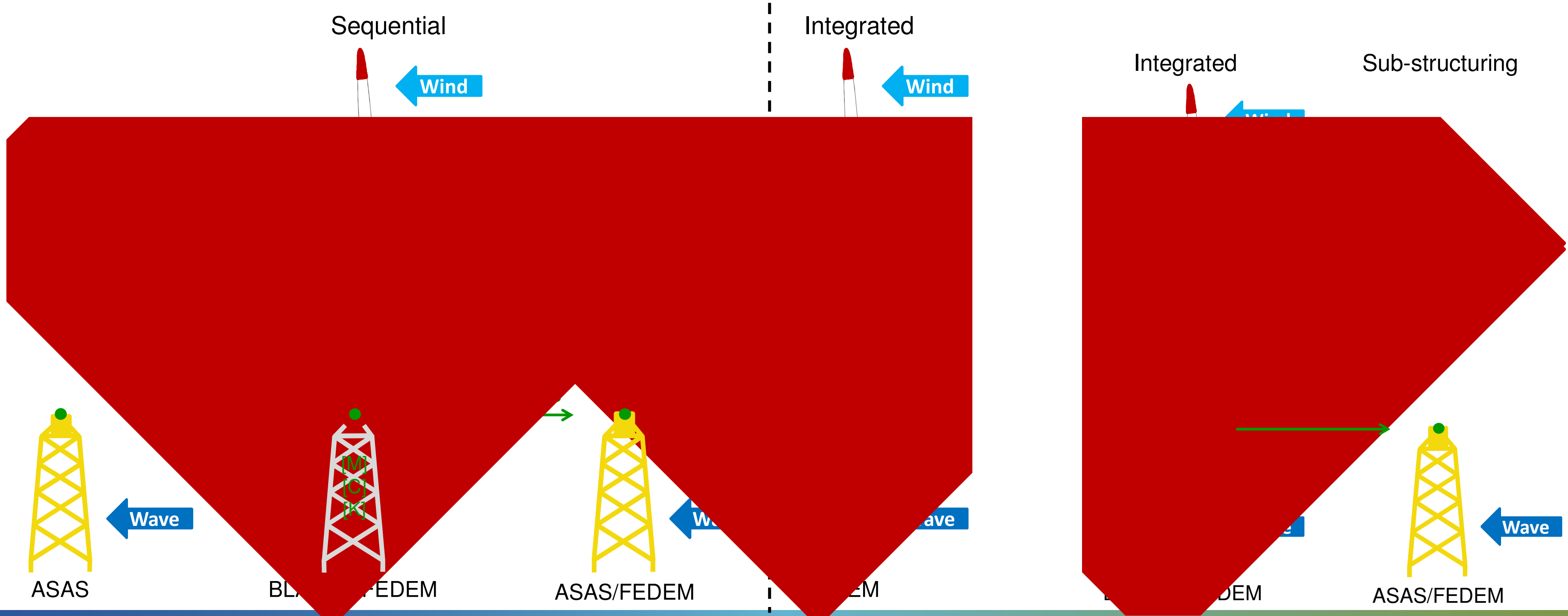
Key research questions (4/9)

- Example (WAVESLAM)
  - Experiments by Tørum et al. on slamming loads for a complex, multi-member jacket
  - Much smaller response than predicted by relevant design standard



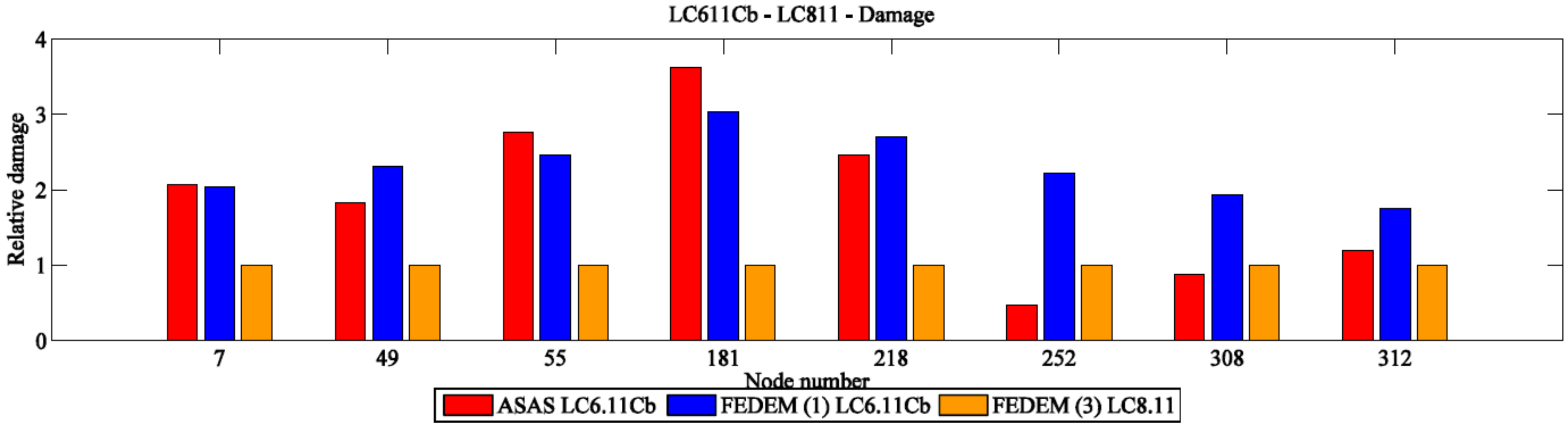
Key research questions (5/9)

- Example: Sequential analysis of support structures
  - reduced support structure models lead to overprediction of fatigue
  - but: not always / everywhere!



Key research questions (6/9)

- Integrated analysis
  - Up to 200 percent decrease in fatigue loads - conservative
  - Highest differences in lower bays
- However:
  - up to 50 percent more fatigue in some locations
  - X-brace bay 3 – close to top of jacket

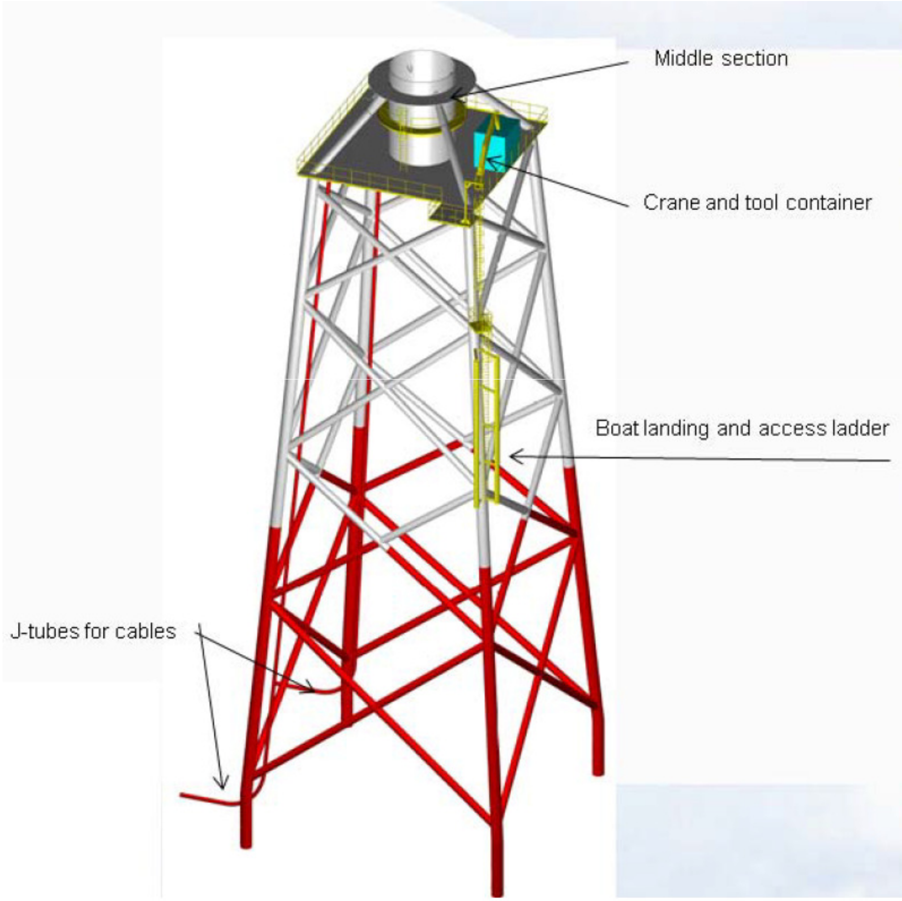


Key research questions (7/9)

- Optimization of performance

Key research questions (8/9)

- ► Example: sizing of jacket support structures
  - 1000+ parameters (diameters, wall thickness)
- ► Estimating fatigue damage?
  - 1000+ simulations (10 min loadcases)



Key research questions (9/9)

- Experience from offshore oil & gas:
  - Typical: Frequency-domain methods
  - Typical: Simplified damage estimation
  - Typical: Overestimation of 100+ percent – conservative sizing!

Outlook (1/2)

- We need to increase our understanding
  - Wave forces on offshore wind turbines
  - Scour
  - Soil-pile interaction
  - …
- Only achieved through better model tests
  - «In-the-loop» hybrid testing
  - Geotechnical centrifuge modeling
  - More realistic wind fields in ocean basin tests
  - …

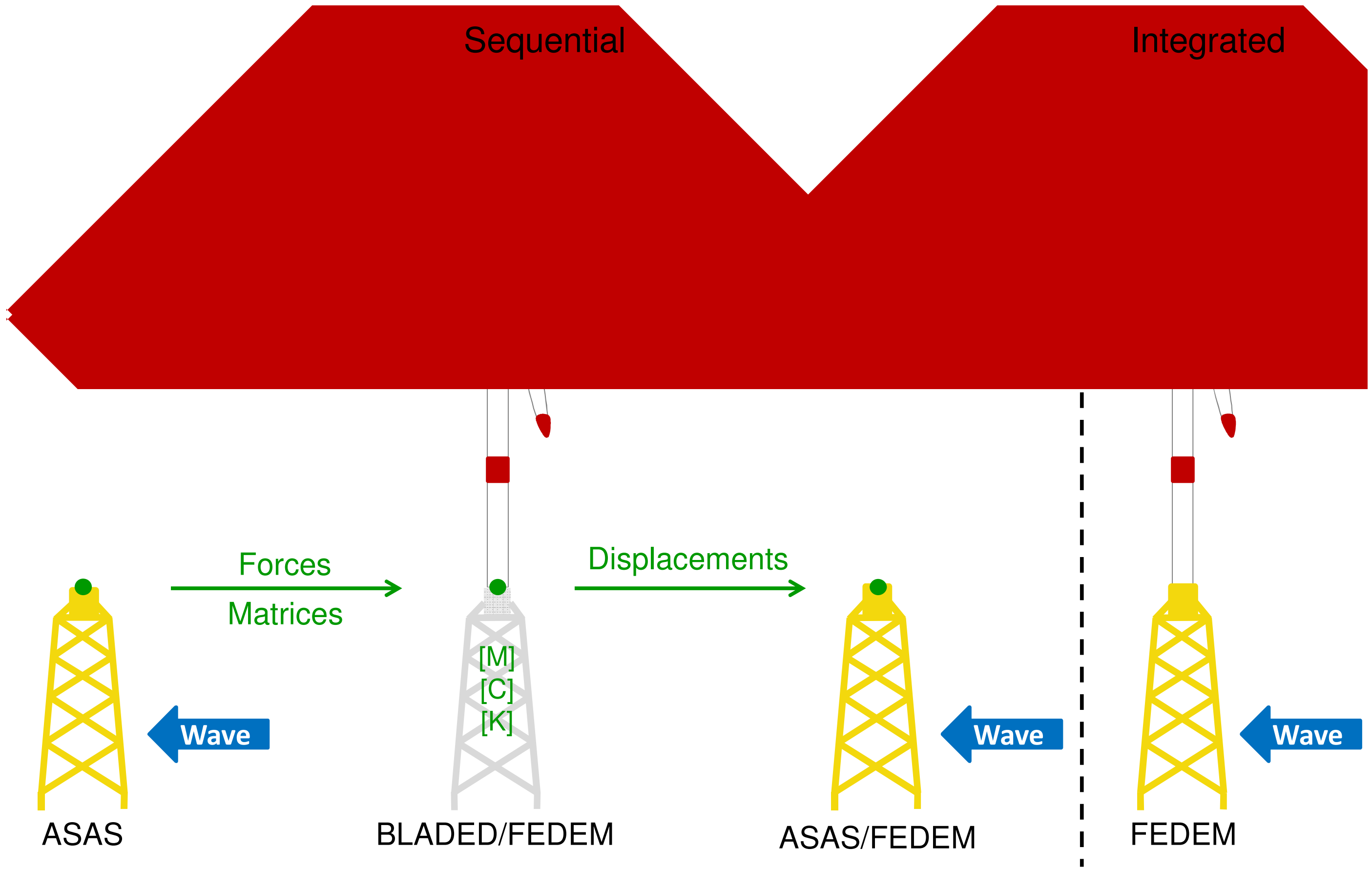
Outlook (2/2)

- Equally important
  - Resulting information from model tests needs to be synthesized in the form of an engineering approach or theoretical model,
  - These theoretical models need to be implemented in current software, and
  - These methods need to find their way into revised design standards
- Private sector industry
  - Should be aware that their actions do influence public research to a large degree
  - Not only short-term financial implications should govern their research agendas – or their degree of scepticism toward otherwise basic research

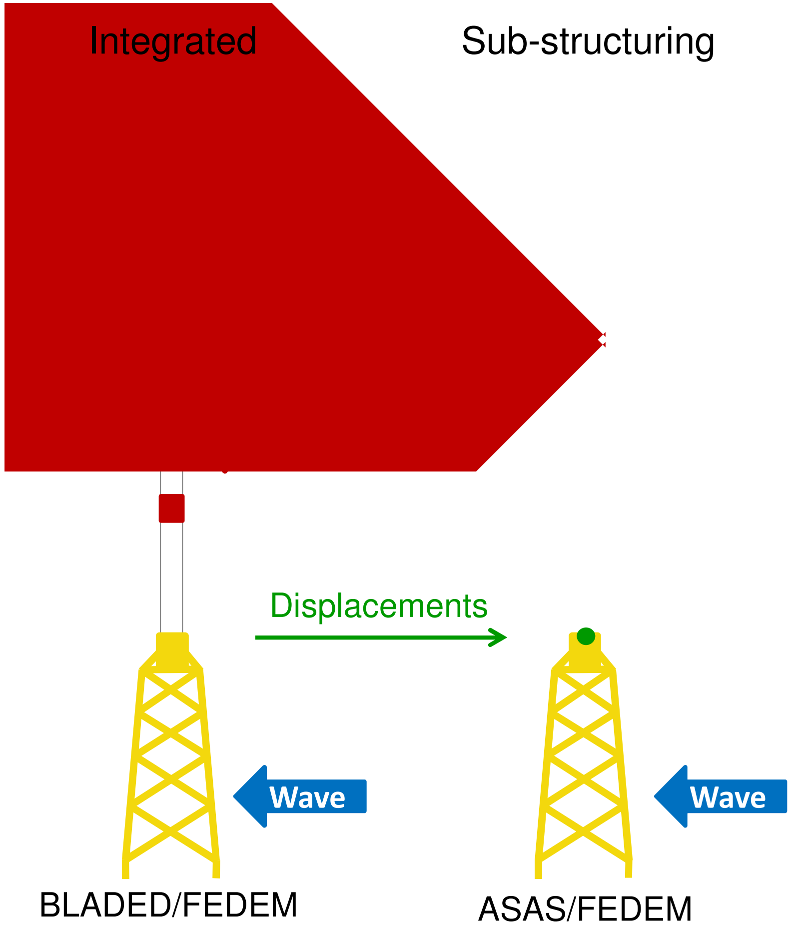
Final impulse…

► Contact: michael.muskulus@ntnu.no

Sequential analysis / Integrated analysis



Integrated analysis / Sub-structuring



Significant number of spin-off projects

- **Example recent projects:**
  - RCN KPN: ProOfGrids - Protection and Fault Handling in Offshore HVDC Grids (2012-2016) 23 MNOK; SINTEF ER, Statnett, Statoil, SIEMENS, EdF, etc.
  - RCN KPN: Fluid Structure Interactions for Wind Turbines (2012-2015) 20 MNOK; SINTEF ICT, Statoil, TrønderEnergi, Kjeller Vindteknikk, etc.
  - RCN IPN: FAROFF - Far offshore operation and maintenance vessel concept .. (2012-2013) 8 MNOK; Statkraft, SINTEF ER, MARINTEK, etc
  - RCN IPN: WINDSENSE - Add-on instrumentation system for wind turbines (2012-2014) 22 MNOK; Kongsberg, SINTEF ER, MARINTEK, etc.
  - EU FP7: EERA-DTOC (2012-2015), DTU, Fraunhofer, SINTEF ER, etc.
  - EU FP7: InnWind (2012-2016), DTU, Fraunhofer, SINEF ER, etc.

- **Example new applications in development:**
  - RCN IPN: Offhore energy storage (application);SubHydro, MARINTEK, SINTEF ER, etc.
  - EU FP7: LeanWind (application); Cork / MARINTEK, SINTEF ER, etc.
  - EU FP7: EERA IRP wind (application); DTU, SINTEF ER, MARINTEK, etc.
  - …

- **Total spin-offs since start-up (excluding bilateral projects) is 31 projects with a sum budget of +950 MNOK (incl. external parties)**

Results are disseminated efficiently

- ► Industry involvement in WP / workshops
- ► Started seminar series on Industry meets Science with WMN & AMN; next Europa as home-market, 6 December, Trondheim
- ► Wind energy R&D conference held every January in Trondheim since 2004; next DeepWind'2014, 24-25 January.

- ► Efficient use of web, newsletters and e-room
- ► Publications by NOWITECH include 158 papers (75 per-reviewed) and 77 reports, all stored at e-room database

Why jacket support structures?

- More transparent to wave loads
- Less material cost (but more labor-intensive)

Adapted from Marc Seidel (EWEA Offshore 2011):

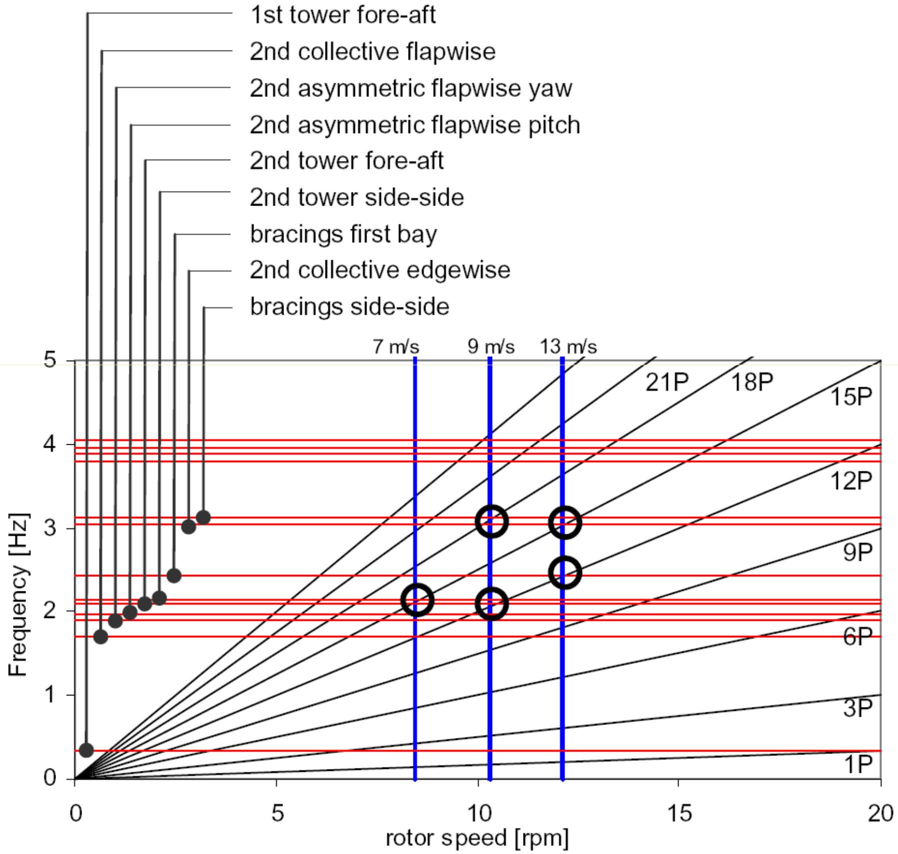
Monopiles	Jackets
• Excitation of *global vibration* by waves in fundamental mode	• Stiff jacket structure prevents global vibrations
• *Misaligned waves* cause large fatigue loads	• Misalignment effects negligible?
• Significant impact of *secondary structures* (e.g., boat landing)	• Secondary structure not important?
• *Soil data* most important parameter	• Soil has negligible influence?
• Fatigue loads often *higher for idling turbine*: Reduced availability must be considered	• 100 percent availability is conservative

Jackets are also easier to design?

Challenges for the design of jacket support structures

- Irregular and transient loads
  - Nonlinear analysis in time domain
  - Large variability due to turbulence and irregular waves
- Uncertainty about soil conditions
- Fatigue-driven
  - Large number of load cases
- Importance of local vibrations (Böker 2009)

  Excitable from higher-order rotor modes



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Beatrice demonstrator project (2006)

Projects with the OWEC Quattropod®

- Beatrice (2006)
  - 2 OJQ at 45m
- Alpha Ventus (2009)
  - 6 OJQ at 29m
- Ormonde (2010)
  - 30 OJQ at 21m
- Thornton Bank II+III (2011-2012):
  - 48 OJQ + 1 transformer at 27m

OWEC TOWER AS

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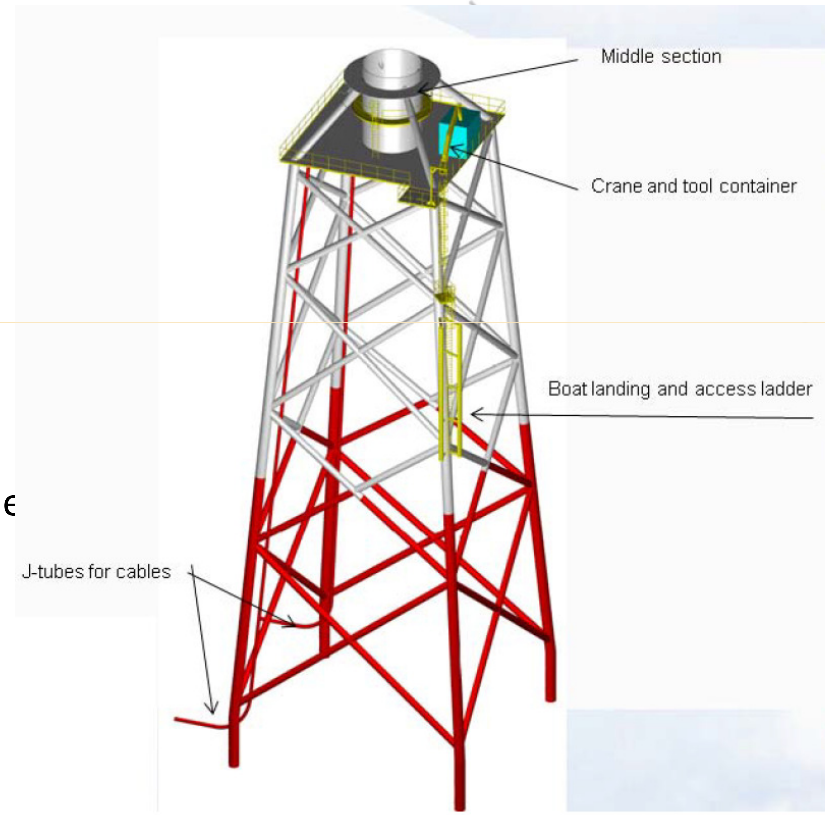
Load simulation and analysis of jacket structures

- OWEC Quattropod®
  - Commercial jacket support structure
  - More than 80 structures built so far
- Complex multi-member structures
  - Transition piece
  - Boat landing and ladders
  - J-tubes
- Certification analysis in ANSYS ASAS
  - Nonlinear transient FE analysis
  - Beam elements, shell elements and nonline springs + dashpots
  - Rigid offsets at joints
  - Freedom releases (boat landings)
  - Rayleigh damping
  - More than 900 nodes and 1300 elements



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Analysis approaches used in the past

- Partitioned analysis
  - Simplified analysis, because of…
    - (1) need for an interface between turbine and support structure designer, and
    - (2) limitations of software
  - Superposition method (Kühn)
    - Support structure and wind turbine are analyzed separately
    - Problem: aerodynamic damping, inaccurate
  - Semi-integrated approach (Seidel)
    - Use simplified support structure model (monopile) in aerodynamic analysis
    - Retrieval run with true support structure and displacements at interface node
    - Problem: torsion not well captured
  - **Sequential approach** (Seidel)
    - Guyan reduction: replace support structure by stiffness, mass and damping matrices and a wave load time series
- More accurate: Integrated analysis
  - Fully coupled (co-simulation)
  - **Fully integrated approach**

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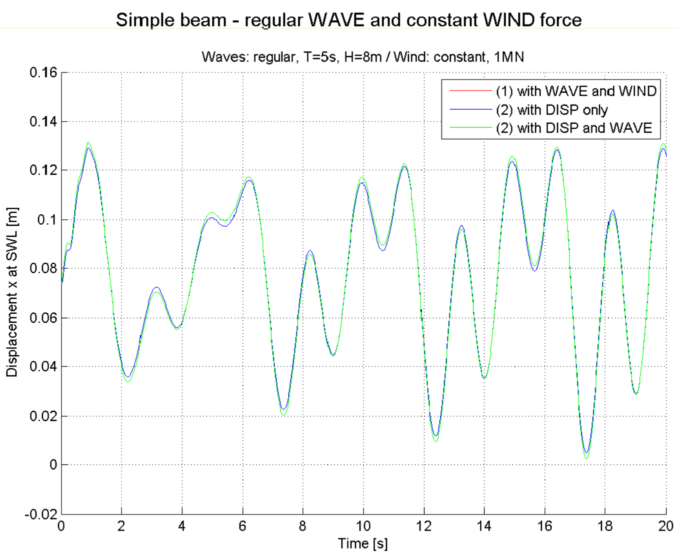
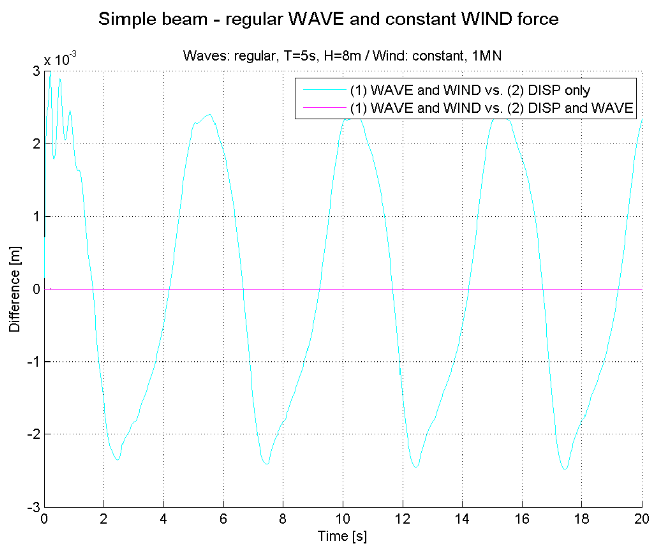
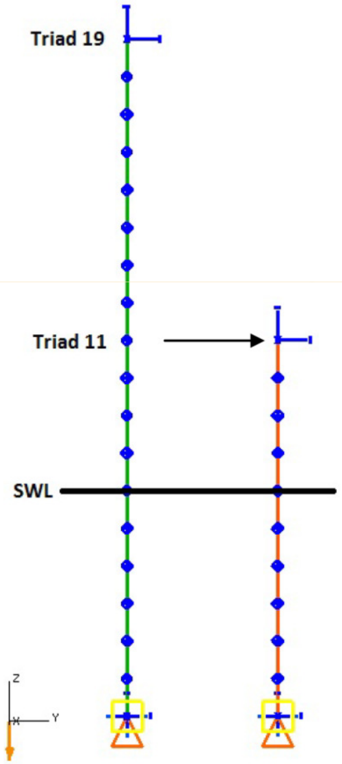
A common misconception about partitioned analysis

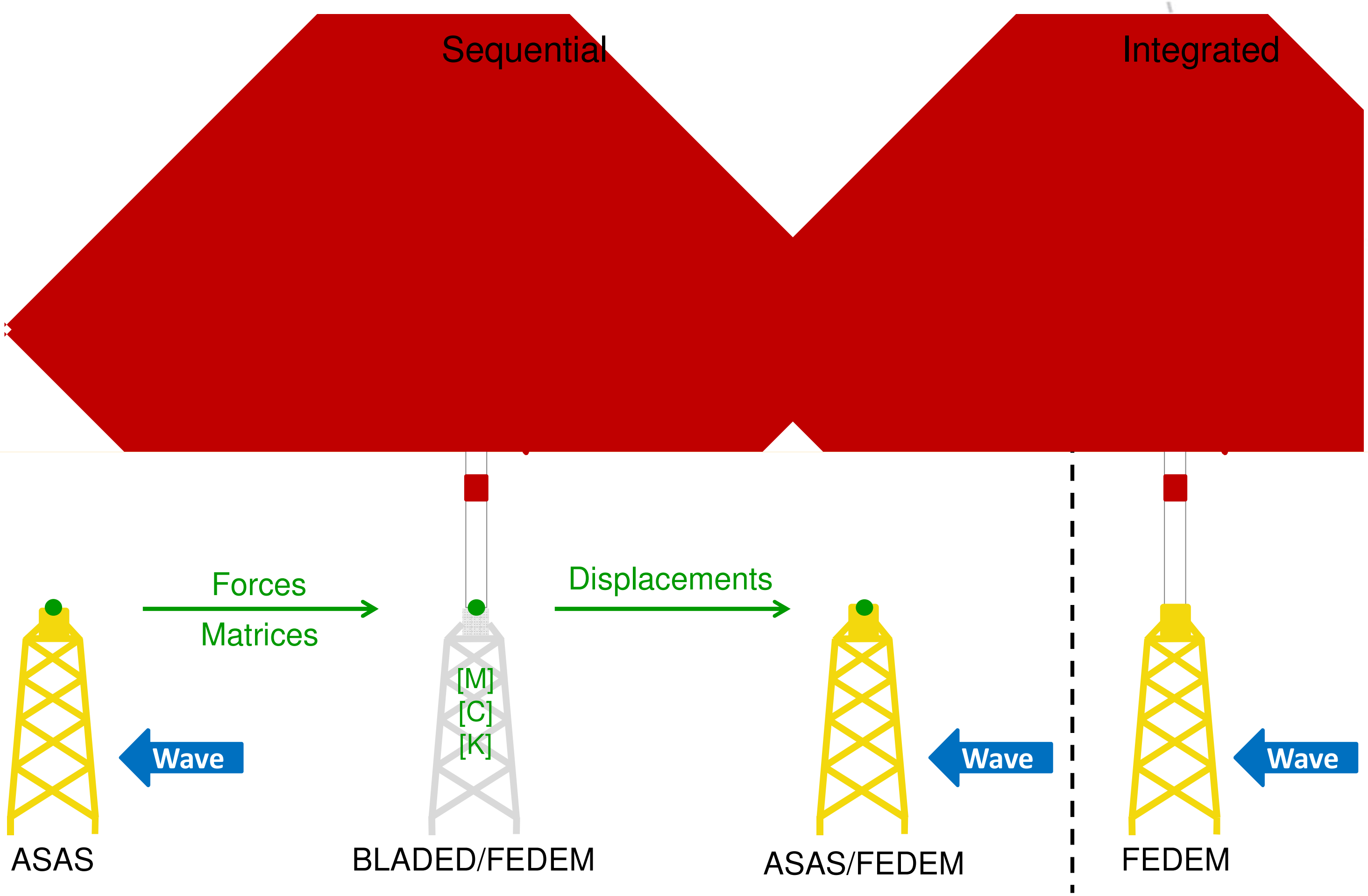
- Partitioned analysis is exact
  - When used with the same part, environment, and displacements (boundary condition)
  - Special case of substructuring
  - Controversy: use of simplified (reduced) parts
- Example: simple beam model with wind and wave loads
  - Necessary to include waves in re-analysis also







Sequential analysis / Integrated analysis



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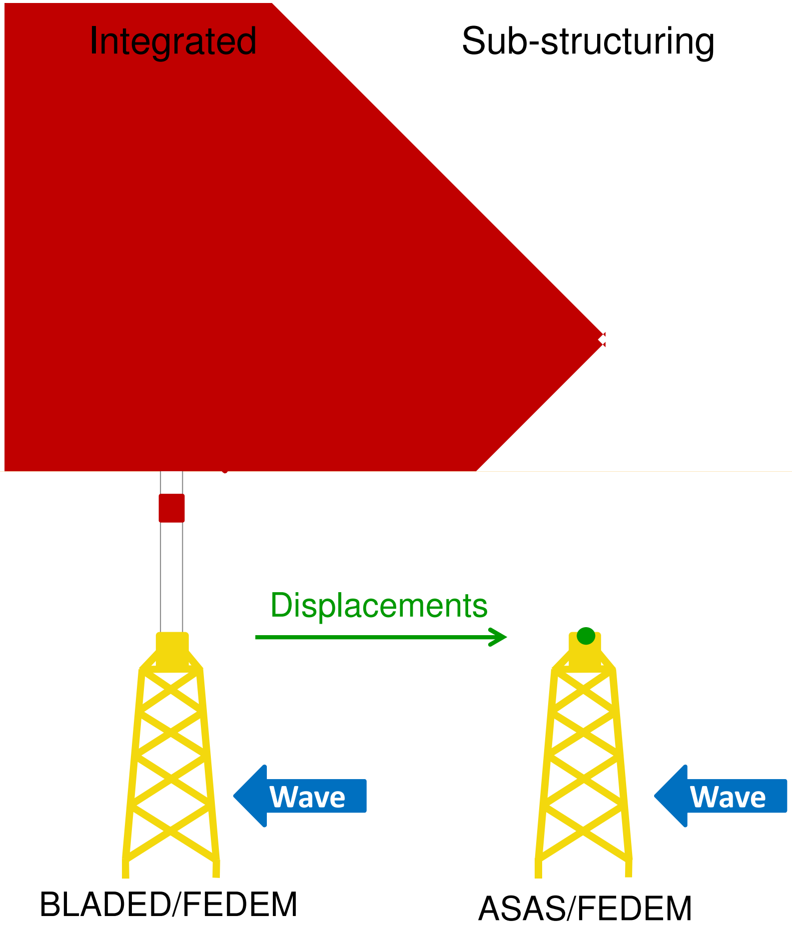
Integrated analysis / Sub-structuring



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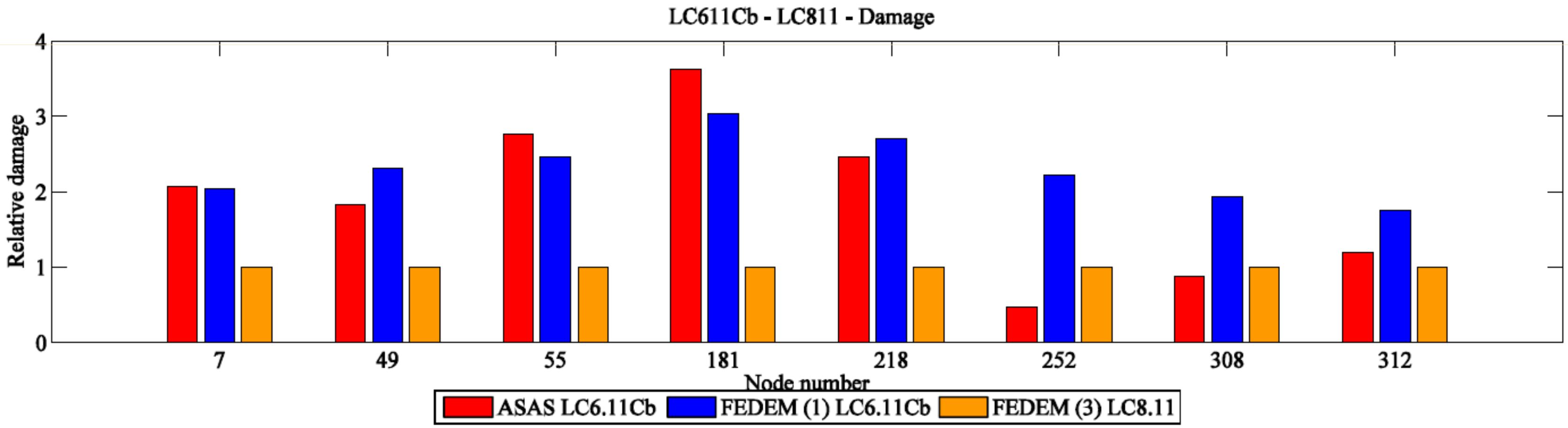
Sequential versus integrated analysis

- Integrated analysis
  - Up to 200 percent decrease in fatigue loads – conservatively
  - Highest differences in lower bays
- However, up to 50 percent more fatigue in some locations
  - X-brace bay 3 – close to top of jacket



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Static and decay load cases

<table>
<tr><th></th><th>Load case</th><th>Description</th><th>Magnitude</th><th>Gravity</th><th>Water</th><th>Marine growth</th></tr>
<tr><td rowspan="3">Static</td><td>LC 0.1</td><td>Equilibrium state</td><td>-</td><td>no</td><td>no</td><td>no</td></tr>
<tr><td>LC 1.1</td><td>Static horizontal force load at tower bottom in positive x dir.</td><td>1 MN</td><td rowspan="2">no</td><td rowspan="2">no</td><td rowspan="2">no</td></tr>
<tr><td>LC 1.2</td><td>Static moment load at tower bottom on the vertical axis.</td><td>1 MNm</td></tr>
<tr><td rowspan="2">Decay</td><td>LC 2.1</td><td>Decay load, horizontal force load at tower bottom along x.</td><td rowspan="2">1MN at t=0s</td><td>no</td><td>no</td><td rowspan="2">no</td></tr>
<tr><td>LC 2.2</td><td>No tower top and no tower present (ASAS and FEDEM only).</td><td>yes</td><td>yes</td></tr>
<tr><td rowspan="9">Dynamic</td><td>LC 3.0</td><td rowspan="3">Regular waves in positive x direction.</td><td>H=2m, T=30s</td><td rowspan="5">yes</td><td rowspan="5">yes</td><td rowspan="5">no</td></tr>
<tr><td>LC 3.1</td><td>H=6m, T=10s</td></tr>
<tr><td>LC 3.2</td><td>H=2m, T=6s</td></tr>
<tr><td>LC 3.3</td><td rowspan="2">Irregular waves with Pierson-Moskowitz (PM) sea wave spectrum in positive x direction.</td><td>H_s=6m, T_p=10s</td></tr>
<tr><td>LC 3.4</td><td>H_s=2m, T_p=6s</td></tr>
<tr><td>LC 3.5</td><td rowspan="2">Regular waves in positive x direction.</td><td>H=6m, T=10s</td><td rowspan="4">yes</td><td rowspan="4">yes</td><td rowspan="4">yes</td></tr>
<tr><td>LC 3.6</td><td>H=2m, T=6s</td></tr>
<tr><td>LC 3.7</td><td rowspan="2">Irregular waves with Pierson-Moskowitz (PM) sea wave spectrum in positive x direction.</td><td>H_s=6m, T_p=10s</td></tr>
<tr><td>LC 3.8</td><td>H_s=2m, T_p=6s</td></tr>
</table>

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Sequential analysis – retrieval run

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	Load case	Description	Magnitude	Gravity	Water	Marine growth
Sequential analysis	LC 4.11	Time series (FLEX5), displacements at tower bottom in all DOFs. No tower top and no tower present. Sea state as defined in table in section 3.4.1.	TB23_RJQ_B_Fat_08_000_011_disp.dat	yes	yes	yes
	LC 4.25		TB23_RJQ_B_Fat_20_000_025_disp.dat			
	LC 4.30		TB23_RJQ_B_Fat_30_000_030_disp.dat			
	LC 4.110	Time series (FLEX5), displacements at tower bottom in all DOFs. No tower top and no tower present. No waves.	TB23_RJQ_B_Fat_08_000_011_disp.dat	yes	yes	yes
	LC 4.250		TB23_RJQ_B_Fat_20_000_025_disp.dat			
	LC 4.11r	Time series (FLEX5), displacements at tower bottom in all DOFs. No tower top and no tower present. Regular waves in positive x direction.	H=6m, T=10s	yes	yes	yes
	LC 4.25r		H=6m, T=10s			
	LC 4.11e	Time series (FLEX5), displacements at tower bottom in all DOFs. No tower top and no tower present. Irregular waves with JS sea wave spectrum in positive x direction.	H_s=12m, T_p=15s, γ=1.06	yes	yes	yes
	LC 4.25e		H_s=12m, T_p=15s, γ =2.13			

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Integrated analysis

	Load case	Description	Magnitude	Gravity	Water	Marine growth
Integrated analysis	LC 5.11	Modified wind turbine model NREL 5MW. Complete support structure as defined in ASAS.	Environmental conditions as specified in table in Chapter 3.6 with constant wind	yes	yes	yes
	LC 5.25					
	LC 5.110	Modified wind turbine model NREL 5MW. Complete support structure as defined in ASAS. No waves.		yes	yes	yes
	LC 5.250					
	LC 7.11	Modified wind turbine model NREL 5MW. Complete support structure as defined in ASAS.	Environmental conditions as specified in table in Chapter 3.6. Ambient turbulence: TI50	yes	yes	yes
	LC 7.25					
	LC 7.110	Modified wind turbine model NREL 5MW. Complete support structure as defined in ASAS. No waves.		yes	yes	yes
	LC 7.250					
	LC 8.11	Modified wind turbine model NREL 5MW. Complete support structure as defined in ASAS.	Environmental conditions as specified in table in Chapter 3.6. Ambient turbulence for steel structures (m=4)	yes	yes	yes
	LC 8.25					
	LC 8.30					

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Sequential analysis – complete run

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	Load case	Description	Magnitude	Gravity	Water	Marine growth
Sequential analysis	LC 6.11X	A: Computing of generalized matrices	Environmental conditions as specified in table in Chapter 3.6.	yes	yes	yes
	LC 6.25X	B: Modified wind turbine model NREL 5MW. Jacket structure represented by mass, damping and stiffness matrices.				
	LC 6.30X	C: Detailed model of OJQ, with displacements of step 2.				

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Sub-structuring

	Load case	Description	Magnitude	Gravity	Water	Marine growth
Sub-structuring	LC 5.11wwsf/b	Time Series of LC5.X or LC5.X.0 (f: FEDEM b: BLADED), displacements at tower bottom in all DOFs. No tower top and no tower present. Sea state defined as follow: LC5.X.w f/b-Input-File does include waves LC5.X.0 f/b-Input-File doesn't include waves LC5.X.X.w The sequential analysis does include waves LC5.X.X.0 The sequential analysis doesn't include waves If waves are considered: Sea state as defined in table in Chapter 3.6. No turbulence.	f/b-INPUT-FILE	yes	yes	yes
	LC 5.25wwsf/b		f/b-INPUT-FILE			
	LC 5.110wsf/b		f/b-INPUT-FILE	yes	yes	yes
	LC 5.250wsf/b		f/b-INPUT-FILE			
	LC 5.11w0sf/b		f/b-INPUT-FILE	yes	yes	yes
	LC 5.25w0sf/b		f/b-INPUT-FILE			
	LC 5.1100sf/b		f/b-INPUT-FILE	yes	yes	yes
	LC 5.2500sf/b		f/b-INPUT-FILE			
	LC 8.11sf/b	Time Series of LC8.X (f: FEDEM b: BLADED), displacements at tower bottom in all DOFs. No tower top and no tower present.	f/b-INPUT-FILE	yes	yes	yes
	LC 8.25sf/b		f/b-INPUT-FILE			

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Goals of this study

Load simulation for a complex, realistic jacket structure

- Verification of the analysis
  Are there differences in load calculations between different analysis codes?
- Verification of the methodology
  Are there differences between sequential and integrated load calculations?
- Specific issues
  What is the influence of simplifications in the structural model?
  - Defeaturing (boat landings, J-tubes)
  - Software limitations (freedom releases, shell elements)

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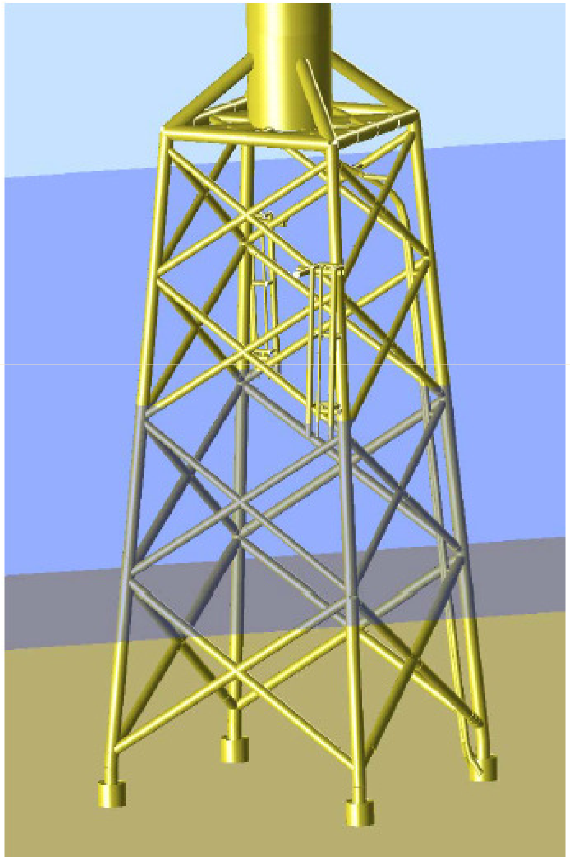
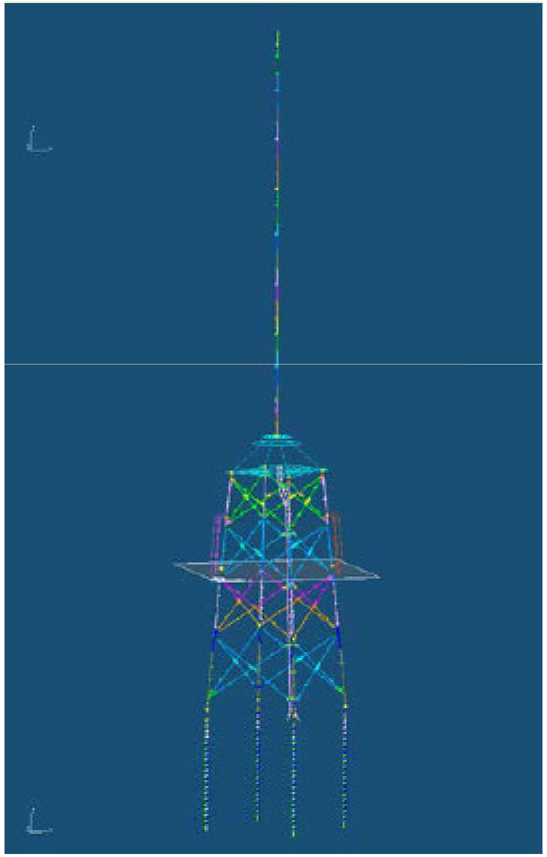
Models implemented in three software packages

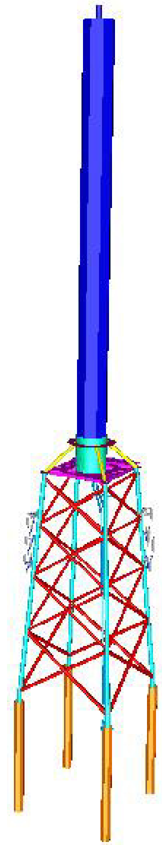
GL Garrad Hassan Bladed



FEDEM Windpower



ANSYS ASAS



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GL Garrad Hassan BLADED

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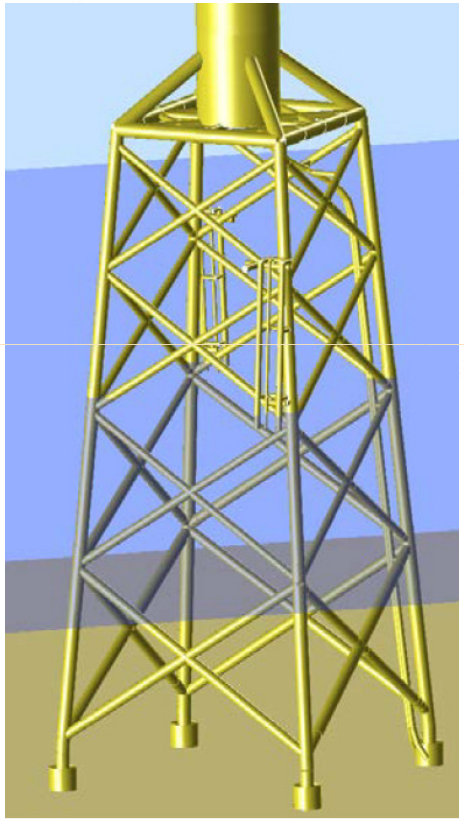
- Wind turbine model for integrated analysis
  - NREL 5MW turbine + additional 100 tons (6 MW)

- Limitations
  - Maximum no. nodes and elements: 750 / 1500
    Stability issues way before this limit
  - Not possible to run structural analysis without wind turbine model
  - No shell elements available
  - No (explicit) rigid offsets
  - No freedom releases

- Two distinct implementations
  - Rigid foundation, simplified structure (736 elements)
    For comparison with similar model in FEDEM Windpower
  - Support structure ”soil model” (matrices + load time series)
    For sequential analysis



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Damping in BLADED

- ASAS: Rayleigh damping
- BLADED: modal damping
- Simple relationship if the same damping for all elements

$$\zeta(\omega) = \frac{1}{2}\left(\frac{\alpha}{\omega} + \beta\omega\right)$$

- For unequal damping
  - In principle: direct calculation
  - In practice: no software has this feature
- New approach
  - Average
  - Weighted by the magnitude of the corresponding eigenvector (modal participation)

	Frequenz [Hz]	ω_{0i} [−]	α [−]	β [−]	D_i [−]
Blade Mode	0.662	4.159	0.000000	0.004775	0.009930
	1.082	6.798	0.000000	0.004775	0.016230
	1.868	11.737	0.000000	0.004775	0.028020
	3.908	24.555	0.000000	0.004775	0.058620
	4.297	26.999	0.000000	0.004775	0.064455
	7.213	45.321	0.000000	0.004775	0.108195
	9.348	58.735	0.000000	0.004775	0.140220
Tower Mode	0.307	1.929	0.034835	0.001932	0.010893
	0.308	1.935	0.035272	0.001964	0.011013
	1.624	10.204	0.032305	0.001657	0.010037
	2.411	15.149	0.024178	0.001703	0.013700
	2.801	17.599	0.023928	0.001709	0.015719
	3.445	21.646	0.025827	0.001553	0.017403
	3.499	21.985	0.025946	0.001550	0.017632
	4.844	30.436	0.030636	0.001876	0.029053
	6.197	38.937	0.028039	0.001549	0.030509
	6.217	39.063	0.027879	0.001545	0.030540
	6.409	40.269	0.029071	0.001591	0.032399
	6.517	40.948	0.029207	0.001596	0.033042

FEDEM Windpower

Fedem Technology

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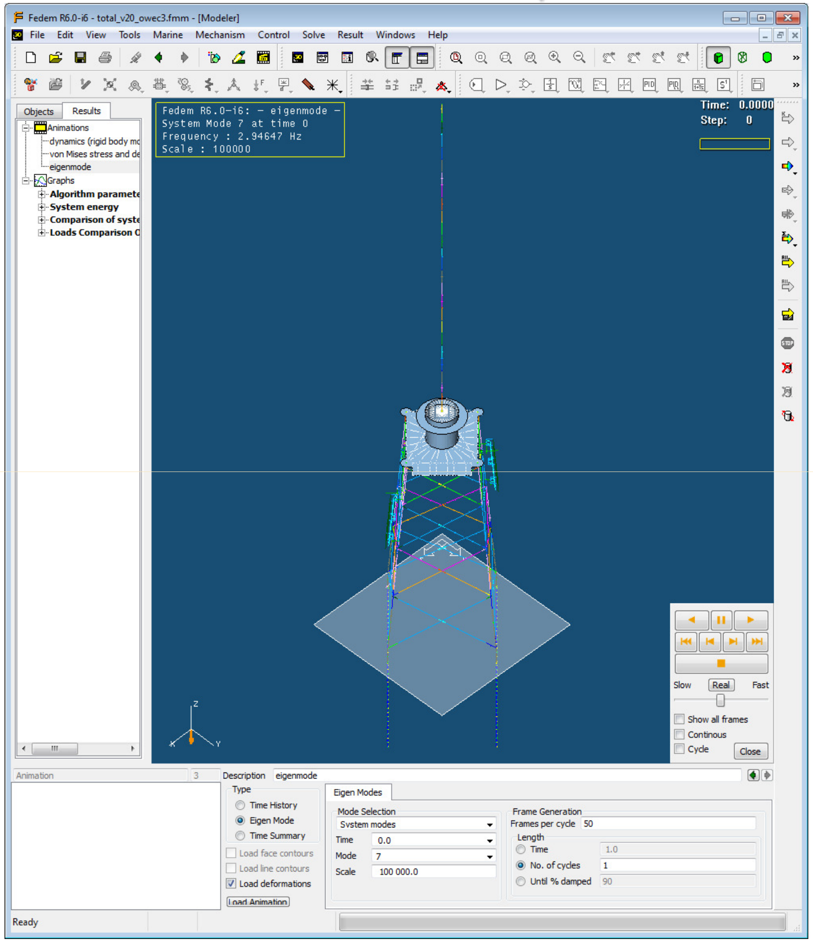
- Integrated analysis tool
  - Flexible multibody solver
  - Developed and extensively used in automotive industry
  - Wind loads from NREL AeroDyn (integrated into the software)
  - Wave loads implemented (Morrison approach)
  - Pre-release version
  - Licensed through DNV



- Limitations
  - No generic stiffness, mass, or damping matrices
  - No different random seeds for irregular waves
  - Euler-Bernoulli beam theory
    Quadratic shape functions
    First-order continuous derivatives

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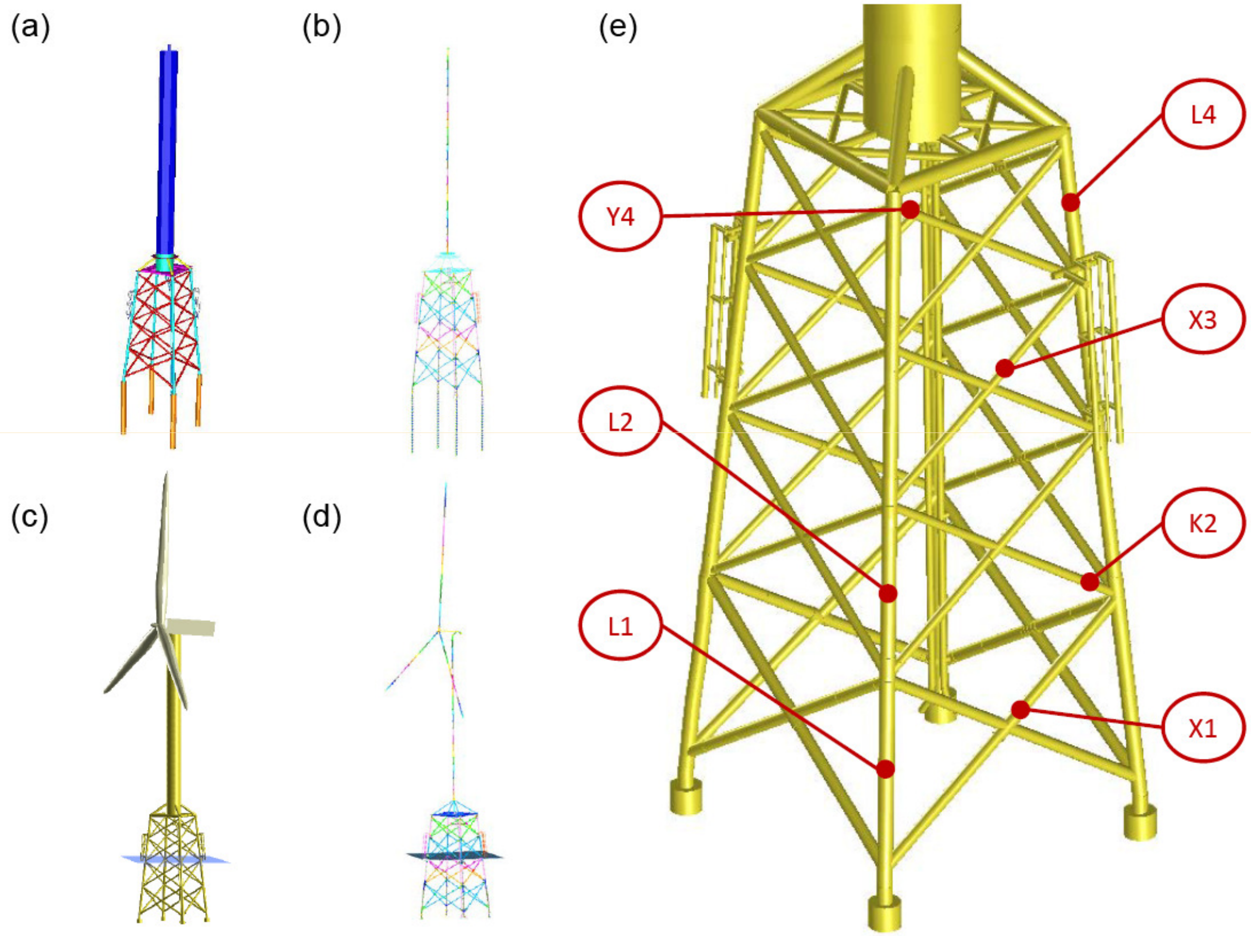
Output stations



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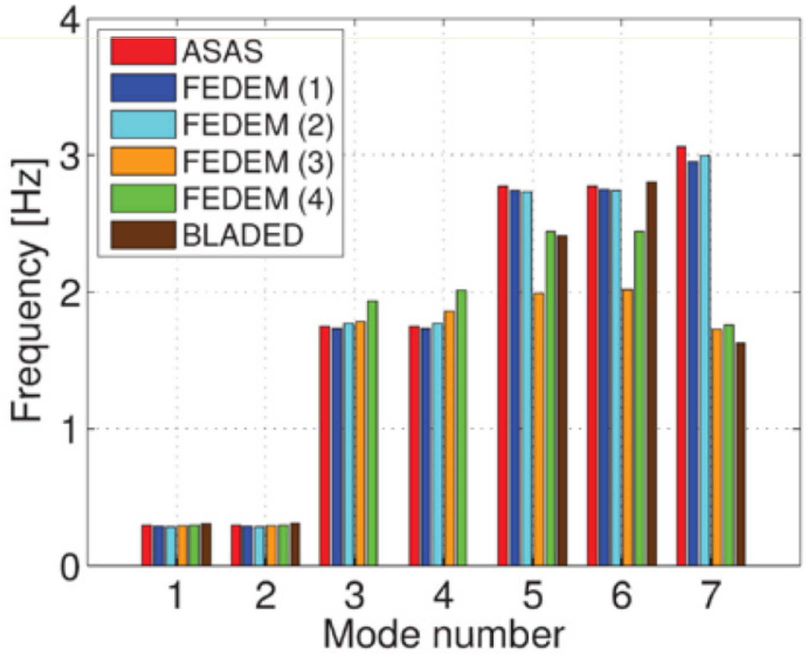
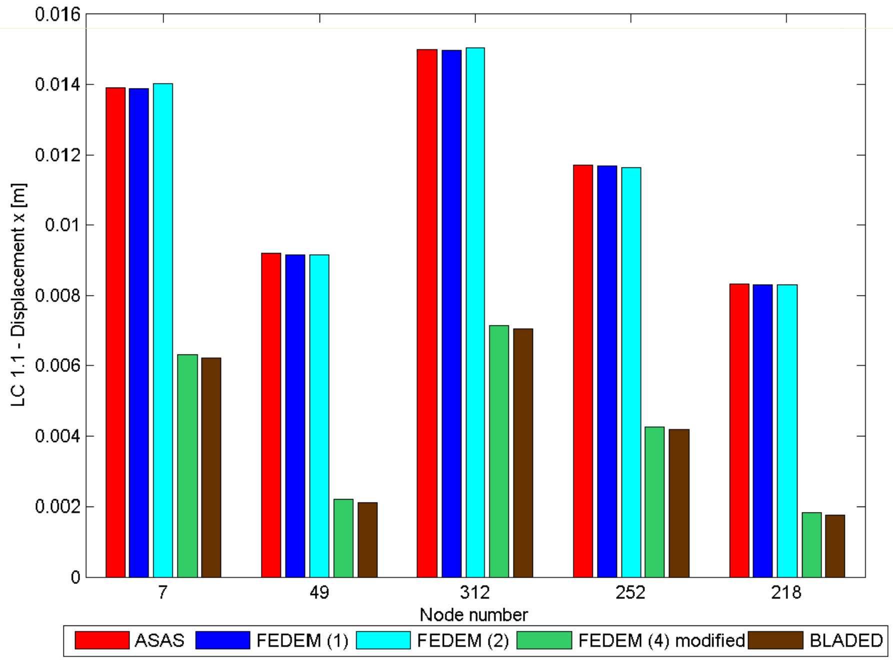
First comparisons

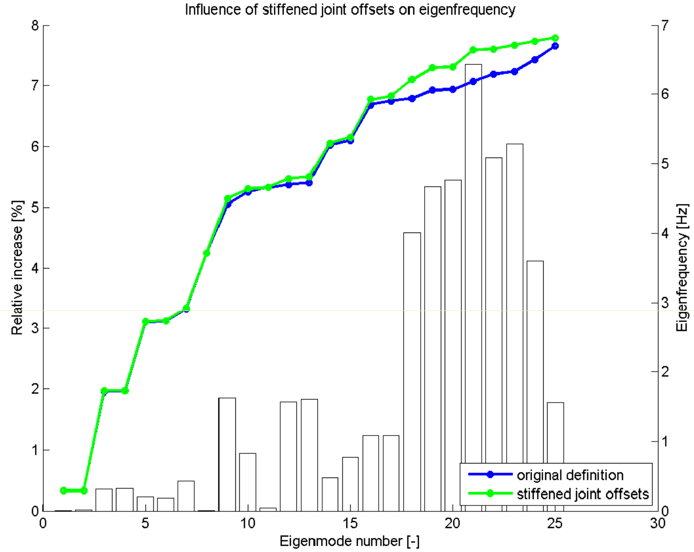
- Mass check (1337 tons +/- 1.5%)
- CoG check (+/- 5%)
- Eigenfrequency check (+/- 5%)
- Static force (1MN; LC1.1) and static moment (1MNm)
  - Model check: Integrated forces / moments at pile head
  - Displacements
- Reduced transition piece (FEDEM2): well matched

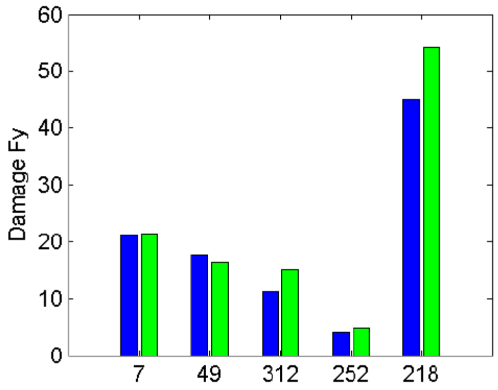


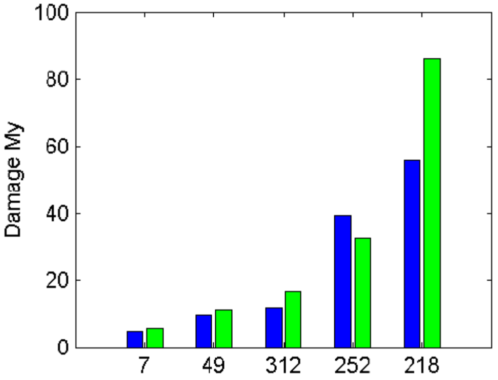


Influence of rigid offsets

- Studied in FEDEM
- Influence on eigenfrequencies
  - negligible (<2%) for lower eigenfrequencies
  - up to 10% difference for higher (local support structure) modes
- Influence on fatigue damage
  - Assessed by damage-equivalent-displacements (relative damage factor)
  - 5-30% increases with offsets (green)
  - but also reduction of up to 10% in some joints







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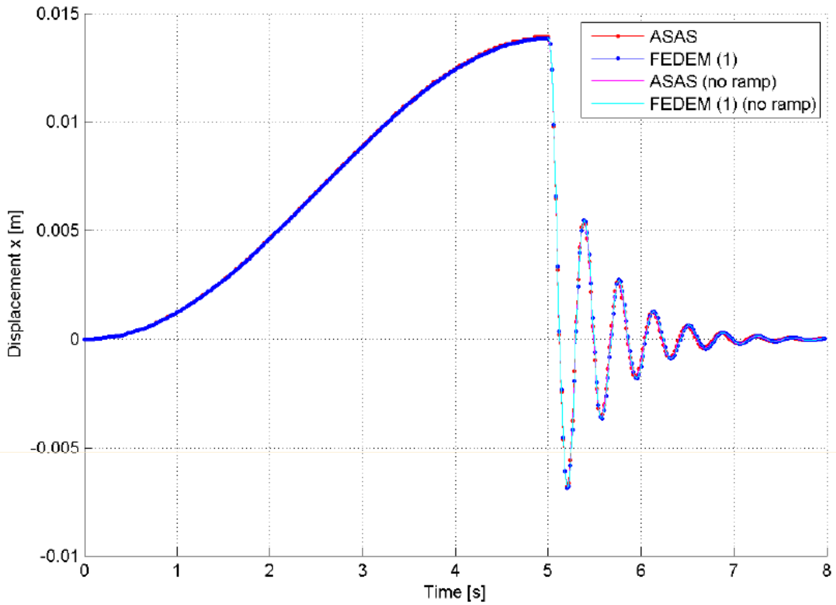
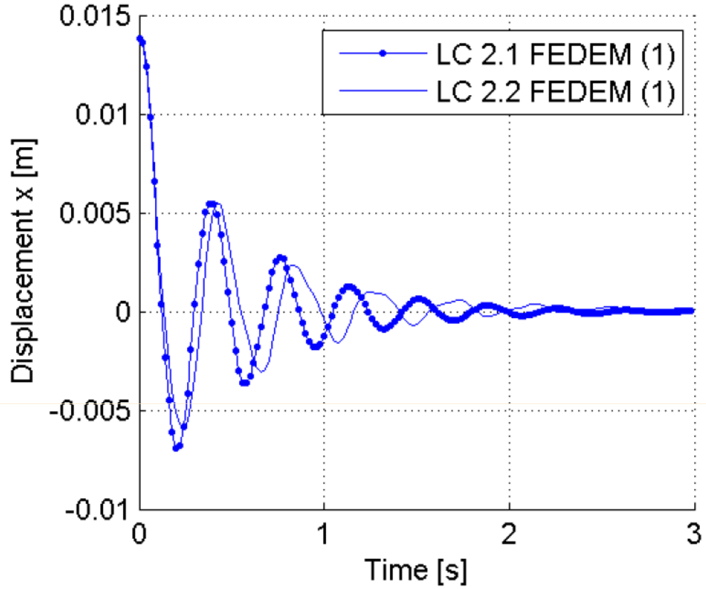
Decay tests





- Good agreement between models (ASAS and FEDEM)
- Influence of added mass visible
- NB: need to include small wave in ASAS also for still-water case (!)

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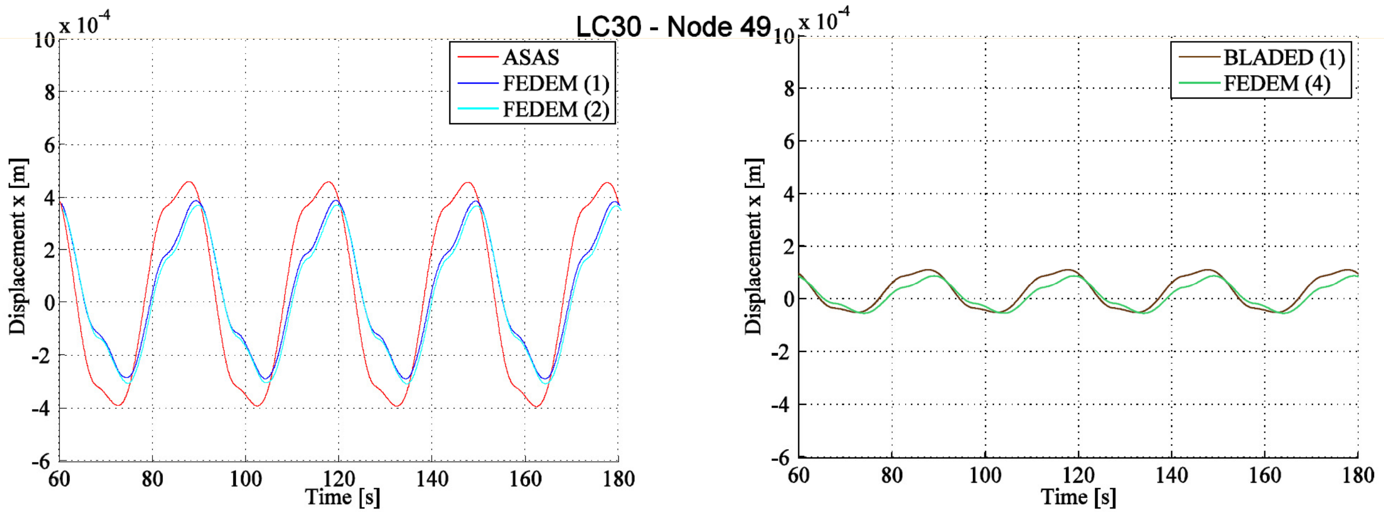
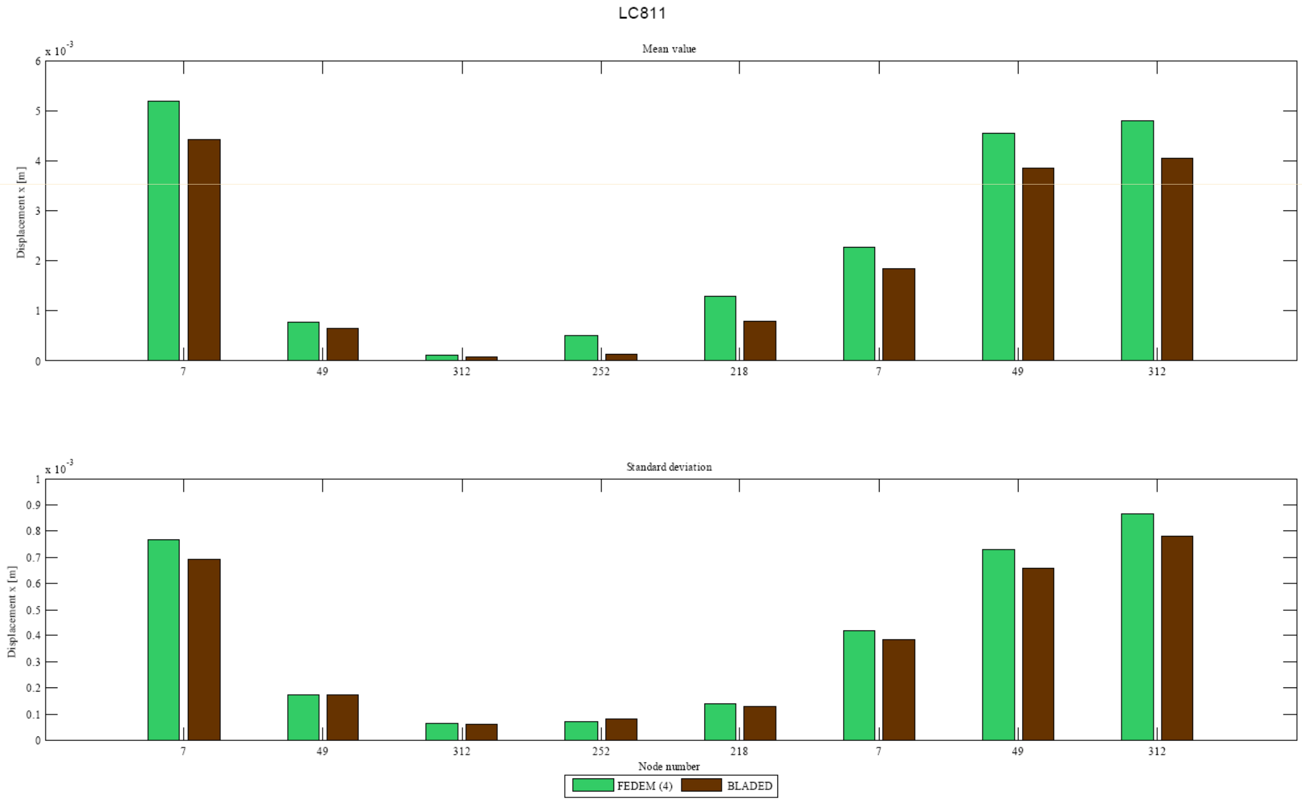
Issue: Discretization of wave loads?

- Regular wave loading
- Differences in amplitude that cannot be explained (ASAS vs. FEDEM)
- Up to 100 percent difference in some cases
  Larger for smaller waves – closer to eigenfrequency
- Quasi-static wave loads (period T=30s)
  Still differences of up to 25 percent
- Most likely differences in discretization of wave loads (no. integration points)



Integrated analysis in BLADED / FEDEM

- BLADED more suitable: allows for general matrices
- Slightly less response in FEDEM
  - up to 15 percent difference in mean, up to 10 percent in SD
  - again, calculation of wave loads?



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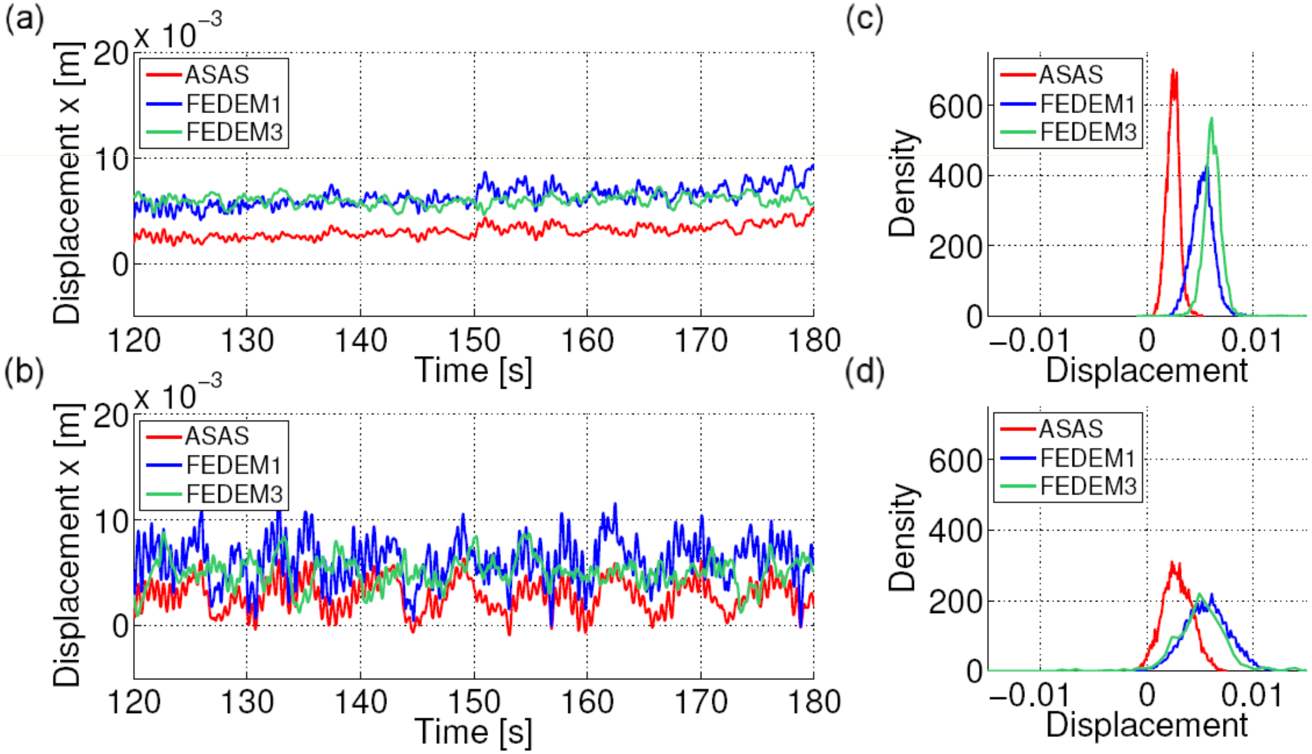
Sequential versus integrated analysis

- Two fatigue load cases
  - A: 8 m/s wind, TI = 0.153; Hs = 1.00 m, Tp = 4.95 s
  - B: 20 m/s wind; TI = 0.121; Hs = 2.59 m; Tp = 6.99 s



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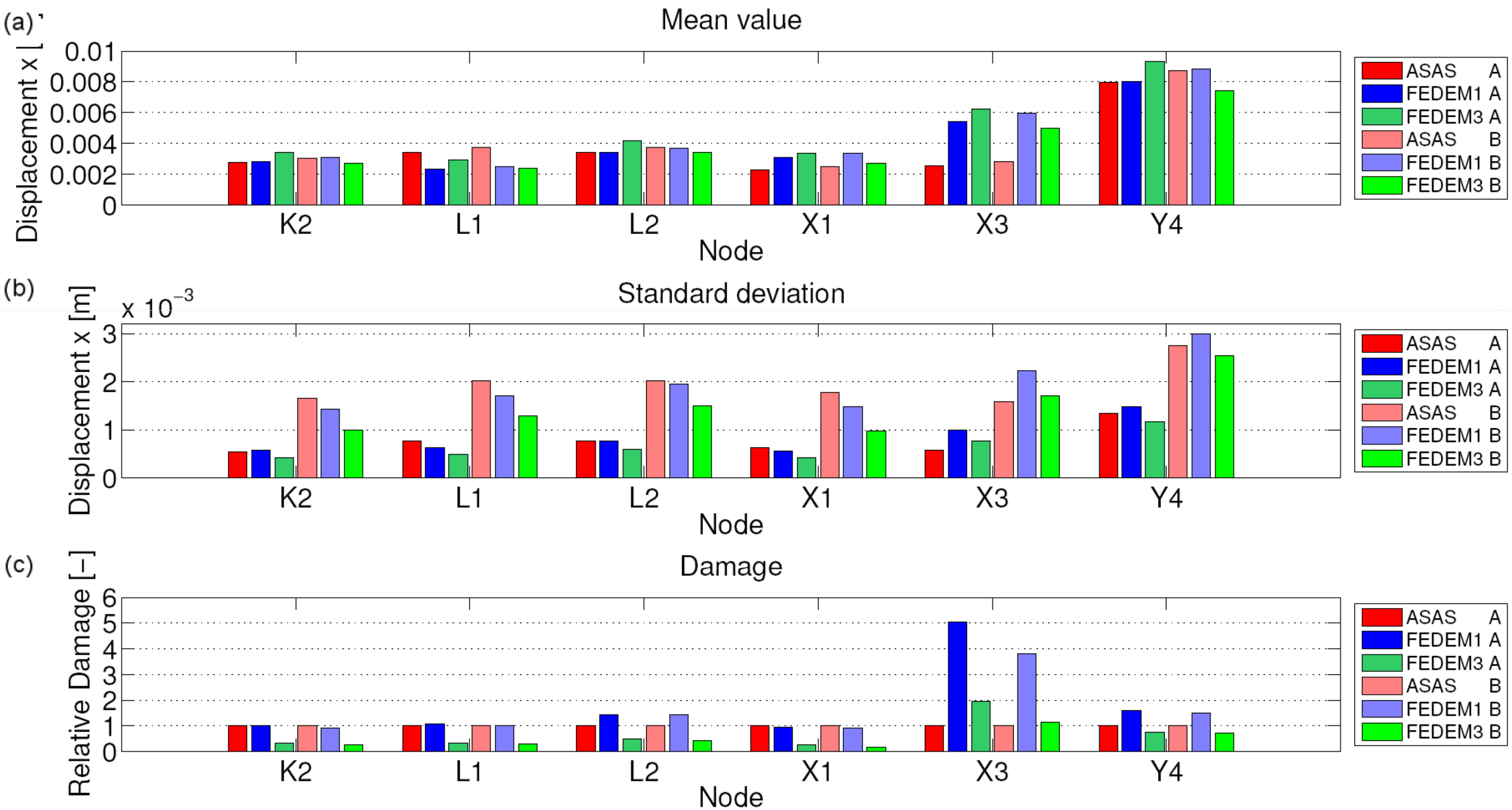
Sequential versus integrated analysis



Final thoughts

- Wave load calculation seems to differ in different analysis codes – need to understand this better
- No suitable software tool at the moment (commercially available, integrated analysis, beam code checks)
- Integrated analysis generally more favorable for fatigue cases (significant differences)
- Implications for design: Possibilities for further optimization and cost-savings

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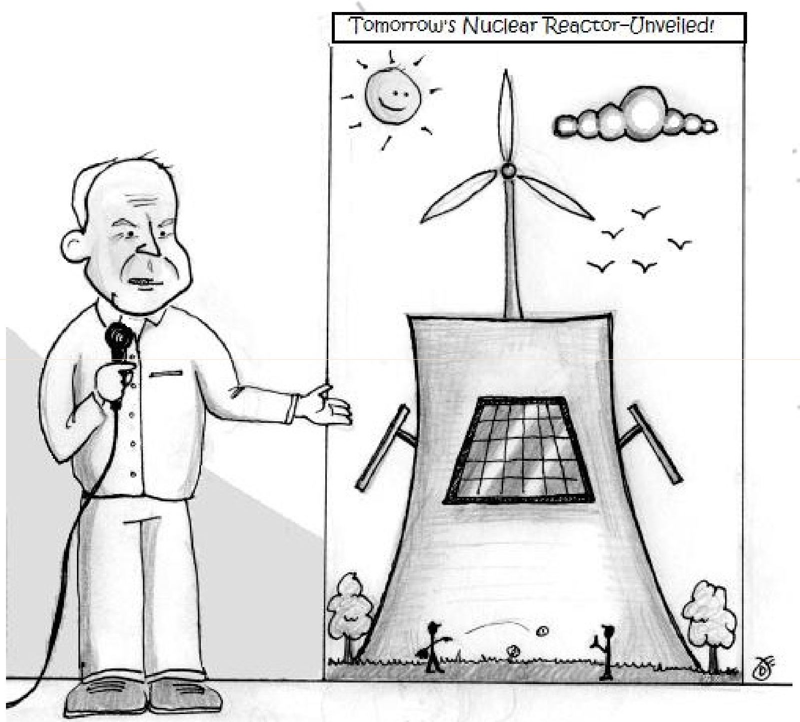

"...and each of the 45 nuclear reactors will have a wind turbine on top and four solar panels surrounding it!..."

Offshore wind turbine technology group

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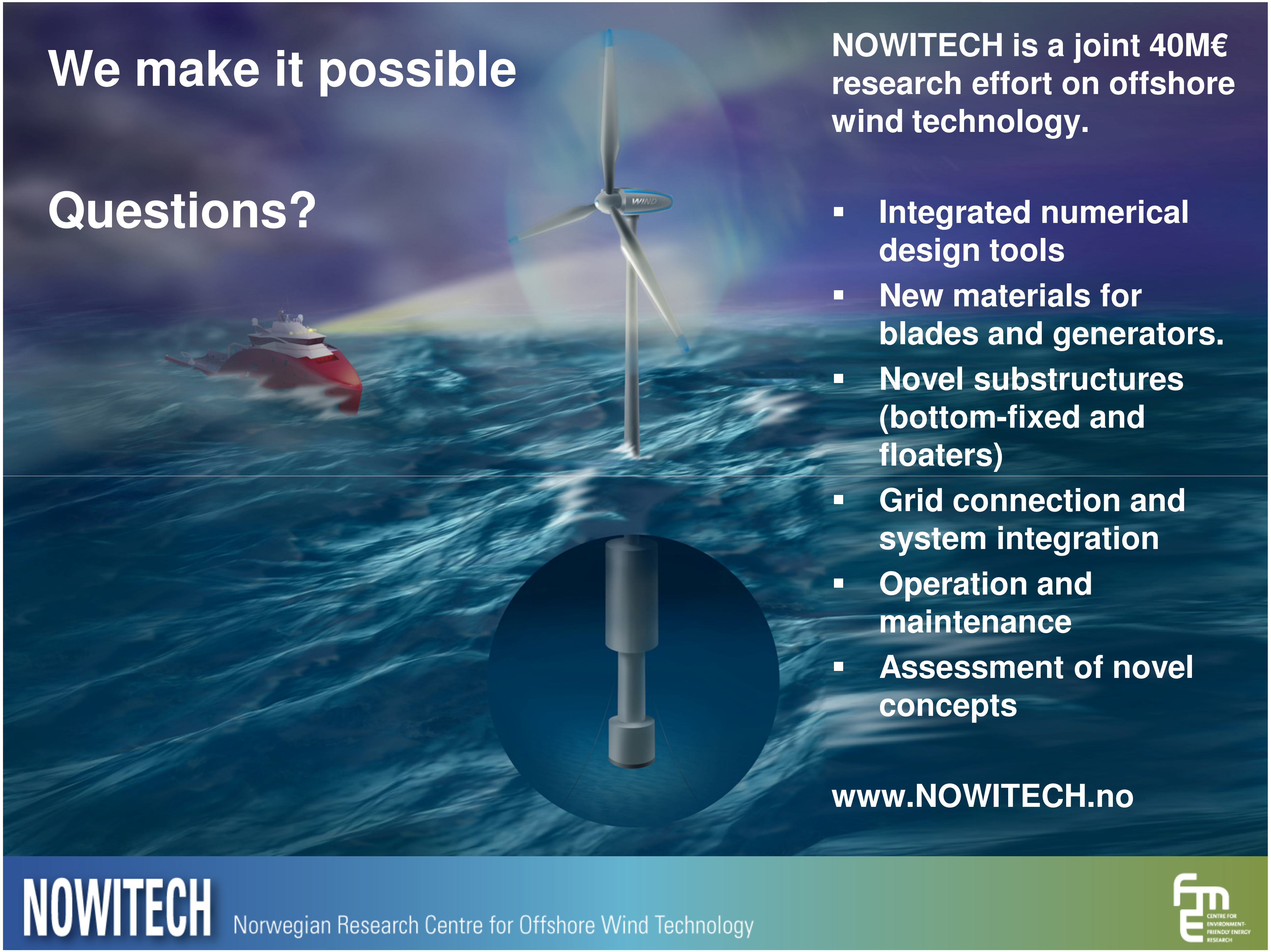
michael.muskulus@ntnu.no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