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Report

EERA JP Wind Energy

Joint Workshop 27 – 28 June 2018
SP6: Offshore & SP5: System integration: Offshore grids

Author(s)
John Olav Tande
Harald G. Svendsen

SINTEF Energy Research AS
Power Conversion and Transmission
2018-09-17

SINTEF

SINTEF Energi AS
SINTEF Energy Research AS
Address:
Postboks 4761 Torgarden
NO-7465 Trondheim
NORWAY
Switchboard: +47 73592000

Enterprise /VAT No:
NO 939 350 675 MVA

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SP6: Offshore & SP5: System integration: Offshore grids

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AUTHOR(S)
John Olav Tande
Harald G. Svendsen

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ABSTRACT

This document contains the proceedings of the joint workshop in Trondheim 27-28 June 2018, including presentations given.

PREPARED BY
John Olav Tande

SIGNATURE

CHECKED BY
Harald Svendsen

SIGNATURE

APPROVED BY
Knut Samdal

SIGNATURE

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SINTEF

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APPENDICES

1 Introduction

EERA Joint Programme Wind is one of 17 joint programmes within the European Energy Research Alliance (EERA). Its vision is to be the globally leading R&D community in wind energy, creating synergy advantages for European research organisations and industry in support of the green energy transition and the SET-Plan goals. EERA JP WIND has 50 member organisations and 8 sub-programmes.

The sub-programmes *System Integration* (SP5) and *Offshore Balance of Plant* (SP6) have closely related research topics in the interface between offshore wind plant and the grid connection, notably offshore grids. It was therefore agreed to organise a joint workshop, hosted by SINTEF in Trondheim, 27-28 June 2018.

The workshop was well represented with participants from the majority of EERA research institutes active in the relevant fields represented. In total, there were 21 participants from 16 different organisations.

The workshop contained one part with presentations of ongoing relevant activities, and one part with discussions on potential collaborations and joint project proposals.

2 Agenda

Wednesday 27 June

12:00 Lunch
13:00 Welcome
13:10 Brief introduction to SP5 (grid) and SP6 (offshore)
13:30 Presentation of EU & national projects:
20 min CONCERT project, DTU (Tuhfe Gökmen)
20 min NSON project, Fraunhofer (Denis Mende)
9 min NTNU (Magnus Korpås)
20 min NSON.DK project, DTU (Nicolaos Cutululis)
10 min Break
9 min VTT (Erkka Rinne)
9 min CRES (Nikolaos Stefanatos)
9 min Uni Strathclyde (Olimpo Anaya-Lara)
9 min TU Munich (Filippo Campagnolo)
20 min BESTPATHS project, SINTEF
9 min CENER (Xabier Munduate)
16:15 Visit to SmartGrid lab
17:15 Sum-up/end day 1
19:00 Dinner (city centre, "Ristorantino")

Thursday 28 June

09:00 Presentation of project: PROMOTioN, DTU (Nicolaos Cutululis)
09:20 Review of relevant EU calls (Harald Svendsen)
09:40 Discussions
–joint project applications
–alignment of research efforts / joint publications
11:45 Sum-up day 2
12:00 Lunch
13:00 End of workshop

13:00 SP5 meeting
15:00 end of SP5 meeting

3 Participants

Name	Institution
John OlavTande	SINTEF Energi
Nicolaous Cutululis	DTU
Tuhfe Gökmen	DTU
Harald Svendsen	SINTEF Energi
Salvatore D'Arco	SINTEF Energi
Olimpo Anaya-Lara	Strathclyde University
Salvador Ceballos Recio	Tecnalia
Magnus Korpås	NTNU
Erkka Rinne	VTT
Denis Mende	Fraunhofer IWES
Oscar Salgado	Ikerlan
Nikolaos Stefanatos	CRES
Roy Stenbro	IFE
Filippo Campagnolo	TU München
Christian Karl	Uni Hannover
Jose Luis Dominguez	IREC
Xabier Munduate	CENER
Michał Kosmecki	Institute of Power Engineering, Poland
Koen Hermans	ECN TNO
Til K Vrana	SINTEF Energi
Hans Christian Bolstad	SINTEF Energi

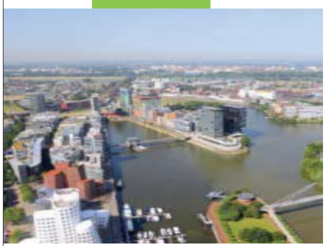
From left: N Stefanatos, M Kosmecki, C Karl, F Campagnolo, R Stenbro, D Mende, TK Vrana, O Anaya-Lara, O Salgado, J Tande, JL Dominguez, N Cutululis, X Munduate, HG Svendsen, S Ceballos, E Rinne, K Hermans, HC Bolstad. Absent: T Gökmen, S D'Arco, M Korpås

4 Presentations

EERA JP Wind Energy

SP Offshore Balance of Plant

John Olav Giæver Tande
Coordinator SP Offshore BOP
Chief Scientist, SINTEF
John.tande@sintef.no



EERA JP WIND - a vehicle for collaboration

- EERA is an organisation under the EU SET-Plan
- EERA JP WIND is one of 17 Joint Programmes
- 50 member organisations
- Building trust & knowledge exchange
- Major EU projects setup through EERA JP WIND collaboration
- Organization into EERA JP WIND 2.0 was agreed at the Steering Committee meeting 13/3-2018

EERA JP WIND 2.0

Lean. Transparent. Independent.

EERA JP WIND 2.0

Vision

To be the globally leading R&D community in wind energy

creating synergy advantages for European research organisations and industry in support of the green energy transition and the SET-Plan goals.

Mission

Build and maintain a world-class wind energy research and innovation community in Europe

through increased alignment and coordination of national and European efforts in support of the industry of today and to enable the industry of tomorrow.

EERA JP WIND 2.0 - Objective & overall strategy

In order to fulfill its mission and vision, EERA JP WIND will work towards the following 5 Objectives:

1. **Strategic leadership** in prioritizing and promoting research at TRL 1-5 and working with Industry to coordinate research priority setting at higher TRLs towards the European and national policy makers
2. **Enhance knowledge** sharing through joint events and communication platforms
3. Coordinate dedicated **mobility programmes** for researchers to increase collaboration through dedicated mobility programmes
4. **Sharing infrastructures** to improve the efficiency of use and easy of access of state of the art infrastructure
5. **Enable data sharing and management** in accordance with the European Commission's F.A.I.R principles

EERA JP WIND 2.0 sub-programmes

Coordination

- SP1: Programme planning and outreach
  - Strategic roadmaps and plans
  - Publish yearly R&D priorities
  - Training and mobility
- SP2: Research Infrastructure, testing and standards
  - Standard agreements and procedures, getting external funding
  - Dissemination and open data

Research

- SP3: Wind conditions and climatic effects
- SP4: Aerodynamics, loads and control
- SP5: System integration
- SP6: Offshore Balance of Plant
- SP7: Structures, materials and components
- SP8: Planning & Deployment, social, environmental and economic issues

EERA European Energy Research Alliance

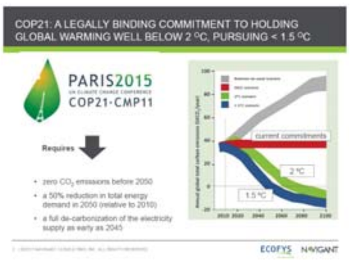
SP6: Offshore Balance of Plant

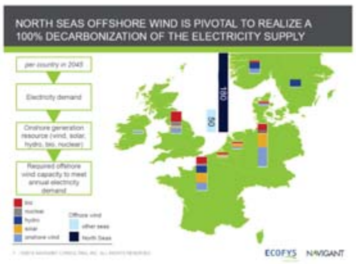
Overall objective

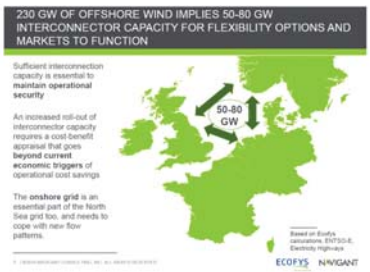
Pre-competitive research laying a scientific foundation for the industrial development of more cost effective offshore wind farms and enabling large scale deployment at any seas

EERA European Energy Research Alliance

Offshore wind is set to be big







#NSEforum2017 with Statoil, Shell, Energinet.dk, Tennet and EU VP Energy Union

Strong need for offshore wind R&D. Research agenda for SP6 Offshore BOP is in preparation

- **RT1: Design optimization through validation studies offshore**
  Measured data for model benchmarking
- **RT2: Characterization and interaction of wind, wave and current,**
  Soil-structure interaction, Improved design basis
- **RT3: System engineering,**
  Wind farm design optimization / planning tools (pre-FID)
- **RT4: Innovative wind farm electric grid connection for offshore applications**
  Component modeling for electrical stress and interaction analysis
- **RT5: Mechanical and electrical design conditions for electrical infrastructure**
- **RT6: Control, Operation and Maintenance of offshore wind farms**
  Design tools and methods for improved/optimized control, operation and maintenance of (clusters of) offshore wind farms; Materials, coatings and degradation process
- **RT7: Novel concepts for deep sea, including multi-use of wind farm areas**
  giving step-changes in technology for reducing cost of energy from offshore wind farms

Suggestions for EU / transnational projects (1 of 2)

- **Site characterization for improved design basis**
- **Specific Challenge**: Improve design basis for offshore wind farms and provide better measurement methodology and modelling systems for characterization of met-ocean and soil conditions.
- **Scope**: Multiscale environmental modeling; Met-ocean measurement methods; Ground model development

- **Electrical infrastructure**
- **Specific Challenge**: Develop tools and technologies for reliable and cost efficient grid connection of large offshore wind farms and clusters of wind farms
- **Scope**: Component modeling for electrical stress and interaction analysis; Collection and transmission system design tools and application analysis; Lab testing of new technologies

- **Design analysis of support structures, transportation and installation**
- **Specific Challenge**: Develop new and efficient methods and technologies to support innovations in design and installation of offshore wind turbine foundations and structures
- **Scope**: Integrated design assessment and optimization of substructures and foundations; Loads and response modelling; Transport and installation

From: EERA Medium to long term Research Strategy and Roadmap, 2016

Suggestions for EU / transnational projects (2 of 2)

- **Operational control and maintenance**
- **Specific Challenge**: Develop new methods, tools, and advanced technologies for operational control and maintenance for large offshore wind farms.
- **Scope**: Model-based RT control algorithms for minimizing LCoE; Health monitoring and inspection systems; Optimal logistics & maintenance

- **Offshore wind farm for research and innovation**
- **Specific Challenge**: Provide open access to data and pronounced opportunities to carry out test and measurement campaigns.
- **Scope**: Scope will depend on the agreements that can be made with industry on open access, e.g. it can be limited to some very specific measurement campaigns.

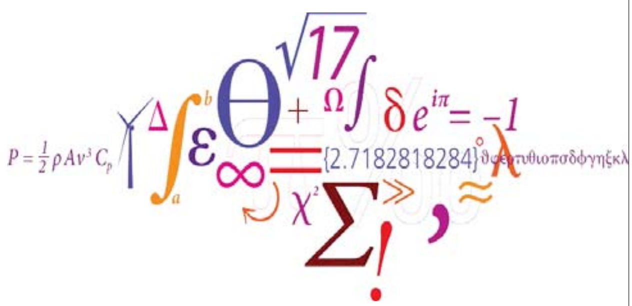
- **Systems Engineering of Wind Power Plants**
- **Specific Challenge**: Optimize the design and system dynamics of wind power plants and plant clusters, considering the relevant physical processes (e.g. turbines, grid, atmosphere) and stakeholders
- **Scope**: Unified dynamic analysis tools to enable systems-level studies; Model validation with measurements at operating plants; International competitions through IEA Task 37

From: EERA Medium to long term Research Strategy and Roadmap, 2016

CONCERT : Control and Uncertainties in real-time power curves

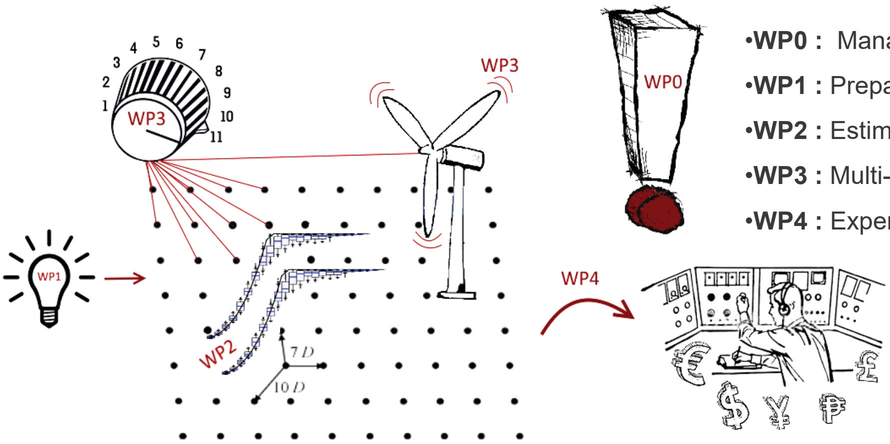
Gregor Giebel & **Tuhfe Göçmen** → **WP2**
Nicolaos Cutululis & **Jonas Kazda** → **WP3**

DTU Wind Energy



DTU Wind Energy
Department of Wind Energy

CONCERT - Overview



- **WP0 :** Management and Dissemination
- **WP1 :** Preparation, Market investigation, Literature Review
- **WP2 :** Estimation and Mitigation of Uncertainty
- **WP3 :** Multi-Objective Wind Power Plant (WPP) Control
- **WP4 :** Experimental Verification and Trading Markets Aspects

- Here we focus on the latest results in WP2 : Estimation and reduction of uncertainty in WF Scale Possible Power!

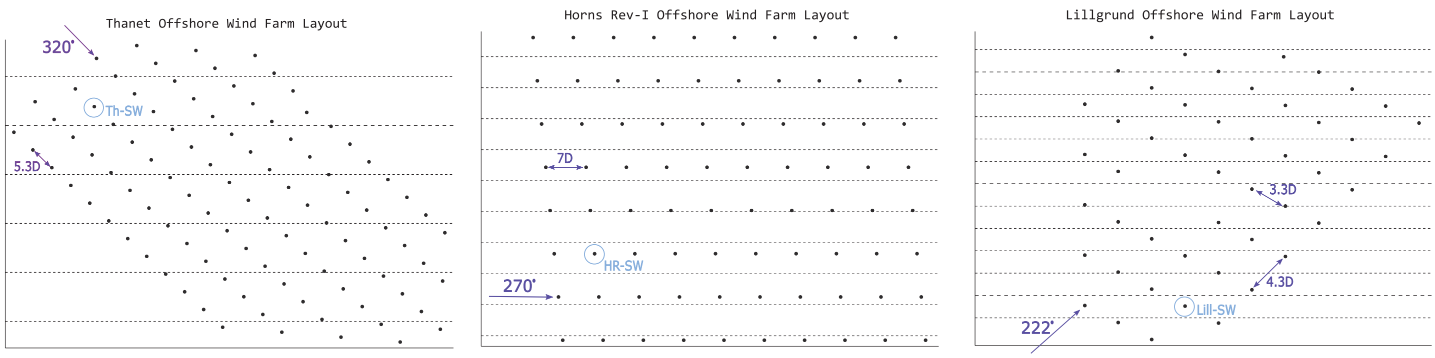
Introduction & Motivation to WP2

- Possible / Available / Reserve Power of a wind farm
  - o Power System integration / Electricity Market / **Wake Modelling**
- Different Problems / Different time scales
- Ultimately, regulated by the grid codes (especially offshore)
  - o DK : Energinet.dk → Data collection @ 5mins, quality check @ 15mins. The error should be within ±5% of the actual power
  - o DE : TSO Consortium → Data collection @ 1min, quality check **@ 1mins**. The **std** of the **1min error < 5%** (pilot phase since October) & The **std** of the **1min error < 3.3%** (after pilot phase)

- We need to be fast & reliable & accurate (enough) in modelling the wake for operational offshore wind farms!

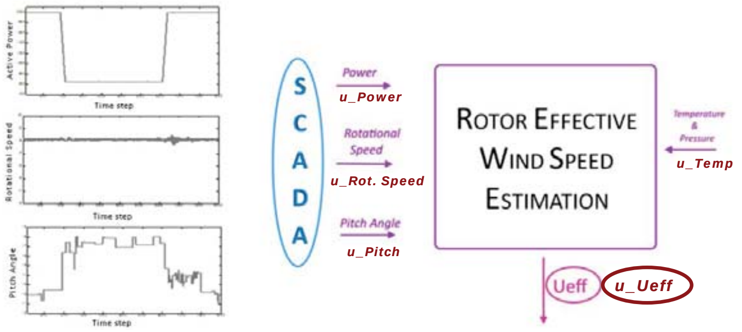
Wind Farms & Data

- 3 WFs: similar turbine range (2MW -3MW), changing spacings
- Focus on single wake for now
  - o Avoid additional uncertainties e.g. wake summation & meandering
- Continous time series with perpendicular wind, around ±15°
- Nominal operation periods



Wind Farms & Data

- Purely SCADA based modelling
  - o 1-sec resolution
  - o 1-hour historical data for parameter calibration / training
    - ▪ Based on Ueff
  - o Following 1-hour for validation / test
    - ▪ Based on Ueff
    - ▪ 1-min Percentage error distribution
      - ✓ 5% std → 3.375% in IQR
- Uncertainties
  - o Input SCADA uncertainties
  - o Propagated in Ueff estimation procedure
    - ▪ **u_Ueff = σ_{Ueff} = 0.3 m/s**



"Tuhfe Göçmen, Gregor Giebel, Niels Kjølstad Poulsen, and Mahmood Mirzaei. Wind speed estimationand parametrization of wake models for downregulated offshore wind farms within the scope of PossPOW project. *Journal of Physics: Conference Series*, 524(1):012156, 2014"

"Tuhfe Göçmen and Gregor Giebel. Estimation of turbulence intensity using rotor effective wind speed in Lillgrund and Horns Rev-I offshore wind farms. *Renewable Energy*, 99:524–532, 2016"

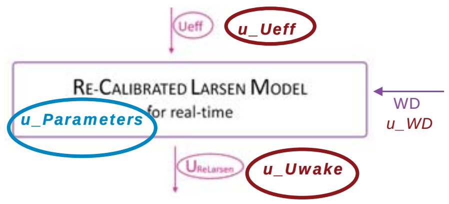
"IEC 61400–12-2, wind turbines: part 12–2: Power performance of electricity producing wind turbines based on nacelle anemometry." Switzerland, Geneva (2013)

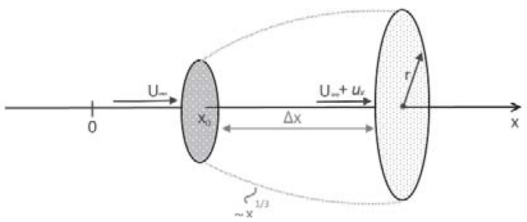
"IEC 61400–12-1, wind turbines: part 12–2: Power performance of electricity producing wind turbines" Switzerland, Geneva (2005)

"Göçmen, T & Giebel, G, Uncertainties and Wakes for Short-term Power Production of a Wind Farm. in Proceedings of the 2018 Wind Energy Symposium. AIAA. DOI: 10.2514/6.2018-0252"

Short-term Wake Modelling

Re-calibration of Larsen Model





$$u_x(x,r) = -\frac{U_\infty}{9}\left(c_T A(x_0+\Delta x)^{-2}\right)^{\frac{1}{3}}\left\{r^{\frac{3}{2}}\left(3c_1^2 c_T A(x_0+\Delta x)\right)^{-\frac{1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3c_1^2\right)^{-\frac{1}{5}}\right\}^2$$

- 2 variables to adjust: $\boxed{x_0 = p_1 \cdot c_{\mathrm{T}}^{p_2} + p_3 \cdot TI}$ $\boxed{c_1 = p_4 \cdot c_{\mathrm{T}}^{p_5} + p_6 \cdot TI}$
- 3-stages of calibration
  - o Nonlinear LSE fit in Thanet → *prior parameter distribution, no uncertainty*
    - ▪ Horns Rev-I test case
  - o Bayesian fit to Horns Rev-I data → *updated prior, uncertainty included*
    - ▪ Horns Rev-I & Lillgrund test case
  - o Bayesian fit to Lillgrund data
    - ▪ Lillgrund test

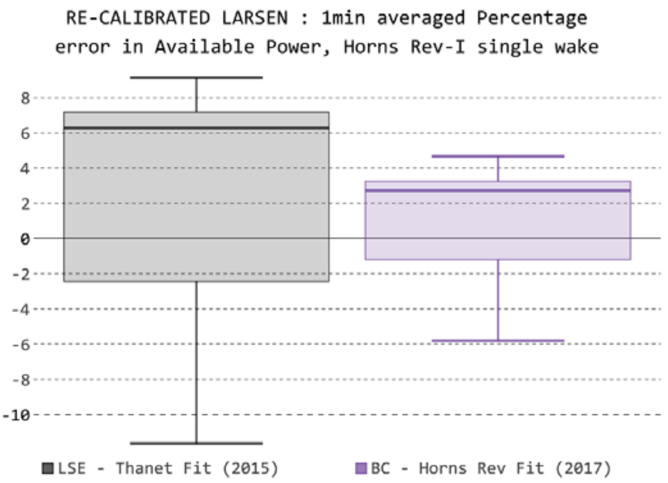
"Gunner Chr Larsen.A simple wake calculation procedure. Risø National Labaratory, Roskilde, Denmark,1988"

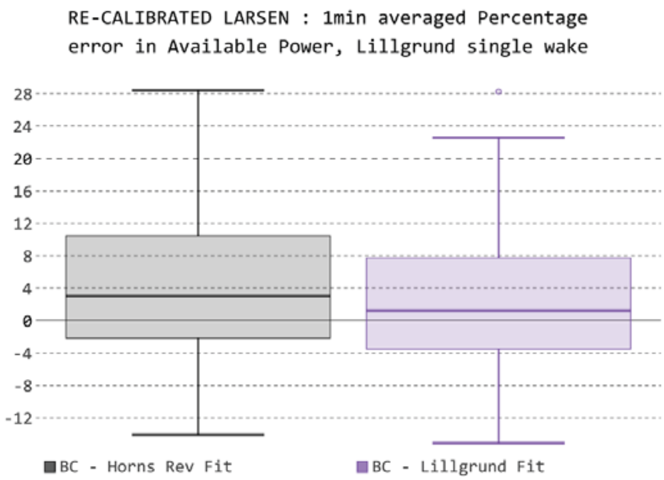
"Gunner C Larsen. A simple stationary semi-analytical wake model. Technical Report August, Risø DTU,2009"

Short-term Wake Modelling

Re-calibration of Larsen Model

- Re-calibrated Larsen → WF (and time) specific parameters

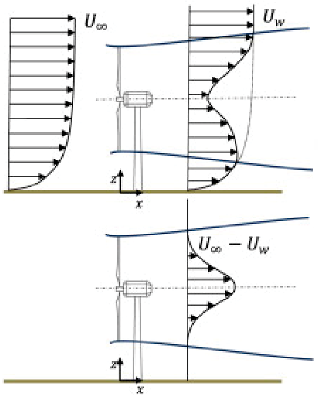


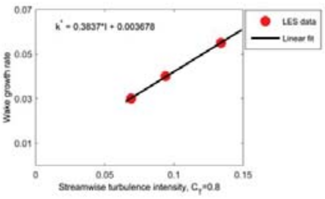


Short-term Wake Modelling

Gaussian Deficit Model

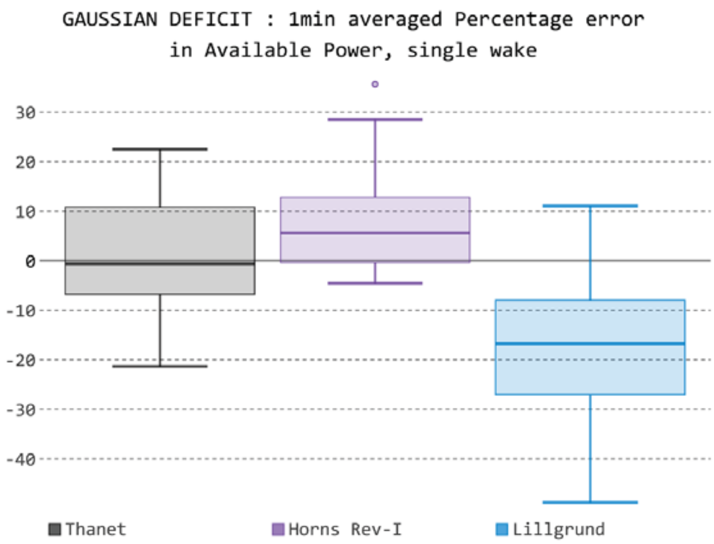
- Gaussian Deficit →First Time in 1Hz SCADA





$$k^* = a\,TI + b$$

$$a = 0.3837$$
$$b = 0.003678$$



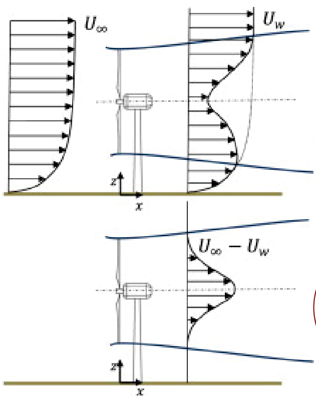
Majid Bastankhah and Fernando Port´e-Agel. A new analytical model for wind-turbine wakes. *Renewable Energy*, 70:116–123, 2014

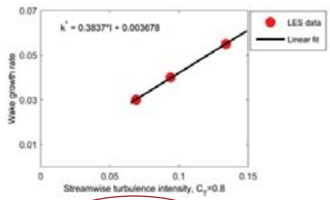
Mahdi Abkar and Fernando Porte-Agel. Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study. *Physics of Fluids*, 27(3):1–20, 2015

Short-term Wake Modelling

Re-calibration of Gaussian Deficit Model

- Gaussian Deficit →Bayesian Re-calibration

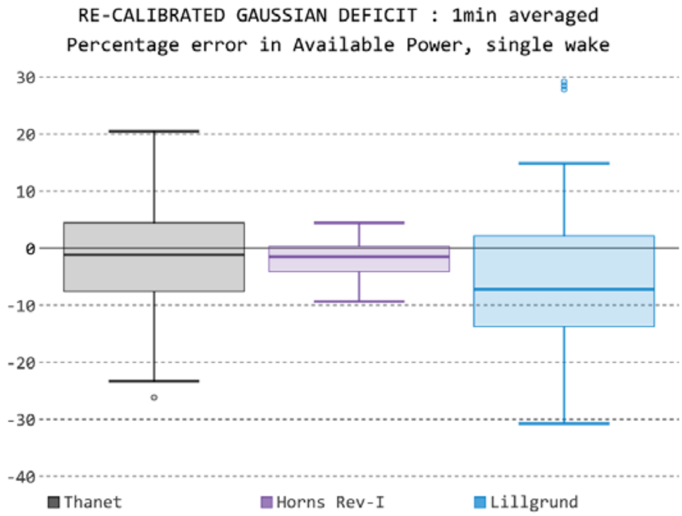




$$k^* = a\,TI + b$$

$$a = 0.3837$$
$$b = 0.003678$$

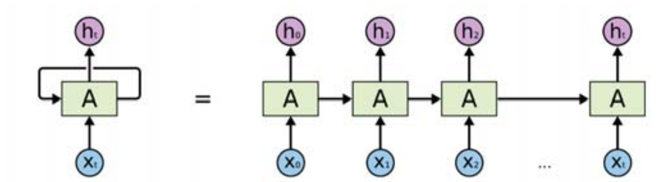
	a	b
Thanet	0.421	0.0025
Horns Rev	0.223	0.0039
Lillgrund	2.42	0.0042



Short-term Wake Modelling

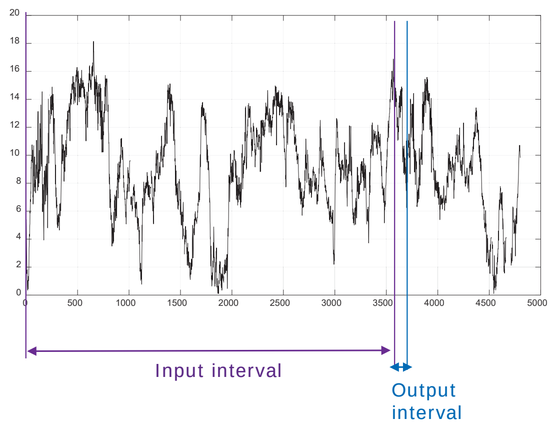
Machine Learning for short-term wakes

- Machine Learning Platform – TensorFlow
  - With Keras wrapper in Python
  - Fast & easy to apply
- The deep learning algorithm – LSTM
  - Long Short-term Memory
  - Special building unit for RNN
  - Shown to perform faster & better for highly fluctuating time series



http://colah.github.io/posts/2015-08-Understanding-LSTMs/

- The inputs from the upstream turbines
  - Defined at every minute (WD dependent)
  - WD, Ueff, std(Ueff), ct + uncertainties
  - Data fed for the previous 1-hour
    - Time window of 1-hour shifted forward at every minute



Short-term Wake Modelling

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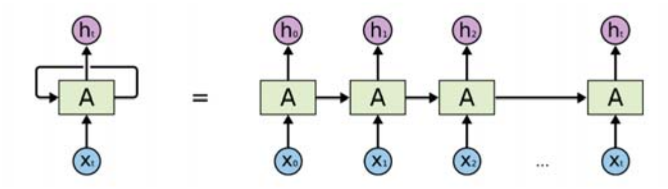

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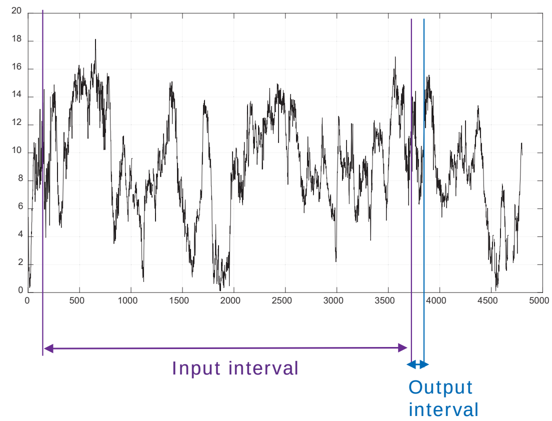
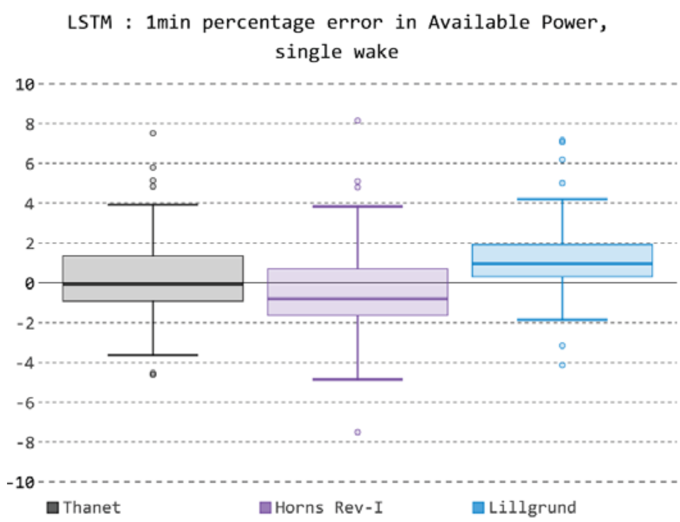


Short-term Wake Modelling

Machine Learning for short-term wakes

- Machine Learning Platform – TensorFlow
- The inputs from the upstream turbines
  - Defined at every minute (WD dependent)
  - WD, Ueff, std(Ueff), ct + uncertainties
  - Data fed for the previous 1-hour
    - Time window of 1-hour shifted forward at every minute
- The output
  - Ueff at the downstream turbine
- New network (or model) per WF per turbine per minute
  - Still feasible real time!
    - 20 epochs
    - Batch size = 64
    - Single hidden layer with 18 neurons



Conclusion

- **Strict regulations on power**
  – Short-term (1min ave.) & highly accurate (σ<5%) power estimations
  – Fast, robust, accurate models with improved uncertainty
- **Reduction of the uncertainty in the physical models?**
  – SCADA data : widely available, provides valuable information
  – Bayesian calibration is efficient to further train the existing physical models
    - Better at handling uncertainties
    - Narrower error distribution & reduction of the mean
  – However,
    - Still a strong presence of the input uncertainty – sensor/data accuracy
    - Simplified models, limited capability to model higher resolution dynamics
      – Especially prominent with "more complex" wake cases → clear trend with spacing
- **Is ML the future of short-term wake modelling?**
  – Fast, flexible and accurate
    - A new model at every minute at every turbine
    - Can easily be combined with 'conventional' forecasting
    - Exciting application possibilities for WF control and market trading

Questions?

- **Concert & PossPOW project website:**
  – http://www.posspow.vindenergi.dtu.dk/

Northern Seas Offshore Network (NSON)

- Overview project results NSON-DE (2014-2017)
- Planned NSON-DE follow-up

Denis Mende, Philipp Härtel
Fraunhofer Institute for Energy Economics and Energy System Technology IEE

EERA JP Wind-Workshop
June 27/28, 2018
Trondheim

Presentation mainly based on

15th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2018
Trondheim, January 18, 2018

Fraunhofer IEE

Northern Seas Offshore Network (NSON)

Challenges and its way forward

Philipp Härtel, Denis Mende, Kurt Rohrig, Energy Economics and Grid Operation, Fraunhofer IEE
Philipp Hahn, Andreas Bley, Institute of Mathematics, University of Kassel

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

15th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2018
Trondheim, January 18, 2018

Leibniz Universität Hannover | UNIKASSEL VERSITÄT | Fraunhofer IEE

Agenda

I	Northern Seas Offshore Network (NSON)
II	Wrap-up of NSON project in Germany (NSON-DE)
III	Challenges for future research

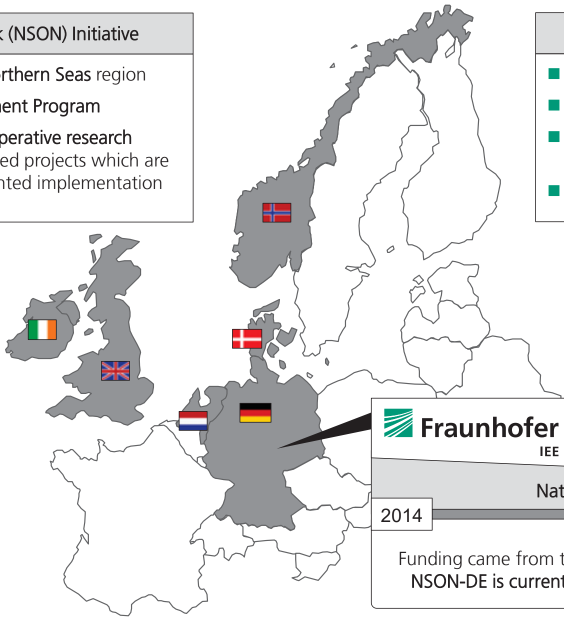
Agenda

I	Northern Seas Offshore Network (NSON)
II	Wrap-up of NSON project in Germany (NSON-DE)
III	Challenges for future research

University of Kassel, IEH/IfES of Leibniz University Hannover and Fraunhofer IEE are the partners of the national project in Germany (NSON-DE)

Northern Seas Offshore Network (NSON) Initiative

- Pursuing an **offshore grid in the Northern Seas** region
- **Research, Development & Deployment Program**
- **Following the Berlin Model for cooperative research** activities in Europe: nationally funded projects which are guided by a simple and target-oriented implementation



Objectives of the NSON Initiative

- **Harnessing, sharing**, and **trading of offshore wind** resources
- Supporting the **utilisation** of **offshore** region's **wind resources**
- Making the **national markets more effient** by increasing connection capacities
- Providing **balancing from Nordic hydropower**

Fraunhofer IEE + UNIKASSEL VERSITÄT + Leibniz Universität Hannover

National NSON project in Germany (NSON-DE)

2014 → 2017

Funding came from the Federal Ministry for Economic Affairs and Energy (BMWi)

NSON-DE is currently being finalised - report to be published by June this year

Agenda

I	Northern Seas Offshore Network (NSON)
II	**Wrap-up of NSON project in Germany (NSON-DE)**
III	Challenges for future research <> NSON-follow-up

NSON-DE has four modelling stages to investigate potential NSON configurations and their impacts on both the German and European energy supply system with consistent data sets and feedback loops

Modelling stages		Geographical focus
Market-based grid planning	1	European energy market areas + offshore grid region (offshore hubs)
Technology-based grid planning	2	Offshore grid region (single wind farms)
Offshore grid validation	3	Offshore grid region (single wind farms)
Onshore grid repercussions	4	Onshore transmission system (German market area)

The market-based grid planning determines and assesses market-driven investment decisions in a potential NSON, adequately accounting for the directly and indirectly connected onshore market areas

Modelling stages		Geographical focus
Market-based grid planning	1	European energy market areas + offshore grid region (offshore hubs)
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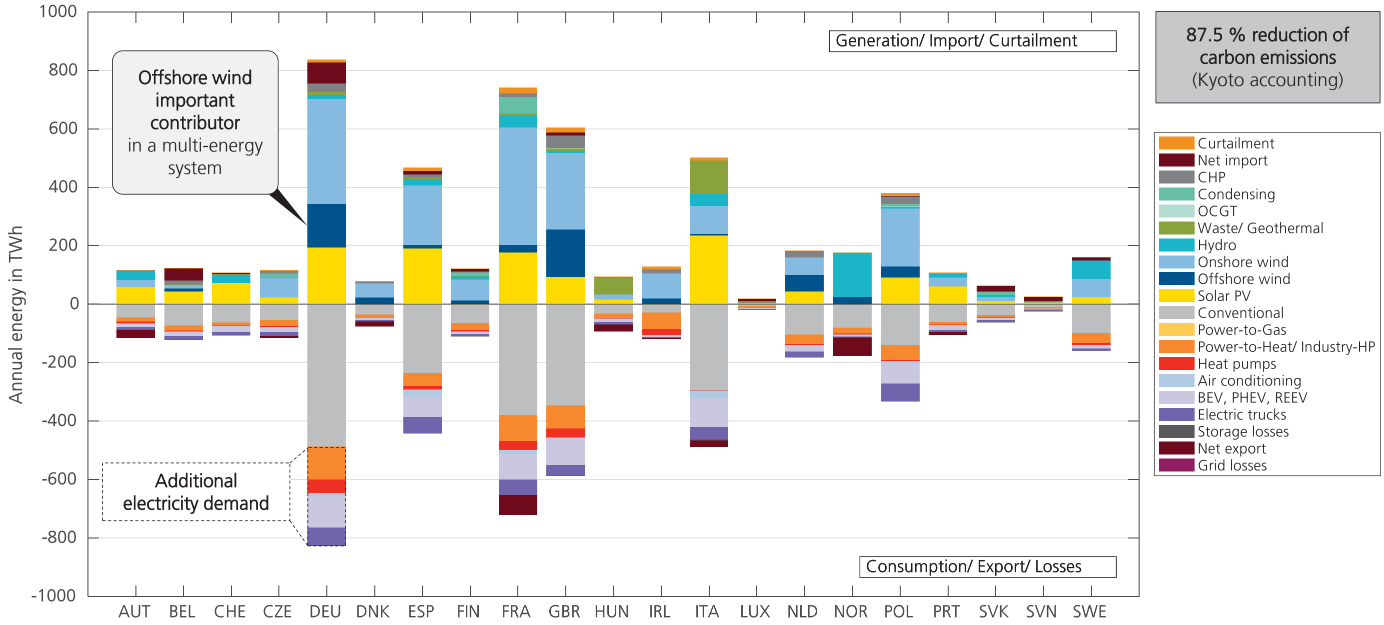
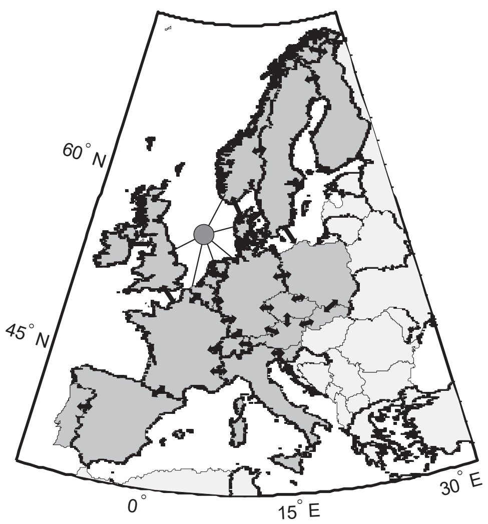
Long-term NSON 2050 scenario features high level of decarbonisation due to coupled operation of energy sectors – capturing interaction and flexibility is essential in offshore grid expansion planning



NSON scenarios were created with the cross-sectoral dispatch and investment model SCOPE at Fraunhofer IEE.

The large-scale offshore grid expansion planning model has a particular focus on capturing future energy system flexibility in the onshore market areas



Multi Market Area Dispatch and Offshore Grid Expansion Model (static, deterministic TEP)

Onshore market area

- Load coverage of residual load
- Technical restrictions of the hydro-thermal plants
- Technical restrictions of other flexibility options (such as battery storage, heat pumps, flexible CHP, electric vehicles and trucks)

Offshore grid region (area)

- Load coverage/ node balance of offshore hubs with wind generation/ curtailment/ storage
- Investment decision variables in AC/DC offshore grid infrastructure (including integers for fixed costs of cables, converters, and platforms)[1)]

Power exchange between areas

- Im-/ export between onshore market areas
- Im-/ export between onshore market areas and offshore grid region

! **Centralised/ closed solution of the full-year problem** (i.e. consecutive 8760 h) **with high unit** (blocks) and **investment details** (integer cable and platform costs) **is not tractable**

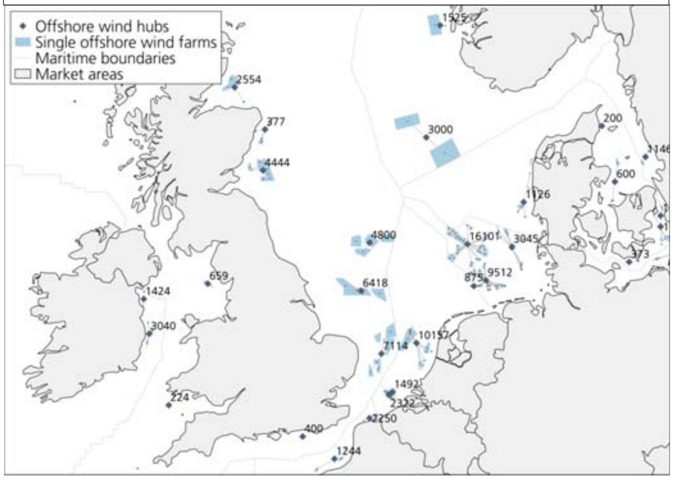
Careful aggregation of unit details + Regional decomposition approach (proximal bundle) applied to improve the solvability of the offshore grid planning problem

[1)] Härtel et al. 2017 Review of investment model cost parameters for VSC HVDC transmission infrastructure *Electric Power Systems Research* **151** 419.

Consistent spatial and meteorological data is used to adequately capture the offshore grid region – final case studies will investigate three topology paradigms for NSON 2030 and 2050

Spatial and structural offshore wind data set

Single offshore wind farms[1)] and **clustered offshore wind hubs** relevant **for offshore grid investment decisions** in the NSON 2050 scenario
(values indicate installed generation capacity at offshore wind hubs in MW)



Meteorological data set

Meteorological data from the COSMO-EU model is used to obtain

- site-specific **offshore wind production profiles**
- site-specific **CAPEX**, **OPEX**, and **LCOE data**

for **different investment periods** (5 year stages)

Final NSON case studies

NSON 2030	NSON 2050

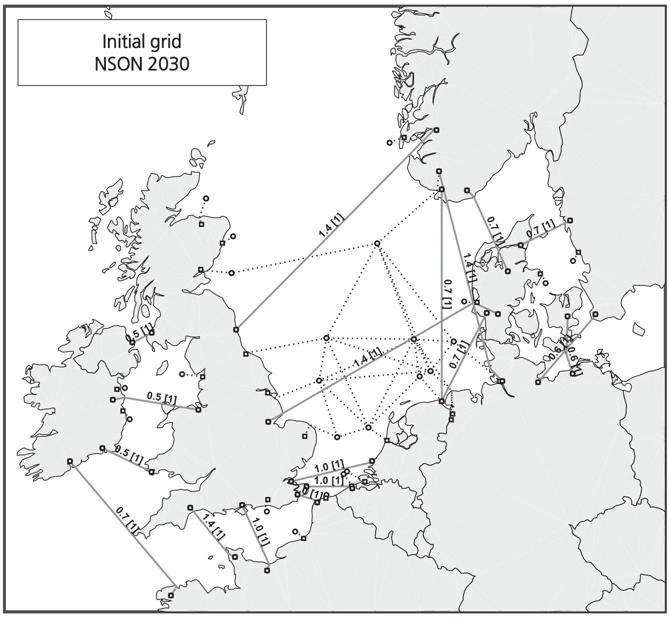
Topology paradigms:

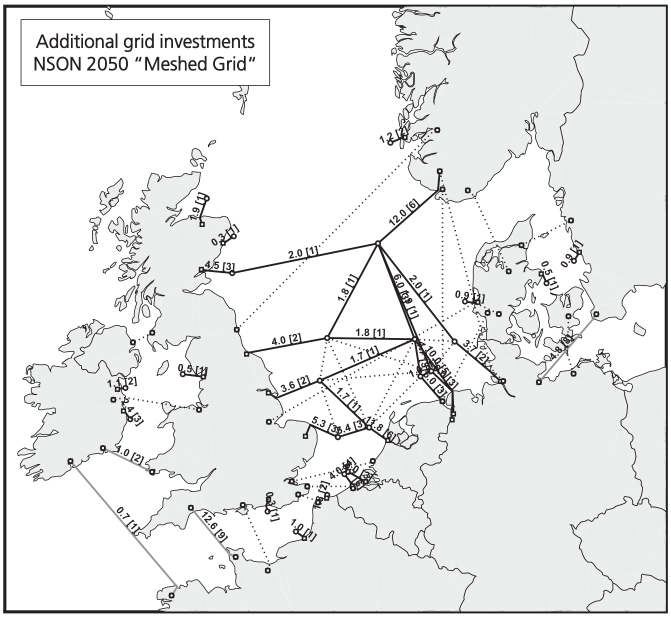
- **"Status Quo"** allowing radial offshore hub connections and no expansion on existing interconnector corridors
- **"Business as Usual"** allowing radial offshore hub connections and expansion on existing interconnector corridors
- **"Meshed Grid"** allowing meshed offshore hub connections and expansion on existing interconnector corridors

1) Based on 4C Offshore 2017 Offshore Wind Farms Intelligence Database (Suffolk) https://www.4coffshore.com/.

PRELIMINARY

Initial grid configuration shows realised and planned interconnector projects in Northern Europe – "Meshed Grid" shows investments in both interconnector and integrated offshore wind connections





The technology-based grid planning stage narrows the focus to the offshore grid region and investigates it with a higher level of detail

Modelling stages		Geographical focus
Market-based grid planning	1	European energy market areas + offshore grid region (offshore hubs)
Technology-based grid planning	**2**	**Offshore grid region (single wind farms)**
Offshore grid validation	3	Offshore grid region (single wind farms)
Onshore grid repercussions	4	Onshore transmission system (German market area)

Technology-based grid planning stage simultaneously optimises locations of future wind farms, their connection(s) to shore, and the main technical components

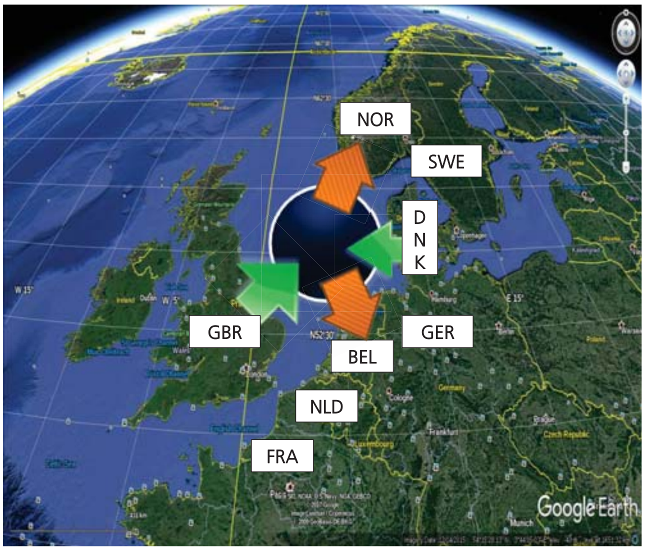
Market-based grid planning

Resulting output data
- **Full-year time series data of power exchange** between offshore region and onshore market areas
- Country-specific **offshore wind capacity targets**

Input

Technology-based grid planning

Goals
- **Planning a detailed offshore grid** with its spatial and technical configuration
- **Co-optimise single wind farm investments**
- Considering **incremental expansion** of the offshore grid **for a long-term horizon** 2050 (multi-stage)
- Satisfying **exchange demands** and offshore wind **capacity targets**



Planning aspects and technical requirements demand some simplifications when co-optimising grid planning and wind farm locations

Offshore region	Raster hubs	Potential wind farm locations
		

Planning aspects	
Vast number of potential locations	Incremental construction plan

Technical requirements		
Technical equipment (converters, transformers, switches)	Platforms for the equipment	Various line types (AC, DC, voltage levels, etc.)

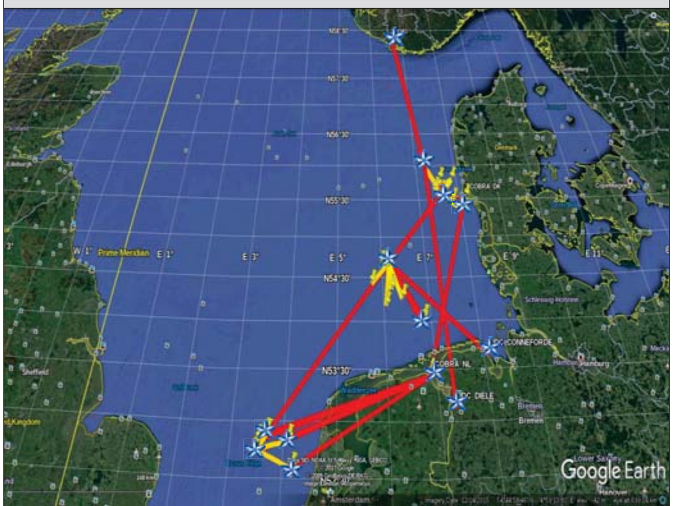
Necessary simplifications

- Neglecting physical laws of power flow
- Temporal resolution (consider subset of weather year)

EXEMPLARY

A test grid instance was used to test the mixed-integer linear program and newly developed heuristics to quickly compute feasible initial solutions

Test grid instance



DC lines AC lines Converter

Benchmark test system for the offshore grid in the North Sea[1]

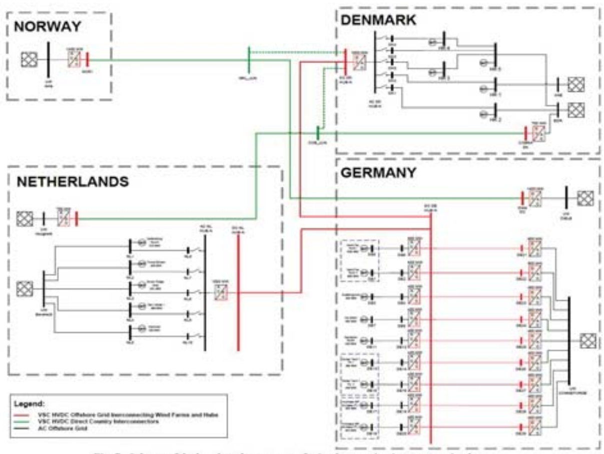


Fig. 7. Scheme of the benchmark test system for implementation into system simulator

[1] Rudion et al. 2010 Toward a Benchmark test system for the offshore grid in the North Sea *IEEE PES General Meeting*, Minneapolis, 1-8.

The offshore grid validation stage tests the grid planning results using power system analysis software assessing approximation errors

Modelling stages		Geographical focus
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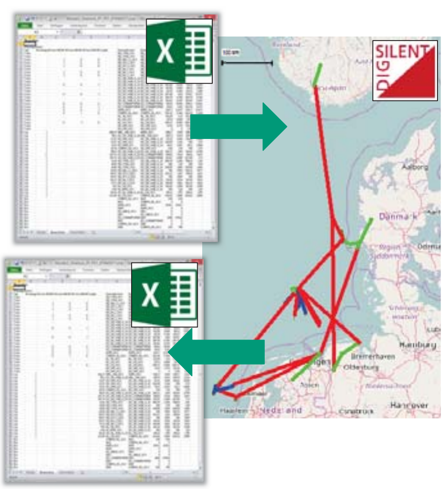
Offshore grid validation	**3**	**Offshore grid region (single wind farms)**
Onshore grid repercussions	4	Onshore transmission system (German market area)

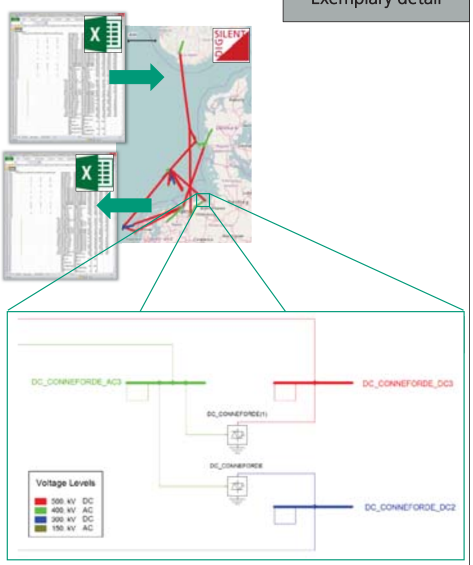
Due to a large number of time steps and scenarios, an automated approach was developed to electrically validate the market- and technology-based grid planning results



- Electrical data of components
- Grid topology & connection of elements
- Definition of node types and control schemes
- Power flow calculation
- Documentation of data and power flow results
- Comparison with grid planning assumptions
  - Component powers
  - Power flows in the grid
  - Losses of elements

Exemplary results of offshore grid validation show validity of simplified approach in technology based grid planning based on optimization methods

Exemplary detail



Exemplary results for test instance

- Difference in exchange powers well below 1 % (1)
- Different routing in real power flow compared to planning stage, overall power flows matching (2)
- Cable/line losses overestimated (no voltage differences and reactive powers in planning stage) (3)
- Converter losses underestimated (4)

Komponente	Anzahl	Planung $\sum\|P^p\|$ in MW	Planung $\sum P^p_{loss}$ in MW	Verifikation $\sum\|P^v\|$ in MW	Verifikation $\sum P^v_{loss}$ in MW	Differenz $\sum\|\Delta P^{p,v}\|$ in MW	Differenz $\|\sum \Delta P^{p,v}_{loss}\|$ in MW
Transformator	1	44,69	0,19	44,60	0,16	0,10	0,03
Leitung/Kabel	41	9927,50	42,13	9612,77	18,80	1543,26	23,39
Konverter/Umrichter	20	5850,19	58,50	5841,73	74,50	29,77	16,00
Onshore Marktgebiet	4	4200,24	-	4222,66	-	41,95	-

Component powers | Power flows in the grid | Losses of elements

Onshore grid repercussions induced by different offshore grid topologies are assessed for the onshore transmission system of the German market area

Modelling stages		Geographical focus
Market-based grid planning	1	European energy market areas + offshore grid region (offshore hubs)
Technology-based grid planning	2	Offshore grid region (single wind farms)
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Onshore grid repercussions	4	Onshore transmission system (German market area)

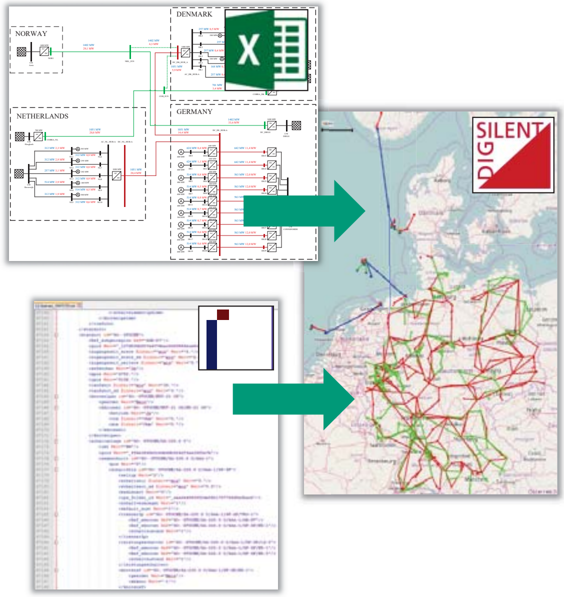
Market simulation data and offshore grid planning data for the NSON 2030 scenario are combined with a detailed model representing the German part of the continental European transmission system

Regionalised generation and consumption data sets

- **Renewable generation types:** onshore wind, offshore wind (i.e. offshore grid exchange), roof-top PV, utility-scale PV, flexible and inflexible biomass, waste, scrapwood, conventional and pumped hydro
- **Thermal generation types:** extraction condensing units (CHP), back-pressure units (CHP), condensing units, gas turbines
- **Traditional load types:** households, trade and services, industry, agriculture, public transport, pumped hydro
- **Additional load types:** battery and plug-in hybrid electric vehicles, electric overhead line trucks, industry heat pumps, decentralised air- and ground-source heat pumps, direct electric heating units (CHP and non-CHP), air-conditioning

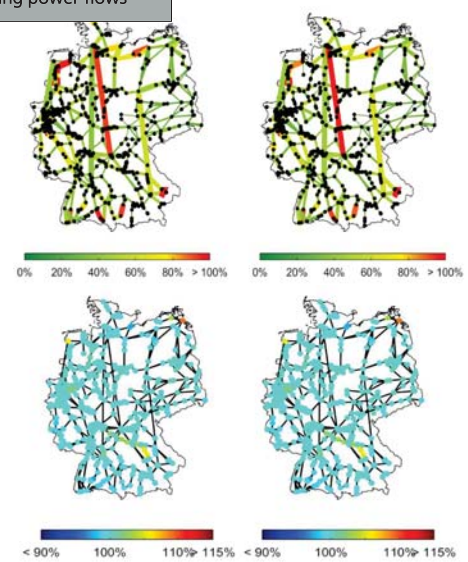
Assessment of onshore grid repercussions

- **Model** of the German transmission system **based on** the **German grid development plan** for 2030
- SCOPE model delivers **unit- and node-specific input data**
- **Implementation of offshore power flows into German grid** (due to market exchanges)
- Comparison of results and **impact analysis of market coupling through meshed offshore system**

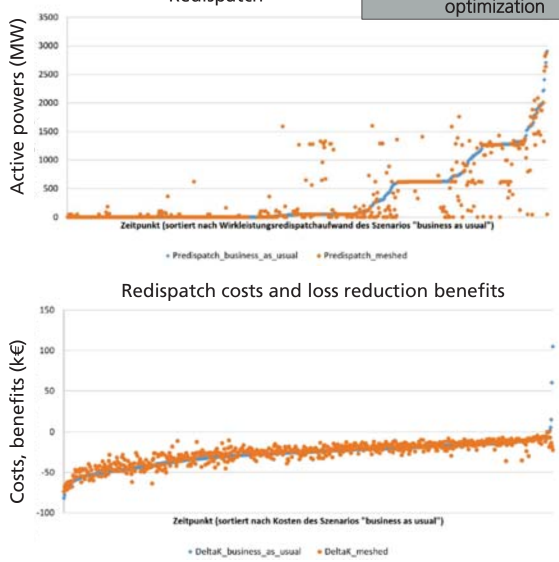


Calculation of power flow time series and redispatch & loss optimization to evaluate repercussions of different offshore grid scenarios ("Business as Usual" and "Meshed Grid")

Resulting power flows



Redispatch | Redispatch & loss optimization



Agenda

I	Northern Seas Offshore Network (NSON)
II	Wrap-up of NSON project in Germany (NSON-DE)
III	Challenges for future research

Remaining challenges for further research identified over the course of the NSON-DE project

Flexibility and uncertainty in future energy systems

- **Competition** of offshore grids **with future onshore flexibility options**
- **Uncertainty** from **bottom-up** developments and **top-down** target definitions
- **Simultaneous optimisation of generation and transmission expansion** for a highly decarbonised system heavily relying on wind and solar

Market integration and cost-benefit sharing

- **Harmonised cross-border rules of the involved market areas** (time-scales, market products)
- **Cost-benefit allocation** and **sharing methods** for both directly and indirectly connected market areas

Grid operation

- **Optimized grid and plant control** in normal operation
- **Dynamic control concepts** in normal operation as well as in fault and emergency situations

Grid planning

- Efficiently solving **optimisation problems capturing technical complexity** and **operational flexibility** in the grid planning stages
- **Handling time series data computationally more efficiently**
- Incorporate **statistically known data uncertainties** or **barely predictable** political, technological, or economic **uncertainties**

Power Link Islands (PLI)

- **Artificial island for transnational power exchange** and **distribution of offshore wind resources**, while hosting other services such as operation and maintenance for offshore wind farms
- **High uncertainty** associated with the **investment costs** and **potential locations**
- **Combined assessment of** the investment **costs and** the economic **benefits** a PLI offers

Thank you very much for your attention!
Discussion & Remarks?

Fraunhofer
IEE

Dipl.-Ing. Denis Mende
Systems Engineering and Distribution Grids
Fraunhofer Institute for Energy Economics
and Energy System Technology IEE

Königstor 59 | 34119 Kassel / Germany
Phone +49 561 7294-425
denis.mende@iee.fraunhofer.de

Fraunhofer
IEE

M.Sc. Philipp Härtel
Energy Economics and Grid Operation
Fraunhofer Institute for Energy Economics
and Energy System Technology IEE

Königstor 59 | 34119 Kassel
Phone +49 561 7294-471 | Fax +49 561 7294-260
philipp.haertel@iee.fraunhofer.de

NTNU

Norwegian University of Science and Technology

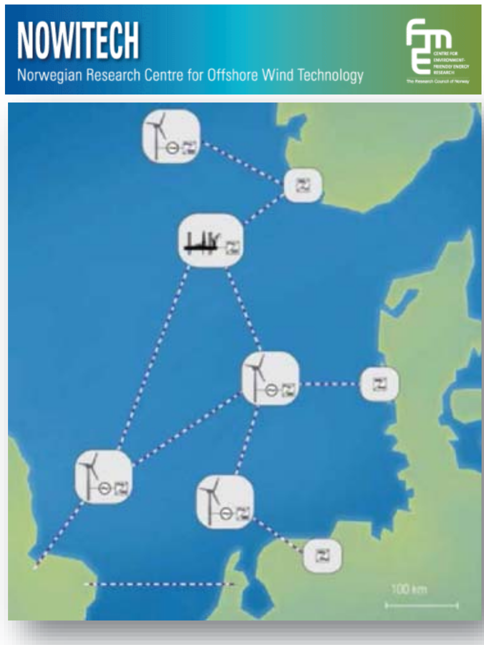
Planning of offshore grids & wind: Ongoing activities at NTNU

EERA JP Wind WS june 2018

Prof. Magnus Korpås

Dept. of Electric Power Engineering

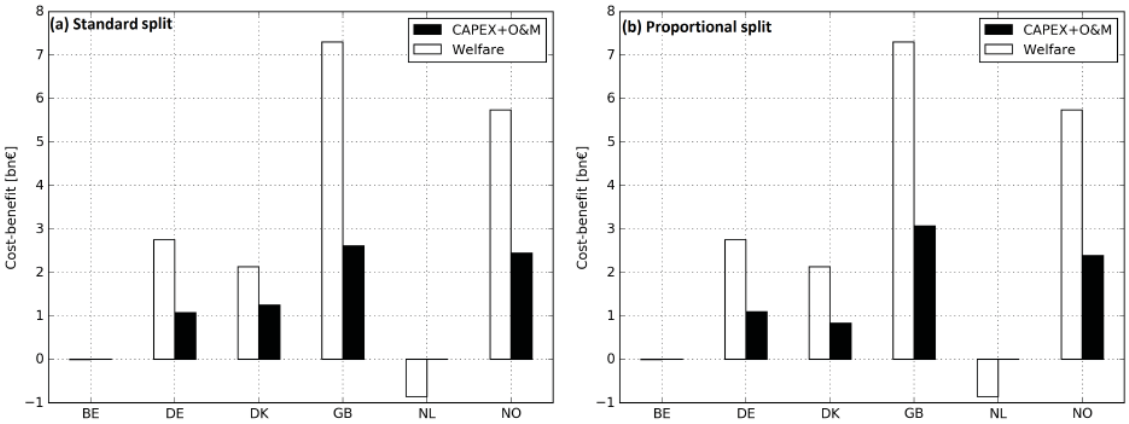
NTNU

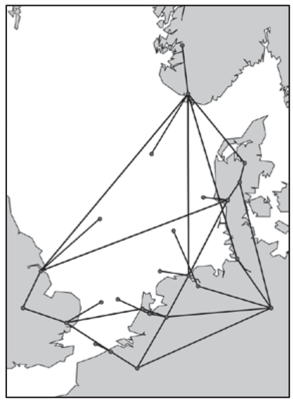


Transmission expansion planning

- NTNU NSON-PhD Martin Kristiansen
  - Multinational transmission expansion planning: Exploring engineering-economic decision support for a future North Sea Offshore Grid
  - Collaboration with SINTEF (Harald Svendsen), Fraunhofer (Philip Härtel), Berkely (Shmuel Oren) Johns Hopkins University (Ben Hobbs), Universidad Adolfo Ibanez (Francisco Munoz)
  - 8 scientific papers
  - Expected PhD dissertation Autumn 2018

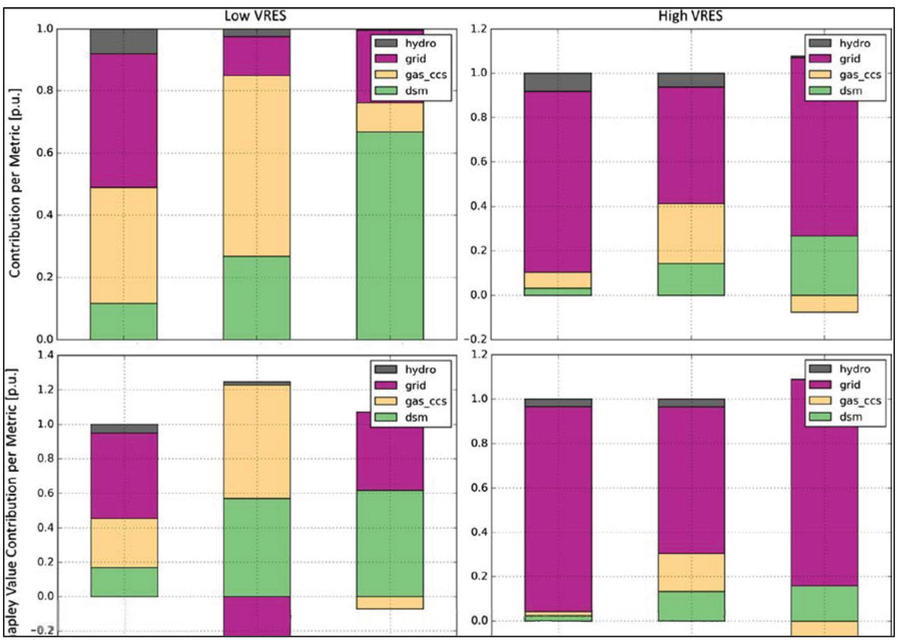
Cost allocation between connected countries

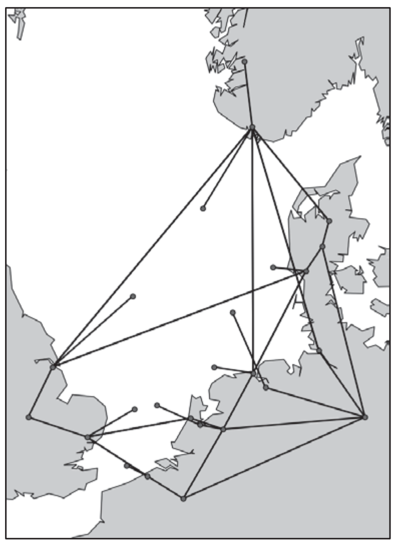




Kristiansen et al, Working paper 2018

Benefit contributions of different flexibility options





Kristiansen et al, Applied Energy 2018

Transmission expansion planning

- MSc thesis by Simon Risanger (2018)
  - A strategic investment model for multinational transmission expansion planning: Comparing competitive and centrally planned solutions for a North Sea Offshore Grid
- MSc thesis by Erik Solli (2017)
  - Assessing the economic benefits and power grid impacts of the power link island project
  - Followed up by DeepWind paper by Kristiansen/Korpås/Farahmand

"PLI yields significant costs savings for an integrated NSOG"

Relevant findings from the optimization model:

Different comparisons of radial- and ***PLI integration of OWP capacity yields system cost savings up to €19 B over 30 years*** *depending on the degrees of freedom in the planning model.*

*When trying to anticipate the impact of generator expansion, the added value from the PLI is still significant (**~€11 B**).*

*Assuming other flexible grid integration alternatives, such as a meshed grid, the added value of a PLI is expected to be around **€ 2B**.*

Key takeaways so far:

The PLI provides a more ***cost-efficient OWP integration*** *than radial solutions,* ***reducing curtailment of wind*** *as well as increasing trade possibilities (**spatial flexibility** at a lower investment cost).*

It is shown that ***the relative value of a PLI increases when the level of offshore wind power capacity increases****.*

Limitations and future work:

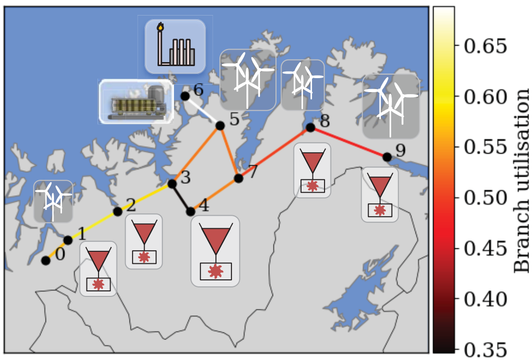
cost uncertainty *// Unit commitment // multi-sector // onshore grid representation // local flexibility*

Large-scale wind-hydrogen systems

- PhD Espen Flo Bødal
  - Norwegian Research Council project coordinated by SINTEF
  - Liquid hydrogen production from wind and hydro power in Norway
  - Possible energy carrier for offshore wind in the North Sea and onshore wind in North Norway
  - Paper at DeepWind 2018: Production of Hydrogen from Wind and Hydro Power in Constrained Transmission grids, Considering the Stochasticity of Wind Power
  - Collaboration with MIT (Audun Botterud and the LIDS group)

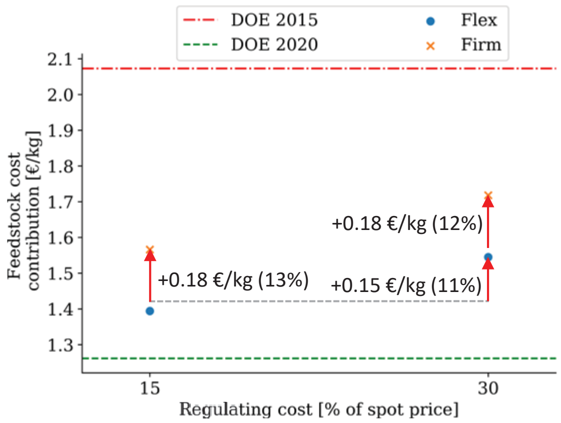
Case study: Finnmark in northern Norway

- Good wind power potential and LNG production facility
- Weak transmission connection to the rest of the Nordic power system
- Grid case based on previous model: grid capacity expansion form hydrogen to wind (5-7-8)
- More wind power, ~3X current installed capacity (175 to 544 MW)
- 50 ton hydrogen per day from renewable energy sources
- Modelled by a 9 bus system
- Simulated with 2015 time series for wind, price and load over one year



Hydrogen feedstock cost

Hydrogen production cost compared to US Department of Energy (DOE) targets for 2015 and 2020 for centralized hydrogen production.
(Target values are exchanged from 2015 $ to 2015 € in plot)



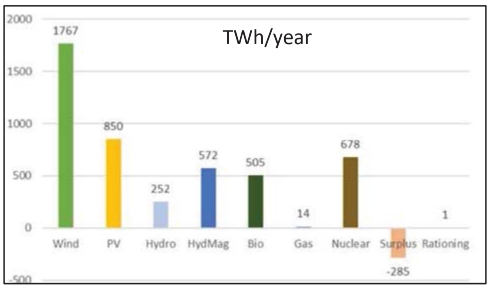
Central Water Electrolysis H2A Example Cost Contributions[a,b]

Characteristics	Units	2011 Status[c]	2015[d]	2020[e]
Capital cost contribution	$/kg	0.60	0.50	0.40
Feedstock cost contribution	$/kg	3.20	2.30	1.40
Fixed O&M cost contribution	$/kg	0.20	0.10	0.10
Other variable cost contribution	$/kg	0.10	0.10	0.10
Total hydrogen levelized cost (plant gate)	$/kg	4.10	3.20	2.00

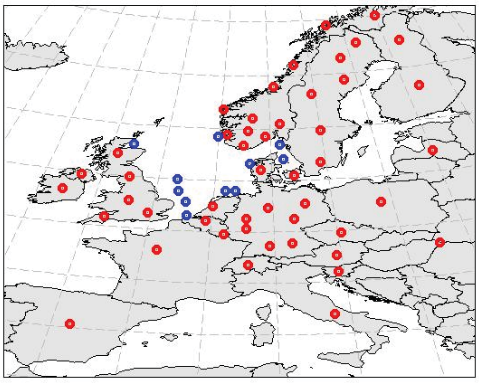
https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis

Simulation of hydro utilization in 2050

- Scenarios from EU-project eHighWay 2050
  - MANY new interconnections in the North Sea
- 20 GW expansion of Norwegian hydro power
- Comparison of the **SOVN** and **EMPS** models
- 75 climatic years

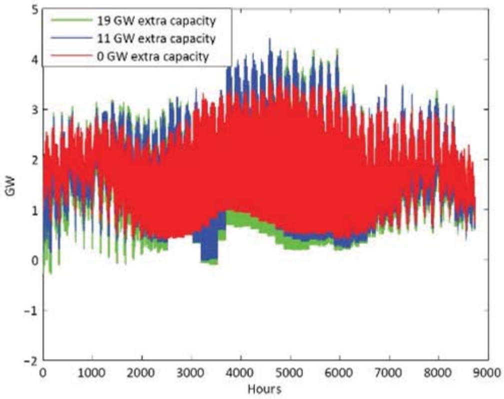


- The **SOVN** model has higher hydro detail and gives better representation of short-term variations and flexibillity.
- The **SOVN** model solves a very large formal LP-problem while the **EMPS** model includes a lot of advanced heuristic (in addition to formal optimization)

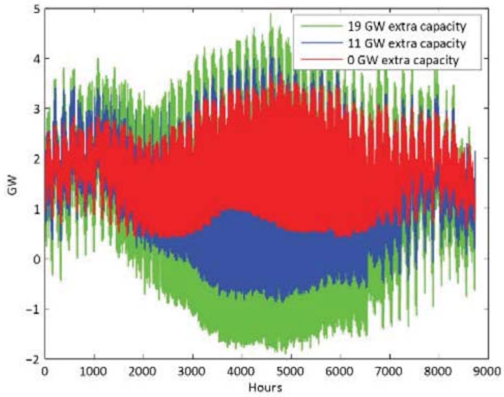


Simulated power production in south of Norway 2050

- The higher detailed model SOVN gives better pumping representation
- More details necessary as the scenarios includes more variable wind and solar power
- Computational time is an issue



EMPS model



SOVN model

The Norwegian Energy Research Conference 2018

- Presentation «Offshore wind in the future European energy system»
- The aim was to describe how large-scale solutions (offshore wind, hydro balancing, HVDC) fits with the «small-scale revolution» (PV, batteries, DR, ..)
- In addition: Reflections on the development of offshore wind in Norway

More RES yields large-scale grid solutions…

Figure: TenneT

…and small-scale grid solutions. Both works!

Figure: Telsa

The two trends explained:

- **Large-scale solutions**
  - Integration and harmonisation of markets and regulation
  - Interconnectors
  - Large onshore and offshore wind farms, PV farms
  - Large investments, economics of scale
  - Large-scale flexibility:Gas turbines, (pumped) hydro, compressed-air, FACTS, hydrogen

The two trends explained:

- **Small-scale solutions**
  - Rooftop PV
  - Local markets
  - Distributed flexibility: demand response, home batteries, V2G
  - Many smaller investments, easier to finance
  - Local ownership, local committment
  - Micro-grid solutions and independency
  - Integration with the heat and transport sector

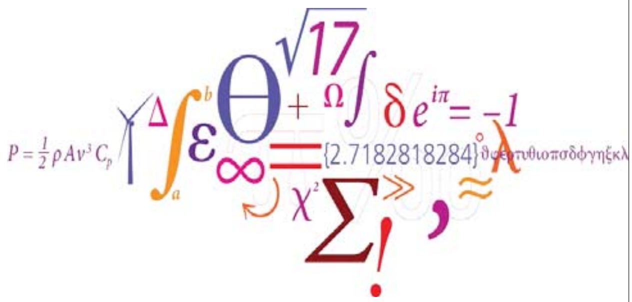
Offshore wind in Norway

- Norway is already a net exporter of electricity
- The export will certainly grow due to:
  - Green certificates: Onshore wind and hydro
  - More PV on buildings and reduced need for el-heating
  - Electrification of transport does not counteract this very much
- On top of this, Norway has a huge offshore wind potential that should be harvested:
  - Export to Europe to fulfill EU 2050-targets in a cost-efficient way
  - Supply to oil&gas platforms for reduction of domestic emissions
  - Enable more use of electricity in Norway for
    - Energy-intensive industry, computer centres, hydrogen production..

NSON-DK
Project and scenarios

Matti Koivisto
Juan Gea Bermudez
Kaushik Das
Poul Sørensen

Nicolaos Cutululis



DTU Wind Energy
Department of Wind Energy

DTU Management Engineering
Department of Management Engineering

NSON-DK

DTU Wind Energy Department of Wind Energy | DTU Management Engineering Department of Management Engineering | Ea Energy Analyses

- Objective
  - to study how the future massive offshore wind power and the associated offshore grid development will affect the Danish power system
  - on short term, medium term and long term in the transition towards a future sustainable energy system
  - Danish part of EERA initiative
- Part of EERA NSON initiative:

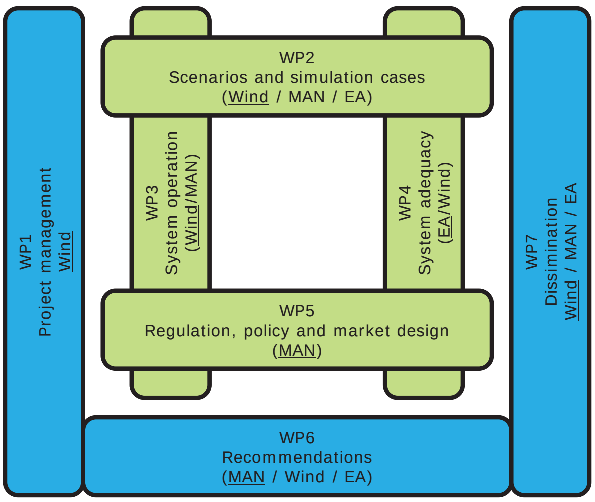
SINTEF, Fraunhofer IWES, University of Strathclyde Glasgow, ECN, DTU

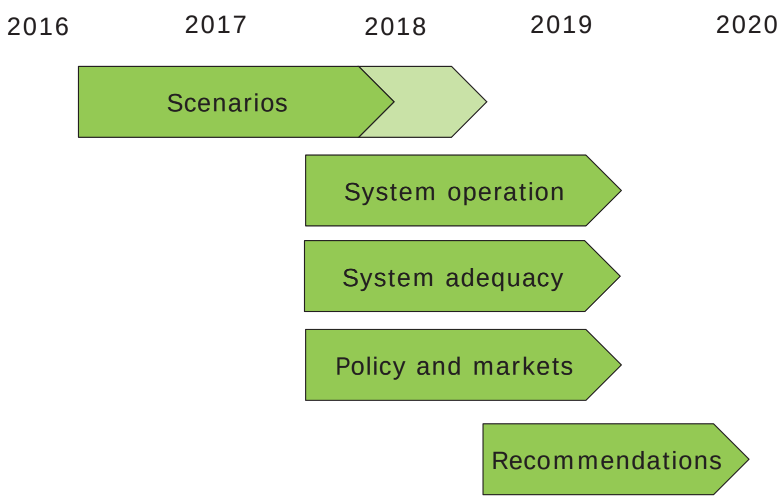
- Partners
  - DTU Wind Energy (lead)
  - DTU Management Engineering
  - Ea Energyanlayses
- Funding
  - 7.5 mio DKK (1 mio Euro)
  - Danish Energy Technology Development and Demonstration program
    - EUDP contract #64018-0032
    - Originally granted by Energinet.dk Forskel program #2016-1-12438
- Timeline
  - April 2016 – January 2020

NSON-DK research questions

- How will the offshore wind power development ***affect the variability and uncertainty*** of variable renewable generation in the Danish power system and neighboring systems?
- How will this increased variability and uncertainty from the offshore wind power development together with onshore renewable generation development ***influence the balancing and need for reserves in the Danish power system***?
- How will the offshore wind power and offshore grid development ***influence the electricity markets*** in future systems with large scale energy storage and coordination of the electricity system with other energy systems (mainly heat and transport)?
- How will the scale and architecture of the offshore grid development ***influence the adequacy and security of supply in the Danish power system***?
- Which ***policy instruments*** should be applied to support an effective and cost-efficient transition of the Danish power system combining the offshore development with energy storage and coordination between energy systems?

NSON-DK work packages and timeline

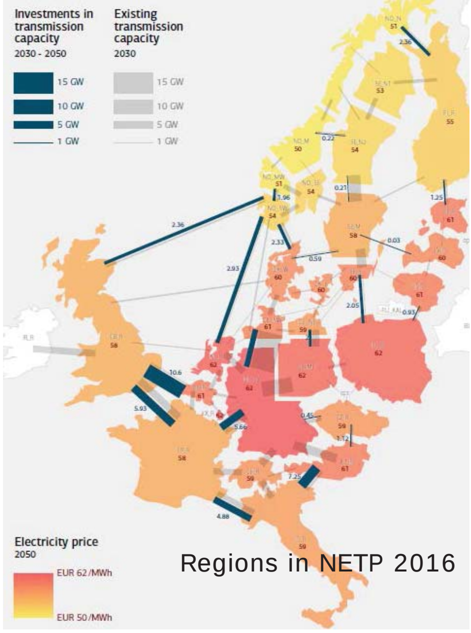




DTU Wind Energy, Technical University of Denmark EERA JP Wind SP5 and SP6 joint workshop 2018-06-27

NSON-DK scenarios

- Specified until 2050
- Radial and meshed scenarios
- Overall European energy system scenario comes from Nordic Energy Technology Perspectives (NETP) 2016
  - http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/
  - Generation investments
  - Transmission line investments
- The scenarios are built using the Balmorel tool
- Main reasons for updating the NETP scenario in NSON-DK:
  - Update VRE generation costs
    - Coming down faster than expected in NETP 2016
  - Include meshed grid set-up
    - With all cost parameters



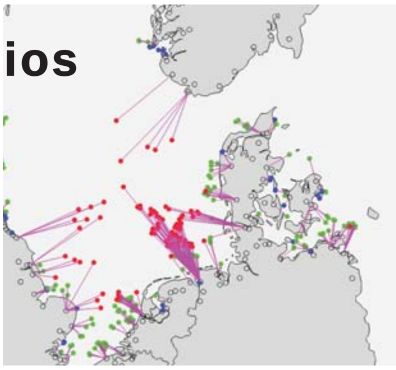
Regions in NETP 2016

The radial and meshed scenarios

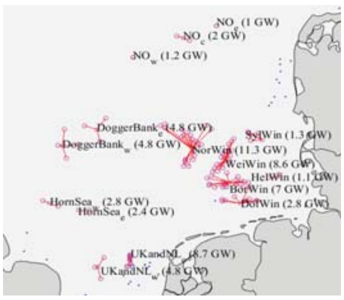
There are two main scenarios in NSON-DK:

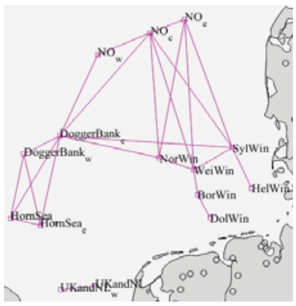
1) Radial
   - Offshore wind power plants (OWPPs) are connected radially to onshore
   - Only radial transmission lines are allowed in the North Sea
2) Meshed
   - North Sea offshore meshed grid a possibility in the investment optimization
   - OWPPs can be connected to hubs
   - Hubs can be connected to each other
   - Hubs are connected to onshore

- Otherwise the two scenarios are specified with the same cost parameters, etc.



Possible OWPPs radially connected





Possible hubs (with maximum investable GW), and some example connections in the meshed scenario

Region in focus: North Sea countries

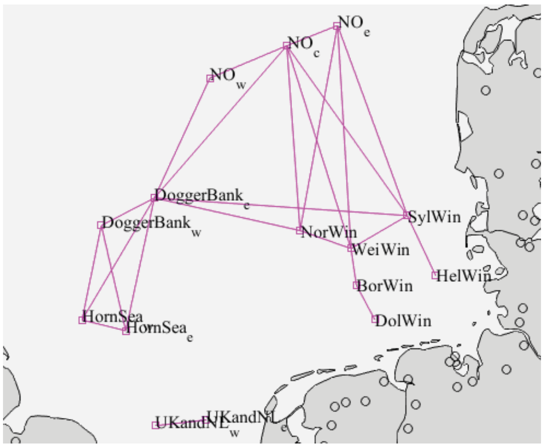
- Countries with investment optimization are highlighted in the map
  - DK, NO, UK (GB power system only), BE, NL, DE
  - Optimized using the Balmorel model
- Neighbouring countries are also part of the modelling
  - They are taken into account in electricity trading
  - They experience investment development (generation and transmission) until 2050 as specified in the NETP 2016 scenario

Modification to the NETP 2016 scenario

1. Updated/added costs
   - Offshore and onshore wind, and solar PV costs
     - Especially offshore wind and solar PV get cheaper towards 2050
     - Data from Danish Technology Catalogue by the Danish Energy Agency
   - Offshore grid related costs
     - Source: P. Härtel et al, "*Review of investment model cost parameters for VSC HVDC transmission infrastructure*", Electric Power Systems Research, 2017
     - Cost reduction until is 2050 assumed
2. Onshore wind and solar PV investments are modelled in more detail
   - Capacity factors decrease when more generation is invested in
   - Assumed that best locations are utilised first
3. Future technological development of wind power is modelled
   - Increasing hub height and decreasing specific power
4. The meshed case is created
   - Modelling required mixed integer programming in Balmorel
5. Decommissioning of fossil fuel units is modelled

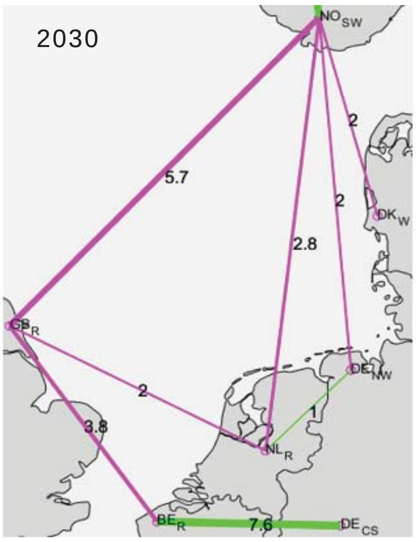
The meshed scenario

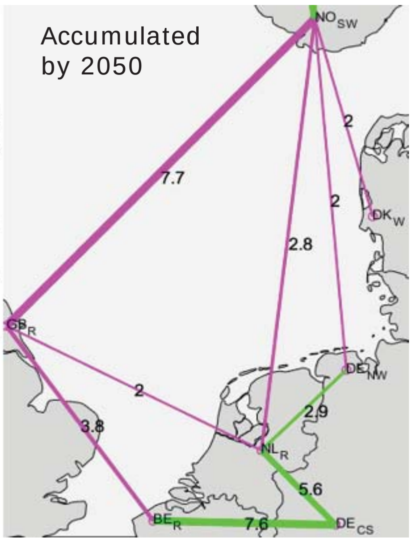
- Balmorel investment optimization can invest in
  - Connections between hubs
  - Connections from hub to shore
  - OWPPs connected to hubs
    - With GW limits specified
- Each hub has its own wind generation profile
- When investing in hub-connected OWPPs
  - + Higher capacity factors
  - + Generation can be exported to more countries
  - - Hub investment is needed
  - - Connection can be longer (because of going via a hub)
- Hub cost is a very important parameter for Balmorel when choosing if hub-connected OWPPs should be invested in



Some of the available hub-to-hub connections

The radial scenario (transmission)

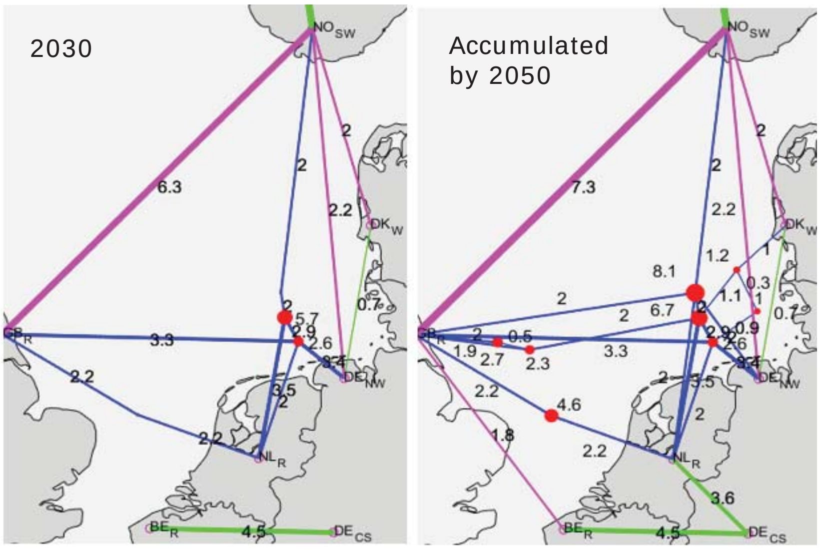




Transmission investments (these come on top of development assumed by 2020). Green = on-land line, magenta = offshore line

- NOTE: These are not final results!
  - Scenarios will be finalized in summer 2018
- Norway increasingly connected to most other countries
- UK expected to be highly connected to other countries
- Note: DE north to south transmission capacity assumed to be 17.6 GW by 2020 (assumption coming from NETP 2016)
  - No additional investments seen in NSON-DK scenarios
- NOTE: Line costs are calculated using more detailed locations than shown on the map (especially UK)

The meshed scenario (transmission)



Transmission investments (on top of assumed development by 2020). Blue = Non-radial line, Red = hub generation investment (line between DK and DE is on-land, although appears offshore)

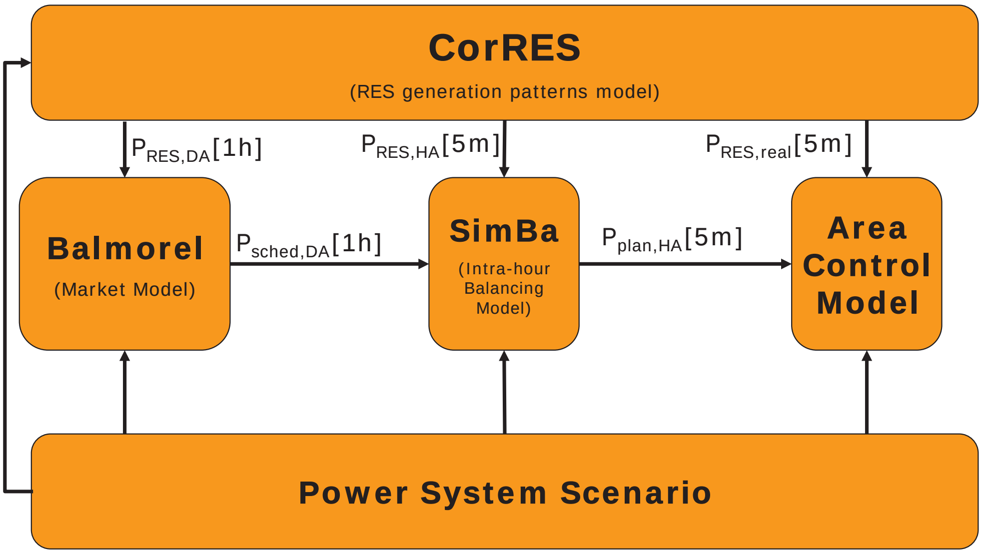
- NOTE: These are not final results!
  - Scenarios will be finalized in summer 2018
- Major hubs in DE and UK
- Some lines are built already in 2030 waiting for hub investments in 2050
  - Balmorel optimizes 2030 and 2050 together
- Overall, the transmission capacities between countries remain quite similar to the radial case
  - But now some of the transmission capacity is provided by the meshed grid
- The big DE hubs connect most countries together

Overview of wind generation capacities in the scenarios

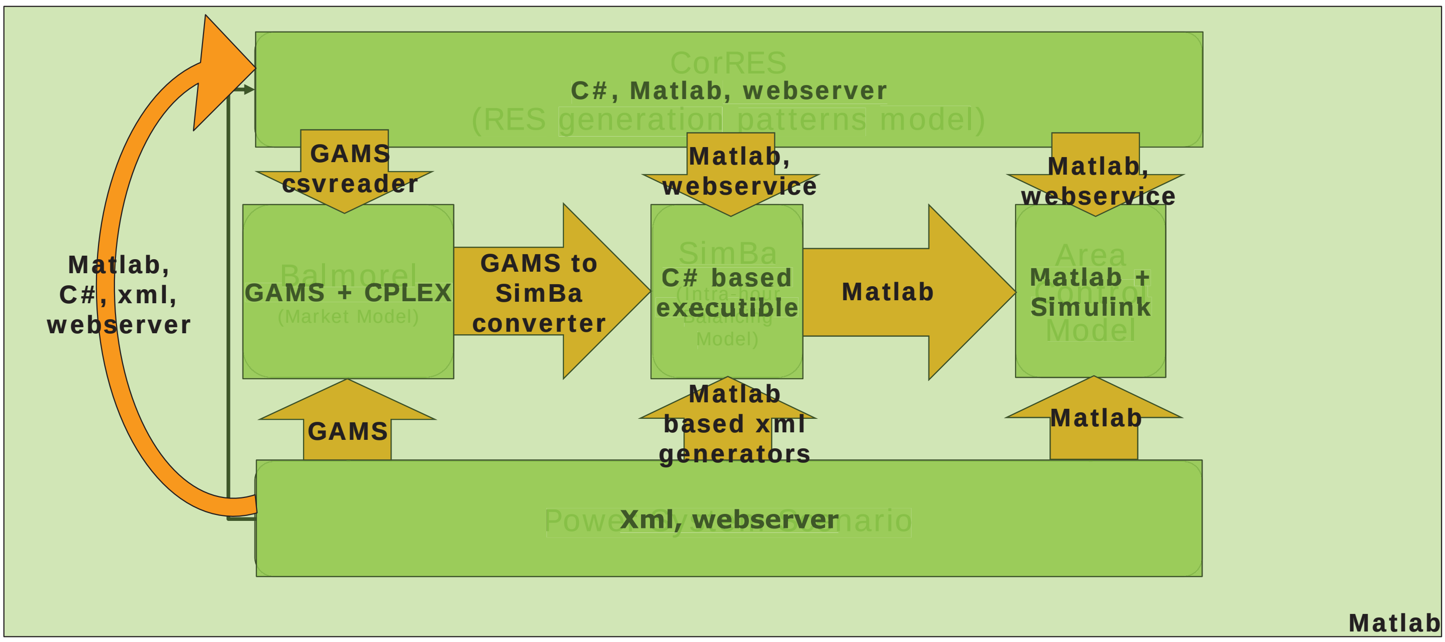
	Offshore wind			Onshore wind		
Scenario	Starting point	2030	2050	Starting point	2030	2050
Radial	22.2	73.7	110.4	75.7	102.8	117.4
Meshed	22.2	72.9 (12 %)	115.3 (27 %)	75.7	102.9	111.3

- NOTE: These are not final results! Scenarios will be finalized in summer 2018
- These are the total capacities in GW (existing + additional investments)
  - Aggregates of the region in focus (DK, NO, DE, GB, NL, BE)
  - % in offshore wind shows the share invested in hubs
- Meshed scenario shows around 5 GW more offshore wind than the radial scenario
- A full NSON-DK scenario report will be available soon (summer 2018)

Model Chain Development (Ongoing work)



Software Platforms (Ongoing work)

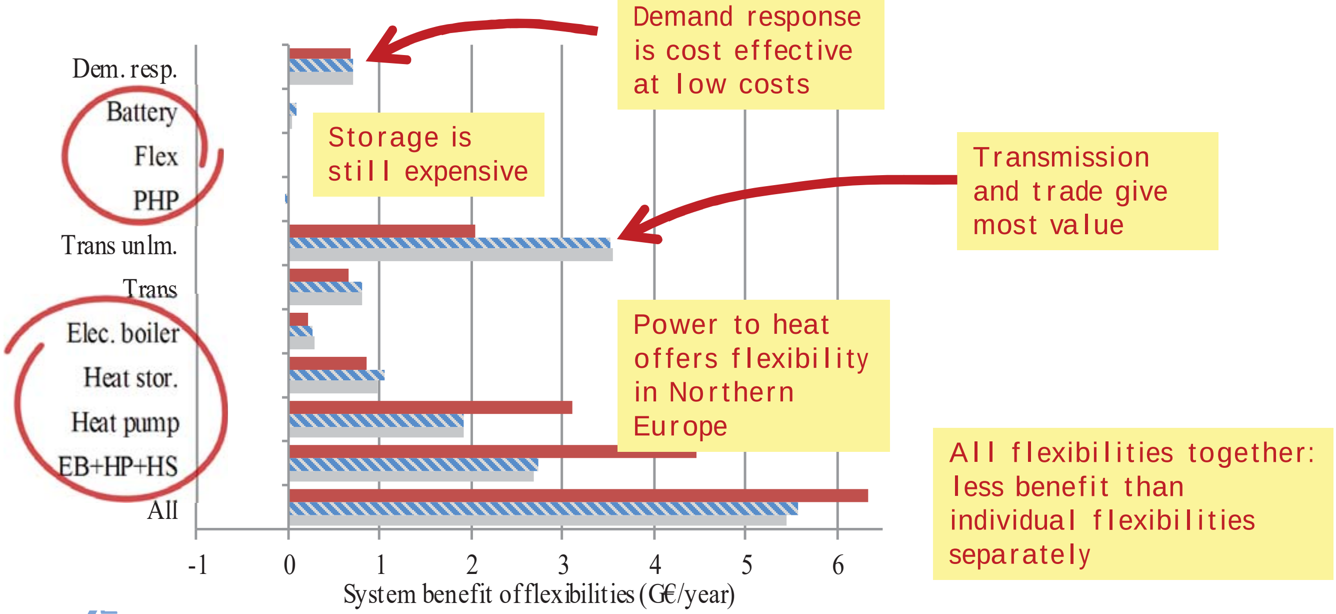


Design and Operation of Power systems with large amounts of VRE

Erkka Rinne, Research Scientist

EERA JP Wind SP 5&6 workshop
Trondheim, 27–28 June 2018

Case: North Europe, ~40 % wind
Power system operational costs for one year, difference of with/without flexibility option

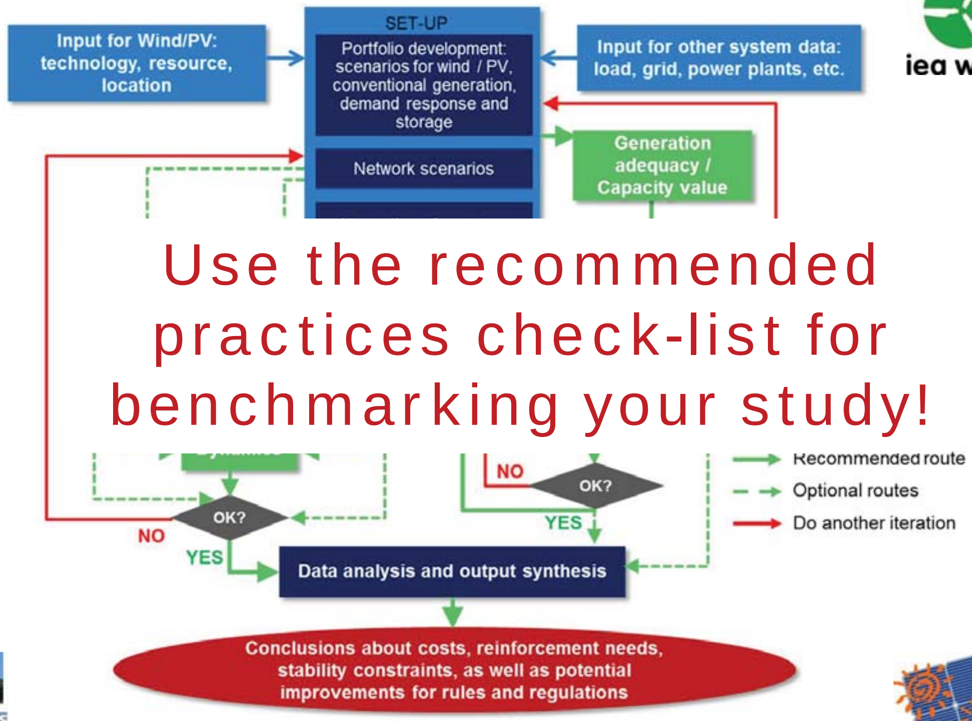


J. Kiviluoma, E. Rinne, and N. Helistö, “Comparison of flexibility options to improve the value of variable power generation,” *Int. J. Sustain. Energy*, Aug. 2017.

Recommended Practices for wind/PV integration studies

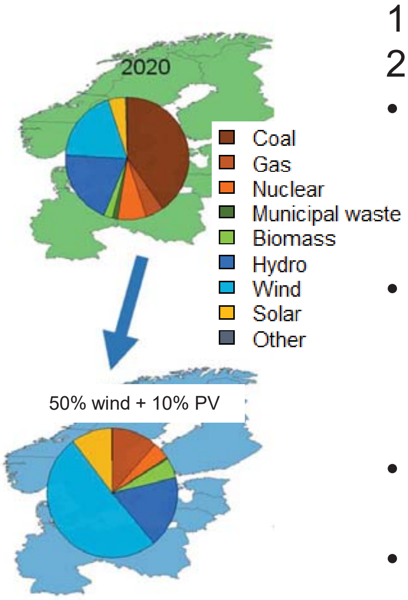
A complete study with links between phases

Most studies analyse part of the impacts – goals and approaches differ



Use the recommended practices check-list for benchmarking your study!

Market prices in the future – an example of 2050



1. Optimised generation capacity (Balmorel)
2. Hour-to-hour simulation (WILMAR JMM)

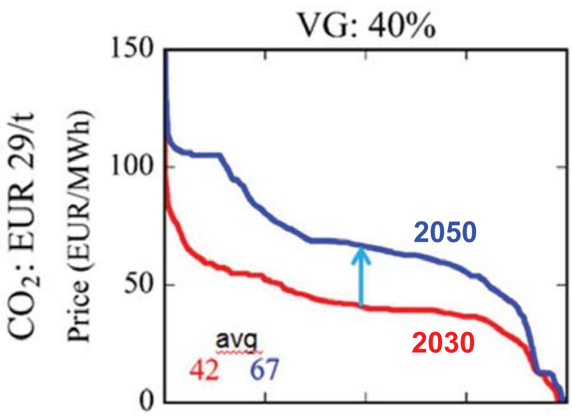
- Including:
  - new transmission (total 32 GW)
  - flexible heating
  - CO_2 price €49/tonne
- Not included:
  - demand response
  - electric vehicles
  - batteries
- Sensitivity analysis to different amounts of VRES (**not** a price forecast)
- Wind power and solar PV prices decreased to get 40–60% annual penetration (22% in 2020)

www.flexefinalreport.fi

EL-TRAN strategic RESEARCH

Reducing overcapacity leads to higher prices

Price duration curves



Assumptions:

2030 still some old capacity left

2050 no more overcapacity

www.flexefinalreport.fi

N. Helistö, J. Kiviluoma & H. Holttinen, "Sensitivity of electricity prices in energy-only markets with large amounts of zero marginal cost generation," *14th International Conference on the European Energy Market, EEM 2017*, Dresden, Germany, 6-9 June, 2017

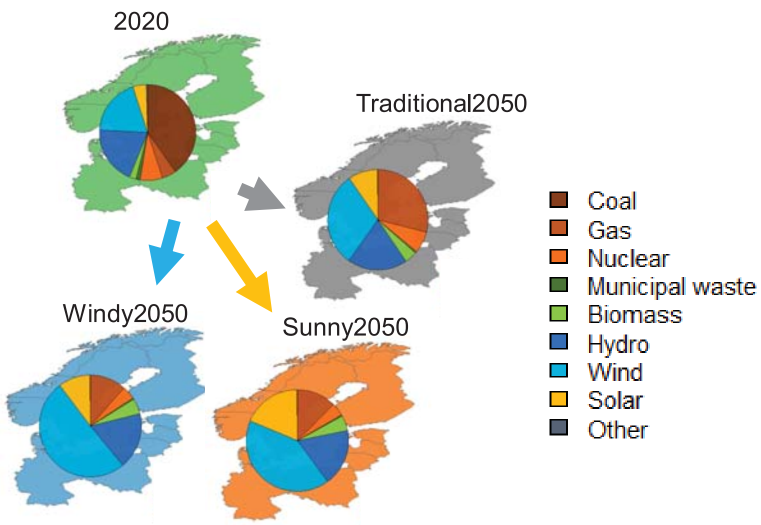
EL-TRAN strategicRESEARCH

FLEXe scenarios

Input	2020	2050 Trad.	2050 Windy	2050 Sunny
CO_2 (€/tonne)	17	12	49	
Nat. gas (€/GJ)	8	10		
Coal (€/GJ)	2.7	N/A		
Wind (€/kW)	1,600	1,600	1,310	1,340
PV (€/kW)	1,394	550	520	270
VG target share (%)	**25**	**40**	**60**	**60**

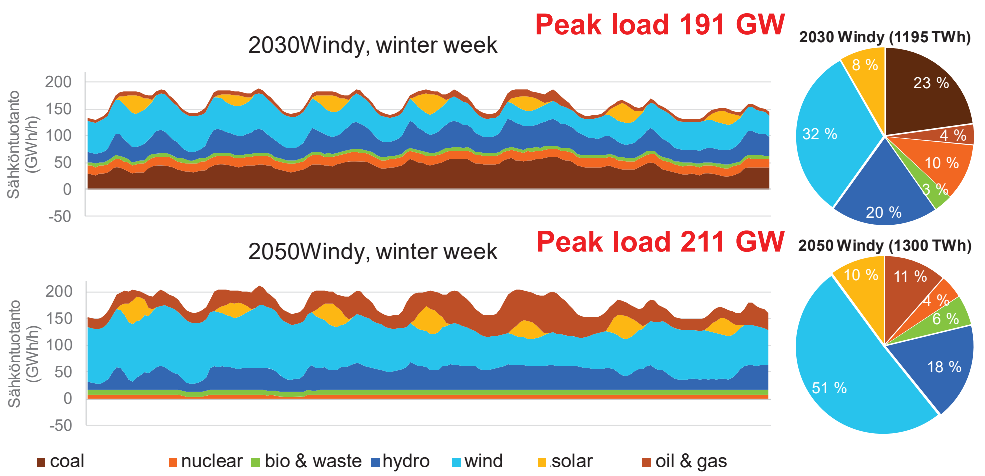
Transmission capacity increase (GW)	
Traditional2050	10
Windy2050	32
Sunny2050	29

Annual electricity production



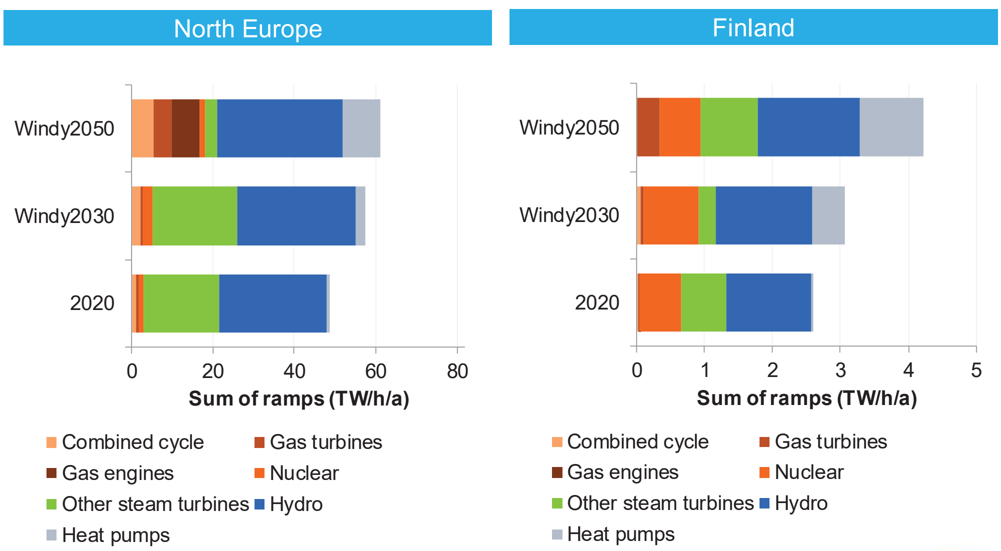
EL-TRAN strategicRESEARCH

Electricity generation in North Europe



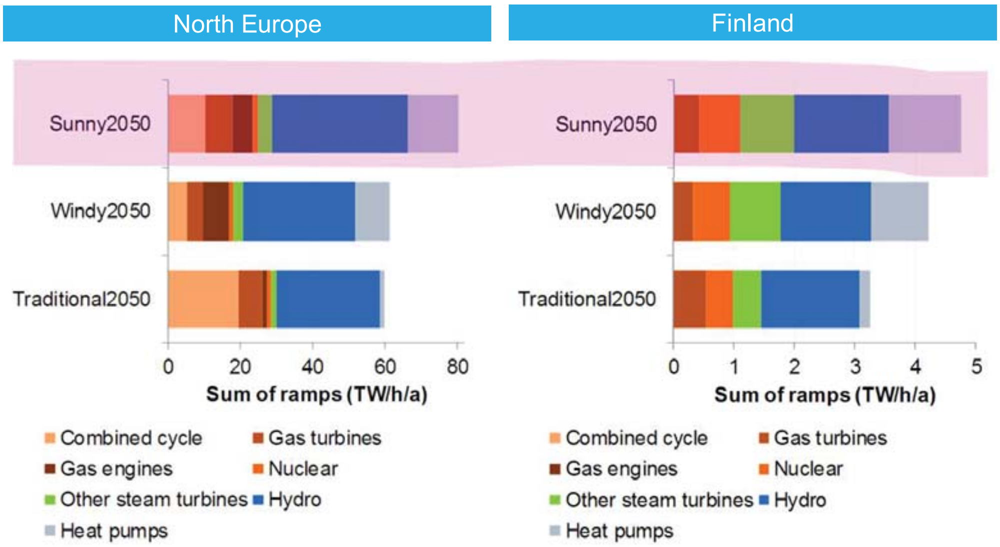
Note: coal, peat & oil not used for elec. generation anymore in 2050

Total ramping increases as share of VRES increases



Other steam turbine fuels: wood, wood waste, straw, municipal waste, industrial waste, natural gas (and coal, peat, fuel oil in 2020 and 2030)

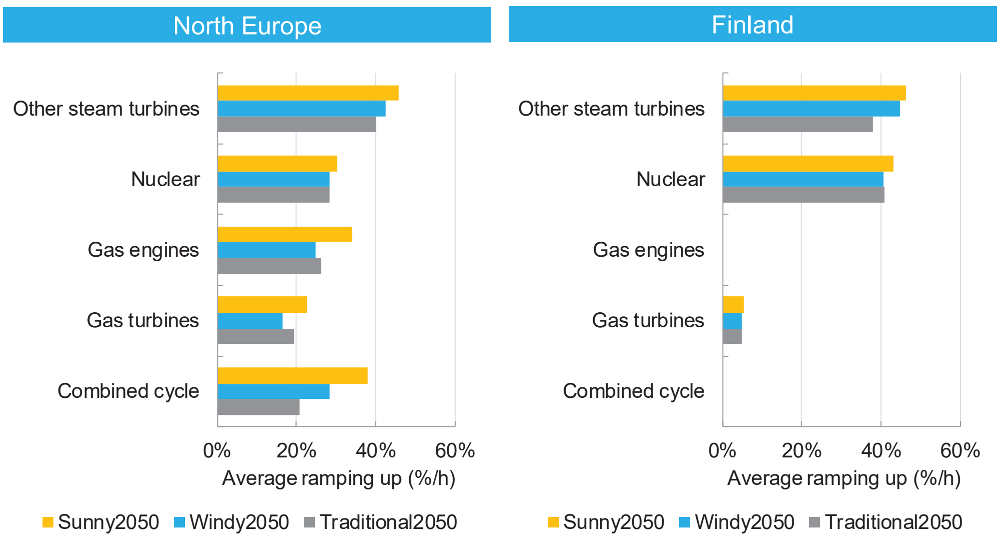
Total ramping higher in the 'sunny' scenario



Other steam turbine fuels: wood, wood waste, straw, municipal waste, industrial waste, natural gas (and coal, peat, fuel oil in 2020 and 2030)

EL-TRAN strategicRESEARCH

Average size of up-ramps per generation type



Biggest ramps require CHP and nuclear plants (not happening often, though)

EL-TRAN strategicRESEARCH

Hydropower scheduling with large amounts of VRES

- How will large amounts of VRES (wind power, solar PV) affect hydropower scheduling?
- Can water values be used if there is no 'avoided costs'?
- How uncertainty should be presented and in what detail?
- What is the effect of scheduling horizon length?

Spine Open-source toolbox for modelling integrated energy systems

Open Source (free)
- Spine Model: Julia + JuMP
- Spine Toolbox: Python + Qt

Fast
- Julia optimisation
- Efficient problem formulation
- Parallelization

Flexible
- (Spine = a model generator, models are created by specifying data) →'one stop shop' for different modelling activities
- Both **long-term and short-term planning**
- Possibility to model **different energy sectors**
- Flexible selection of level of detail, e.g., trade-based, DC and AC load flow grid representation

User friendly
- Project based workflow
- Examples for accessing commonly used open data sources
- Automated, smart and integrated data conversion (temporal, spatial, technological)
- Easy to define and compare a lot of different scenarios
- Allows to incorporate different model types (in a later stage): e.g., agent-based models, Nash equilibrium models, PSS®E power system models, etc.

www.spine-model.org
@Spine_Project

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N. 774629.

Erkka.Rinne@vtt.fi

www.vttresearch.com

#vttpeople / @VTTFinland

EERA JP Wind : Workshop of SP5 (system integration) & SP6 (offshore), Trondheim 27/6/2018

Offshore and system integration perspectives in the Greek Archipelagos

Nikos Stefanatos
CRES, Wind Energy Department

ΚΑΠΕ CRES | CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING

EERA Coordinating energy research for a low carbon Europe

- **Wind energy : Targets and Status**
- Resources
- Offshore & Grid integration: Status and opportunities
- Synergies

RES : EU & National Targets for Greece

2020 : **EU « 20-20-20» guidelines**

- 20% reduction of greenhouse emmissions
- 20% RES contribution on total energy consumption
- 20% energy saving

Greece : National targets RES 2020

- 20% RES contribution to total energy consumption
- **40% RES share in electrical energy**

2030 : **European Parliament decision (17/1/2018)**

35% RES share on total energy consumption in EU on 2030

National targets for 2030 : Not defined yet

Greece : National Targets for RES 2030 (Assumption for 35% EU target, study by TUWien**)

33% RES share on total energy consumption

60% RES share on electrical energy

** G. Resch, C. Panzer, A. Ortner "2030 RES Targets for EU-a brief pre-assessment" TUWien-EEG , Vienna 2014

Nikos Stefanatos
CRES, Wind Energy Department

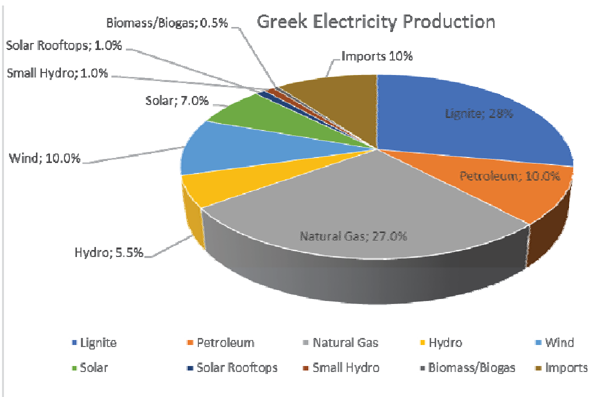
RES : Greece, today

RES Share on electricity production

(Compilation from TSOs provisional data for 2017)

Wind energy	: 10.0%
Photovoltaics	: 8.0%
Hydro	: 6.5%
Biomas	: 0.5%
TOTAL RES	**: 25.0%**

Lignite	: 28 %
Natural Gas	: 27 %
Diesel Oil	: 10%
Imports	: 10%



**For 3 months in 2017,
the Greek electrical system was
powered by Renewables only**

Nikos Stefanatos
CRES, Wind Energy Department

RES in Greece: Today and until 2030

Installed RES capacity in Greece as per 31/12/2017 – comparison with targets (MW)

	2017	2020		2030 (estimation*)	
		Targeт	Deficit	Target*	Deficit*
Wind	2650	7500	**4350**	11250	**8600**
Hydro	3400	3000	-400	4500	1100
PV	2605	2500	-105	3750	1135
Other RES	60	300	240	450	390
ΣΥΝΟΛΟ	**8715**	**13300**	**4085**	**19950**	**10875**

* Estimated, National Targets not set.

Considerable new wind capacity is needed in the next years

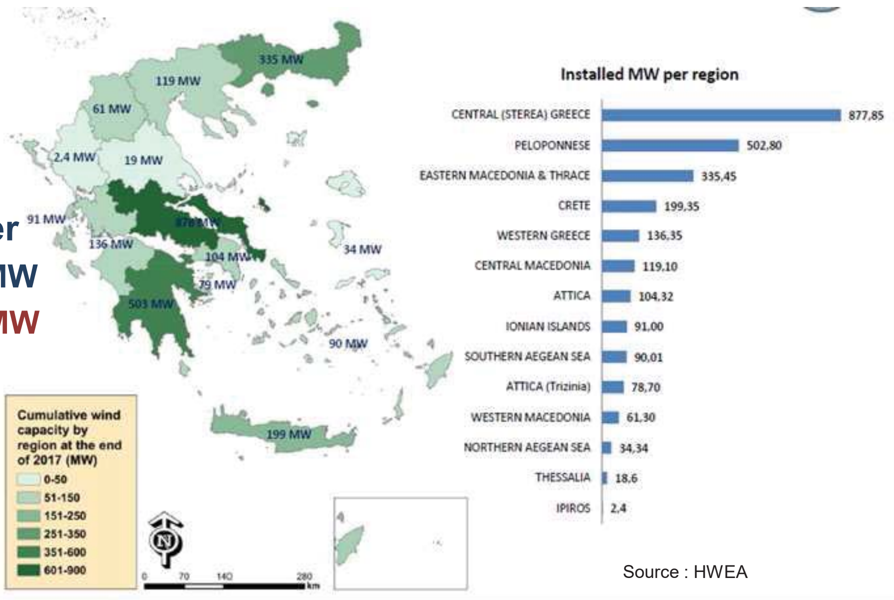
Nikos Stefanatos
CRES, Wind Energy Department

Offshore and system integration perspectives in the Greek Archipelagos,
EERA JP Wind Workshop , Trondheim 27/6/2018

Wind energy installations in Greece (end 2017)

Total installed power

- On shore : 2652 MW
- Offshore: 0 MW



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CRES, Wind Energy Department

Barriers we must overcome !

Legal framework for Offshore in Greece

- Applications for **offshore wind farms NOT ACCEPTED**, since 2010, until the National Program for the Development of Marine wind farms is prepared
- National Framework for the Maritime Spatial Planning in alignment to EU Guideline 2014/89 just voted – Regional and special planning (like the “National Program for the Development of Marine Wind Farms) to follow.
- Regulation Authority of Energy guideline (2012): “Applications involving **floating installations** (of wind energy) **cannot be evaluated** for the time being, since the floating wind turbine technology is not mature.

Offshore and system integration perspectives in the Greek Archipelagos,
EERA JP Wind Workshop , Trondheim 27/6/2018

Electricity market in Greece

- **UNTILL NOW – Feed in Tariff**
  - All wind projects that already have secured “connection contracts” and will be connected until **mid 2019** will get a fixed **Feed in Tariff of 87 €MWh** for 20 years.
- **FROM NOW ON - Tenders**
  - **New tendering system** in effect as of 2018
  - **Regular tenders** to be issued by the Regulating Authority of Energy for production permits eligible for special RES sliding cap above market price up to the bid price.
  - Separate **auctions per technology** (solar or wind) **and mixed auctions** for large projects (solar > 10MW and wind >50MW)
  - **900 MW of wind** plus **1200 MW of mixed** auctions planned for 2018-2020
  - **Only mature projects** allowed (with “final grid connection terms”)
  - **Small Wind** projects **P_{nom}<3MW** (private projects) or **P_{nom}<6MW** (energy communities) excluded from tendering, will receive **Feed in tariff 98 €MWh**
  - Wind projects **not applying for cap** above market price can proceed as conventional projects participating in electricity market (market price for 2017 around 50 €MWh)

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Electricity market in Greece

- First tender to be run on 2/7/2018
  - Up to **176 MW** for Wind for projects 3MW<P_{nom}<50MW will be assigned
  - Starting price for wind : **90 €MWh (maximum** bid price)
  - There is no restriction / differentiation between onshore or offshore projects (but offshore are not allowed ….)
- Supplementary tender for non-assigned capacity **(~ 120MW**) later this year
- 400 MW Mixed technology tender for large projects (>50MW) later this year
- One Regional tender for mixed technology, later this year (capacity not defined)
- Option for other **special tenders** (regional or technology specific) exists, but nothing concrete is planned, not expected in 2018.

Offshore and system integration perspectives in the Greek Archipelagos,
EERA JP Wind Workshop , Trondheim 27/6/2018

- Wind energy : Targets and Status
- **Resources – Offshore**
- Offshore & Grid integration : Status and opportunities
- Synergies

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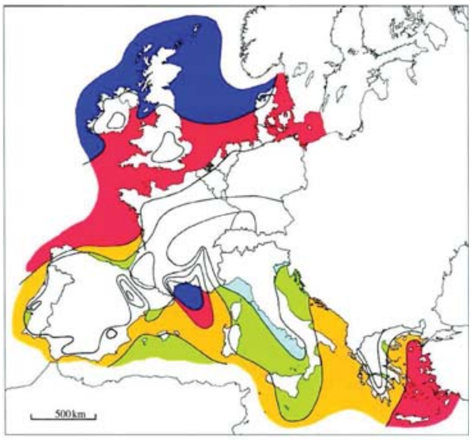
European Wind Atlas :1989, Offshore



wind resources over open sea (more than 10km offshore) for five standard heights										
	10m		25m		50m		100m		200m	
	ms^{-1}	$W m^{-2}$	ms^{-1}	$W m^{-2}$	ms^{-1}	$W m^{-2}$	ms^{-1}	$W m^{-2}$	ms^{-1}	$W m^{-2}$
(blue)	>8.0	>600	>8.5	>700	>9.0	>800	>10.0	>1100	>11.0	>1500
(red)	7.0–8.0	350–600	7.5–8.5	450–700	8.0–9.0	600–800	8.5–10.0	650–1100	9.5–11.0	900–1500
(orange)	6.0–7.0	250–300	6.5–7.5	300–450	7.0–8.0	400–600	7.5 – 8.5	450 – 650	8.0 – 9.5	600 – 900
(green)	4.5–6.0	100–250	5.0–6.5	150–300	5.5–7.0	200–400	6.0 – 7.5	250 – 450	6.5 – 8.0	300 – 600
(light blue)	<4.5	<100	<5.0	<150	<5.5	<200	<6.0	<250	<6.5	<300

Credit: *European Wind Atlas*. Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark.

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Offshore and system integration perspectives in the Greek Archipelagos,
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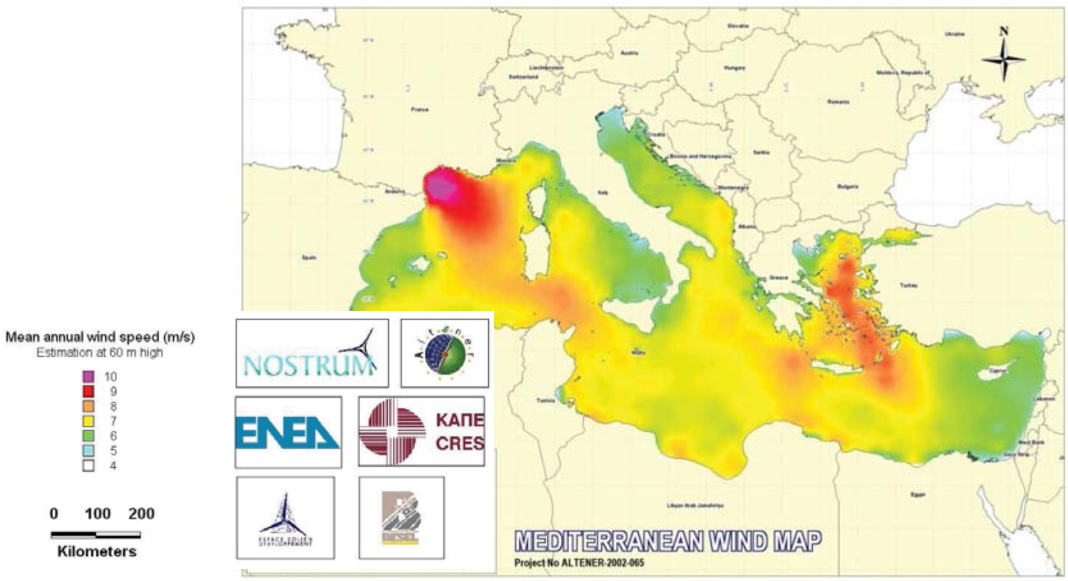
Offshore wind potential in the Mediterranean



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Preliminary planning for offshore wind in Greece

“Strategic environmental Assessment of the National Program for the development of marine wind farms”

- Project assigned by the Ministry of Energy and Environment to a consortium consisting of CRES (coordinator), HCMR (Hellenic Center for Marine Research) and ENVECO consulting company (funded by EU-ERDF/ΕΣΠΑ 2007-2013 /MIS 375406)
- Preliminary assessment of offshore wind potential in the Greek seas, and investigation of possible areas for offshore wind development
- Screening for technical and environmental restrictions and conflict of uses (tourism, fishing, military etc)
- **Only FIXED BOTTOM** foundation examined

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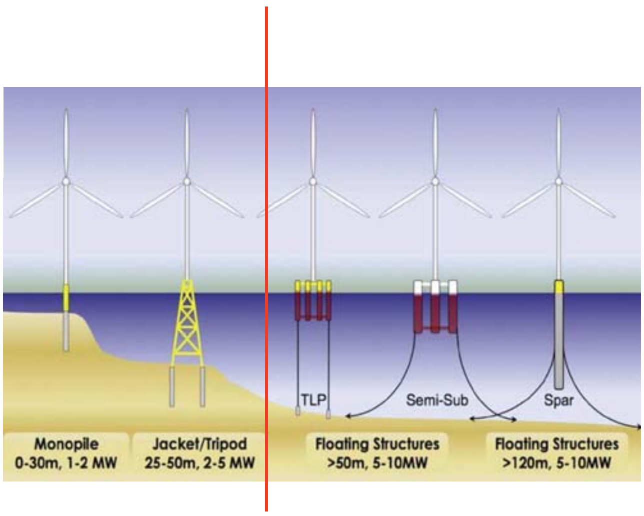
Offshore wind : Substructure types

For fixed bottom foundations:

50m limit

Gravity foundation
typical 0-10m



50m limit line

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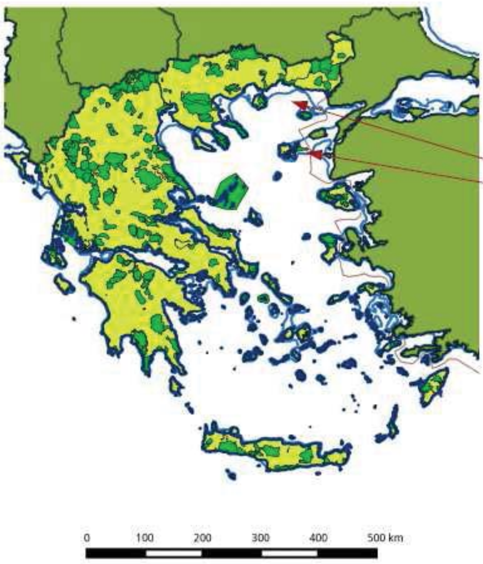
Offshore wind in Greece : The 50m limit



Blue line: 50m iso-depth contour "limit line" for fixed bottom application

«Strategic environmental Assessment of the National Program for the development of marine wind farms», CRES, NCMR, ENVECO funded by Ministry of Energy and Environment, ERDF – ESPA

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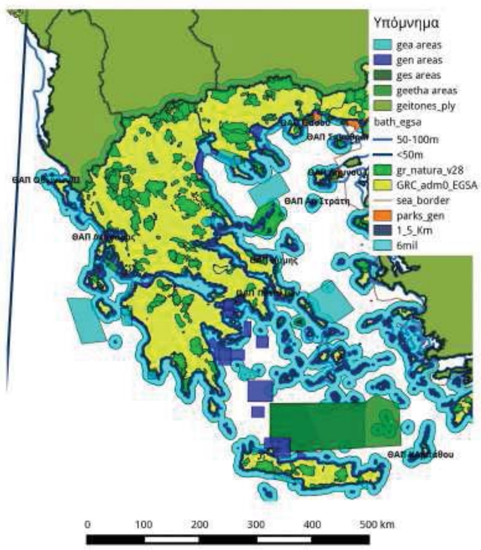
Offshore and system integration perspectives in the Greek Archipelagos,
EERA JP Wind Workshop , Trondheim 27/6/2018

Offshore wind in Greece : Other restrictions



- **< 50m** depth
- Distance from shore
  1.5km < Dist< 11 km (=6nm)
- Nature protection areas
- Other uses (mainly military training areas)

«Strategic environmental Assessment of the National Program for the development of marine wind farms», CRES, NCMR, ENVECO funded by Ministry of Energy and Environment, ERDF – ESPA

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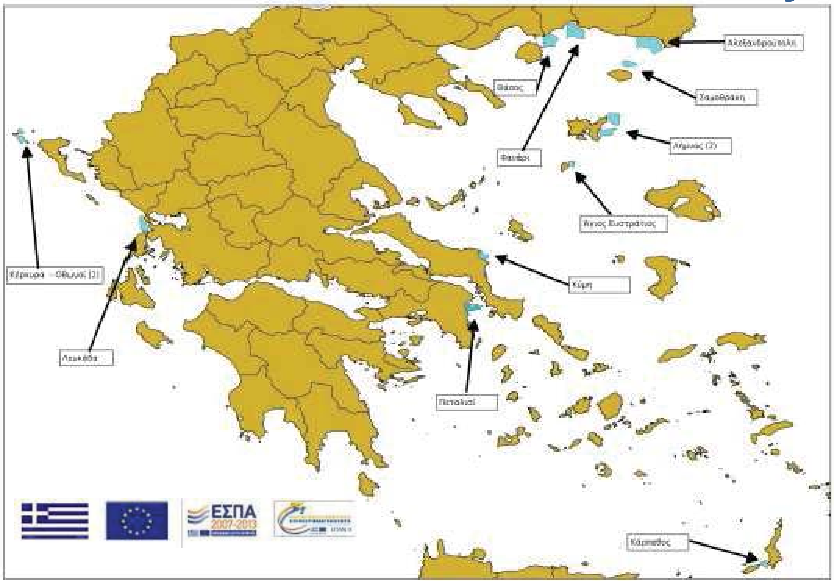
Nikos Stefanatos
CRES, Wind Energy Department

EERA

Offshore wind in Greece : Preliminary mapping



Fixed bottom only
(depth<50m)

«Strategic environmental Assessment of the National Program for the development of marine wind farms», CRES, NCMR, ENVECO funded by Ministry of Energy and Environment, ERDF – ESPA

Offshore and system integration perspectives in the Greek Archipelagos,
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Offshore wind in Greece : Cumulative capacity

	A- Basic	B-Typical	C-High
WT Nominal Power	5MW	7MW	7MW
Diameter (D)	130m	154m	154m
Hub height	100m	125m	125m
Spacing	1000m (7.7D)	1232m (8D)	924m (6D)
Wind turbines (total)	391	306	536
Total Nominal power [MW]	**1955**	**2142**	**3682**

Fixed bottom only
(depth<50m)

Scenario A: Minimum distance from shore : 1.5km
Scenarios B & C : Minimum distance from shore : 3.0km, at some cases 6km

«Strategic environmental Assessment of the National Program for the development of marine wind farms», CRES, NCMR, ENVECO funded by Ministry of Energy and Environment, ERDF – ESPA

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CRES, Wind Energy Department

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- Wind energy : Targets and Status
- Resources
- Offshore & Grid integration : Status and opportunities
  – **The Grid**
- Synergies

Offshore and system integration perspectives in the Greek Archipelagos,
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Grid integration : The Aegean sea case, today

- **Isolated small systems (island clusters)**
  - P_{max} > 100 MW : 2 systems
  - 2 MW < P_{max} < 100 MW : 20 systems
  - P_{max} < 2MW : 10 systems
- Crete is the biggest system, with 813MW total installed capacity (200 MW wind)
- Operating mainly **on diesel oil** (mostly internal combustion engines, and some gas turbines in larger islands)
- Electricity prices subsidized to national mean value through a «Public interest» levy paid by all electricity consumers in Greece at an

  extra cost of **600mio€ year**

  (about 300mio € for Creta only)

Source: S. Papathanasiou : ELENA Project/ DAFNI Network http://www.dafni.net.gr/

Grid integration : The Aegean sea case –Interconnections planned -1

- **Cyclades Cluster** (12 small islands to be connected to mainland)
  - **3 x 200 MVA AC** links (108 km larger subsea length)
  - Phase 1 :Operating (Andros, Tinos,and Syros, to be followed by Mykonos, Paros & Naxos shortly)
- **Crete 1 :**
  - **200 MVA AC** link to southern Peloponnese
  - **176 km**, largest AC link in the world
  - Tender issued 2018, planned operation 2022
- **Crete 2** :
  - **1000 MVA DC** link to Attica (360km)
  - Will cover all loads of Crete (813 MW total installed capacity, 200MW wind)
  - Will allow for excess RES production to be handled
  - To be part of **EuroAsia interconnector**
  - Planned operation : 2023

Source: ADMHE (TSO- Greece) «10 years Development plan for Greek Transmission System 2015-2024».

Offshore and system integration perspectives in the Greek Archipelagos,
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Grid integration : The Aegean sea case –Interconnections planned* -2

•**North-East Aegean Link** : Interconnection of major east Aegean islands and the Dodekanese complex to North Greece (Macedonia).

- Phase 1: 500 MVA, 650 km DC link, north part, Planned for 2025

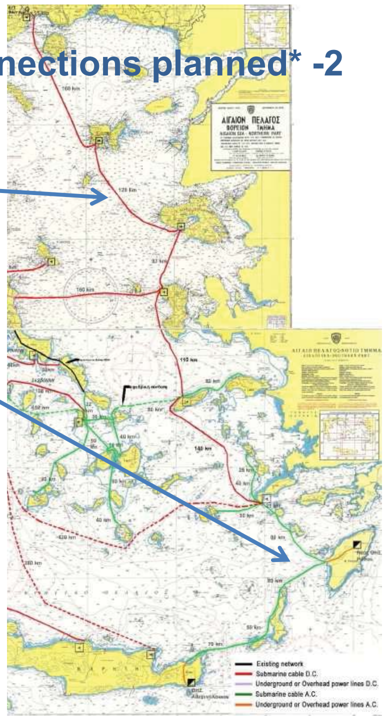
•**South-East Agean Link** : Interconnections of major south east Aegean islands (Rhodos, Kos, and others) to Crete

Planned : 2025

•**Special purpose interconnections**

- Onshore wind projects involving 2500 MW on 7 large wind farm clusters
- Special purpose links to be constructed by the wind farm owners

*** Provisional : Routing and technical characteristics of the links under discussion**



Grid integration : The Aegean sea case –Offshore and grids

Provision for extra wind capacity (onshore and offshore) in the planned links

•Cyclades Links : 200 MW
•Creta links : 800 MW
•North East Aegean Link : 500 MW
•South East Aegean Link : 600 MW

Estimations: Routing and technical characteristics of the links under discussion

Offshore projects planned

- **Offshore - Fixed bottom** :
  - 3300 MW applied,
  - 342 MW awarded production license.
  - **ALL offshore frozen since 2010**, expecting Strategic Offshore Wind planning

•Offshore - Floating : Nothing (yet..)

Offshore and system integration perspectives in the Greek Archipelagos,
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- Wind energy : Targets and Status
- Resources
- Offshore & Grid integration : Status and opportunities
- **Synergies**

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National Framework for Maritime Spatial Planning

- National obligation under EU Guideline 2014/89/EE
- Regional Maritime Spatial Plans

  Must allow for "energy production by RES"

  …….Work needed now…

Grid Interconnections in various planning phases

…….Work needed now…

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GreenIsland Project

Aim : Convert a diesel powered system to
Hybrid (wind + solar + storage)

- Small isolated system (peak load **350kW**)
- Annual average wind speed **9 m/sec** (at 30m AGL)
- **RES penetration target > 80%**
- Planning : Operational on 2020
- Project developer : CRES
- Budget: 8.5 mio€
- Funding: Greek Government and ERDF

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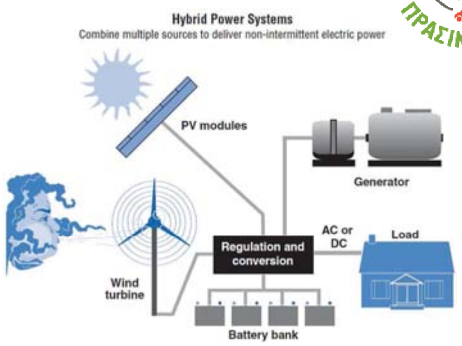
CRES, Wind Energy Department

GreenIsland Project

Main technical characteristics

- 800-1000 kW **Wind turbine**
- 150 kW **PV array**
- 2.5MWh **battery storage** (Li-ions)
- **Thermal power storage** for district heating
- **Electromobility** (electric vehicles and charging stations)
- **Energy efficiency** on buildings
- **Conventional generators** as back-up units
- System **optimization** for **>80% RES** penetration rate
- Extensive **testing and monitoring** program

SCADA system and individual RD grade systems for WT power curve, power quality, harmonics, flicker etc



This is not another isolated off-grid application

This is a small scale model of the Main Grid of tomorrow

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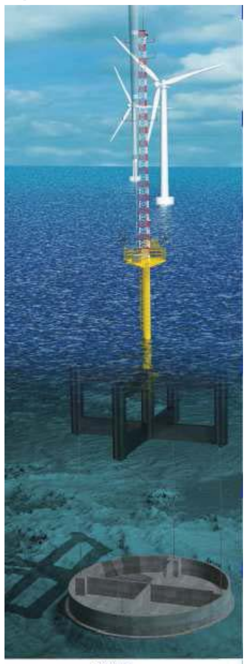
FloatMastBlue

- **Floating platform** developed by FLoatMast Ltd for accurate wind regime measurements
- **TLP type** (tension leg platform) for minimum tilting and movements
- **Re-Deployable**
- **Lidar and met mast** equipped with cups and Sonic, mast measuring height 40m from sea level.
- Capable to support **power curve measurements** in line with standards
- **Displacement and acceleration** sensors on the platform
- **Loads monitoring** on the retention wires and at structural parts
- To be deployed in Aegean sea, **Q4 of 2018**.
- CRES is subcontractor for wind regime and loads measurements (planning, monitoring and evaluation). Data can be available for R&D use, in communication with the developer of the platform



Funded by EU under Horizon 2020-SME tool

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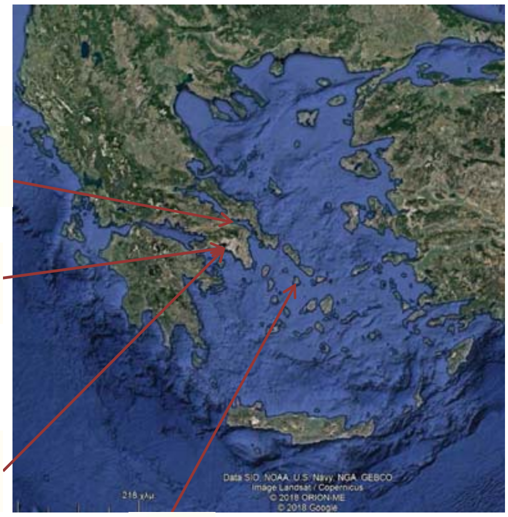
CRES, Wind Energy Department

Maritime manufacturing capabilities in the Greek Archipelagos

- Four major shipbuilding centers
  - 7 floating docks up to 50.000 DWT
  - 3 fixed docks (up to 500.000 DWT, the biggest in the Mediterranean).
  - Floating cranes up to 200tn etc
- Long tradition and skills
  - First Greek-made vessel with all steel hull was built at Neorion Shipyards, Syros in **1892**
- Infrastructure and skills under-exploited



КАПЕ CRES

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PELAGOS PROJECT

Interreg Mediterranean PELAGOS

A sustainable marine economy to become a reality…

A project to increase the innovation capacities and cooperation of **BLUE ENERGY** actors in **MED** through promoting a transnational **CLUSTER**, bringing them together in order to develop a shared understanding of the challenges and collectively devise workable solutions.

КАПЕ CRES

Interreg Mediterranean PELAGOS

PARTNERSHIP

PELAGOS with partners from Croatia, Cyprus, Greece, France, Italy, Portugal and Spain aims at establishing a Transnational **Mediterranean Innovative Cluster** in order to accelerate the development of Blue Energy (BE) in Mediterranean marine areas. The Cluster will be composed of seven **(7) National Hubs** and will be supported by the already established French sea cluster **Pôle Mer Méditerranée.**

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Offshore and system integration perspectives in the Greek Archipelagos, EERA JP Wind Workshop , Trondheim 27/6/2018

Offshore and Grid integration in the Greek Archipelagos - What do we have (in numbers) :

- **8-9 m/sec** annual mean wind speed
- **8 GW** deficit in wind power to be covered by 2030
- **2 GW** of isolated island grids, operating on diesel oil at an extra cost of 600mio Euros per year
- >**2000 km of subsea interconnections** planned for the next 10 years
- Mapped potential for **1.5 GW to 4.0 GW of offshore** wind energy plants (fixed bottom only, floating potential not mapped)
- **Floating offshore** technology coming in maturity
- Significant marine manufacturing capacity **(4 shipyards)** on the spot
- **National Strategic Planning** for marine energy in the making
- Active **Clustering** networks

Looks like Great Perspectives for Offshore Grid Integration project(s)

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Offshore and system integration perspectives in the Greek Archipelagos,
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Agios Georgios wind farm
73.2 MW,
(23 x Vestas V90 & V112, 20km south of Sounion)
Credit: TERNA Energy S.A (www.terna-energy.com)

Thank you for your attention

Nikos Stefanatos
CRES, Wind Energy Department

Renewable Energy: A UK perspective

Professor Olimpo Anaya-Lara

EERA SP5 and SP6 workshop

27-28 June 2018, Trondheim

Testing in SYSLAB. (T. Nielsen)

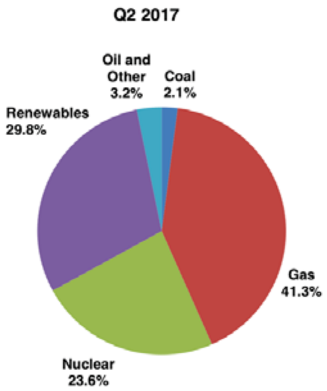
Testing of Soft Open Point Power Electronic Device

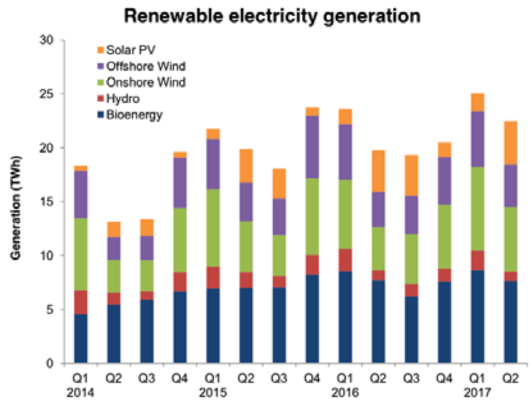
Outline

1. UK targets from renewables
2. UK energy challenges and needs
3. Cooperation at national and international level
4. Long-term vision

UK targets from renewables

- **EU 20/20/20** target of 20% of energy to come from renewables by 2020, with an associated CO2 emissions reduction target of 20% (relative to 1990)
- **Targets have been relative to electricity generation (mainly)**, e.g. the UK Government's target of 20% or the Scottish Government's target of 50% of electricity demand to be met from renewables by 2020.
- Today, **targets are set related more to total energy usage**. (e.g. the Scottish Government's target of 50% of energy usage to be met from renewables by 2030).

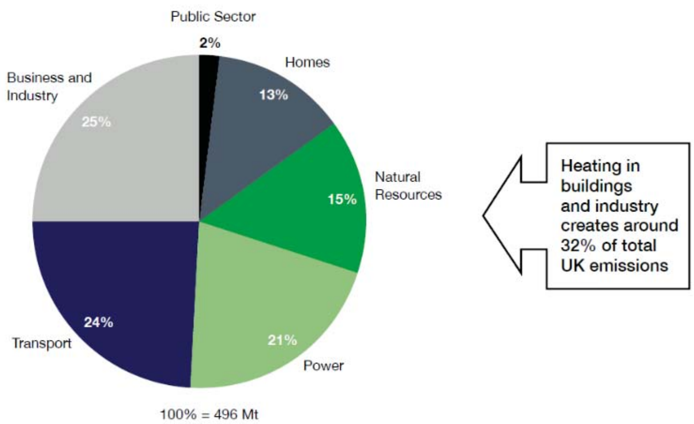




Source: Department for Business, Energy & Industrial Strategy

UK policies and proposals – some examples

- Improving the energy efficiency of our homes.
- Rolling out **low-carbon heating** (e.g. invest in low-carbon heating).
- Accelerating the shift to **low carbon transport** (e.g. Develop one of the best electric vehicle charging networks in the world).
- Delivering **Clean, Smart, Flexible Power** (e.g. Improve the route to market for renewable technologies).



Source: BEIS

UK energy system challenges and needs

Pressing energy challenges

- It is likely that the UK economy will move towards a decarbonised future with a consequent **increase in electricity demand**, e.g. through the replacement of petrol and diesel **vehicles by electric ones**.
- A future GB power system is envisaged with a **very large penetration of offshore wind energy**, perhaps, as much 30GW of offshore wind by 2030 and 50GW by 2050.
- The UK has a strong seasonal variation in energy demand.
- Aging electricity grid.

Needs

- Technology development across the energy sector.
- Reinforcements to achieve the grid infrastructure needed for higher penetration of renewables.
- Knowledge and expertise in testing protocols, procedures.
- Development of standards.
- Grid integration assisted by multi-site HITL implementations (and virtual labs).
- Digitisation, Big Data
- Think BIG with a long-term vision in mind.

Supergen Wind Energy Technologies

- EPSRC funded
  - Phase 1 ~ £2.5M 2006-2010
  - Phase 2 ~ £4.8M 2010-2014
- Consortium of 7 academic institutions
- Chair: Bill Leithead, University of Strathclyde

University of Strathclyde Glasgow · Science & Technology Facilities Council Rutherford Appleton Laboratory · Durham University School of Engineering · Manchester Metropolitan University · Loughborough University · Manchester 1824 · UniS University of Surrey

Supergen Wind Energy Technologies

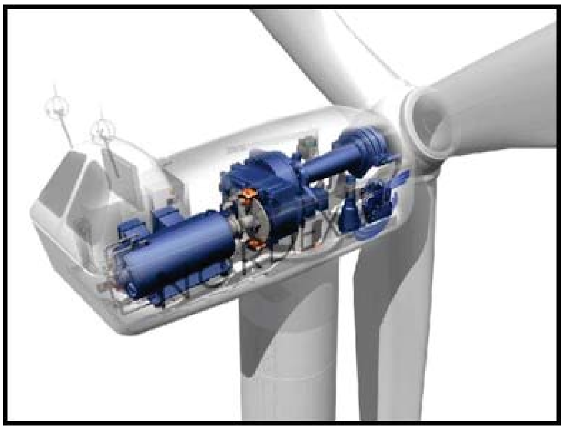
- Turbines as part of an integrated wind farm
- Technologies aimed at a robust, lower cost and reliable Offshore Wind Power Station
- Key Areas
  - Wakes
  - Radar
  - Blade materials
  - Fault detection
  - Foundations
  - Control
  - Connection
  - Economics

Supergen Wind Hub (phase 3)

University of Strathclyde Engineering

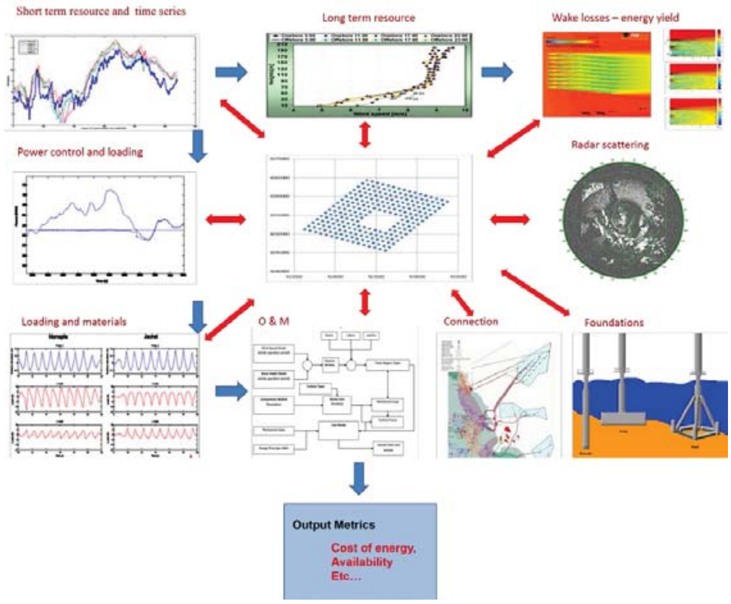
- SUPERGEN Wind members:

  Universities of Strathclyde, Durham, Loughborough, Cranfield, Manchester, Oxford, Surrey, Bristol, Dundee, Imperial College London, alongside STFC, DNV-GL, OREC.



Our research scope

- Planning and Consenting
- Design, Manufacturing and Installation
- Operation, Maintenance and Decommissioning



National and international cooperation

Key instrument

- Sharing infrastructure, data, expertise, lessons learnt and more.
- Academia expertise and facilities (addressing higher TRLs).

Thank you!

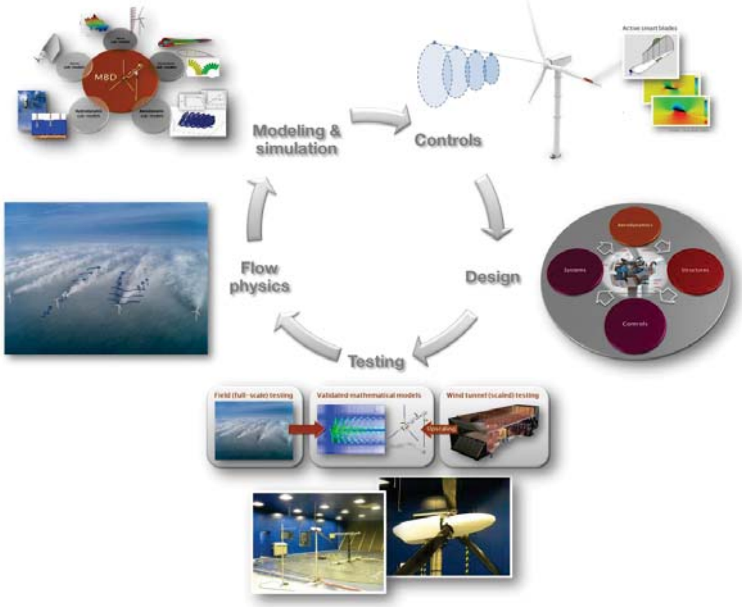
Scroby Sands offshore wind farm (E.On)

Technische Universität München
Wind Energy Institute

Wind Energy Institute

Prof. Dr. Carlo L. Bottasso

Email: carlo.bottasso@tum.de Web: http://www.wind.mw.tum.de



Dr. Filippo Campagnolo

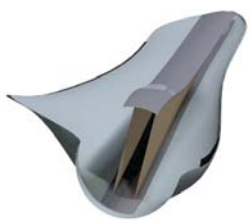
EERA JP Wind Workshop, 27th June 2018
Trondheim, Norway

Wind Energy

Areas of Competence

◀
Modeling and simulation of wind energy systems
Multibody dynamics, computational mechanics
Model reduction and system identification

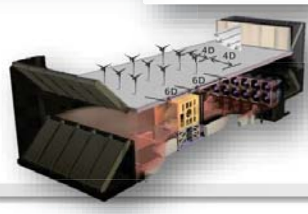
▶
Wind turbine control
Observers in support of advanced controllers
Stability analysis of periodic systems

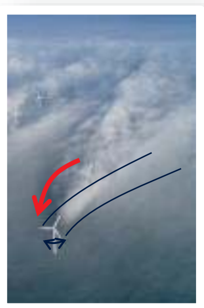


◀
Automated holistic design of wind turbines
Multidisciplinary design optimization
Aeroservoelasticity, load analysis

▶
Design and manufacturing of
aeroelastically scaled models
Wind tunnel testing
Data analysis

◀
Wake modeling
Wake control and load mitigation
Wind plant control
Operation & maintenance





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Selected Highlights

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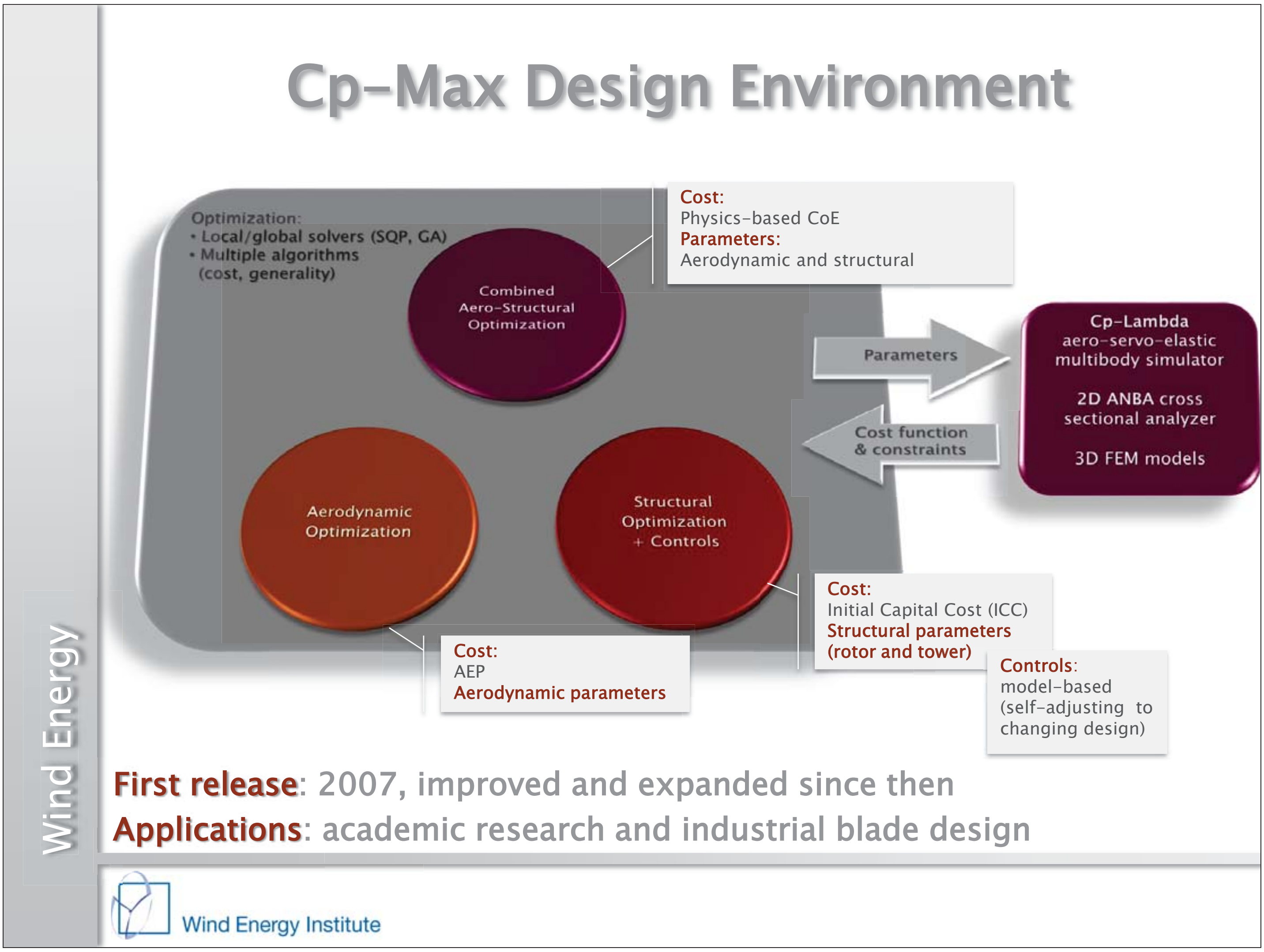
Selected Highlights in Design & Simulation


Cp-Max Design Environment
Optimization:
• Local/global solvers (SQP, GA)
• Multiple algorithms (cost, generality)
Combined Aero-Structural Optimization
Cost: Physics-based CoE
Parameters: Aerodynamic and structural
Parameters
Cost function & constraints
Cp-Lambda aero-servo-elastic multibody simulator
2D ANBA cross sectional analyzer
3D FEM models
Aerodynamic Optimization
Structural Optimization + Controls
Cost: Initial Capital Cost (ICC)
Structural parameters (rotor and tower)
Cost: AEP
Aerodynamic parameters
Controls: model-based (self-adjusting to changing design)
First release: 2007, improved and expanded since then
Applications: academic research and industrial blade design
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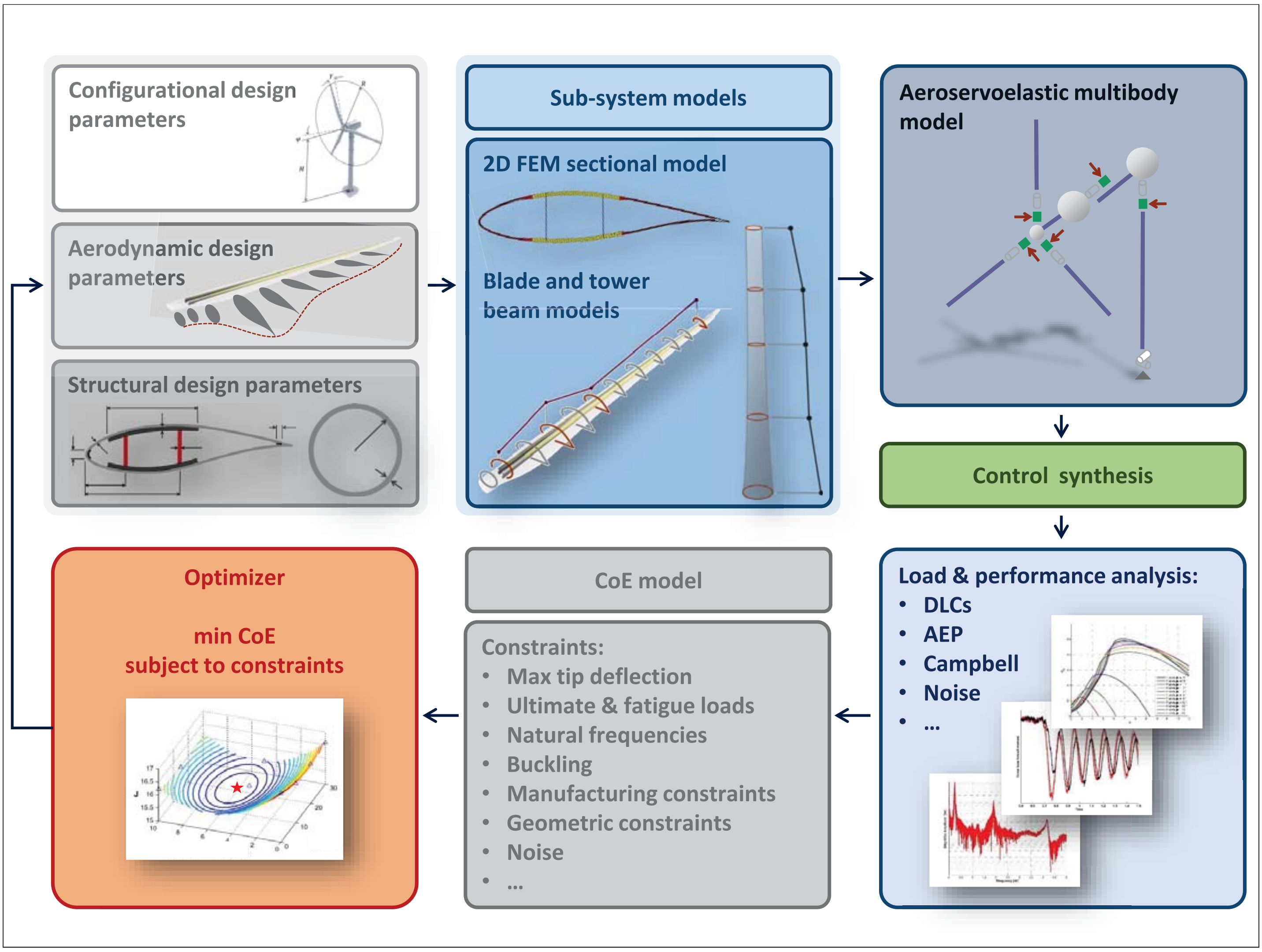
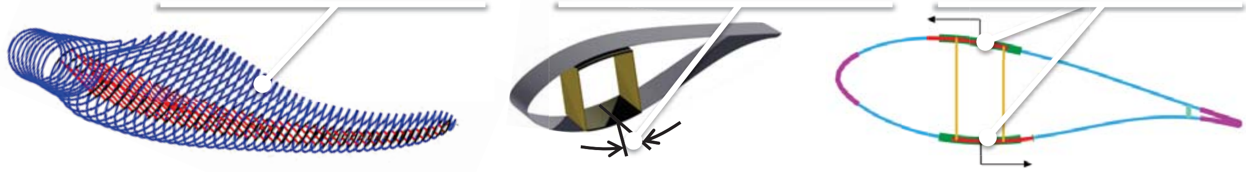

Configurational design parameters
Aerodynamic design parameters
Structural design parameters
Sub-system models
2D FEM sectional model
Blade and tower beam models
Aeroservoelastic multibody model
Control synthesis
Load & performance analysis:
• DLCs
• AEP
• Campbell
• Noise
• ...
Optimizer
min CoE
subject to constraints
CoE model
Constraints:
• Max tip deflection
• Ultimate & fatigue loads
• Natural frequencies
• Buckling
• Manufacturing constraints
• Geometric constraints
• Noise
• ...

Applications: Passive Load Alleviation

Full-span passive load mitigation:
Loaded structure deforms in order to self-reduce loading



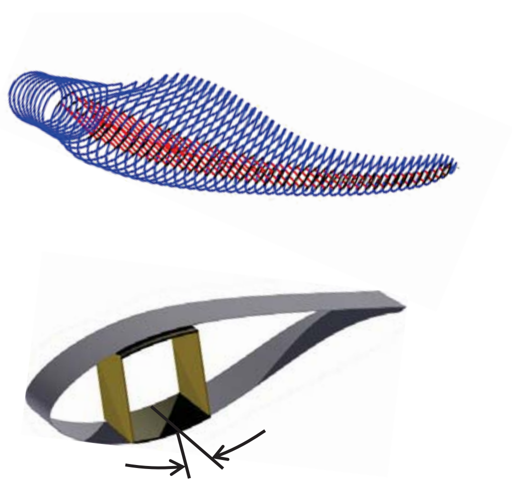
Potential advantages: no actuators, no moving parts, no sensors

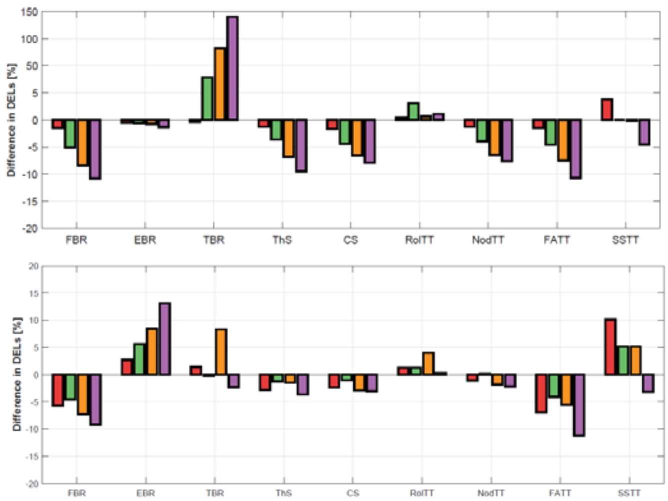
Application: IEA Task 37 3.35MW wind turbine

1. Each passive technology individually
2. Integrated passive technologies: larger rotor at similar loading

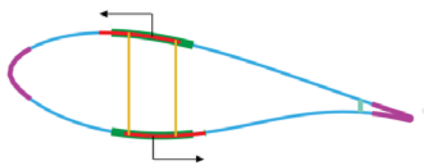
(Details in Bortolotti et al., Wind Energy, 2017)

Applications: Passive Load Alleviation





S-BTC & F-BTC: significant DEL and ultimate load benefits



O-BTC: limited benefits due to large spar caps and pronounced blade slenderness

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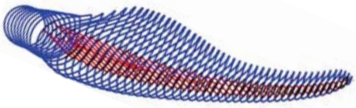
(Details in Bortolotti et al., Wind Energy, 2017)

Applications: Passive Load Alleviation

Optimal **combination of sweep and fiber rotation** (F-S-BTC):
larger rotor at similar loading



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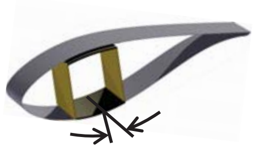


Constraints

Constraints on ultimate loads

Load component	FBR	EBR	TBR	ThS	CS
Value	13.51 MNm	6.84 MNm	0.29 MNm	0.834 MN	8.81 MNm
Enforced	yes	yes	no	yes	yes
Load component	RolTT	NodTT	FATT	SSTT	
Value	4.69 MNm	7.42 MNm	0.75 MN	0.48 MN	
Enforced	yes	yes	yes	yes	

Constraint on fatigue DEL @ N=10^7, Wöhler exponent m=4

Load component	FBR	EBR	TBR	ThS	CS
Value	6.61 MNm	13.34 MNm	0.08 MNm	0.26 MN	6.02 MNm
Enforced	yes	yes	no	yes	yes
Load component	RolTT	NodTT	FATT	SSTT	
Value	1.45 MNm	6.10 MNm	0.36 MN	0.27 MN	
Enforced	no	yes	yes	yes	

Results

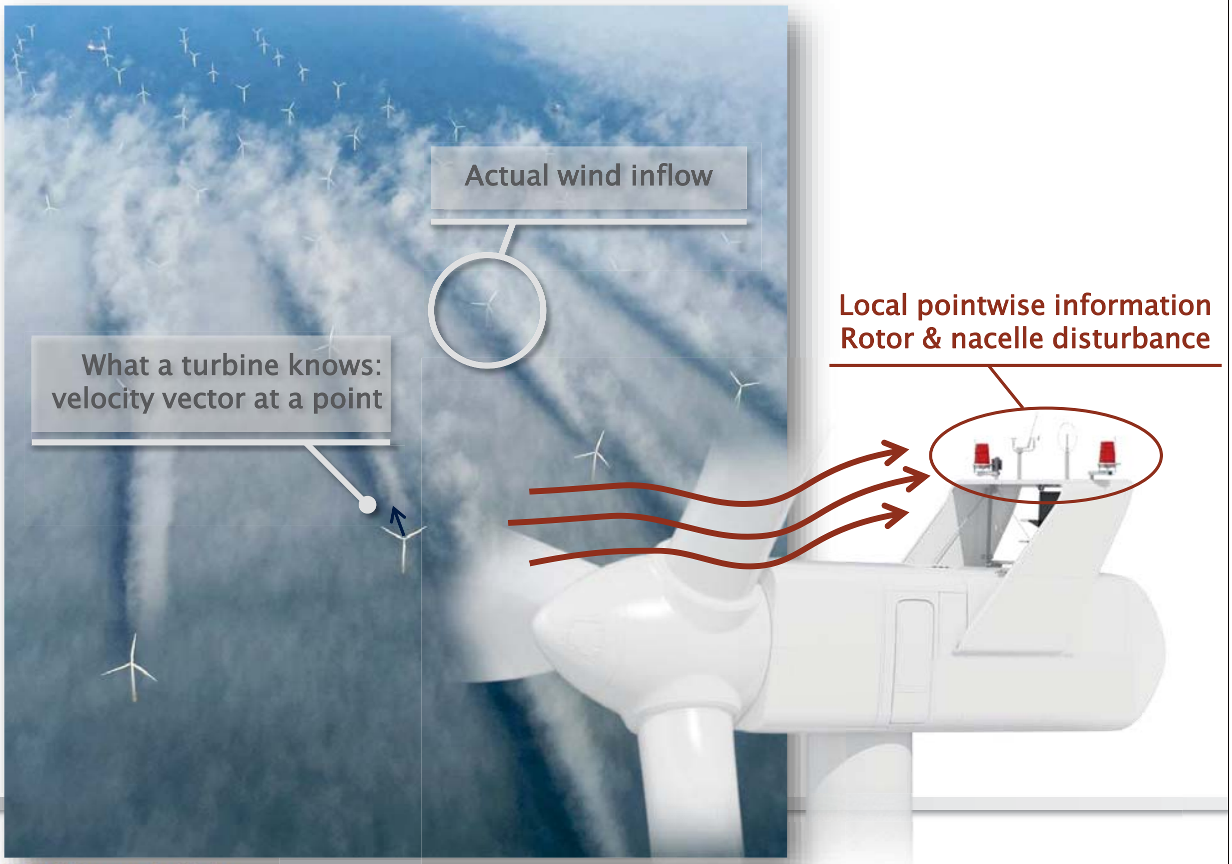
Data	Baseline	F-S-BTC Optimum	Difference
Rotor diameter	130.0 m	136.0 m	+4.6%
Rotor cone angle	3.0 deg	8.0 deg	+166.7%
Nacelle uptilt angle	5.0 deg	6.0 deg	+20.0%
Blade mass	17,525 kg	14,560 kg	-16.9%
Blade cost	127.9 k$	126.2 k$	-1.3%
Tower mass	365 ton	292 ton	+20.0%
Tower cost	548.5 k$	438.2 k$	+20.1%
Aerodynamic AEP	15.01 GWh	15.40 GWh	+2.6%
Electrical AEP	13.96 GWh	14.32 GWh	+2.6%
ICC	3,885.2 k$	3,850.9 k$	-0.9%
CoE	42.00 $/MWh	40.82 $/MWh	-2.8%

New regulation in region II to limit AEP loss (**variable fine pitch setting**)

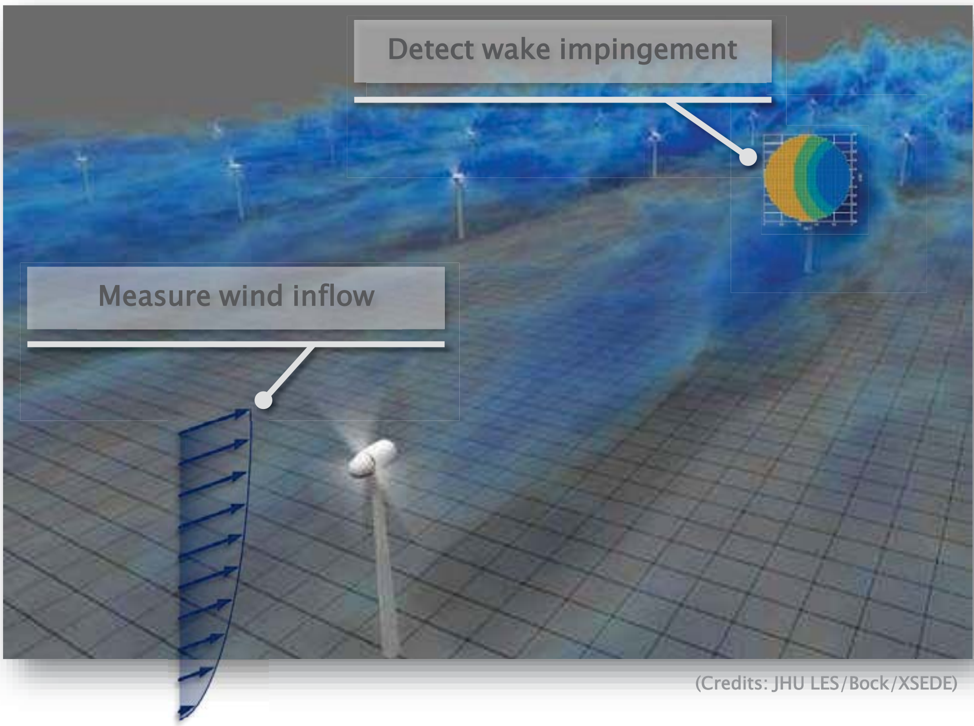
(Details in Bortolotti et al., Wind Energy, 2017)

Selected Highlights in Supporting Technologies

Current Wind Inflow Awareness

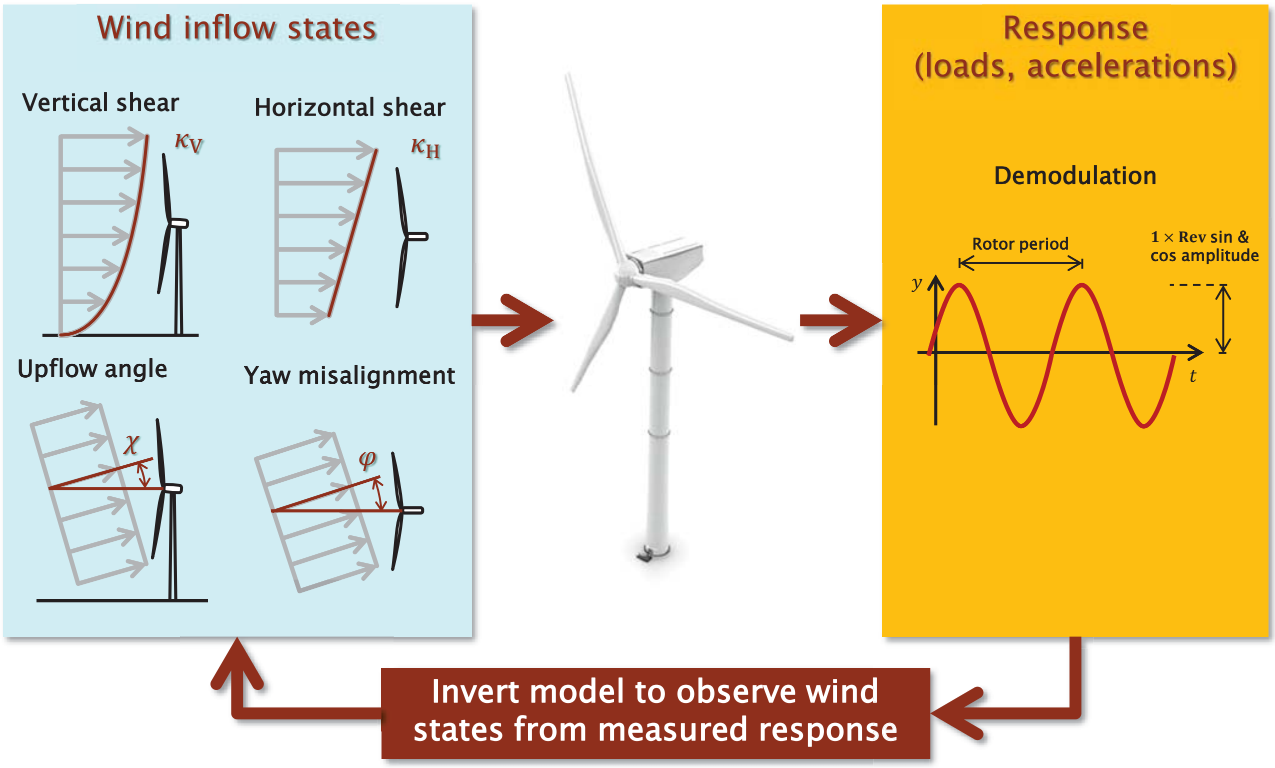


The Rotor as a Wind Sensor



(Credits: JHU LES/Bock/XSEDE)

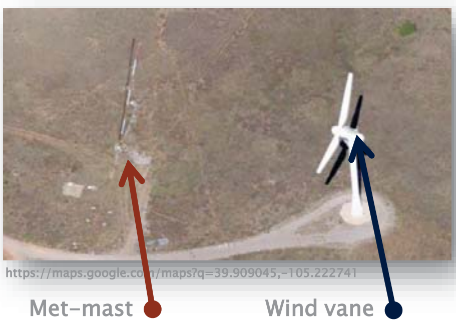
The Rotor as a Wind Sensor: the Concept

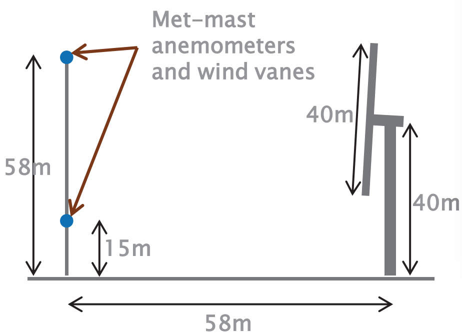


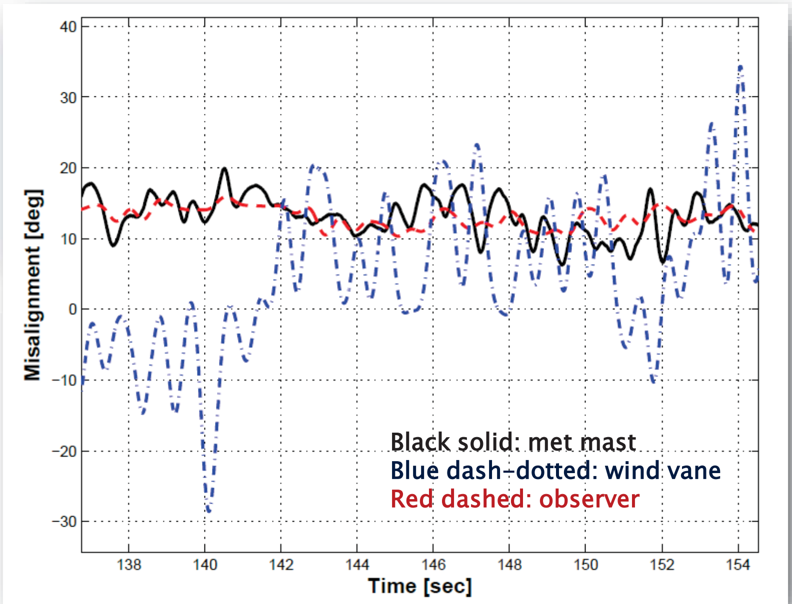
Selected Research Highlights

Field Testing of Misalignment Observer

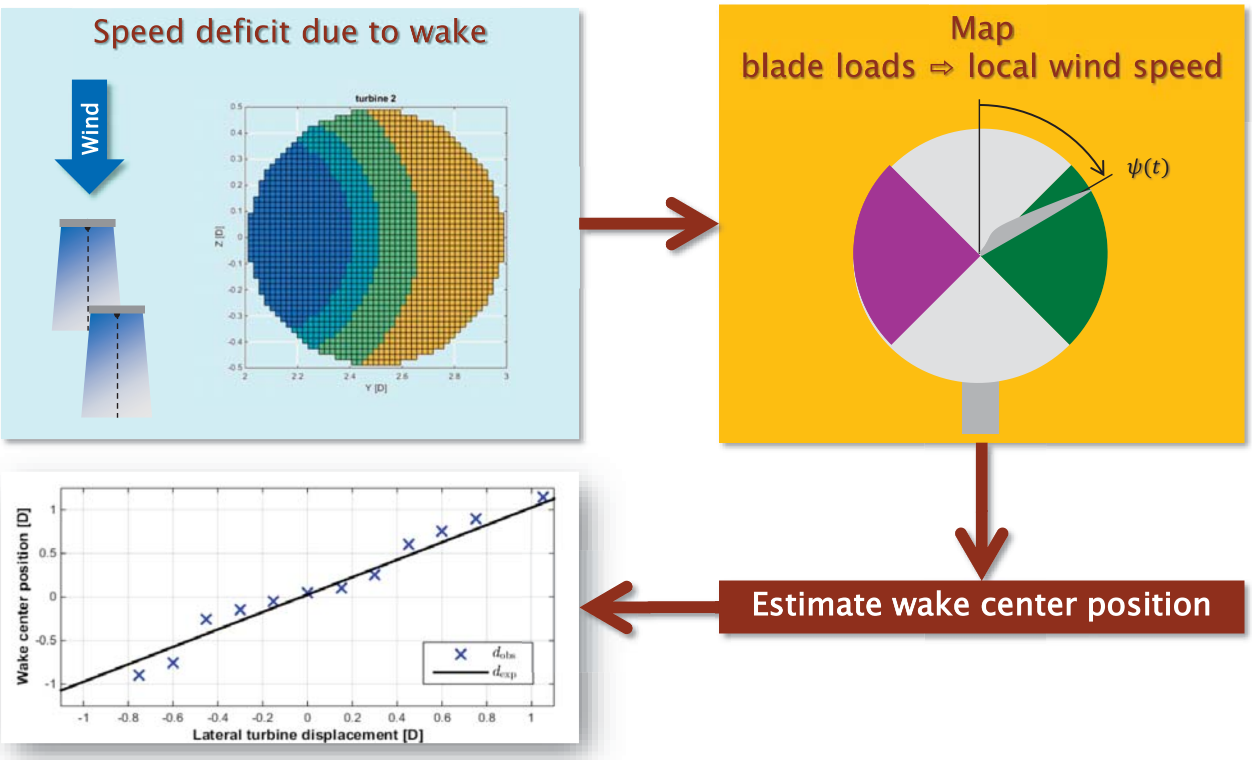
NREL Controls Advanced Research
Turbine CART 3 (USA, CO) ▼







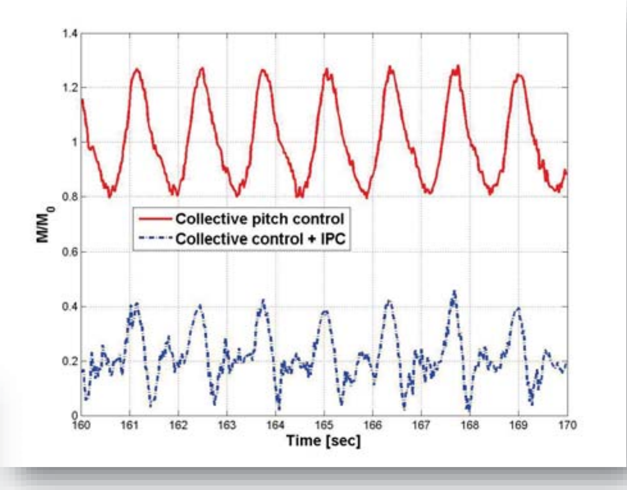
Wake Detector

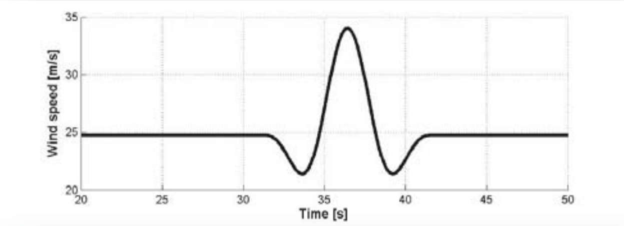


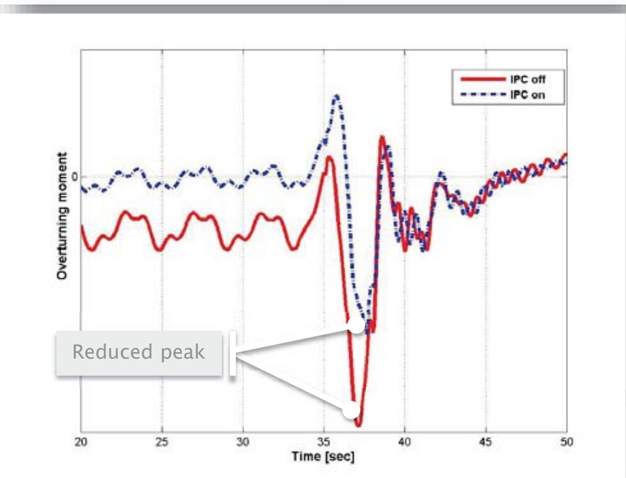
Selected Highlights in Controls

Cyclic Pitch for the Reduction of Ultimate Loads

Remark: IPC reduces average loads ▸







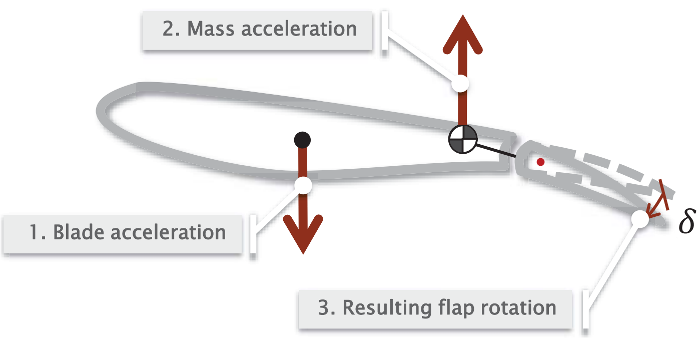
◂ **Consequence**: gust loads may be reduced because initial loading is lower (example, DLC 1.6: EOG50 @ cut-out)

Selected Research Highlights

Load Alleviation: the Passive Flap

Working principle:

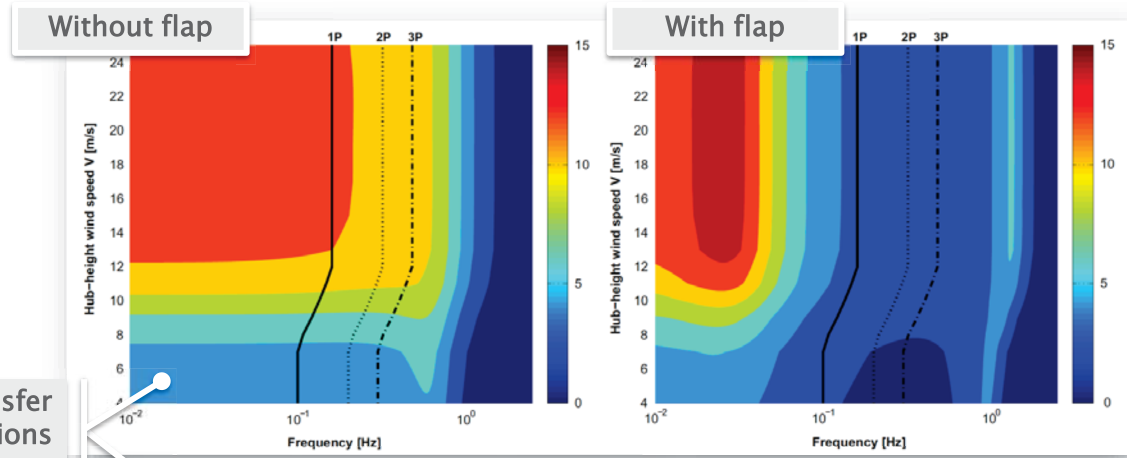
- Aerodynamically balanced: does not respond to deliberate pitch angle changes (control)
- Dynamically unbalanced: out-of-plane accelerations induce opposing flap rotations



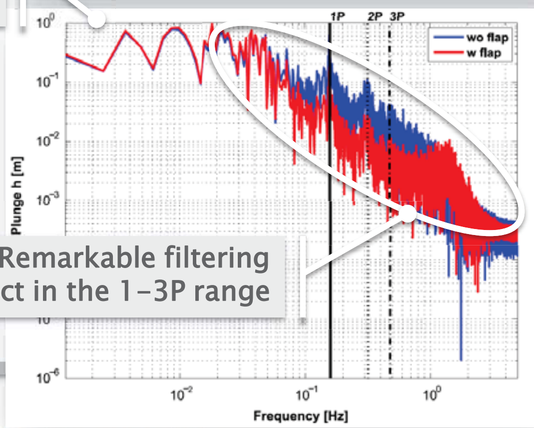
No sensors, no actuators

Selected Research Highlights

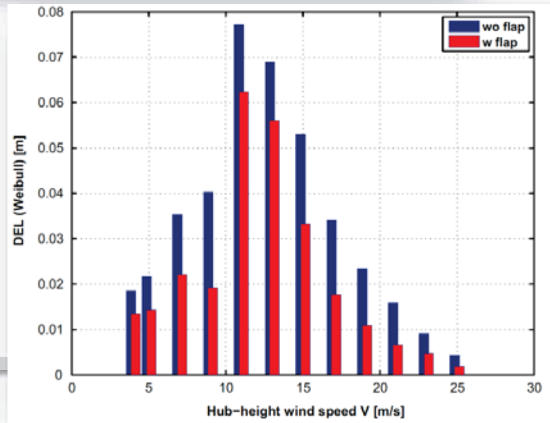
The Passive Flap



Transfer functions AoA–Plunge



Remarkable filtering effect in the 1–3P range

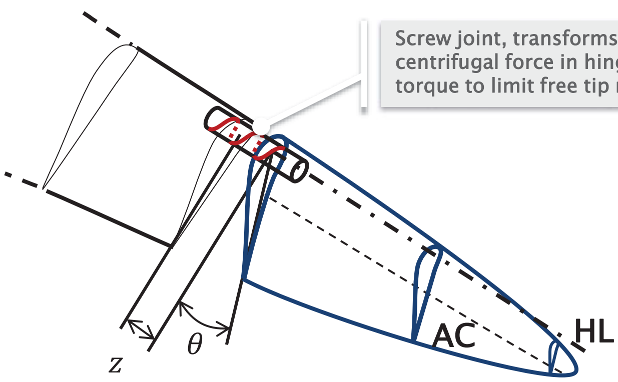


Selected Research Highlights

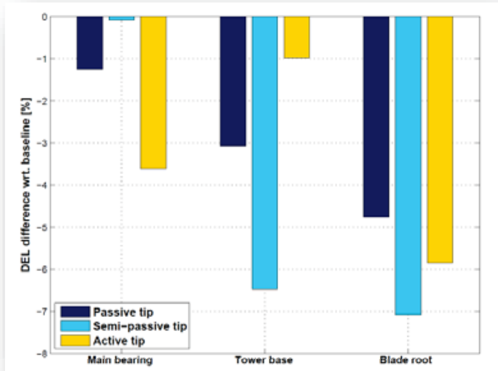
The Passive Tip

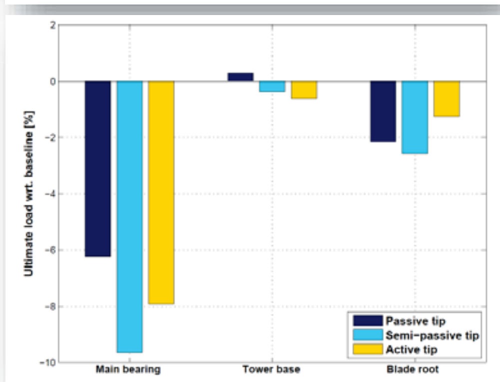
Working principle:

- Aerodynamically unbalanced: changes of AoA are opposed by tip rotation
- Dynamically balanced



No sensors, no actuators



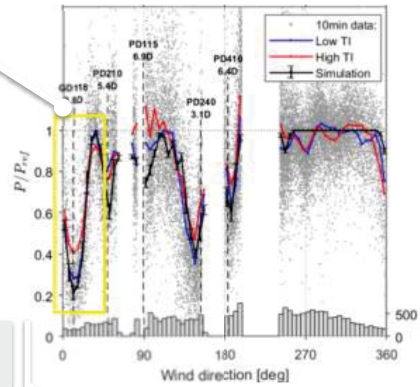


Wake Deflection Wind Farm Control

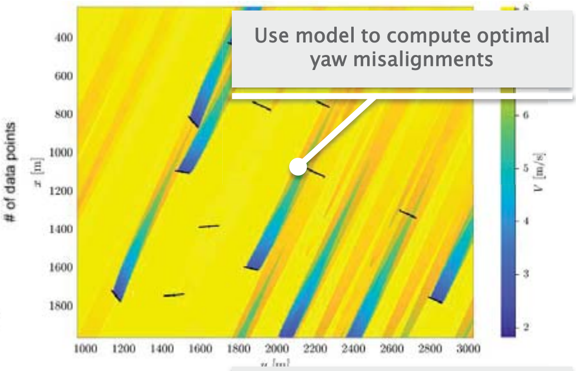
Selected Research Highlights

12 WTs in the North of Germany, 1-year SCADA data

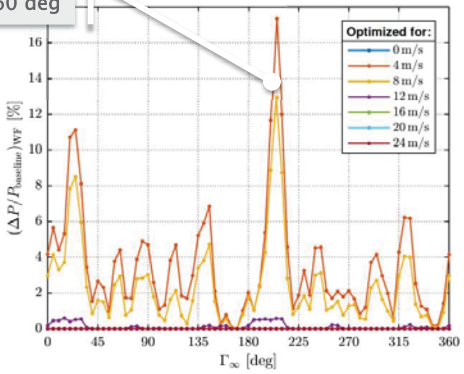
FLORIS-like model predicts well measured power losses



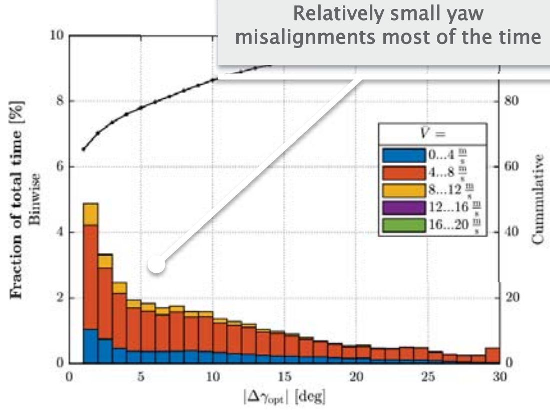
Use model to compute optimal yaw misalignments



AEP improvement: 1.5-2%
Mostly for one prevalent wind direction, but wake deflection is beneficial over 360 deg



Relatively small yaw misalignments most of the time



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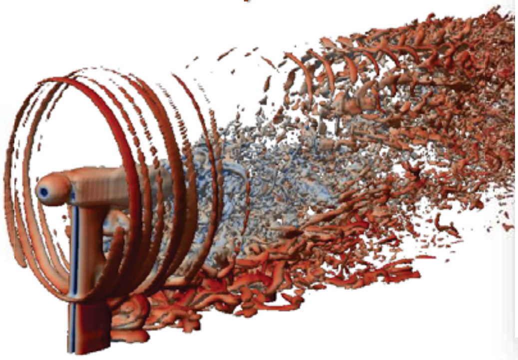
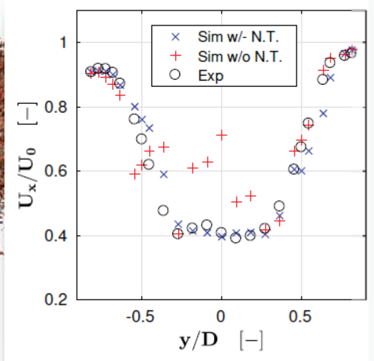
Selected Highlights in Experimental Testing

Selected Research Highlights

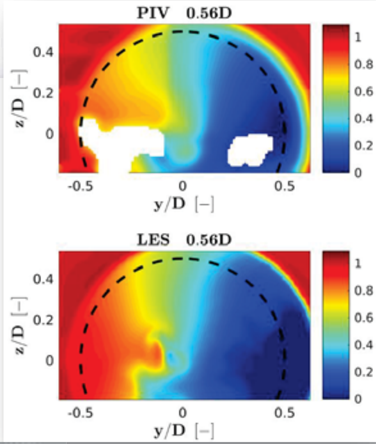
The Role of Wind Tunnel Testing: Aerodynamics and Beyond

Validation of digital copy of scaled facility ▶





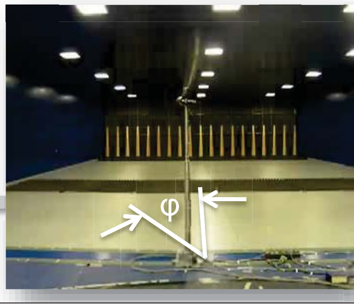
With/without nacelle & tower

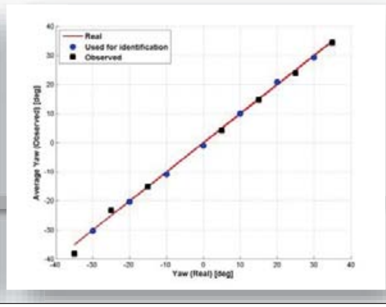


Cyclic pitch control

▼ Floating wind turbine

▼ Wind direction observer

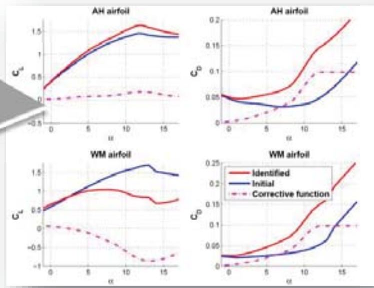




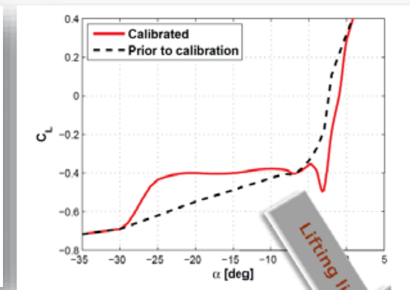
Calibration of Shutdown Model

Wind tunnel shut-down ▲

Exp. response

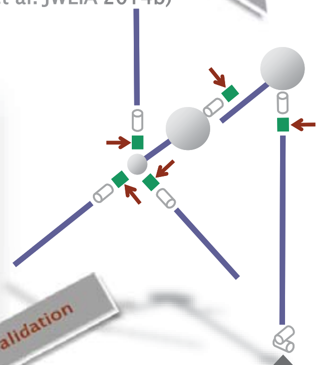


▲ Airfoil lift and drag identified from exp. rotor power and thrust (SVD ML estimator, Bottasso et al. JWEIA 2014a)



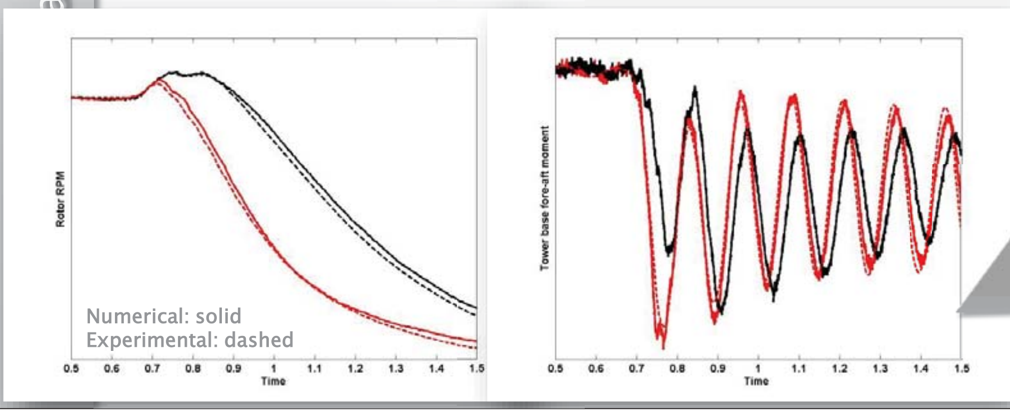
▲ Calibration at negative AOAs from exp. shutdown (Bottasso et al. JWEIA 2014b)

Lifting lines



Cp-Lambda multibody aeroservoelastic FEM

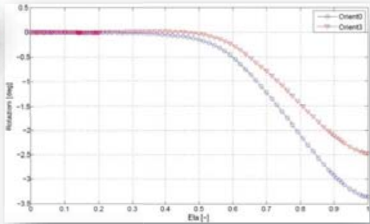
Validation



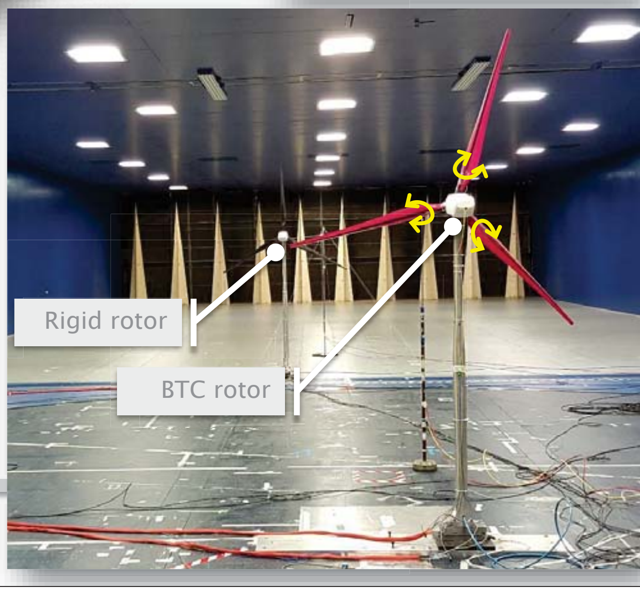
Selected Research Highlights

Active and Passive Load Alleviation in Waked Conditions

Aeroelastically-scaled **bend-twist coupled** blade:



Partial waked condition ▸



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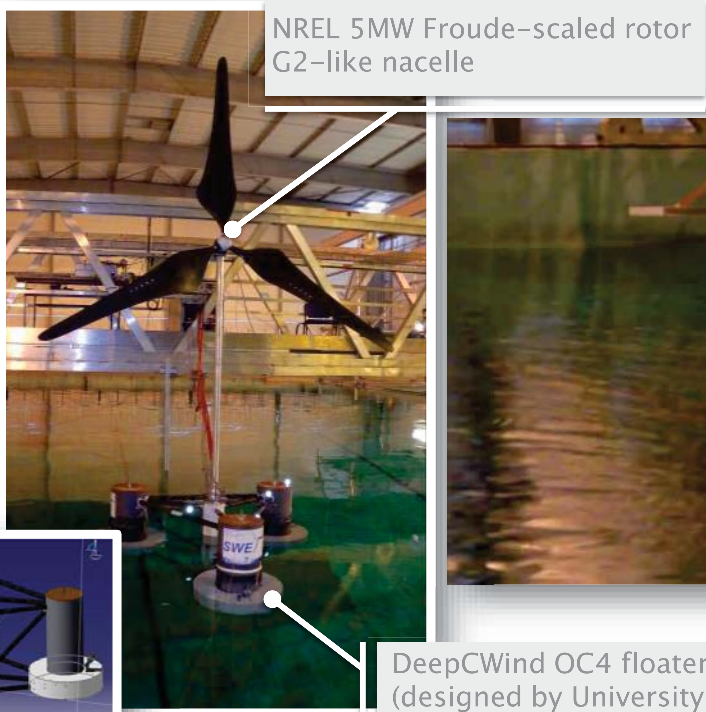
ed Research Highlights

Floating Offshore Wind Turbine Testing in a Wave-Wind Tank

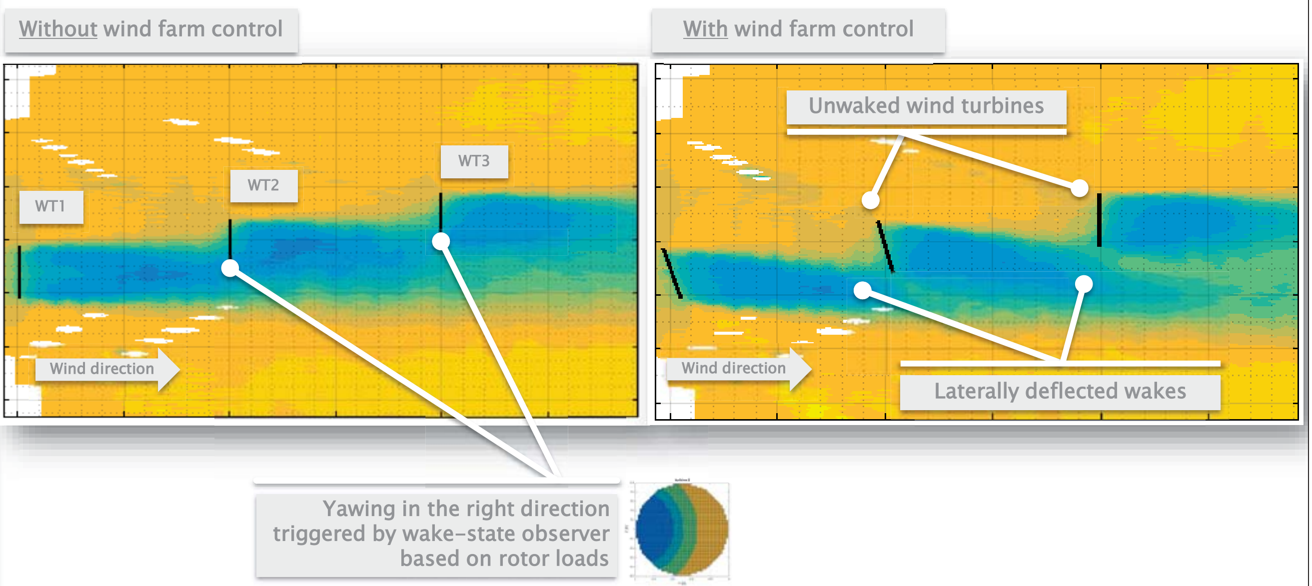
- Actively controlled model (individual pitch/torque)
- Tested at the wave-wind tank of the École Centrale de Nantes (France)



Energy Institute

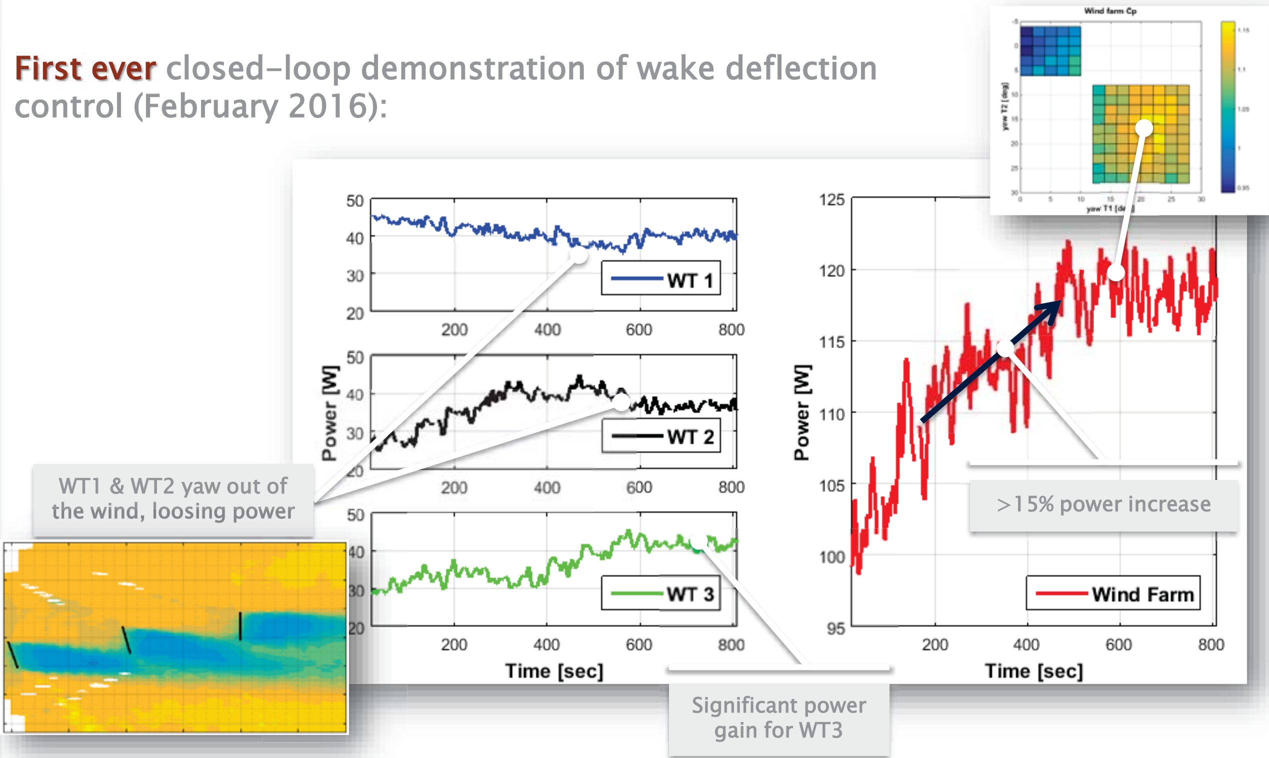
Wake Deflection Wind Farm Control

Wake visualization with DTU scanning LiDARs:



Wake Deflection Wind Farm Control

First ever closed-loop demonstration of wake deflection control (February 2016):

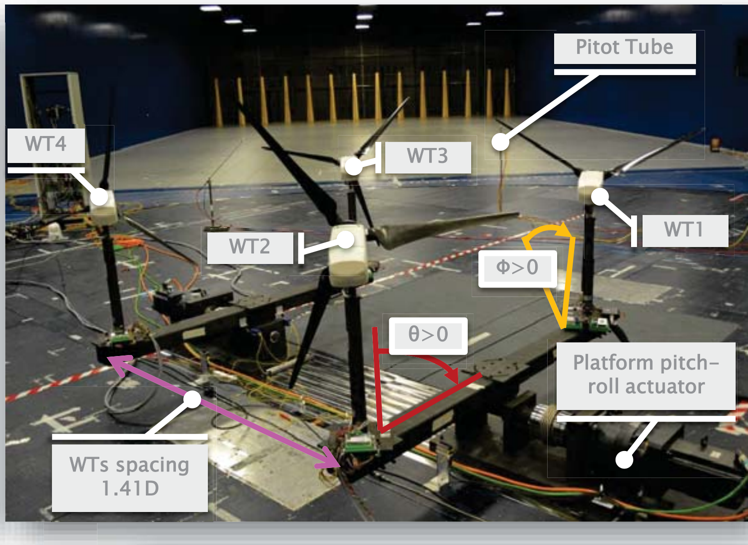


Control algorithm: closed-loop extremum seeking formulation

Selected Research Highlights

Wake Redirection of Floating Cluster

▲ WWHybrid floating platform concept
KRISO – Korea Research Institute of Ships and Ocean Engineering



▼ Power effect by misalignment (θ=10 deg)

		WT1		WT2		WT3		WT4		WF	
	Φ^{WT1}	P	ΔP, %	P	ΔP, %	P	ΔP, %	P	Δ P, %	P	ΔP, %
$W_s = 4$ m/sec	0 deg	12.98	-	4.0	-	12.34	-	3.25	-	32.56	-
	15 deg	11.67	-10.1	6.49	63.1	12.98	5.2	3.34	2.8	34.49	5.9
	25 deg	9.92	-23.6	8.82	121.6	12.87	4.3	3.26	0.2	34.87	7.1
$W_s = 5$ m/sec	0 deg	23.28	-	11.12	-	23.28	-	8.79	-	66.45	-
	15 deg	22.78	-2.2	13.54	21.8	23.28	0.	9.58	9.0	69.18	4.1
	25 deg	20.5	-12.0	17.38	56.3	23.24	-0.1	8.56	-2.6	69.68	4.8

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Selected Highlights in Operation and Maintenance

Online Safe-Envelope Monitoring & Protection

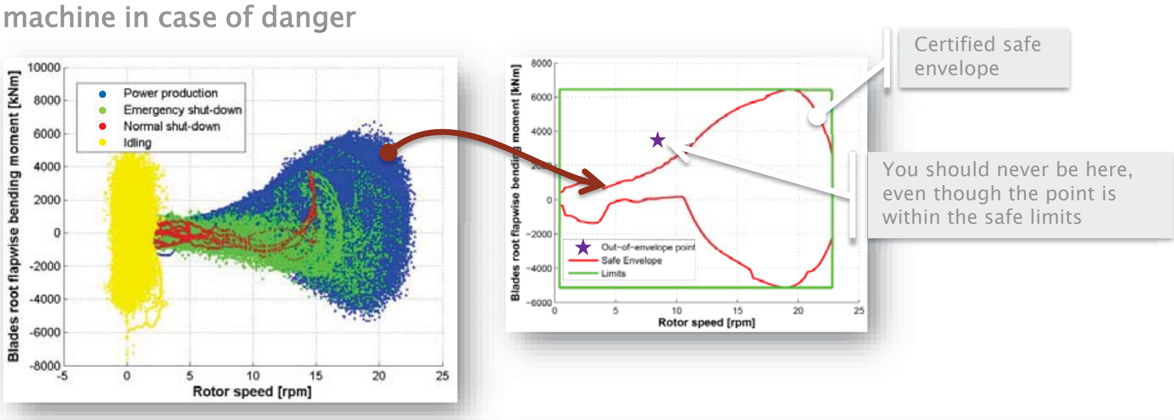
Motivation: avoid leaving the safe operational envelope

Goal: extend lifetime, condition monitoring

Envelope monitoring against unforeseeable events

Motivation: difficult to model/predict problems (e.g., software bugs, rare multiple faults) may affect the behavior in unforeseeable ways

Methodology: pre-compute certified safe state-space, predict crossing of boundary, shut down machine in case of danger

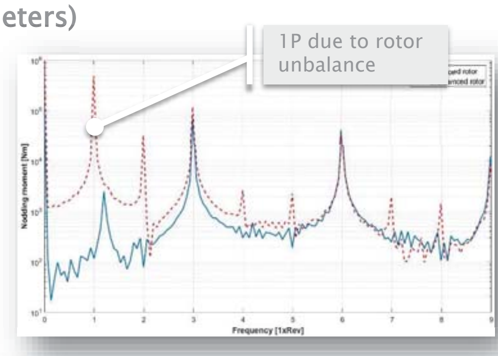


Automatic Rotor Rebalancing

Motivation: unbalanced rotors lead to vibrations and reduced lifetime

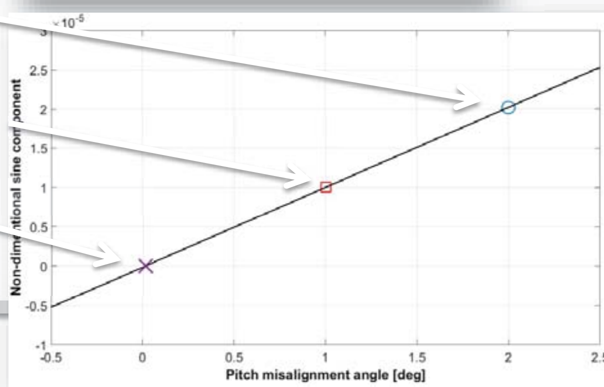
Goal: automatically rebalance a rotor, without stopping the wind turbine and without complex equipment (need only nacelle accelerometers)

Methodology: detect 1P harmonic & assume linearity pitch offset – 1P amplitude



Procedure:

1. Detect 1P harmonic in nacelle acceleration
2. Detected misaligned blade(s) based on phase
3. Pitch misaligned blade (second measurement)
4. Identify pitch for zero unbalance
5. Pitch blade(s) to rebalance rotor



Best Paths
Transmission for sustainability

22 November 2017

DEMO 1

DEVELOPMENT OF A DC FACILITY TO SIMULATE OFFSHORE MULTITERMINAL HVDC GRIDS AND THEIR INTERACTION WITH WIND GENERATORS

BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.

BestPaths Project

- Large energy project in FP7 (39 partners from 11 countries, 62 M€ budget)
- Objective is help to overcome the challenges of integrating renewable energies into Europe's energy mix. It aims to develop novel network technologies to increase the pan-European transmission network capacity and electricity system flexibility.
- The project unites expert partners around five large-scale demonstrations to validate the technical feasibility, costs, impacts and benefits of the tested grid technologies.
- SINTEF Energy hosting demo 1

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DEMO 1
HVDC links in offshore wind farms and offshore interconnections

The aim of this demonstration is to reduce the risks of HVDC links connecting offshore wind farms and to foster new suppliers and sub-suppliers of HVDC technology.

DEMO 2
HVDC-VSC Multivendor Interoperability

The goal of the demonstration is to outline the conditions to ensure maximum interoperability for HVDC-VSC converters connected to a DC system.

DEMO 3
Upgrading multi-terminal HVDC links using innovative components

The demonstration aims to design, develop and test new technological solutions allowing to upgrade multi-terminal HVDC links.

DEMO 4
Innovative Repowering of AC Corridors

Demo 4 objectives are addressed in three parallel sub-projects.

DEMO 5
Superconductor cables power up for DC grids

Prototype scale validation of the technical feasibility of integrating DC superconducting cable links within an AC meshed network.

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DEMO1 OBJECTIVES

1. To investigate the **electrical interactions** between **HVDC link converters and wind turbine converters in offshore wind farms**.
2. To **de-risk** the **multivendor and multiterminal schemes** in terms of resonances, power flow and control.
3. To **demonstrate** the **results in a laboratory environment** using **scaled models** (4-terminal DC grid with MMC VSC prototypes and a Real Time Digital Simulator system to emulate the AC grid).
4. To use the validated models to simulate a **real grid with offshore wind farms connected in HVDC**.

IBERDROLA — Demo leader Utility & RES operator knowledge	
Definition of models and simulation of scenarios CARDIFF UNIVERSITY / PRIFYSGOL CAERDYDD, University of Strathclyde Glasgow, RSE, SINTEF, tecnalia Inspiring Business	Knowledge on WTG & Power Electronics models Gamesa Electric
	System operation knowledge ENERGINET

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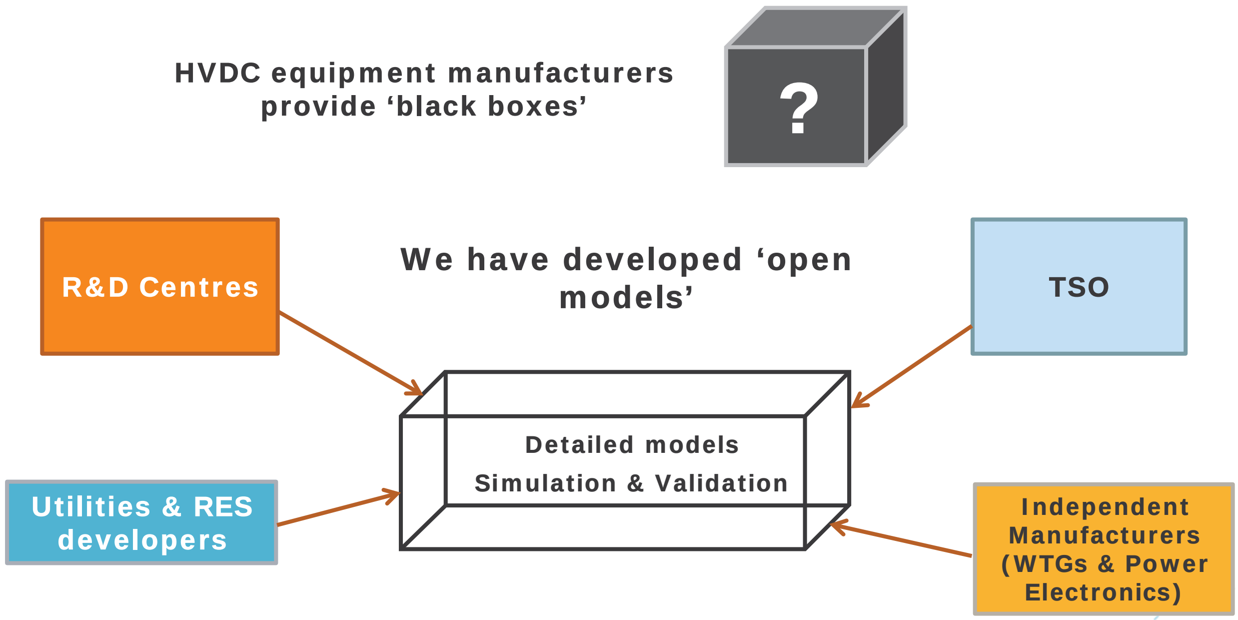
Introduction

Demo 1 Description



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The 'Open Access' Toolbox

- A **set of models and control algorithms** has been **developed, simulated and assessed**.
- Their portability as ***basic building blocks*** will enable researchers and designers to study and simulate any system configuration of their choice.
- These have been published in the **BEST PATHS website** as a **MATLAB/ Simulink '*Open Access' Toolbox:*** http://www.bestpaths-project.eu/.

BEST PATHS stands for "BE… Commission under the Sever… …nded by the European …greement no. 612748.

The 'Open Access' Toolbox

- The **user manual** comes with the published models and **accompanying examples**

- Specific blocks include models of:
  - High level controllers
  - Converter stations
  - AC grid
  - DC cables
  - Wind farm

The 'Open Access' Toolbox

➢ Converter Stations

- Averaged and switched models for a ***modular multilevel converter*** (MMC)
- The combined averaged-switched model consists of two blocks:
  - ***Power electronics block***,
  - ***Low level controller* block:** circulating current reference generation, circulating current controller, Nearest Level Control modulation strategy & sub-module voltage regulator.

➢ High Level Controller

- It allows converter operation in ***three control modes*** to cover the main control needs for different system configurations.
  - **Mode 0:** The converter sets the voltage and frequency.
  - **Mode 1:** DC voltage and reactive power are regulated. DC voltage *vs* active power droop is available.
  - **Mode 2:** Active and reactive power are regulated. Active power *vs* DC voltage droop is available.

➢ AC Grid

- AC network adapted from the classical ***nine-bus power system***.

The 'Open Access' Toolbox

- **DC Cable**
  - The ***DC cable section*** has been modelled as a one-phase, frequency-dependent, **travelling wave model**.
  - It is based on the ***universal line model*** (ULM), which takes into account the frequency dependence of parameters.
- **Wind Farm**
  - The aim of this model is to accurately represent the behaviour of an ***aggregated offshore wind farm*** (OWF).
  - To avoid large simulation times and undesirable computer burden, simplifications have been carried out in the electrical system:
    - The converter of the **wind turbine generator** (WTG) is modelled with ***averaged-model based voltage sources***.
    - A ***current source*** represents the remaining WTGs of the OWF. The **current injection** of the first WTG is properly **scaled** to complete the rated power of the whole OWF.
  - The detailed WTG contains
    - A ***permanent magnet synchronous generator*** model;
    - Averaged models of ***machine-side and grid-side converters***, including filters and the ***DC link***;
    - An LV/MV ***transformer*** and ***internal control algorithms***.

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Topologies under Examination

System configurations have been implemented in Simulink

- A number of ***topologies*** has been **modelled, simulated and analysed**.
- The topologies considered constitute ***likely scenarios*** to be adopted for the transmission of offshore wind energy in future years.
- The ***computer simulation*** of the system configurations will help to:
  - **Improve the knowledge** on the **integration of OWFs via HVDC links** or future **MTDC grids**;
  - **Identify possible interactions** between **wind turbines**, **converters**, **HVDC links** and/or **grids**, and the **onshore grid**;
  - **Reduce uncertainties** from OWFs connected to MTDC and **multi-vendor HVDC schemes**, and, consequently, **de-risk the use** of these technologies.

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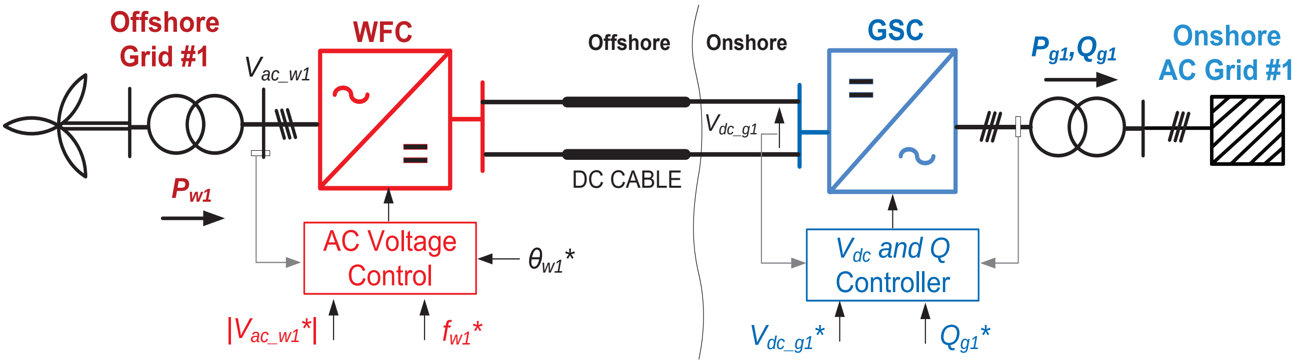
Topologies under Examination

Point-to-Point HVDC Link (Topology A)

- Easiest system configuration representing ***HVDC links*** under construction nowadays.
- Power generated by an OWF is transferred to an onshore AC grid.



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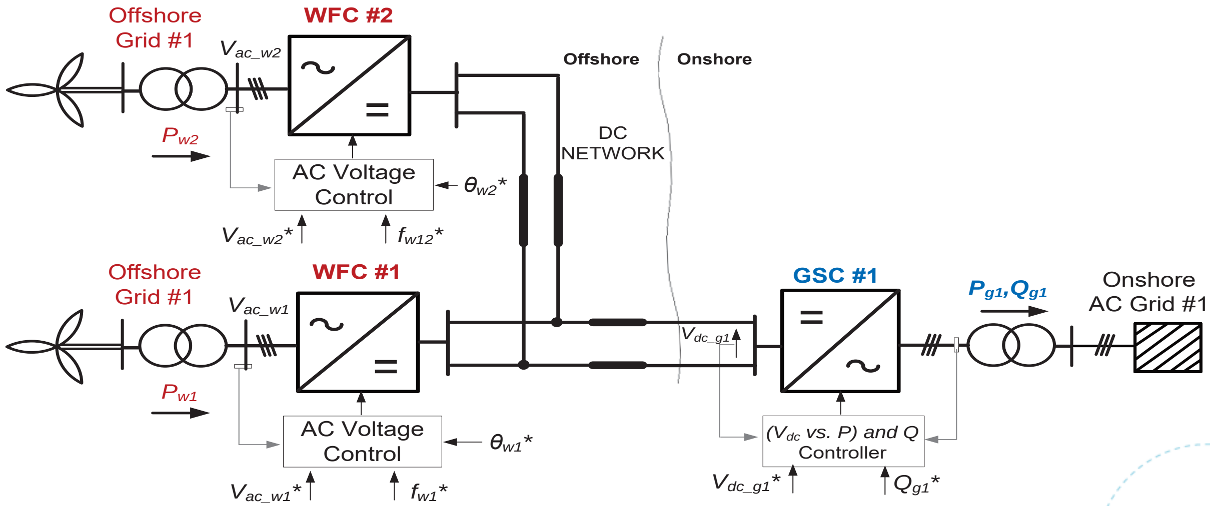
Topologies under Examination

Three-Terminal HVDC System

- Three-converter terminals are connected to form a MTDC grid.
- Power is transferred from the two HVDC-connected OWFs to an onshore AC grid.



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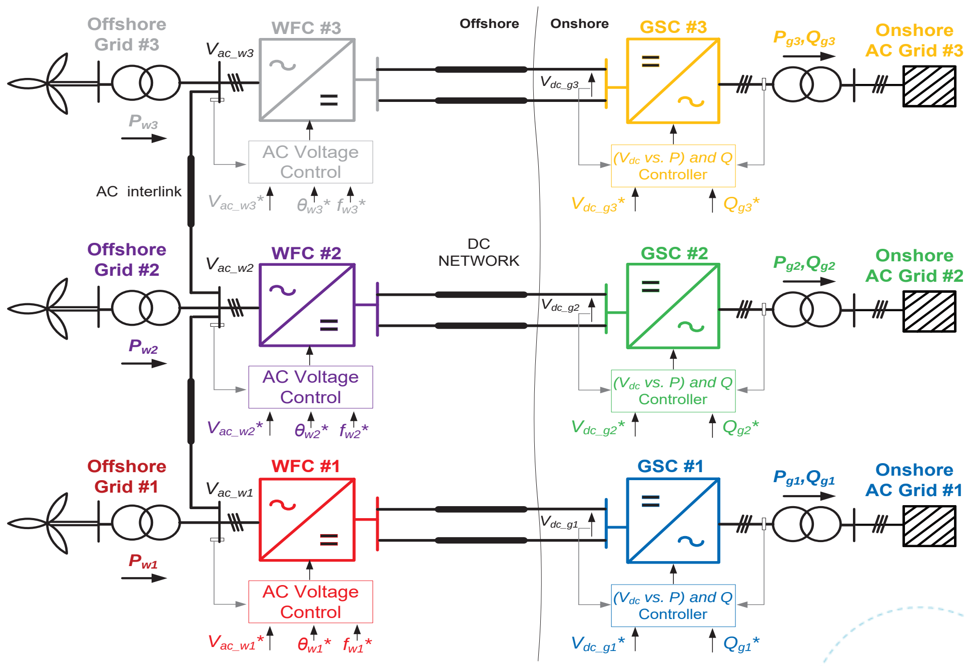
Topologies under Examination

Six-Terminal HVDC System with Offshore AC Links (Topology B)

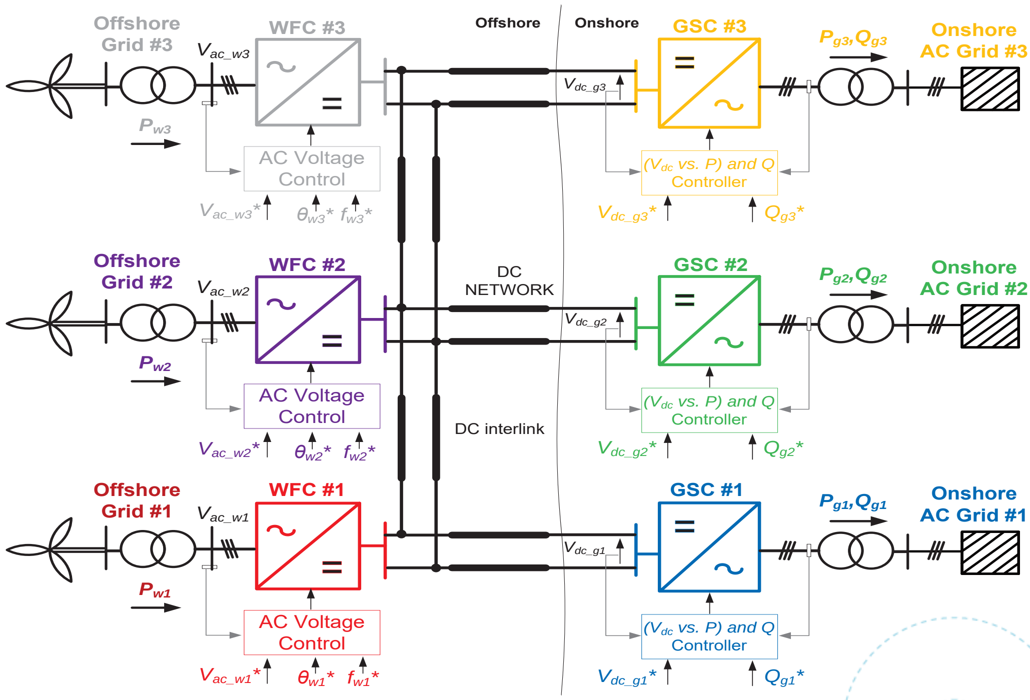
- Three offshore converter stations are connected to form an ***offshore AC grid***.
- OWFs are connected to this grid, with offshore converter stations being connected to onshore AC grids using ***point-to-point links***.
- The three onshore AC grids are not connected together.



Topologies under Examination

Six-Terminal HVDC System with Offshore DC Links (Topology C)

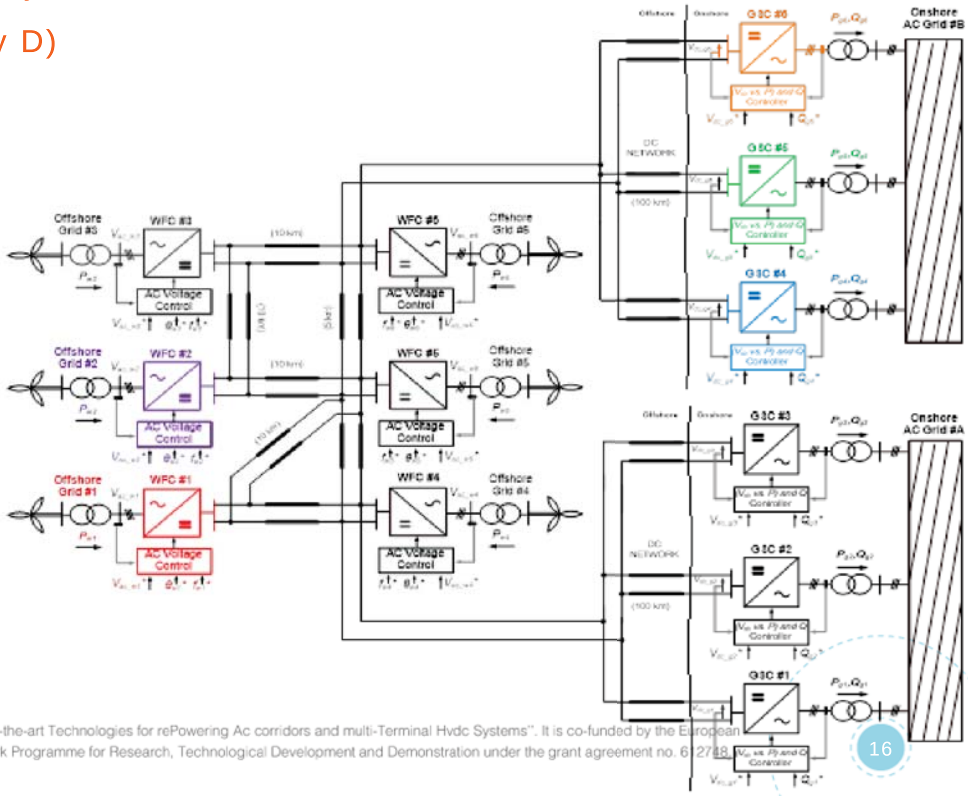
- Includes a ***six-terminal MTDC*** grid with two offshore DC links.
- Power generated by three OWFs is transferred to different onshore AC grids.
- The OWF converter stations are coupled at the DC side.



Topologies under Examination

Twelve-Terminal HVDC System with Offshore DC Links (Topology D)

- The DC sides of the converter stations are connected forming a ***meshed MTDC grid***.
- This topology concentrates most of the **technical challenges** that will be found in the development of MTDC meshed networks.



BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.

Introduction Demonstrator

- The converters developed were **installed in the Norwegian National Smart Grid Laboratory**, jointly operated by SINTEF Energy Research and the Norwegian University of Science and Technology
- **Commissioned in June 2017** with the help from experts form Energinet
- Detailed **description in deliverable 8.1** (available for download in the project website)
- Demoed for companies outside Best Paths in May during a special dissemination event
- The facility will be **available to any stakeholder** after the project ends

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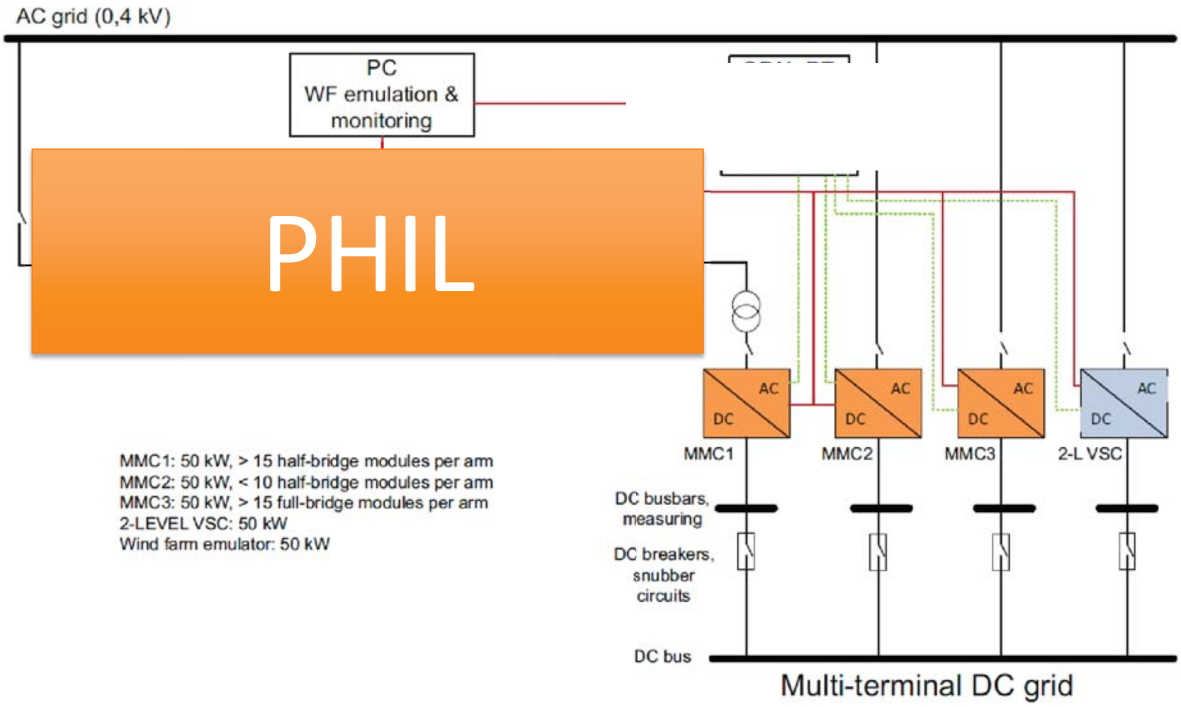
Original scheme as in the application



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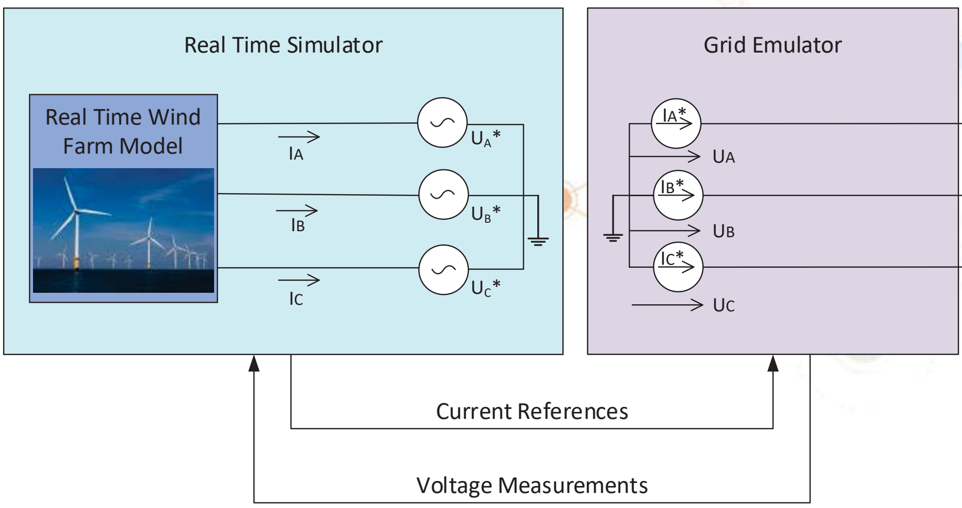
Wind Farm Emulator

Power Hardware in the Loop implementation combining the real time simulator and the grid emulator

- Flexibility in the model simulated
- Possibility to reproduce faster dynamics



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Scaling procedure

- The demonstrator system is scaled based on an existing reference system
- Scaling criteria for the laboratory model:
  - Trade-off between the cost and the performance: More levels improve waveform and reduce the arm inductance, but increase the cost
  - Voltage ratings of semiconductors: the more number of levels, the lower voltage rating of the semiconductor devices
  - Grid current ripple: the more number of modules, the smaller the current ripple

# of cells per arm	400 (Reference system)	18	12	6
DC Voltage	640 kV	700 V	700 V	700 V
Rated power	1059 MVA	60 kVA	60 kVA	60 kVA
Rated current	1836 A	83.2 A	83.2 A	83.2 A
Cell capacitance	10 mF(29 ms*)	21.3mF(28 ms*)	14.2 mF(28 ms*)	5.9 mF(24 ms*)
Arm inductance	50 mH	1.4 mH	1.4 mH	1.4 mH
TRX Inductance	60 mH (0.18 pu*)	1.7 mH(0.2 pu*)	1.7 mH(0.2 pu)	1.7 mH(0.2 pu)

Table: Cell capacitances and arm inductances for ref. model and lab. model

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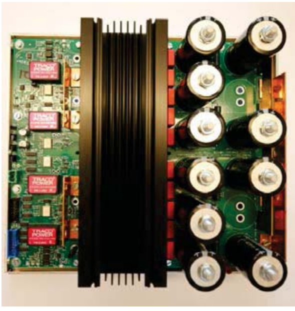
Hardware Overview

- Three **MMC converters were designed from scratch** for Best Paths
  - MMC with HB cells, 18 cells per arm
  - MMC with FB cells, 12 cells per arm
  - MMC with HB cells, 6 cells per arm
- During this year all the **converter components have been built and successfully tested** at full rating
  - 42 modules
  - 144 power cell boards
  - 1764 capacitors



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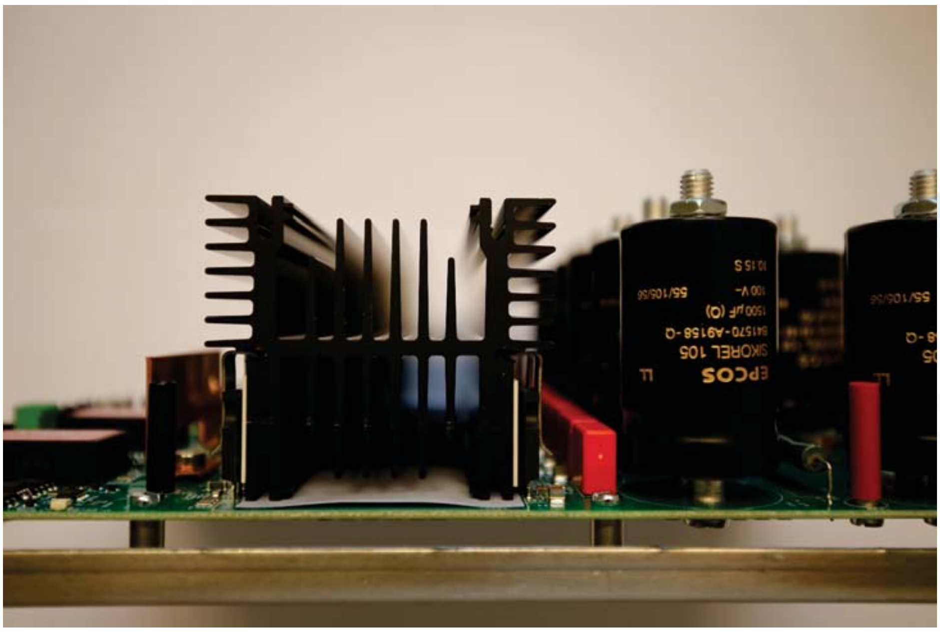

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MMC Architecture Overview

Central control level (1 for 3 MMCs)

- OPAL-RT based
- Control of circulating currents and grid currents, reference generation for modulation, Grid synchronization etc.

Arm control level (6 per MMC)

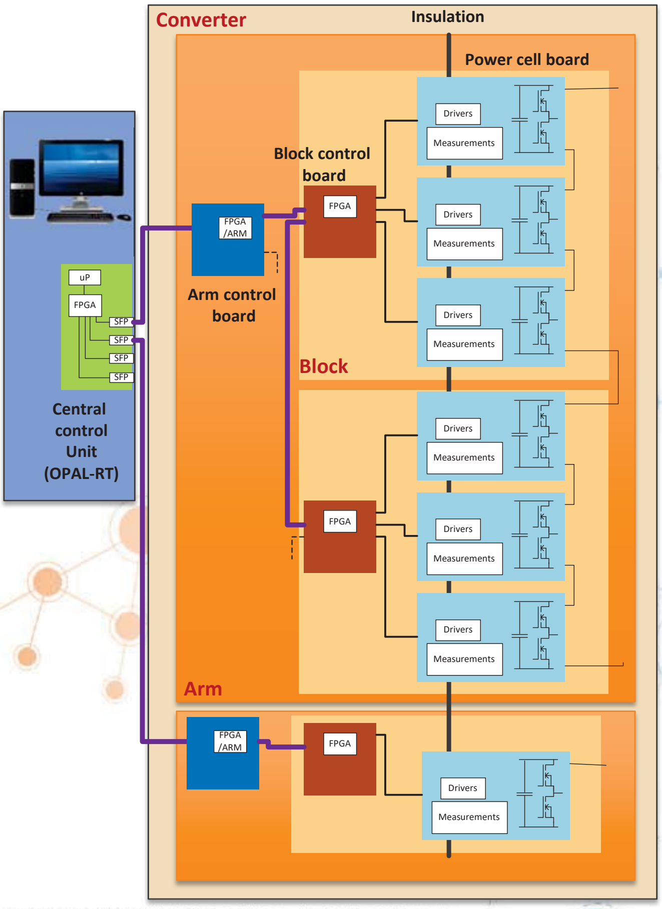
- Control functions as sorting and balancing, signal distribution
- Separate custom control board - FPGA based

Block/Rack control level

- Measurement and status inputs, gate control signal generation.
- Separate FPGA based control board

Power module board

- Includes capacitors and MOSFETS
- Measurement, switching, low level protection



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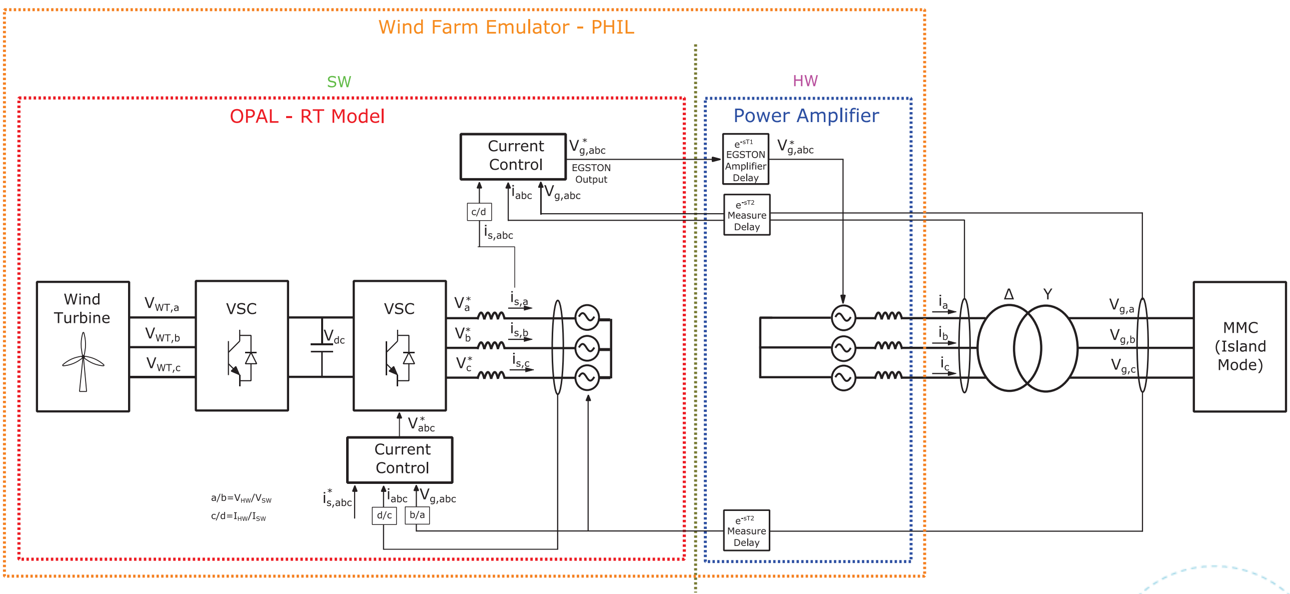
P-HIL emulation of an agregated wind farm model

- Objective: The wind farm operation is emulated using a controlled power amplifier following a Power HIL (P-HIL) approach



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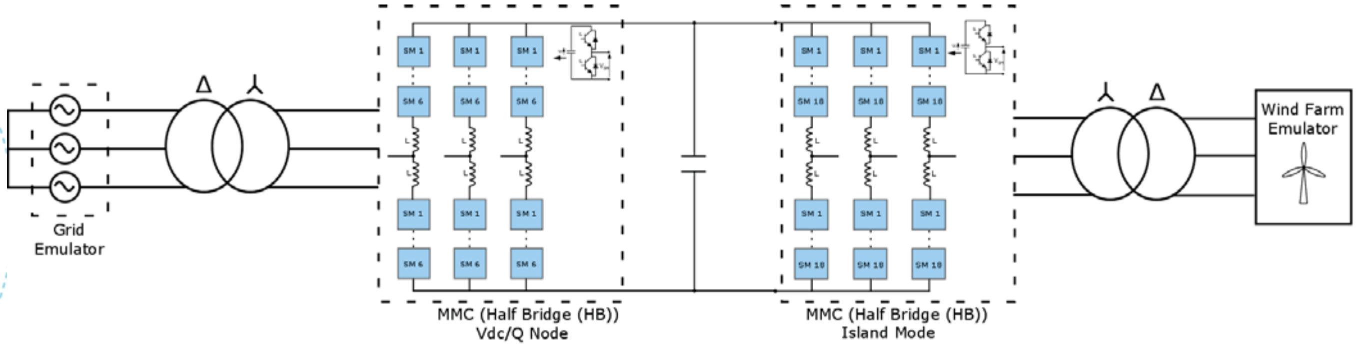
Two-terminal link



<u>Objective</u>:

Evaluate the operation of the point-to-point link when the WF power varies.

<u>Procedure</u>

- Change active power of the WF from 0 to 1 p.u. with ramp rate limitation 10 p.u./s

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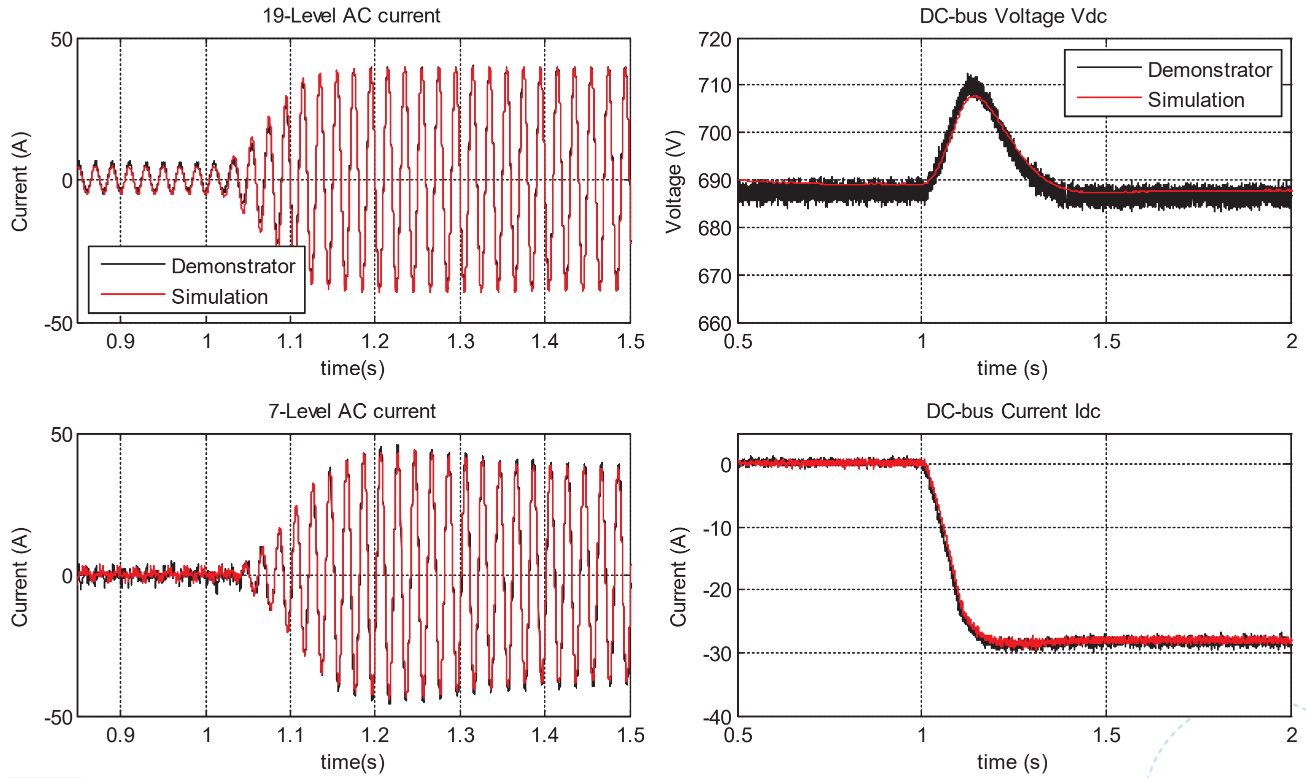
Two-terminal link -Results



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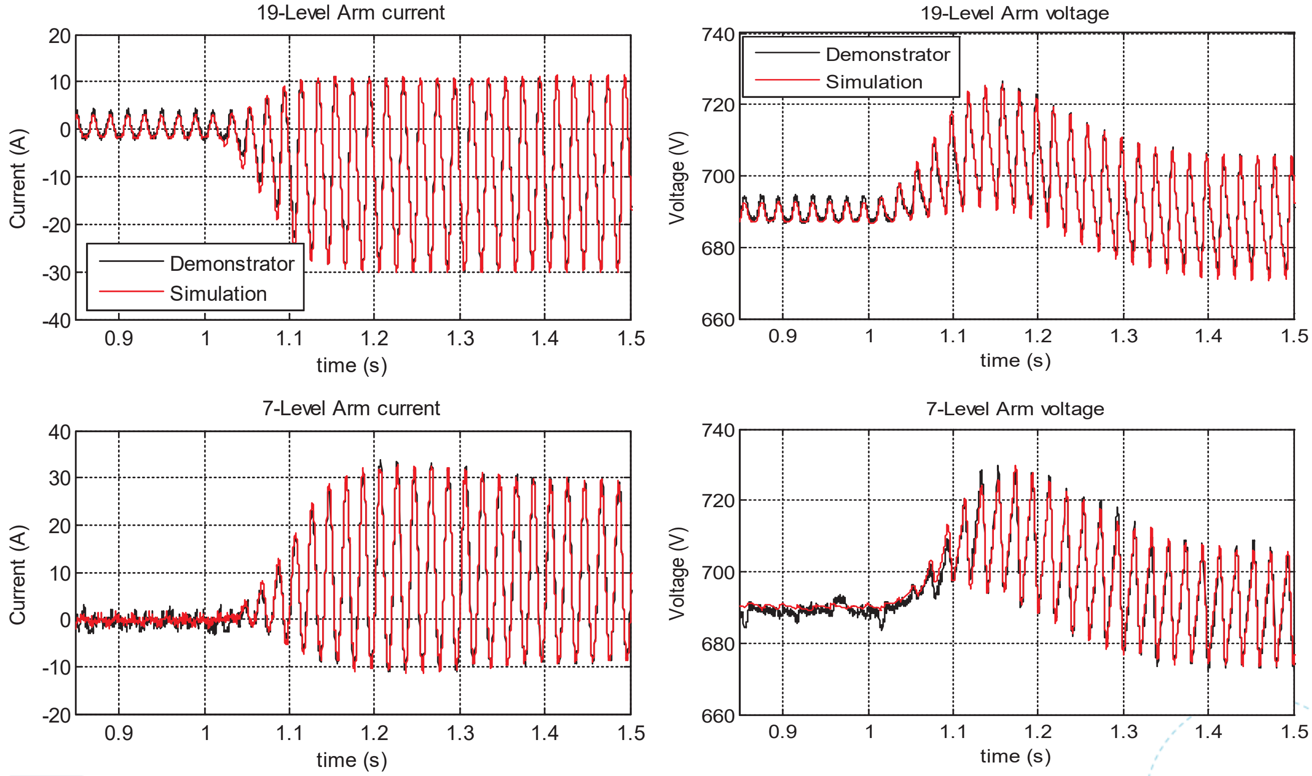
Two-terminal link -Results



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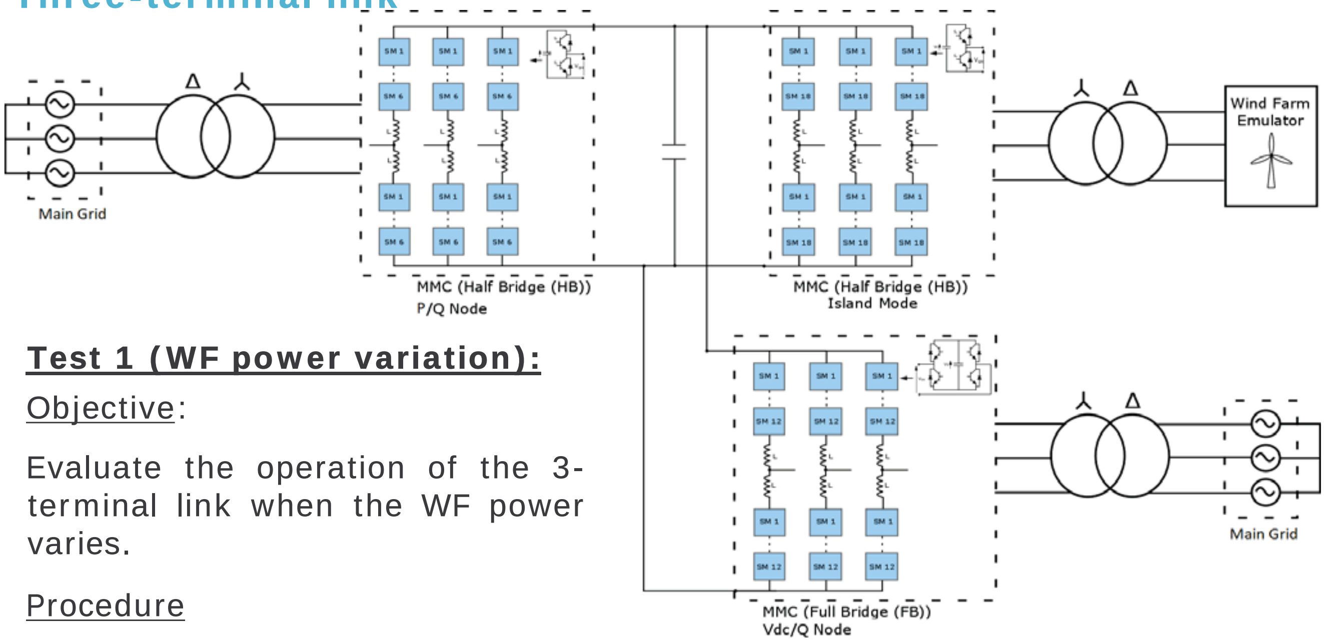
Three-terminal link



<u>Test 1 (WF power variation):</u>

<u>Objective</u>:

Evaluate the operation of the 3-terminal link when the WF power varies.

<u>Procedure</u>

- Set the power of the PQ node to -0.5 p.u (injecting power into the grid).
- Change active power of the WF from 0 to 1 p.u. with ramp rate limitation 10 p.u./s

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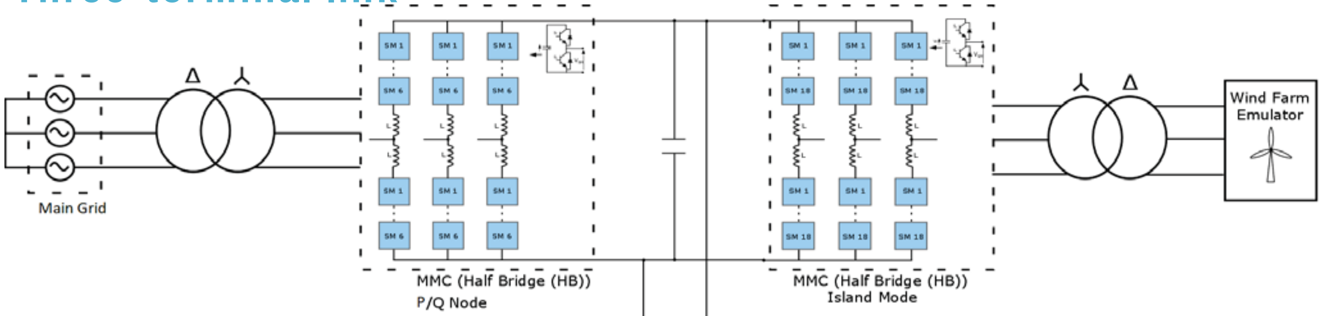
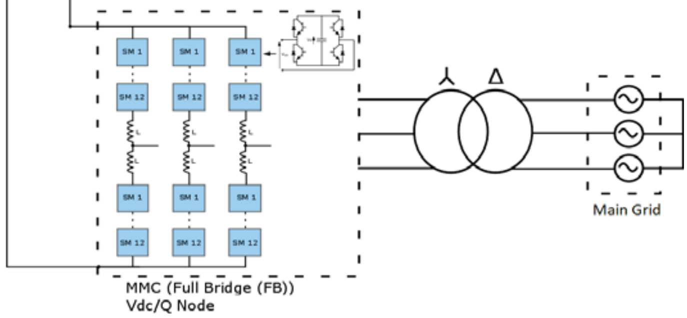
Three-terminal link





Test 2 (Reallocation of power between grid-connected converters:

Objective:

Evaluate the operation of the 3-terminal link when the power flow of the PQ node is reversed.

Procedure

- Set the power of the WF to 0.5 p.u.
- Change the active power of the PQ node from -0.5 to 0.5 p.u. with ramp rate limitation 10 p.u./s

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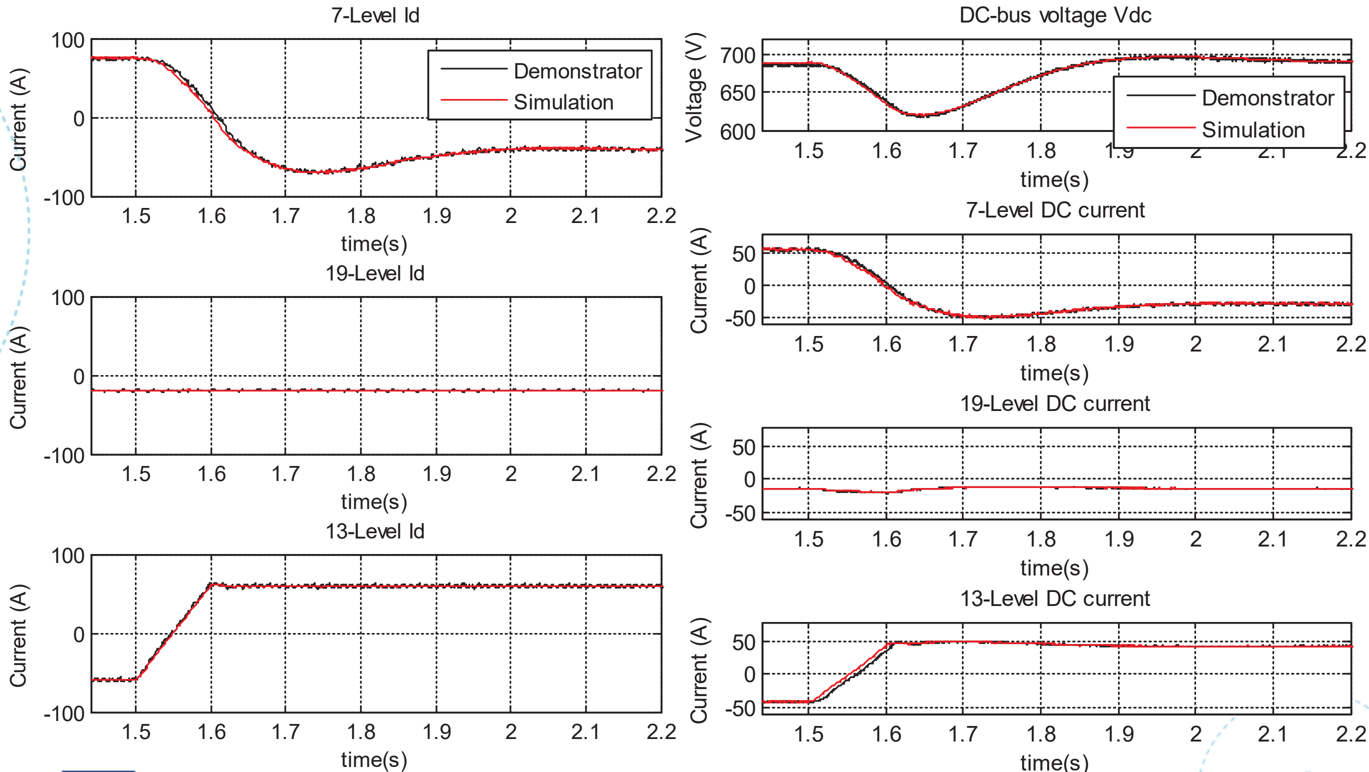
Three-terminal link –Results Test 2



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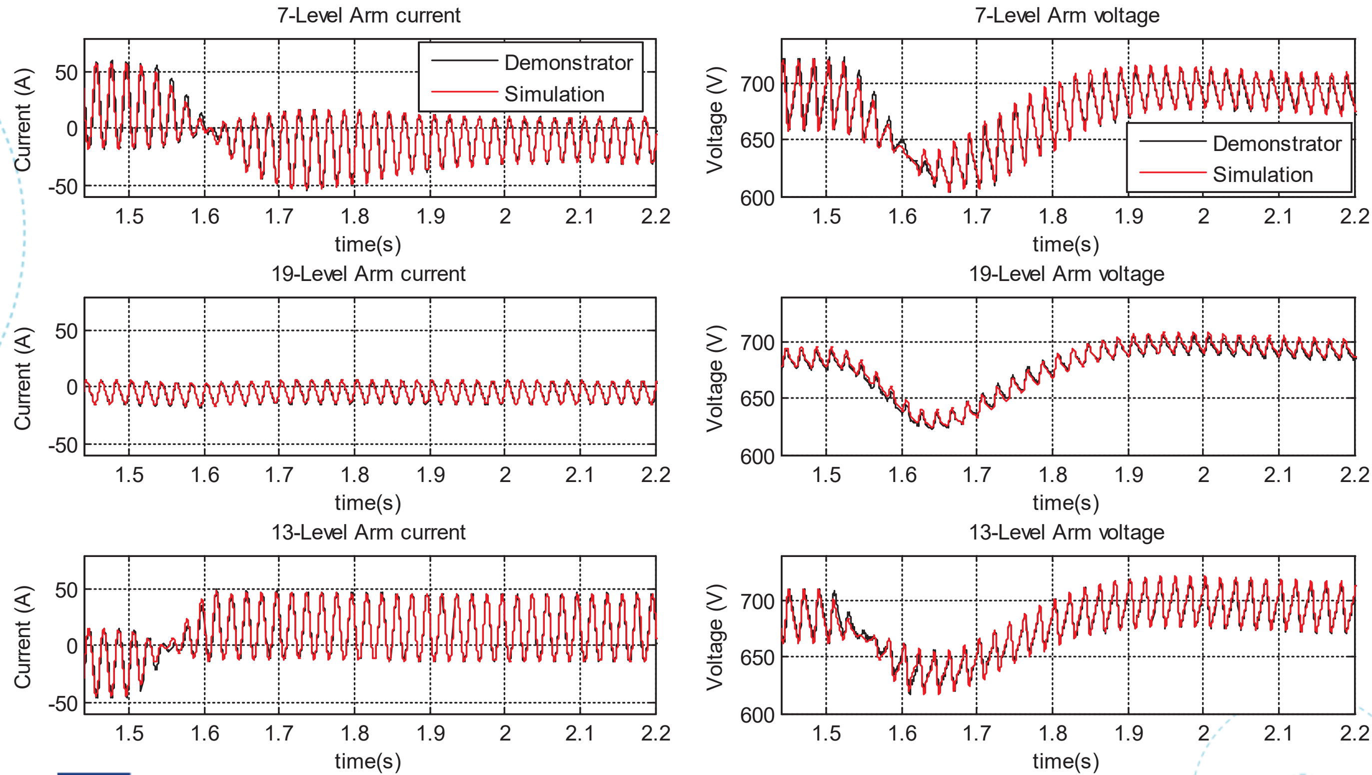
Three-terminal link –Results Test 2



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KPI Evaluation

- Comparison between experimental and simution results when there is a step change in the current reference.

- KPI assesment for the steady state values based on the Mean Absolute Error (MAE)

$$MAE = \frac{\frac{1}{N}\sum_{i=a}^{a+N}|x_i - y_i|}{I_{nom}} * 100$$

				Target value	Measured (max. diff.)
KPI.D1.7	Demonstrator performance at converter unit level	KPI.D1.7.1	Steady state performance (single unit)	Difference <15%	0.15%/0.05%
		KPI.D1.7.2	Rise time for steo in current reference (single unit)	Difference <15%	0.9%
		KPI.D1.7.3	Overshoot for step in current reference (single unit)	Difference <15%	0.49%/0.16%
		KPI.D1.7.4	Settling time for step in current reference (single unit)	Difference <15%	1.9%
KPI.D1.8	Demonstrator performance at system level	KPI.D1.8.1	Steady state performance (system level)	Difference <15%	1.23%/0.7%
		KPI.D1.8.2	Rise time for steo in current reference (system level)	Difference <15%	7.2%
		KPI.D1.8.3	Overshoot for step in current reference (System level)	Difference <15%	1.47%/0.76%
		KPI.D1.8.4	Settling time for step in current reference (System level)	Difference <15%	<0.05% negligible

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Lessons learnt

➢ **It is important to tune the models to have a good matching between experimental and simulation results.**

- **Cons:**
    - It takes a long time.
- **Pros:**
    - The assumptions and simplifications made to develop the models are validated.
    - Since the matching is good simulation studies carried out with the models are trustworthy.
        - Therefore, critical working conditions can be analysed safely by means of simulations before making experimental tests.
        - The models can be used to study simulation scenarios too complex to be implemented experimentally.
        - The models are a reliable tool to develop and validate new control techniques and tuning of controllers.
    - It helps to detect and fix mistakes in the model

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5. Conclusions

As evident from all the presentations, SP5 and SP6 sub-programme participants are engaged in a wide range of research activities related to grid integration of offshore wind plants. Updates on the status of various European and national projects were presented and discussed during the session and afterwards.

Based on the current status and available funding opportunities, potential new collaborative efforts such as joint publications and project proposals were discussed. Concrete actions were agreed to follow-up on two potential EU calls – the *EU mobility programme* and the call on *Research on advanced tools and technological development* (LC-SC3-ES-6-2019).

The next physical meeting place for SP members will be the EERA JP WIND Annual Event in Amsterdam 17-18 September 2018, where SP5 and SP6 activities will be presented in different sessions.

In summary, this joint workshop was successful in bringing together leading scientists within the fields of joint interest for SP5 and SP6, improving personal relationships, strengthening the network and allowing fruitful discussions with agreed concrete actions.

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