Final report

1.1 Project details

Project title	IEA vind annex 25 - fase 3
Project identification (program abbrev. and file)	EUDP 64012-0135
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde
Project partners	-
CVR (central business register)	30060946
Date for submission	25.03.2015

1.2 Short description of project objective and results

The objective of Task 25 is to analyse and further develop the methodology to assess the impact of wind power on power systems. The Task has established an international forum for exchange of knowledge and experiences related to power system operation with large amounts of wind power and has actively followed parallel activities with Transmission System Operators other R&D Task work. The participants have collected and shared information on the experience gained and the studies made up to and during the task. The case studies have addressed different aspects of power system operation and design, mainly: balancing, grid impacts and capacity credit of wind power.

IEA Wind Task 25 started with producing a state-of-the-art report on the knowledge and results that have been gathered so far, published in the VTT Working Papers series in 2007. Summary reports of the two previous phases have also been published as VTT reports: 2009 (VTT Research Notes 2493) and 2013 (VTT Technology T75). Currently, the final summary report for the phase 3, 2012-2014 is under preparation and will include all the DTU results. In these reports, a summary of selected, recently finished studies was presented. The Task 25 has developed guidelines on the recommended methodologies when estimating the system impacts and the costs of wind power integration, published in 2013 as RP16 of IEA Wind. All these reports are available in the Task 25 web site http://www.ieawind.org/task_25.html#

1.3 Executive summary

An R&D Task titled “Design and Operation of Power Systems with Large Amounts of Wind Power” was formed in 2006 within the “IEA Implementing Agreement on the Co-operation in the Research, Development and Deployment of Wind Turbine Systems” (www.ieawind.org) as Task 25. The aim of the R&D task is to collect and share information on the experience gained and the studies made on power system impacts of wind power, and review methodologies, tools and data used.

The objective of Task 25 is to analyse and further develop the methodology to assess the impact of wind power on power systems. The Task has established an international forum for ex-change of knowledge and experiences related to power system operation with large amounts of wind power and has actively followed parallel activities with Transmission System Operators other R&D Task work. The participants have collected and shared information on the experience gained and the studies made up to and during the task. The case studies have addressed different aspects of power system operation and design, mainly: balancing, grid impacts and capacity credit of wind power.

Since Task 25 was initiated in 2006 for a three years period, it has been extended twice, so at this stage, the work is in three phases:

- Phase 1 (2006 – 2008)
- Phase 2 (2009 – 2011)
- Phase 3 (2012 – 2014)

The characteristics of variability and uncertainty in wind power are presented from experience of measured data from large-scale wind power production and forecasting. This data is important as input to integration studies. There is a significant geographic smoothing effect in both variability and uncertainty of wind power when looking at power system wide areas.

The mean absolute error (MAE) for large-scale wind power production forecast errors is currently in the range of 3–6% of installed wind capacity when forecasting day-ahead (12–36 hours ahead.) and 1-3 % when forecasting hour ahead. The uncertainty of wind power production will be reduced as more accurate forecasting methods are developed and combined. Large shares of offshore wind power, on the other hand, will increase the forecast errors.

Because wind power output varies, it is now widely recognized that wind-induced reserves should be calculated dynamically: if allocation is estimated once per day for the next day instead of using the same reserve requirement for all days, the low-wind days will make less requirements on the system. Avoiding allocation of unnecessary reserve is cost effective and can be needed in higher penetration levels of wind power. The time steps chosen for dispatch and market operation can also influence the quantity and type of reserve required for balancing.

The variability and uncertainty of wind power will impact how the balance of the conventional power plant in a system is run. Changing the output level from the plants will incur costs due to additional ramping and starts/stops.

Grid reinforcement may be needed for handling larger power flows and maintaining stable voltage, and is commonly needed if new generation is installed in weak grids far from load centres. The issue is generally the same, be it modern wind power plants or any other power plants. The grid reinforcement needed for wind power is therefore very dependent on where the wind power plants are located relative to load and grid infrastructure, and one must expect results to vary from country to country.

Estimating the integration costs of wind power is challenging because capturing and allocating costs are not straightforward. The system services of transmission grid and real-time balancing are there for all users. While it is very difficult to calculate the costs of integrating wind, estimates indicate that these costs are manageable. When considering the question of integration costs, it is also important to keep in mind that all generation sources, including nuclear and fossil plants, have costs associated with integrating them in the grid and managing their individual characteristic operational capabilities to provide a stable and reliable electricity supply to meet varying load.

1.4 Project objectives

The objective of Task 25 is to analyse and further develop the methodology to assess the impact of wind power on power systems. The Task has established an international forum for exchange of knowledge and experiences related to power system operation with large amounts of wind power and has actively followed parallel activities with Transmission System Operators other R&D Task work. The participants have collected and shared information on the experience gained and the studies made up to and during the task. The case studies have addressed different aspects of power system operation and design, mainly: balancing, grid impacts and capacity credit of wind power.

The following countries and institutes have participated in phase 3 of Task 25:

Country	Organisation
Canada	Hydro Quebec
China	State Grid Energy Research Institute
Denmark	Technical University of Denmark – DTU Wind Energy Energinet.dk
Europe	EWEA European Wind Energy Association
Finland	VTT Technical Research Centre of Finland
Germany	Amprion Fraunhofer IWES
Ireland	Eirgrid SEI UCD ECAR
Italy	Terna
Japan	Tokyo University of Science Kansai University TEPCO
Norway	Statnett SINTEF
Netherlands	TenneT ECN TUDelft
Portugal	REN INESC-Porto LNEG IST
Spain	REE University Castilla La Mancha
Sweden	KTH
UK	Centre for Distributed Generation & Sustainable Electrical Energy
USA	NREL UWIG DOE

Meetings:

- Rome, Italy March 21-22 2012
  - o DTU contribution: Poul Sørensen, IEC 61400-27 STANDARD ON ELECTRICAL SIMULATION MODELS FOR WIND POWER GENERATION (annex 1)
- Tokyo, Japan 17-18 October, 2012
  - o DTU contribution: Nicolaos A. Cutululis, Offshore Wind Power Variability (annex 2)
- Helsinki, Finland May, 2013
  - o DTU contribution: Nicolaos A. Cutululis, EU TWENTIES project (annex 3)
- Beijing, China, October 2013
  - o DTU contribution: Nicolaos A. Cutululis, TWENTIES – Wind power variability results (annex 4)
- Golden, Colorado, April 2014
  - o DTU contribution: Nicolaos A. Cutululis, SIMBA Simulation of balancing in the Danish power system (annex 5)
- Munich, Germany, September 2014
  - o DTU contribution: Poul Sørensen, Ancillary services – Definitions, technical capabilities, value and drivers (annex 6)

1.5 Project results and dissemination of results

This section summarises recent findings on wind integration from studies made and real experience in integration from the 16 countries participating in the International Energy Agency (IEA) Wind collaboration research Task 25. Many wind integration studies already incorporate solar energy and most of the results discussed are also valid for other variable renewables besides wind power.

The national case studies address several impacts of wind on power systems. In this report they are grouped under balancing the power system on different short-term time scales; grid congestion, reinforcement, and stability as well as power adequacy (i.e., capacity value of wind). Experience of integration as well as enhancing technologies are also addressed in this report.

The characteristics of variability and uncertainty in wind power are presented from experience of measured data from large-scale wind power production and forecasting. This data is important as input to integration studies. There is a significant geographic smoothing effect in both variability and uncertainty of wind power when looking at power system wide areas. Failure to capture this smoothing effect will affect the estimates for wind impacts on power systems. The smoothing effect of variability can be seen in the measured extreme variations, that are smaller for larger size areas. Variability is also lower for shorter time scales. The smoothing effect can also be seen in that there is more time during the year with an average level of production (less peaks; less zero production time). There is more time when the variability is close to zero when looking at larger areas. The mean absolute error (MAE) for large-scale wind power production forecast errors is currently in the range of 3–6% of installed wind capacity when forecasting day-ahead (12–36 hours ahead.) and 1-3 % when forecasting hour ahead. The uncertainty of wind power production will be reduced as more accurate forecasting methods are developed and combined. Large shares of offshore wind power, on the other hand, will increase the forecast errors. Note that this increase is not observable when the forecast error is normalized by the mean production which is much higher for offshore locations.

The operating reserve requirement addresses short-term flexibility for power plants that can respond to load and generation unbalances. These are caused mainly by unpredicted variations. Also, any variability inside the time step for the dispatch interval, often in the range of 5–60 minutes, is managed with operating reserves. The reserves are operated according to total system net imbalances, for generation and demand, not for each individual source of imbalance. The computation of reserve requirements necessitates data for uncertainty and variability for demand, wind generation, and other generation as inputs. For wind power, the forecast horizon time scale is a crucial assumption because the uncertainty will reduce more significantly than demand at shorter time scales. There is a large range of results for estimates of increases in reserve requirements. This is mainly due to different time scales of uncertainty taken into account in different studies:

- If only hourly variability of wind is taken into account when estimating the increase in short-term reserve requirement, the results are 3% of installed wind capacity or less, with penetrations below 20% of gross demand.
- When 4-hour forecast errors of wind power are taken into account, an increase in short-term reserve requirement of up to 9–10% of installed wind capacity has been reported for penetration levels of 7–20% of gross demand.

Increasing reserve requirement is usually calculated for the worst case. However, this does not necessarily mean new investments for reserve capacity – rather, generators that were formerly used to provide energy could now be used to provide reserves. The experience so far is that wind power has not caused investments for new reserve capacity. However, some new pumped hydro schemes are planned in the Iberian peninsula to manage more than 20% wind penetration levels in the future.

Because wind power output varies, it is now widely recognized that wind-induced reserves should be calculated dynamically: if allocation is estimated once per day for the next day instead of using the same reserve requirement for all days, the low-wind days will make less requirements on the system. Avoiding allocation of unnecessary reserve is cost effective and can be needed in higher penetration levels of wind power. The time steps chosen for dispatch and market operation can also influence the quantity and type of reserve required for balancing. For example, markets that operate at 5 minute time steps, can automatically extract balancing capability from the generators that will ramp to fulfil their schedule for the next 5-minute period.

The variability and uncertainty of wind power will impact how the balance of the conventional power plant in a system is run. Changing the output level from the plants will incur costs due to additional ramping and starts/stops. To study the impact of wind on operation of power systems, simulation model runs that optimise the dispatch of all power plants to meet varying load are made. Most results on balancing costs are based on comparing costs of system operation without wind and adding different amounts of wind. It is challenging to extract system balancing costs from the total operational costs, including fuel costs. Any alternative to wind would also influence fuel costs. At wind penetrations of up to 20% of gross demand (energy), system operating cost increases, arising from wind variability and uncertainty amounting to approximately 1–4.5 €/MWh. This is 10% or less of the wholesale value of the wind energy. In addition to estimates, there is some experience with actual balancing costs for the existing wind power from electricity markets: 1.3–1.5 €/MWh for 16% wind penetration (Spain), and 1.4–2.6 €/MWh for 24% wind penetration (West Denmark). When estimating balancing costs, a general conclusion is that if interconnection capacity is allowed to be used for balancing purposes, then the balancing costs are lower compared to the case where they are not allowed to be used. Other important factors that were identified as reducing integration costs were: aggregating wind plant output over large geographical regions, and scheduling the power system operation closer to the delivery hour.

Grid reinforcement may be needed for handling larger power flows and maintaining stable voltage, and is commonly needed if new generation is installed in weak grids far from load centres. The issue is generally the same, be it modern wind power plants or any other power plants. The grid reinforcement needed for wind power is therefore very dependent on where the wind power plants are located relative to load and grid infrastructure, and one must expect results to vary from country to country. Grid studies involve a more detailed simulation of power flows in the transmission grid, to confirm the steady-state adequacy and utilization of the transmission system and to assess if the grid is sufficiently strong to cope with added wind power plants also during significant failures. Dynamic system stability analyses are usually not performed at lower penetration levels unless particular stability issues are foreseen in the system. Wind turbine capabilities are still evolving and may mitigate some potential impacts of wind power. There is a trend towards regional planning efforts around the world. The large offshore plans in Europe have launched new research on offshore grids. The allocation of grid investments to wind power is challenging, in a similar manner to balancing costs. System operators rarely make allocation of grid infrastructure because new infrastructure usually benefits all users. The investments are made for improving electricity market operation, to increase the security of the system and to bring about strategic transitions in the long-term sustainability of electricity supply. Even in cases where wind power would be the main reason for investing, after the grid is built, it is not possible to allocate the benefits to any single user.

Wind power's contribution to the system's power adequacy is its capacity value. Wind power has a capacity value in addition to its energy value. The recommended methodology for assessing the capacity value of wind power is Effective Load Carrying Capability (ELCC) based on loss of load expectancy calculations. The capacity value of wind will decrease as wind penetration increases. The results summarised in this report show a range from 40% of installed wind power capacity (in situations with low wind penetration and a high-capacity factor at times of peak load) to 5% in higher wind penetrations, or if regional wind power output profiles correlate negatively with the system load profile (i.e., low capacity factor at times of peak load). Aggregation benefits apply to capacity credit calculations – for larger geographical areas, the capacity credit will be higher.

There is already significant experience in integrating wind power in power systems. The mitigation of wind power impacts include more flexible operational methods, incentivising flexibility in other generating plants, increasing interconnection to neighbouring regions, and application of demand-side flexibility. Electricity storage is still not as cost effective in larger power systems as other means of flexibility, but is already seeing initial applications in places with limited transmission. Electricity markets, with cross-border trade of intra-day; balancing resources; and emerging ancillary services markets are seen as a positive development for future large penetration levels of wind power.

Estimating the integration costs of wind power is challenging because capturing and allocating costs are not straightforward. The system services of transmission grid and real-time balancing are there for all users. While it is very difficult to calculate the costs of integrating wind, estimates indicate that these costs are manageable. When considering the question of integration costs, it is also important to keep in mind that all generation sources, including nuclear and fossil plants, have costs associated with integrating them in the grid and managing their individual characteristic operational capabilities to provide a stable and reliable electricity supply to meet varying load.

In 2011 the group started working towards a first Recommended Practices for Wind Integration Studies, and this was continued in the 2012-14 period and launched in October, 2013. Summary reports and bibliography have been updated in both phases 2009-11 and 2012-14. New database of wind power generation time series was gathered by the participants having access to data that can be published in 2014, and work on fact sheets as an alternative dissemination method addressing other than wind integration specialists started in 2014. The collaborative journal articles have been addressing issues like variability, forecast errors, reserve requirement methodology, dynamic stability, transmission planning, unit commitment and economic dispatch, flexibility comparisons of power systems and curtailments:

- Wind Power Forecasting Error Distributions: An International Comparison
B.-M. Hodge (NREL, USA), H. Holttinen, S. Sillanpää (VTT, Finland), E. Gómez-Lázaro (University of Castilla-La Mancha, Spain), R. Scharff, L. Söder (KTH, Sweden), X. G. Larsén, G. Giebel (DTU Wind, Denmark), D. Flynn (University College Dublin, Ireland), D. Lew, M. Milligan (NREL, USA), J. Dobschinski (Fraunhofer IWES, Germany) WIW12-125

- Task 25 - Recommendations for Wind Integration Studies
H. Holttinen (VTT, Finland) M. O'Malley, J. Dillon, D. Flynn (University College Dublin, Ireland), M. Milligan (NREL, USA), L. Söder (KTH, Sweden), A.Orths, H.Abildgaard (Energinet.dk, Denmark), J. C. Smith (UVIG, USA), F. Van Hulle (EWEA, Belgium) WIW12-101

- Contribution of Energy Storage for Large-scale Integration of Variable Generation
A. Estanqueiro (LNEG, Portugal), A. Årdal (SINTEF, Norway), C. O'Dwyer, D. Flynn (University College Cublin, Ireland), D. Huertas-Hernando (SINTEF, Norway), D. Lew (NREL, USA), E. Gómez-Lázaro (University of Castilla-La Mancha, Spain), E. Carlini (Terna, Italy), E. Solvang (SINTEF, Norway), E. Ela (NREL, USA), J. Kiviluoma (VTT, Finland), L. Rodrigues (LNEG, Portugal), M. Amelin (KTH, Sweden) WIW12-177

- Ancillary Services for the European Grid with High Shares of Wind and Solar Power
F. Van Hulle (EWEA, Belgium), H. Holttinen, J. Kiviluoma (VTT, Finland) N. Cutululis (DTU, Denmark) WIW12-217

- Flexibility Chart - Evaluation on Diversity of Flexibility in Various Areas
Y. Yasuda (Kansai University, Japan), A. R. Årdal (SINTEF, Norway), E. M. Carlini (Terna, Italy), A. Estanqueiro (LNEG, Portugal), D. Flynn (University College Dublin, Ireland), E. Gómez-Lázaro (University Castilla-La Mancha, Spain), H. Holttinen, J. Kiviluoma (VTT, Finland), F. Van Hulle (XP WIND, Belgium), J. Kondoh (Tokyo University of Science, Japan), B. Lange (Fraunhofer IWES, Germany), N. Menemenlis (IREQ/Hydro-Québec, Canada), M. Milligan (NREL, USA), A. Orths (Energinet.dk, Denmark), C. Smith (UVIG, USA), L. Søder (Royal Institut of Technology/KTH, Sweden) (WIW13-1029)

- Wind and Solar Curtailment
D. Lew, L. Bird, M. Milligan, B. Speer, X. Wang (NREL, USA), E. Carlini (TERNA, Italy), A. Estanqueiro (LNEG, Portugal), D. Flynn (University College Dublin, Ireland), E. Gomez-Lazaro (University Castilla-La Mancha, Spain), H. Holttinen (VTT, Finland), N. Menemenlis (IREQ/Hydro-Québec, Canada), A. Orths (Energinet.dk, Denmark), C. Smith (UVIG, USA), L. Søder (Royal Institut of Technology/KTH, Sweden), P. Sørensen, A. Altiparmakis (DTU, Denmark), Y. Yasuda (Kansai University, Japan) (WIW13-1146)

- Wind Integration Cost and Cost-Causation
M. Milligan, B. Kirby (NREL, USA), H. Holttinen, J. Kiviluoma (VTT, Finland), A. Estanqueiro (LNEG, Portugal), S. Martín-Martínez, E. Gómez Lázaro (University Castilla-La Mancha, Spain), I. Pineda (EWEA, Belgium), J. C. Smith (UVIG, USA) (WIW13-1232)

- Analysis of Variability and Uncertainty in Wind Power Forecasting: An International Comparison
J. Zhang, B.-M. Hodge (NREL, USA), J. Miettinen, H. Holttinen (VTT, Finland), E. Gómez-Lázaro (University Castilla-La Mancha, Spain), N. Cutululis, M. Litong-Palima, P. Sørensen (DTU Wind Energy, Denmark), A. L. Lovholm, E. Berge (Kjeller Vindteknikk, Denmark), J. Dobschinski (Fraunhofer IWES, Germany) (WIW13-1115)

- Cost-effective Primary Frequency Response at High Asynchronous Generation Levels
J. Kiviluoma (VTT, Finland), F. van Hulle (XP Wind, Belgium), A. Gubina (University College Dublin, Ireland), N. Cutululis (DTU Wind Energy, Denmark) (WIW13-1101)

- Summary of Experiences and Studies for Wind Integration – IEA Wind Task 25
H. Holttinen (VTT, Finland), A. Robitaille (Hydro-Québec, Canada), A. Orths (Energinet.dk, Denmark), I. Pineda (EWEA, Belgium), B. Lange, (Fraunhofer IWES, Germany), E. Carlini (Terna, Italy), O'Malley, J. Dillon (University College Dublin, Ireland), J. O. Tande (SINTEF, Norway), A. Estanqueiro (LNEG, Portugal), E. Gómez-Lázaro (University of Castilla-La Mancha, Spain), L. Søder (Royal Institute of Technology KTH, Sweden), M. Milligan (NREL, USA), C. Smith (UVIG, USA) (WIW13-1106)

- An Objective Measure of Interconnection Usage for High Levels of Wind Integration
Y. Yasuda (Kansai University, Japan), A. Estanqueiro (LNEG, Portugal), N. Cutululis (DTU, Denmark), E. Gómez-Lázaro (University of Castilla-La Mancha, Spain), J. Kondoh (Tokyo University of Science, Japan), M. Milligan (NREL, USA), H. Holttinen (VTT, Finland), A. Orths (Energinet.dk, Denmark), J. C. Smith (UVIG, USA) (WIW14-1227)

- Estimating the Reduction of Generating System CO2 Emissions Resulting from Significant Wind Energy Penetration
H. Holttinen, J. Kiviluoma (VTT, Finland), J. McCann, M. Clancy (SEAI, Ireland), I. Pineda (EWEA, Belgium), M. Milligan (NREL, USA) (WIW14-1114)

- Economic Grid Support from Variable Renewables: REserviceS Project Summary
F. Van Hulle (XP Wind, Belgium), F. Chapalain (EDSO 4SG, Belgium), N. Cutululis (DTU, Denmark), H. Holttinen, J. Kiviluoma (VTT, Finland), L. M. Faiella (Fraunhofer IWES, Germany), I. Pineda (EWEA, Belgium), M. Rekinger (EPIA, Belgium) (WIW14-1127)

- Index for Wind Power Variability
J. Kiviluoma, H. Holttinen (VTT, Finland), R. Scharff (KTH Royal Institute of Technology, Sweden), D. E. Weir (Norwegian Water Resources and Energy Directorate, Norway), N. Cutululis, M. Litong-Palima (DTU Wind Energy, Denmark), M. Milligan (NREL, USA) (WIW14-1154)

Furthermore, as part of the cooperation in Task 25, DTU Wind Energy representatives have been invited to participate in a panel session presenting the recent advancements on wind power integration aspects in IEEE PES General Meeting 2015:

Panel Abstract *(max. 150 words)*
The integration of variable renewable energy resources (RES) – or “green generation” impacts the electricity system in various ways and its success depends on a number of different aspects. Many European and US power systems are currently subject to a transition process. Both, real life experience and simulation studies from several European countries will be presented, highlighting operational and planning aspects in the light of overall economic efficiency. Results from international collaborations are given as well: - a big European research project finalized investigations on the provision of ancillary services from RES and - a global IEA collaboration evaluates investigation methods to estimate changed power systems’ changed CO2 emission profiles. The challenge of how to efficiently provide system flexibility, system reliability related suitable market designs is compared and contrasted between the US and Europe.

Papers / Presentations *(author(s), topic)*
1. Ch. Klabunde, P. Lombardi, N. Moskalenko, P. Komarnicki, Z. Styczynski (OvGU, DE). **Optimal Onshore Wind Power Integration supported by Local Energy Storages**
2. S. Martín Martínez, A. Honrubia Escribano, M. Cañas Carretón and E. Gómez Lázaro, (UCLM, ES) **Generation Flexibility and Wind Power Curtailment Correlation: The Spanish Case**

3. Nicolaos A. Cutululis-DTU Wind (DK), Juha Kiviluoma, Hannele Holttinen-VTT (FI), Frans Van Hulle-XP Wind (BE), Luis Mariano Faiella-IWES (DE), Manöel Rekinger-EPIA (BE), Ivan Pineda-EWEA (BE):
Ancillary Services from Wind and Solar PV: Capabilities, Costs and Benefits

4. Damian Flynn (UCD, IE)
Planning High Wind Penetrated Systems considering System Dynamic Aspects - The Irish Case

5. Juha Kiviluoma, Hannele Holttinen (VTT, FI), Ivan Pineda (EWEA, BE), John Mc Cann, Matthew Clancy (SEAI, IR); Michael Milligan (NREL, USA); Antje Orths, Peter B. Eriksen (Energinet.dk, DK)
Reduction of CO_2 Emissions due to Wind Energy – Methods and Issues in Estimating Operational Emission Reductions

6. Vera Silva, Gregoire Prime, Miguel Lopez-Botet-Zulueta, Timothee Hinchliffe, Ye Wang, Marie Perrot, Dominique Daniel (EdF, FR)
Integration of Variable Renewable Generation in the European Power Systems - Technical and Economic Challenges

7. Charlie Smith (UVIG, US)
Integration of Variable Renewable Generation - Update on Evolutions of US and EU Market Designs

1.6 Utilization of project results

Several of the partners from Task 25 formed a consortium that successfully applied for and finalised the EU REserviceS project (www.reservices-project.eu), Economic grid support from variable renewables was the first study to investigate wind and solar based grid support services at EU level. It has provided technical and economic guidelines and recommendations for the design of a European market for ancillary services, as well as for future network codes within the Third Liberalisation Package.
The cooperation is expected to continue in Phase IV, with more joint research proposals and publications.

1.7 Project conclusion and perspective

The relevance of the activities in Task 25 was recognized and an extension was approved by the IEA WIND Executive Committee in 2014. Phase IV is covering the period 2015-2017. DTU has applied in the spring EUDP call for funding to support the Danish participation. The expected results are:

- Enhanced international collaboration and coordination in the field of wind and PV integration
- Set of case studies on wind and other variable generation integration, especially cases combining wind and PV, high-penetration cases, implications on market design and operation and evolved methodologies including assessment of costs and value of wind integration, uncertainty assessment and additional operational methods incorporated into planning models
- Database for large scale wind power production time series – from real data from hundreds or thousands of turbines in an area relevant for power system studies, to be enlarged to cover also PV, load and other relevant time series data available
- Benchmarking more simple methodology (FAST2 tool of IEA Paris) to give first estimates on the wind integration effort in new countries planning to start implementation of wind energy;

- Collaborative journal articles summarising and further analysing the work in national case studies
- A workshop targeted for TSO audience, and general short summaries of wind integration targeted for non-technical audience
- Updated library of wind integration case studies and bibliography of reports;
- Updated Recommended Practices report
- Updated summary describing the range of wind power impacts and costs for different power systems, including a list of system operation practices and technologies that mitigate and lower unfavourable impacts of wind power and support enhanced penetration of wind power.

Annex

Annex 1

IEC 61400-27 STANDARD ON ELECTRICAL SIMULATION MODELS FOR WIND POWER GENERATION

POUL SØRENSEN, DTU WIND ENERGY

CONVENER OF IEC 61400-27

IEC TC 88 (Technical Committee for wind power)

- 61400-1 Design requirements for wind turbines
- 61400-2 Safety for small wind turbines
- 61400-3 Design requirements for offshore wind turbines
- 61400-4 Wind turbine gearboxes
- 61400-5 Wind turbine rotor blades
- 61400-11 Acoustic niose measurement techniques
- 61400-12 Power performance
- 61400-13 Measurement of mechanical loads
- 61400-21 Measurement and assessment of power quality …
- 61400-22 Conformity testing and certification – rules and procedures
- 61400-23 Full scale structural testing of rotor blades
- 61400-24 Lightning protection of wind turbines
- 61400-25 Communication …
- 61400-26 Availability
- 61400-27 Electrical simulation models for wind power generation

IEC 61400-27 – purpose

Part 1 – wind turbines

- Definition of generic terms and parameters for wind turbine models
- Specification of dynamic simulation models:
  - Standard models for generic wind turbine topologies/ concepts / configurations on the market.
  - A method to create models for future wind turbine concepts.
- Specification of a method for validation of wind turbine simulation models

Part 2 – wind power plants

- Definition of generic terms and parameters for wind power plant models
- Specification a method to create models for wind power plants including wind turbines, auxcillary equipment and wind power plant controller.
- Specification of a method for validation of wind power plant simulation models

Potential users of the standard

- TSOs and DSOs are end users of the models, performing power system stability studies as part of the planning as well as the operation of the power systems,
- wind plant owners are typically responsible to provide the wind power plant models to TSO and/or DSO prior to plant commissioning,
- wind turbine manufacturers will typically provide the wind turbine models to the owner,
- developers of power system simulation software will use the standard to implement standard wind power models as part of the software library, and
- education and research communities, who can also benefit from the generic models, as the manufacturer specific models are typically confidential.

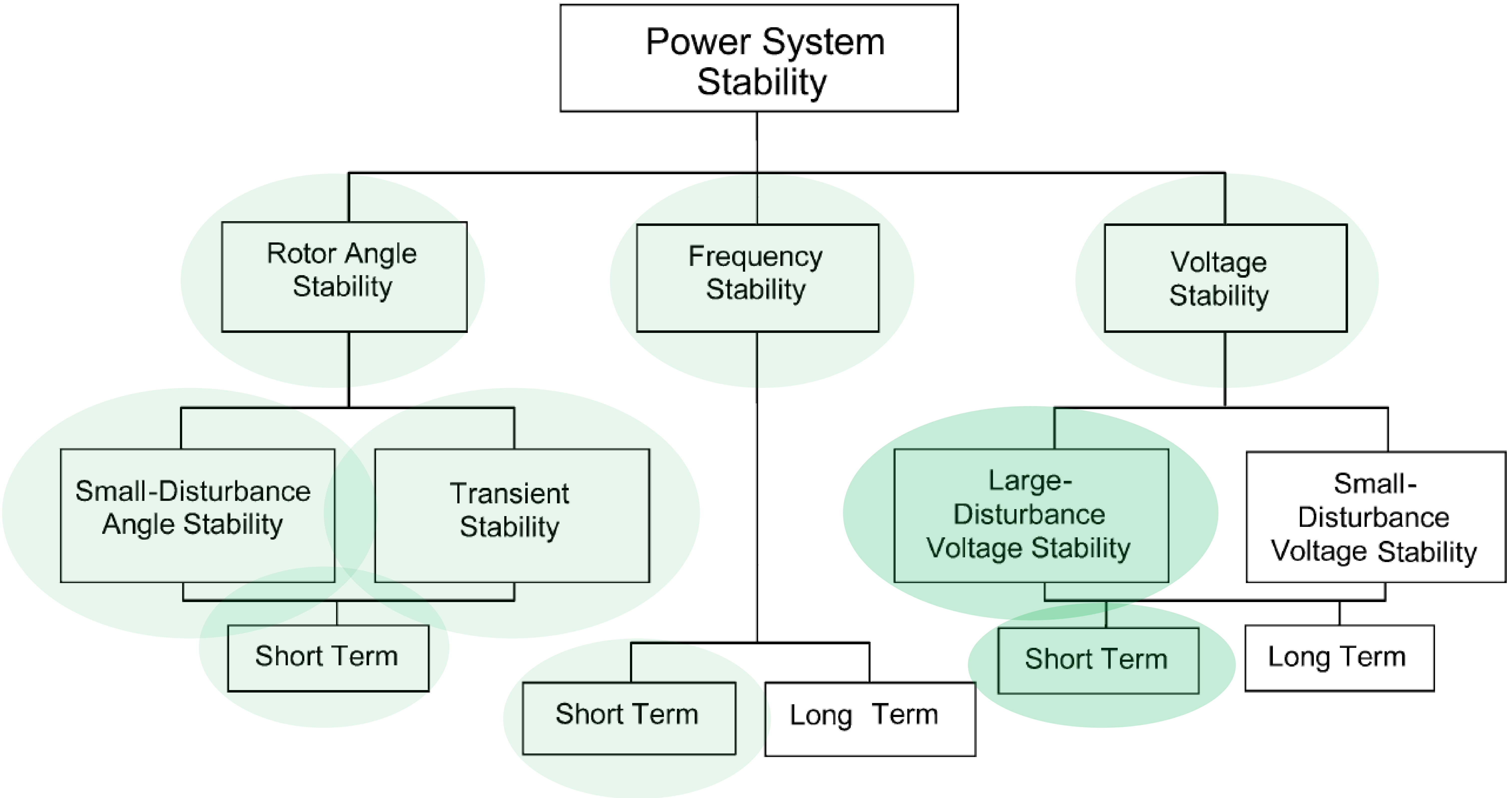
Members

Presently 43 experts, 16 countries

- Vladislav Akhmatov, Energinet.dk (DK)
- Björn Andresen, Siemens Wind Power (DK)
- Babak Badrzadeh, Vestas (DK)
- Graeme Bathurst, TNEI Services Ltd (GB)
- Herman Bayem, EDF R&D (FR)
- Yongning Chi, CEPRI (CN)
- Michael Ebnicher, Bachmann electronic GmbH (AT)
- Jarle Eek, STATKRAFT (NO)
- Abraham Ellis, Sandia National Laboratories (US)
- Jens Fortmann, REpower Systems AG (DE)
- Tobias Gehlhaar, Germanischer Lloyd I S GmbH (DE)
- Nikolaus Goldenbaum, Siemens Wind Power (DK)
- Emilio Gómez Lázaro, UCLM Research Institute (ES)
- Ralph Hendriks, SIEMENS PTI (NL)
- Eunhye Jang, KEMCO (KR)
- Francisco Jiménez Buendía, GAMESA (ES)
- Knud Johansen, Energinet.dk (DK)
- Yuriy Kazachkov, Siemens PTI (US)
- SeogJoo Kim, Korea Electrotechnology Research Institute (KERI) (KR)
- Hee-Sang Ko, Samsung Heavy Industries (KR)
- Soonman Kwon, Korea Electrotechnology Research Institute (KERI) (KR)
- Åke Larsson, Vattenfall (SE)
- Brian Malone, Eirgrid (IE)
- Jeferson Marques, Enercon (DE)
- Nicholas Miller, GE Energy (US)
- Alberto Molina Martín, ENERGY TO QUALITY S.L. (ES)
- Seungpil Moon, Korea Electric Power Company (KEPCO) (KR)
- Ana Morales, DIgSILENT Spain (ES)
- Eduard Muljadi, National Renewable Energy Laboratory (US)
- Jouko Niiranen, ABB (FI)
- Yasuyuki Oguro, Japan Electrical Manufacturers' Association (JP)
- Javier Pérez-Jacoiste, Gamesa (ES)
- Pouyan Pourbeik, Electric Power Research Institute (US)
- Javier Manuel Rodrigo, EDP Renovaveis (ES)
- Bernhard Schowe, FGH (DE)
- Seung-Ho Song, Kwangwoon University (KR)
- Poul Sørensen, Technical University of Denmark (DK)
- Salim Temtem, Eirgrid (IE)
- Larisa Vladimirovna Varigina, RusHydro (RU)
- Edwin Wiggelinkhuizen, ECN Wind Energy (NL)
- Mike Wöbbeking, Germanischer Lloyd I S GmbH (DE)
- Yoh Yasuda, Kansai University (JP)
- Robert M Zavadil, EnerNex (US)

Purpose of models

- IEC 61400-27 models are developed to represent wind power generation in studies of **large-disturbance short term voltage stability** phenomena, but they will also be **applicable** to study **other dynamic short term** phenomena:



Classification of power system stability according to IEEE/CIGRE Joint Task Force on Stability Terms and Definitions. (© IEEE 2004)

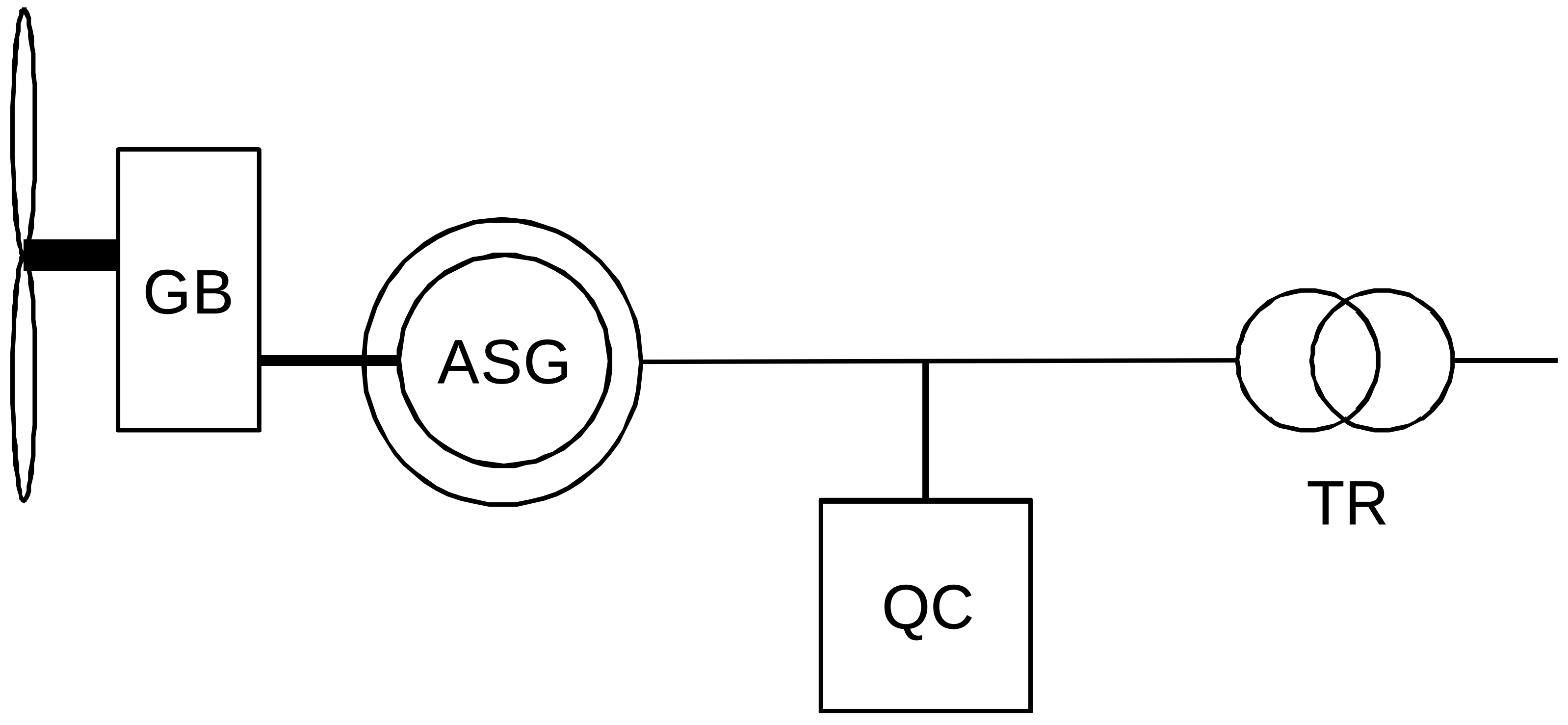
Model specifications 1 / 2

- The models are for fundamental frequency positive sequence response.
- The models span the existing categories (type 1-4) of currently developed wind turbine generator technologies
- The models are modular in nature to allow for the potential of augmentation in case of future technologies being developed, or future supplemental controls features.
- The models are to be used primarily for power system stability studies and thus should represent all dynamics affected and relevant during
  - short circuits (balanced and unbalanced) on the transmission grid (external to the wind power plant, including voltage recovery),
  - grid frequency disturbances,
  - electromechanical modes of synchronous generator rotor oscillations
  - reference value changes
- The models should be valid for typical power system frequency deviations (recommended +/- 6% from system nominal frequency)

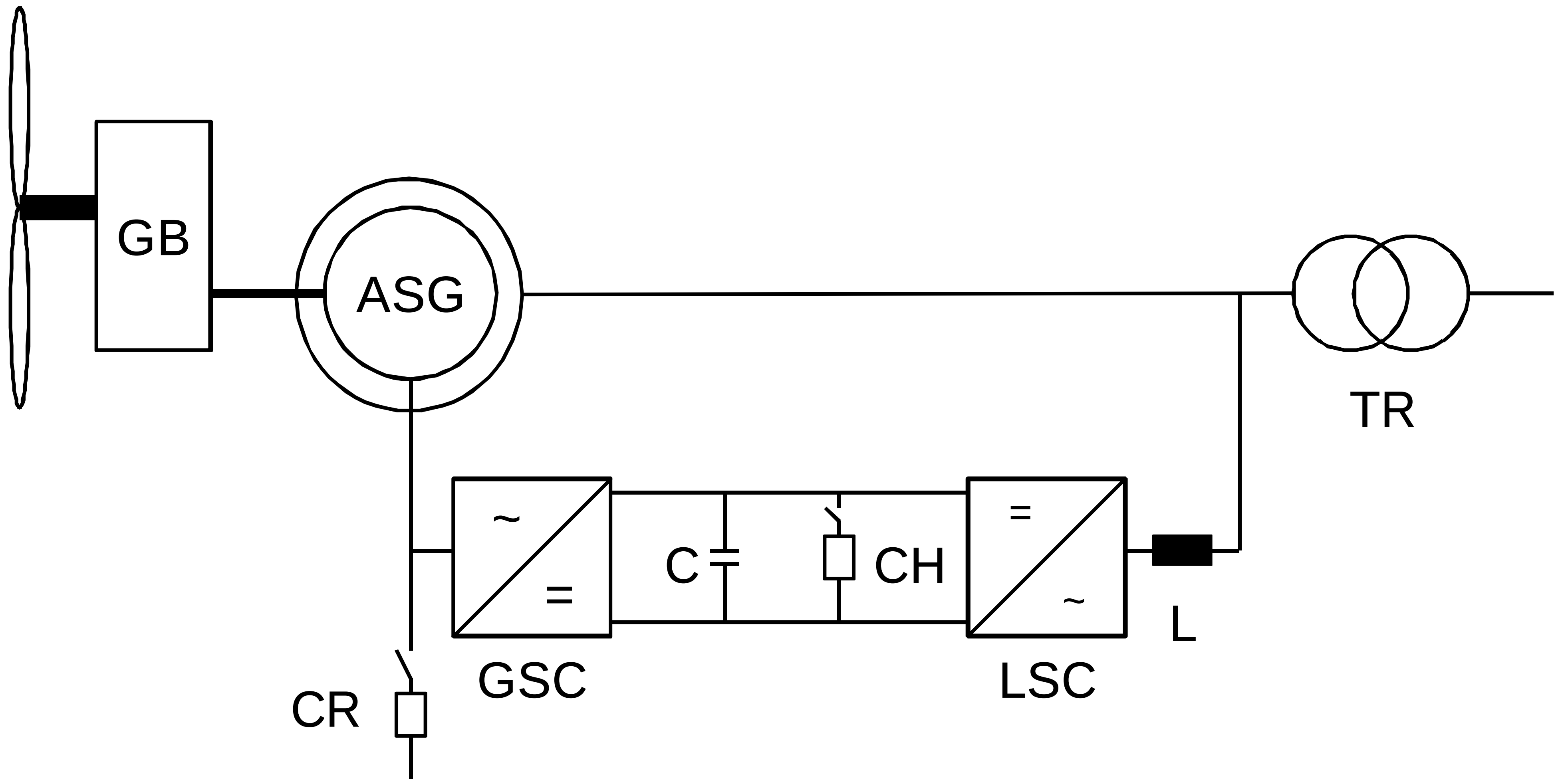
Model specifications 2 / 2

- The models should be valid for steady state voltage deviations (recommended +/- 10% from system nominal voltage)
- The typical simulation time frame of interest is from 10 to 30 seconds. Wind speed is assumed to be constant during such a time frame.
- The models are specified to work with simulation time steps up to ¼ cycle. As a consequence, the smallest time constants which can be included are ½ cycle, and therefore the bandwidth of the model cannot be greater than 15 Hz.
- The models should initialize to a steady state from power flow solutions at full or partial power.
- External conditions like wind speed should be taken into account where it can have significant influence on the power swings.
- Over/under frequency, over current and over/under voltage protection should be modelled where it exists in the control.
- The turbine-generator inertia and first shaft torsional mode should be taken into account where it can have significant influence on the power swings.

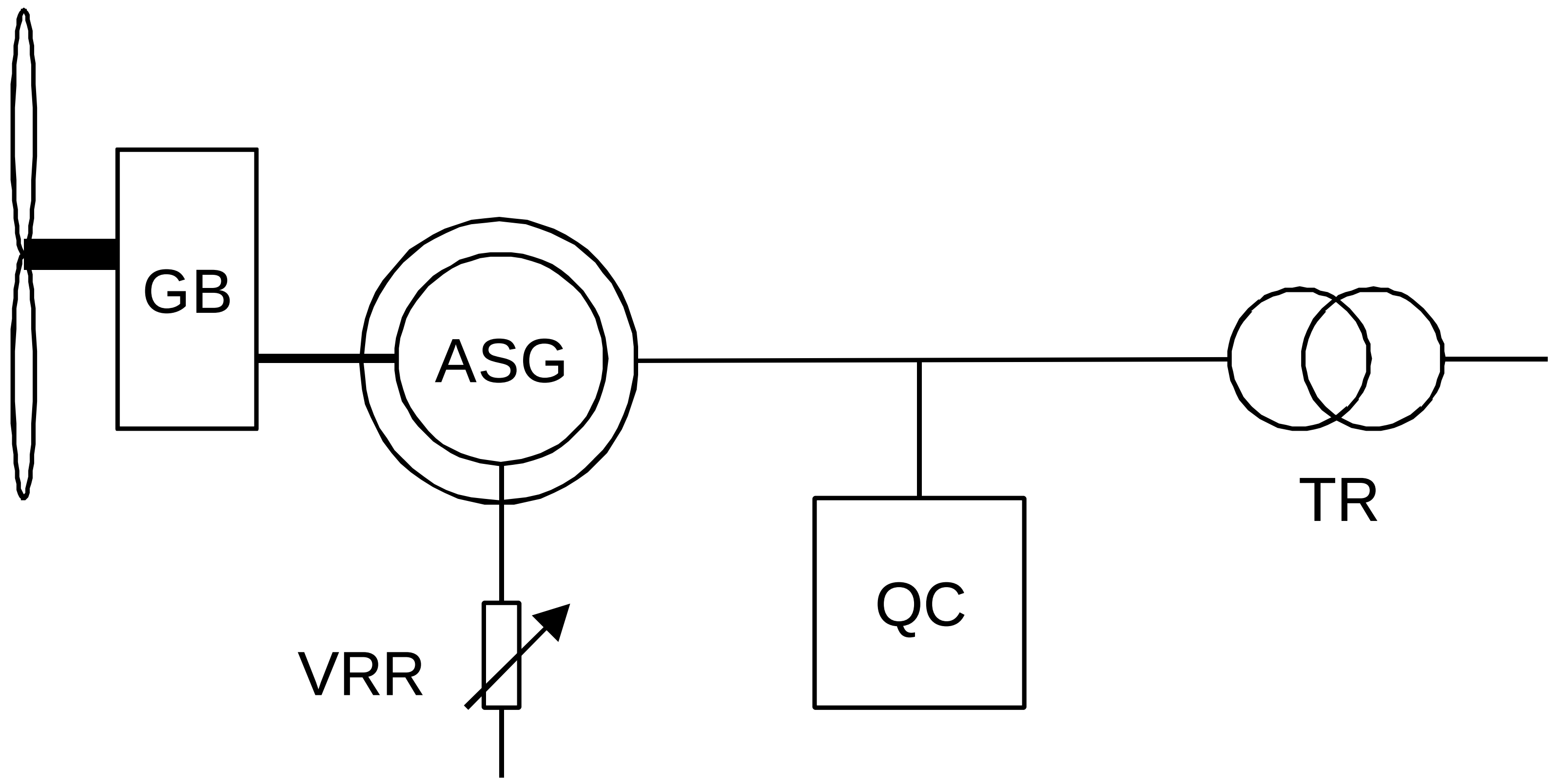
Wind turbine types



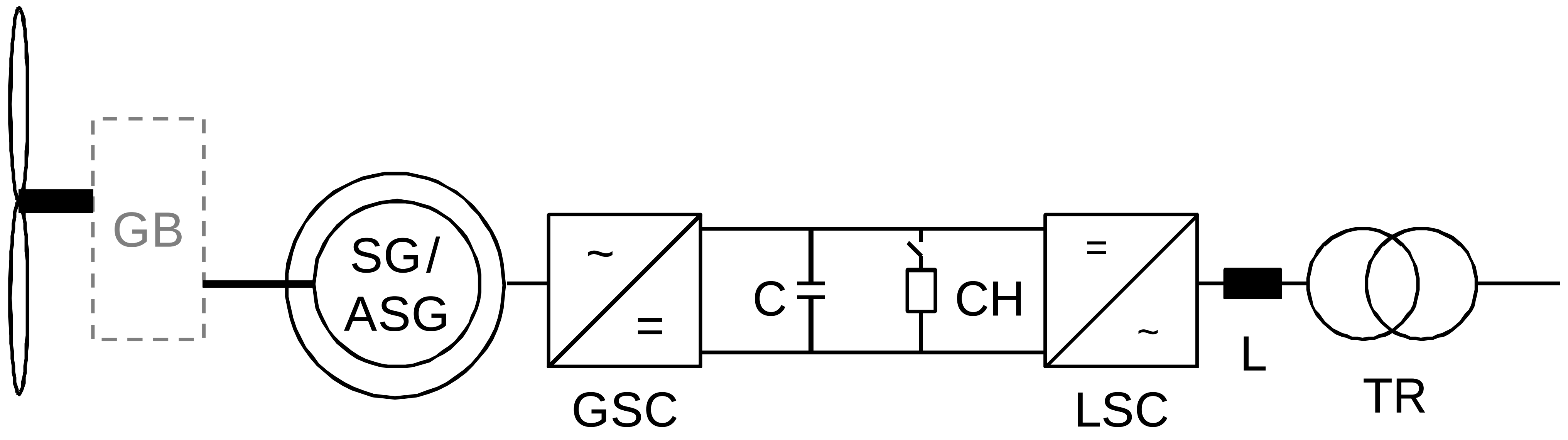
Type 1



Type 3



Type 2



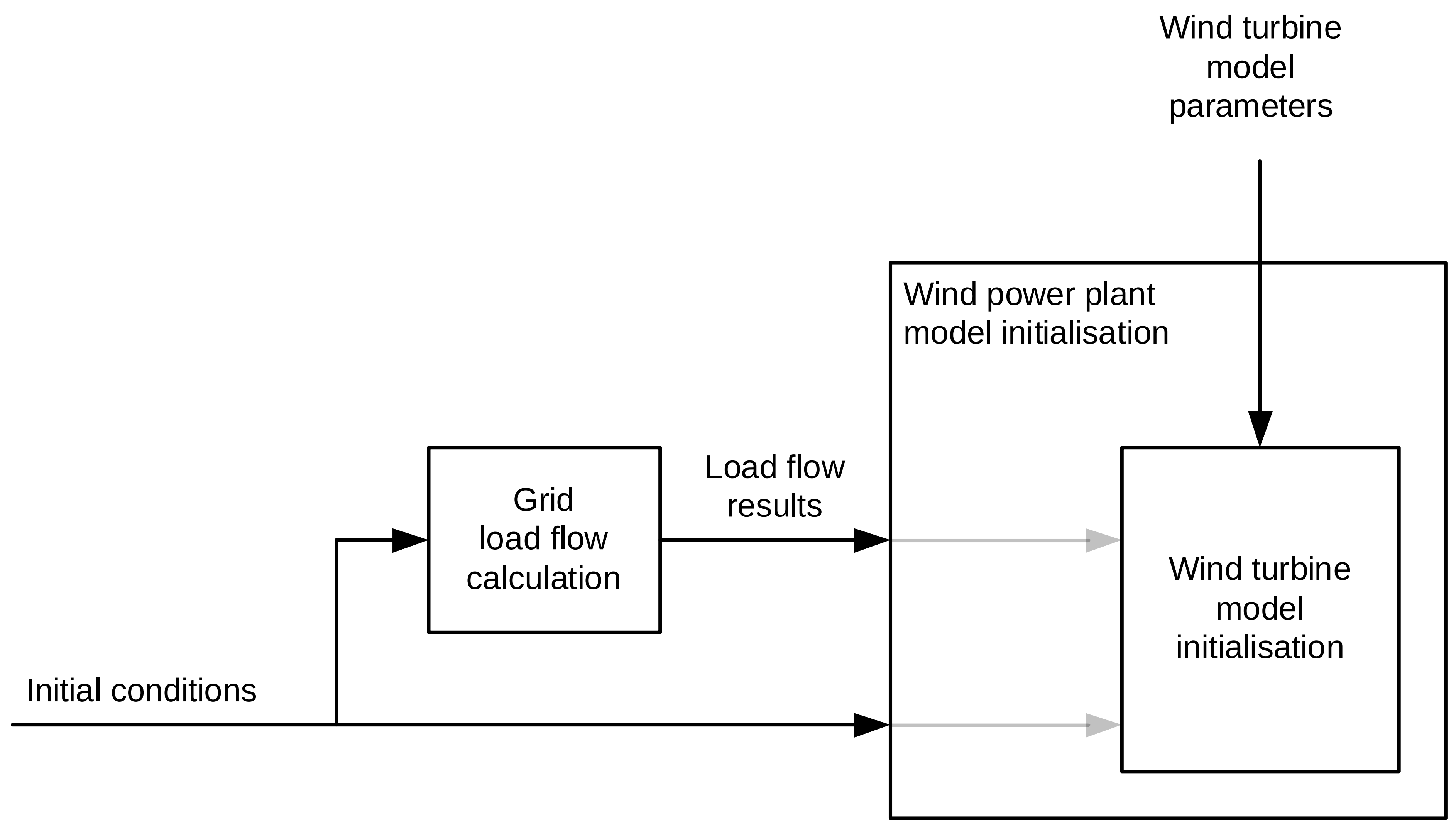
Type 4

ASG: Asynchronous generator
GB: Gearbox
QC: Reactive power compensation
SG: Synchronous generator
TR: Transformer
VRR: Variable rotor resistance

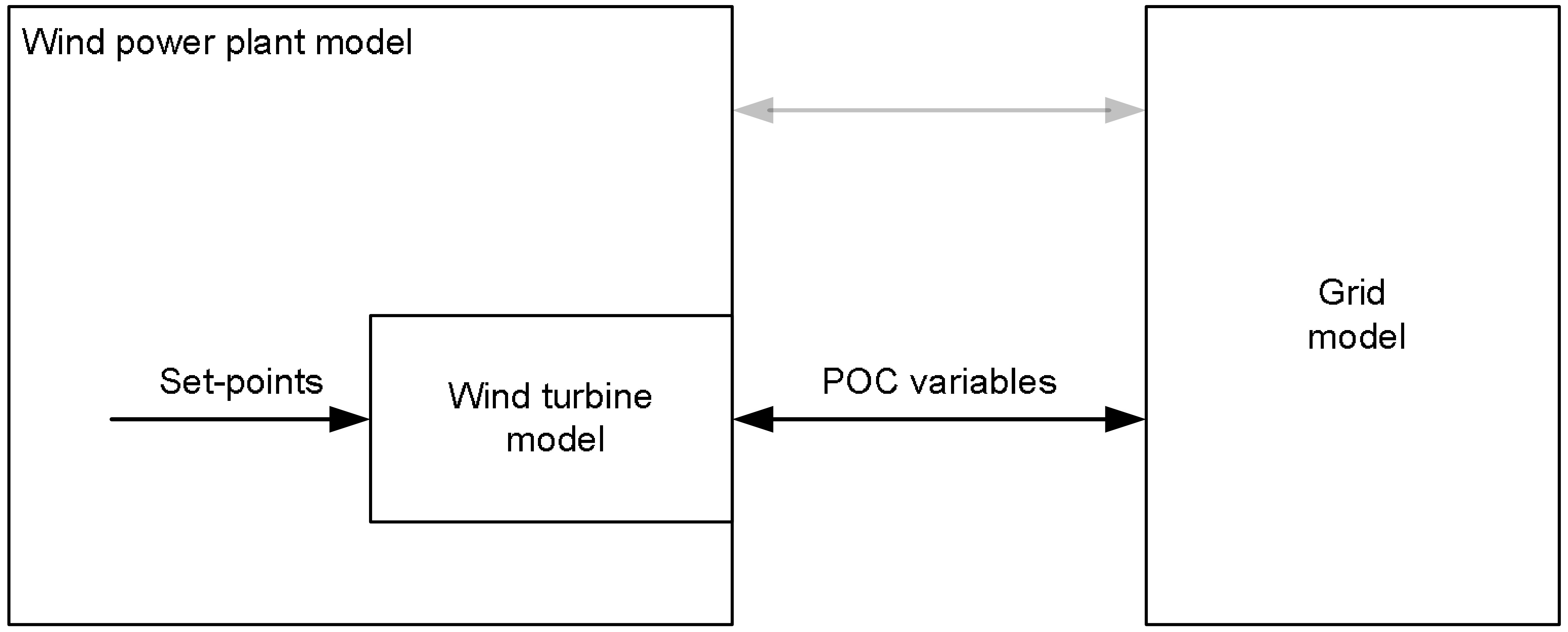
GSC: Generator side converter
LSC: Line side converter
CR: Crowbar
C: DC link capacitor
CH: Chopper
L: Series inductance

Wind turbine model interface

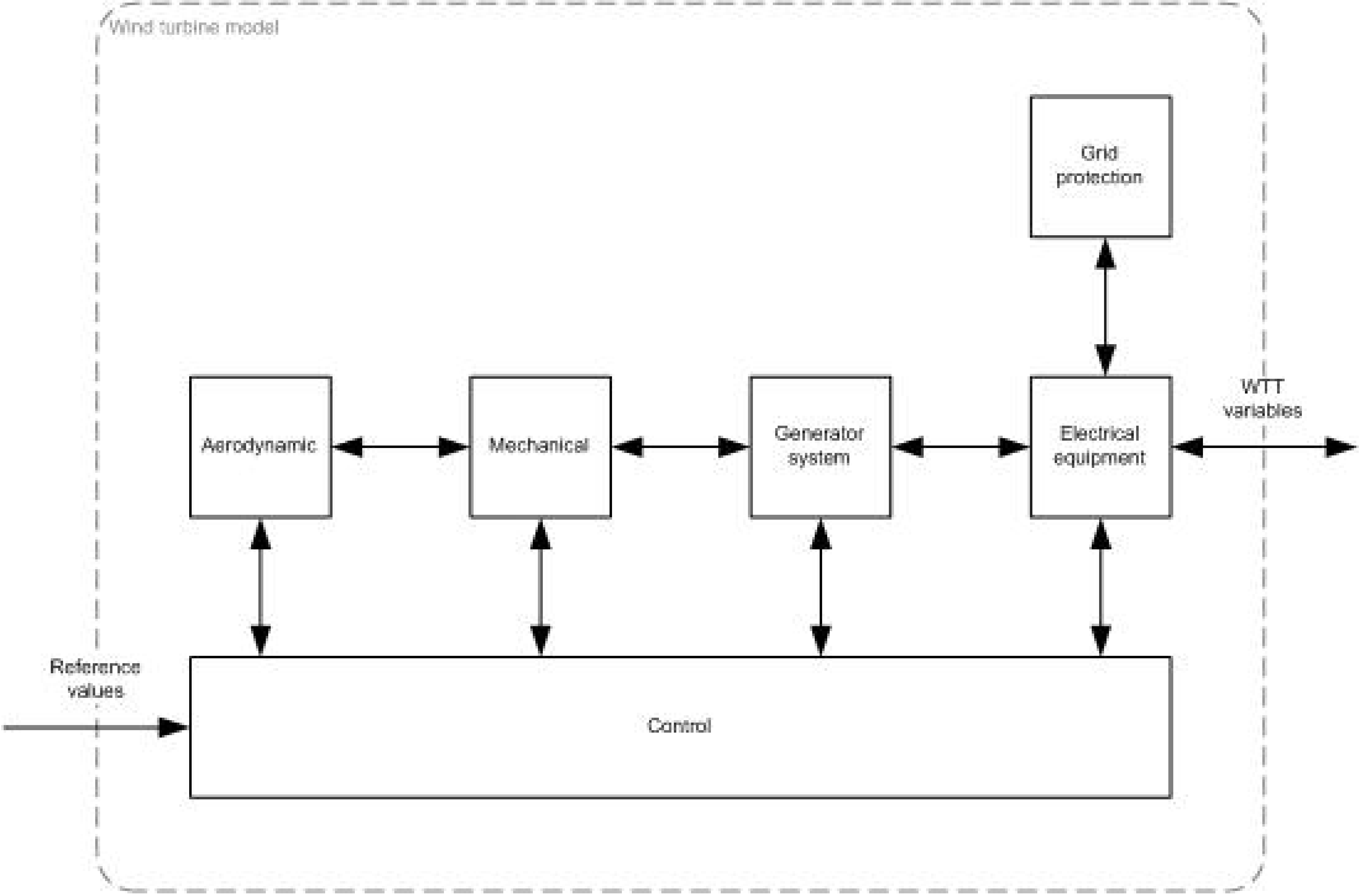
Initialisation



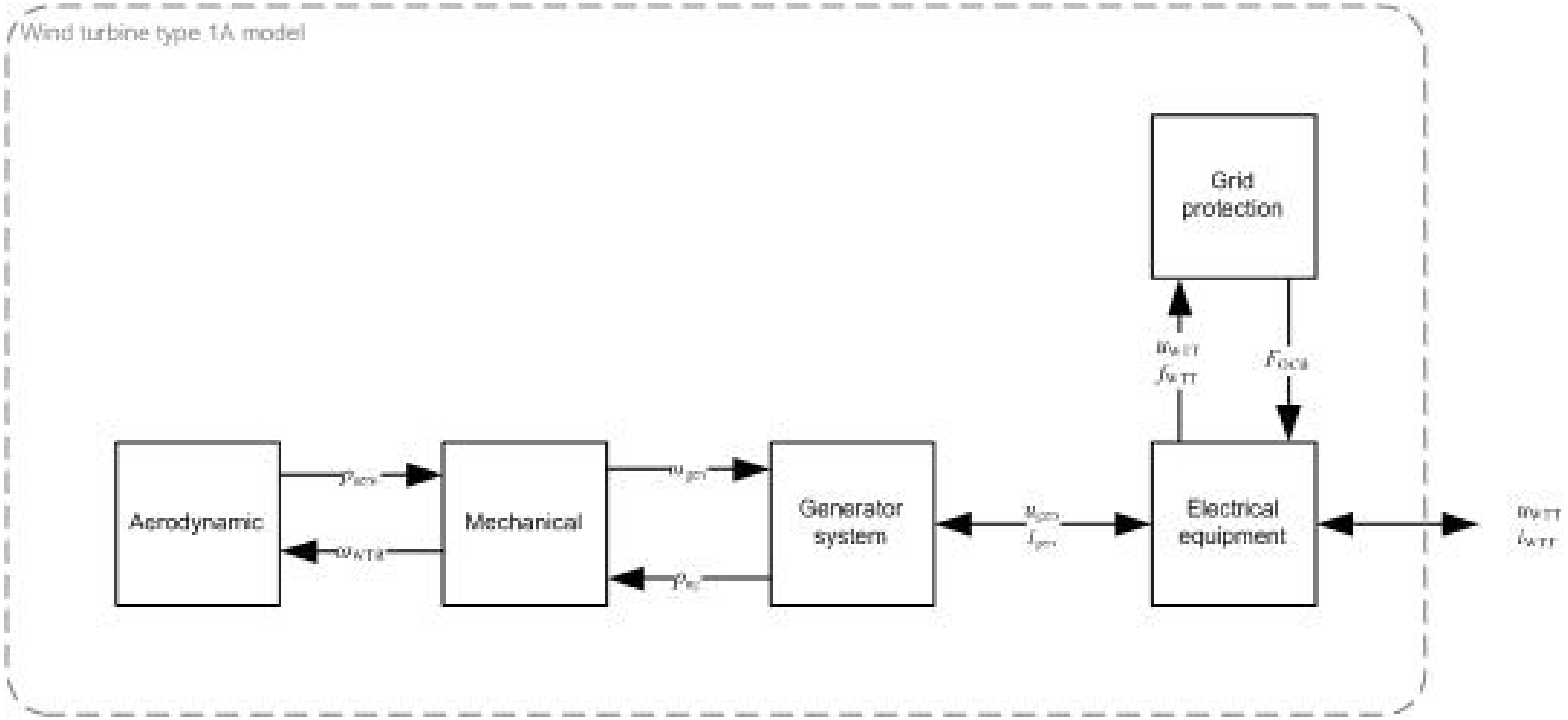
Runtime



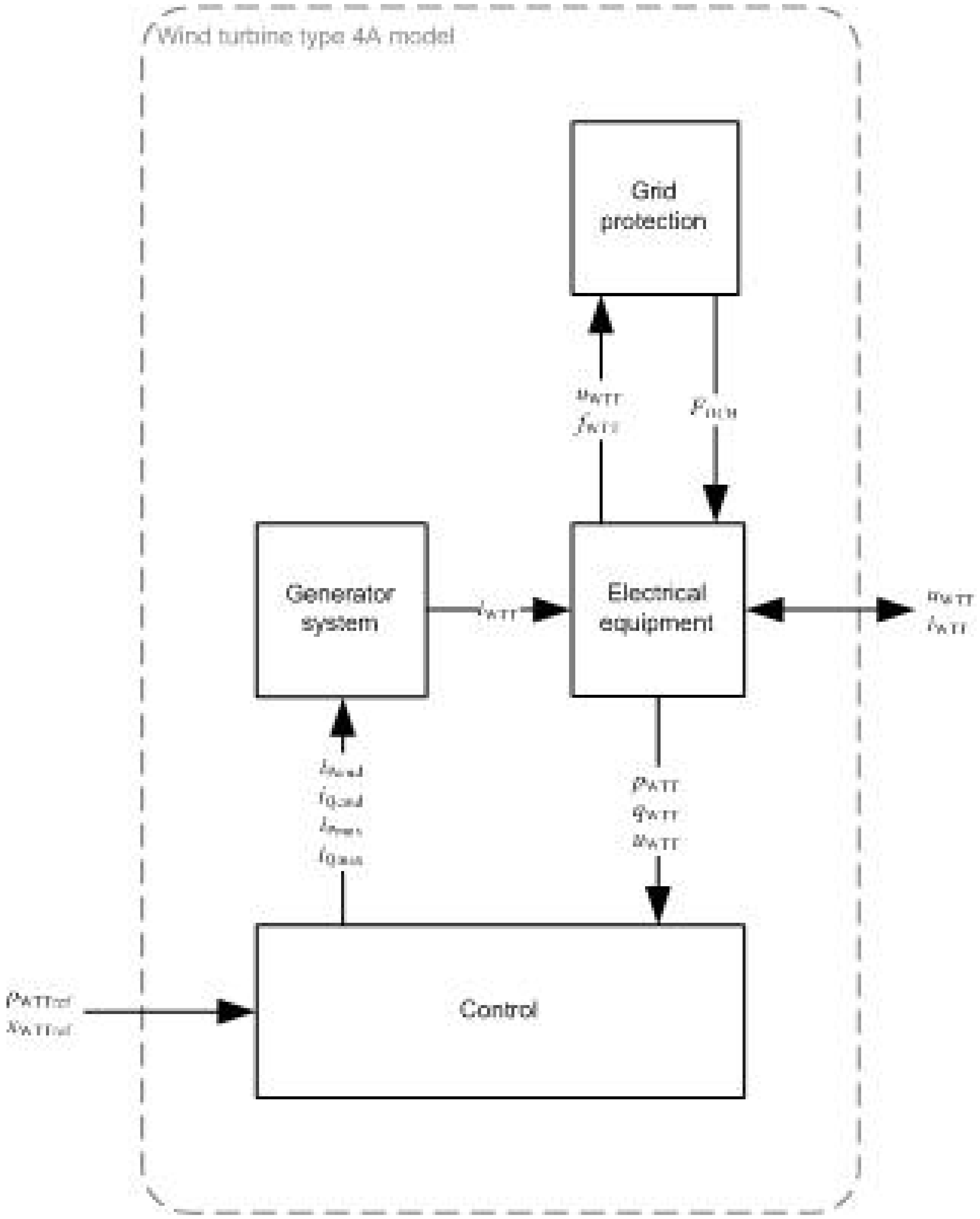
Generic wind turbine model structure



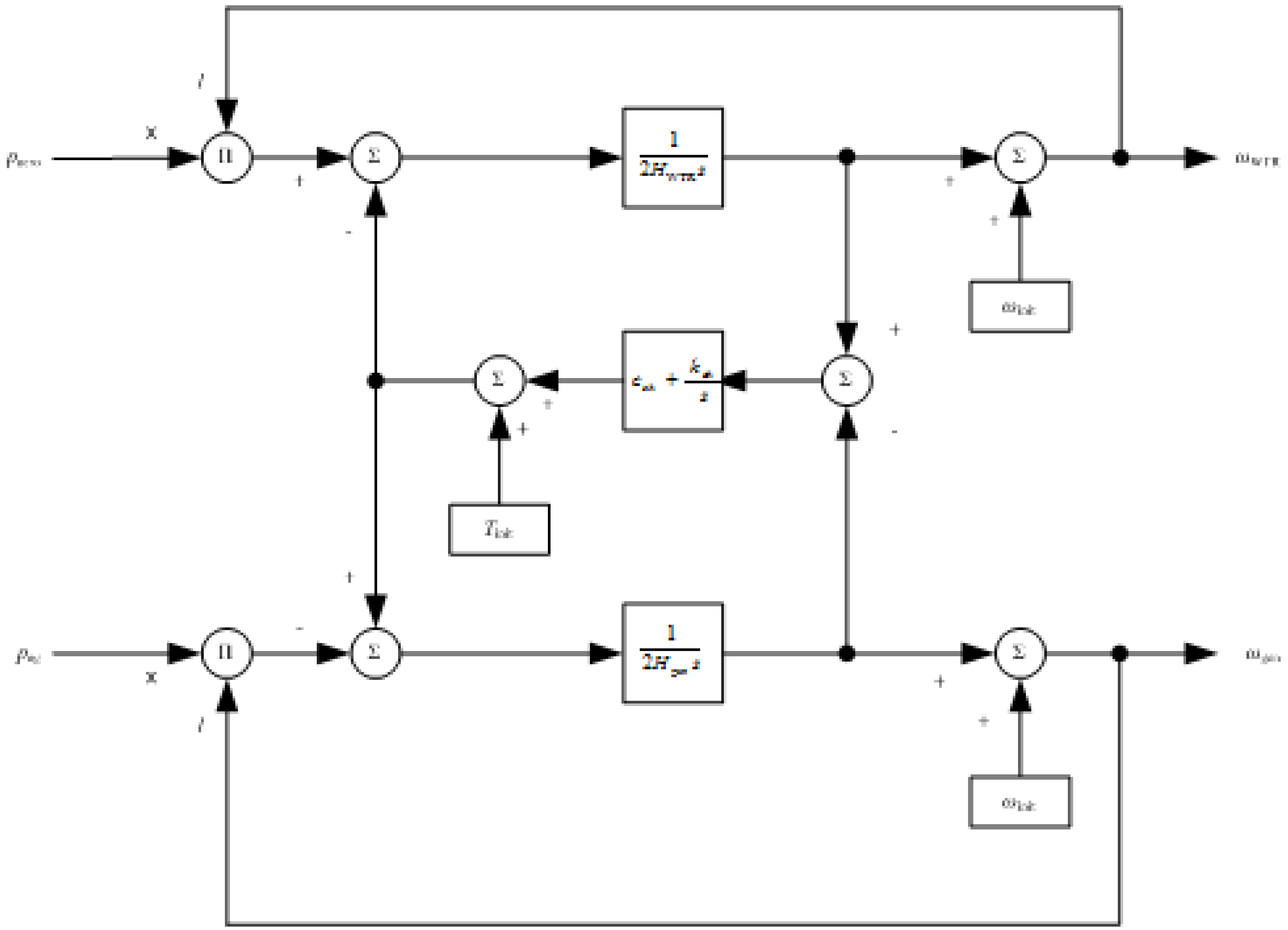
Example: Type 1A structure



Example: Type 4A structure

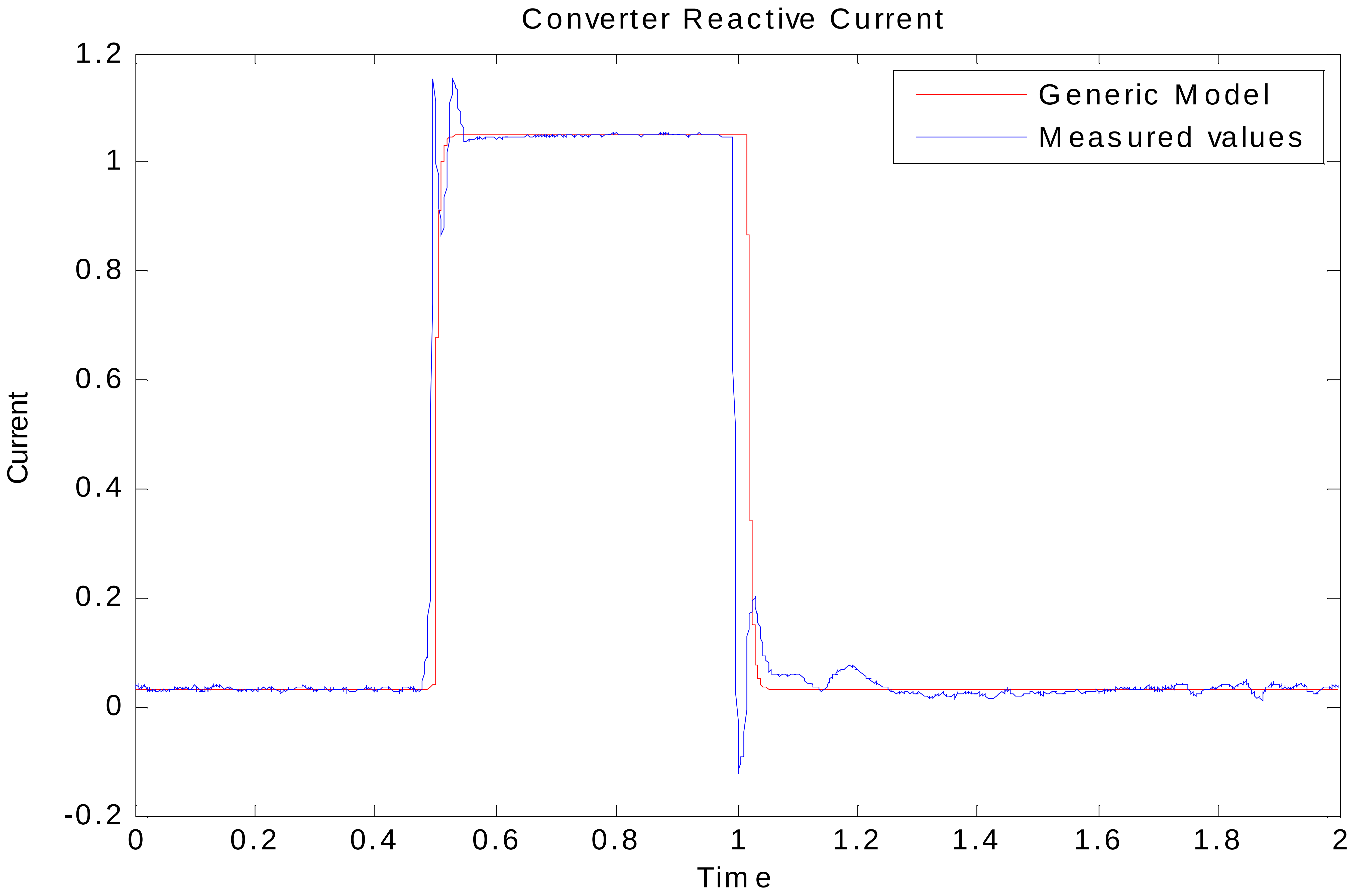


Library example: 2 mass model



Validation procedure

- Validation procedures are about comparing simulations to measurements (tests or event logging)



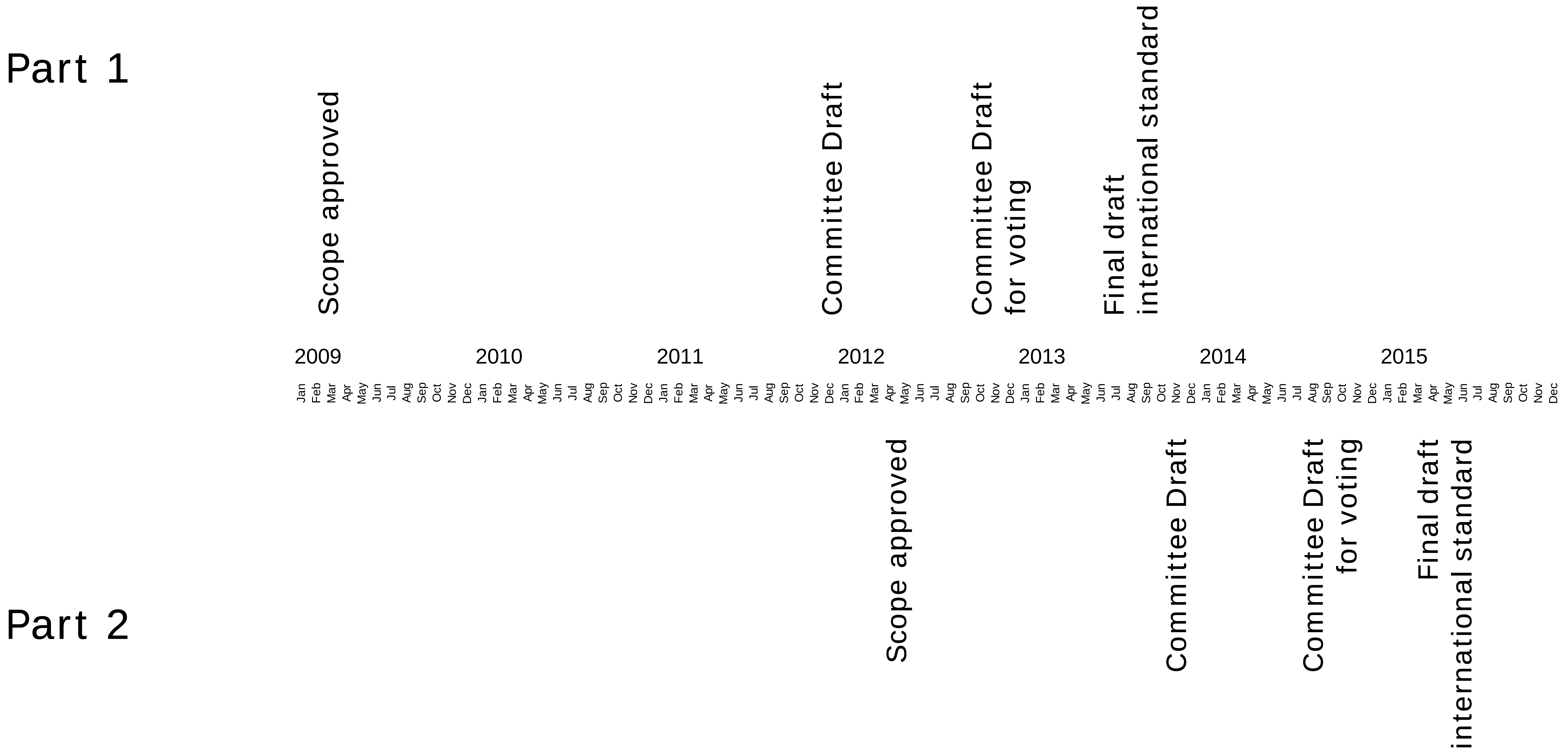
Validation procedure

- National procedures for validation are quite different
  - USA “engineering judgement”
  - Germany definitions of transient and quasi steady state periods
  - Spanish discard of 15 % worst values

- Based on IEC 61400-21 – measurement and assessment of power quality
  - Low voltage ride-through
  - Power setpoint change
  - Reactive power setpoint change
  - Grid protection functionality test (of disconnection levels and times)

- Limitations:
  - The validation is limited by the available tests
  - The test and measurement procedures introduce errors which limit the possible accuracy as specified in the validation procedure
  - Validation of reactive power capability is not included

IEC 61400-27 – timeline



Thank you

www.iec.ch (Search TC88 WG27)

Convener of IEC 61400-27:
Poul Sørensen, Technical University of Denmark, Department of Wind Energy,
posq@risoe.dtu.dk

Annex 2

Twenties
Transmitting wind

Offshore wind power variability in 2020 and 2030

Nicolaos Cutululis,

DTU Wind Energy

Technical University of Denmark

SEVENTH FRAMEWORK PROGRAMME

EUROPEAN COMMISION

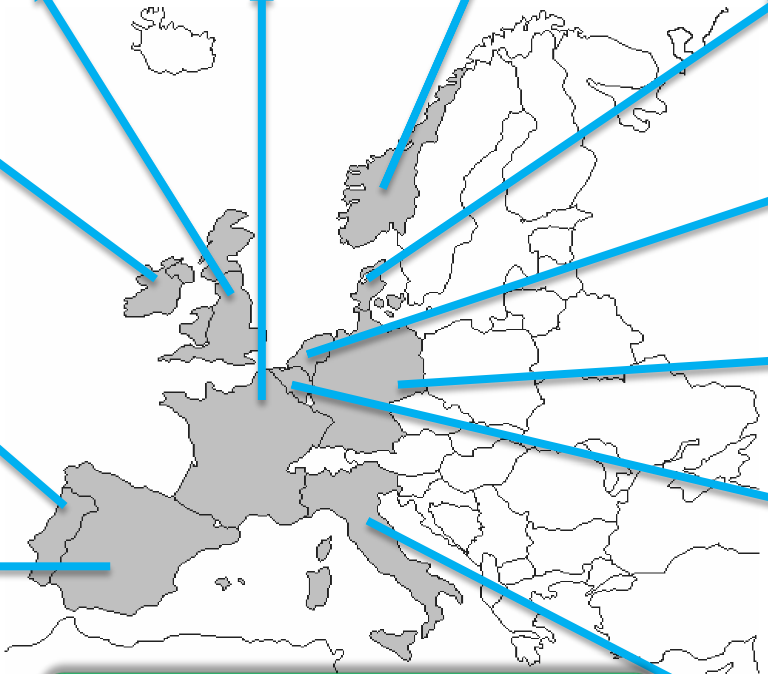
IEA Wind, DTU participation phase 3, 17 October 2012, Tokyo, Japan

TWENTIES

Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions

Consortium and budget

10 European Member States
1 Associated Country



United Kingdom (2)
ALSTOM GRID
UNIVERSITY OF STRATHCLYDE

France (2)
RTE
EDF

Norway
SINTEF

Denmark (3)
DONG ENERGY
ENERGINET
DTU ENERGY

Ireland
UCD

Portugal
INESC-PORTO

The Netherlands
TENNET

Germany (3)
FRAUNHOFER IWES
50 HzT
SIEMENS Wind Power

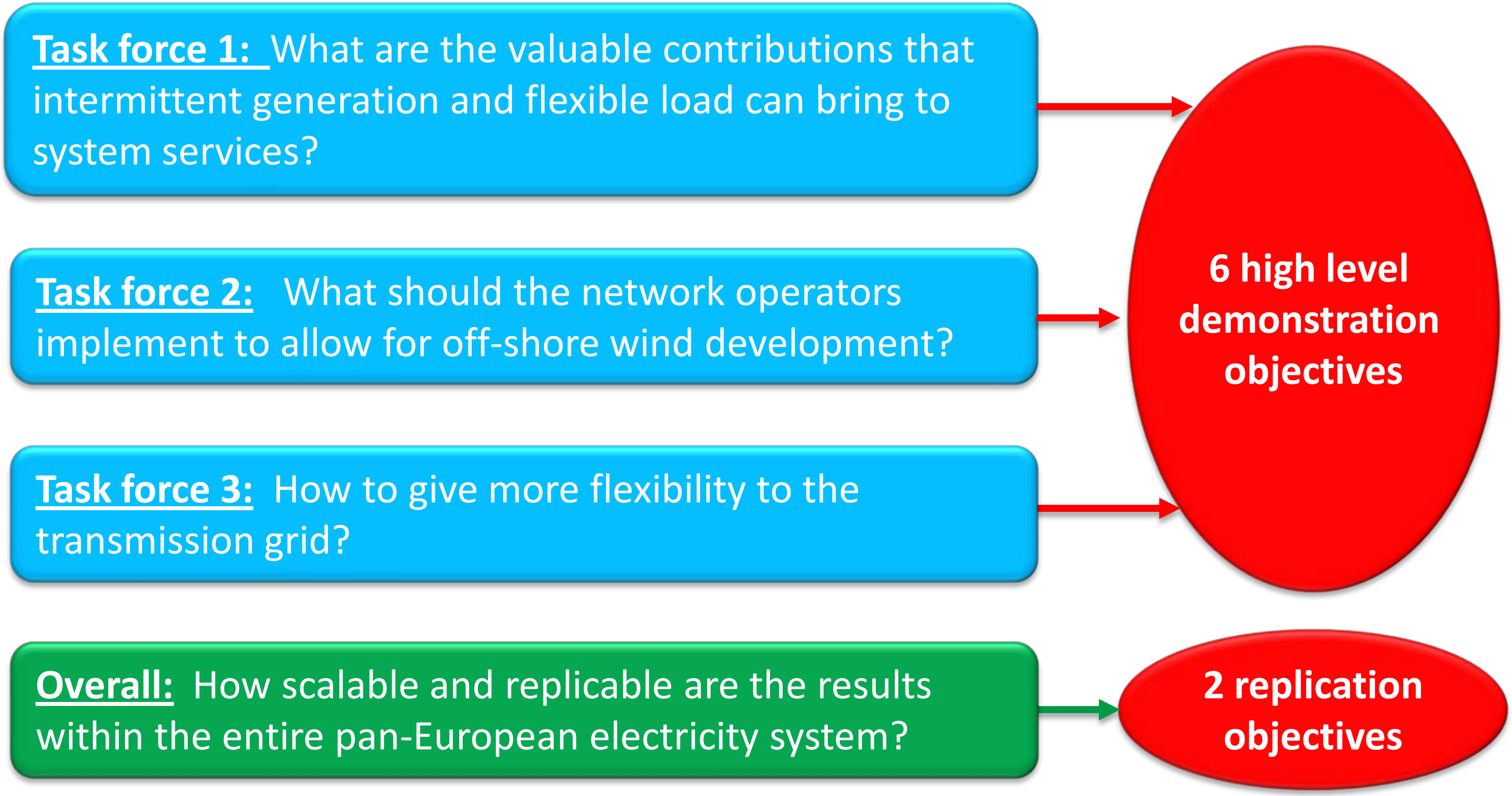
Spain (5)
RED ELECTRICA DE ESPAÑA
IBERDROLA
ITT COMILLAS
GAMESA
ABB S.A.

Belgium (6)
ELIA SYSTEM OPERATOR
EWEA
CORESO
UNIVERSITY LIEGE
UNIVERSITY LEUVEN
UNIVERSITE LIBRE BRUXELLES

Italy
RSE

Total budget: 56.8 M€
EU contribution: 31.8 M€

Project objectives



Task force 1: What are the valuable contributions that intermittent generation and flexible load can bring to system services?

Task force 2: What should the network operators implement to allow for off-shore wind development?

Task force 3: How to give more flexibility to the transmission grid?

Overall: How scalable and replicable are the results within the entire pan-European electricity system?

6 high level demonstration objectives

2 replication objectives

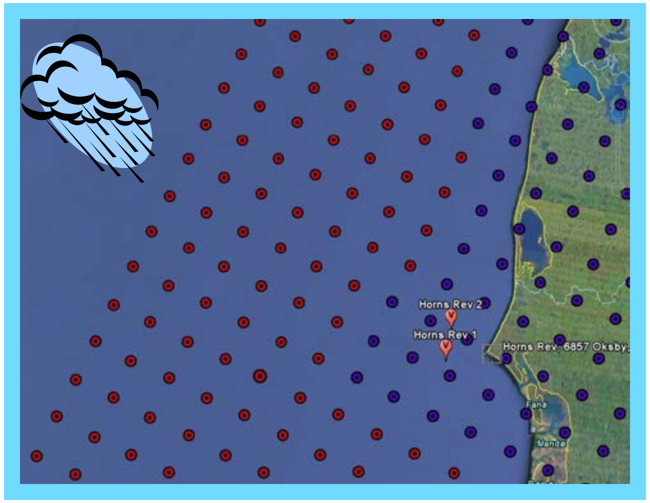
DEMO 4 STORM MANAGEMENT (Leader: ENERGINET)

Main objective

- Demonstrate shut down of wind farms under stormy conditions without jeopardizing safety of the system.

Approach

- Horns Rev 2 (200MW).
- Flexible turbine control.
- Storm front forecasts.
- Investigate cost of changed production associated with the planned down regulation.
- Coordinate wind farm control with HVDC interconnector control and with hydro power plant operation.



Wind power

Water power

Replication work packages: barriers and up scaling

WP 15: Economic impacts of the demonstrations, barriers towards scaling up and solutions (Leader: IIT)

- Assess the local **economic and/or technological impact** of each demo.
- Identify the **barriers to scale-up** the outcomes at a member-state or regional level, and propose **solutions** to overcome these barriers.

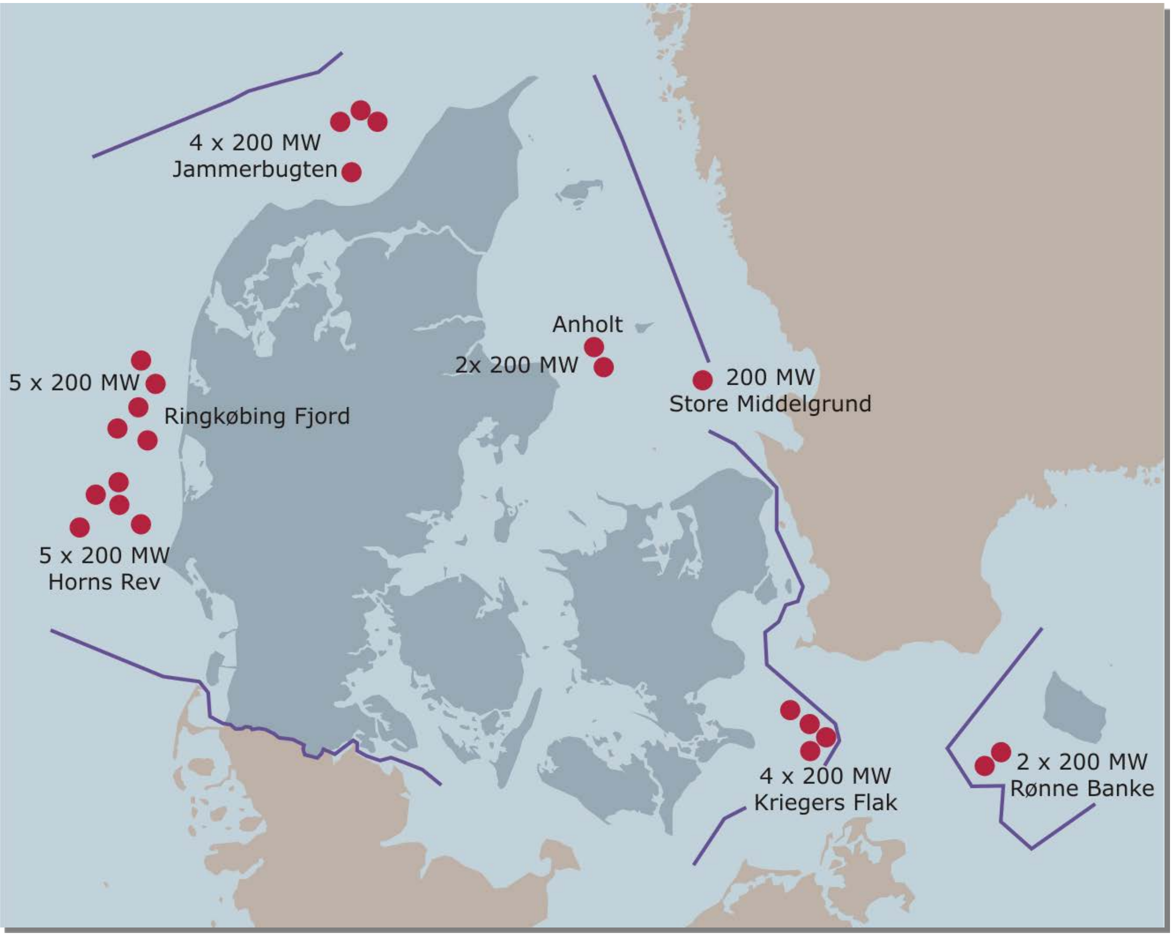
WP 16: EU wide integrating assessment of demonstration replication potential (Leader: DTU Wind Energy)

- Assess **portability** of voltage control, frequency control and VPP model **to other countries and regions**.
- Evaluate North European 2020 **offshore wind power variability**, **hydro potential and barriers** and **grid restriction** studies.
- Pan European economic impact study.

WP 17: EU Offshore barriers (Leader: TENNET)

- Address the issues of **smart licensing of submarine interconnectors** with and without wind parks in the North Sea and Baltic Sea.
- Identify **common licensing barriers** and propose regulatory measures.

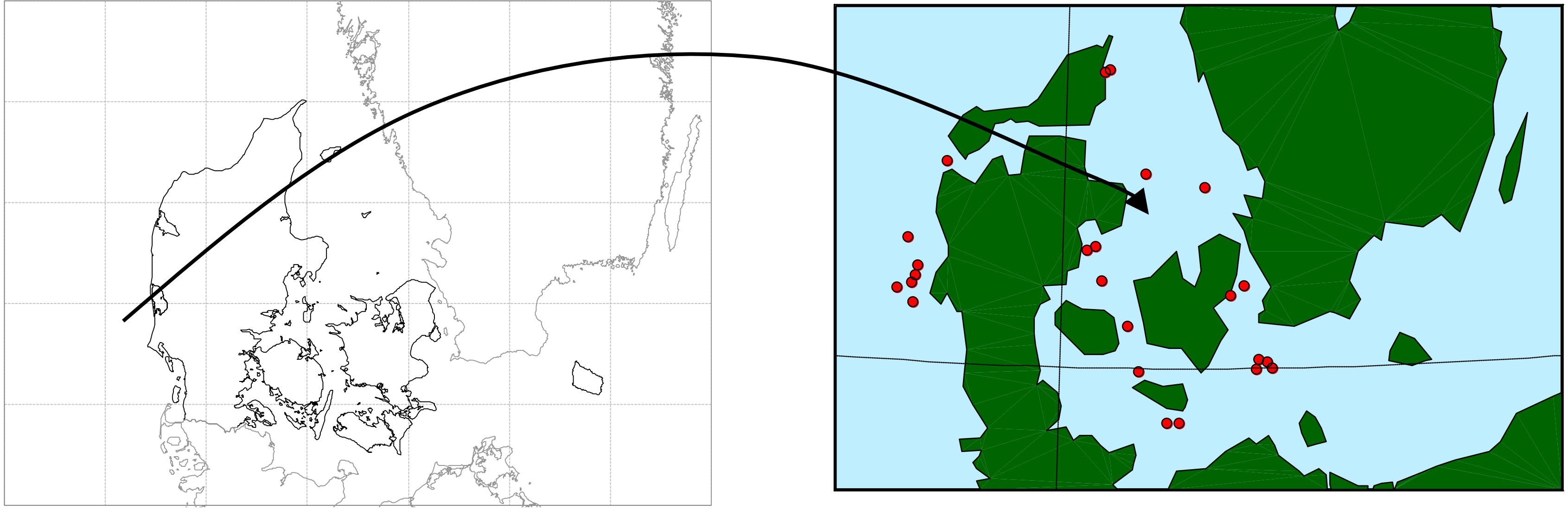
Future offshore projects in Denmark



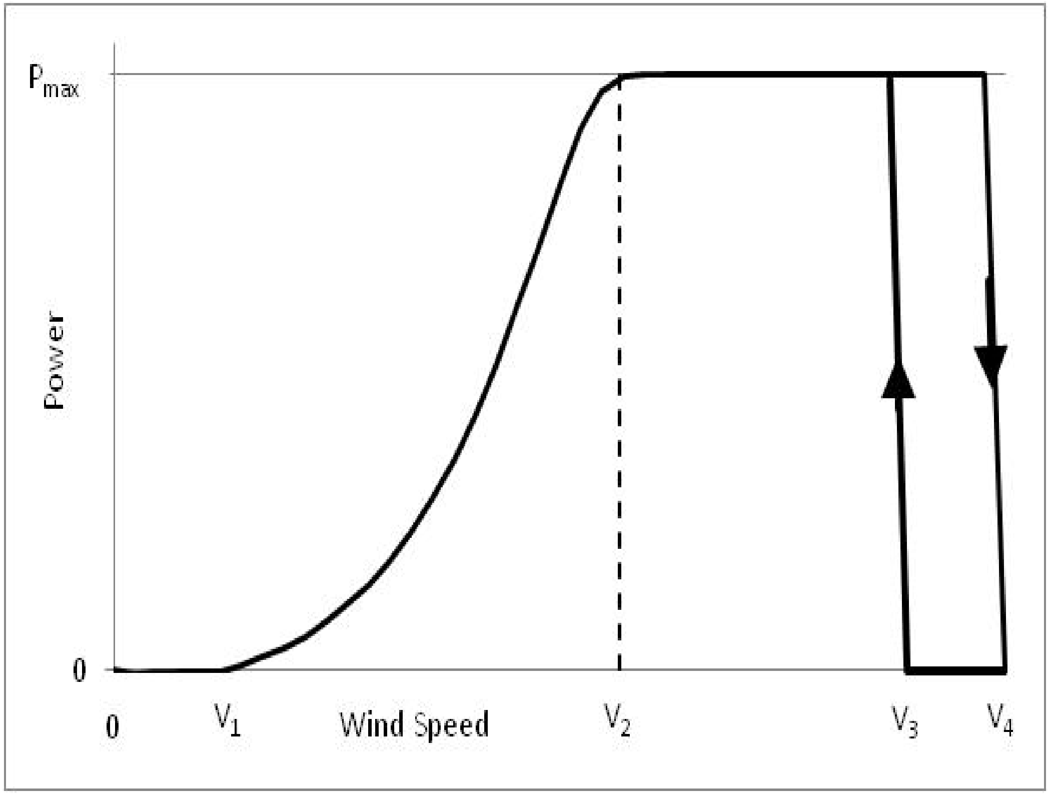
Upscaling of Horns Rev 2 to > 3 GW offshore wind

Base 2.811 MW

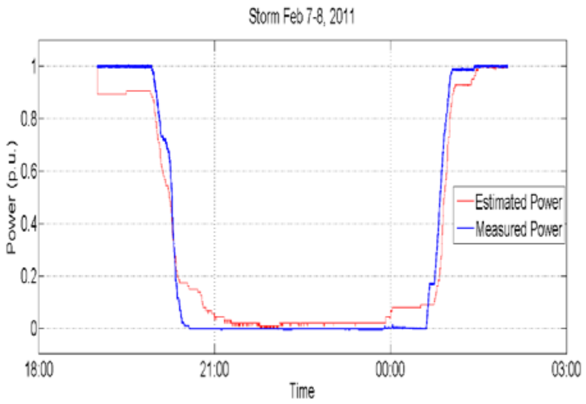
High: **3.211 MW**

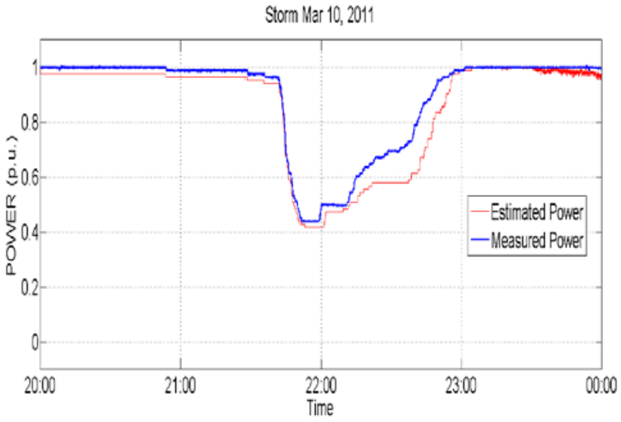


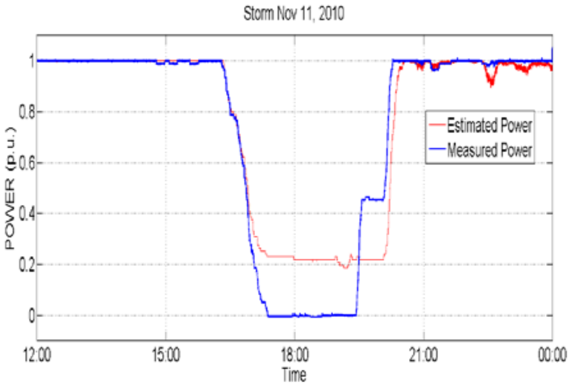
Wind turbine storm control

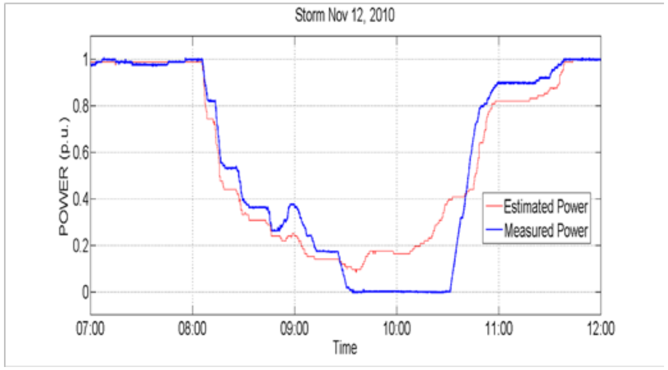


Wind turbine storm control

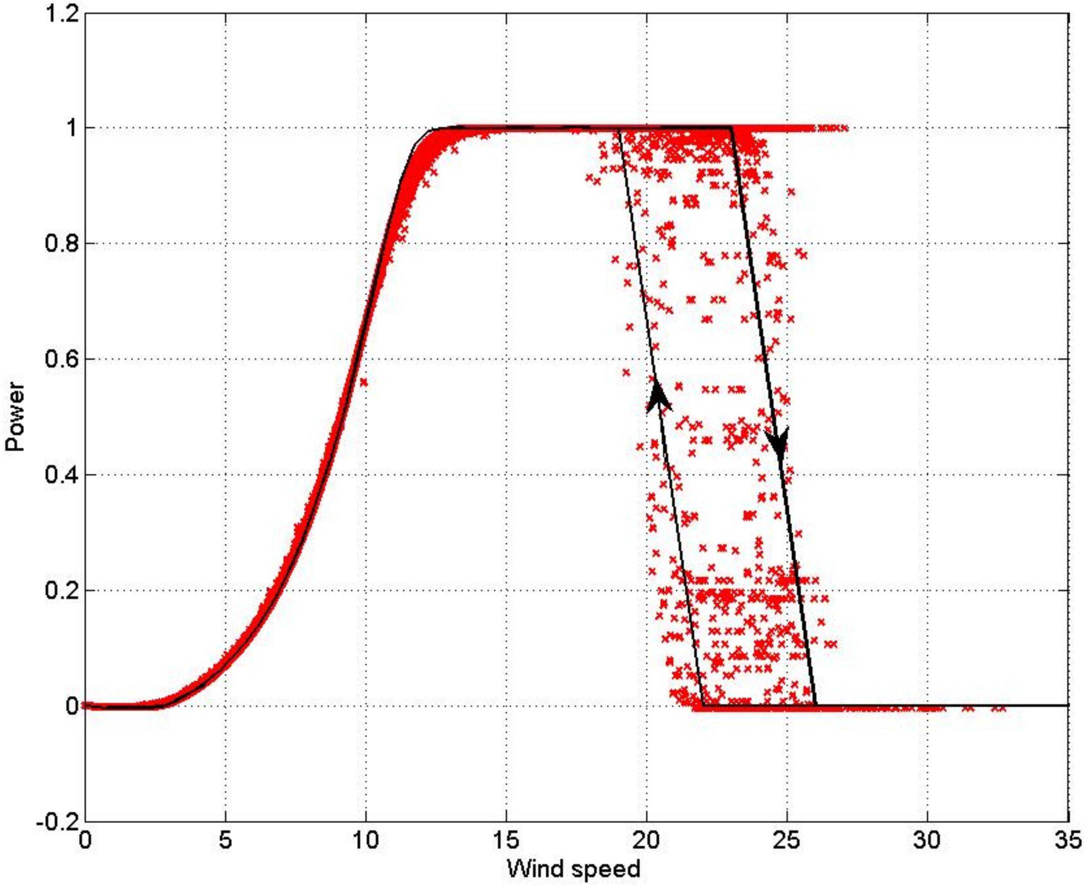








Wind farm storm control



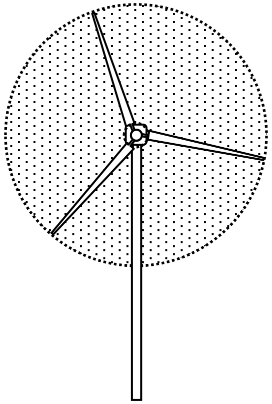
CorWind

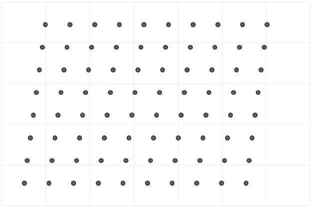
model for simulation of Correlated Wind power fluctuations

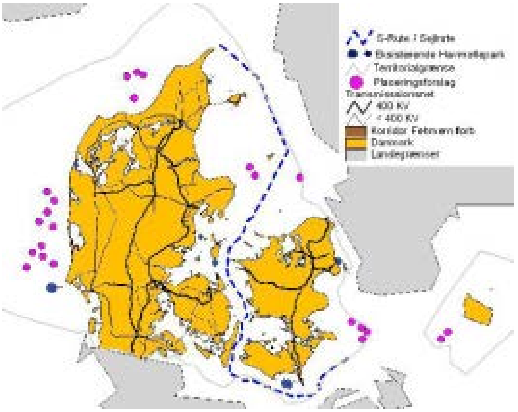
2002

2007

2009







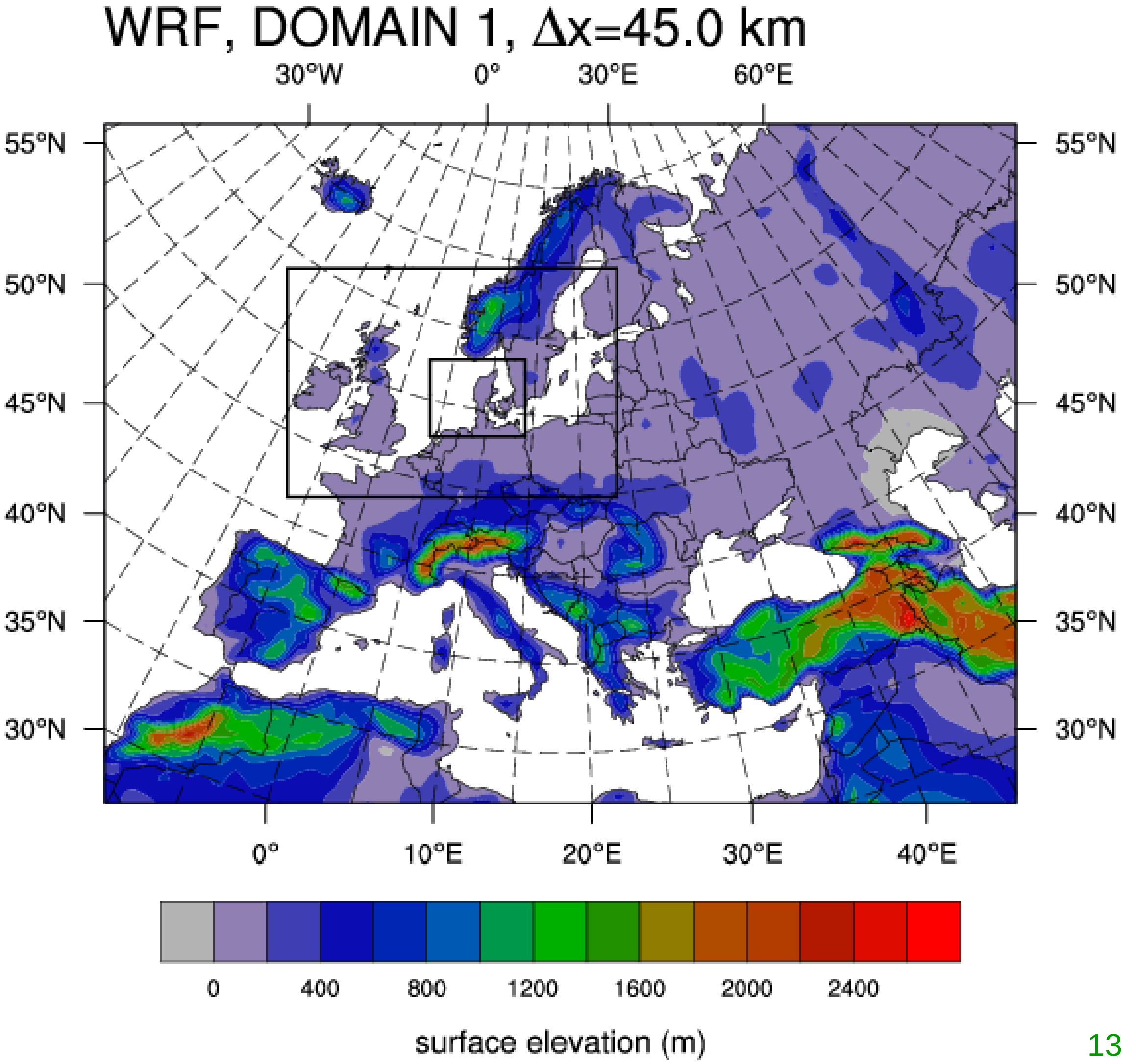
Wind turbine(s)

Wind farm

Power system area

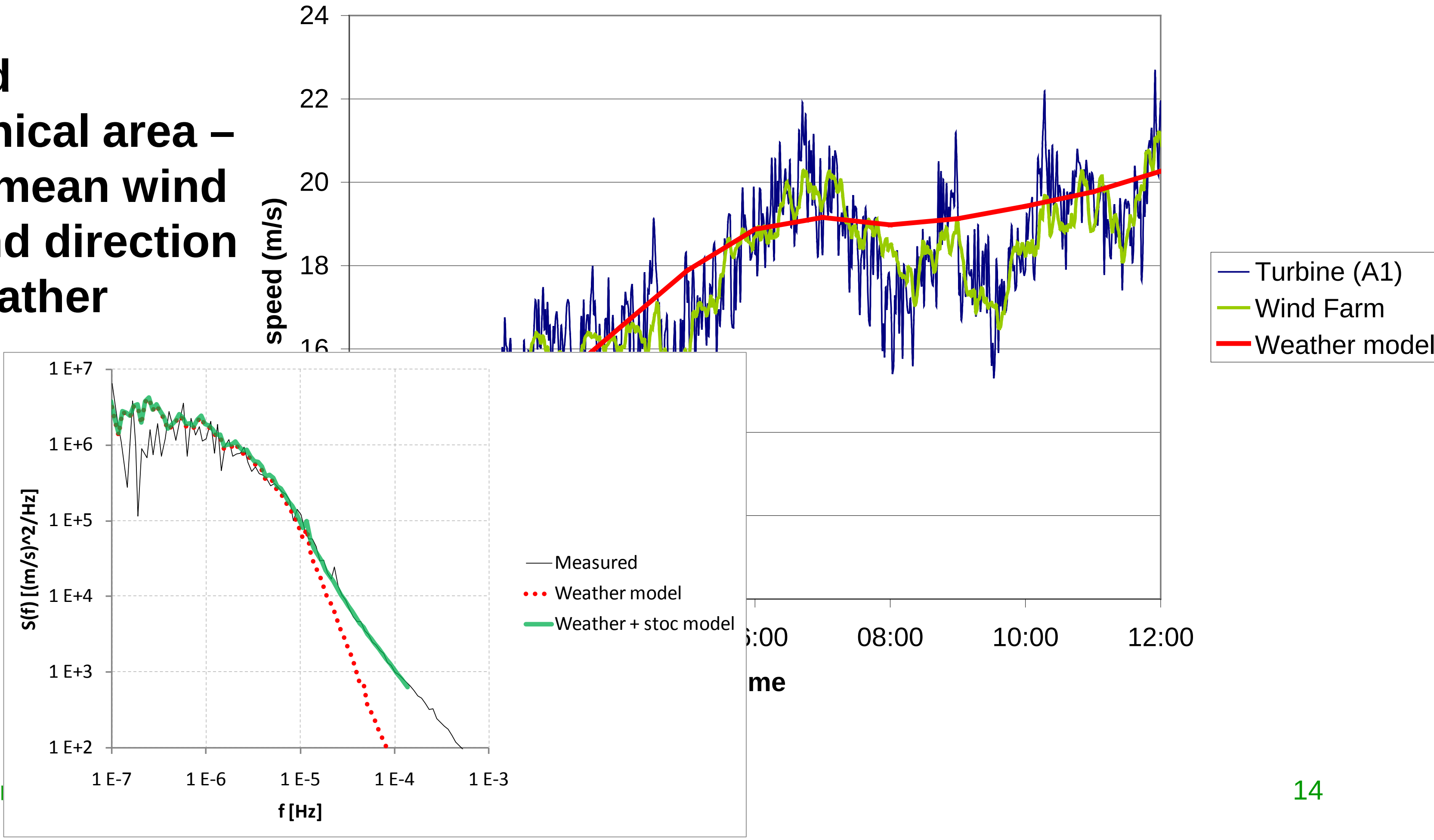
CorWind

Weather model data to include (hourly) mean wind speed variations



CorWind

Extended geographical area – variable mean wind speed and direction (from weather model)



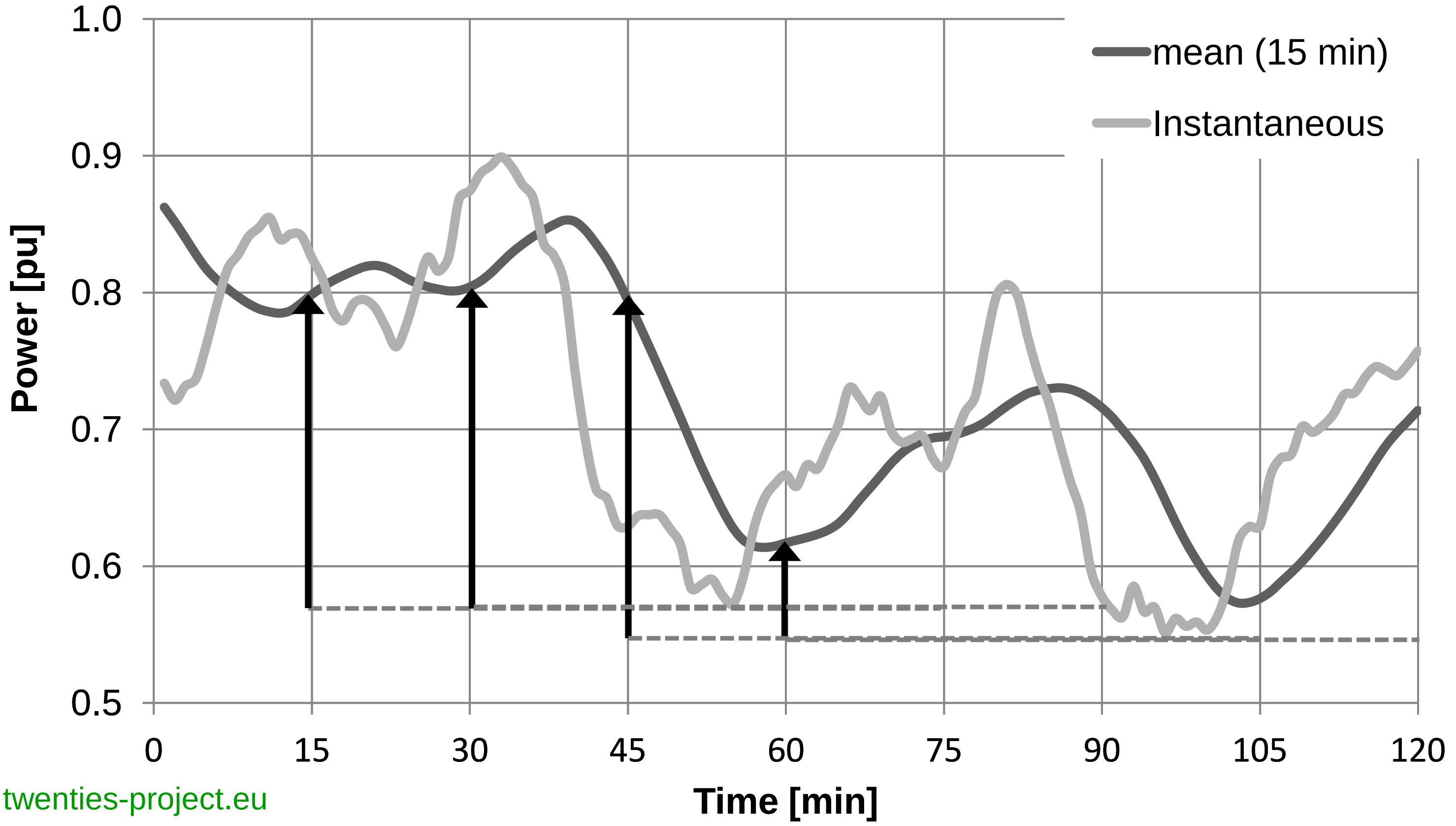
Critical weather periods

2001	01/01/2001
2005	02/01/2005
2007	01/01/2007
	08/01/2007
	18/03/2007
	27/06/2007
	08/11/2007
2008	25/01/2008
	27/02/2008

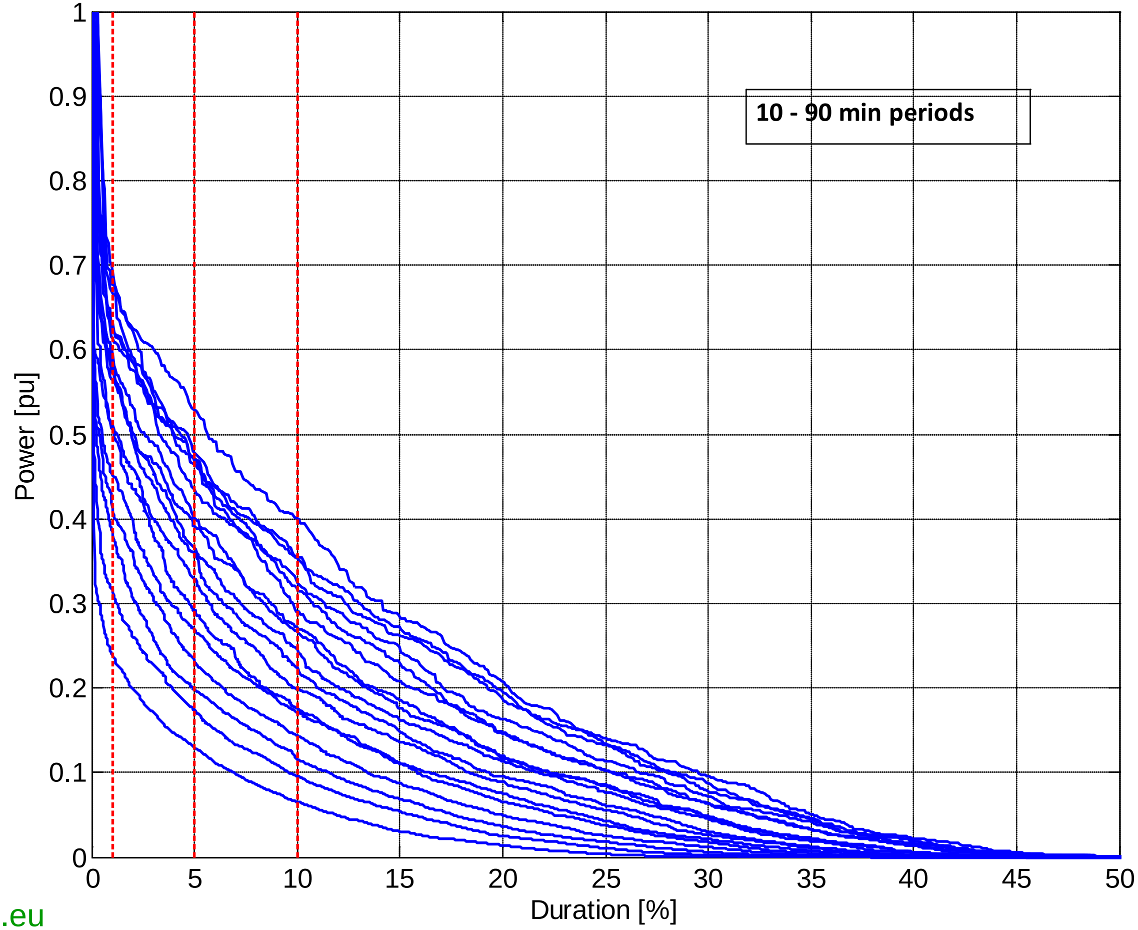
2008	21/03/2008
	13/08/2008
	08/11/2008
2009	11/06/2009
	03/10/2009
2010	11/11/2010
	07/02/2010
2011	10/03/2011

Reserve Requirements

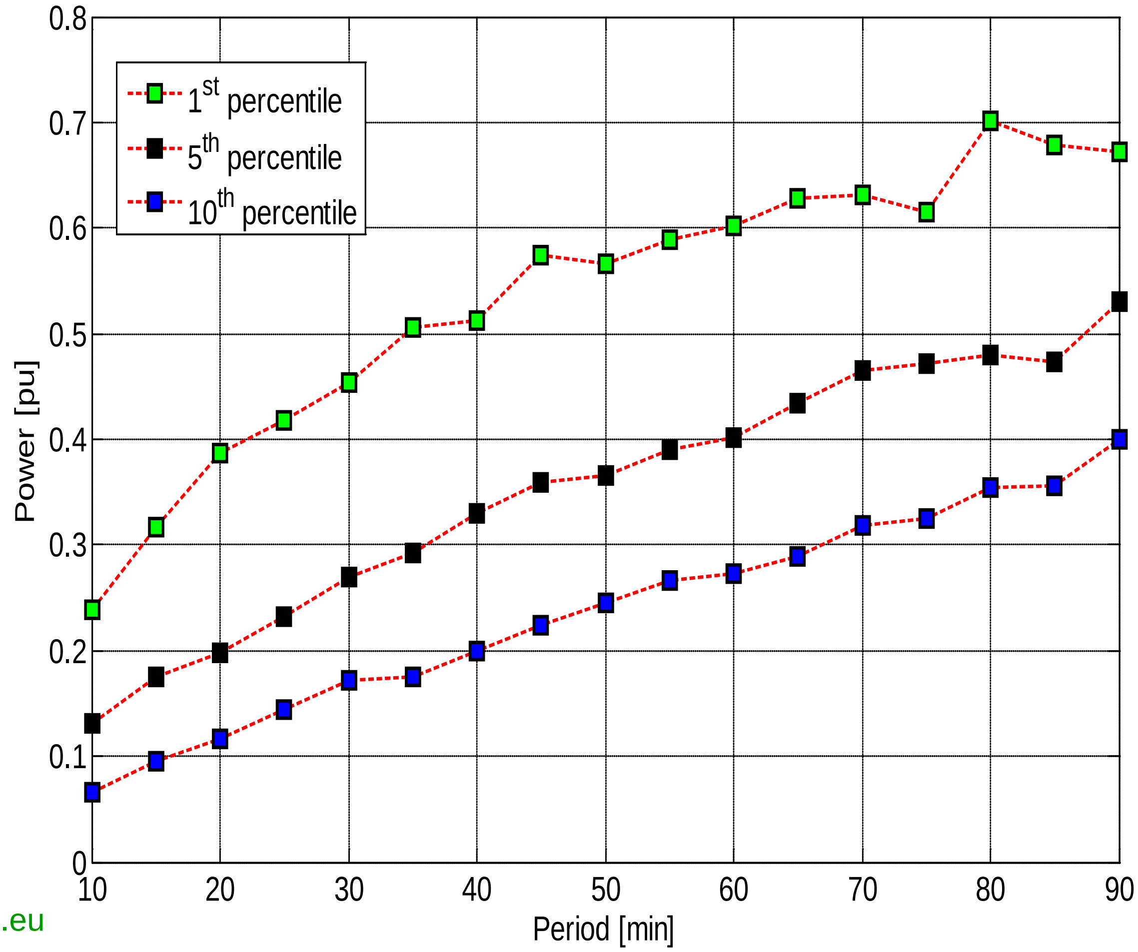
$$P_{\mathrm{res}}(n) = P_{\mathrm{mean}}\left[t(n) - T_{ave}\ ; t(n)\right] - P_{\min}\left[t(n)\,; t\,(n) + T_{win}\right]$$



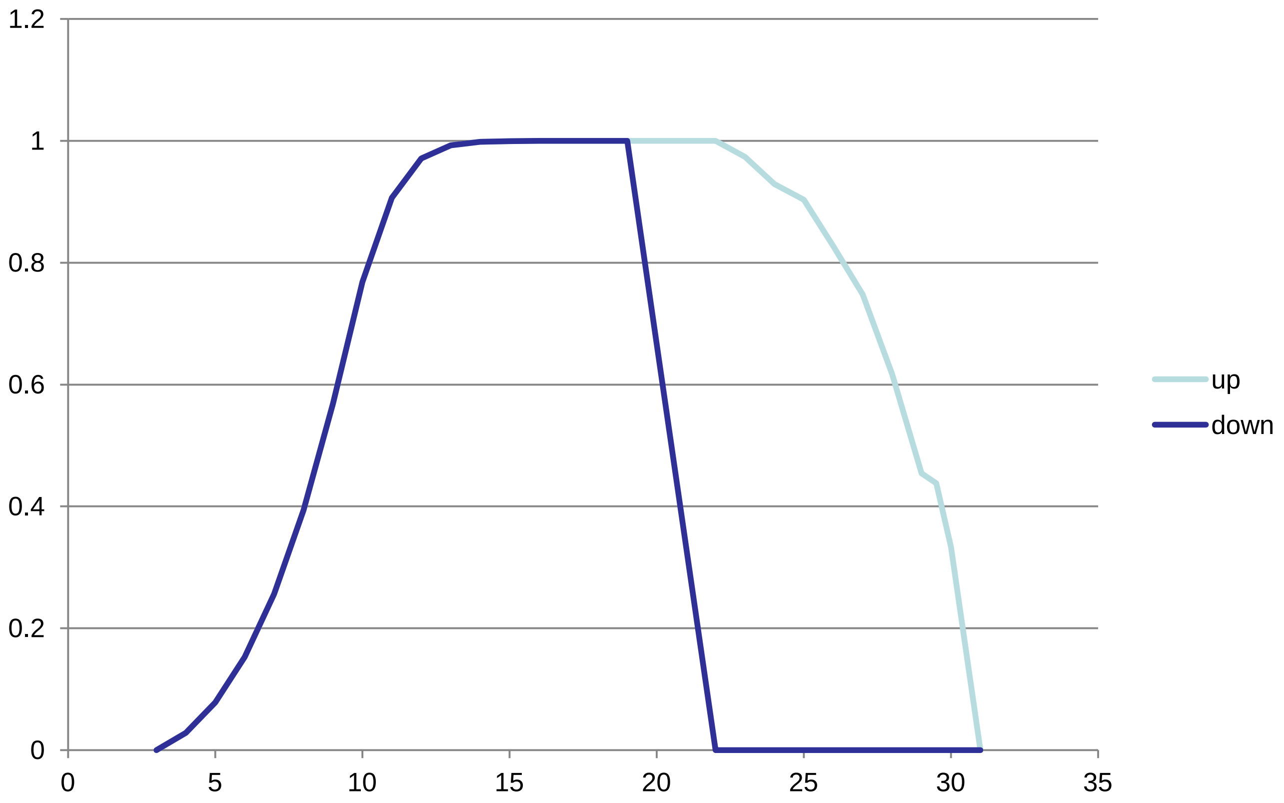
Results – duration curves



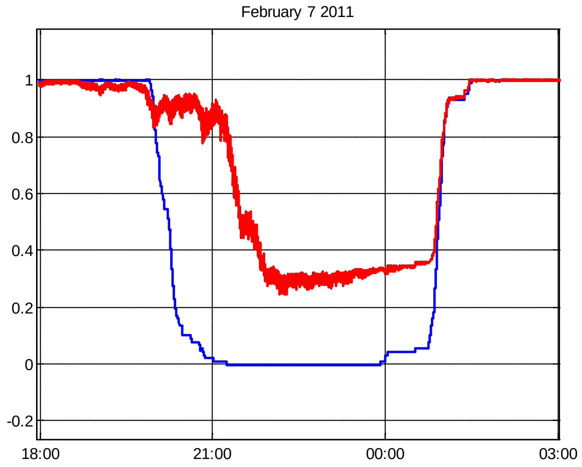
Results – percentiles

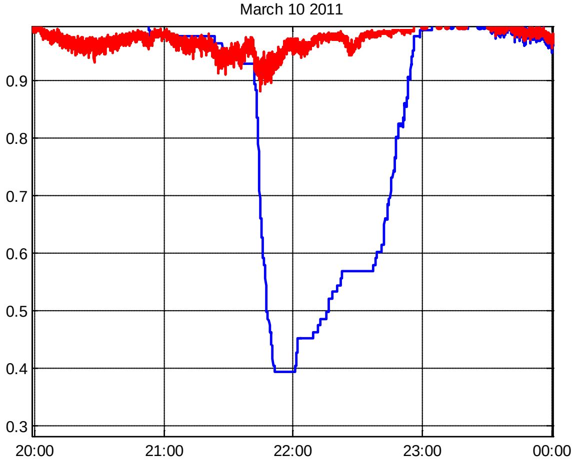


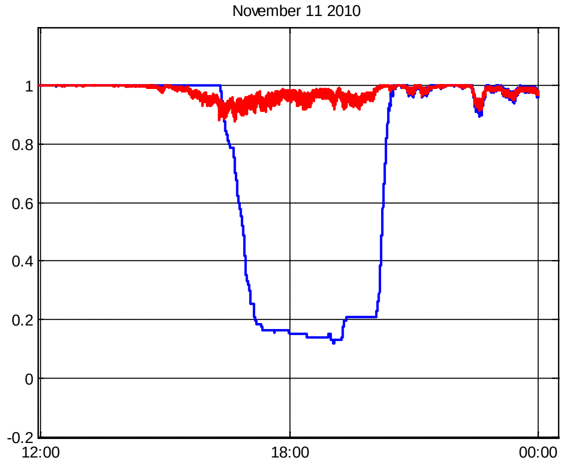
HWRT controller - SWP

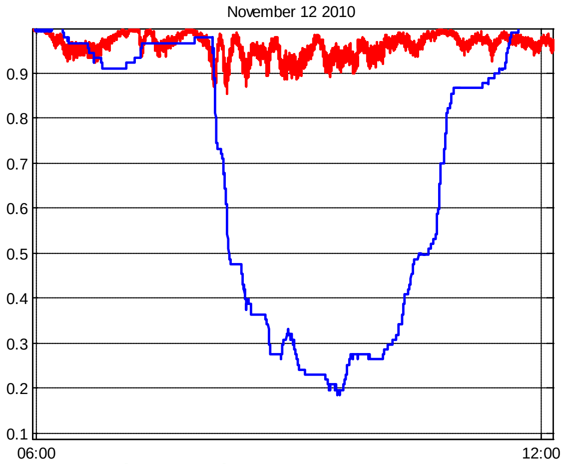


New storm control – Simulated power production


February 7 2011


March 10 2011


November 11 2010


November 12 2010

Replication work packages: barriers and up scaling

WP 15: Economic impacts of the demonstrations, barriers towards scaling up and solutions (Leader: IIT)

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WP 17: EU Offshore barriers (Leader: TENNET)

- Address the issues of **smart licensing of submarine interconnectors** with and without wind parks in the North Sea and Baltic Sea.
- Identify **common licensing barriers** and propose regulatory measures.

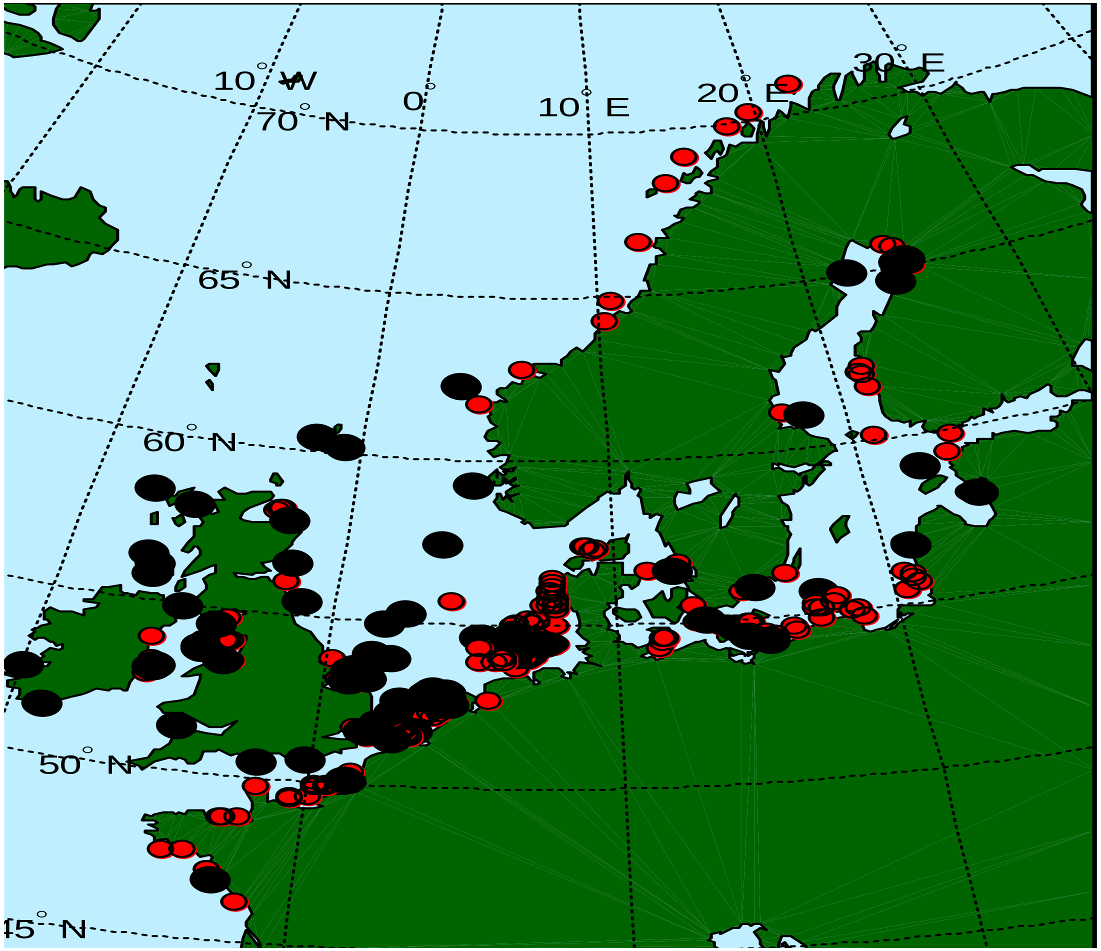
2020/2030 offshore wind scenarios

Country	MW installed end 2020		MW installed end 2030	
	Baseline	High	Baseline	High
Belgium	2,156	2,156	2156	3,956
Denmark	2,811	3,211	4,611	5,811
Estonia	0	0	1410	1,695
Finland	846	1,446	3785	4,933
France	3,275	3,935	5290	7,035
Germany	8,805	12,999	24,063	32382
Ireland	1,419	2,119	4319	3719
Latvia	0	0	400	1,100
Lithuania	0	0	1405	1,000
Netherlands	5,298	6,298	12,794	16,794
Norway	415	1,020	4215	5,540
Poland	500	500	5500	5,300
Sweden	2,239	3,129	5185	8215
UK	13,711	19,381	33601	48371
TOTAL	**41,475**	**56,194**	**108,734**	**145,851**

2020/2030 offshore wind scenarios

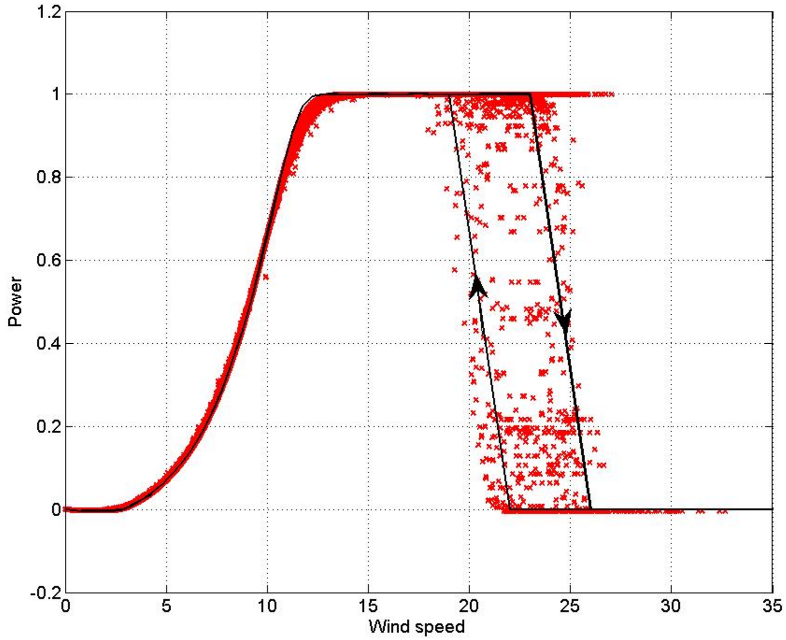
SA	2020		2030	
	Baseline	High	Baseline	High
UCTE	21,421	27,675	52,590	69,454
Nordel	4,924	7,019	15,009	20,512
UK+IR	15,130	21,500	37,920	52,090

2020/2030 offshore wind scenarios



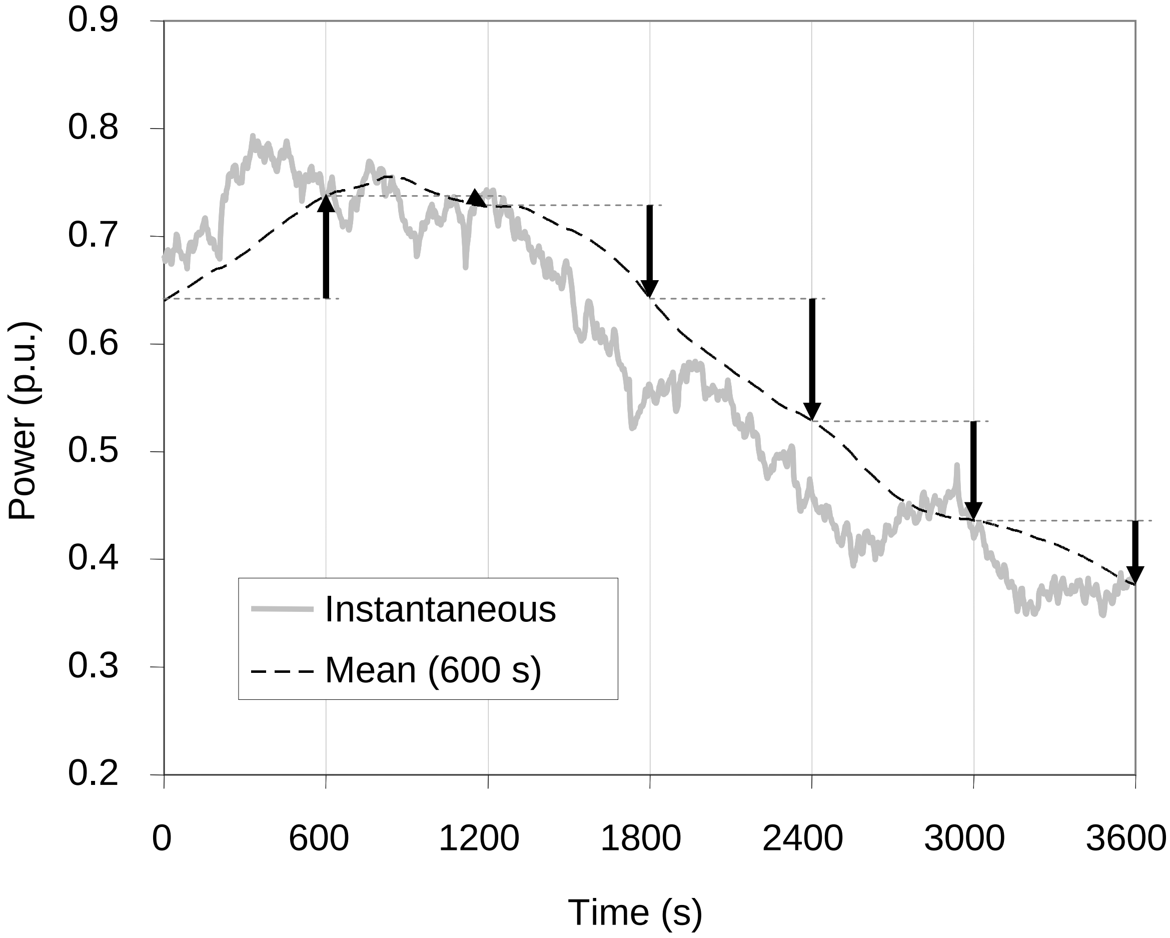
Time series

- Hourly wind speed data from mesoscale model for years 2001, 2005, 2008, 2009, 2010, 2011
- Stochastic part: 5 random seeds
- Time step: 5 minutes
- 15 min variability

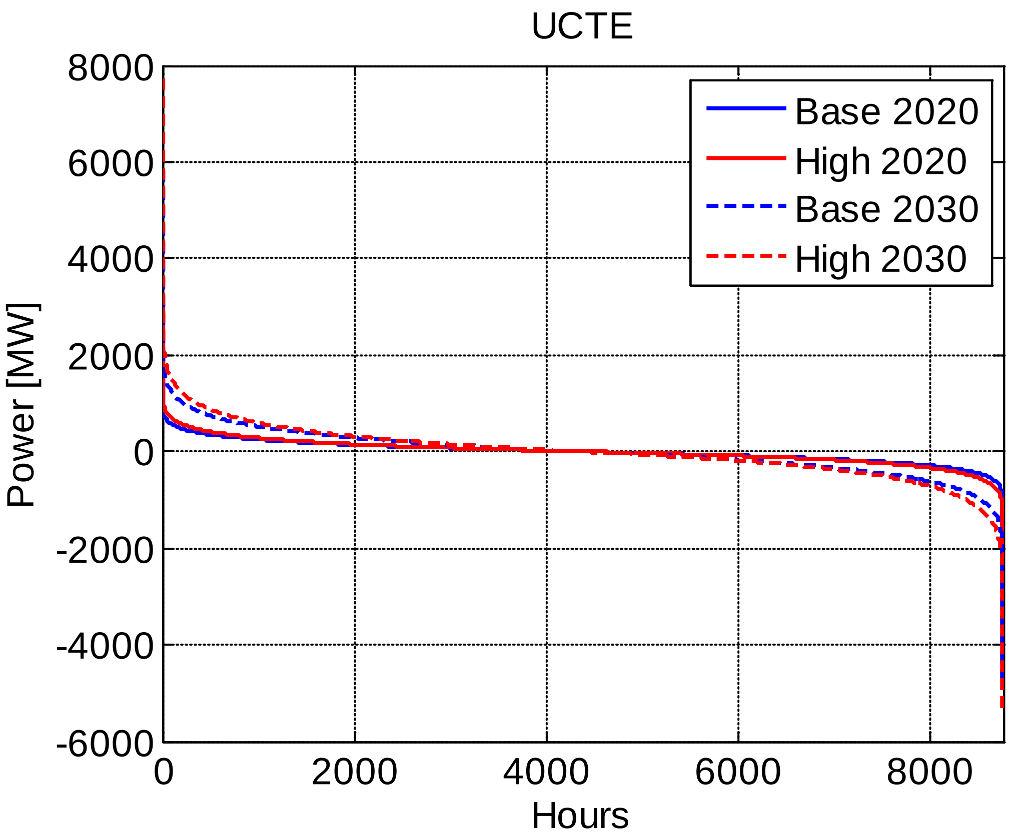


Ramp rates

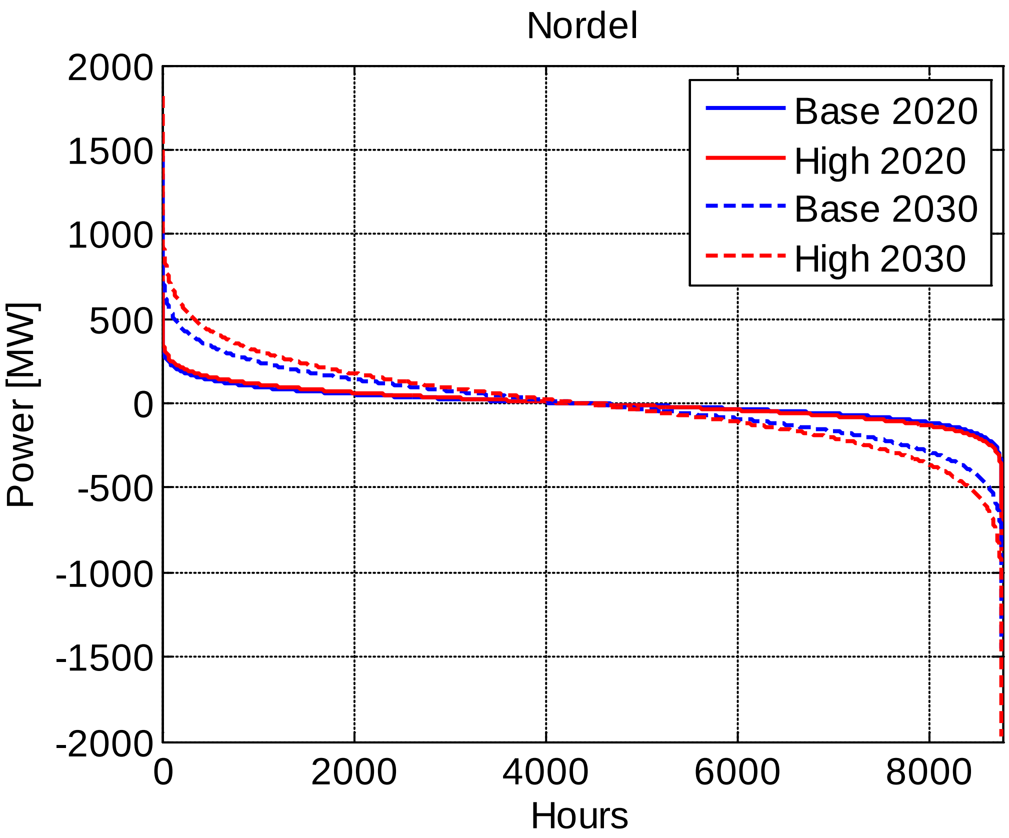
$$P_{\mathrm{ramp}}(n) = P_{\mathrm{mean}}(n+1) - P_{\mathrm{mean}}(n)$$



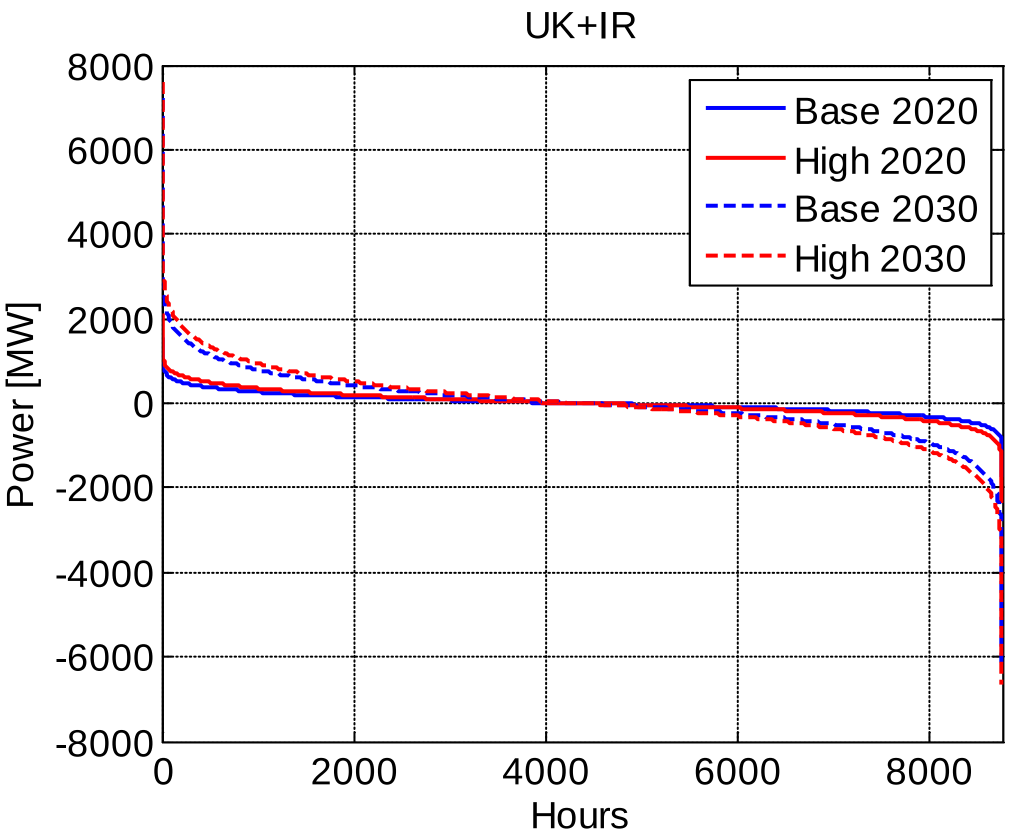
Results


UCTE
Power [MW]
8000
6000
4000
2000
0
-2000
-4000
-6000
0
2000
4000
6000
8000
Hours
Base 2020
High 2020
Base 2030
High 2030

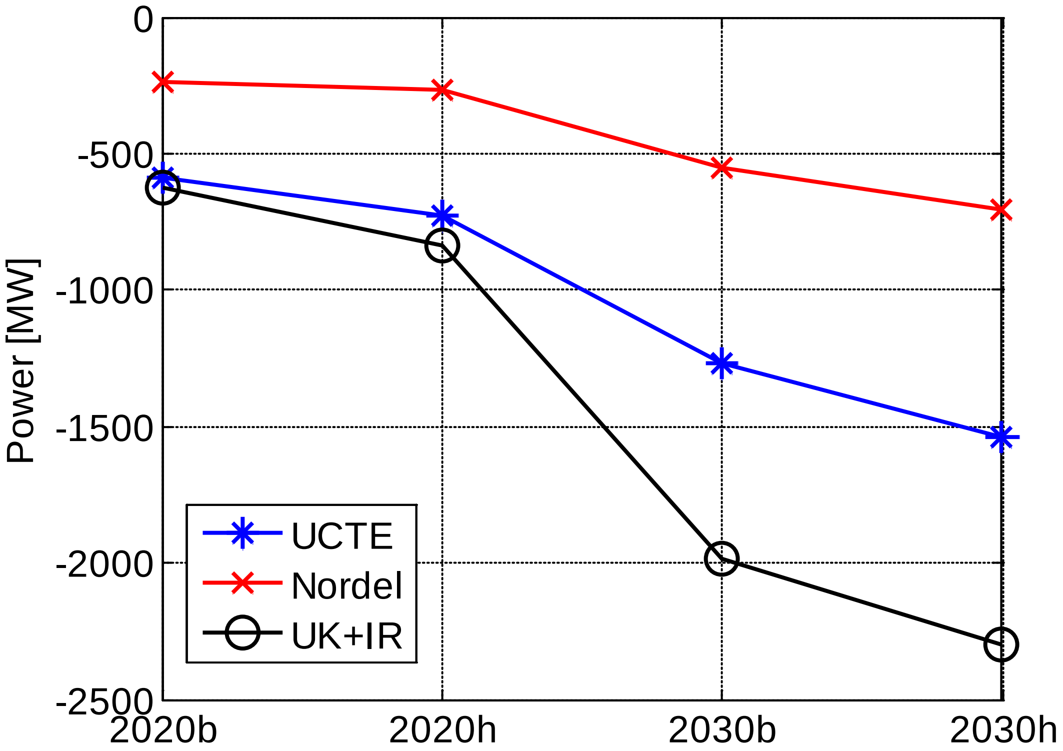
Results


Nordel
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
2000
4000
6000
8000
Hours
Power [MW]
Base 2020
High 2020
Base 2030
High 2030

Results


UK+IR
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
Power [MW]
0
2000
4000
6000
8000
Hours
Base 2020
High 2020
Base 2030
High 2030

Results – 99th percentile



Next steps

- Simulate the critical weather periods with the ”new storm controller”, calculate the reserve requirements and quantify the differences
- Deliver time series for further analysis of the intra-hour balancing in DK – SIMBA
- Simulate and evaluate the offshore wind power variability for 2020/2030 with the ”new storm controller”.

Next steps

Thank you

Annex 3

Twenties
Transmitting wind

TWENTIES project

Nicolaos Cutululis,
DTU Wind Energy
Technical University of Denmark

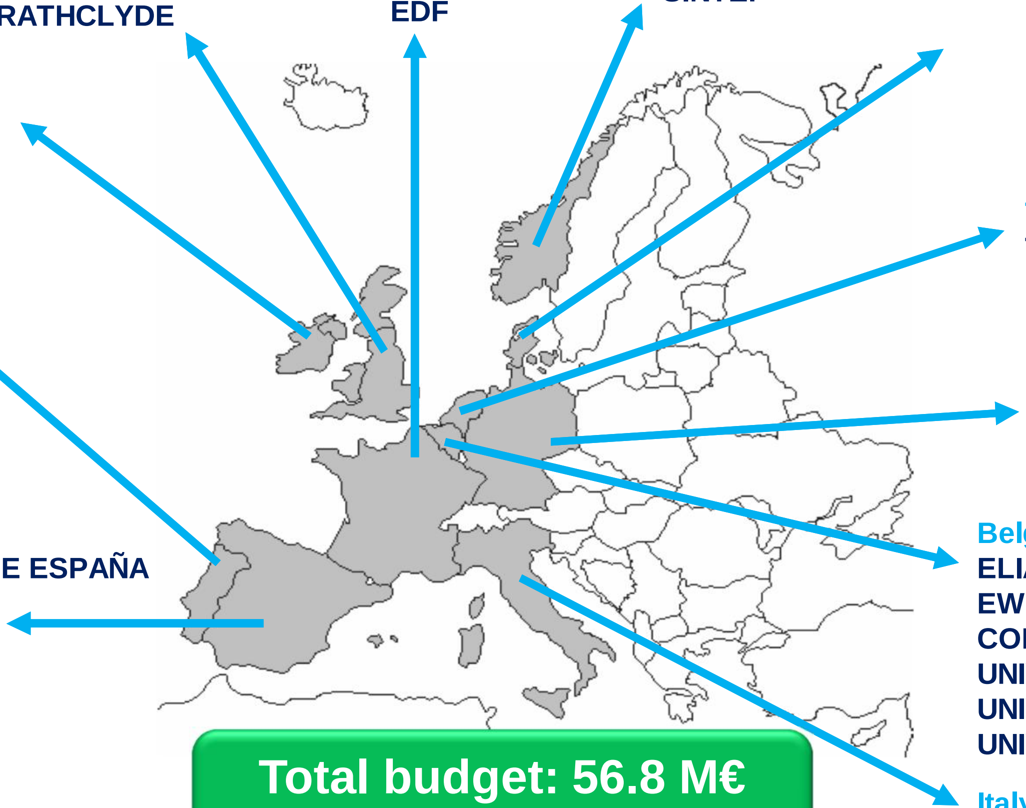
SEVENTH FRAMEWORK PROGRAMME

EUROPEAN COMMISION

IEA Wind, DTU participation phase 3, 22 May 2013, Helsinki

Consortium and budget

10 European Member States
1 Associated Country



United Kingdom (2)
ALSTOM GRID
UNIVERSITY OF STRATHCLYDE

France (2)
RTE
EDF

Norway
SINTEF

Denmark (3)
DONG ENERGY
ENERGINET
DTU ENERGY

Ireland
UCD

Portugal
INESC-PORTO

The Netherlands
TENNET

Germany (3)
FRAUNHOFER IWES
50 HzT
SIEMENS Wind Power

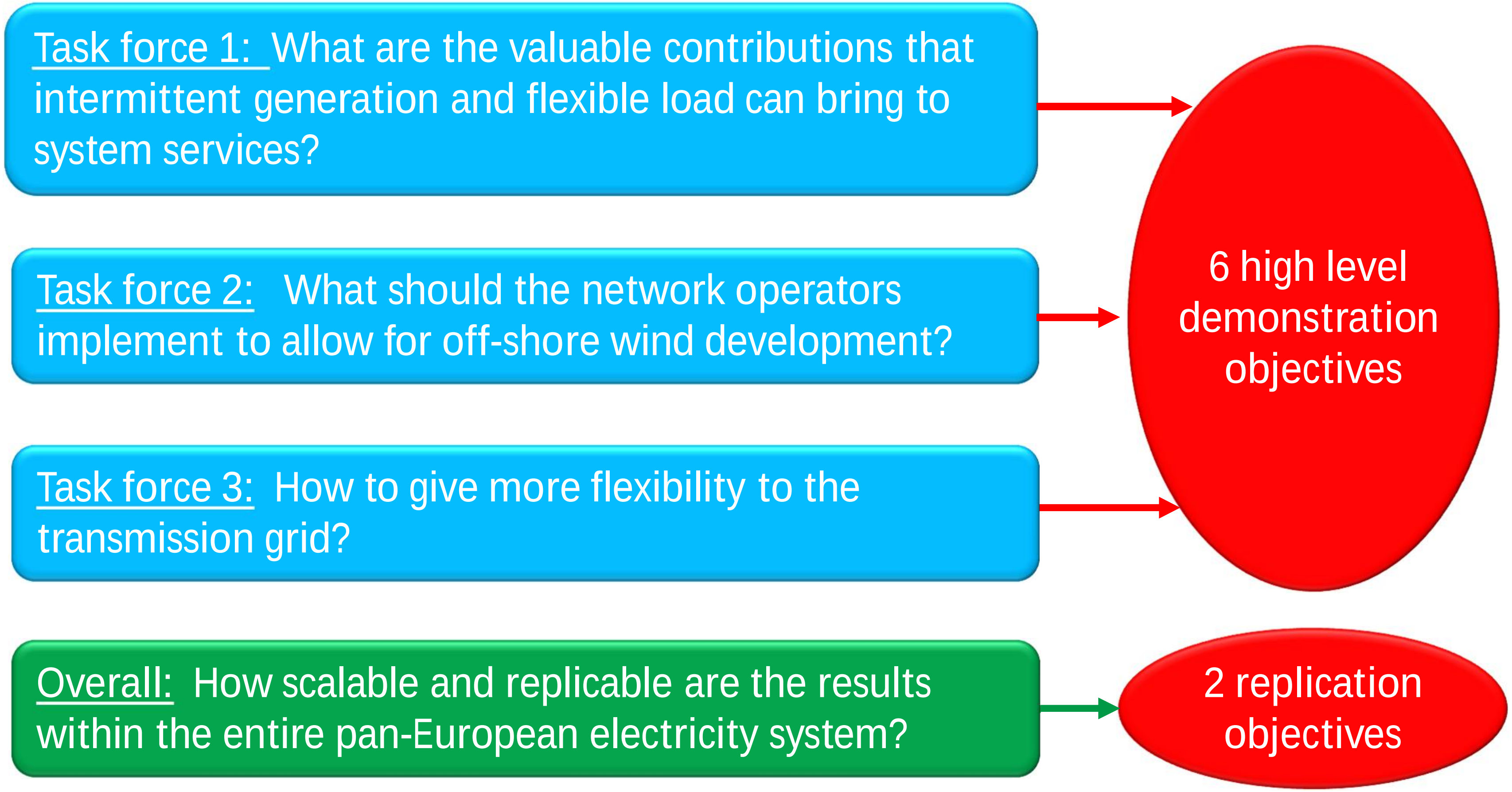
Spain (5)
RED ELECTRICA DE ESPAÑA
IBERDROLA
ITT COMILLAS
GAMESA
ABB S.A.

Belgium (6)
ELIA SYSTEM OPERATOR
EWEA
CORESO
UNIVERSITY LIEGE
UNIVERSITY LEUVEN
UNIVERSITE LIBRE BRUXELLES

Italy
RSE

Total budget: 56.8 M€
EU contribution: 31.8 M€

Project objectives



Task force 1: What are the valuable contributions that intermittent generation and flexible load can bring to system services?

Task force 2: What should the network operators implement to allow for off-shore wind development?

Task force 3: How to give more flexibility to the transmission grid?

6 high level demonstration objectives

Overall: How scalable and replicable are the results within the entire pan-European electricity system?

2 replication objectives

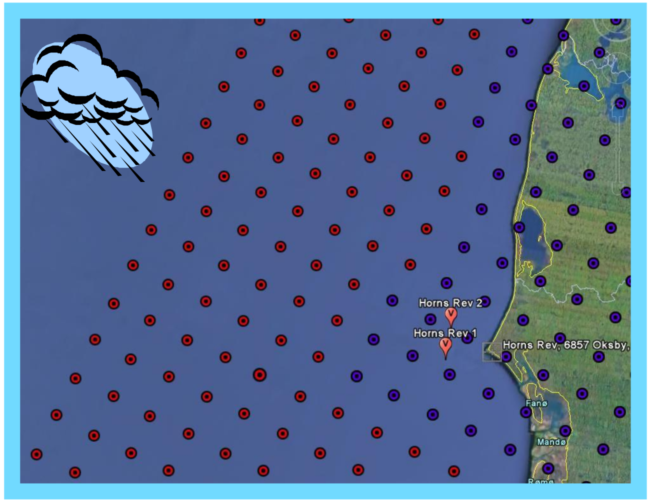
DEMO 4 STORM MANAGEMENT (Leader: ENERGINET)

Main objective

- Demonstrate shut down of wind farms under stormy conditions without jeopardizing safety of the system.

Approach

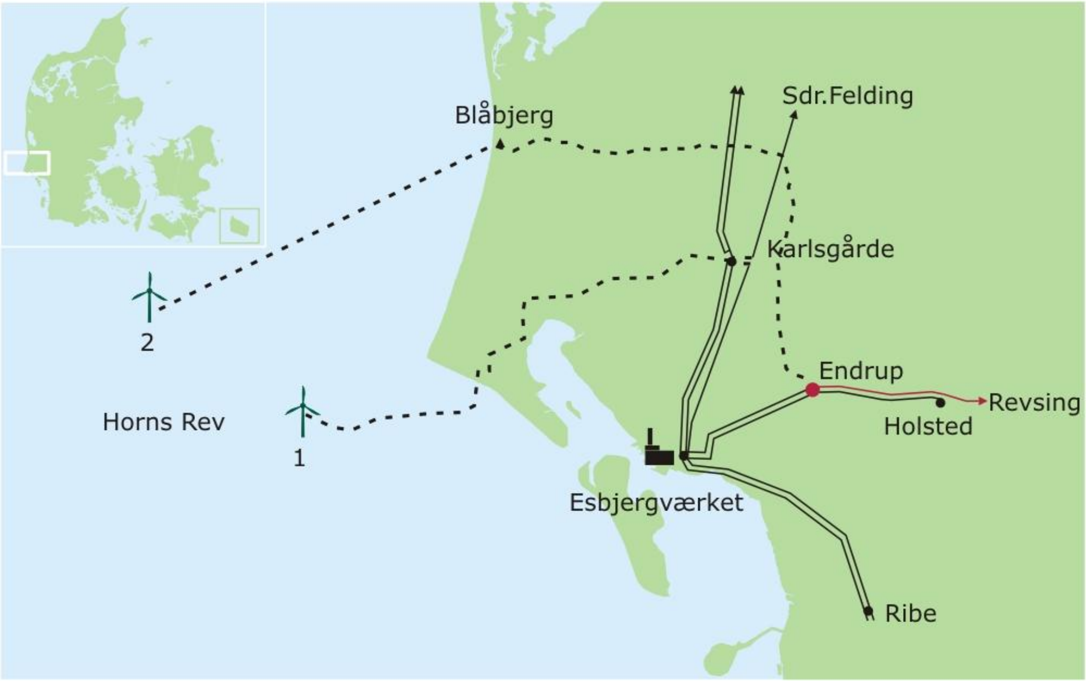
- Horns Rev 2 (200MW).
- Flexible turbine control.
- Storm front forecasts.
- Investigate cost of changed production associated with the planned down regulation.
- Coordinate wind farm control with HVDC interconnector control and with hydro power plant operation.

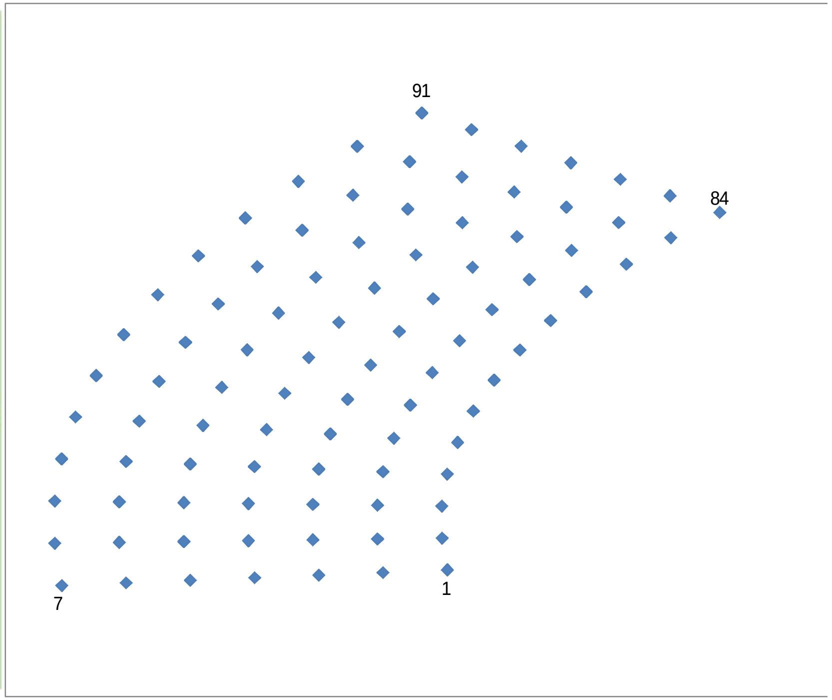


Wind power

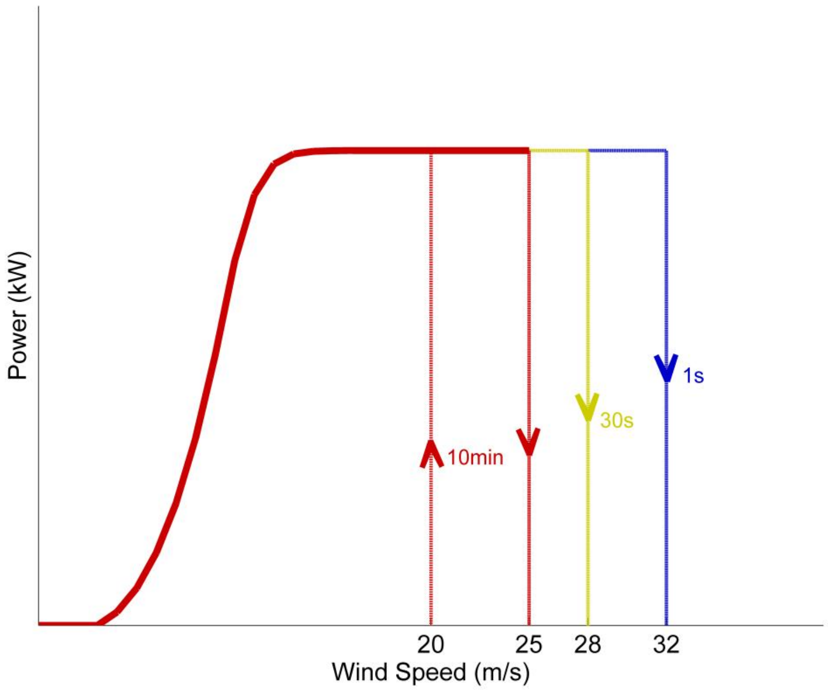
Water power

Horns Rev 2 wind farm location

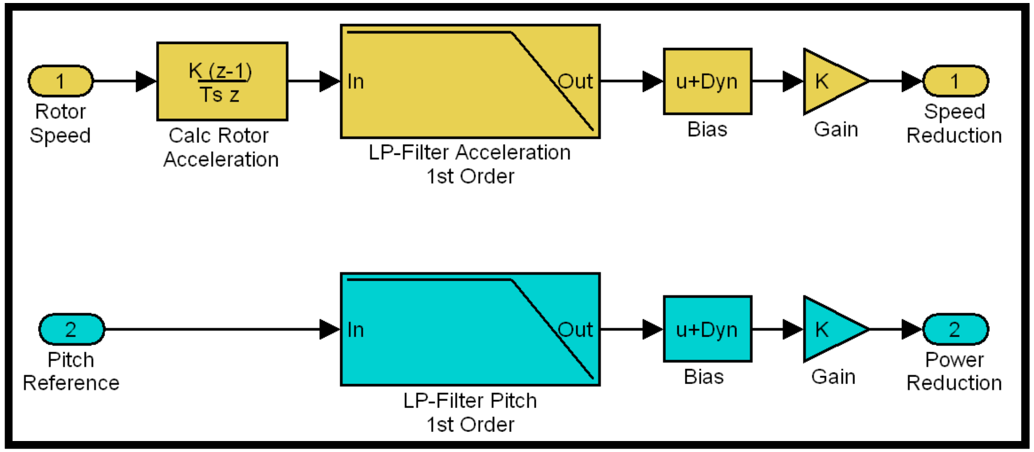




Wind turbine storm control (HWSD)



High Wind Ride Through™ - (HWRT)

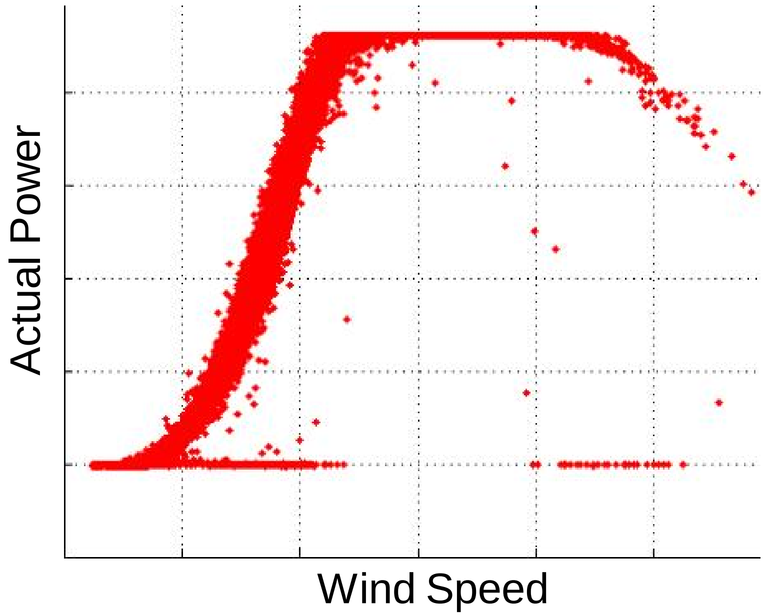


- Two systems work in parallel
- Curtail rotor speed by rotor acceleration
- Curtail actual power with pitch reference
- Bias and gain to determine curtailment

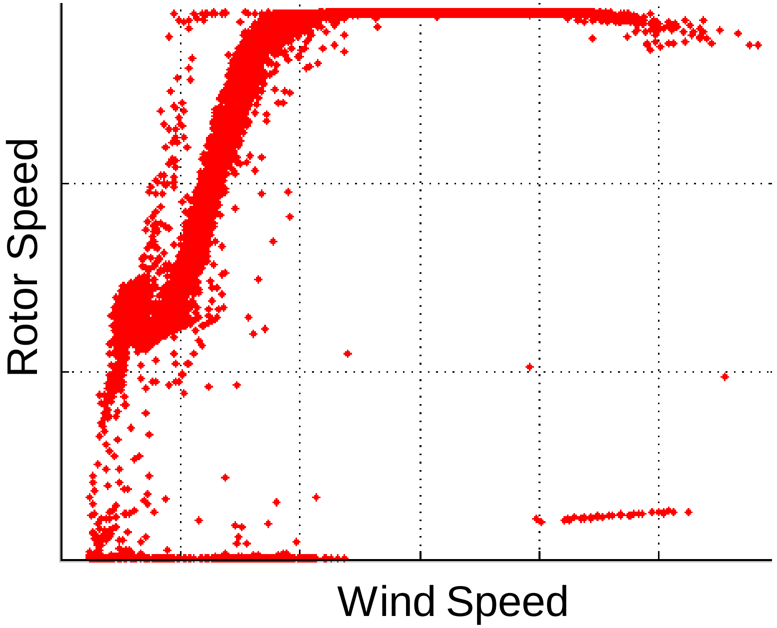
Controller:

High Wind Ride Through™ - (HWRT)

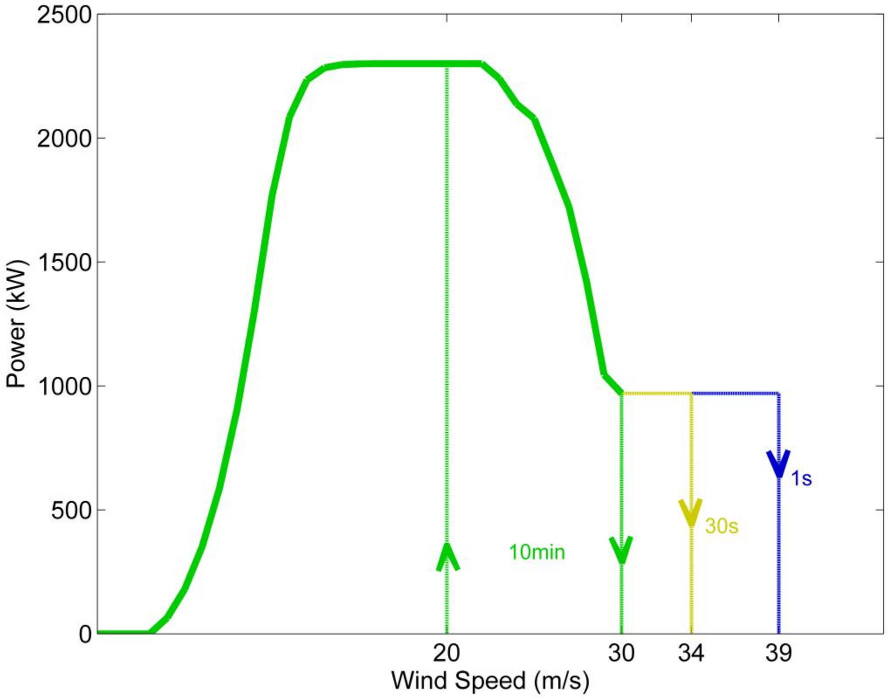
Actual Power vs Wind Speed



Rotor Speed vs Wind Speed



High Wind Ride Through™ - (HWRT)

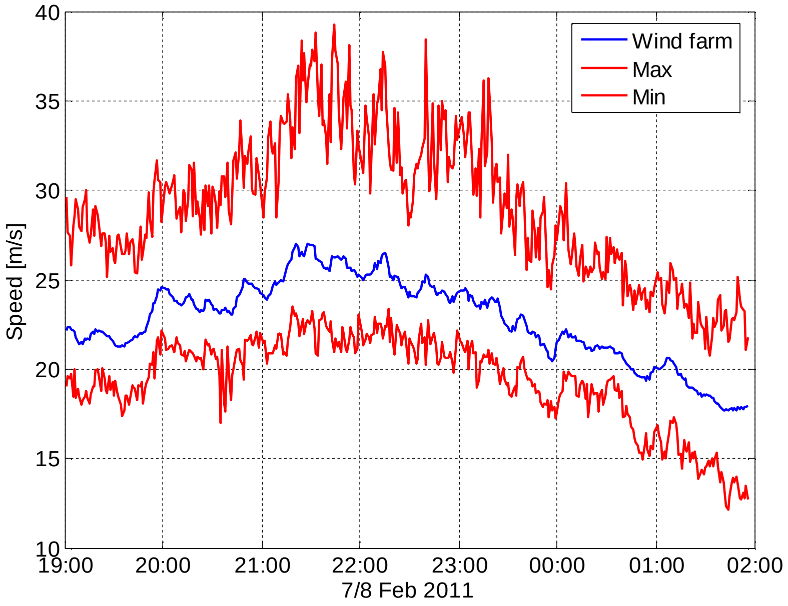


Storm events

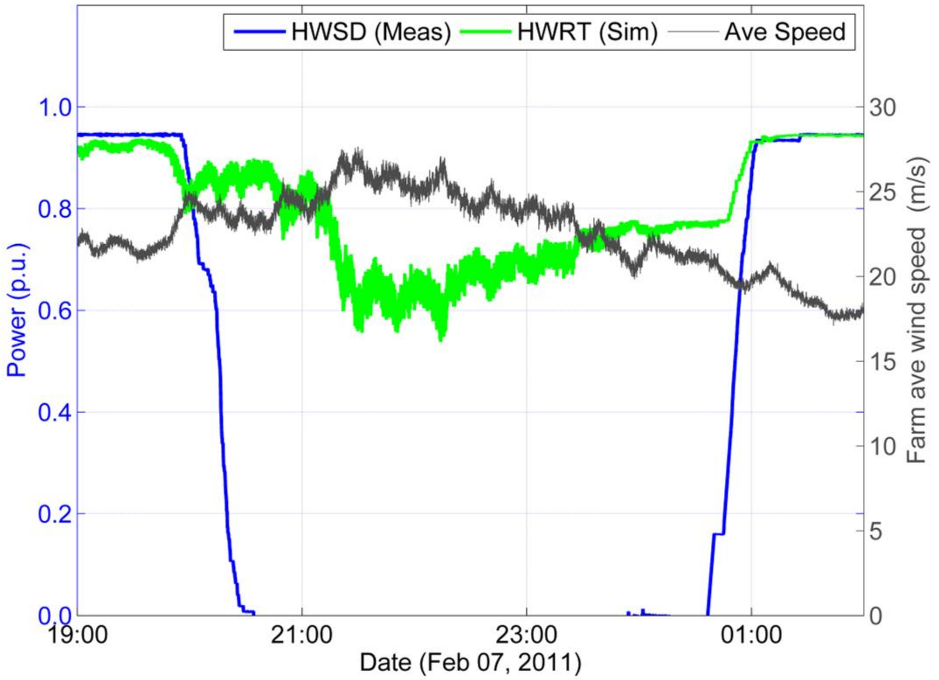
Event nr	Date	Controller
1	11-Nov-10	HWSD
2	12-Nov-10	HWSD
3	07-Feb-11	HWSD
4	24-Sep-12	HWRT
5	14-Dec-12	HWRT
6	30-Jan-13	HWRT

Legend:
HWSD - High Wind Shut Down;
HWRT - High Wind Ride Through

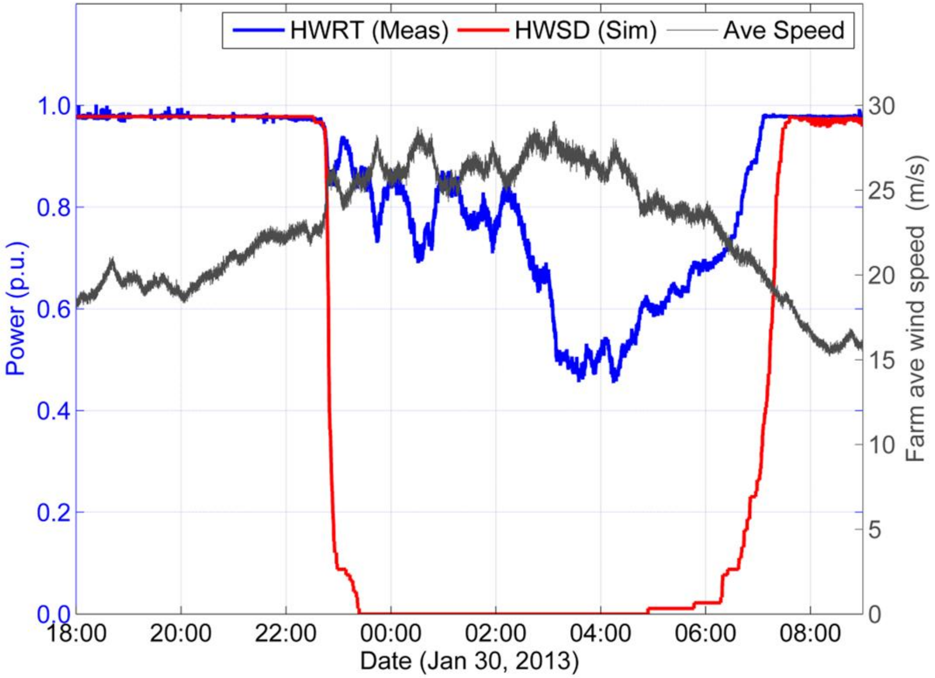
February 7-8 2011



February 7-8 2011

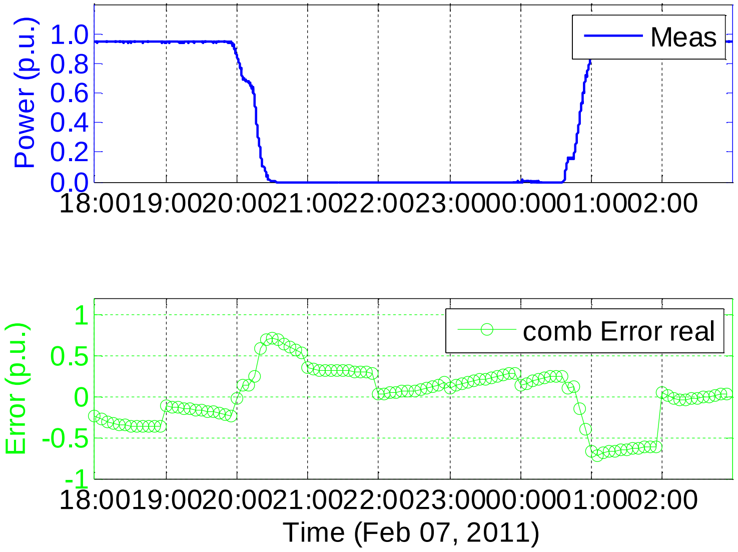


January 30, 2013

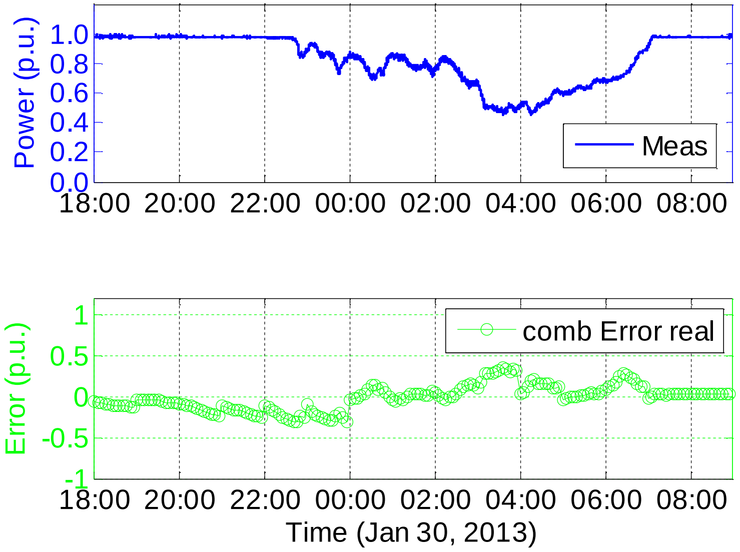


Wind turbine forecast error

February 7-8, 2011



January 30, 2013



Wind turbine forecast error

Event	Max forecast error [p.u.]	Average forecast error [p.u.]	Difference [p.u.]
11-Nov-10	0.80	0.77	0.51
12-Nov-10	0.80		
07-Feb-11	0.72		
24-Sep-12	0.26	0.26	
14-Dec-12	0.18		
30-Jan-13	0.35		

Replication work packages: barriers and up scaling

WP 15: Economic impacts of the demonstrations, barriers towards scaling up and solutions (Leader: IIT)

- Assess the local **economic and/or technological impact** of each demo.
- Identify the **barriers to scale-up** the outcomes at a member-state or regional level, and propose **solutions** to overcome these barriers.

WP 16: EU wide integrating assessment of demonstration replication potential (Leader: DTU Wind Energy)

- Assess **portability** of voltage control, frequency control and VPP model **to other countries and regions**.
- Evaluate North European 2020 **offshore wind power variability**, **hydro potential and barriers** and **grid restriction** studies.
- Pan European economic impact study.

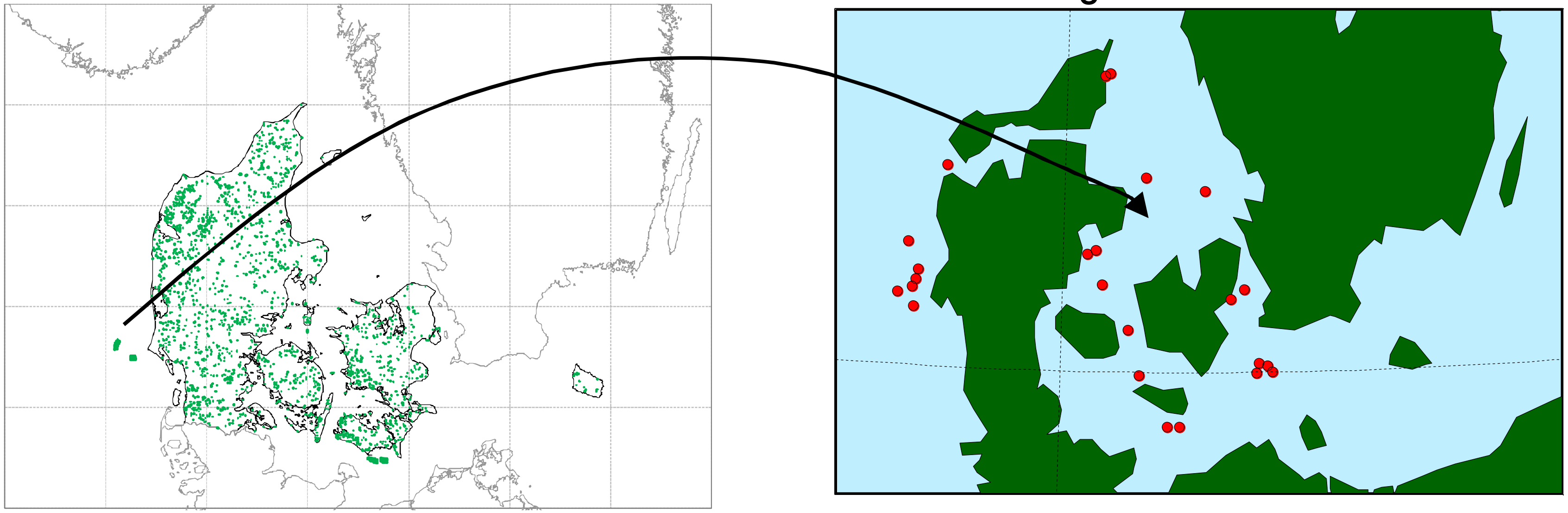
WP 17: EU Offshore barriers (Leader: TENNET)

- Address the issues of **smart licensing of submarine interconnectors** with and without wind parks in the North Sea and Baltic Sea.
- Identify **common licensing barriers** and propose regulatory measures.

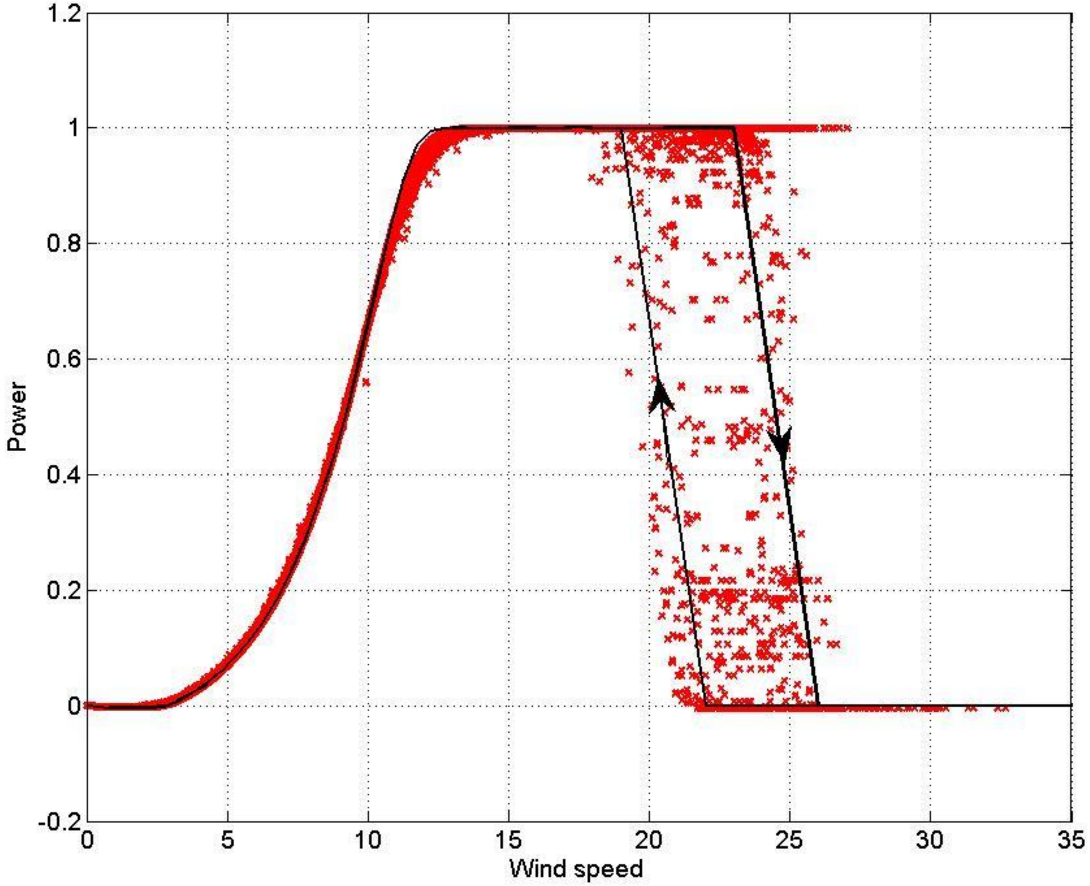
Upscaling of Horns Rev 2 to > 3 GW offshore wind

Base 2.811 MW

High: 3.211 MW



Wind farm storm control

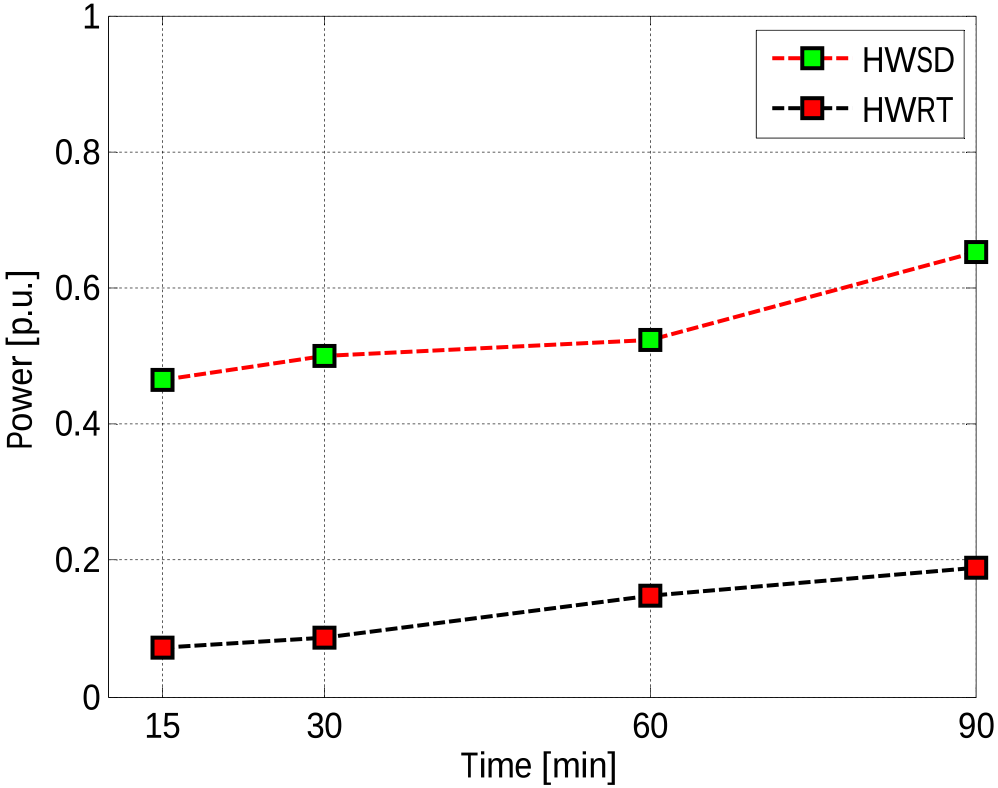


Critical weather periods

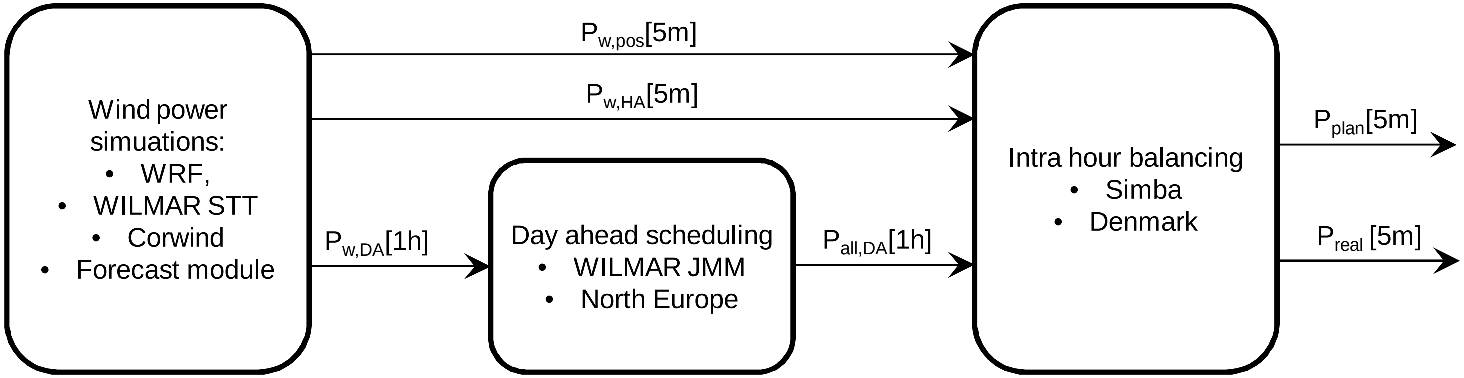
2001	01/01/2001
2005	02/01/2005
2007	01/01/2007
	08/01/2007
	18/03/2007
	27/06/2007
	08/11/2007
2008	25/01/2008
	27/02/2008
2008	21/03/2008
	13/08/2008
	08/11/2008
2009	11/06/2009
	03/10/2009
2010	11/11/2010
	07/02/2010
2011	10/03/2011

Max ramping during storms

$$P_{\text{res}}(n) = P_{\text{mean}}\left[t(n) - T_{ave}\ ; t(n)\right] - P_{\min}\left[t(n)\ ; t(n) + T_{win}\right]$$



Simba + WILMAR Intra hour balancing in storm events



Wind power simuations:
- WRF,
- WILMAR STT
- Corwind
- Forecast module

Day ahead scheduling
- WILMAR JMM
- North Europe

Intra hour balancing
- Simba
- Denmark

Summary

- Wind power forecast error reduced by 50% (of installed capacity)
- Maximum ramping reduced more than three times

Thank you

Annex 4

Twenties
Transmitting wind

TWENTIES – Wind power variability results

Nicolaos A. Cutululis,

DTU Wind Energy

Technical University of Denmark

SEVENTH FRAMEWORK PROGRAMME

EUROPEAN COMMISION

Concept-Idea

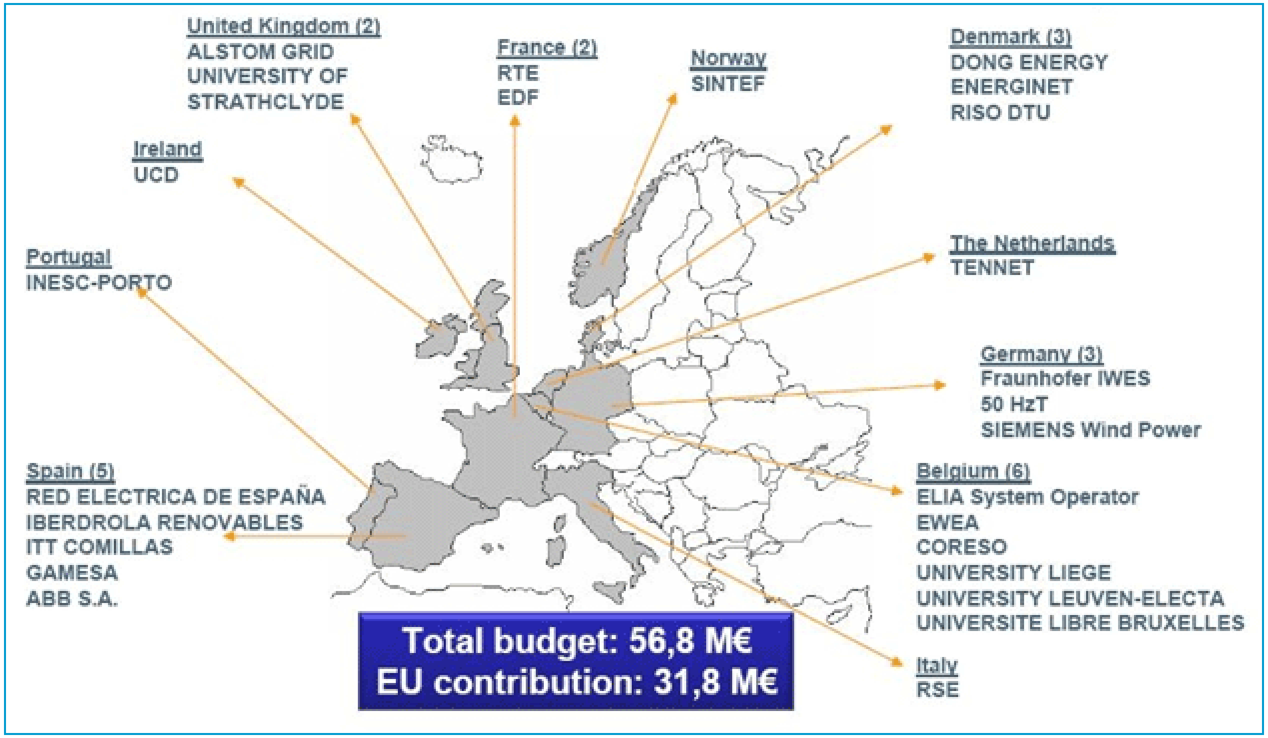
The TWENTIES project aims at:

*“**demonstrating** by early 2014 through real life, large scale demonstrations, **the benefits and impacts of several critical technologies** required to **improve the pan-European transmission network,** thus giving Europe a capability of responding to the increasing share of renewable in its **energy mix by 2020** and beyond while **keeping its present level of reliability performance.”***

To this extent it will be focused in removing several barriers which prevent:

- **pan European electric system** from welcoming more **renewable generated electricity.**
- **renewable-generated electricity** from contributing more efficiently **to the single European electric market.**

Project Partners and budget



United Kingdom (2)
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50 HzT
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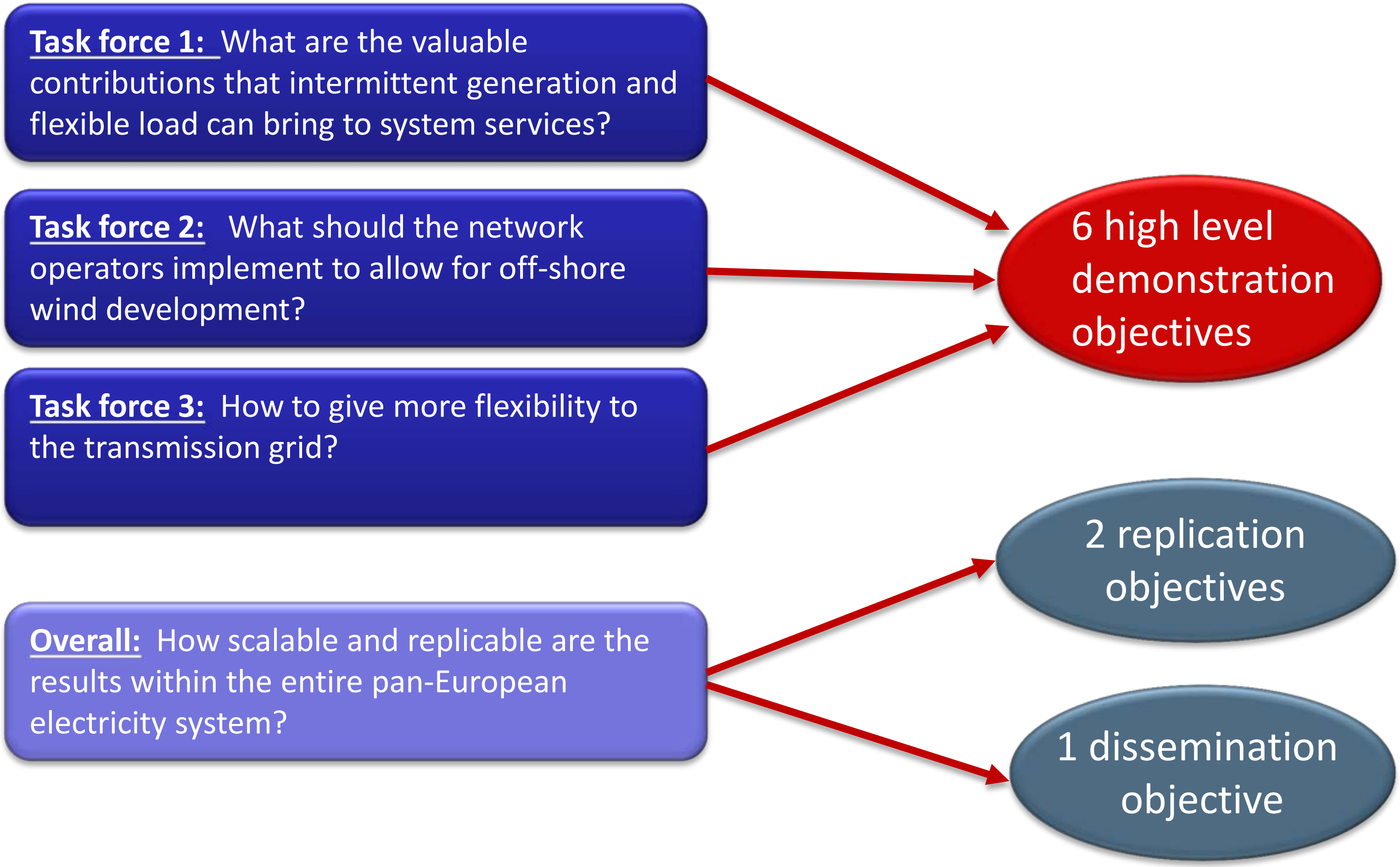
Spain (5)
RED ELECTRICA DE ESPAÑA
IBERDROLA RENOVABLES
ITT COMILLAS
GAMESA
ABB S.A.

Belgium (6)
ELIA System Operator
EWEA
CORESO
UNIVERSITY LIEGE
UNIVERSITY LEUVEN-ELECTA
UNIVERSITE LIBRE BRUXELLES

Italy
RSE

Total budget: 56,8 M€
EU contribution: 31,8 M€

Project objectives



Task force 1: What are the valuable contributions that intermittent generation and flexible load can bring to system services?

Task force 2: What should the network operators implement to allow for off-shore wind development?

Task force 3: How to give more flexibility to the transmission grid?

Overall: How scalable and replicable are the results within the entire pan-European electricity system?

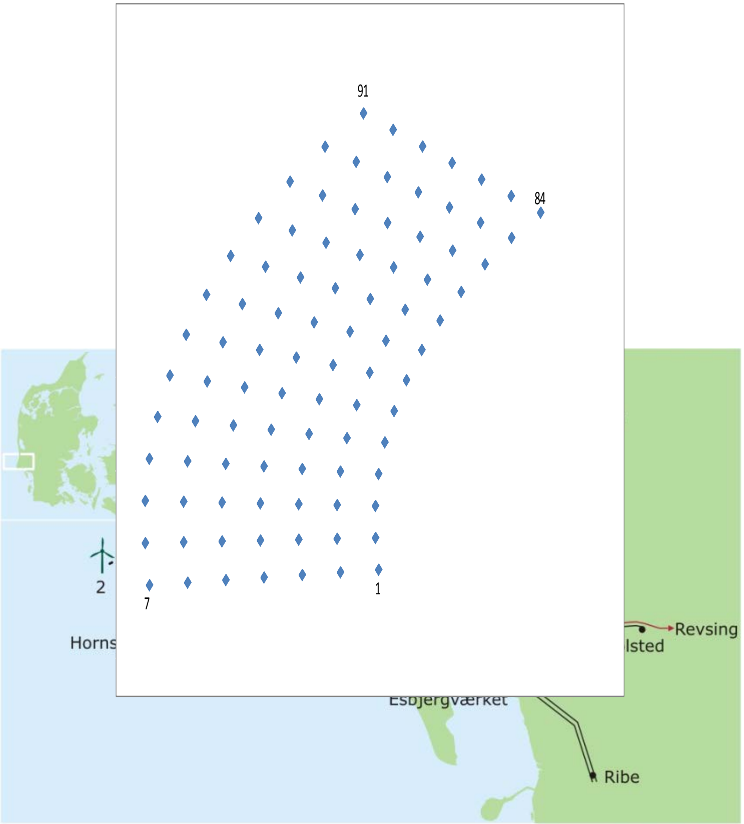
6 high level demonstration objectives

2 replication objectives

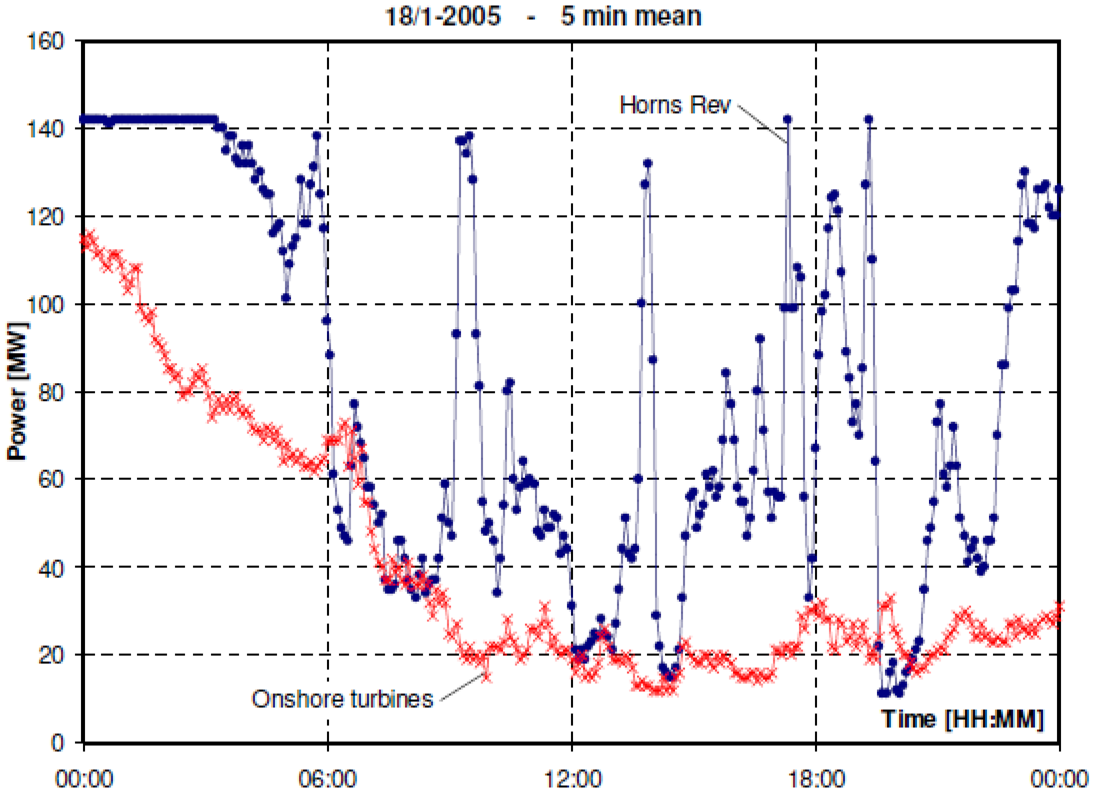
1 dissemination objective

Storm Demonstration

- Lead by Energinet.dk
- Horns Rev 2 wind farm owned by DONG Energy
- 91 x 2.3 MW Siemens wind turbines
- Siemens turbines built with conventional storm control
- Siemens developed and installed High Wind Ride Through™ - (HWRT)
- DTU simulated and analysed impact on forecast errors



Why?

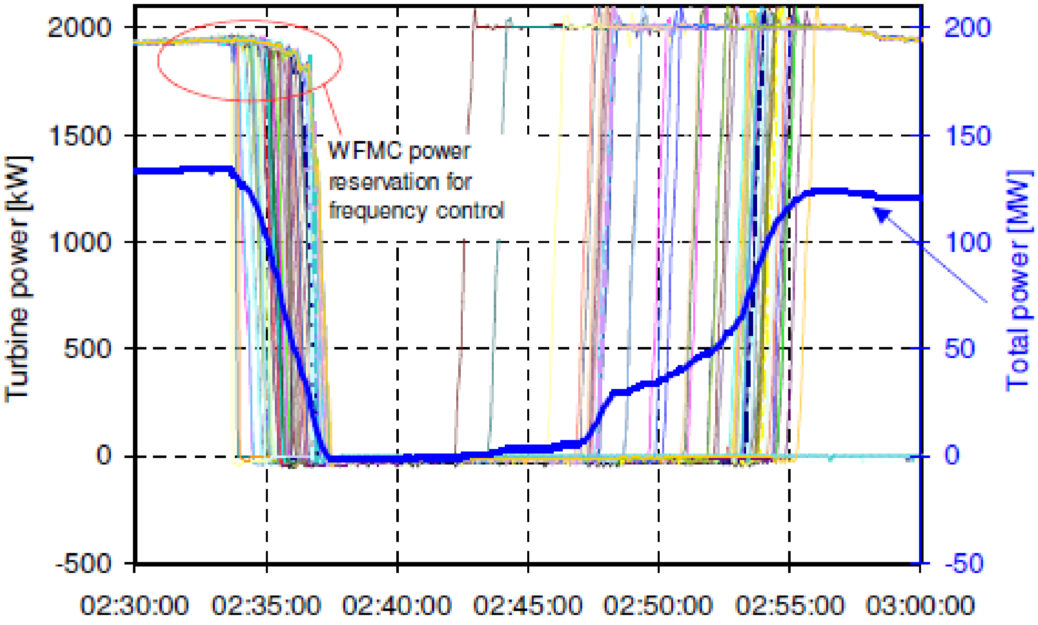


DONG energy

VATTENFALL

Jesper R. Kristoffersen, “*The Horns Rev Wind Farm and the Operational Experience with the Wind Farm Main Controller*”, Copenhagen Offshore Wind 2005, 26-28 October 2005

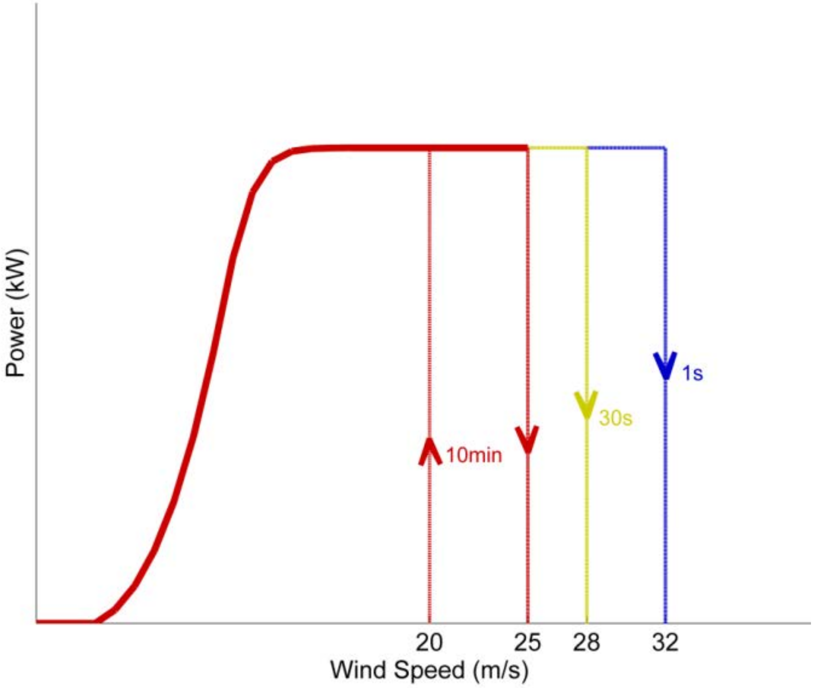
Why?



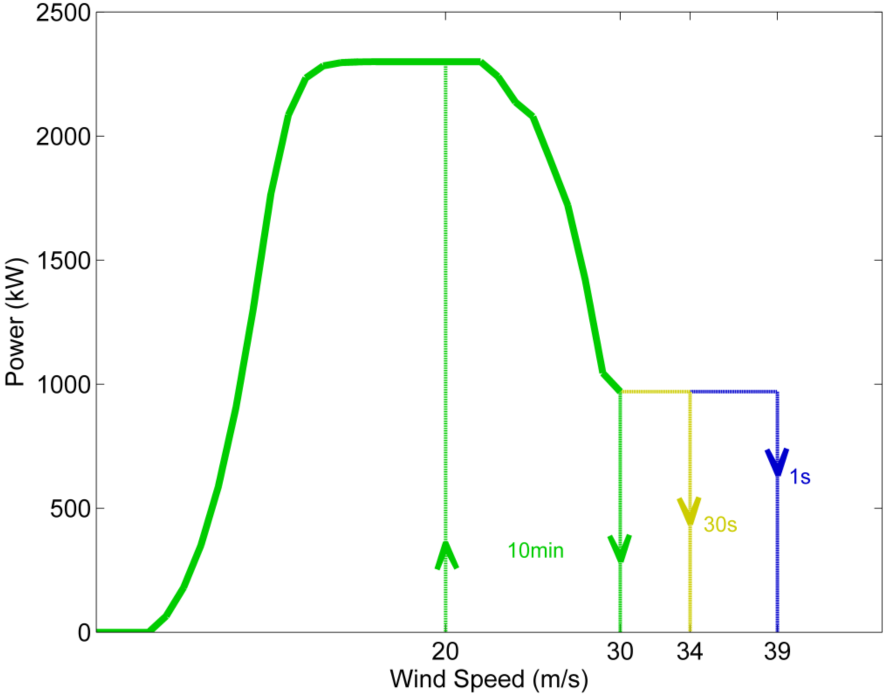
Jesper R. Kristoffersen, "*The Horns Rev Wind Farm and the Operational Experience with the Wind Farm Main Controller*", Copenhagen Offshore Wind 2005, 26-28 October 2005

Wind turbine storm control

HWSD



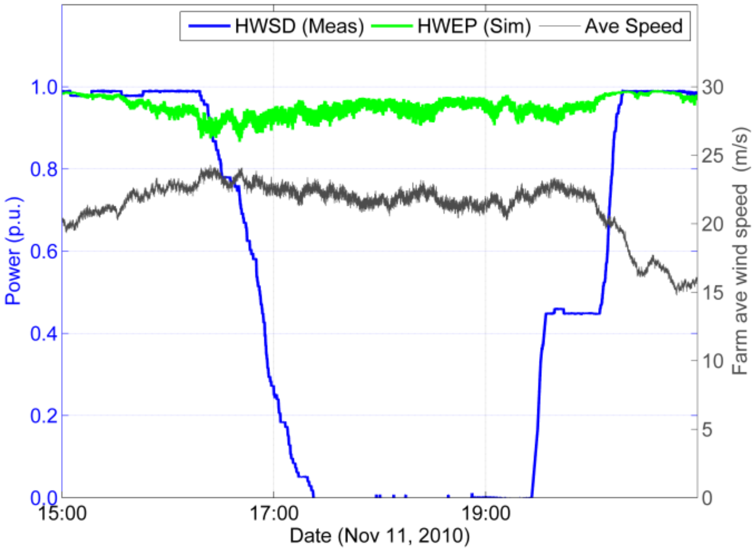
HWEP



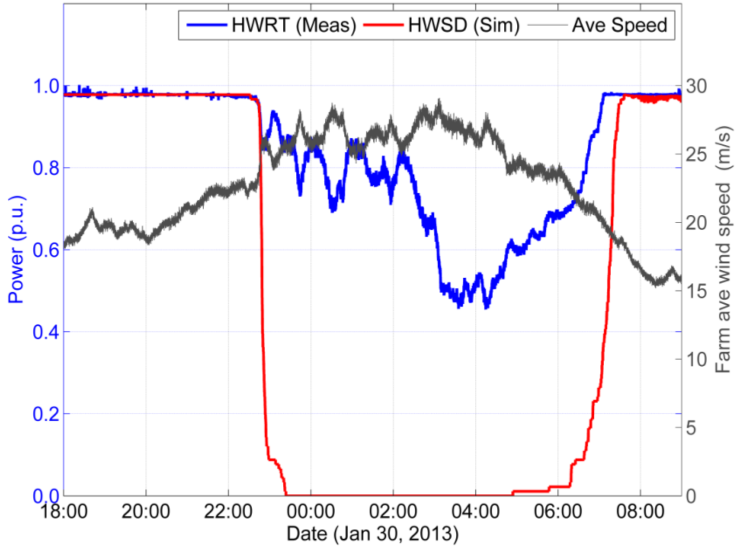
Recorded events

Event nr	Date	Controller
1	11-Nov-10	HWSD
2	12-Nov-10	HWSD
3	07-Feb-11	HWSD
4	24-Sep-12	HWRT
5	14-Dec-12	HWRT
6	30-Jan-13	HWRT

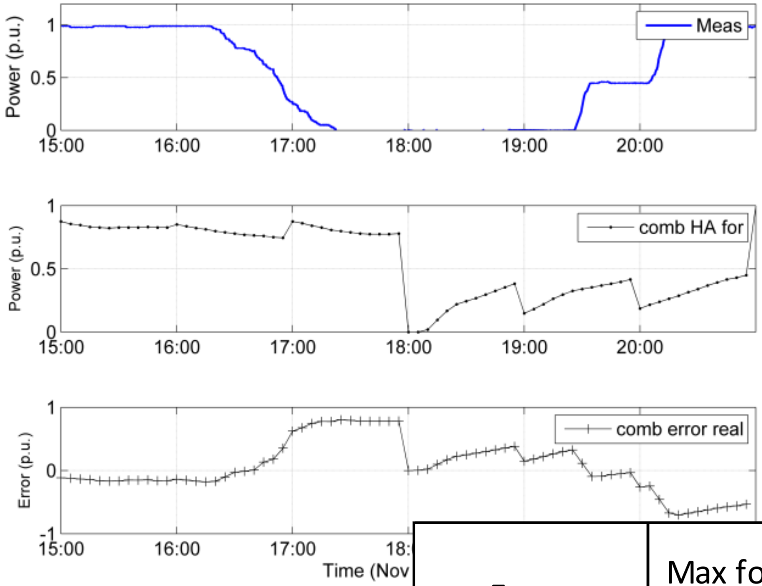
Legend:
HWSD - High Wind Shut Down;
HWRT - High Wind Ride Through

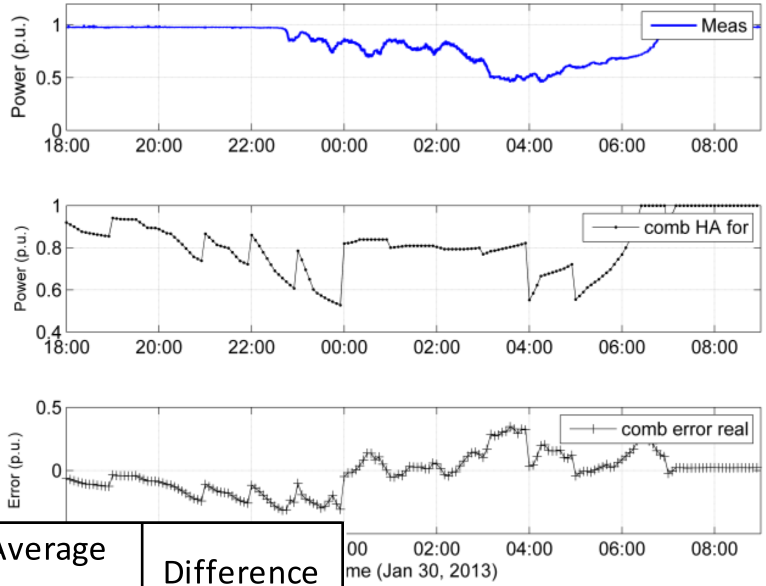


Animation



Forecast error



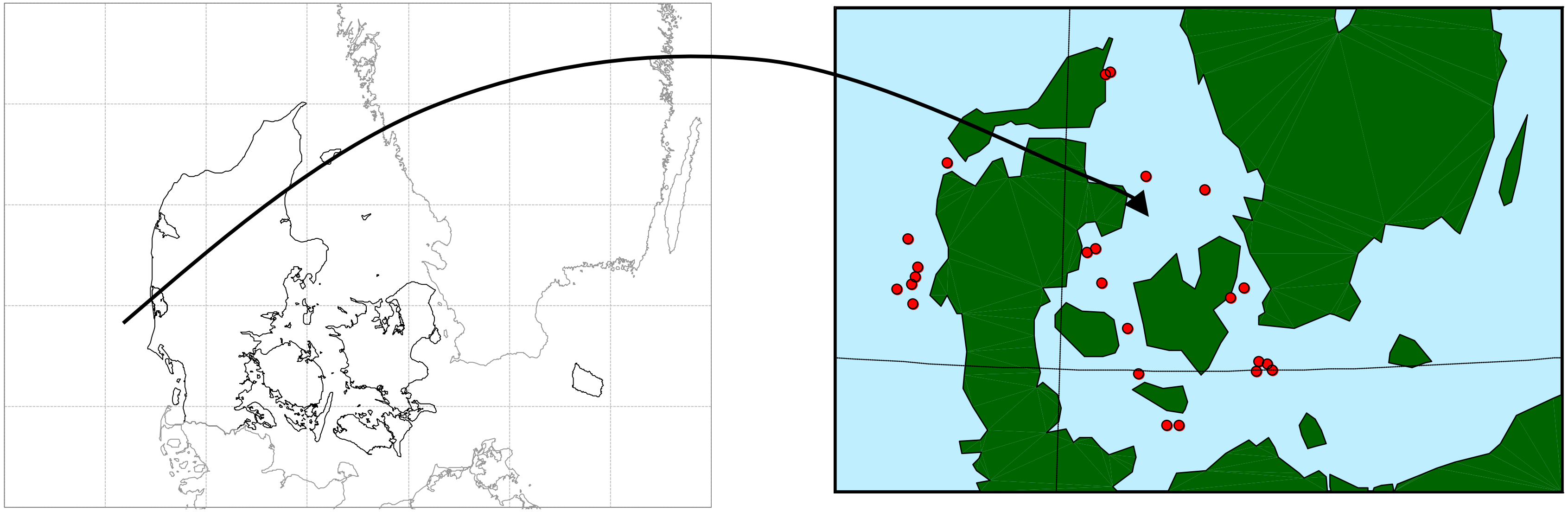


Event	Max forecast error [p.u.]	Average forecast error [p.u.]	Difference [p.u.]
11-Nov-10	0.80	0.77	0.51
12-Nov-10	0.80		
07-Feb-11	0.72		
24-Sep-12	0.26	0.26	
14-Dec-12	0.18		
30-Jan-13	0.35		

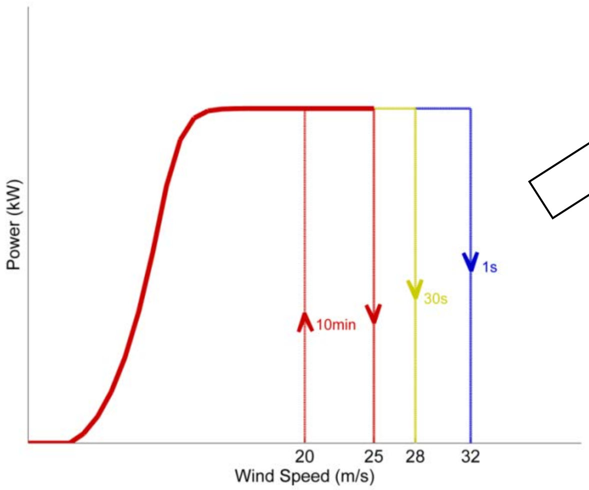
Upscaling of Horns Rev 2 to > 3 GW offshore wind

2020: 2.8 GW

2030: 4.6 GW

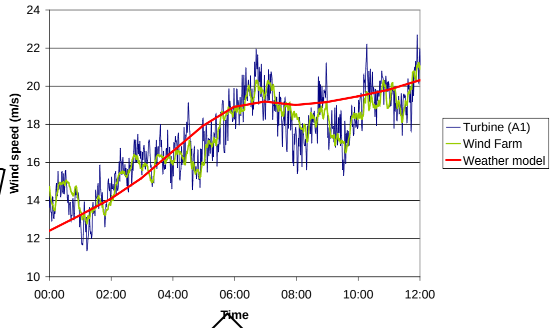


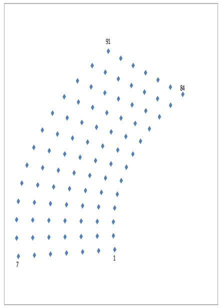
Aggregation of wind farms



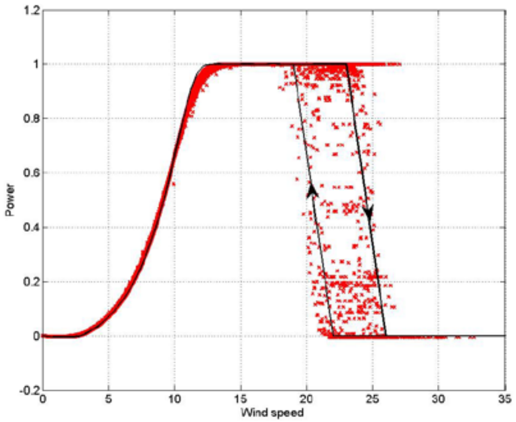
Wind turbine
model

Corwind
simulation





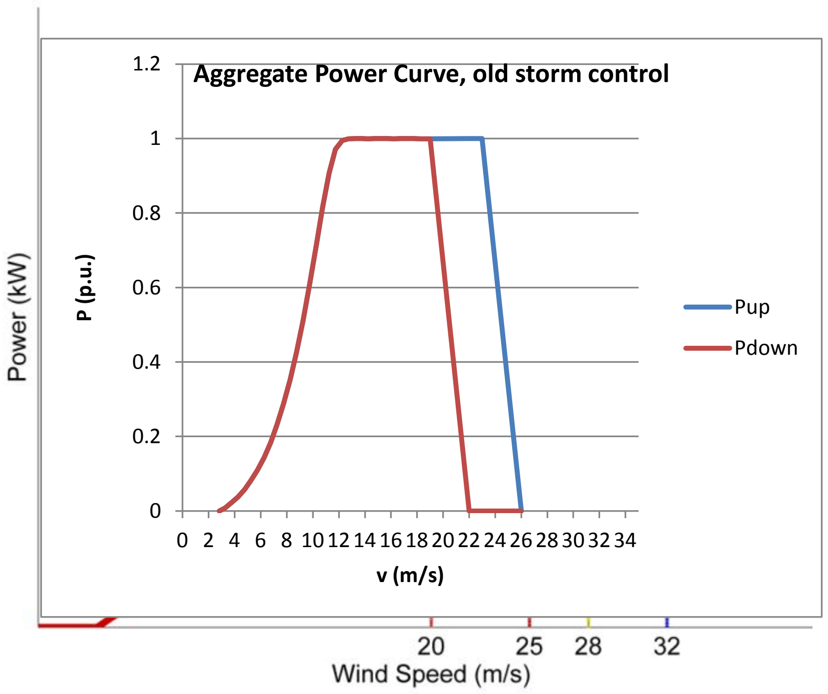
Wind farm
layout



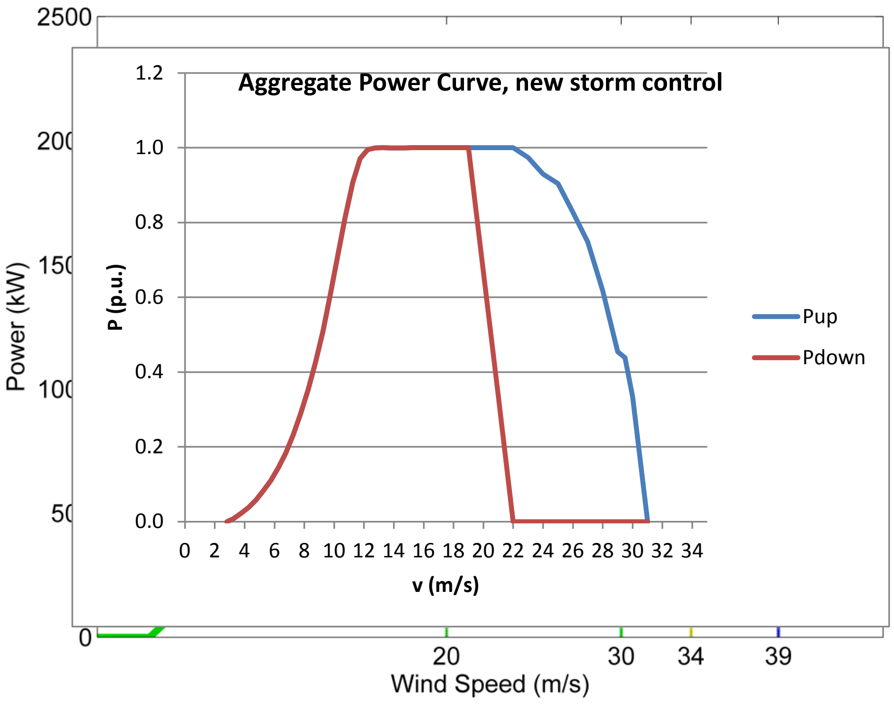
Wind farm
power vs. wind speed

Aggregated wind farm models

HWSD



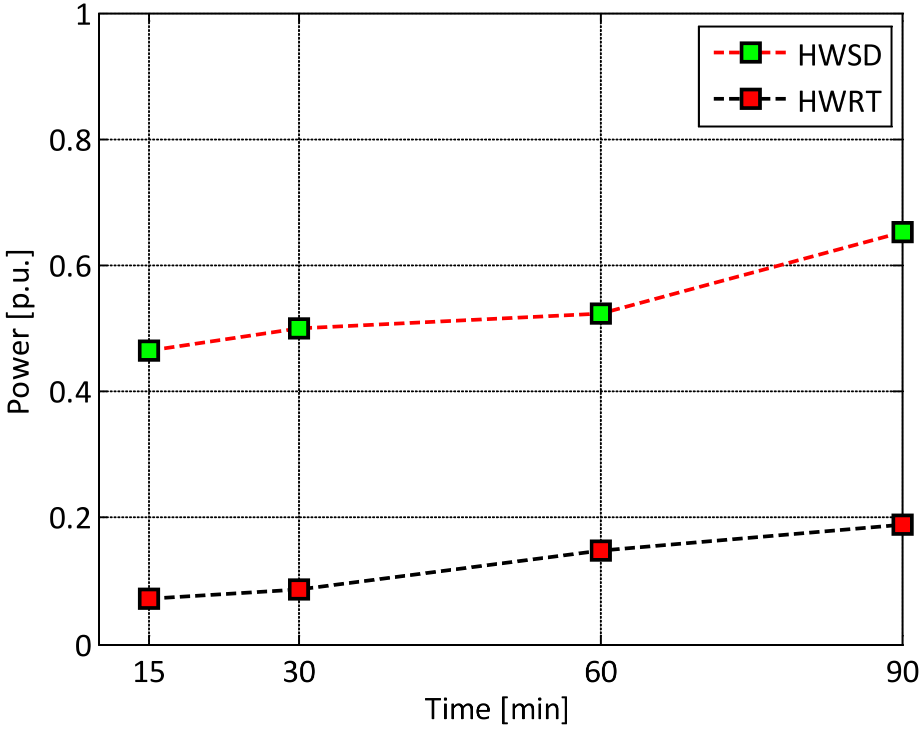
HWEP



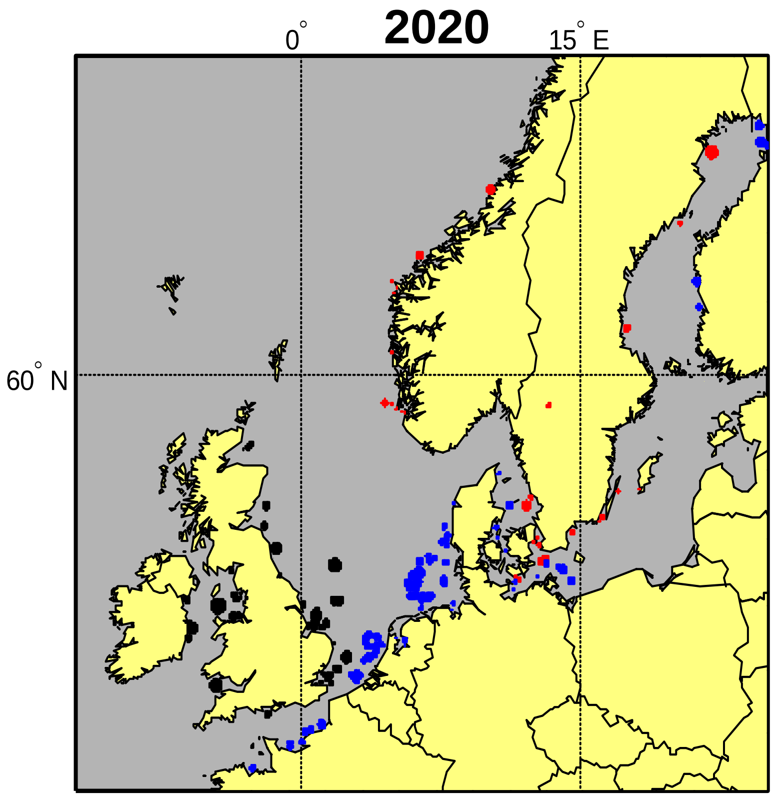
Max ramping during storms – 2020

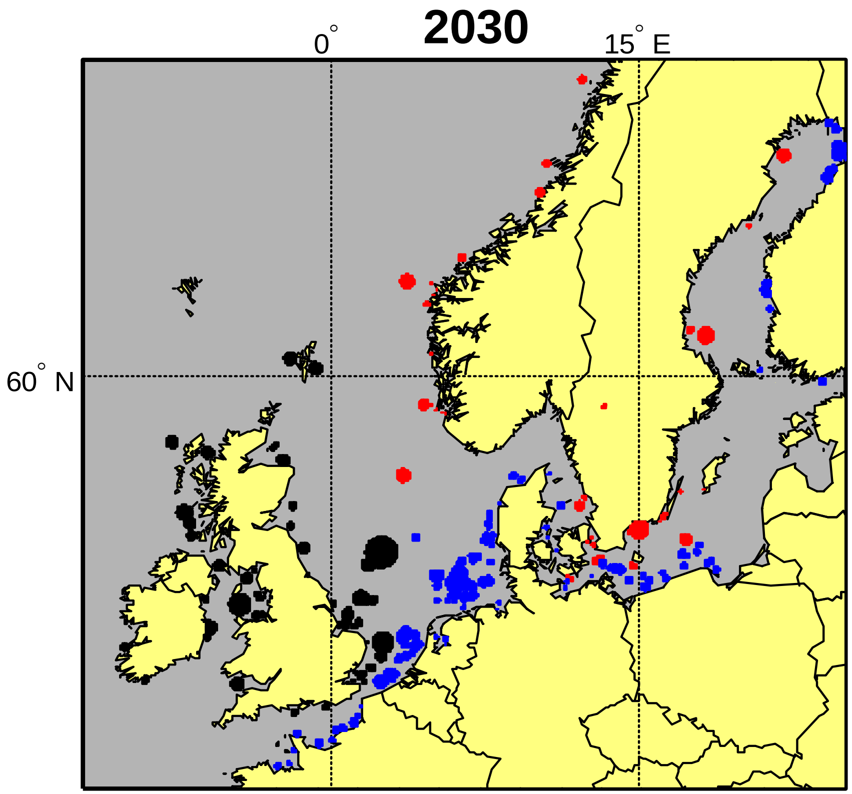
$$P_{\text{ramp-max}}(n) = P_{\text{mean}}\left[t(n) - T_{ave}\,;t(n)\right] - P_{\min}\left[t(n)\,;t\,(n) + T_{win}\right]$$

2001	01/01/2001	**2008**	21/03/2008
2005	02/01/2005		13/08/2008
2007	01/01/2007		08/11/2008
	08/01/2007	**2009**	11/06/2009
	18/03/2007		03/10/2009
	27/06/2007	**2010**	11/11/2010
	08/11/2007		07/02/2010
2008	25/01/2008	**2011**	10/03/2011
	27/02/2008		



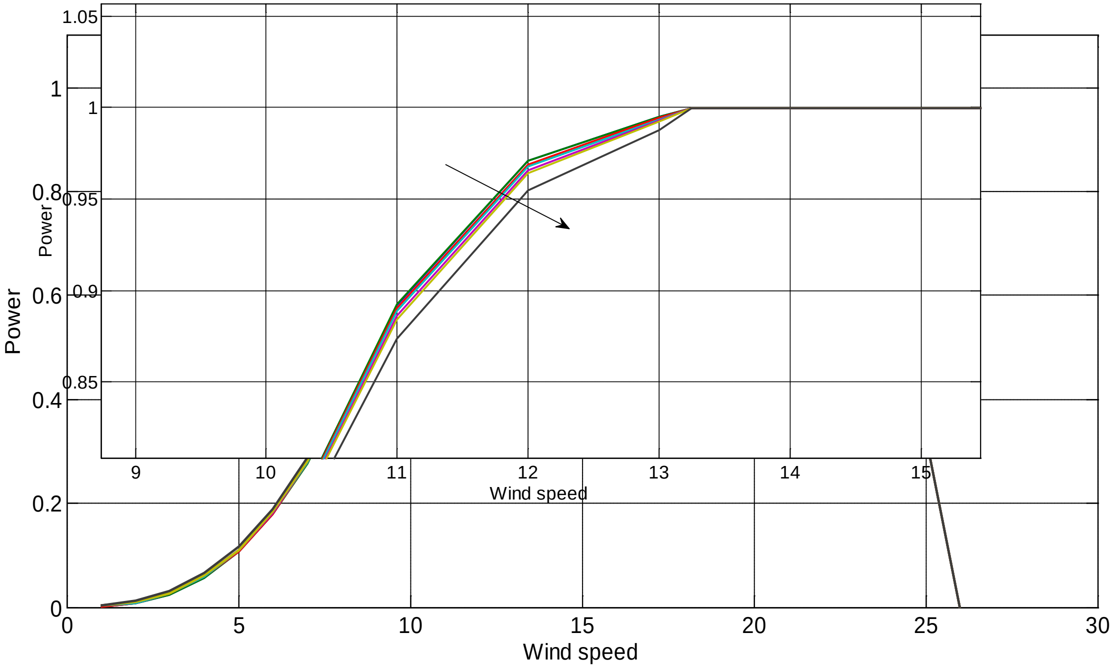
North European wind power variability


2020

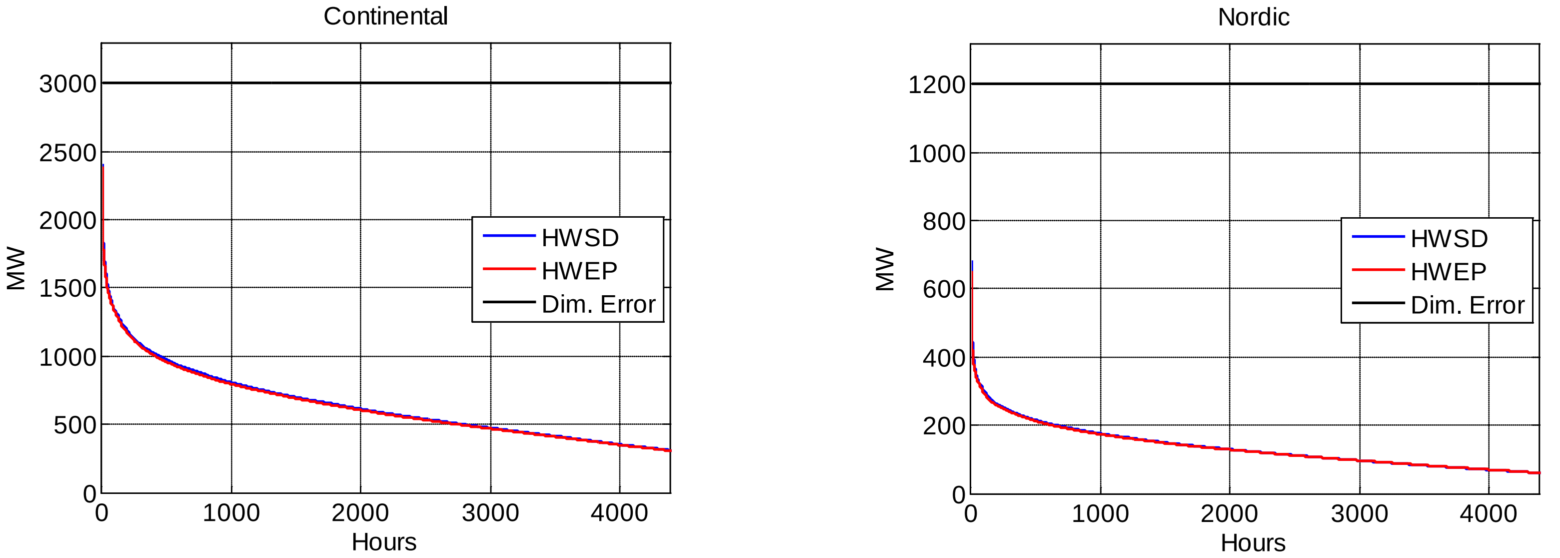

2030

North European wind power variability

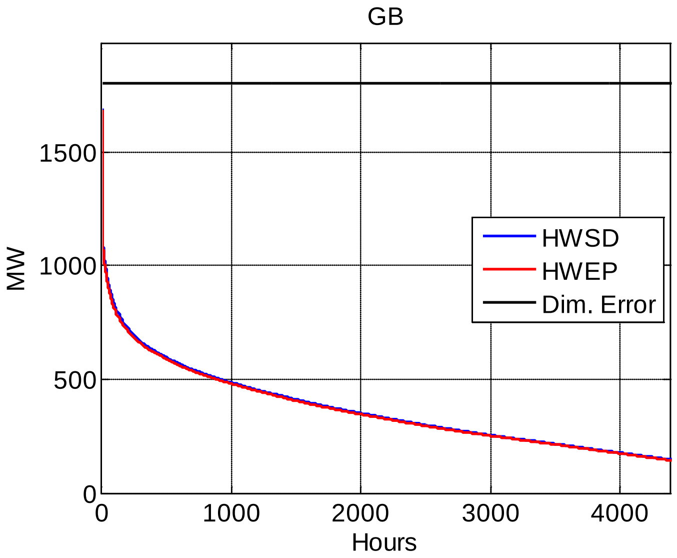
Meteo Year	Calendar Year
1	2001
2	2005
3	2007
4	2008
5	2009
6	2010
7	2011
8	2012

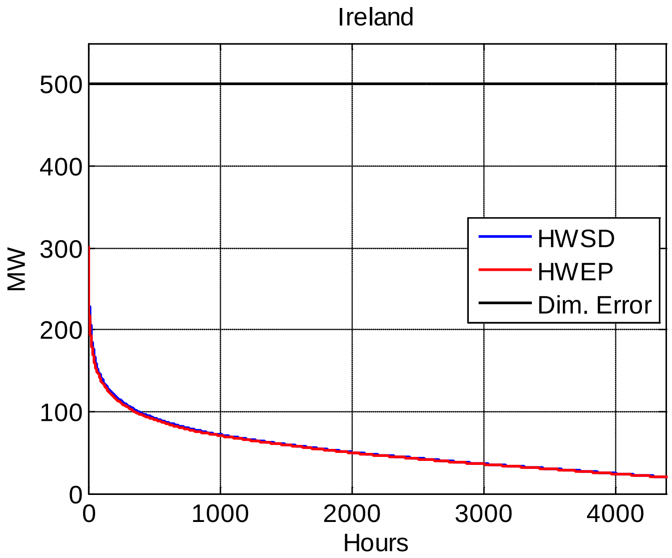


North European wind power variability – max ramping 2020



North European wind power variability – max ramping 2020

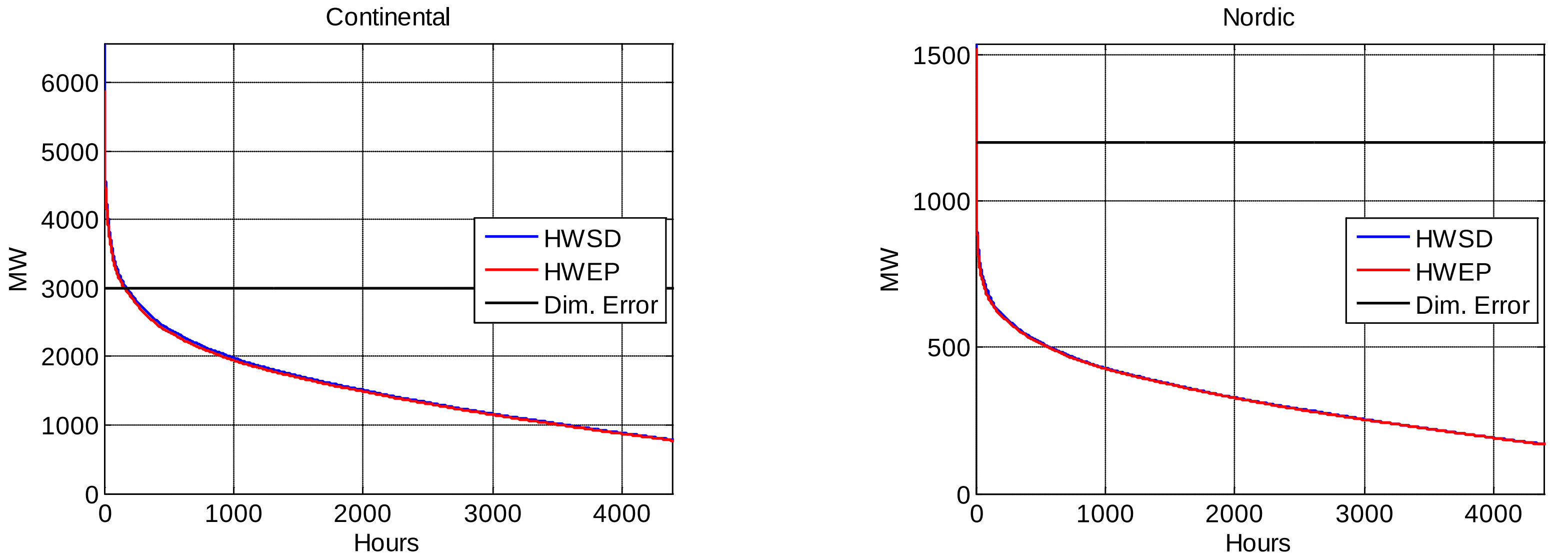




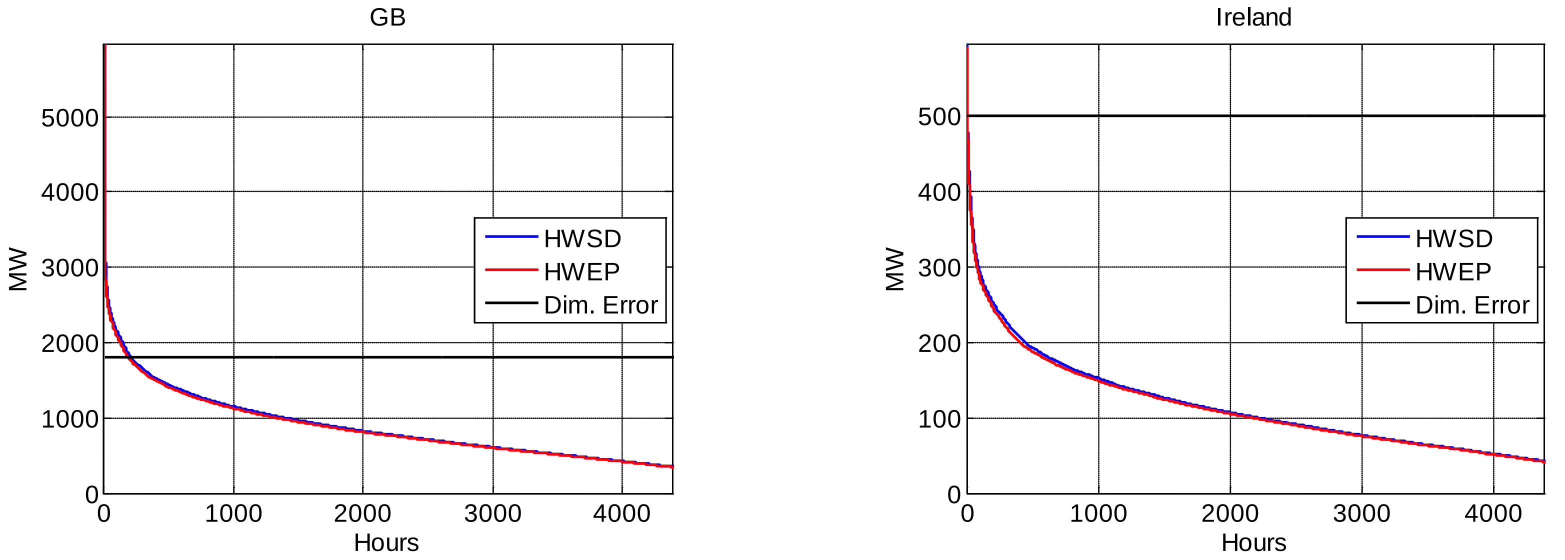
North European wind power variability – max ramping 2020

Synchronous Area	HWSD	HWEP	Reference incident
	MW	MW	MW
Continental	2,413	2,391	3,000
Nordic	684	652	1,200
GB	1,691	1,687	1,800
Ireland	302	302	500

North European wind power variability – max ramping 2030



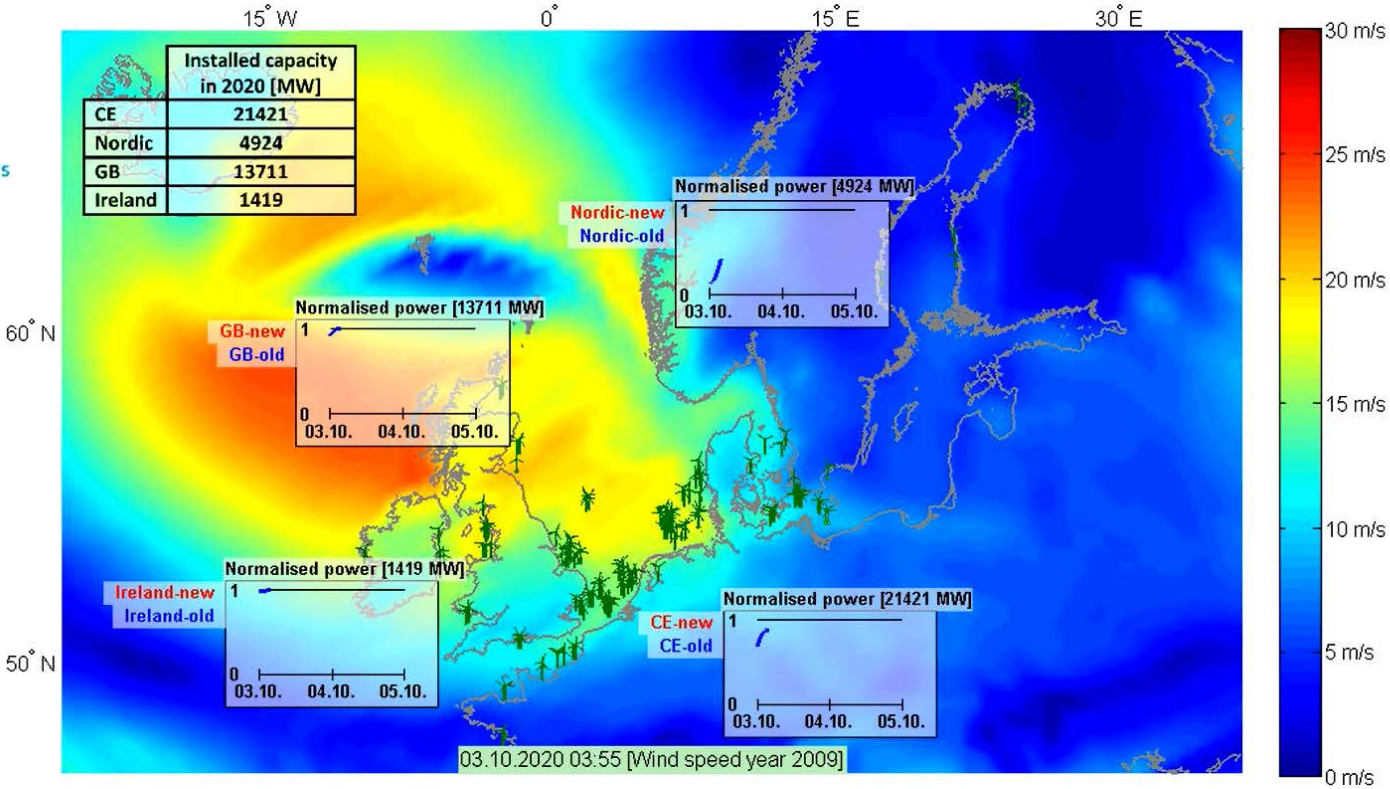
North European wind power variability – max ramping 2030



North European wind power variability – max ramping 2030

Synchronous Area	HWSD	HWEP	Reference incident
	MW	MW	MW
Continental	6,571	5,874	3,000
Nordic	1,540	1,525	1,200
GB	5,972	5,992	1,800
Ireland	595	591	500

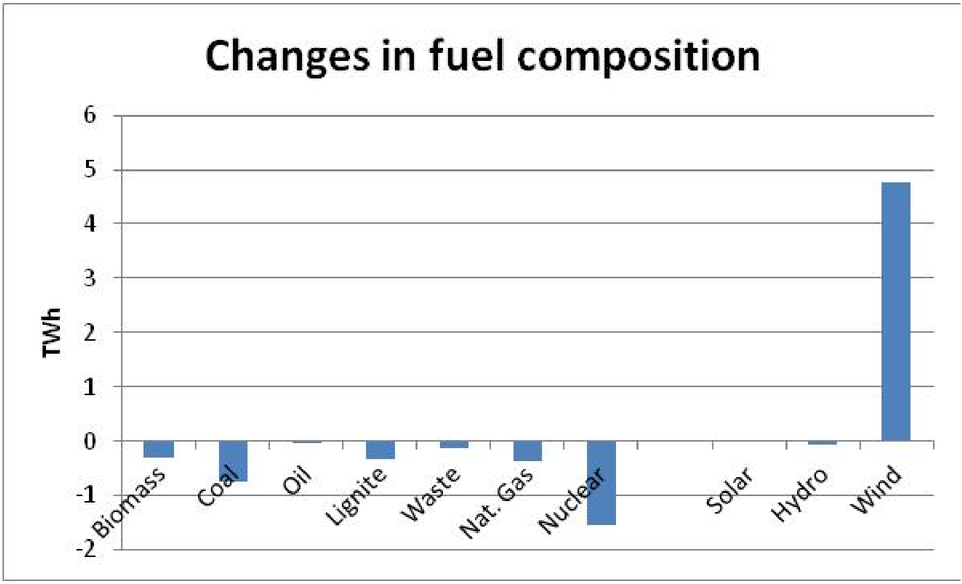
North European wind power variability – a 2020 case

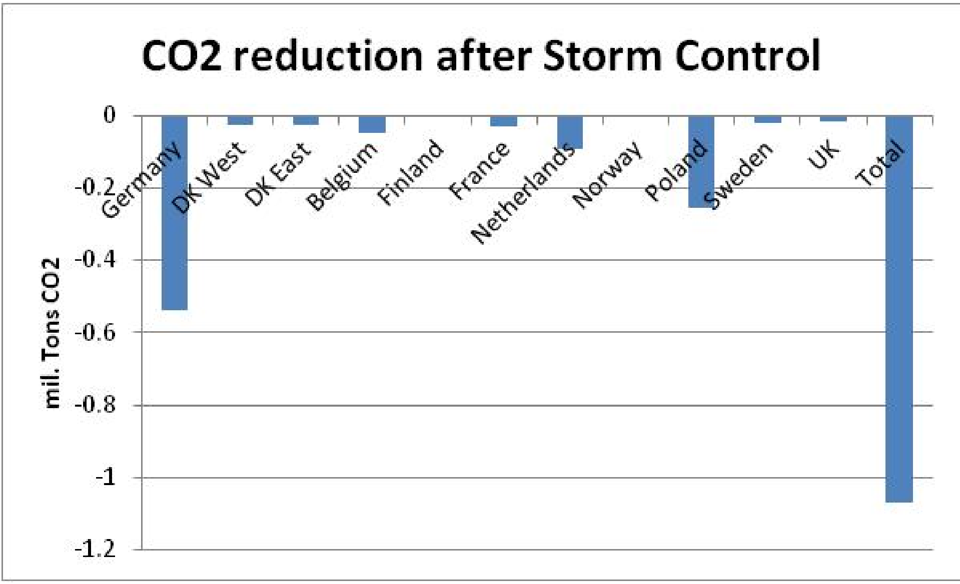


Installed capacity in 2020 [MW]	
CE	21421
Nordic	4924
GB	13711
Ireland	1419

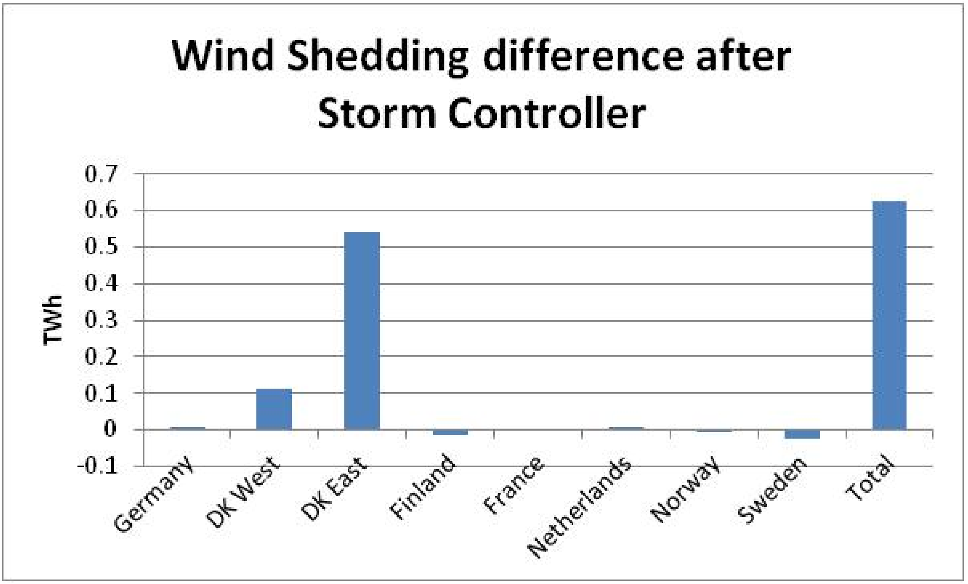
03.10.2020 03:55 [Wind speed year 2009]

North European storm control – economic impact


Changes in fuel composition


CO2 reduction after Storm Control

North European storm control – economic impact



	2020		
	HWSD	HWEP	diff
Total costs (M€)	44100	44005	96
CO2 emission (mil. T CO2)	521	520	1
Realised wind production (TWh/y)	522.76	526.88	4.12
Wind shedding (TWh/y)	15.85	16.48	0.63

Summary

- Wind power forecast error reduced by 50% (of installed capacity)
- Maximum ramping reduced more than three times

- Offshore wind power variability siginficant – should be considered in frequency stability assessment
- Smooth(er) wind power behaviour under storm helps the system:
  - Reduces overall costs
  - Reduces CO_2 emissions

Report: D16.6 Market and system security impact of the storm demonstrations in task-forces TF2

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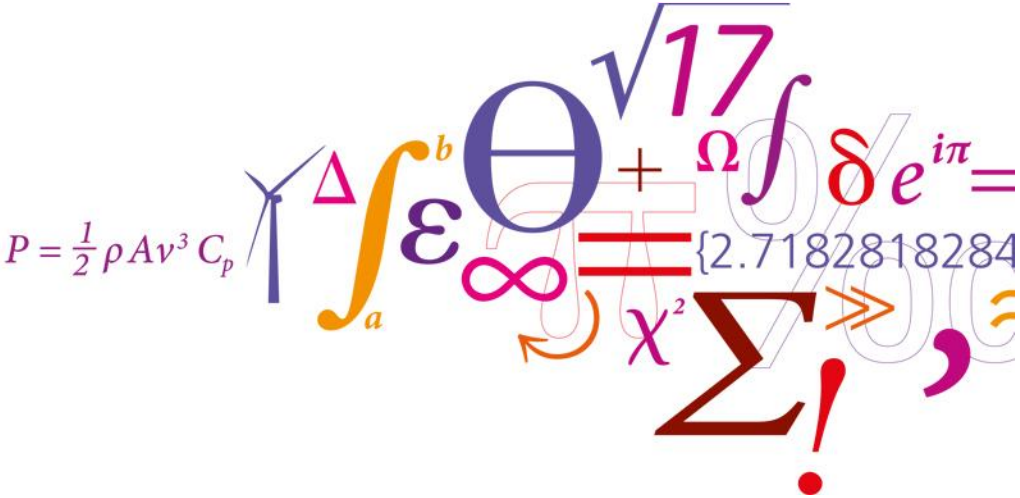
Thank you

Annex 5

SIMBA
Simulation of balancing in the Danish power system

Nicolaos A. Cutululis



DTU Wind Energy
Department of Wind Energy

Aknowledgments

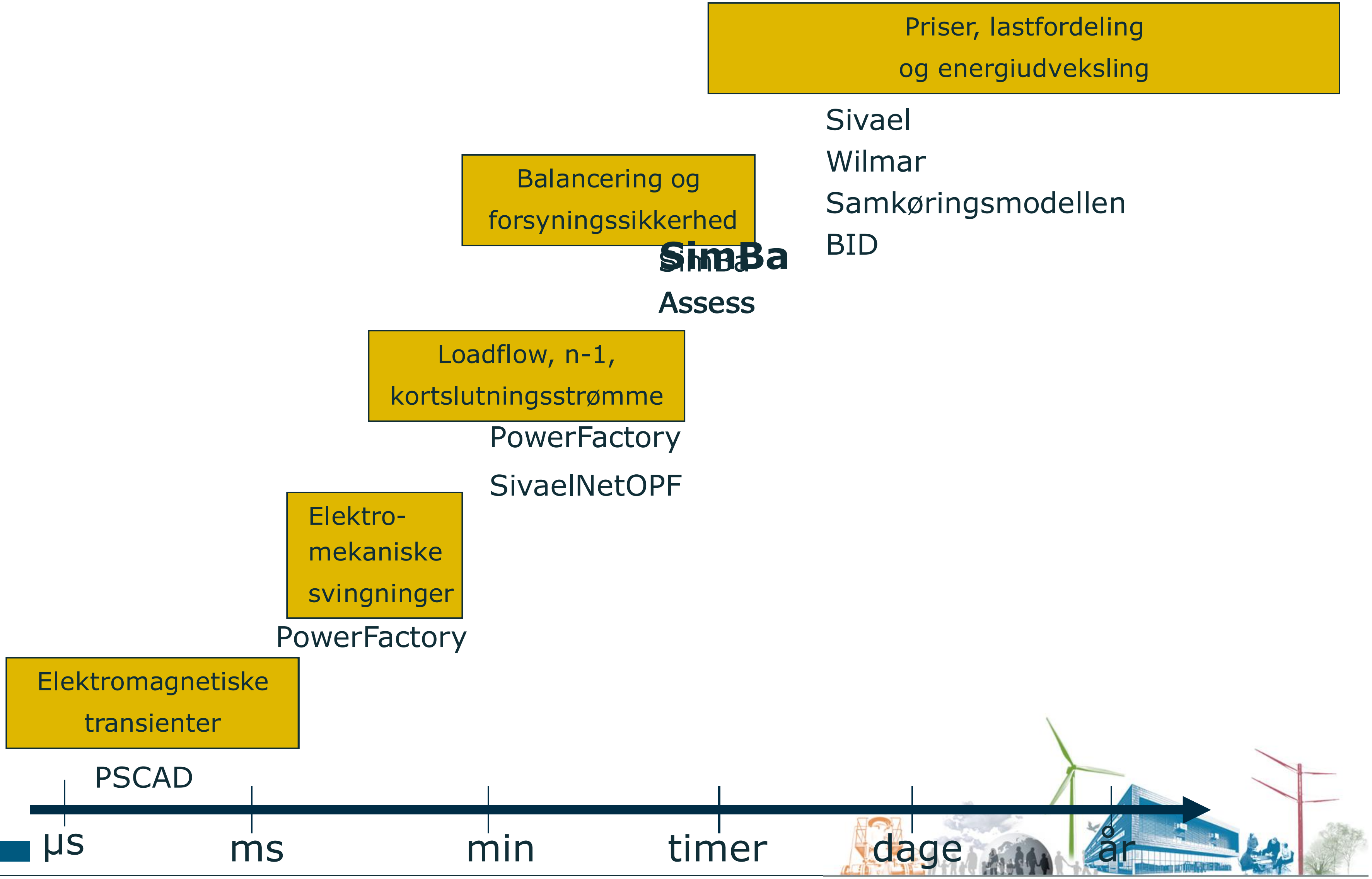
Energinet.dk

- Kirsten Lyck Falk
- Stephan Wöllner
- Nina Detlefsen
- Jens Pedersen
- Hans Abildgaard
- Gitte Agersbæk
- Peter Børre Eriksen

DTU

- Marisciel Litong-Palima
- Petr Maule
- Abdul Basit
- Poul Sørensen

Investigation of potential investments



Priser, lastfordeling og energiudveksling

Sivael
Wilmar
Samkøringsmodellen
BID

Balancering og forsyningssikkerhed

SimBa
SimBa
Assess

Loadflow, n-1, kortslutningsstrømme

PowerFactory

SivaelNetOPF

Elektro-mekaniske svingninger

PowerFactory

Elektromagnetiske transienter

PSCAD

µs ms min timer dage år

Why we started develop Simba

- SimBA = *Sim*ulation of *Ba*lancing
- Need a tool to study how well the system can cope with the challenges new energy sources introduces in intra-hour operational management
- Existing market models can often give an estimate of available reserves available for balancing
- Need a model that can estimate the *demand* for reserves and regulating power
- Need for a model that models actions within the operating hour
- Need to model ancillary services
- Need to be able to model imbalances around hour-shift

SimBa – Simulation of balances

- SimBa is based on Danish principles for balancing
- Simba models the power system analytically and can therefore model a future power system
- SimBa is expected to be able to investigate other market structures for ancillary services
- Gives valuable information on how to balance the system in the future

SimBa – Simulation of balances

- Input
  - technical information regarding production
  - hourly energy values for production and consumption
  - price information
- Output
  - activated regulating power
  - need for fast regulating reserves
  - economic consequences for different market designs
- Tool to analyse the demand for balancing resources

The danish principles for balancing

- Normal use of reserves
    1. Primary reserves (frequency reserves)
    2. Secondary reserves
    3. Tertiary reserves

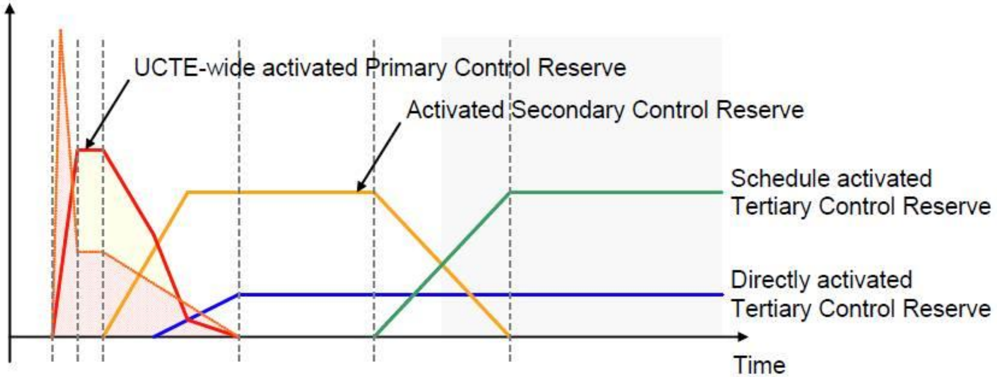


Figure 3: Principle frequency deviation and subsequent activation of reserves

- Use reserves in the opposite direction
    1. Tertiary reserves
    2. Secondary reserves
    3. Primary reserves (frequency reserves)

Danish operational scheduling

- Prediction of RES
  - with a resolution of 5 minutes
  - continually updated with whit most recent meteorological data
  - updated with online measurements from productions units
- Prediction of Demand
  - with a resolution of 5 minutes
  - updated with online calculated calculation of demand
- Schedules for Exchange to neighbouring areas
  - with a resolution of 5 minutes
  - updated with new trades
- Schedules for all production
  - with a resolution of 5 minutes
  - updated with knowledge of schedules
- Based on continuously updated schedules regulating power is activated

Simba – model vs. reality

- The Simba tool is build of seven loosely couplet modules which simulate both the Balance responsible side and the Energinet.dk control center side of the intra-hour marked.
- These modules are:
  - Simba Base
  - DataImport
  - Scheduling
  - Forecasting module
  - Bid generation module
  - Balancing module
  - Reporting module

Links all modules together & GUI

Handles the import from the UC-module

Live reports, Database access

Simba – model vs. reality

- In the Simba model right now, every hour is simulated independently from the hours before and after. This is valid for all modules of Simba.
- In reality
  - Balance responsibles have to make their up- and downregulation bids at least ½ hour before the operational hour. Their bids are valid for one hour.
  - The operator at the control center generates new forecasts and balances the system imbalance by activating bids in a rolling manner (i.e. Bids can be activated during the operation hour but with some activation time and minimum amount)

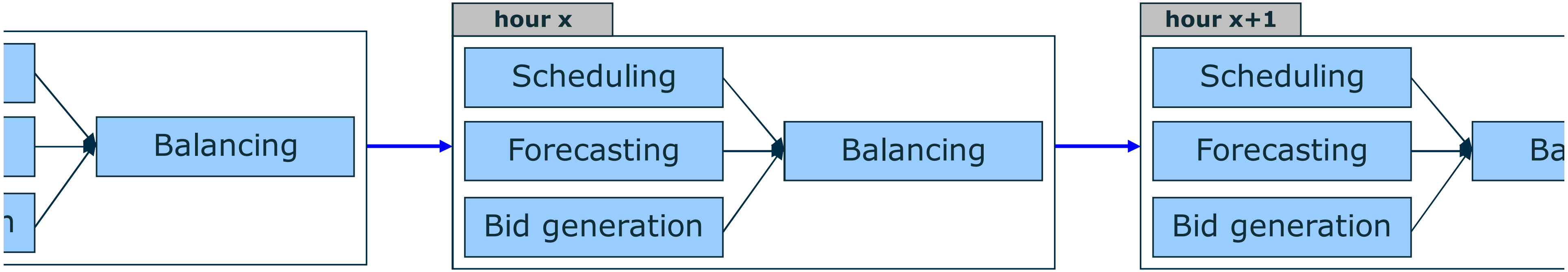


Figure: Simba simulation process, version 1

Simba – model vs. reality

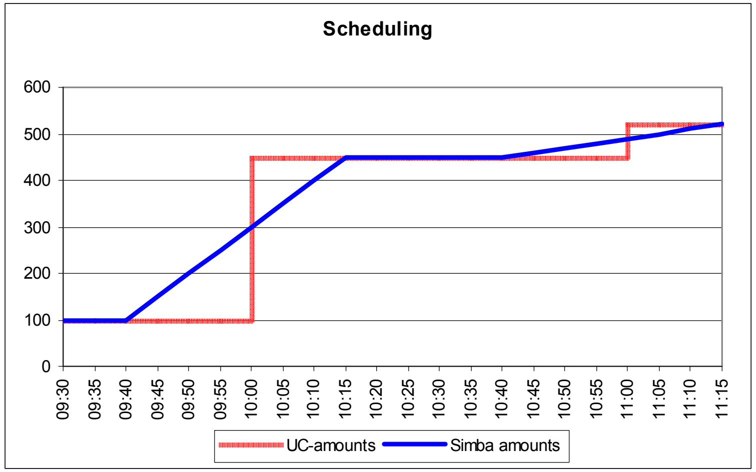
Scheduling (PBRs)

- Production Balance Responsibles have to send detailed power plans (5 min resolution) to Energinet.dk for every hour.
- PBRs are allowed to change their plans also during the operational hour.
- PBRs optimize their plans according to what gives the biggest economical surplus for them
- If an PBR’s power plan does not sum to the energy from their (hourly) energy-plan, he will get an energy-imbalance bill (cheaper)
- If an PBR does not follow his own power plan, he will get a power-imbalance bill (more expensive).
- Conclusion: PBRs will always try to meet their power plans. Sometimes it can be beneficial to produce more/less then promised in the energy plan.

Simba – model vs. reality

Scheduling (Simba)

- The Simba v1 scheduling module converts hourly amounts of energy into (typical) 5min power plans for production which is not forecasted.
- The amount of power is constant during the hour but ramping at both ends is taken into account.
- Ramping speed (MW/min) and duration (min before/after hour shift) can be specified by user.
- Load is interpolated with a spline function.



Simba – model vs. reality

Forecasting (control center)

- Energinet.dk uses forecasts for predicting the system imbalance:
    - Wind production
        - PBRs of offshore windparks predict their production by themselves
        - Energinet.dk predicts the production of other windparks
    - Load
        - Energinet.dk predicts the load for all CBRs (Consumption Balance Responsibles)
- The wind production forecast is based on metrological forecasts (produced four times a day) and afterwards adapted to the actual situation every time, an operator is generating a new forecast.
- The operator can generate updated forecasts as often as he wants.

Simba – model vs. reality

Forecasting (Simba)

- In Simba v1 only the wind production is forecasted.
- Load is (still) part of the scheduling module but load forecasting and flexible load (both load shifting and load cutting) are definitely interesting subjects which we will look at.
- Other deviations of production or outages of lines are not investigated closer.

Simba – model vs. reality

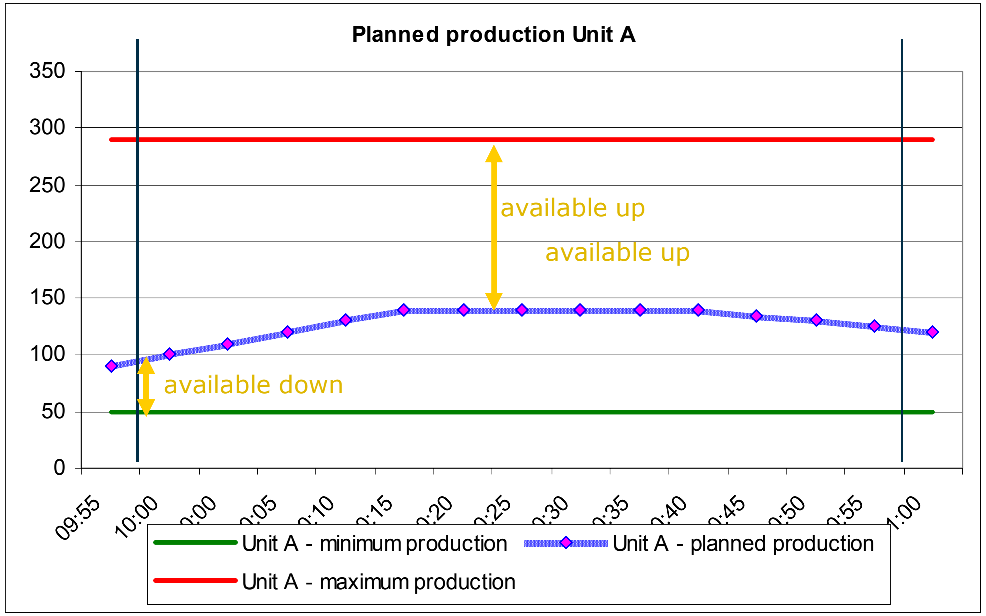
Bid generation (PBRs)

- PBRs deliver both upregulation and downregulation bids based on economical considerations.
- The maximum upregulation power, a PBR can deliver is the difference between the actual production and the installed capacity of all units involved.
- The maximum downregulation power, a PBR can deliver, equals the actual production minus the minimum production of all units involved.
- All bids are send to the national TSO, which sends them to the NOIS (Nordic Operation Information System). NOIS is joint bid list for the regulation power marked of all Nordic countries together.
- Energinet.dk buys also reserves, which are options for regulation power.

Simba – model vs. reality

Bid generation (Simba)

- It has not been investigated in dept how PBRs actually act on the regulation power marked.
- Simba assumes a perfect marked (i.e. all PBRs put all their available capacities on the regulation power marked).



- Bids have a minimum amount MW (user input) and can have different activation speeds (= quality – not implemented yet).

Simba – model vs. reality

Balancing (control center)

- Keeping the system in balance is a continuous process done by an operator in the Energinet.dk control center. It involves:
  - Getting an updated forecast of wind and load which, together with the planned production of the other units, gives a total (im)balance figure for the next hours (with increasing uncertainty).
  - If one nordic power system has an imbalance and another area has an imbalance with opposite sign, power is exchanged directly between these areas as “Power Trade” (“Effektkrafthandel”).
  - Based on the prediction, the operators knowledge of the system and other circumstances, he/she buys up- or downregulations from the NOIS list (first comes first served).
  - If the (im)balance curve evolves in an unpredicted direction, bought regulation power can be cancelled or reverse regulation power can be bought.

Simba – model vs. reality

Balancing (Simba)

- The UC-model sends balances to Simba.
- Imbalances are generated through:
    - Deviations of wind production
    - Spline of consumption
    - Ramping
    - Outages

Simba – model vs. reality

Balancing (Simba)

- In Simba v1 every hour is divided into 2*1/2 hour and every part is balanced independently by:
  - calculation of average imbalance of every area
  - doing possible power trades between neighboring areas
  - while imbalance > minimum bid activation size
    - activation of bids from NOIS-list(1)

(1) Bids from other areas are only activated if is possible to import/export to this area.

Example of results: Balancing – Bid activation

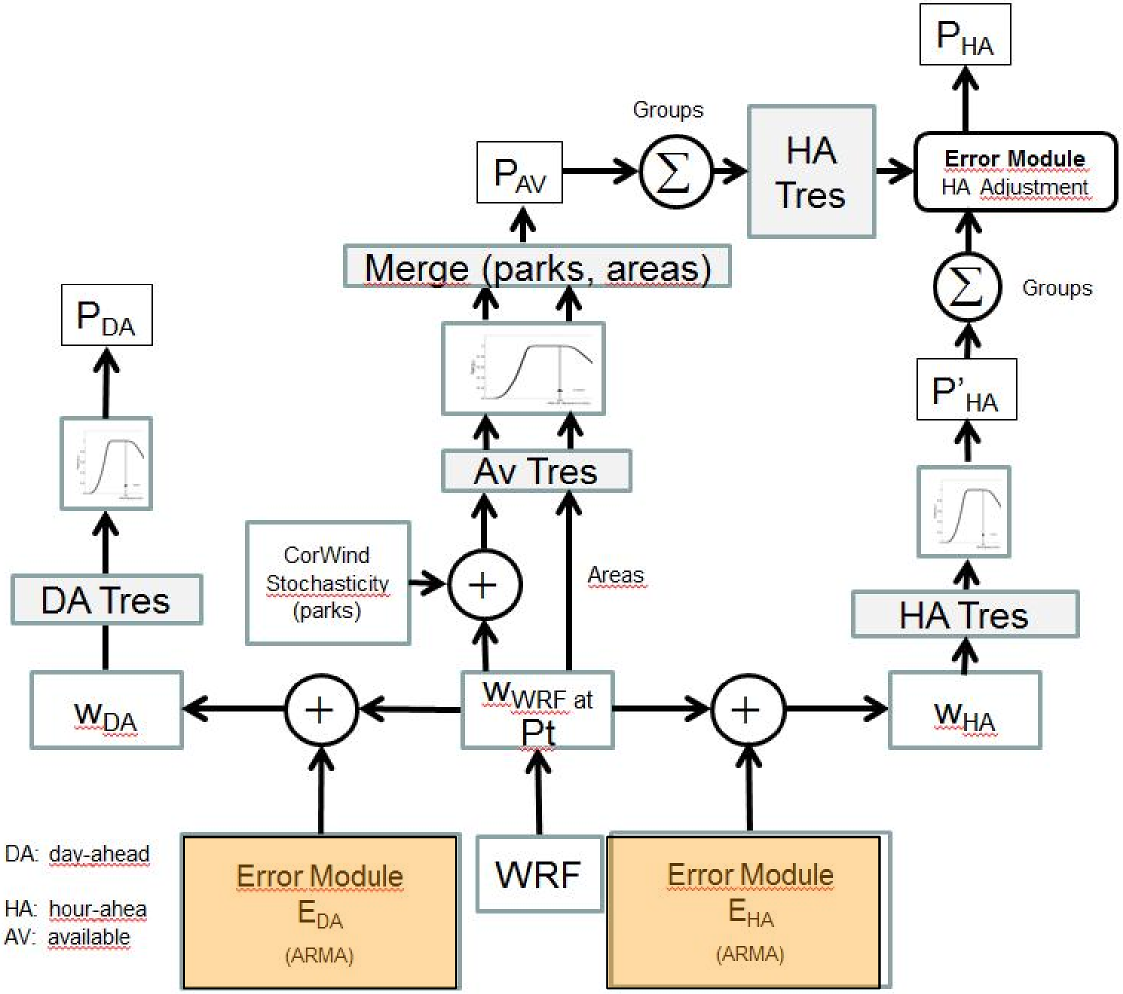
StartTime	EndTime	MWh	Price	BalanceResp.	Activated from	Activated to	Activated MWh
02/01/2010 07:00	02/01/2010 08:00	17.26	84.25	DK2 PBA	02/01/2010 07:00	02/01/2010 07:30	17.26
02/01/2010 07:00	02/01/2010 08:00	8.76	328.65	DK1 PBA			
02/01/2010 07:00	02/01/2010 08:00	56.86	345.26	DK2 PBA	02/01/2010 07:00	02/01/2010 07:30	44.36
02/01/2010 07:00	02/01/2010 08:00	8.67	354.80	DK1 PBA			
02/01/2010 07:00	02/01/2010 08:00	60.00	364.74	DK2 PBA			
02/01/2010 07:00	02/01/2010 08:00	44.17	369.05	DK2 PBA			
02/01/2010 07:00	02/01/2010 08:00	30.00	380.90	DK2 PBA			
02/01/2010 07:00	02/01/2010 08:00	10000.00	521.38	Norge(exp/imp_DK1)			
02/01/2010 07:00	02/01/2010 08:00	10000.00	521.38	Tyskland(exp/imp_DK2)			

StartTime	EndTime	MWh	Price	BalanceResp.	Activated from	Activated to	Activated MWh
02/01/2010 07:00	02/01/2010 08:00	17.26	84.25	DK2 PBA	02/01/2010 07:30	02/01/2010 08:00	17.26
02/01/2010 07:00	02/01/2010 08:00	8.76	328.65	DK1 PBA			
02/01/2010 07:00	02/01/2010 08:00	56.86	345.26	DK2 PBA	02/01/2010 07:30	02/01/2010 08:00	56.86
02/01/2010 07:00	02/01/2010 08:00	8.67	354.80	DK1 PBA			
02/01/2010 07:00	02/01/2010 08:00	60.00	364.74	DK2 PBA	02/01/2010 07:30	02/01/2010 08:00	24.97
02/01/2010 07:00	02/01/2010 08:00	44.17	369.05	DK2 PBA			
02/01/2010 07:00	02/01/2010 08:00	30.00	380.90	DK2 PBA			
02/01/2010 07:00	02/01/2010 08:00	10000.00	521.38	Norge(exp/imp_DK1)			
02/01/2010 07:00	02/01/2010 08:00	10000.00	521.38	Tyskland(exp/imp_DK2)			

Example of results – yearly report on imbalance

Area	Type	Unit	Min	Max	Avg	Sum	1%	2,50%	50%	97,50%	100%
DK1	Imbalance_pos	MWh	0,03	237,95	38,02	153.842,20	0,42	1,01	26,72	152,21	181,3
DK1	Imbalance_neg	MWh	0	-471,29	-63,69	-310.949,80	-0,45	-1,11	-32,03	-344,98	-374,11
DK1	Bid_up	MWh	900	1.441,13	976,29	726.359,10	905,91	906,65	919,61	1.304,74	1.367,14
DK1	Bid_down	MWh	0	-474,42	-258,15	-192.061,90	0	-10,95	-276,75	-468,87	-471,55
DK1	Regulation_up	MWh	0	461,78	76,34	301.256,90	10,24	10,5	41,21	367,12	393,62
DK1	Regulation_down	MWh	0	-198,62	-47,43	-145.410,80	-10,3	-11,16	-35,7	-158,31	-179,34
DK1	Restimbalance_up	MWh	0	258,17	33,28	155.164,10	0,3	0,93	24,3	111,15	134,1
DK1	Restimbalance_down	MWh	0	-215,37	-27,57	-117.588,50	-0,36	-0,88	-19,56	-103,43	-133,92

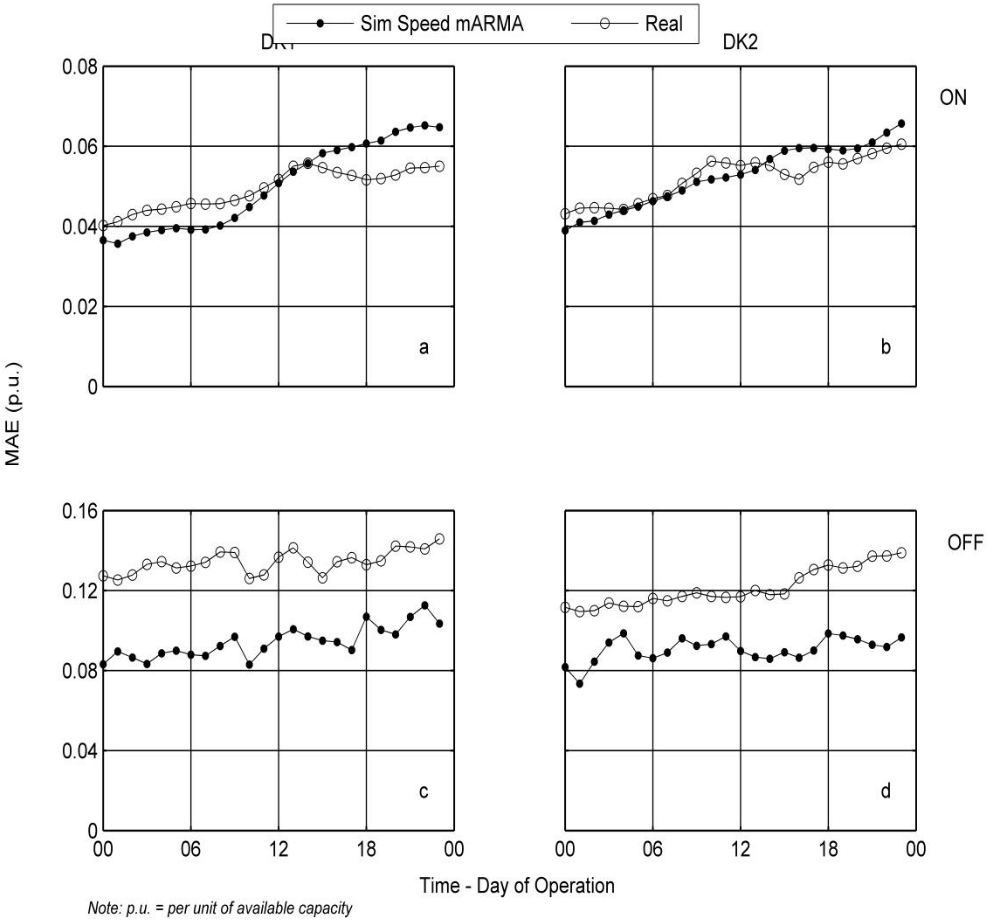
Wind Speed Error Module in CorWind (2013)



P: power
w: wind speed
E: speed error
WRF: wind speed database

DA: day-ahead
HA: hour-ahea
AV: available

Assessment (Comparison with Data)



Overview of future tasks for the wind power module

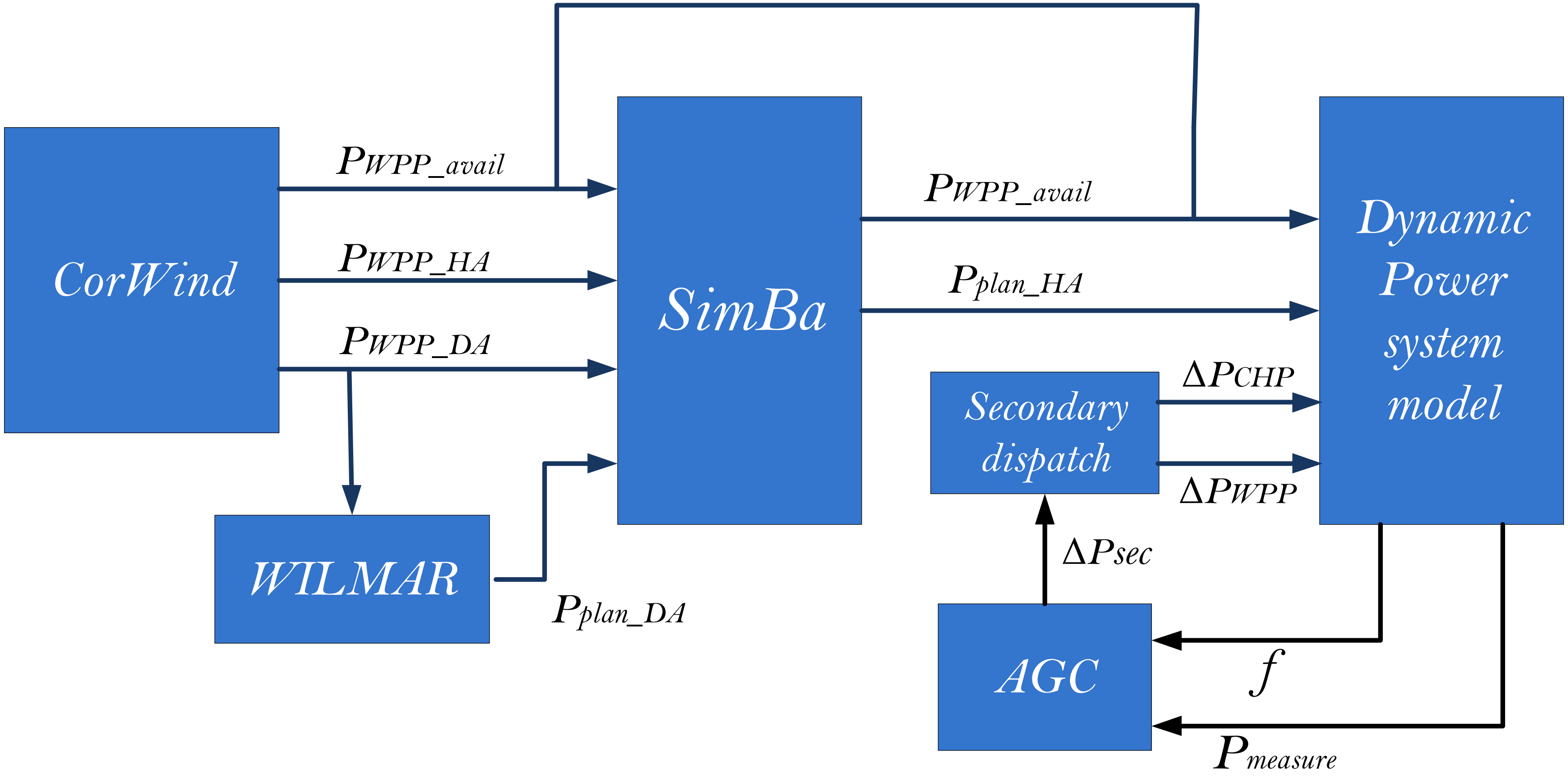
- Admittance function (“filter”) model for areas
  - Now point / area = with / without stochastic
  - Future:
    - Always include stochastic contribution
    - Admittance function will take into account the smoothing due to the size of the area
  - Admittance function determined by
    - Actual wind turbine P_N and position ***or***
    - Characteristic area size
  - Data analysis: correlation between the forecast errors of a new met forecast compared to (eg) 6 hour earlier met forecast
  - Model for inclusion of this correlation in multivariate ARMA simulation

Wind Power Plant System Services

The objective is to develop and analyse models and control strategies for wind power plants, which increase the capability of wind farms to provide system services. The emphasis is on active power balancing of future power systems with high wind power penetration

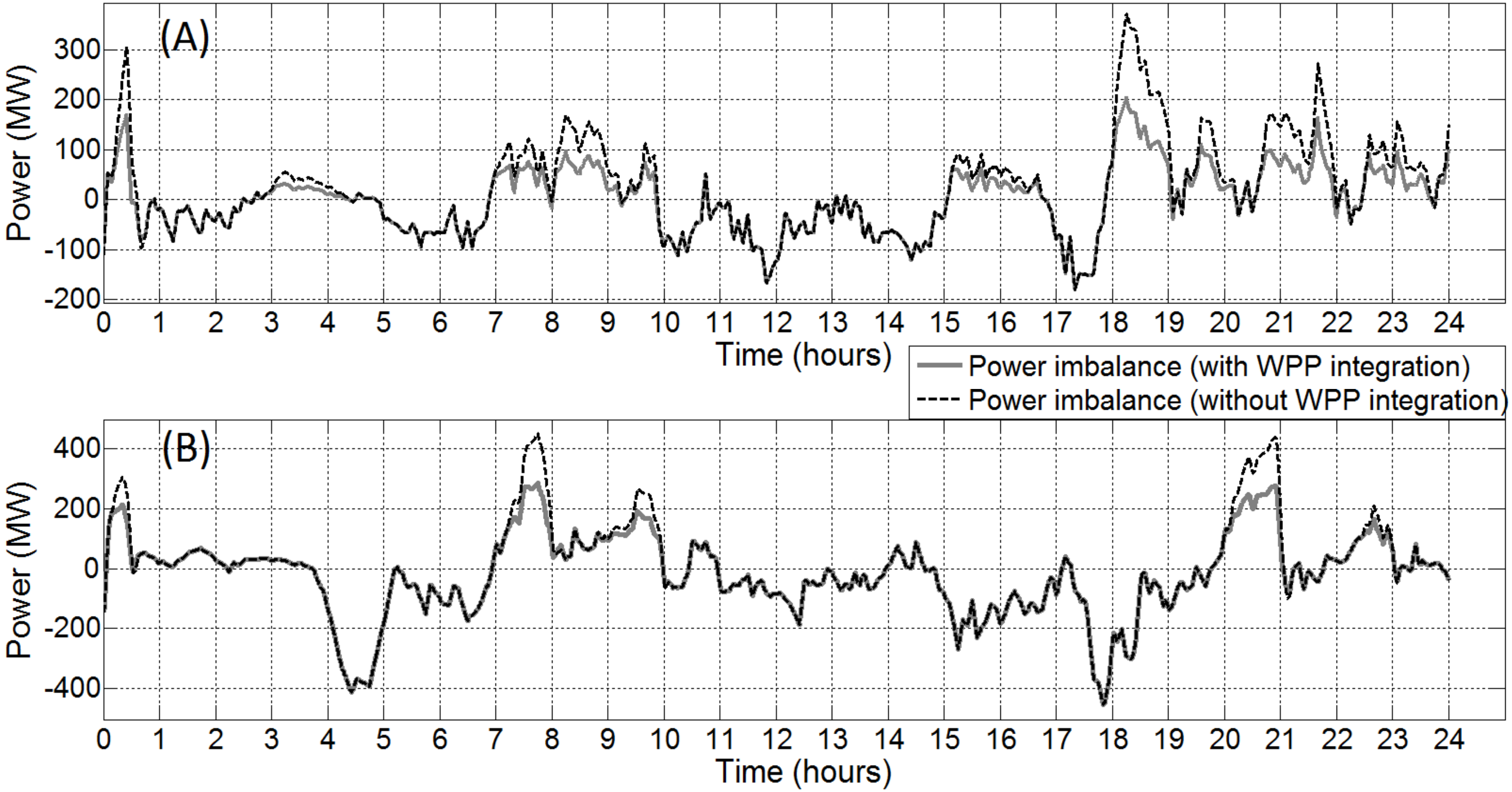
- Danish power system has been modelled for this study, considering the future power generation and power exchange capacities i.e. as planned for 2020
- The power system model includes sub models for the Automatic Generation Control system, aggregated models for centralized and de-centralized combine heat and power plants, wind power plants and interconnections with neighbouring power systems.

Overview



CorWind
P_{WPP_avail}
P_{WPP_HA}
P_{WPP_DA}
WILMAR
P_{plan_DA}
SimBa
P_{WPP_avail}
P_{plan_HA}
Secondary dispatch
ΔP_{CHP}
ΔP_{WPP}
ΔP_{sec}
AGC
f
$P_{measure}$
Dynamic Power system model

Power imbalance – (A) Eastern Danish power system; (B) Western Danish power system



Simba in 2014 in ENDK

- Backtesting (take one year, run SIMBA and compare results)
- Reality check
- New balancing algorithm

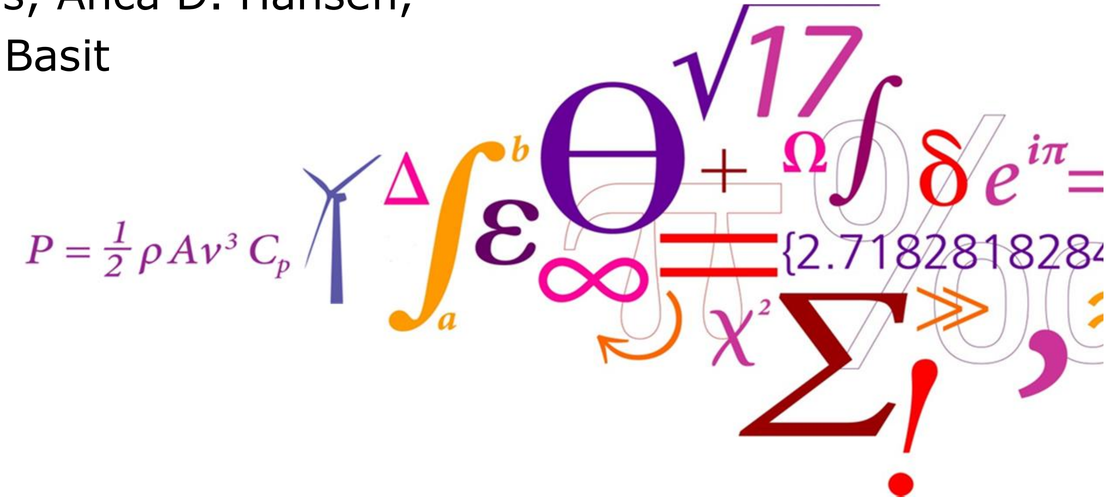
Use of SIMBA in EUSP

- 2013
    - Energy Agreement Analyses
      Part of a programme of analyses of the Danish energy agreement of 2012
      Measurement of maximum imbalances in 7 different model scenarios
- 2014
    - Stress tests of the system
        - Test design not nearly ready yet – only a few ideas
        - Close-up view rather than long-term view (covered with other models)
        - Challenge the involved assumptions
        - Put focus on extreme situations rather than normal situations

Annex 6

Ancillary services – Definitions, technical capabilities, value and drivers

Poul Sørensen, Nicolaos Cutululis, Anca D. Hansen,
Müfit Altin, Lorenzo Zeni, Abdul Basit



DTU Wind Energy
Department of Wind Energy

Outline

Ancillary Services: Research Results From Wind Power Plants

- ***Definitions and requirements*** for ancillary service
- ***Technical capabilities*** of wind power plants to provide ancillary services - ***state-of-the-art industry and R&D*** (simulation based) perspectives
- What are the ***economic incentives and barriers*** to providing ancillary services?

Definitions of ancillary services

- CIGRÉ report - overview of International Practices
  - ***definitions*** for ancillary services can ***differ significantly*** based on who is using the terms. While some definitions emphasize the importance of ancillary services for ***system security and reliability***, others mention the use of ancillary services to ***support electricity transfers from generation to load*** and to ***maintain power quality***
- Some TSOs are including ***more specific types*** of ancillary services ***than others*** because
  - ***differences in*** the ***definitions*** (above)
  - some of the required properties of the generation plants are ***embedded in conventional power plants*** using directly grid connected synchronous generators.
  - ***new ancillary service products*** seem to pop up in power systems ***with large scale penetration of renewables***.

Requirements for – and types of – ancillary services

- Active power ***reserves*** (using ENTSO-E glossary)
  - Frequency containment reserves (FCR)
  - Frequency restoration reserves (FRR)
  - Replacement reserves (RR)
- Properties required to ***maintain*** power system ***stability*** today (Energinet.dk ancillary service strategy)
  - Short-circuit power
  - Continuous voltage control
  - Voltage support during faults
  - Inertia
- ***Possible additional*** ancillary service ***products*** (research references)
  - Fast frequency response (and inertia support)
  - Synchronising power
  - Power oscillation damping
  - Black-start capability

State of the art technical capabilities in industry

- Horns Rev 2002 (Kristoffersen et.al.) according to first DK technical requirements
  - Primary frequency control
  - Secondary frequency control
  - Reactive power neutral

- Today +
  - Continuous voltage control
  - Voltage support during faults
  - “Inertia” under development – verification?

RESERVICES CONSORTIUM

www.reservices-project.eu

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THE EUROPEAN WIND ENERGY ASSOCIATION

EPIA
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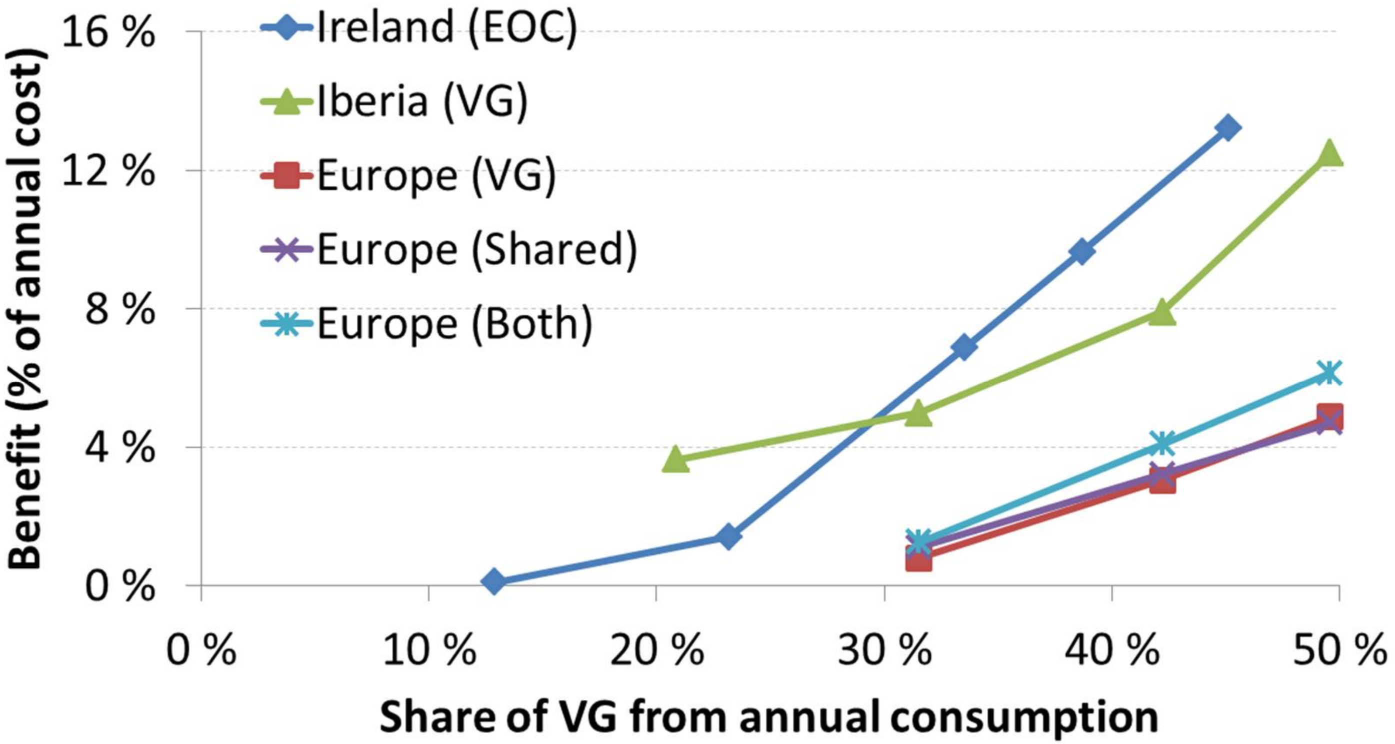
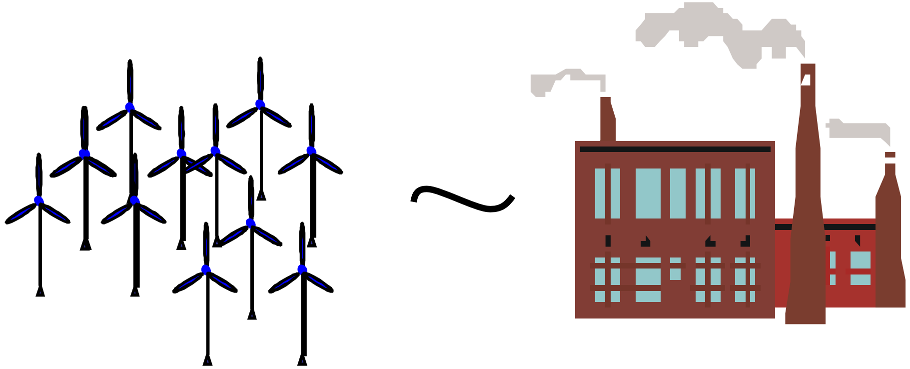
Benefit of VG in frequency support (cases have different assumptions)

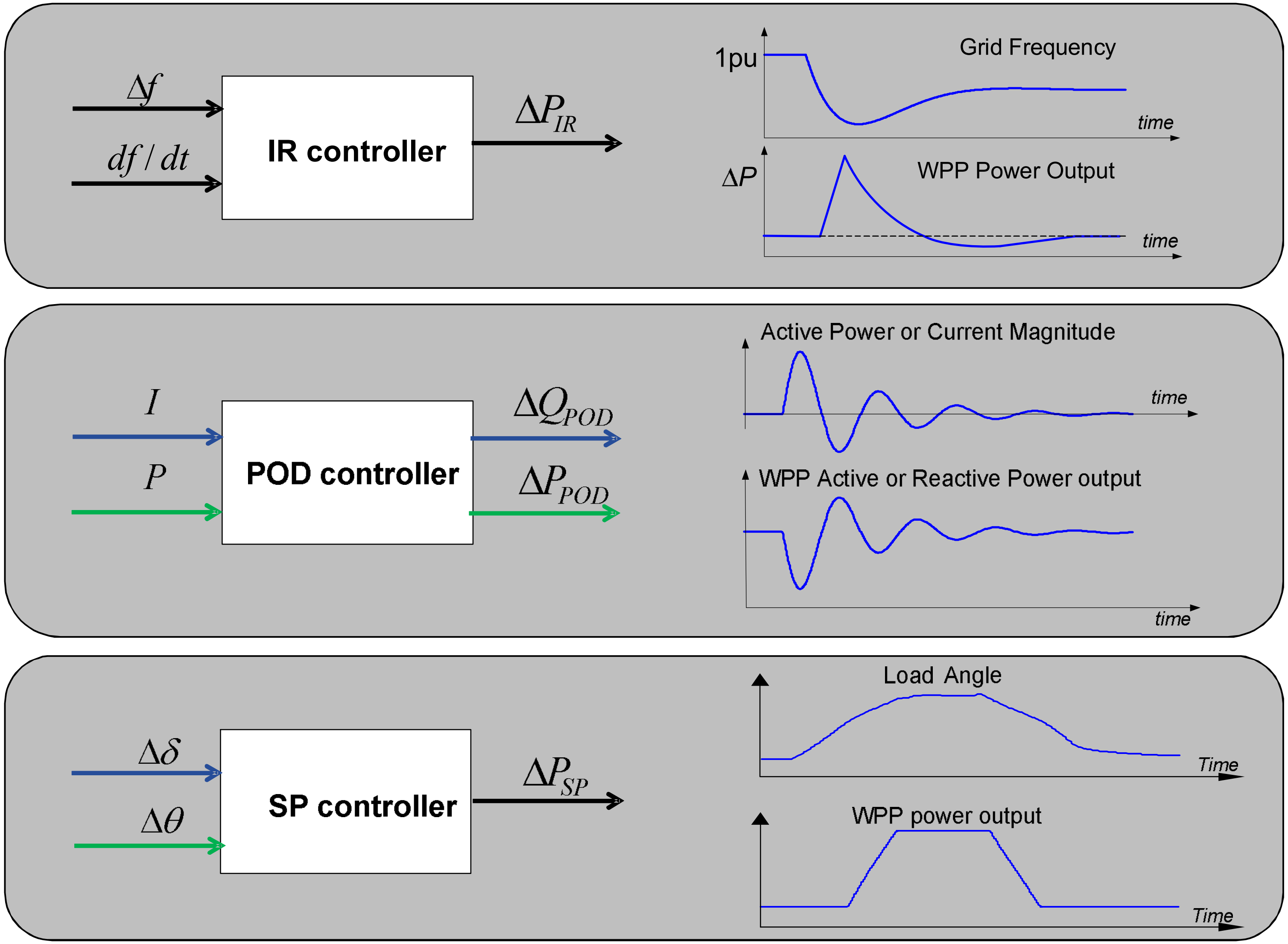


EASEWIND

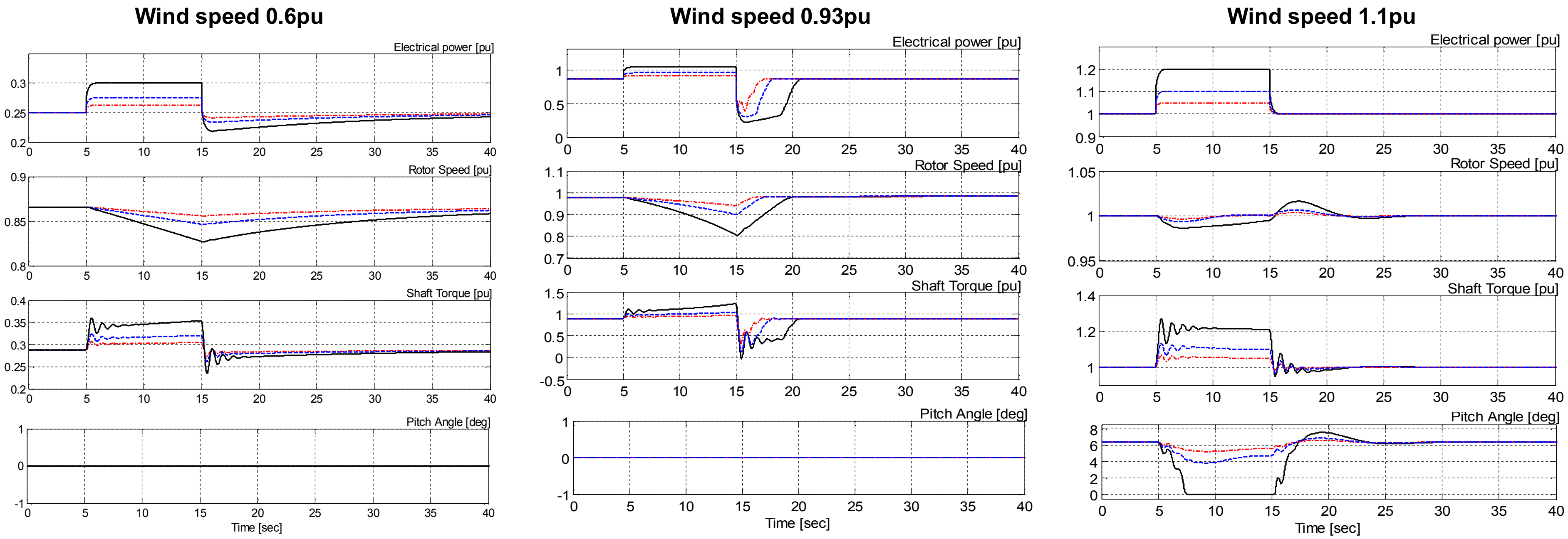
- Long title:
  - Enhanced Ancillary Services from Wind Power Plants
- Objective
  - to develop technical solutions for enabling wind power to have similar power plant characteristics as conventional generation units.
- Funding: ForskEL
- Consortium:
  - Vestas Technology R&D
  - DTU Wind Energy
  - DTU Compute
  - AAU IET



Enhanced ancillary services



Short-term overproduction capability



- Below rated wind speed, the overproduction is followed by ***recovery period***
- The higher the wind speed, the ***shorter*** the recovery period
- The higher the overproduction power:
  - the longer the recovery period and the larger the power underproduction -> ***frequency stability*** might be affected
  - the higher the shaft ***torque*** -> high mechanical stress of the turbine
- No power recovery needed above rated wind speed

OffshoreDC

norden
Nordic Energy Research

DTU

CHALMERS

ABB
Power and productivity
for a better world™

VTT

DONG
energy

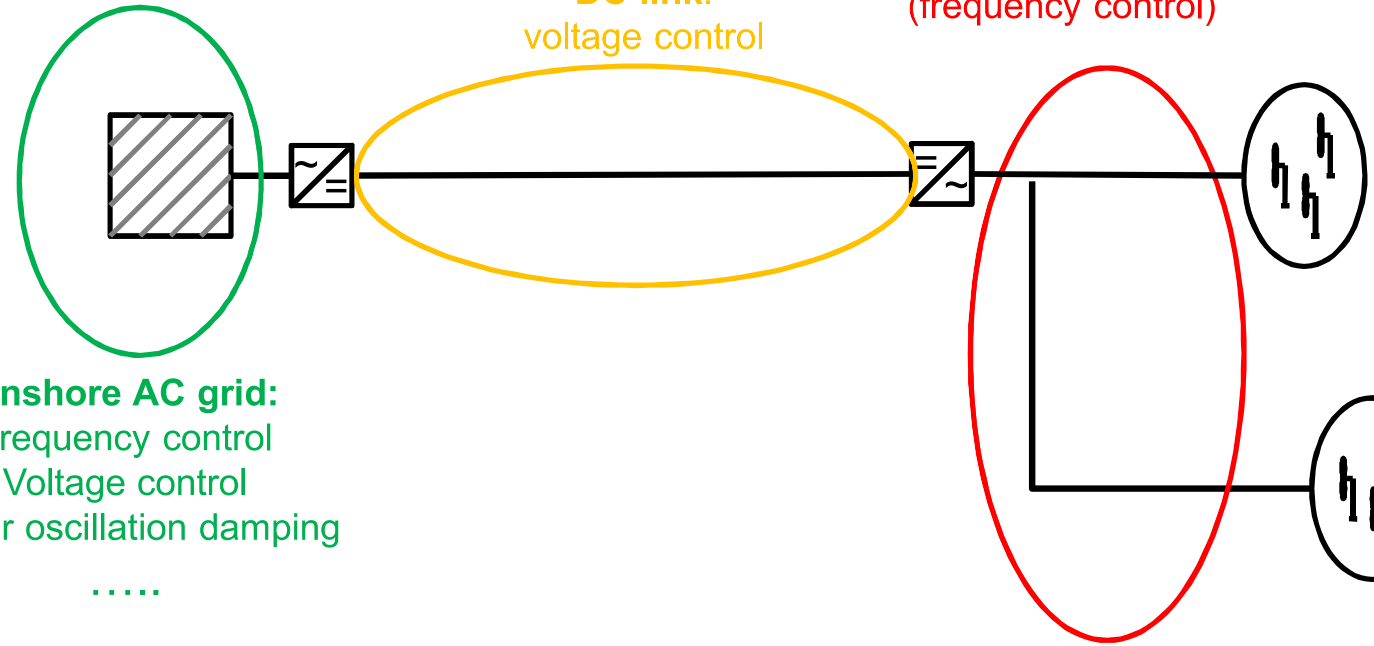
SINTEF

ENERGINET.DK

Statnett

AALBORG UNIVERSITY

Ancillary services with HVDC transmission



Offshore AC grid:
voltage control
(frequency control)

DC link:
voltage control

Onshore AC grid:
Frequency control
Voltage control
Power oscillation damping
…..

Economic incentives and barriers

- Incentives:
  - Technical requirements for grid connection!
  - Higher prices on reserve markets than on stock market (e.g. low – and even negative stock market prices)
  - Co-generation with other production technologies (ramp support)
  - Enables higher wind power penetration
- Barriers:
  - Symmetric (up/down) requirement (Spain – TWENTIES)
    - Downwards reserves from WPPs is feasible with high penetration
    - … loads are more feasible as upwards reserves
  - Length (= prediction horizon) of reserve products
  - Development costs for new products
  - Additional hardware costs
  - Verification needs for new products –certification costs

Questions?