Final report

1. Project details

Project title	IEA Wind Annex 25 - phase V
File no.	64018-0121
Name of the funding scheme	Windenergy (IEA)
Project managing company / institution	DTU Wind Energy
CVR number (central business register)	30060946
Project partners	-
Submission date	27 January 2021

2. Summary

English:

The common international challenge is to adapt the existing power systems to enable a substantial increase of wind and other variable generation shares, namely PV, in a time frame considerably shorter than the lifetime of the assets, meaning that this has to be done in most utility systems with existing infrastructure, and at economically feasible costs. IEA Wind Task 25 Phase V supported this goal by analysing and further developing the methodology to assess the impact of wind power on power systems and by producing information on the range of impacts and best practices to assess the impacts.

The main 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, 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; Collaborative journal articles; Workshops targeted for TSO audience; Updated Recommended Practices report; Updated summary describing the range of wind power impacts and costs for different power systems.

The collaboration has been very successful, resulting in multiple joint publications, exchange of know-how and experience between academia and industry, applications and collaboration in joint research projects, participation in global initiative like the Global Power System Transformation (G-PST) Consortium. It has also resulted in the decision of extending the collaboration to Phase VI, running 2020-2024 and recently approved by IEA ExCo. DTU will participate and lead a work package.

Dansk:

Den fælles internationale udfordring er at tilpasse de eksisterende kraftsystemer til at muliggøre en betydelig forøgelse af vind- og andre aktier med variabel produktion, nemlig PV, i en tidsramme, der er betydeligt kortere end aktivernes levetid, hvilket betyder, at dette skal gøres i de fleste forsyningssystemer med eksisterende infrastruktur og til økonomisk gennemførlige omkostninger. IEA Wind Task 25, fase V, understøttede dette mål ved at analysere og yderligere udvikle metoden til at vurdere indvirkningen af vindkraft på kraftsystemer og ved at producere information om rækkevidden af påvirkninger og bedste praksis til vurdering af påvirkningerne. De vigtigste resultater er: Forbedret internationalt samarbejde og koordinering inden for vind- og solcelle-integration; Sæt af casestudier om integration af vind og anden variabel generation, især tilfælde, der kombinerer vind og solcelle, implikationer for markedsdesign og drift og udviklede metoder, herunder vurdering af omkostninger og værdi af vindintegration, usikkerhedsvurdering og yderligere driftsmetoder, der indgår i planlægningsmodeller; Database til produktion af tidskraft i stor skala for vindkraft; Samarbejdsrelaterede daglige artikler; Workshops rettet mod TSO-publikum; Opdateret anbefalet praksisrapport; Opdateret resumé, der beskriver rækkevidden af vindkraftpåvirkninger og omkostninger for forskellige kraftsystemer. Samarbejdet har været meget vellykket, hvilket har resulteret i flere fælles publikationer, udveksling af know-how og erfaring mellem den akademiske verden og industrien, applikationer og samarbejde i fælles forskningsprojekter, deltagelse i globalt initiativ som Global Power System Transformation (G-PST) Consortium. Det har altså resulteret i beslutningen om at udvide samarbejdet til fase VI, der kører 2020-2024 og for nylig godkendt af IEA ExCo. DTU deltager og leder en arbejdspakke.

3. Project objectives

The project enabled DTU Wind Energy participation in the IEA Wind Task 25 Phase V activities, hence some of the text in this report is stemming directly from the IEA Wind Task 25 Phase V Summary report currently under finalization.

The common international challenge is to adapt the existing power systems to enable a substantial increase of wind and other variable generation shares, namely PV, in a time frame considerably shorter than the lifetime of the assets, meaning that this has to be done in most utility systems with existing infrastructure, and at economically feasible costs. Task 25 supports this goal by analysing and further developing the methodology to assess the impact of wind power on power systems and by producing information on the range of impacts and best practices to assess the impacts

A research and development (R&D) task on the Design and Operation of Power Systems with Large Amounts of Wind Power was formed in 2006 as IEA Wind Task 25. The aim of this R&D task is to collect and share information on the experiences gained and the studies made on power system impacts of wind power and to review methodologies, tools, and data used. The following countries and institutes have been involved in the collaboration:

Canada: Hydro Québec's Research Institute (IREQ)

China: State Grid Energy Research Institute (SGERI)

Denmark: **Technical University of Denmark (DTU)**[1]; Energinet.dk

European Wind Energy Association (WindEurope)

[1] Via the EUDP funded IEA Wind Task 25 Phase V project

Finland (operating agent): Technical Research Centre of Finland (VTT)

France: Electricité de France Research and Development Center (EDF R&D)

Réseau de Transport d'Electricité - Research and Development center (RTE R&D)

Germany: Fraunhofer Institute for Energy Economics and Energy Sys-tem Technology (FraunhoferIEE); Re-search Centre for Energy Econom-ics (FfE)

Ireland: Sustainable Energy Authority of Ireland (SEAI); University Col-lege Dublin (UCD); Energy Reform

Italy: Terna

Japan: University of Kyoto; Central Research Institute of Electric Power Industry (CRIEPI); University of Social Sciences Tokyo

Norway: Norwegian University of Science and Technology (NTNU); Foundation for Scientific and Industrial Research (SINTEF)

Netherlands: Delft University of Technology (TUDelft); TenneT

Portugal: National Laboratory on Energy and Geology (LNEG); Institute for Systems and Computer Engineer-ing, Technology, and Science (IN-ESC-TEC)

Spain: University of Castilla La Mancha, Universidad Pontificia Comillas

Sweden: Royal Institute of Technology (KTH)

United Kingdom: Centre for Sustainable Electricity and Distributed Gen-eration (Imperial College London and Strathclyde University)

United States: National Renewable Energy Laboratory (NREL); Energy System Integration Group (ESIG); U.S. Department of Energy (DOE).

IEA Wind Task 25 produced a report in 2007 on the state-of-the-art knowledge and results on wind integration that had been gathered so far, published in the VTT Working Papers series. Summary reports of three subse-quent phases have also been published by VTT: 2009 (VTT Research Notes 2493), 2013 (VTT Technology T75), 2016 (VTT Technolo-gy T268) and 2018 (VTT Technology T350). These reports presented summaries of selected, recently finished studies. All of these reports are available on the IEA Wind Task 25 website: https://community.ieawind.org/task25/home.

In addition, IEA Wind Task 25 developed guidelines on the recommend-ed methodologies when estimating the system impacts and costs of wind power integration; this was published in 2013 as RP16 of IEA Wind with an update to include also solar PV in 2018. The recommended prac-tices reports are available in the website. The work continues with a sixth period (2021–2024) where the aim is to update the Recommended Practices for Wind and PV Integration Studies.

4. Project implementation

The project evolved mostly as planned. The Corona pandemic forced to move some of the meetings online, hence reducing the networking opportunities (coffee breaks, lunches/dinners, etc), and increasing the time needed to prepare for the meetings (as experience with fully digital meetings was scarce, but the overall objective of knowledge and experience sharing was achieved).

The project implemented all the milestones and achieved all the objectives.

5. Project results

There is an increasing amount of practical experience from wind integration. In 2016 wind energy was covering about 10% of EU power demand, whereas this share increased to 15% in 2019. In some days, wind power covered more than 100% of some Member State's electricity demand (Denmark, Portugal), and high shares were recorded also in Ireland, Spain and Germany. The yearly wind shares in Europe are presented in Figure 1 and in the U.S. in Figure 2.

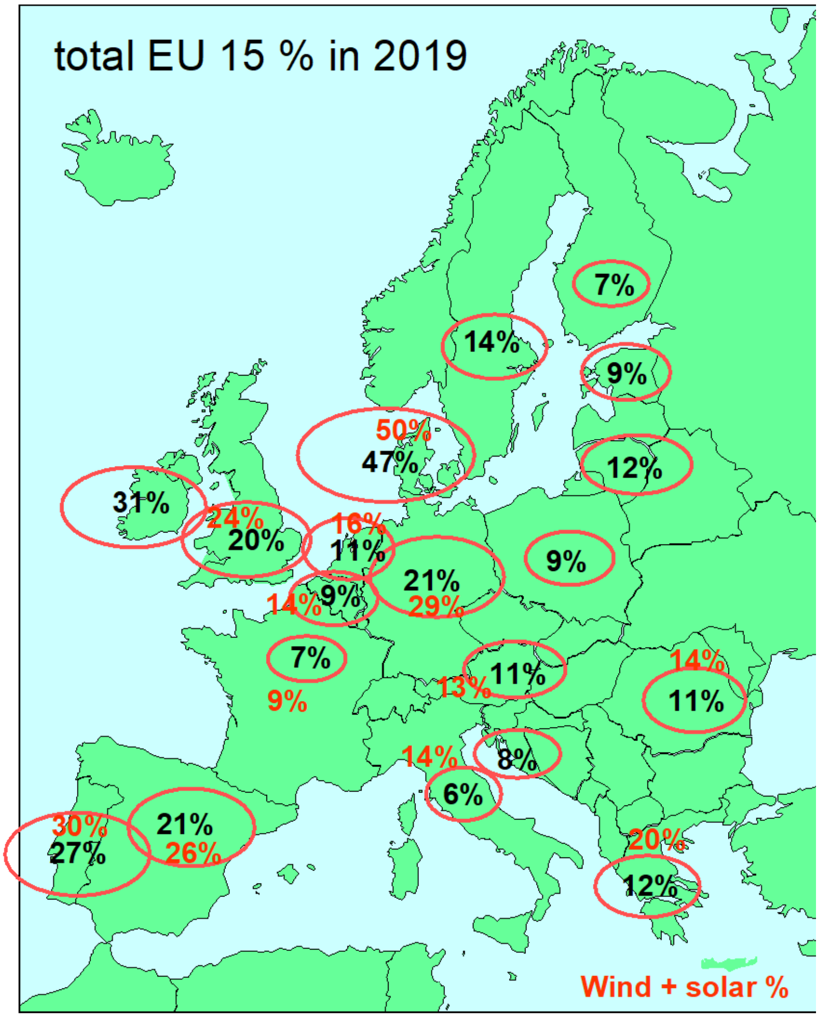

Figure 1. Share of wind generated electricity from total electricity consumption in Europe in 2019 (Source of data IEA TCP Wind Annual Report 2019 and WindEurope statistics). The variable generation shares (wind+solar PV) are shown in red

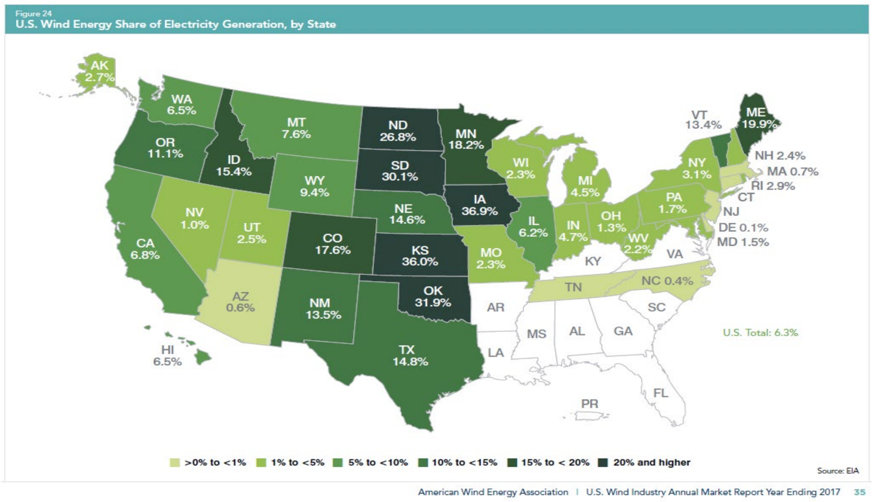

Figure 2. Share of wind generated electricity from total electricity consumption in the U.S. in 2017. Four states had more than 30% average share of wind energy in 2017 (Source: AWEA).

It is also interesting to see the instant high shares of wind, as presented in Table 1 and Figure 3 and Figure 4. As the average share of wind energy does not tell all about the challenges of integrating wind power to power systems, we also use a metric where the installed wind capacity is presented as the share of minimum load and export capability in Figure 3.

Table 1. Average and maximum wind shares recorded in 2017. UPDATE to 2018, 2019, and 2020? Denmark, Ireland, Portugal, Spain, Germany, Sweden, Italy

Country	Wind GW	Wind TWh/a	solar GW	solar TWh/a	Peak load GW	Min load GW	Demand TWh/a	Inter-connectors max export capacity GW	max in an hour	max during a day	max during a month	Wind average share of energy	wind+PV average share of energy	Wind share of peak load	Wind share of min load + max export capability
Denmark	5,5	14,8	1,0	1,0	6,2	1,9	34,1	6,3	139 %	109 %	53 %	43,4 %	46,3 %	89,0 %	67,3 %
Island of Ir	4,5	9,3			6,3	2,4	35,0	1,0				26,5 %	26,5 %	71,0 %	131,5 %
Ireland	3,4	7,4			5,0	2,0	30,0	1,8	79 %			24,8 %	24,8 %	67,4 %	88,6 %
Portugal	5,3	12,3	0,6	1,0	8,8	3,3	51,3	3,8	110 %	82 %	34 %	24,0 %	26,0 %	60,4 %	74,8 %
Spain	22,8	47,5	6,7	13,3	41,4	18,5	267,9	7,6				17,7 %	22,7 %	55,1 %	87,4 %
Germany	50,0	106,6	42,0	40,0	80,6	35,0	602,3	13,8	81 %	71 %	34 %	17,7 %	24,3 %	62,0 %	102,5 %
UK	19,8	49,6	12,8	11,5	50,0	18,1	336,0	4,0	52 %	38 %	23 %	14,8 %	18,2 %	39,7 %	89,8 %
Sweden	6,6	17,6	0,2	0,7	26,6	8,9	140,0	10,0	39 %	32 %	17 %	12,6 %	13,0 %	24,9 %	35,0 %
Italy	9,8	17,5	19,7	24,8	56,6	19,0	320,4	3,6	89 %	63 %	39 %	5,5 %	13,2 %	17,3 %	43,4 %

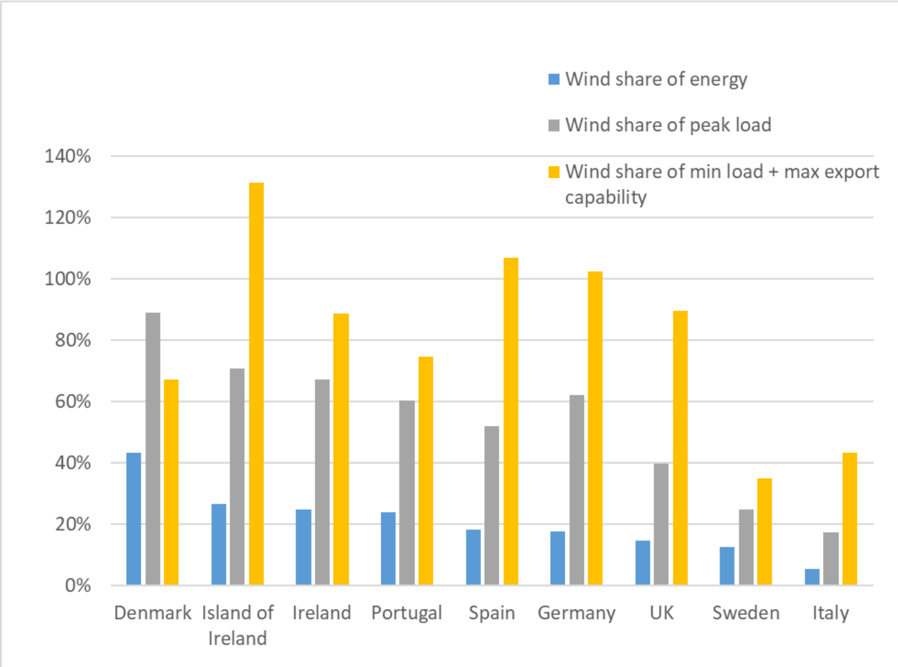

Figure 3. Wind share of consumed electric energy (blue), peak load capacity (grey) and during a critical low load situation (wind installed capacity relative to minimum load and maximum export capacity). (Source: Table 1).

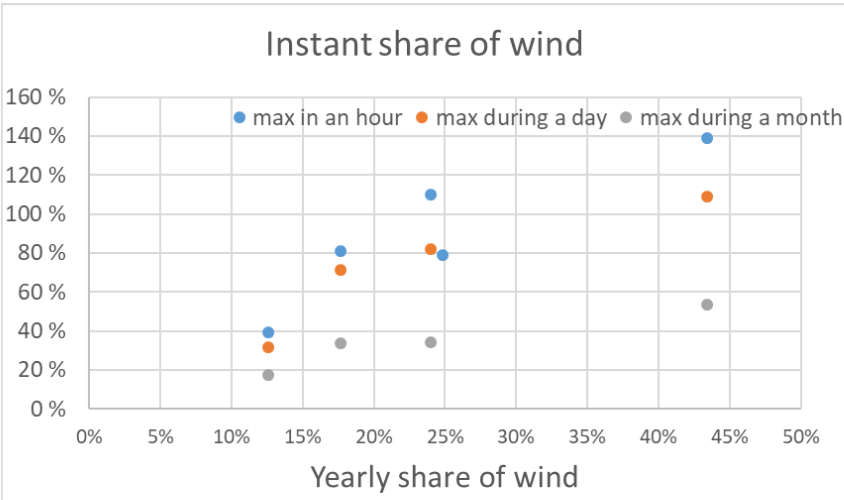

Figure 4. Wind energy share in one hour, day and month, relative to the average share over a year. Recorded values from Sweden, Germany, Portugal, Ireland and Denmark (see also Table 1).

Wind power production introduces additional variability and uncertainty into the operation of the power system, over and above that which is contributed by load and other generation technologies. To meet this challenge, there is a need for more flexibility in the power system. The increased need for flexibility required depends on several factors, such as how much wind power is embedded in the system as well as how much flexibility already exists in the power system. Because system impact studies are often the first steps taken towards defining feasible wind penetration targets within each country or power system control area, it is important that commonly accepted standard methodologies related to these issues are applied.

In this regard, maybe the most important result of the project is the publication of the updated Recommended Practices for Wind and Solar Integration studies[2] by the IEA Wind Task 25 Phase V group. The report has been well received and has become a fundamental document for professionals around the world.

The summary reports that gather findings from experience and study results give valuable information on the challenges, benefits and mitigation possibilities for wind integration and is constantly updated, with the latest published version being Holttinen et al., 2016[3]. This report includes many results, which for ease of space will not be re-included here. Currently, we are finalizing the version that includes all the results from Phase V.

The IEA Wind Task 25 group was very active in dissemination of shared knowledge and experience. The publications targeted different stakeholders:

- Academia and research priorities – via journal articles & conference paper
- Practitioners and professionals – recommended practices and summary reports
- General public – via fact sheets

Journal articles:

- Holttinen, H., Kiviluoma, J., Flynn, D., Smith, C., Orths, A., Eriksen, P. B., Cutululis, N. A., Soder, L., Korpas, M., Estanqueiro, A., MacDowell, J., Tuohy, A., Vrana, T. K., & O'Malley, M. (Accepted/In press). System impact studies for near 100% renewable energy systems dominated by inverter based variable generation. *IEEE Transactions on Power Systems*. https://doi.org/10.1109/TPWRS.2020.3034924
- Söder, L., Tómasson, E., Estanqueiro, A., Flynn, D., Hodge, B-M., Kiviluoma, J., Korpås, M., Neau, E., Couto, A., Pudjianto, D., Strbac, G., Burke, D., Gómez, T., Das, K., Cutululis, N. A., Van Hertem, D., Höschle, H., Matevosyan, J., von Roon, S., ... Vries, L. D. (2020). Review of wind generation within adequacy calculations and capacity markets for different power systems. *Renewable and Sustainable Energy Reviews*, *119*, [109540]. https://doi.org/10.1016/j.rser.2019.109540
- Vrana, T. K., Flynn, D., Gomez-Lazaro, E., Kiviluoma, J., Marcel, D., Cutululis, N. A., & Smith, J. C. (2018). Wind power within European grid codes: Evolution, status and outlook. *Wiley Interdisciplinary Reviews: Energy and Environment*, *7*(3), [e285]. https://doi.org/10.1002/wene.285
- Das, K., Guo, F., Nuño, E., & Cutululis, N. A. (2020). Frequency Stability of Power System with Large Share of Wind Power Under Storm Conditions. *Journal of Modern Power Systems and Clean Energy*, *8*(2), 219-228. https://doi.org/10.35833/MPCE.2018.000433
- Flynn, D., Rather, Z., Ardal, A., Darco, S., Hansen, A. D., Cutululis, N. A., Sørensen, P. E., Estanqueiro, A., Gomez, E., Menemenlis, N., Smith, C., & Wang, Y. (2017). Technical impacts of high penetration levels of wind power on power system stability. *Wiley Interdisciplinary Reviews: Energy and Environment*, *6*(2), [e216]. https://doi.org/10.1002/wene.216
  Hodge, B-MS, Jain, H, Brancucci, C, et al. Addressing technical challenges in 100% variable inverter-based renewable energy power systems. *WIREs Energy Environ*. 2020; 9:e376. https://doi-org.proxy.findit.dtu.dk/10.1002/wene.376
- Miettinen, J, Holttinen, H, Hodge, B-M. Simulating wind power forecast error distributions for spatially aggregated wind power plants. *Wind Energy*. 2020; 23: 45– 62. https://doi.org/10.1002/we.2410
- Holttinen H, et al. Recommended Practises for Wind and PV Integration Studies, IEA-Wind and IEA-PVPS Expert Group Report 16.2, ISBN 978-0-9905075-9-8

Conference publications:

[2] Holttinen H, et al. Recommended Practises for Wind and PV Integration Studies, IEA-Wind and IEA-PVPS Expert Group Report 16.2, ISBN 978-0-9905075-9-8

[3] https://cris.vtt.fi/en/publications/design-and-operation-of-power-systems-with-large-amounts-of-wind--2

- Pérez-Rúa, J-A., Lumbreras, S., Ramos, A., & Cutululis, N. A. (2020). Closed-Loop Two-Stage Stochastic Optimization of Offshore Wind Farm Collection System. *Journal of Physics: Conference Series*, *1618*, [042031]. https://doi.org/10.1088/1742-6596/1618/4/042031
- Jain, A., Das, K., Göksu, Ö., & Cutululis, N. A. (2018). Control Solutions for Blackstart Capability and Islanding Operation of Offshore Wind Power Plants. In *Proceedings of 17th wind Integration workshop* Energynautics GmbH. https://doi.org/10.5281/zenodo.3269542
- Koivisto, M. J., Maule, P., Cutululis, N. A., & Sørensen, P. E. (2019). Effects of Wind Power Technology Development on Large-scale VRE Generation Variability. In *Proceedings of the 13th IEEE PowerTech Milano 2019: Leading innovation for energy transition* IEEE. https://doi.org/10.1109/PTC.2019.8810687
- Söder, L., Estanqueiro, A., Flynn, D., Hodge, B-M., Kiviluoma, J., Korpas, M., Neau, E., Couto, A., Pudjianto, D., Strbac, G., Burke, D. L., Gomez, T., & Das, K. (2018). Wind Generation in Adequacy Calculations and Capacity Markets in Different Power System Control Zones. In *Proceedings of 17th wind Integration workshop* Energynautics GmbH.

Organized special sessions/panel discussion at: Wind Energy Science Conference 2019, Wind Integration Workshop 2019 and 2020, ESIG technical workshops, 2nd International Conference on Large-Scale Grid Integration of Renewable Energy in India, etc.

Presentations at: Wind Integration workshop 2018, 2019 & 2020; WindEurope Conference 2018 & 2019

Factsheets:

- Wind and Solar Integration Issues
- Variability and Predictability of Large-Scale Wind Power
- Balancing Power Systems with Large Share of Wind and Solar Energy
- How Much Wind and Solar Contribute to System Adequacy?
- Storage and Wind Power
- Emission Impacts of Wind Power
- Impacts of Wind (and Solar) Power on Power System Stability
- Transmission Adequacy
- Electrification

6. Utilisation of project results

The main project results are in the form of knowledge and experience sharing. They benefit the participants, by enlarging their own expertize and by comparing/benchmarking methods and approaches. The joint publications offer global views and results of wind and PV integration studies across the world and help share the research agendas.

The cooperation in IEA Wind Task 25 Phase V has also contributed to the development of the Global Power System Transformation (G-PST), a very ambitious and visionary imitative:

“**Visionary Goal:** Dramatically accelerate the transition to low emission and low cost, secure, and reliable power systems, contributing to >50% emission reductions over the next 10 years, with $2 billion of government and donor support for technical, market, and workforce solutions that unlock $10 trillion+ of private sector investment.

Mission: Our Mission is to bring together key actors to foment a rapid clean energy transition at unprecedented scope and scale by providing coordinated and holistic "end-to-end" support and knowledge infusion to power system operators across the 5 Action Pillars."[4]

DTU Wind Energy is a member of the Core technical team, while Energinet is one of the founding System Operators, speaking about the recognition that Denmark has on the topic.

7. Project conclusion and perspective

The activities in Phase V of the IEA Wind Task 25 Phase V have been very successful in exchanging information. There have been significant advantages in forming an international collaboration network designed to share information as well as to compare methodologies and analyse case study results. Through international collaboration, this work has moved forward to formulate best practices in system impact studies for wind power and provide valuable input to discussions of integration costs and acceptable wind power shares in different countries. It has led to collaborative journal articles and international collaboration on projects. It has also established the basis for visiting scientists and the education of new wind integration experts through several PhD and Master theses. Task 25 has provided valuable insight to other international work on wind integration by links established. Continued collaboration with these organisations will assure that careful analyses of the impacts of wind energy and solutions to mitigate potential adverse impacts become available to these groups.

All these have resulted in a unanimous decision to continue the collaboration for a sixth phase, addressing the upcoming challenges related to the shift from studying the challenge of integrating moderate levels of wind in power systems, towards how wind, with solar, can be a backbone of future decarbonised energy systems, including other energy uses than electricity

8. Appendices

Attached presentations given by DTU Wind in the IEA Wind Task 25 Phase V meetings

[4] https://globalpst.org/

MEDOW
MULTI-TERMINAL DC GRID FOR OFFSHORE WIND

DTU

Frequency control from offshore wind power plants connected via MT-HVDC grids

Nicolaos Cutululis
Wind Power Integration
and Control

DTU Wind Energy
Department of Wind Energy

MEDOW
MULTI-TERMINAL DC GRID FOR OFFSHORE WIND

DTU

Aknowledgements

DTU

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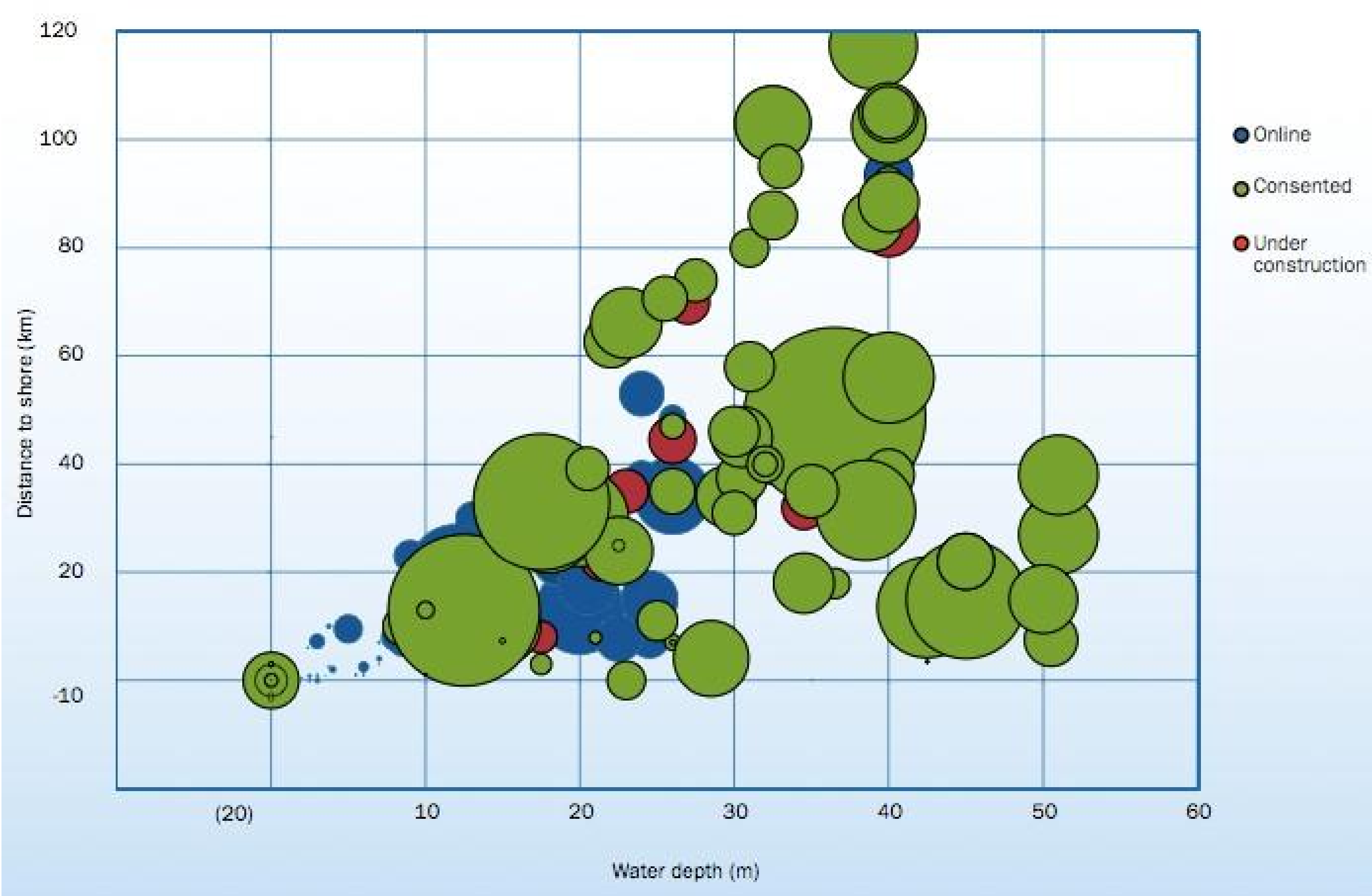
Eduardo P. Araujo
Oriol Gomis

European Academy of Wind Energy
Excellent Wind Young Doctor Award 2017

Agenda

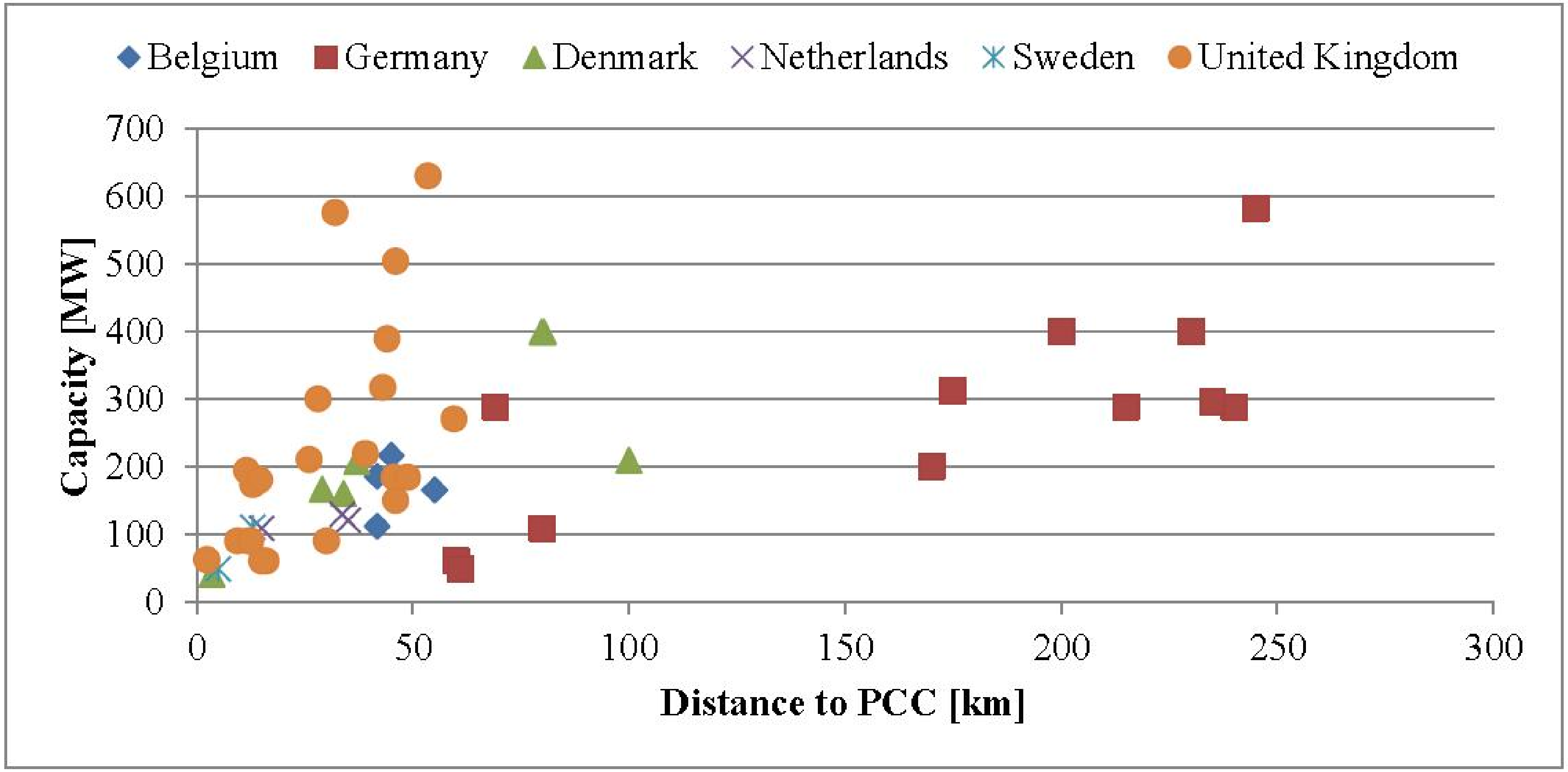
- Need for Fast Primary Frequency Control from WPPs
- Grid layout - Offshore Wind Power Plants (OWPPs) in Multi-Terminal DC Grid
  - Onshore/Offshore HVDC converter control
  - OWPP model and overloading methods of WPPs for FPFC
  - Coordinated frequency control between OWPPs and MTDC system
- Laboratory Scale Experimental Test Set Up
- Simulation and experimental results
- Conclusions

Offshore wind farms - 2014



Water Depth and Distance to Shore of Online, Under Construction and Consented Wind Installations (2014) - EWEA

Offshore wind farms - 2014

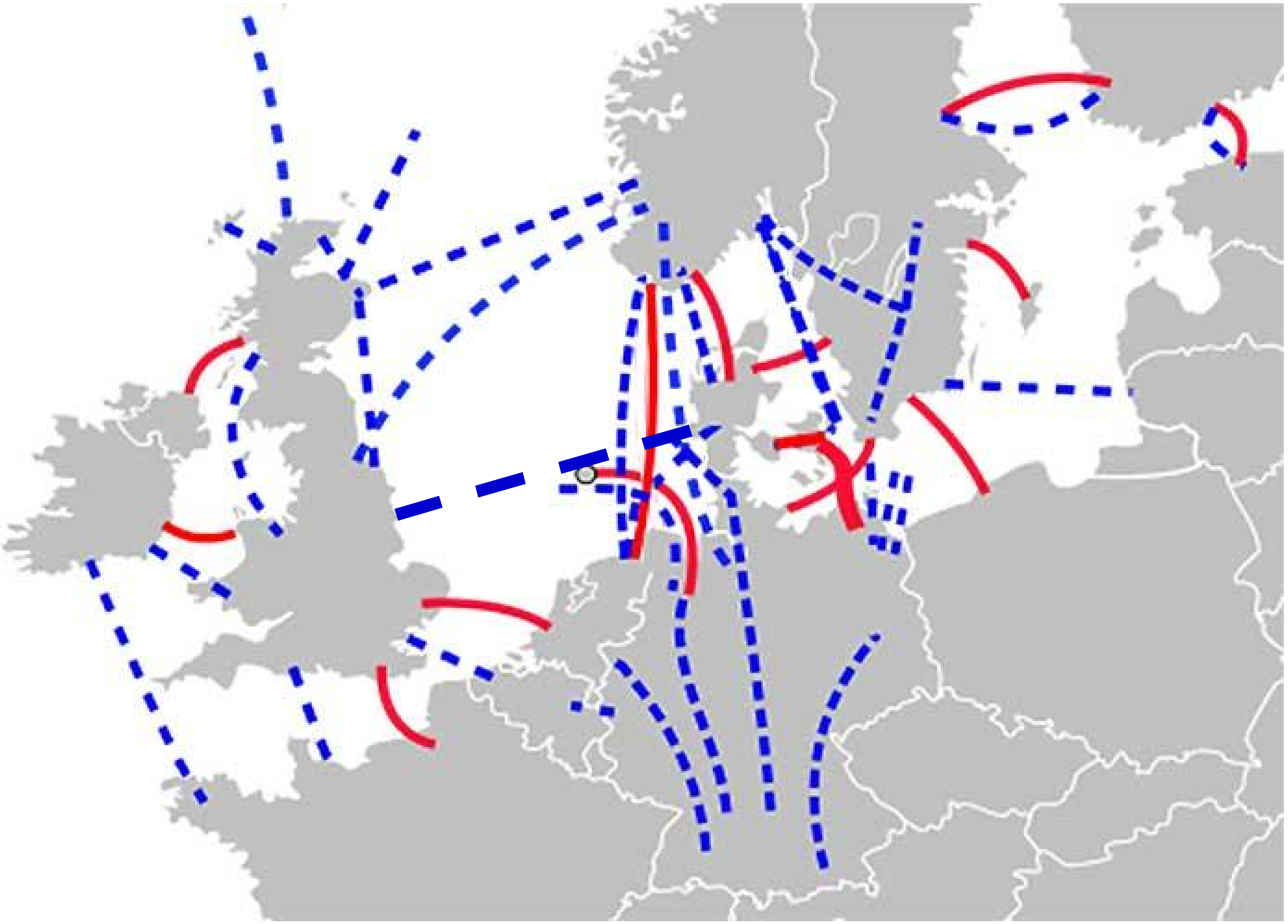


L. Zeni, Power System Integration of VSC-HVDC Connected Wind Power Plants, PhD Thesis, DTU, 2015

German wind farms with HVDC grid connection

Siemens

Existing (red) and planned (blue) HVDC links in Europe



http://www.eee.manchester.ac.uk/our-research/research-groups/pc/researchareas/powerelectronics/vsc/

Need for Fast primary Frequency Control from WPPs

- Increased penetration of HVDC connected WPPs by replacing conventional generation results in **reduced power system inertia:**
  - higher rate of change of frequency (ROCOF) following a loss of infeed or demand
  - risk for drop in frequency to the lower limit or below before primary reserves react

- Need for fast primary control reserves from OWPPs connected through MTDC system acting faster than primary reserves
  - 2014 - National Grid system operability framework report

- Active power support from WPPs for frequency control:
  - down regulating wind turbines - creating some power reserve.
  - **overloading** wind turbines for few seconds - utilizing their kinetic energy

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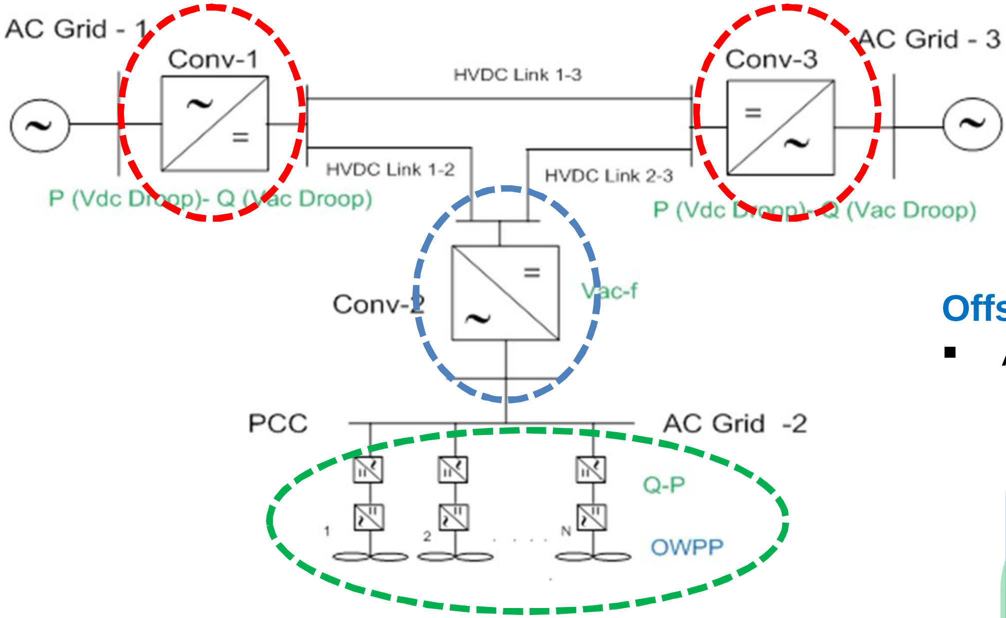
OWPPs in Multi-Terminal DC Grid

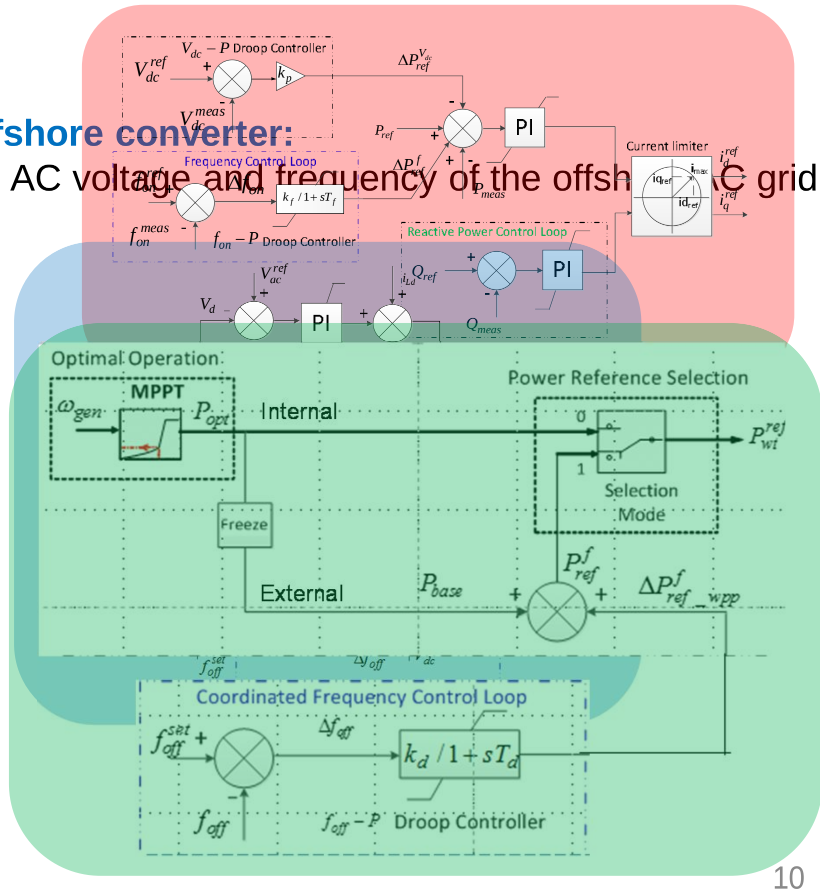


Onshore converters:

- active power balance in the DC Grid

Offshore converter:

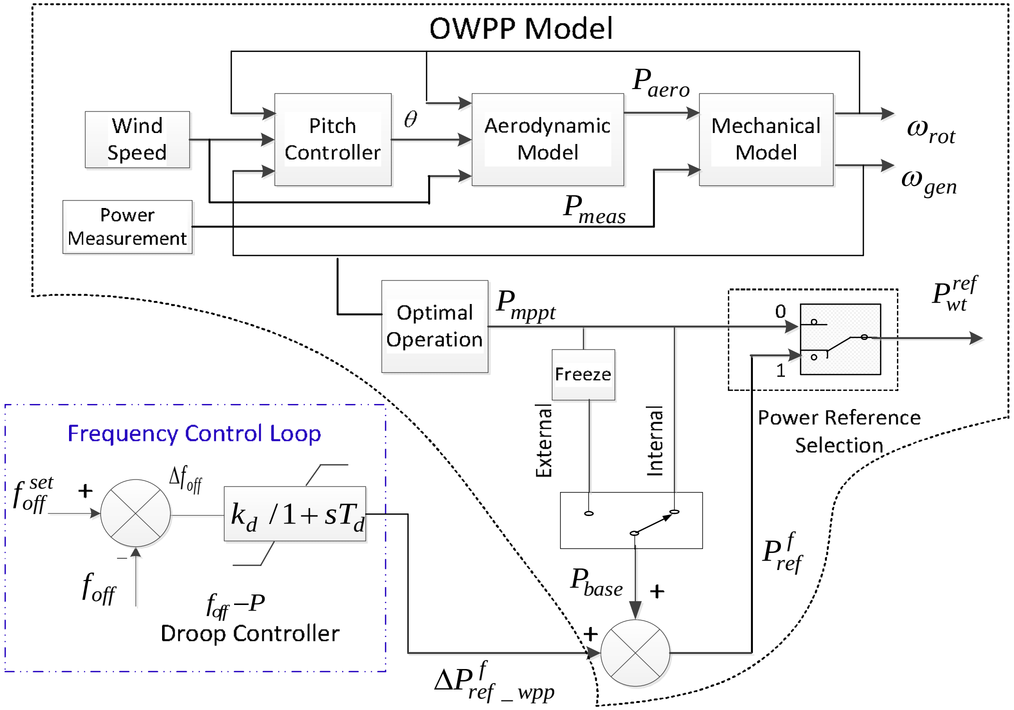
- AC voltage and frequency of the offshore AC grid.

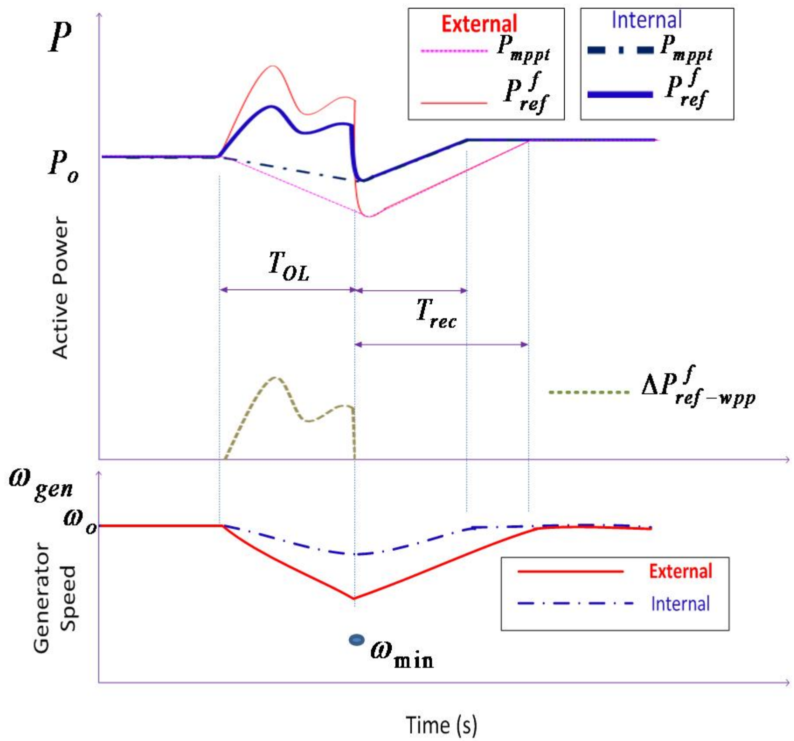


OWPP:

- according to the IEC 61400-27 standard
- adjusted for frequency control studies
- power reference for WPPs based on overloading method:
  - External – no variation of P during overloading
  - Internal – with variation of P during overloading

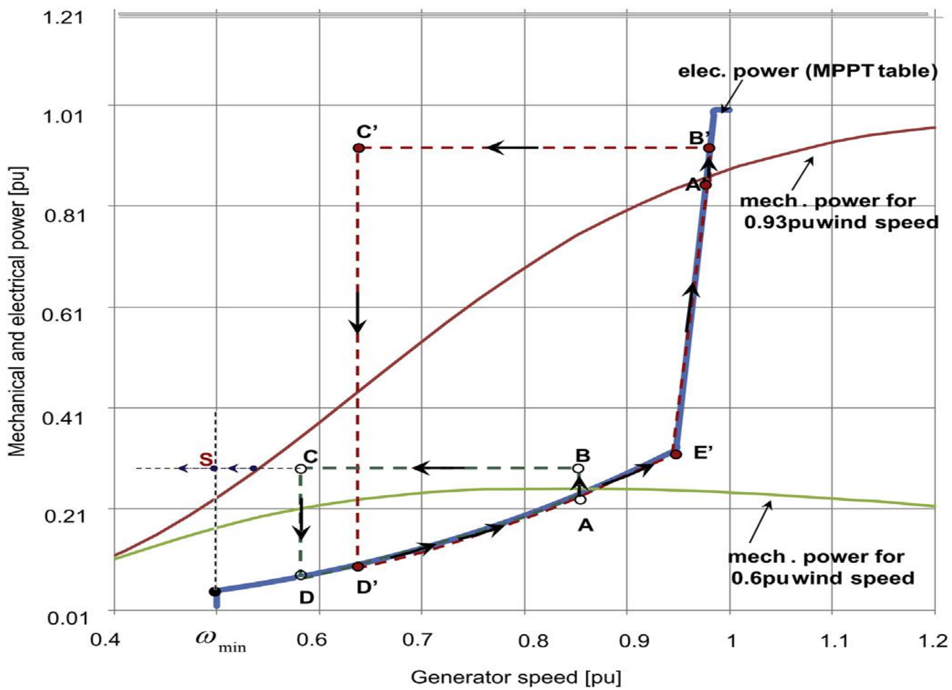
Methods for Overloading the WTs/OWPPs for FPFC

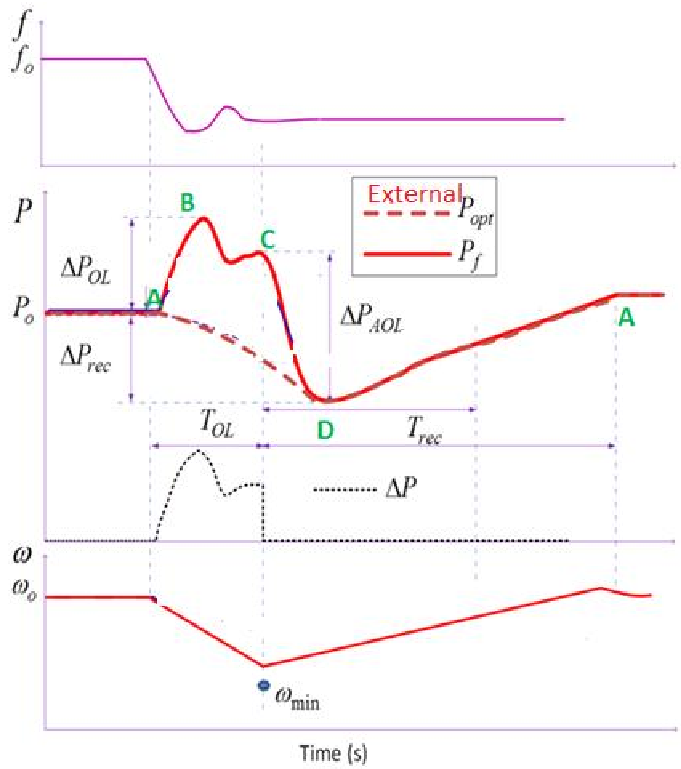




External method does not consider variation of WT power output during overloading period, where as Internal method does.

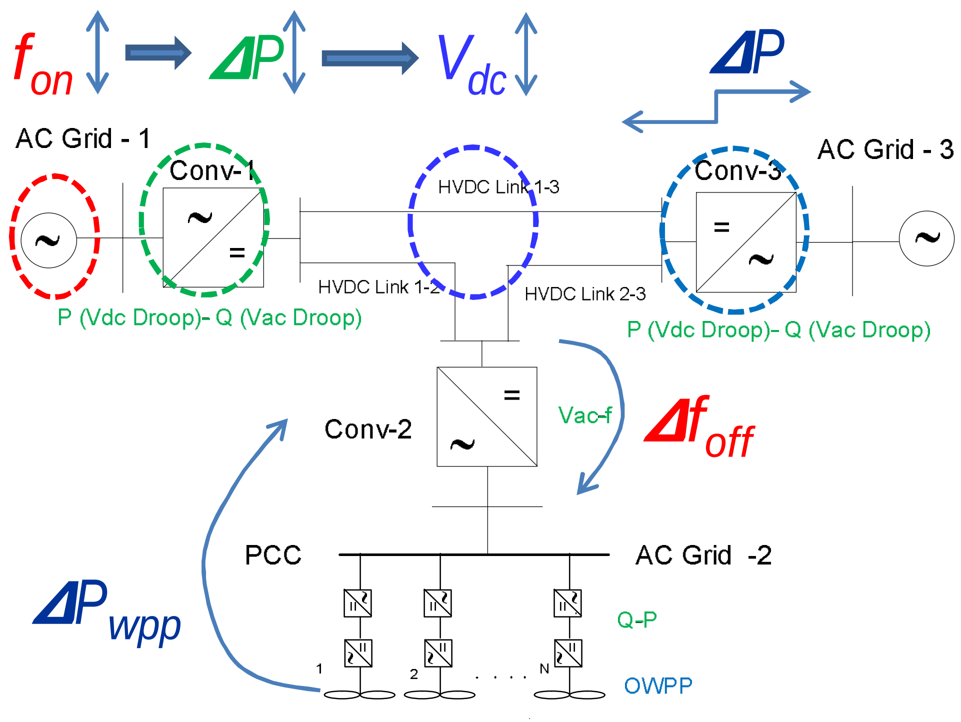
WT Dynamics during the Overload (only External is shown)





Coordinated Frequency Control from OWPPs in MTDC System

- HVDC system <u>decouples</u> OWPP from mainland AC grid – do not respond to onshore AC grid frequency events
- Onshore frequency is <u>replicated</u> at offshore AC Grid <u>without any communication channels</u>



- Any measured frequency deviation leads to a change in the active power reference at the onshore converter.
- The change in active power output of onshore converter results in increase/decrease of DC grid voltage.
- The other onshore converter modulates its power output due to natural droop action.
- Based on the DC voltage, measured at its terminals, the offshore converter modulates offshore grid frequency
- OWPP's active power output is changed according to offshore AC grid frequency.

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MULTI-TERMINAL DC GRID FOR OFFSHORE WIND

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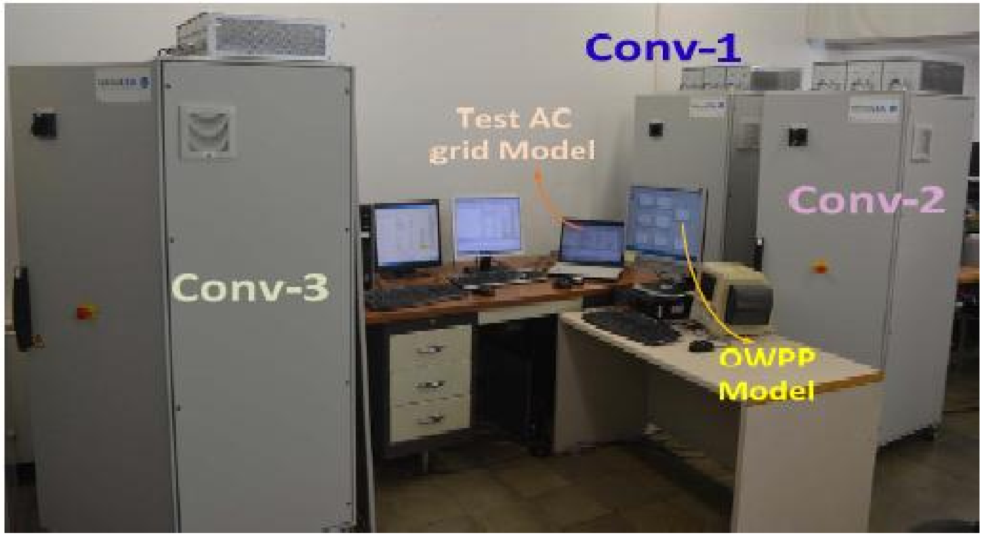
Laboratory Scale Experimental Test Set Up

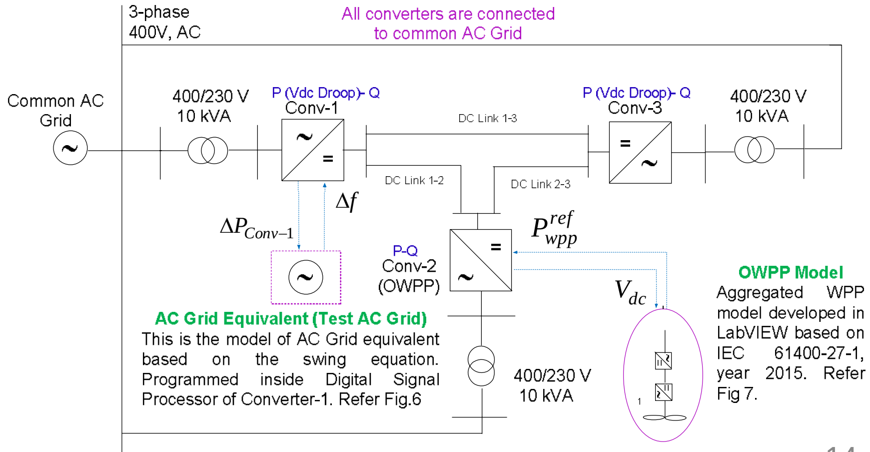
- a laboratory scaled 3-terminal DC grid test set up with an integrated OWPP model is used
- Experiments performed with few modifications:
  - all the converters are connected to same AC grid.
  - AC grid equivalent model to create the frequency event
  - OWPP model is implemented in LabVIEW



100ms communication time between converters

Limitations:

- test performed on a WPP simulation model – not verified:
  - o dynamics of actual WT
  - o Impact on mechanical loading
- time delays in actual frequency measurements are ignored.

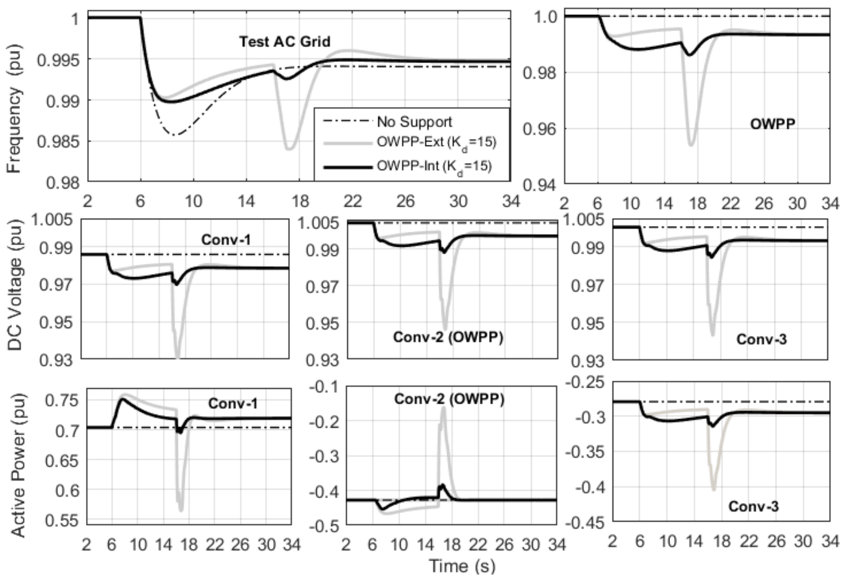


Impact of FPFC from OWPPs on AC/DC grids

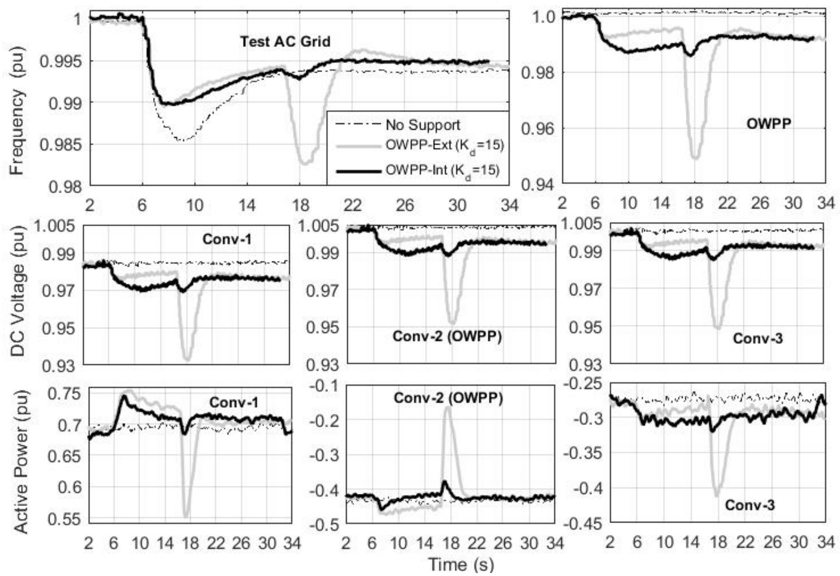
Simulation and Experimental results

15% load change at Test AC Grid	WT overloaded 10s	Constant 0.92pu wind speed

Simulation Results



Experimental Results



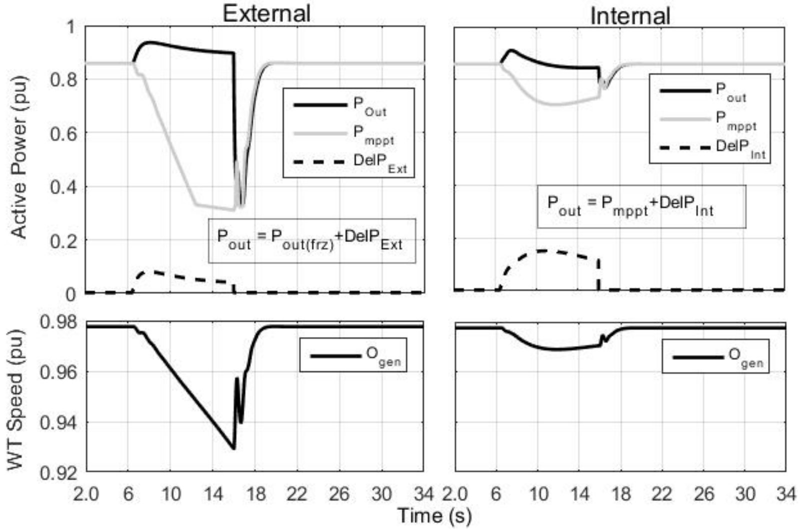
- Simulation results validated: good match between simulations and experiments
- Compared to Internal method, the External overloading method leads to:
  - large secondary dips in AC grid frequency and DC voltage
  - large power drop after the overloading

MULTI-TERMINAL DC GRID FOR OFFSHORE WIND

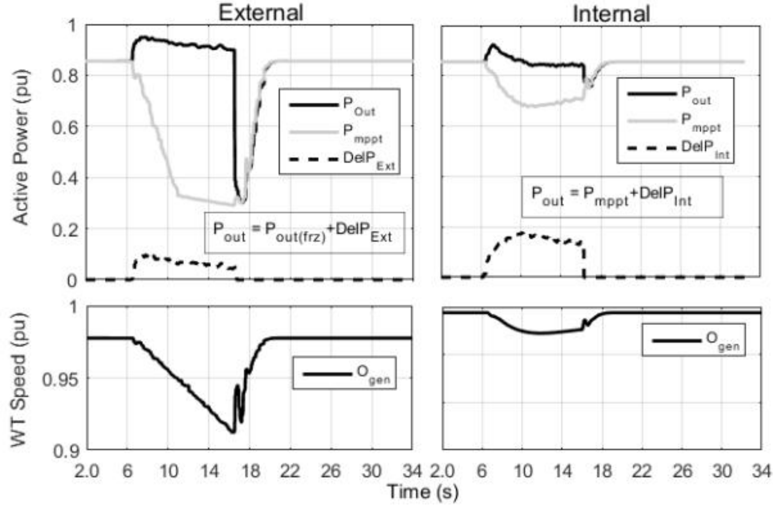
Wind turbine dynamics during FPFC

Simulation and Experimental results

Simulation Results



Experimental Results



External overloading method:

- optimal power output decreases significantly
- rotational speed of WT decreases during overloading
- sudden power drop in WT power output at the end of overload.

Internal overloading method:

- less power drop after the overloading period due to continuous adjustment of optimal output during overloading.

Conclusions

- A coordinated frequency control from OWPP in MTDC grid has been verified through simulations and experimental results:
  - onshore AC grid frequency is replicated at offshore AC grid according to the DC voltage variations. without any communication channels
  - HVDC converters operate in droop control inherently participating in frequency control

- Two overloading methods for active power control support from WTs compared:
  - External overloading method: results in large power drop after the overloading, hence creates secondary effects on AC and DC grids.
  - Internal overloading method: is best suited for FPFC from OWPPs in MTDC grids as it has less negative impacts on DC and AC grids

Simulation of aggregated solar PV forecast errors

Edgar Nuño Martinez, Matti Koivisto, Poul Sørensen
&
Nicolaos A. Cutululis

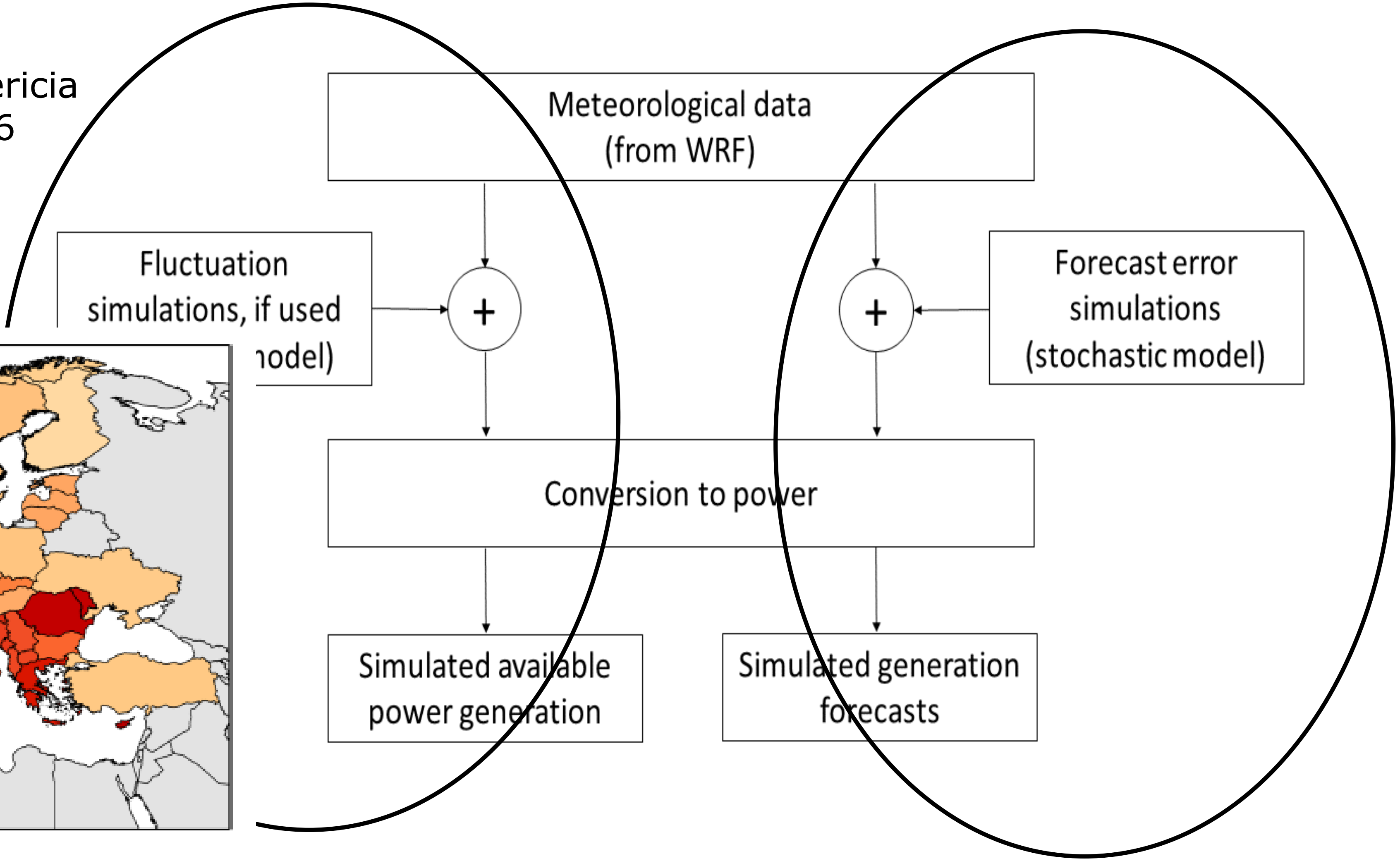
DTU Wind Energy
Department of Wind Energy

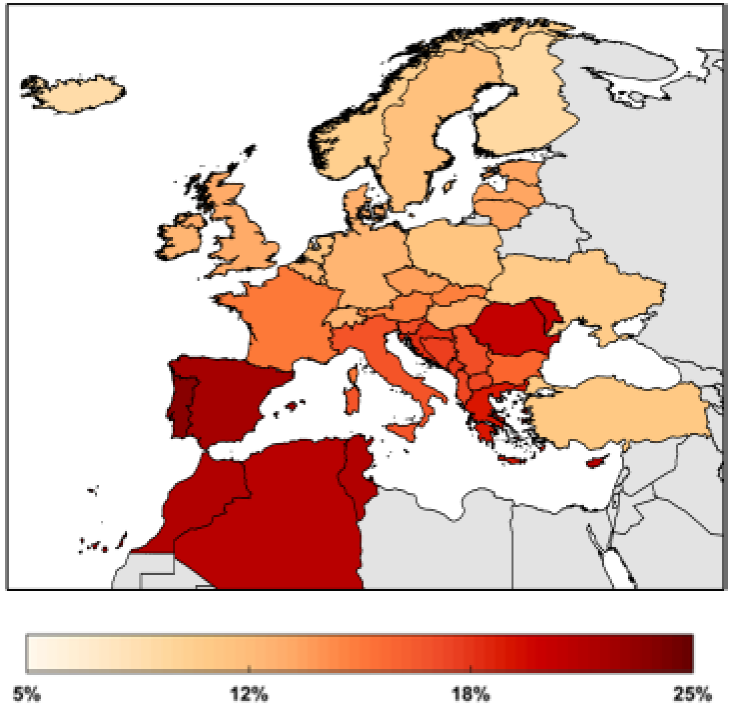
Used for the ENTSO-E's PECD for the TYNDP

Presented in 2012 in Tokyo meeting

CorRES = CorWind + CorPV

Presented in Fredericia meeting, May 2016



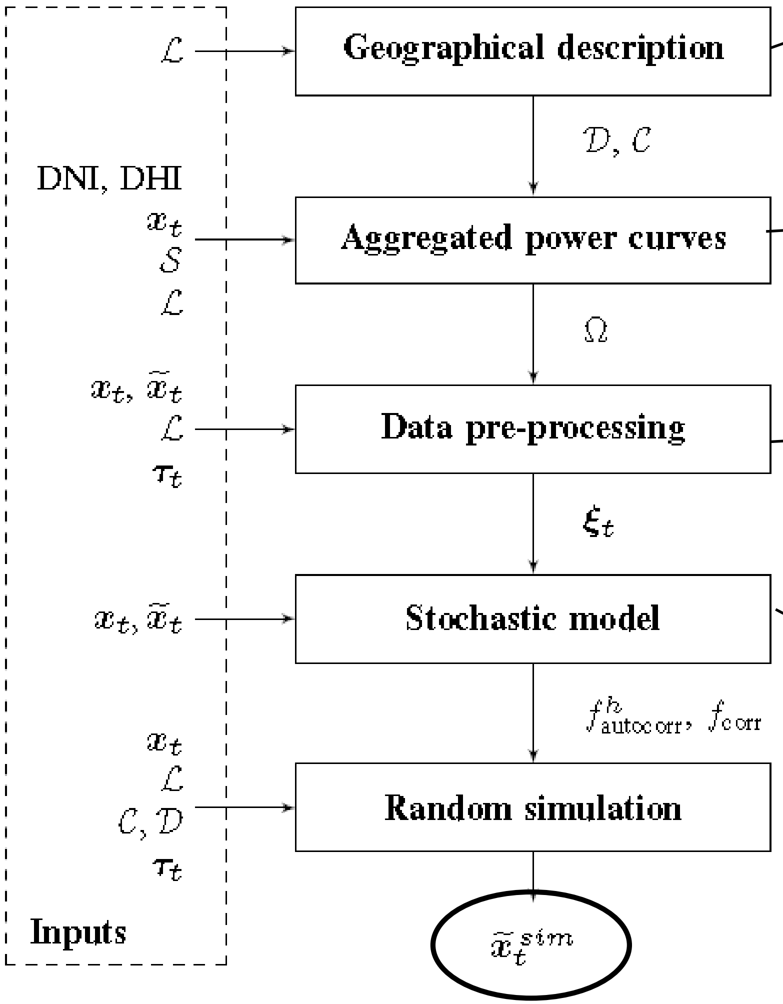


Motivation

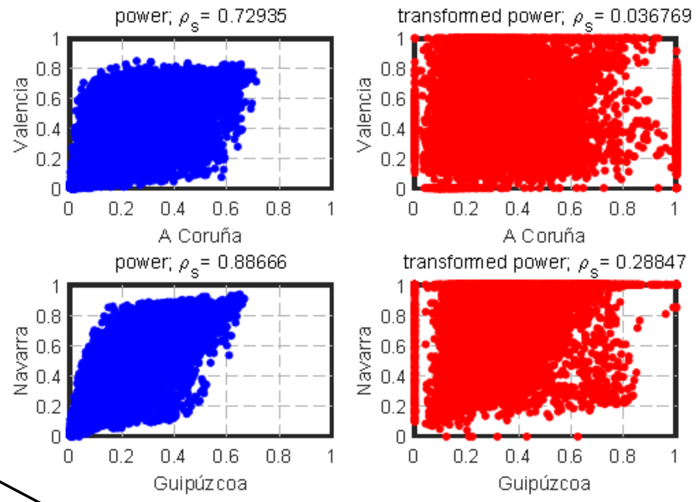
- RES need to be predicted ahead in time
- Uncertainty → several realizations
- Some applications require accurate forecast errors from the error point of view,

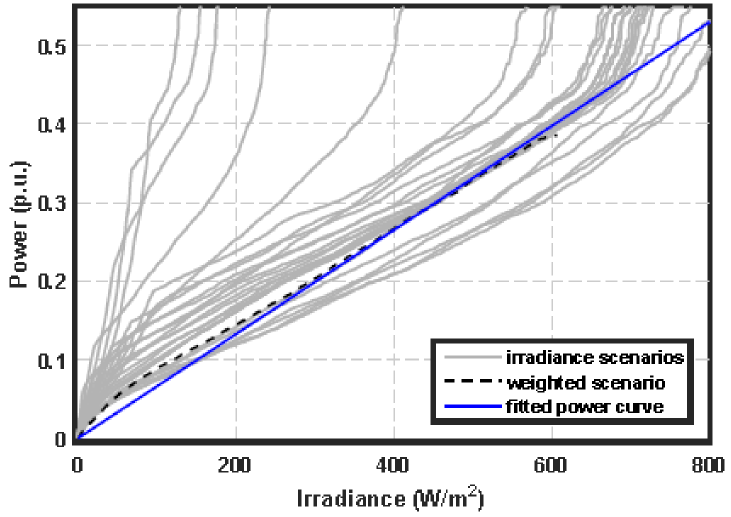
  Not actual predictions!
- Forecast scenario: $\tilde{z}_t^{\text{sim}} = \tilde{z}_t + \xi_t$
- Need to preserve statistical properties: ACF, CCF, etc.

Scenario simulation process



D – diameter and *C* – power center





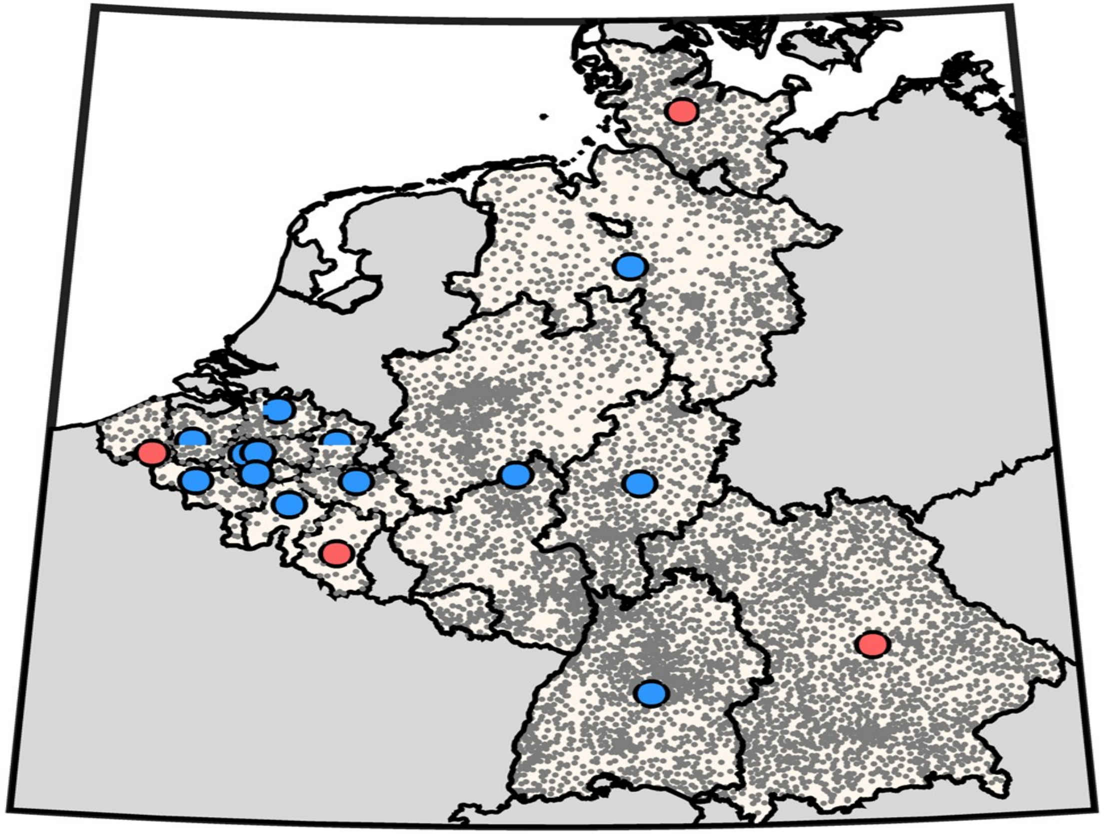
Links spatio-temporal properties to geographical characteristics

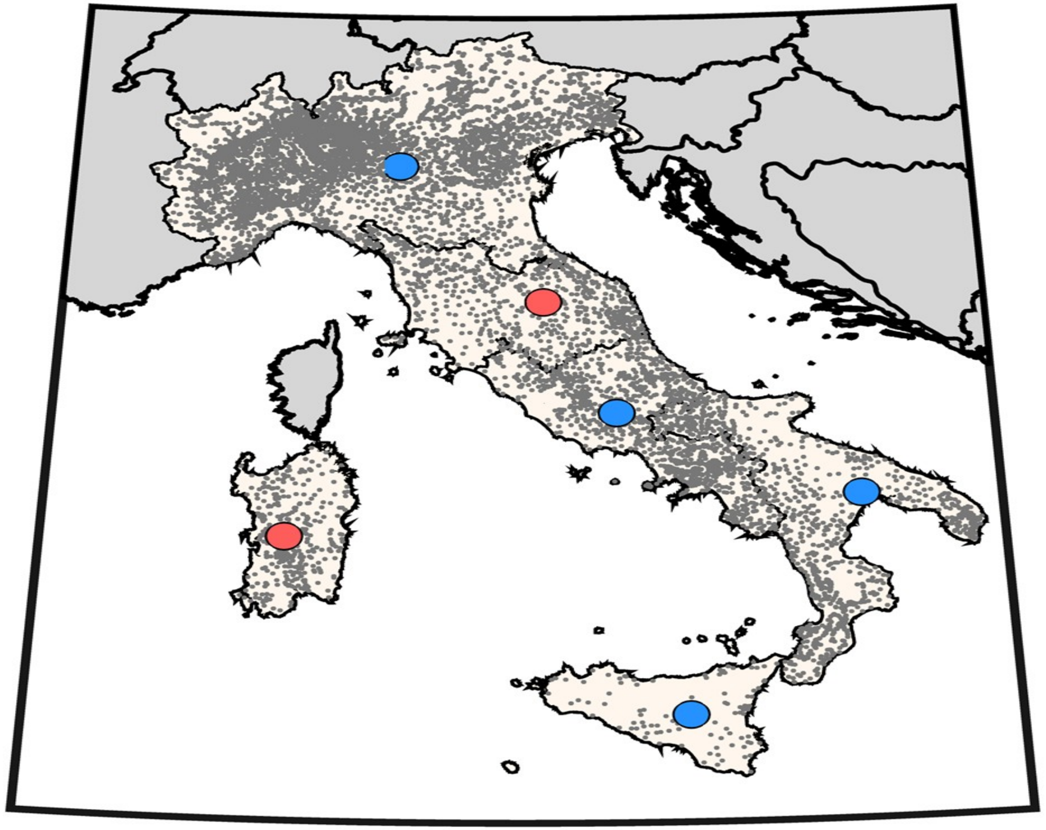
VAR(2); diagonal parameter matrices

$$\begin{bmatrix} b_i^1\\ b_i^2\\ \vdots\\ b_i^{h-1}\\ b_i^h\end{bmatrix} = \begin{bmatrix} 1 & & & & \\ r_i^1 & 1 & & \text{Sym.} & \\ \vdots & \vdots & \ddots & & \\ r_i^{h-2} & r_i^{h-3} & \dots & 1 & \\ r_i^{h-1} & r_i^{h-2} & \dots & r_i^1 & 1\end{bmatrix}^{-1} \times \begin{bmatrix} r_i^1\\ r_i^2\\ \vdots \\ r_i^{h-1}\\ r_i^h\end{bmatrix}$$

Application example

- 23 regions in Europe, different *sizes* and *climatic characteristics*
- Can we generate stochastic scenarios without forecast data?

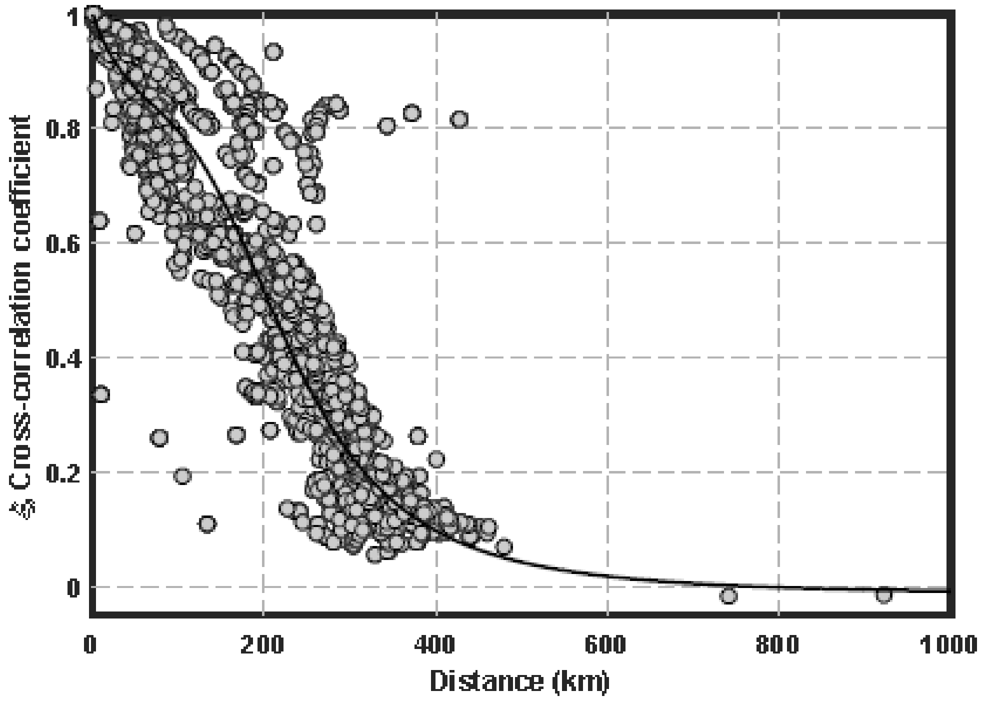




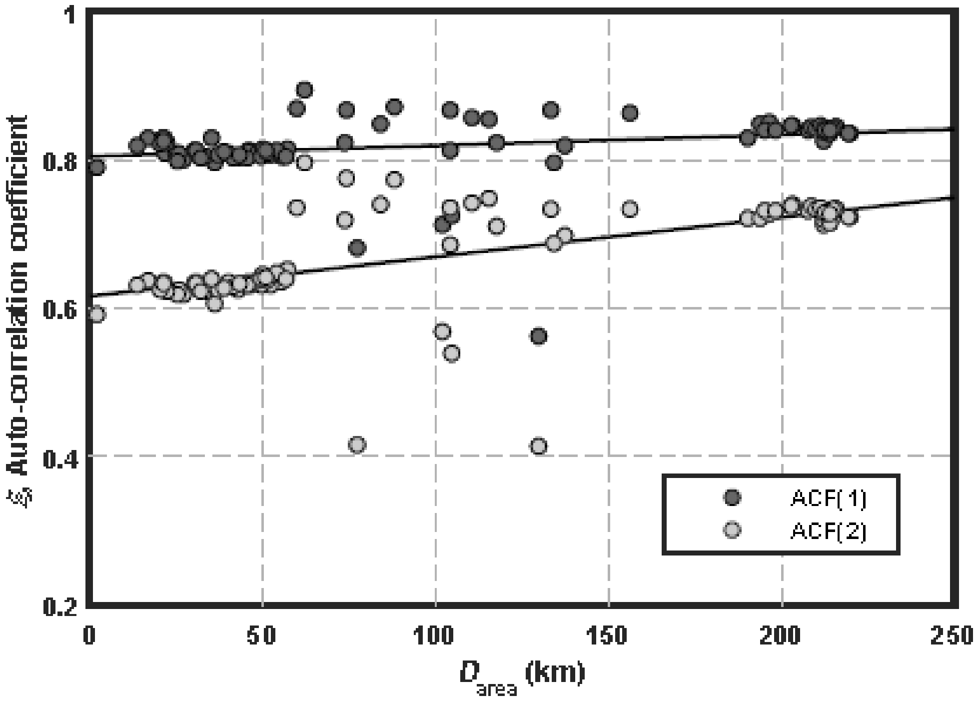
Areas considered in the study. Calibration set (blue) and validation set (red)

Case study II: Stochastic day-ahead PV forecast scenarios

Calibration results (i)

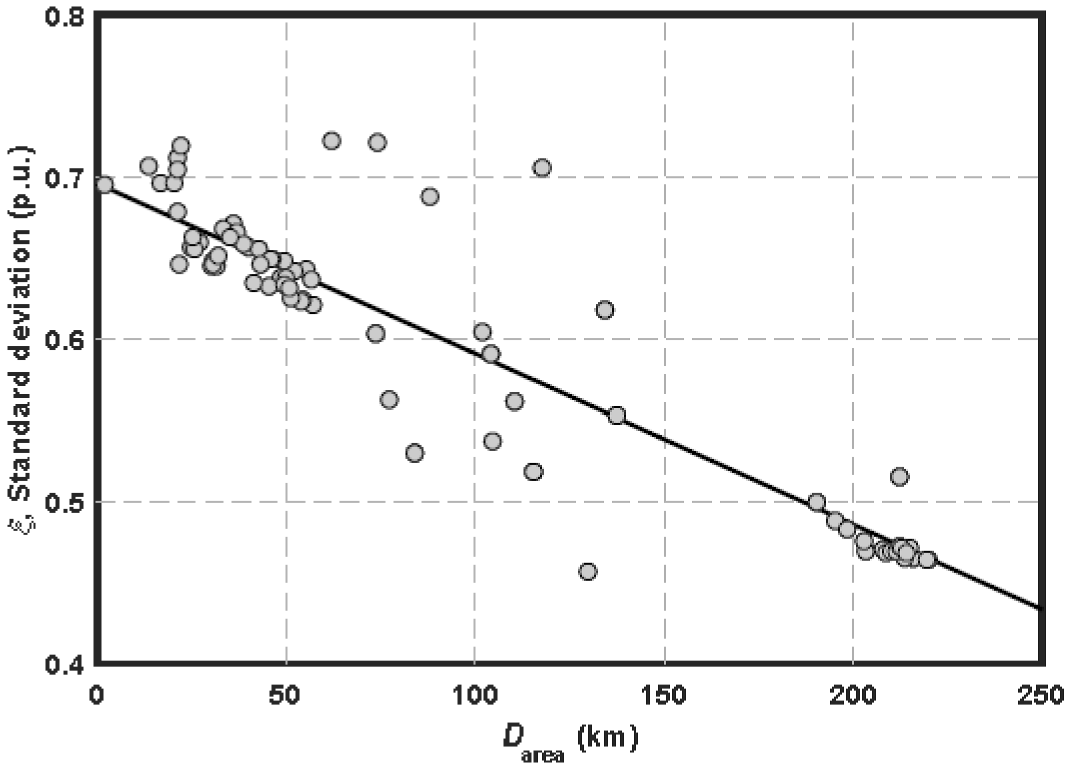


Correlation vs distance between areas



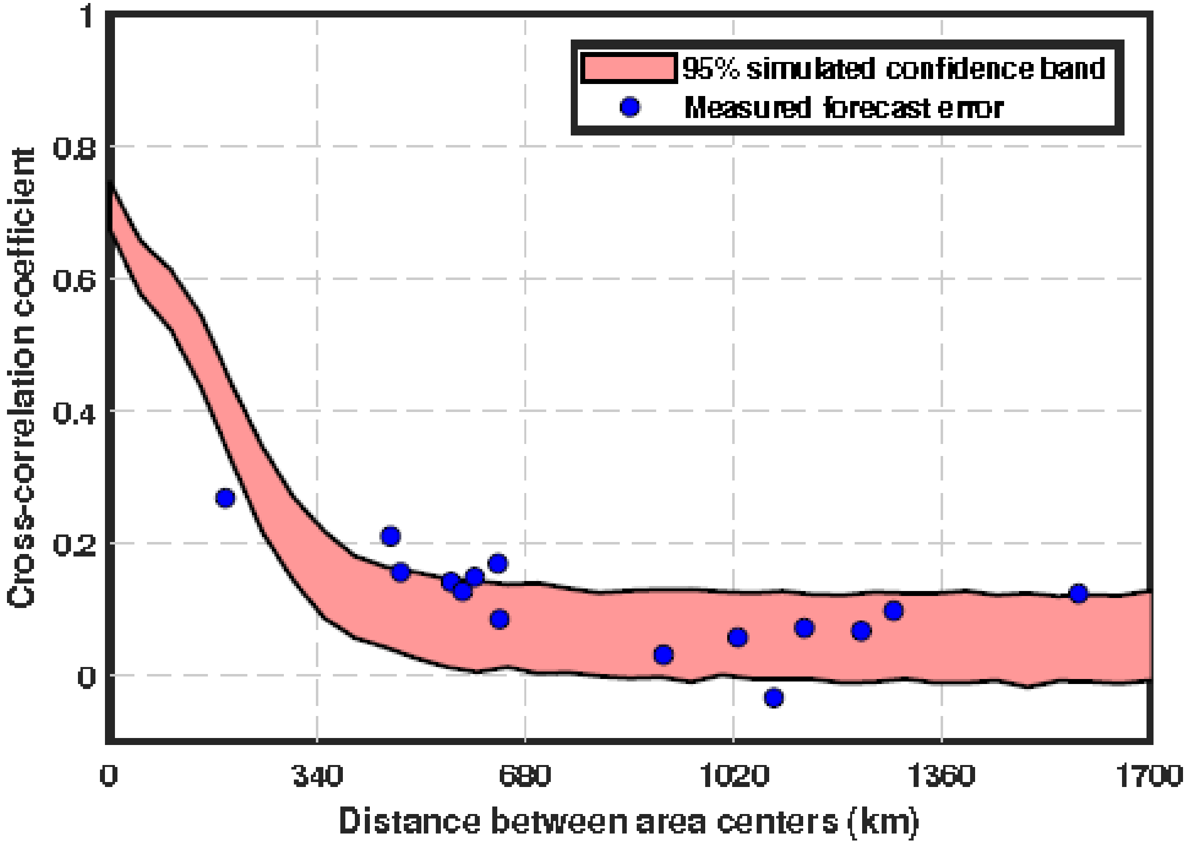
Autocorrelation lags 1 and 2 vs area diameter

Calibration results (ii)



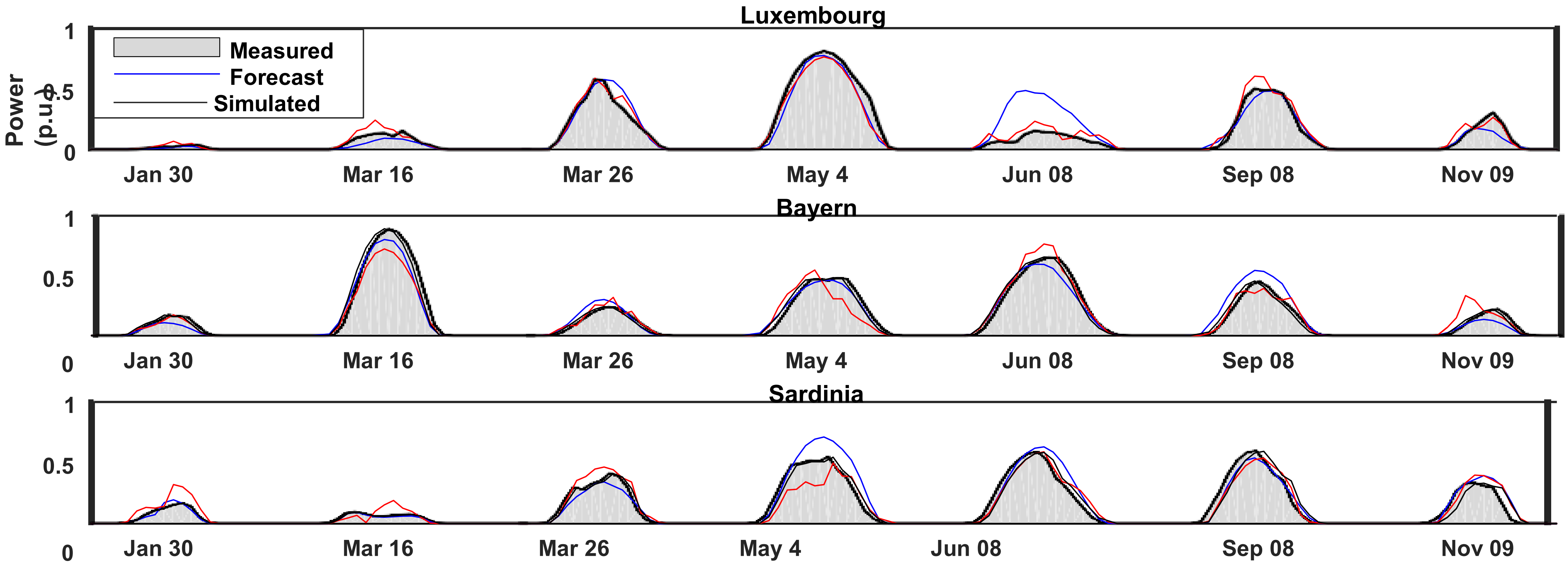
Forecast error standard deviation vs area diameter

Validation results (i)



Cross-correlation of the forecast errors as a function of the distance between area centres.

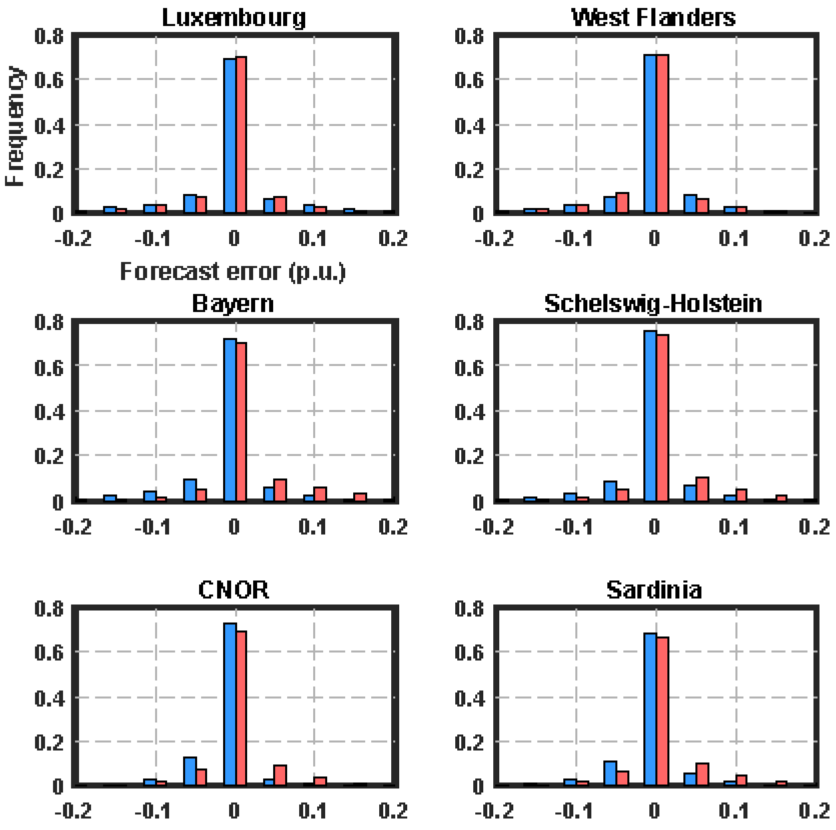
Validation results (ii)



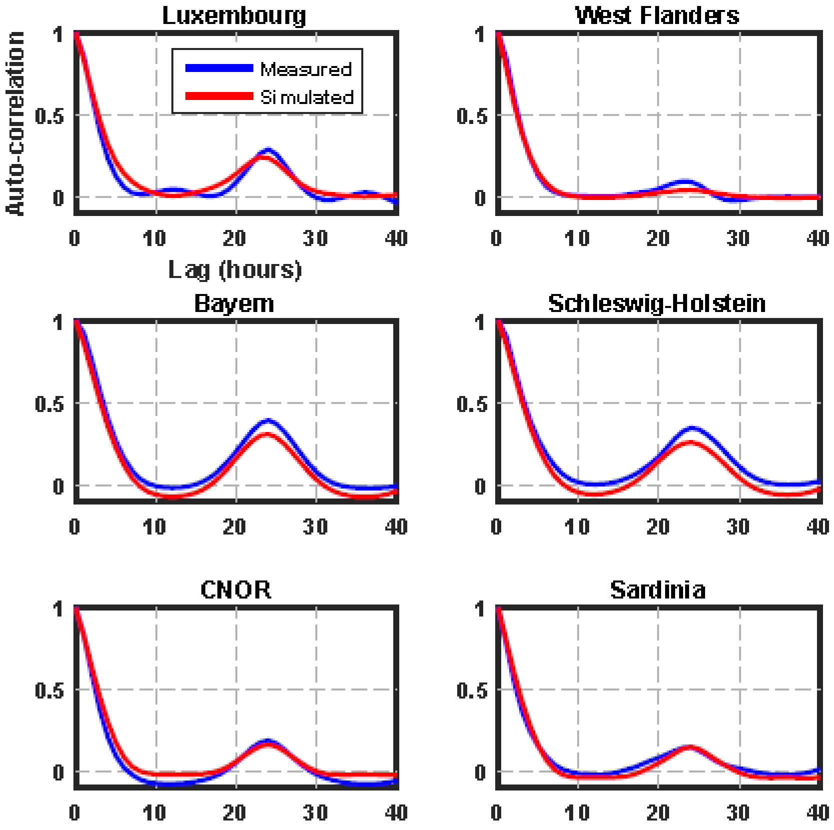
Model realizations for different days of the year

Case study II: Stochastic day-ahead PV forecast scenarios

Validation results (iii)



Forecast error histograms



Forecast error autocorrelation functions

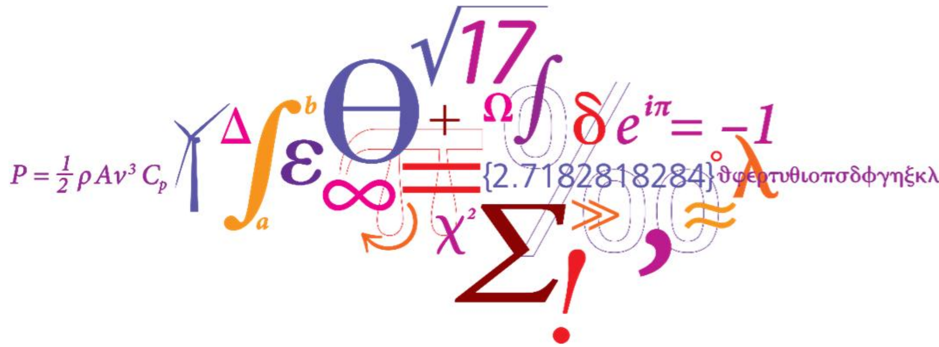
Publications

- Nuno, E, Koivisto, MJ, Cutululis, NA & Sorensen, P 2017, Simulation of regional day-ahead PV power forecast scenarios. in *PowerTech, 2017 IEEE Manchester.*IEEE Xplore. 2017 Ieee Manchester Powertech, DOI: 10.1109/PTC.2017.7981155

- Nuno, E, Koivisto, M.J., Cutululis, NA & P. Sorensen, "On the simulation of aggregated solar PV forecast errors," in *IEEE Transactions on Sustainable Energy,* doi: 10.1109/TSTE.2018.2818727

Wind Power Support in Distribution System

Kaushik Das



Supported by:

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Theofanis Sofianopoulos

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Anca D Hansen

Poul E Sørensen

Nicolaos A. Cutululis

IEA Wind – Task 25

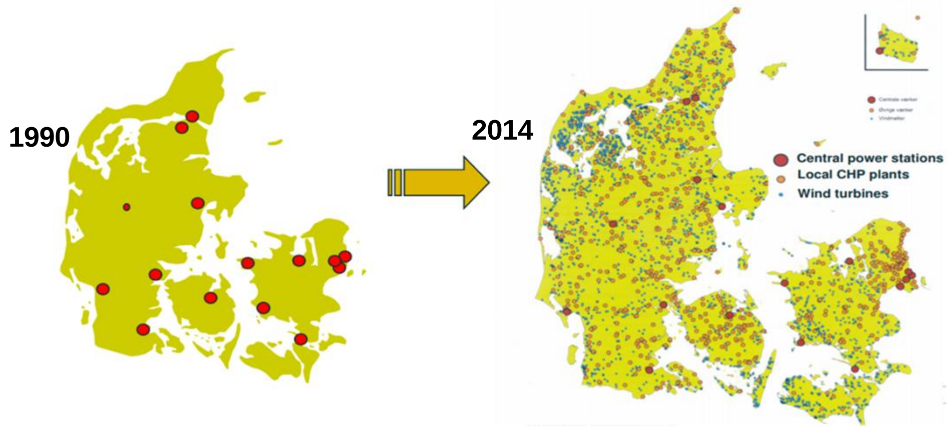
16th October 2018

KTH

DTU Wind Energy
Department of Wind Energy

RES generation in Danish distribution systems

Centralized Plants Vs Distributed Generations



Henning Parbo, “Distributed Generation Trends and Regulation: The Danish Experience”, EPRG Workshop on Distributed Generation and Smart Connections

DSO challenge today:

Large penetration of wind power in distribution networks <u>without any active support:</u>

- Negative impact on power flow / voltage profile/ voltage stability / power balance

Active support from RES for better operation of future distribution networks:

- reduces network losses / congestions / improves voltage profile without reinforcement of grid
- support of transmission network:
  - *MVAR control*
  - *voltage support*
  - *frequency support*

NetVind project

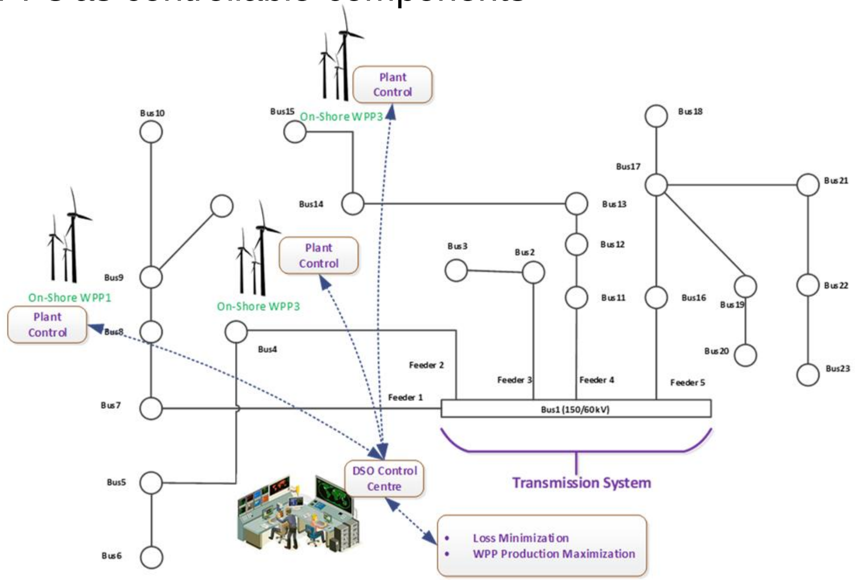
Using wind power plant control in distribution grid operation

Objective

- to improve the operation of a real distribution network with a high penetration of wind power by exploiting the WPP control capabilities.

DSO's challenges

- how to operate the distribution systems by using WPPs as controllable components



Partners

ENIIG Forsyning A/S (leader)
DTU Wind Energy
Danish Energy Association

Project period:

Sep, 2016 – Sep, 2019

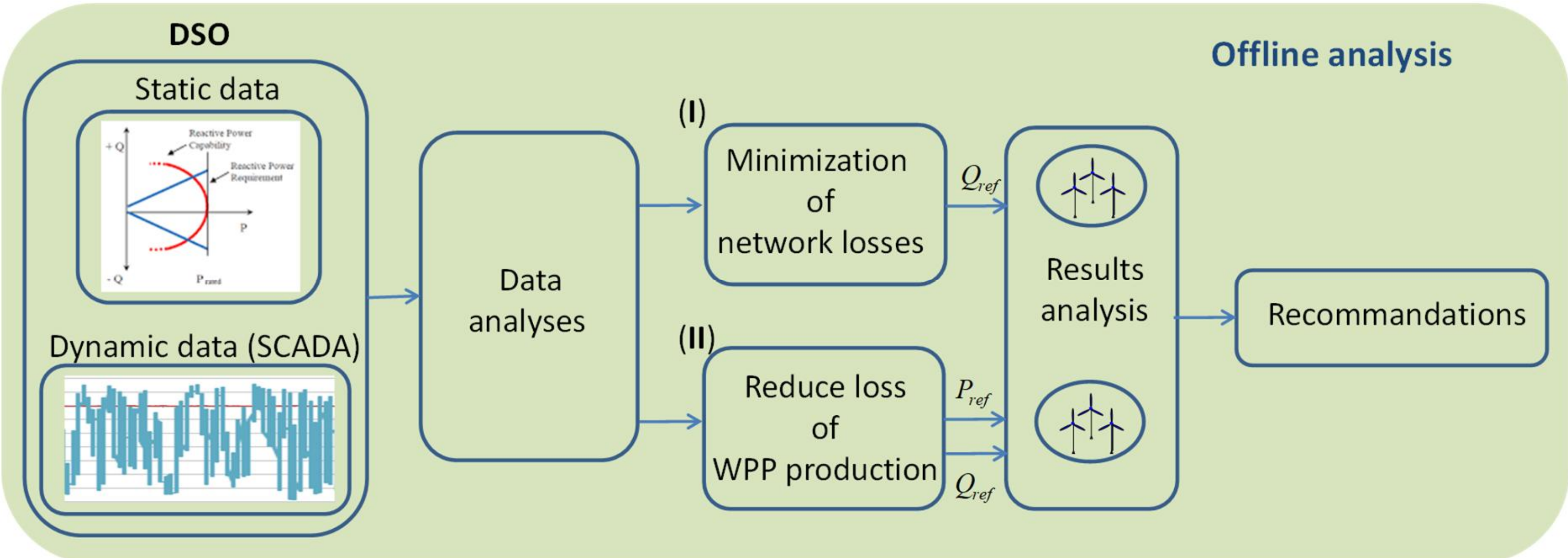
Ongoing

NetVind – offline analysis

- Analyze additional network losses due to wind power generation

- Develop methodologies for optimal control of Wind Power Plants (WPP):
  - to reduce network losses by optimizing the reactive power flow in 60kV network
  - to reduce the loss of power production from WPPs during network reconfigurations

  (i.e. disconnections of certain feeders due to the repair and maintenance of the network)



Online operation for validation and evaluation

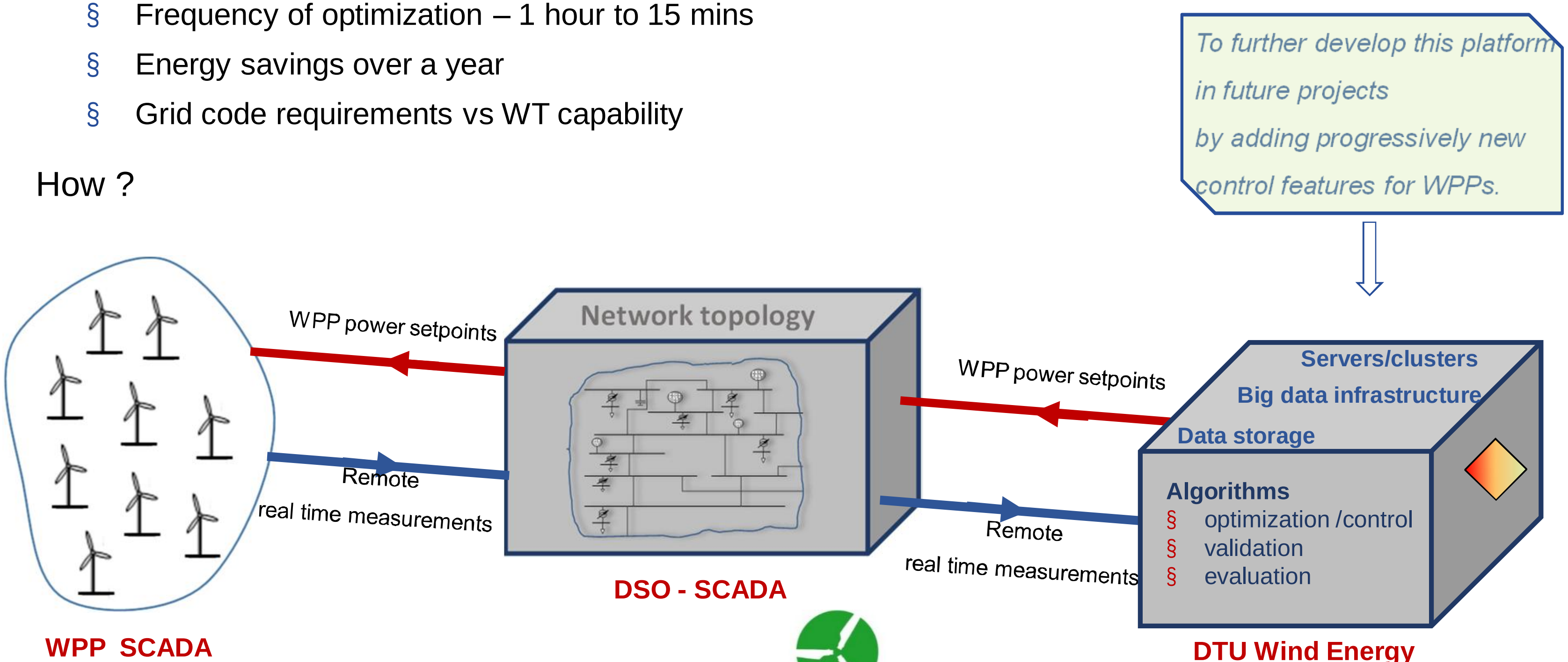
Idea:

- implement and validate the optimization algorithms online in a real distribution power system
- if necessary updated based on actual measurements in the distribution network.

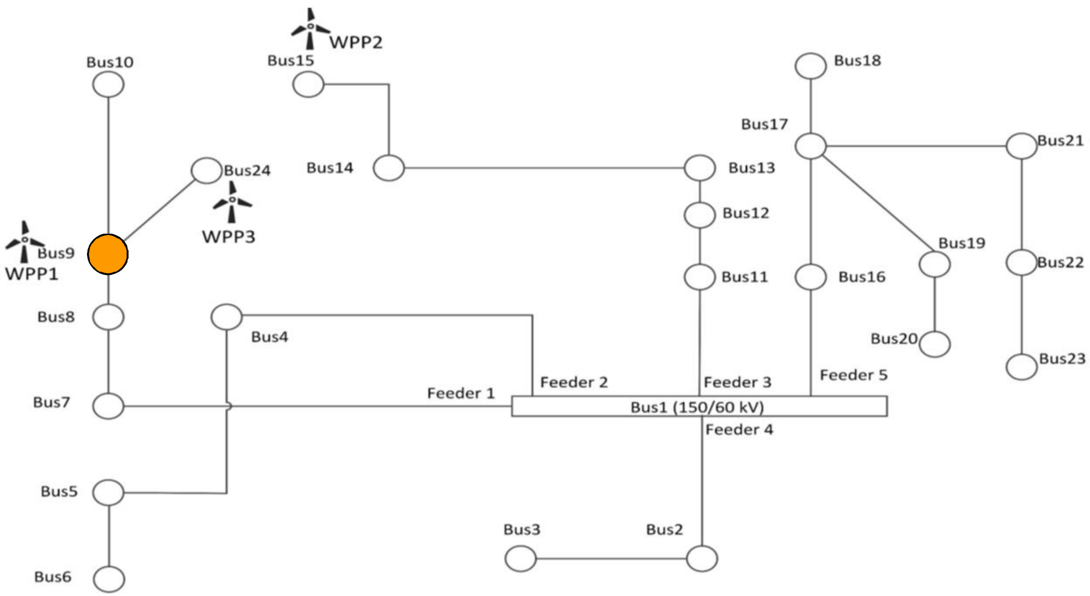
Validation:

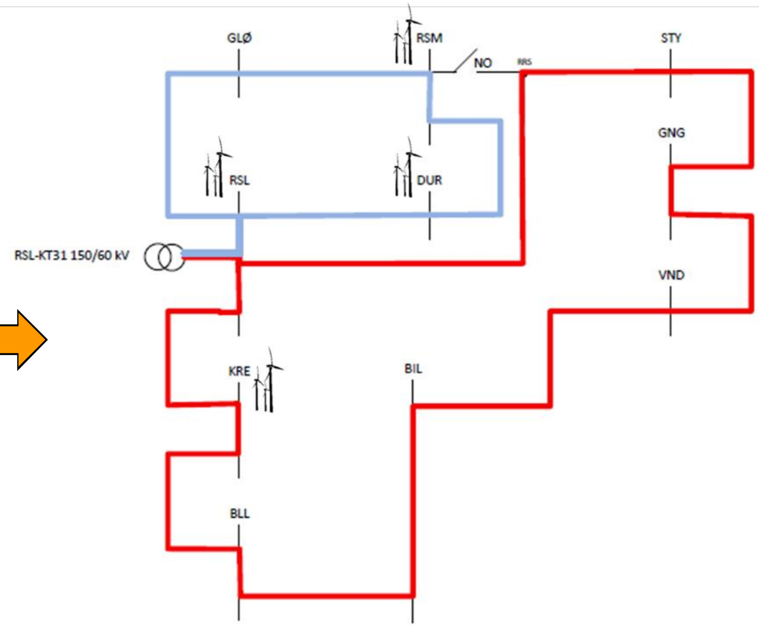
- Communication capabilities
- Different optimization methods
- Frequency of optimization – 1 hour to 15 mins
- Energy savings over a year
- Grid code requirements vs WT capability

How ?



Topology



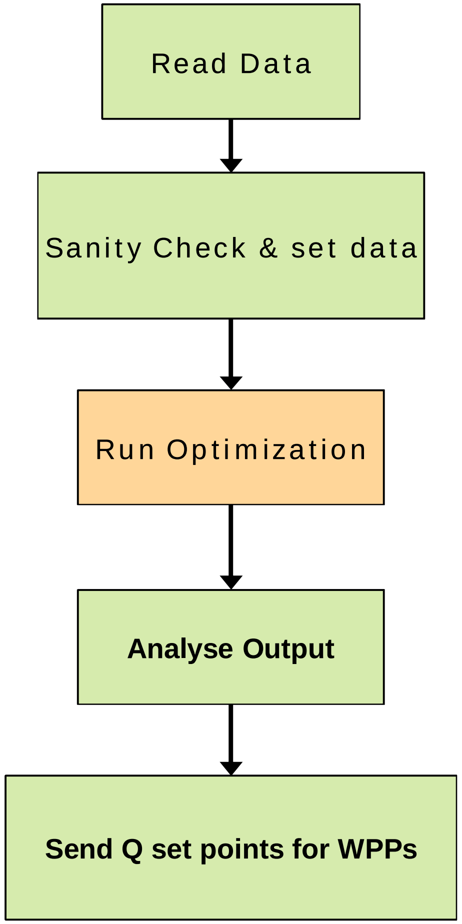


- 60/10kV bus bars
- 3/4 controllable WPPs
- Aggregated Load & other generations connected at 10kV

Assumptions during demonstration

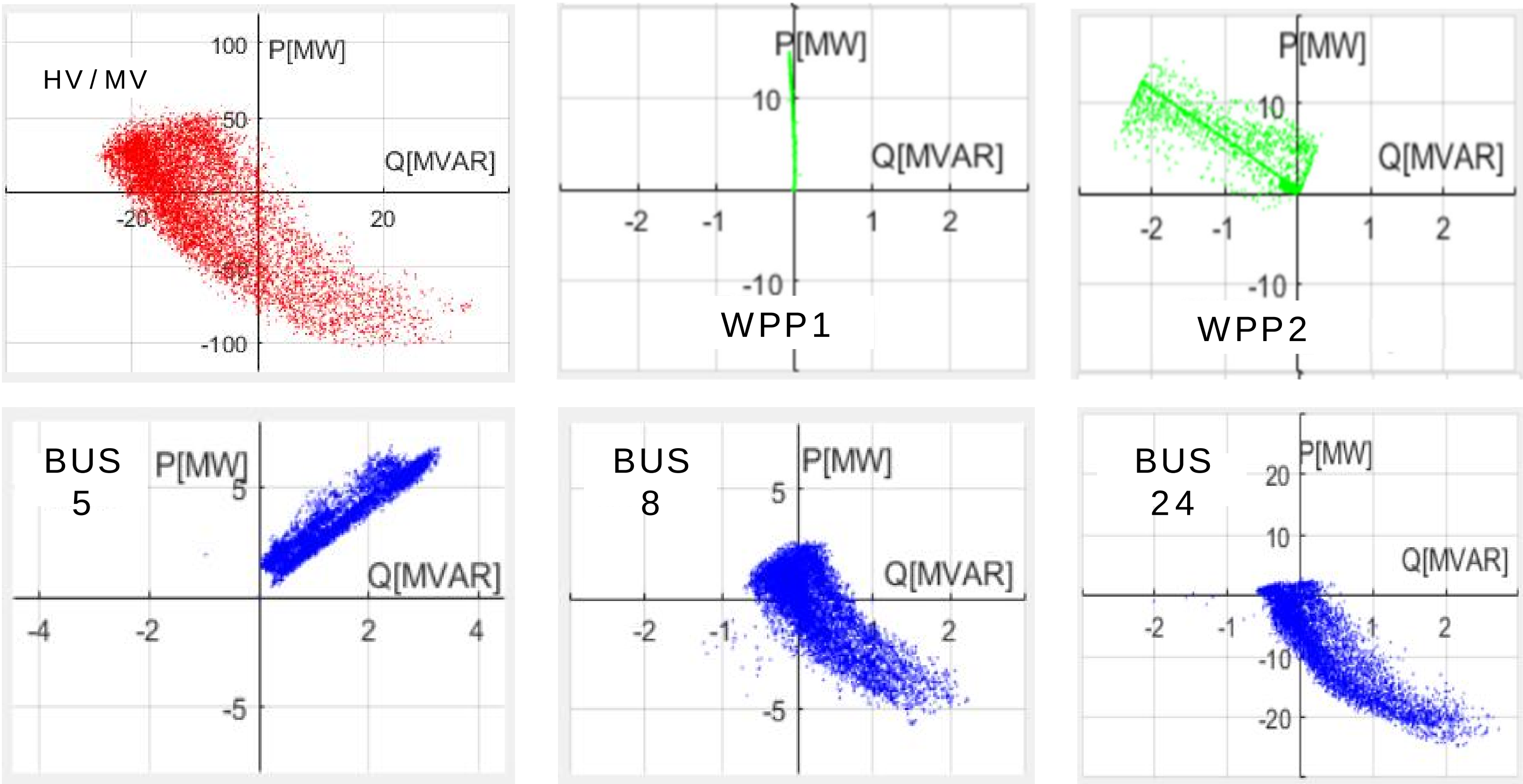
- Topology assumed unchanged for the whole period of study
- Only control variables are Q set points of WPP
- 60/10 kV tap changers are not controlled by the optimization
- Using only healthy data from the complete data set

Flowchart – Minimization of network losses



P-Q plots: Network Characteristics

Demand sign convention is used: positive for demand / negative for generation



bus acting as demand

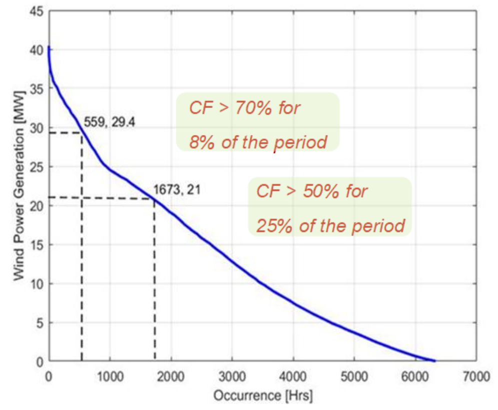
bus acting as demand & generation

bus with WPPs

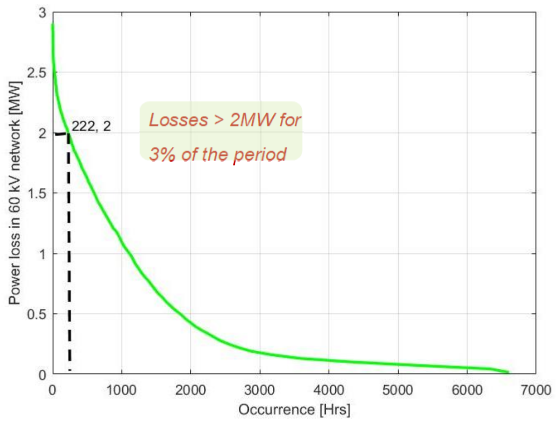
acting mostly as generation

Loss Analysis

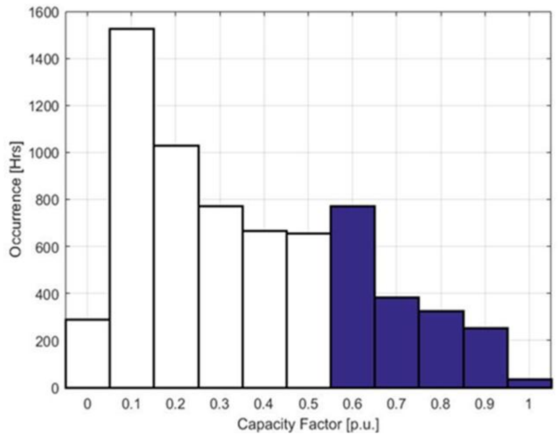
Duration curve for Wind Power Generation



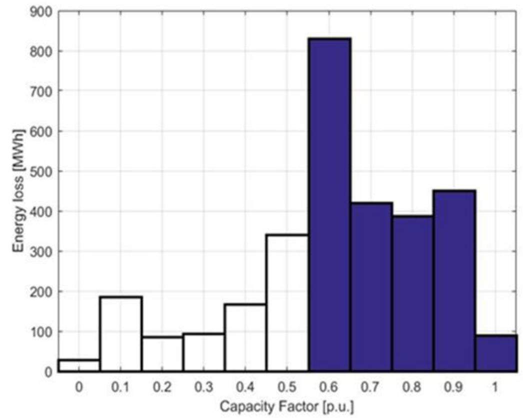
Duration curve for power loss in 60 kV network



Operational hours for WPPs at different capacity factors



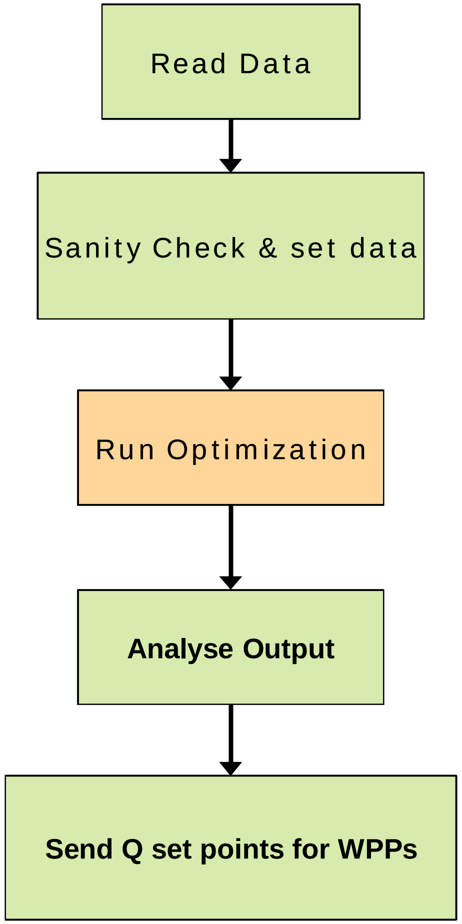
Energy loss in the 60 kV network for different WPP capacity factors



Higher is wind power generation, higher is network loss

Although high wind power generation occurs for small duration, it contributes for major proportion of energy loss

Optimization



- Control variables:
  - Reactive power set point of WPPs

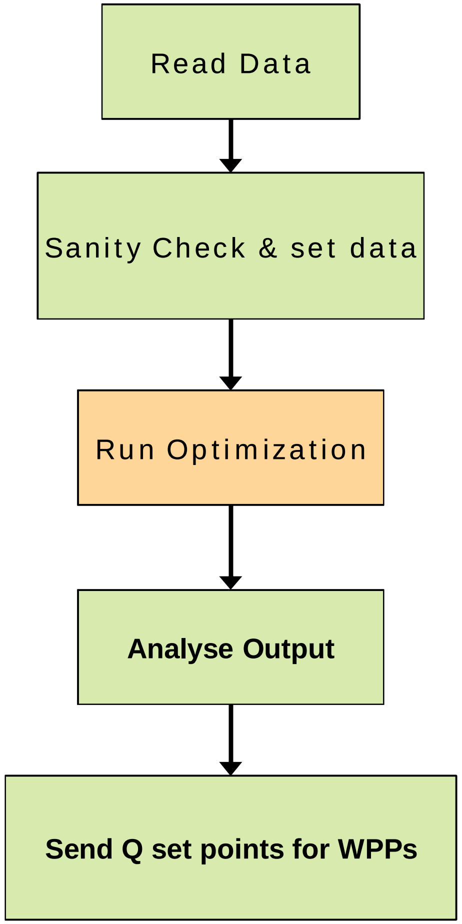
- Objective:
  - Minimize active power loss in 60 kV feeders

- Constraints

  Network constraints
  - Reactive Power Flow Limit to the Transmission Network
  - Power loading limit of the feeders
  - Power loading limits of the transformers
  - Voltage Limits

  WPP constraint
  - WPP capability / Grid code requirements

Optimization



- Control variables:
  - Reactive power set point of WPPs
  - Control of 150/60 kV OLTC
  - (Control of 60/10 kV OLTC)
- Objective:
  - Minimize active power loss in 60 kV feeders
  - Minimize reactive power flow to the transmission network
- Constraints

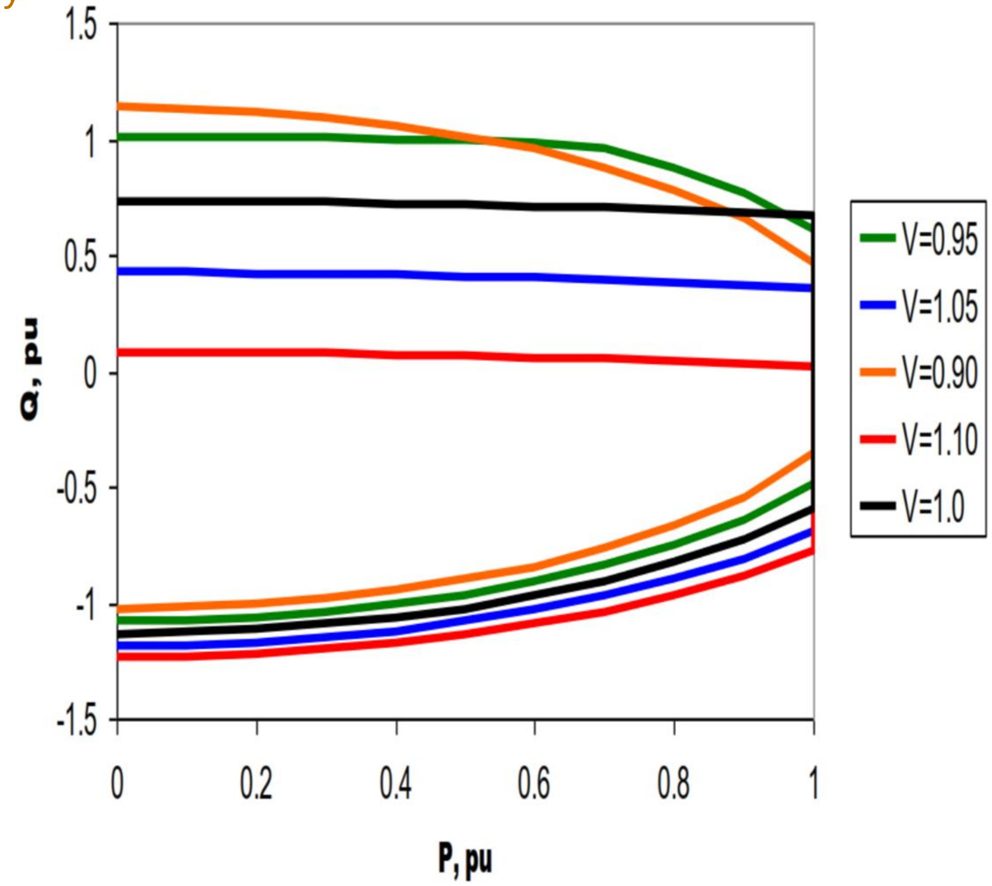
  Network constraints
  - Reactive Power Flow Limit to the Transmission Network
  - Power loading limit of the feeders
  - Power loading limits of the transformers
  - Voltage Limits

  WPP constraint
  - WPP capability / Grid code requirements

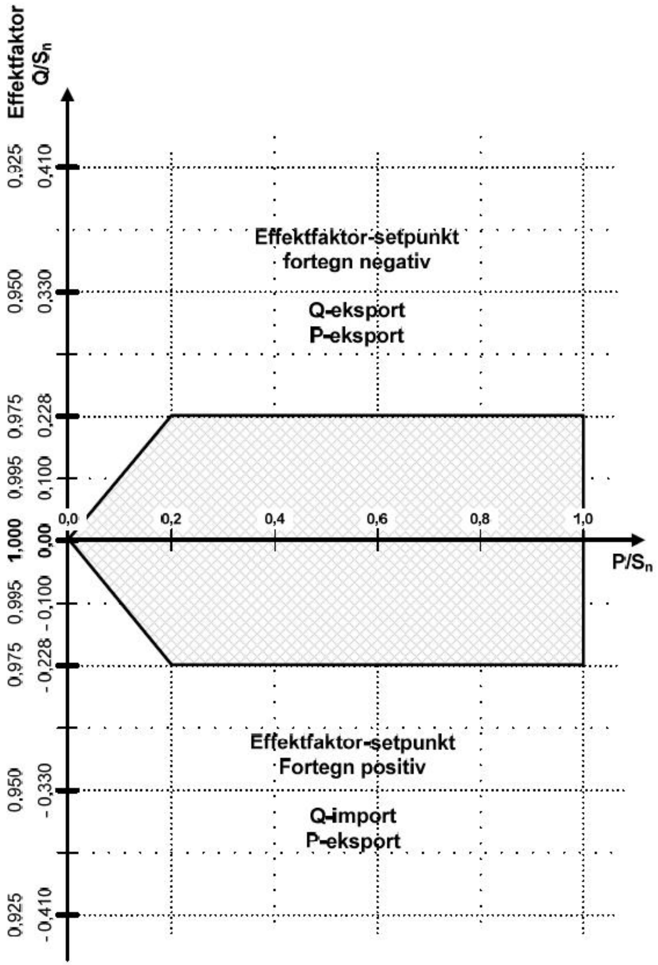
Optimization

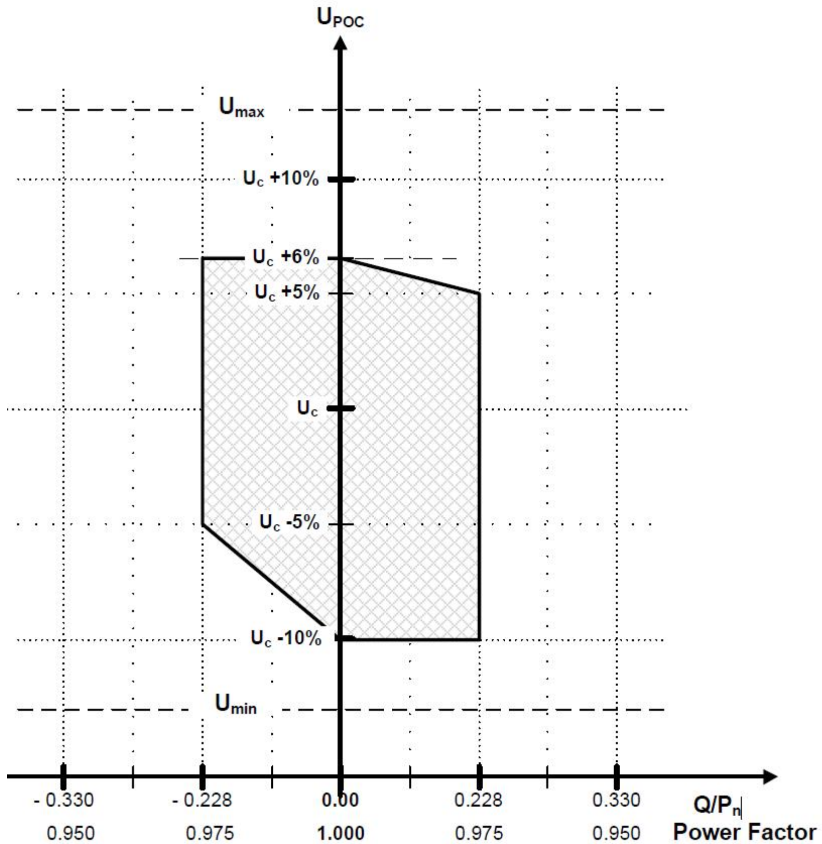
- Read Data
- Sanity Check & set data
- Run Optimization
- Analyse Output
- **Send Q setpoints for WPPs**

Q lower capability< Q set points < Q upper capability



Optimization

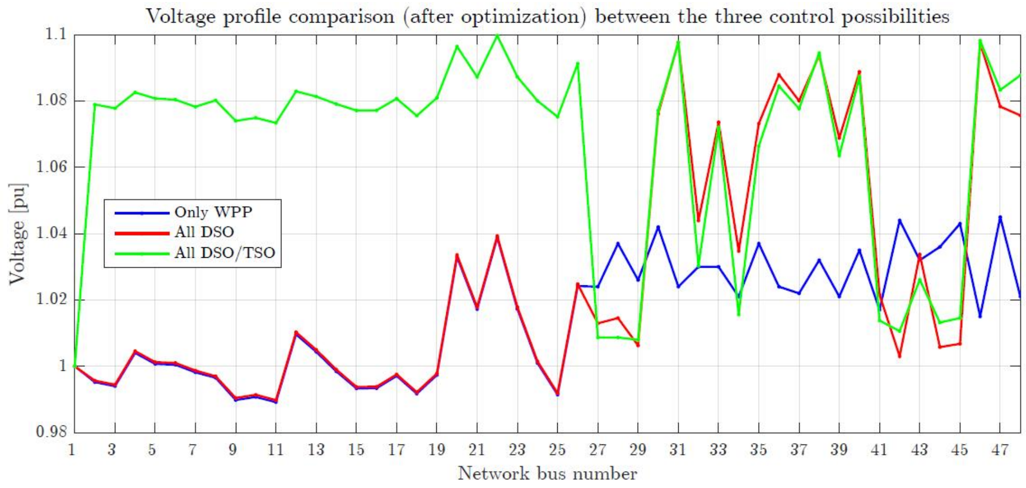


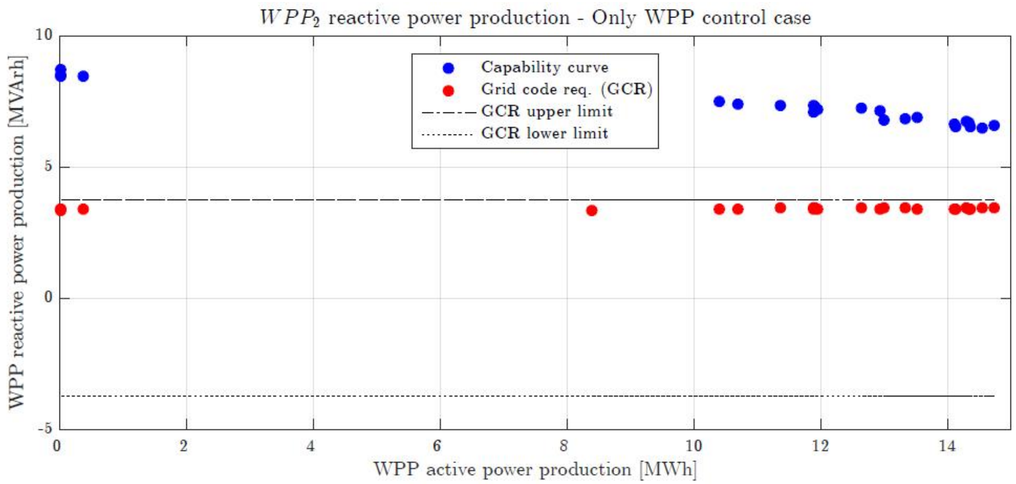


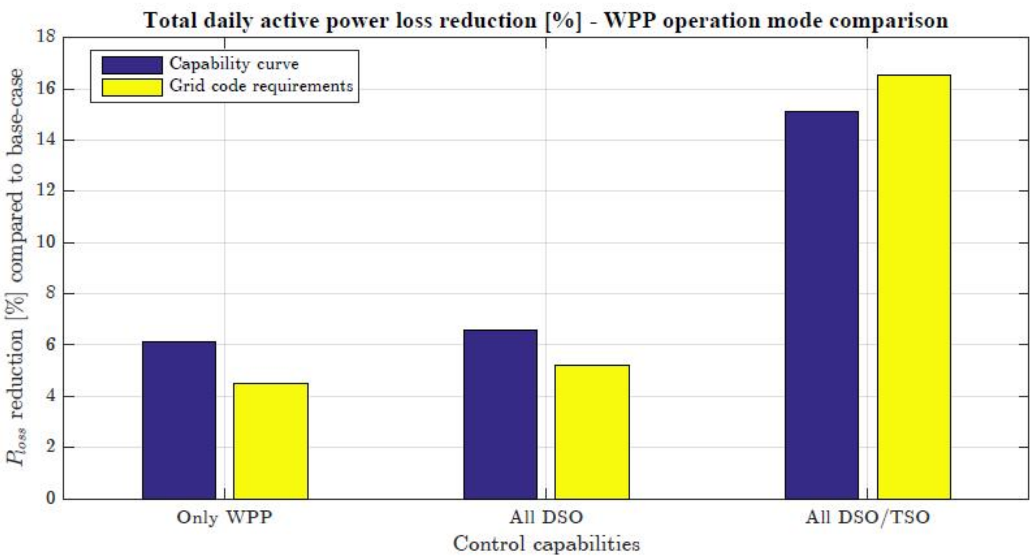
Optimization Methods

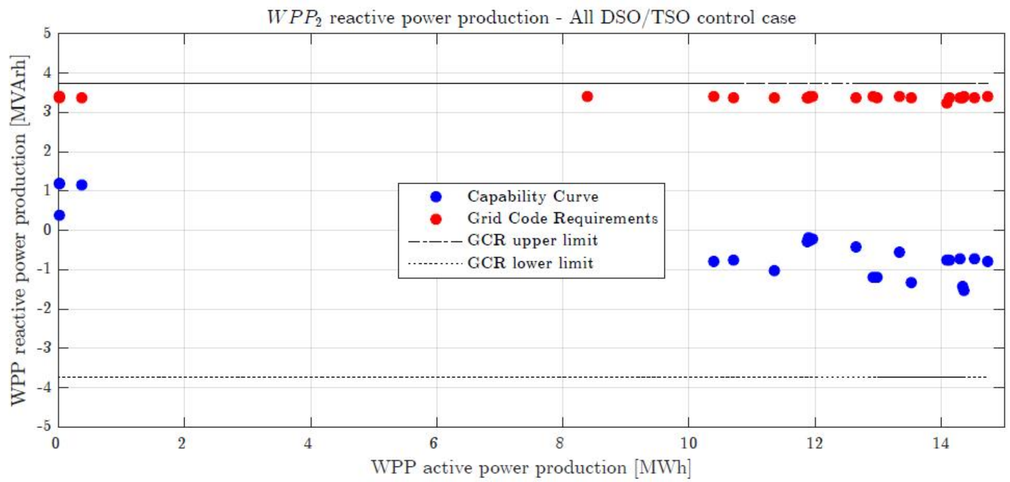
- Mathematically, non-convex non-linear problem
- Choice of solver neither trivial nor absolute
- Mathematical optimization methods:
  - Interior Point Method
- Meta-heuristic methods:
  - Particle Swarm Optimization
    - Linearly Decreasing Inertia Weight PSO (LDW-PSO)
    - Time Varying Acceleration Coefficients PSO (TVAC-PSO)
  - Genetic Algorithm
    - Constant crossover and constant mutation
    - Adaptive crossover and adaptive mutation
    - NSGA-II (ongoing)
- Computation time
  - GA >> PSO >> IPOPT
- Loss reduction
  - Almost similar in average

Single objective – Loss Minimization









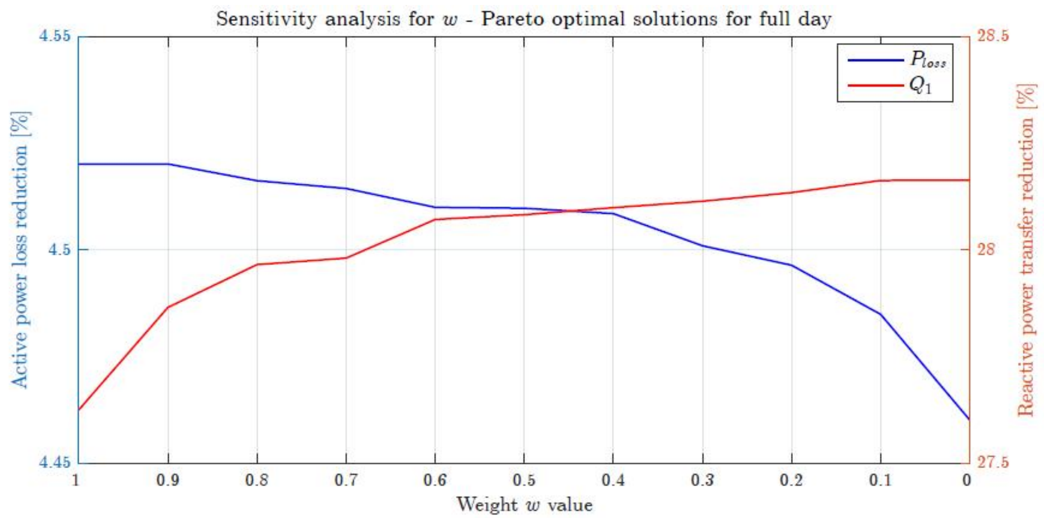
Time series Analysis

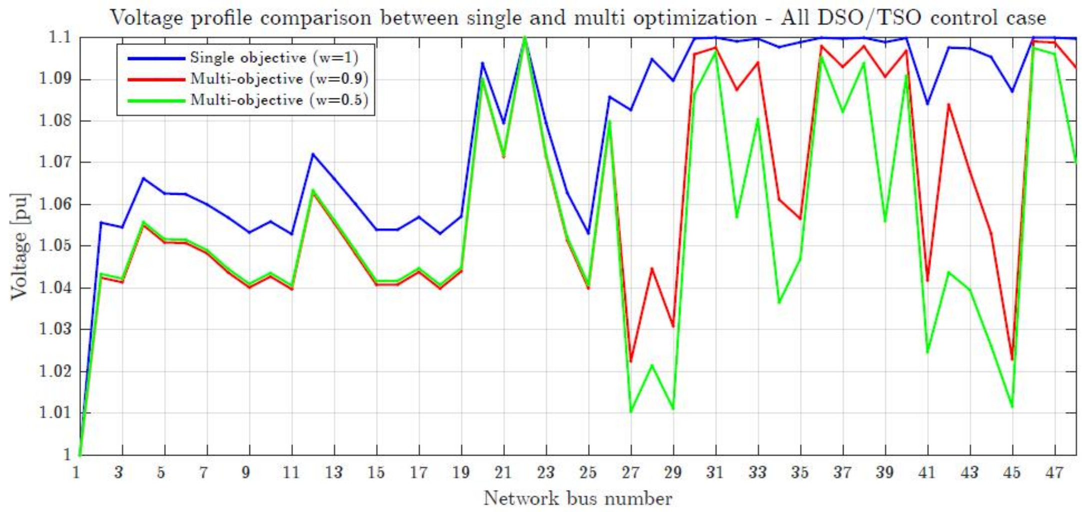
Without Optimization			With Optimization		
			Loss reduction [%]		Energy Saving [MWh]
Power loss [MW]	Number of Hrs	Energy loss [MWh]	Mean	Uncertainty	
0-500	6321	949	3.86%	0.25%	36.6 ± 2.38
500-1000	967	695	0.89%	0.10%	6.2 ± 0.69
1000-1500	674	833	1.84%	0.11%	15.33 ± 0.92
>1500	798	1539	2.91%	0.08%	44.78 ± 1.23
Sum	8760	4016			103 ± 2.92

Using optimization method, estimated energy saving is 103 ± 2.92 MWh for 1 year based on the representative data

Multi-objective – Loss Minimization and MVAr flow to Transmission system

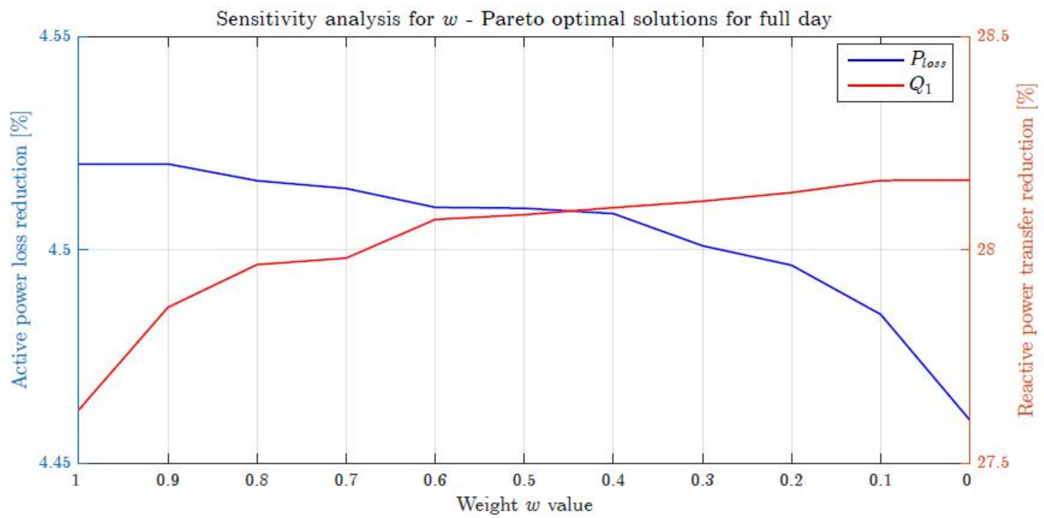
$$\beta_P \cdot w \cdot P_L(x, u(x)) + \beta_Q \cdot (1-w) \cdot \left|Q_T(x, u(x))\right|$$

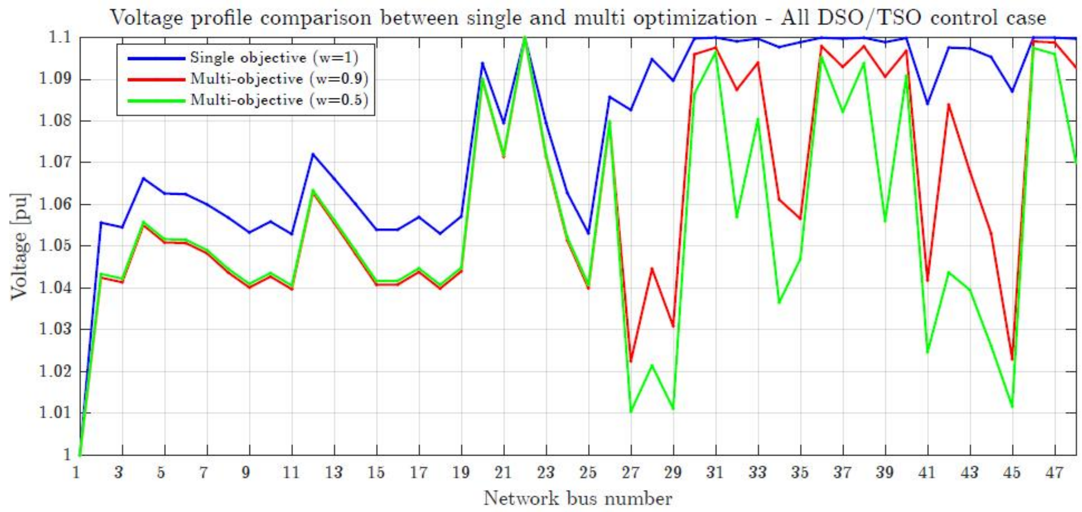




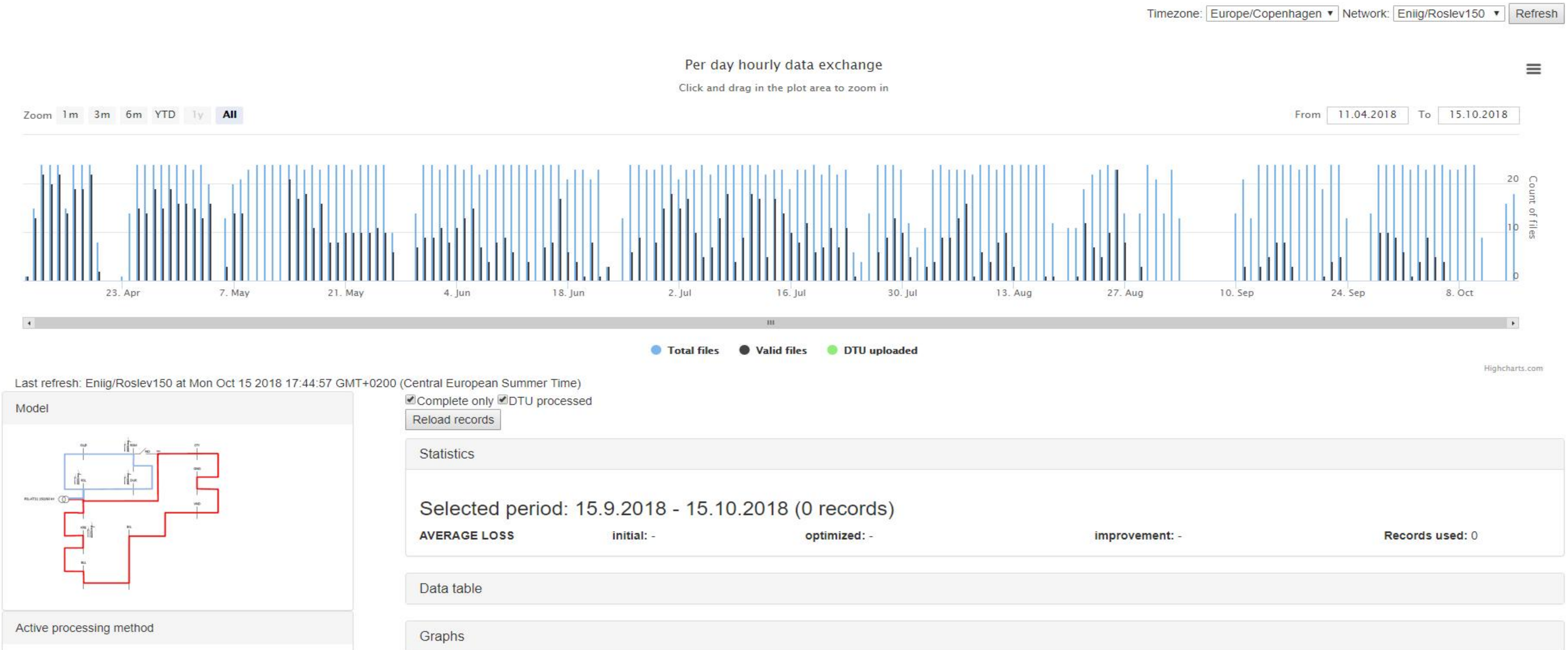
Multi-objective – Loss Minimization and MVAr flow to Transmission system

$$\beta_P \cdot w \cdot P_L(x, u(x)) + \beta_Q \cdot (1-w) \cdot \left|Q_T(x, u(x))\right|$$





Demonstration

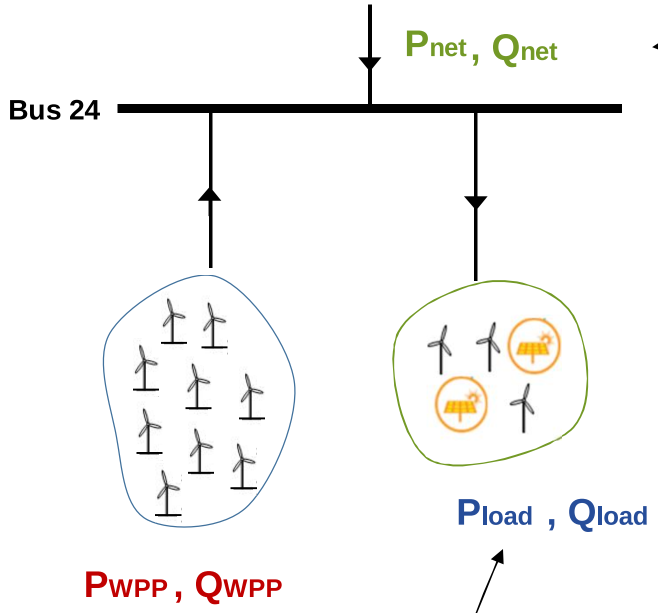


Regulate instead of reinforce whenever possible

Thank you for your attention.

Appendix

Data analysis on Bus 24



$$P_{net} = -P_{WPP} + P_{load}$$

$$Q_{net} = -Q_{WPP} + Q_{load}$$

Weather dependent loads

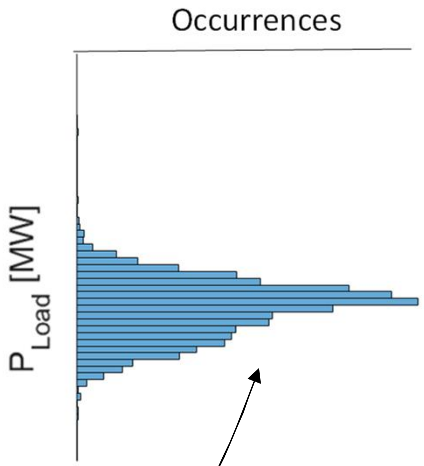
Not available any data on weather dependent loads

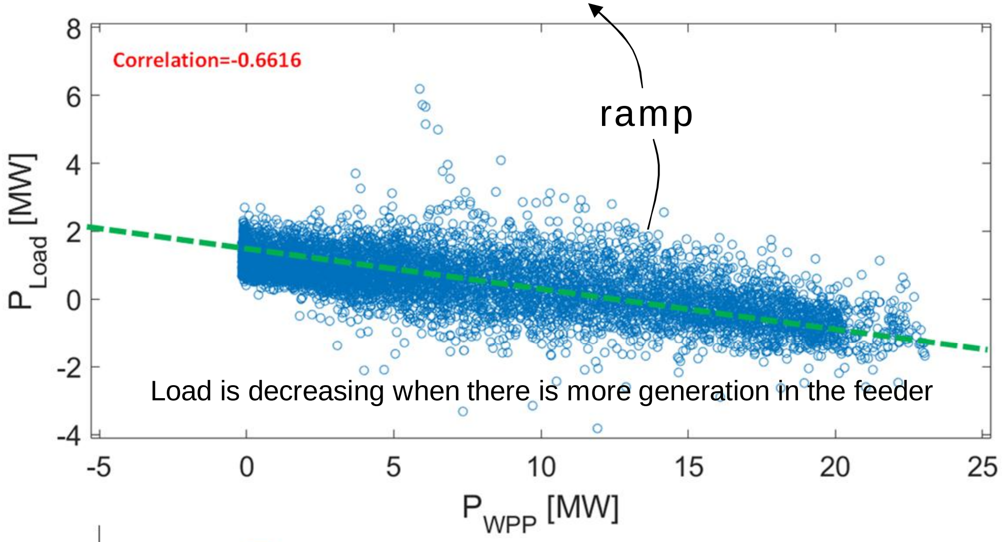
However it is possible to extract some information about them out of available data !!!

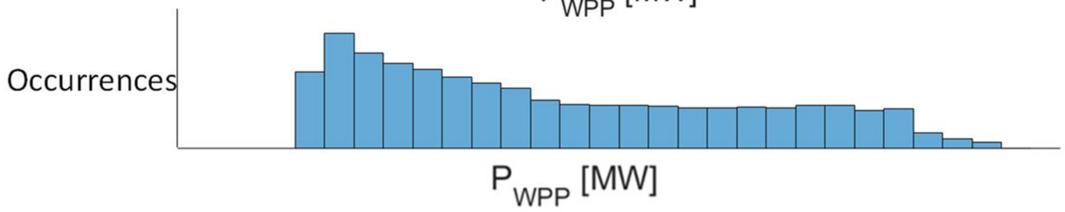
Data analysis on Bus 24

P_{load} is changing with larger P_{WPP}, namely at larger wind speeds:

there are wind turbines in the distributed generations !!!





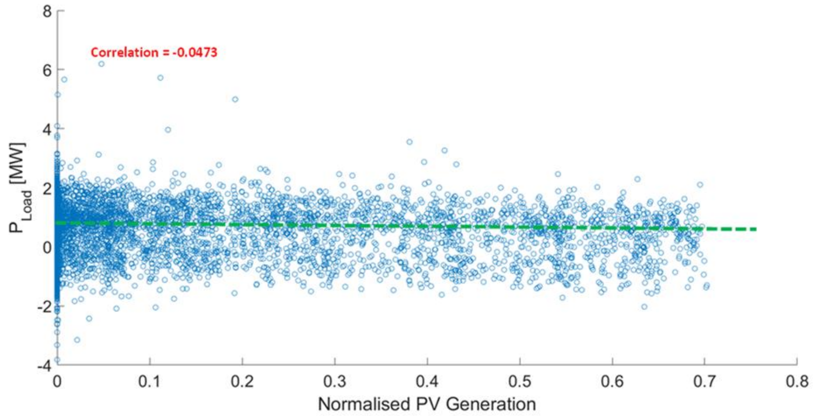


~ Gaussian distribution:

both consumption & generation

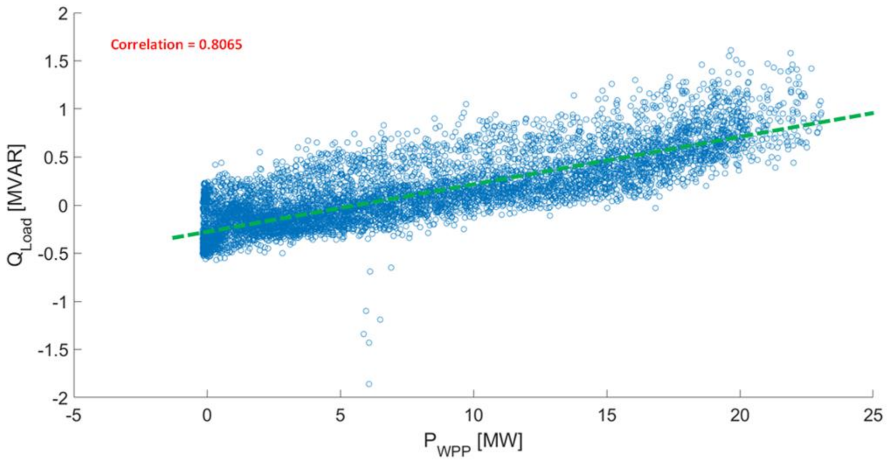
Data analysis on Bus 24

Is it any PV in the distribution generation in Bus24 ?



- No available data for PV
- From meteorological data – model solar radiation in this location and time
- No correlation between load and PV radiation:
- There is no PV in Pload

What types of wind turbines are connected?



WTs are absorbing Q while they are producing power

Type 1 WTs??

Optimization: Method

	Meta-heuristic Optimization	Mathematical Optimization
Handle non-linearities	ü	û
Jacobian/Sensitivity matrix is not required	ü	û
Global optimum	ü	û
Less complex mathematical formulation/ less prone to human error	ü	û
Easy to add new objectives / constraints	ü	û
Easily adaptable for other distribution system topologies	ü	û
Efficient in handling both continuous and discrete variables	ü	û
Less sensitive to optimization parameters	û	ü
Less Computation Time	û	ü
Better understanding and knowhow	û	ü
Less implementation Complexity	û	ü

Mathematical Optimization : Interior Point Method

Meta-heuristic Optimization : Genetic Algorithm, Particle Swarm Optimization

Multi-objective Optimization (using PSO)

Objective1 : Loss Minimization

Objective2 : Minimization of MVAR flow between MV and HV network

WT Capability

Swarm Size = 30 , Initial P_{loss} (kW) = 3135.74 , Initial Q_{tr} (kVar) =-26011.16							
	Simulation Number	Q_1 (MVar)	Q_2 (MVar)	Q_3 (MVar)	ΔP_{loss} %	ΔQ_{tr} %	ΔF %
LDW-PSO	3	5.098	4.760	7.453	-7.23	-71.42	-32.83
	7	7.417	8.272	7.586	-5.65	-94.93	-43.17
	8	7.400	8.808	5.777	-4.82	-89.5	-40.09
	9	5.391	7.759	8.064	-6.72	-86.95	-40.69
TVAC-PSO	2	4.349	9.211	8.009	-6.68	-88.35	-41.25
	3	6.928	7.852	6.839	-5.81	-88.31	-40.73
	7	7.113	7.721	7.494	-5.96	-91.21	-41.56
	8	4.347	7.775	5.518	-6.17	-72.41	-34.23

Highest reduction of power losses but low reduction of reactive power import

Increasing Q of the WPPs does not necessarily mean that the losses will further decrease

Grid Code Requirements

Initial P_{loss} (kW) = 3135.74 , Initial Q_{tr} (kVar) = -26011.16							
Algorithm	Simulations Executed	Swarm Size	Q1 MVar	Q2 MVar	Q3 MVar	ΔP_{loss} %	ΔQ_{tr} %
LDW-PSO	10	10	2.736	3.420	2.736	-4.65	-36.88
	10	30	2.736	3.420	2.736	-4.65	-36.88
TVAC-PSO	10	10	2.736	3.420	2.736	-4.65	-36.88
	10	30	2.736	3.420	2.736	-4.65	-36.88

Conclusion

NetVind (Phase 1) – Ongoing research work

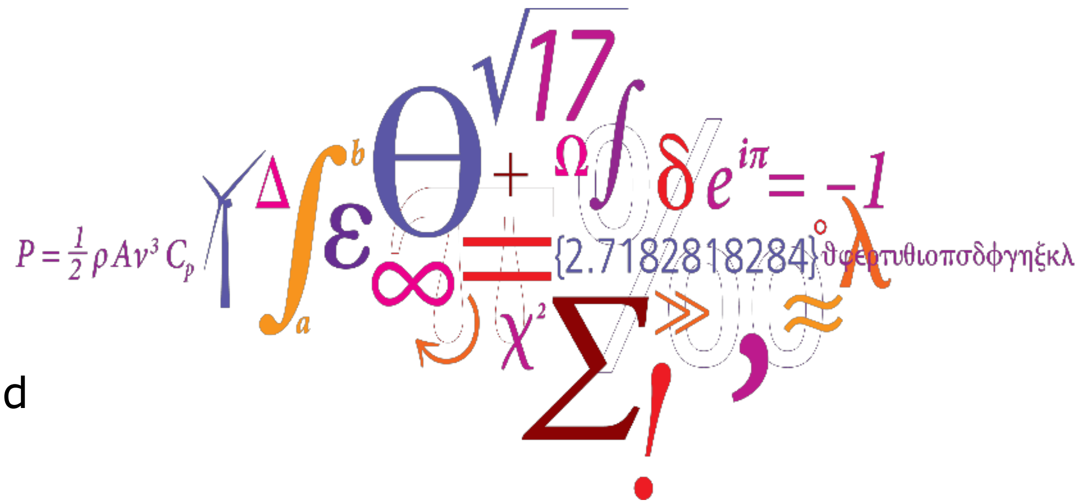
- Energy savings is possible through optimal control of wind power plants
- Without additional investment on equipment like synchronous condensers.
- WPPs have higher capability to support network than the grid code requirements.

Next step: Real time validation

Impact of wind turbine technology development on variability and capacity factors

Matti Koivisto (mkoi@dtu.dk)
Nicolaos Cutululis

DTU Wind Energy



IEA Wind Task 25 meeting, Madrid
9 April 2018

DTU Wind Energy
Department of Wind Energy

Topics

- **Short introduction to CorRES**
  - What it is
  - Ongoing and upcoming developments
- **Impact of wind turbine technology development on capacity factors**
  - Some pan-European results towards 2050
- **Impact of wind turbine technology development on variability**
  - More TWh, less variability

CorRES

- CorRES[1] (Correlations in Renewable Energy Sources)
  - Developed at DTU Wind Energy
  - Simulation tool for variable renewable energy (VRE) generation
  - **Models both wind and solar PV generation**

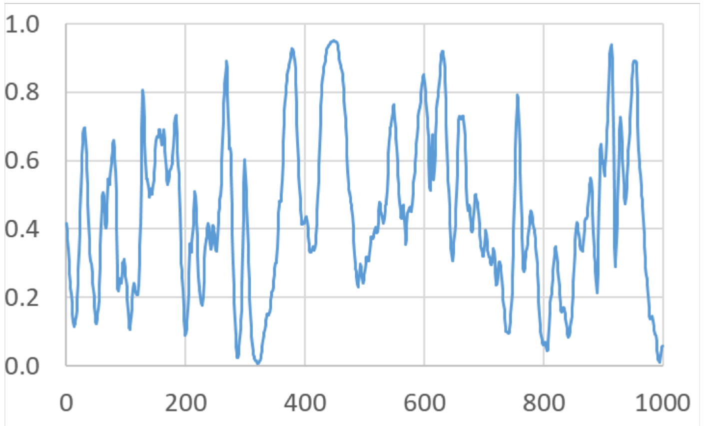
- **Based on meteorological reanalysis data**
  - 35 years of hourly data covering Europe
  - Also other geographical regions (e.g., India in HYBRIDize project)

- Used in many projects
  - Danish and International research projects: e.g., NSON-DK, Flex4RES
  - Pan-European VRE generation simulations for ENTSO-E
    - Used in the modelling for TYNDP

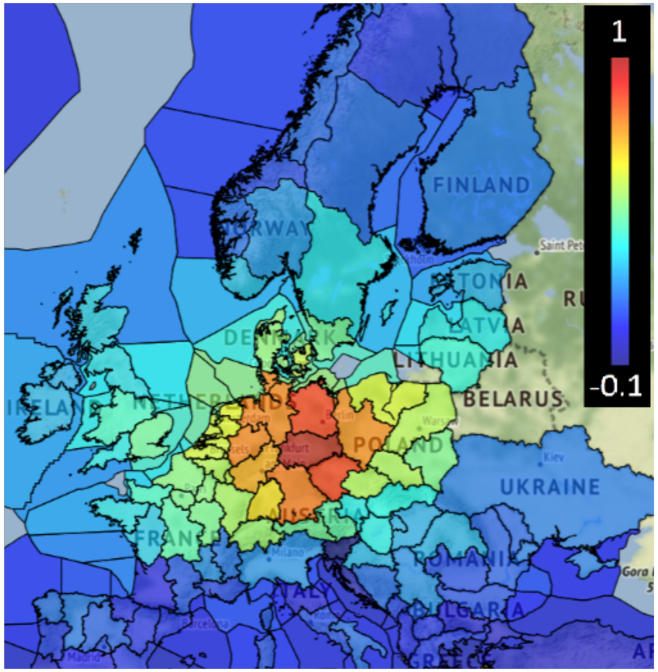
[1]M. Koivisto et al., "Using time series simulation tool for assessing the effects of variable renewable energy generation on power and energy systems", *WIREs Energy and Environment*, e329, 2018 (https://doi.org/10.1002/wene.329)

CorRES: VRE variability

- The reanalysis data provide the main spatiotemporal dependencies for the simulations
  - Stochastic simulations model short-term variability in more detail
- Can be used, e.g., in
  - **Transmission expansion studies**
  - **Assessing system adequacy**



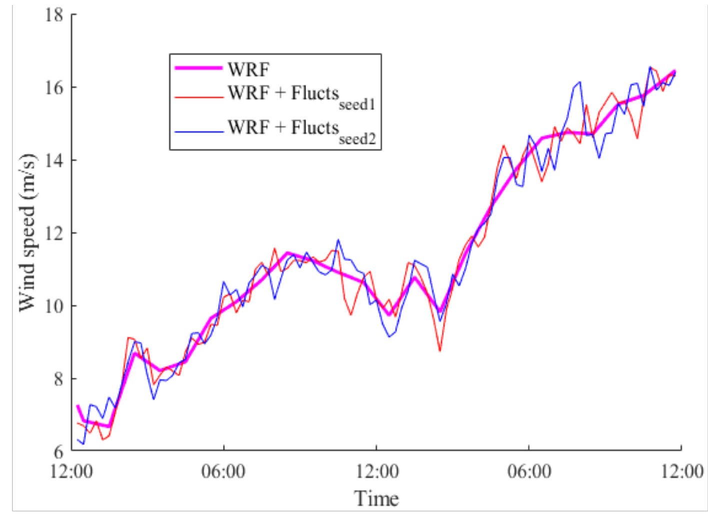
Example 1000 hours of simulated wind generation (Denmark onshore)



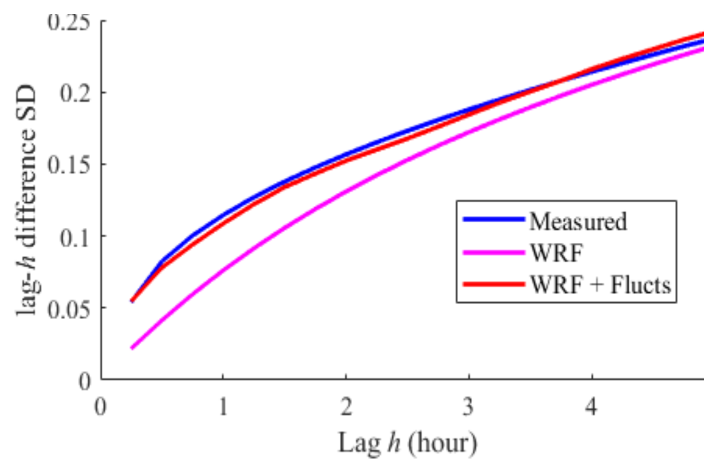
Spatial correlations in wind generation looking from a German onshore region (based on 35 years of simulations)

High frequency (sub-hourly) simulations

- CorRES is based on meteorological reanalysis data
  - Obtained from the WRF model, a mesoscale modelling system
- The reanalysis approach can capture most large-scale variability
  - **However, variations are smoothened because of averaging effects in mesoscale models**
- CorRES utilizes stochastic simulation modelling to better model the high frequency variability[1]
  - Called fluctuations
  - They are combined to the WRF reanalysis data



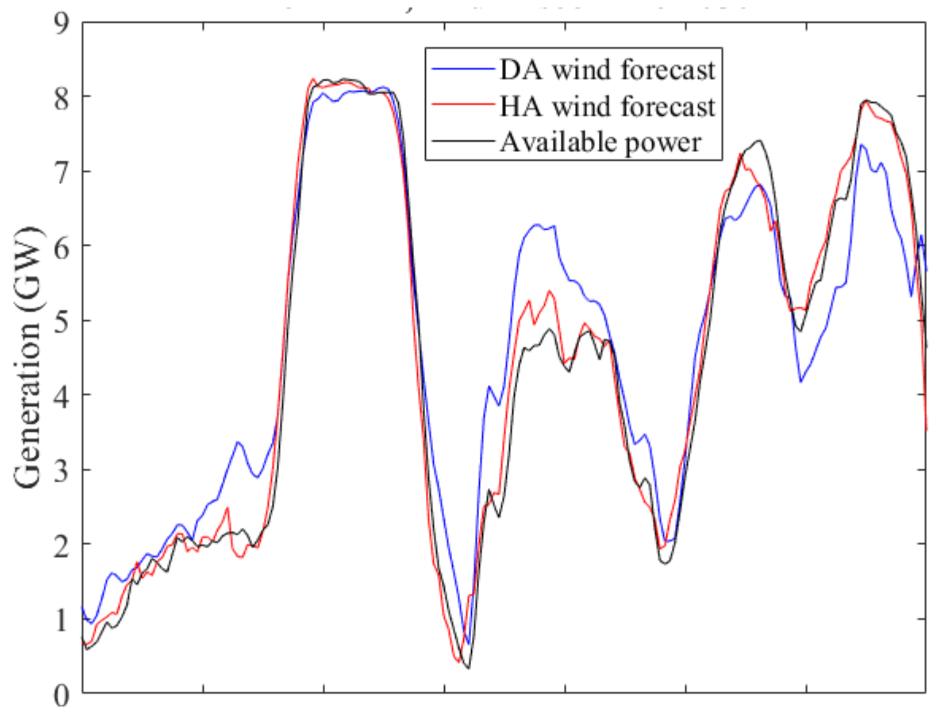
EARLY RESULTS (TO BE PUBLISHED)



[1]P. Sørensen et al., "Modelling of Power Fluctuations from Large Offshore Wind Farms", *Wind Energy*, vol. 11, no. 1, pp. 29-43. February 2008 (https://doi.org/10.1002/we.246)

CorRES: VRE forecast uncertainty

- In addition to VRE generation, **CorRES can simulate VRE forecasts**
- Multivariate ARMA time series simulation is used
  - The forecast error simulation model for solar PV is a recent addition[1]
- Can be used, e.g., in
  - **Assessing balancing needs**
  - **Power system stability studies**



Example regional simulation of available wind generation and forecasts (DA = day-ahead; HA = hour-ahead)

[1]E. Nuño et al, "On the simulation of aggregated solar PV forecast errors", *IEEE Transactions on Sustainable Energy*, vol. 9, no. 4, pp. 1889-1898, October 2018 (https://doi.org/10.1109/TSTE.2018.2818727)

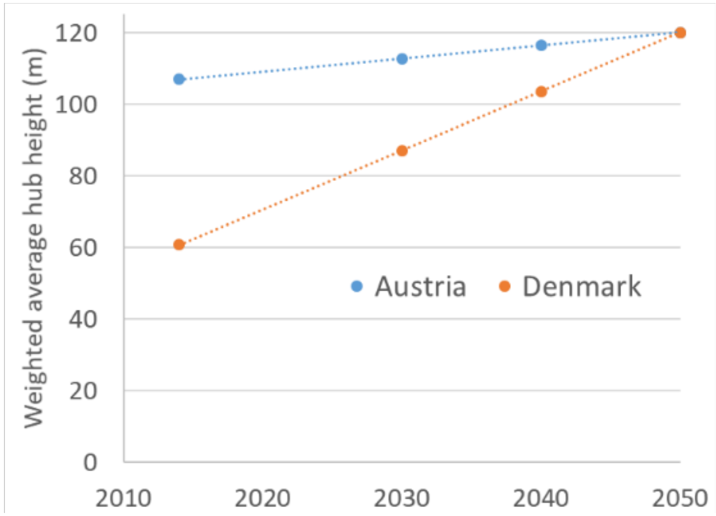
CorRES developments

- Ongoing:
  - Link mesoscale WRF wind speeds to microscale data
    - **Microscale data from Global Wind Atlas**
  - Farm-level power curve for each simulated wind power plant

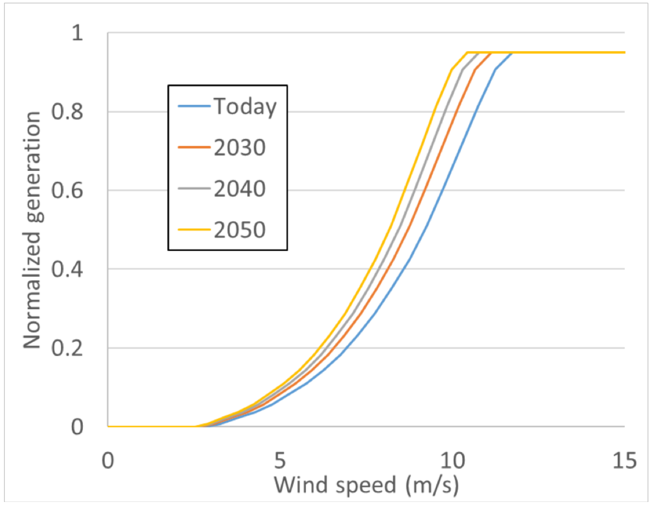
- In upcoming projects:
  - High frequency simulation capability for solar PV
    - Currently for wind only
  - Combine wind and solar PV forecast error simulation models
    - To capture joint uncertainties
  - **Include expected climate change effects to WRF simulations**
    - To move ahead from only using historical reanalysis data
    - Part of the new PSfture project (La Cour Fellowship funding from DTU Wind Energy)

Assumptions about technological development in the future

1. Increasing hub heights
   - Onshore wind is assumed to reach an average of 120 m by 2050
2. Decreasing specific power
   - 30 % reduction by 2050 compared to today



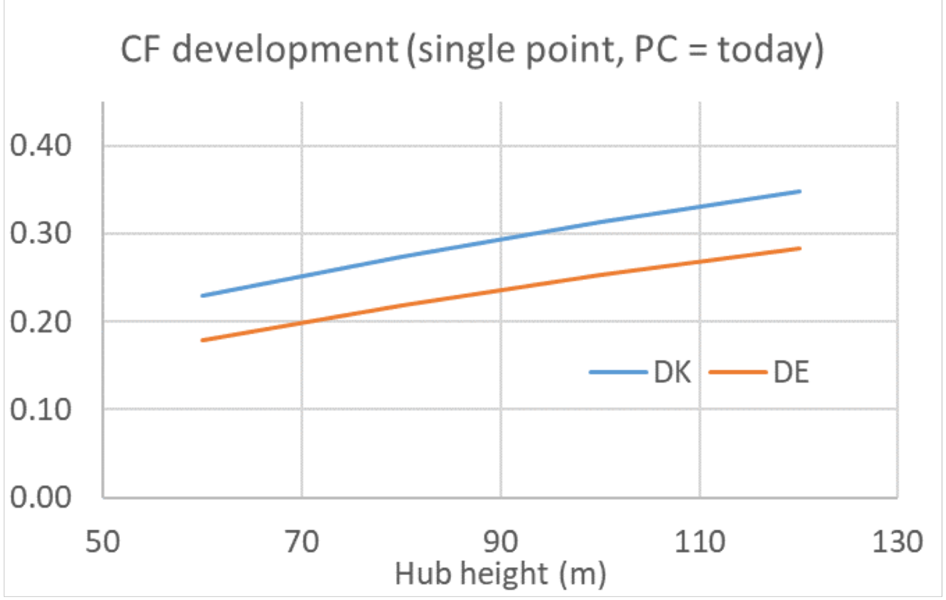
Assumed hub height development in two example countries (onshore wind)



Effect of specific power development on the power curves

The effect of hub height increase: Example simulation for DE and DK

- Single wind power plant (WPP) simulated in this example
  - Using today's average power curve (average of the entire wind fleet)
  - Hub height varies from 60 to 120 m



Resulting capacity factors (CFs)

Hub height	DK	DE
60	0.23	0.17
80	0.27	0.21
100	0.31	0.25
120	0.35	0.28

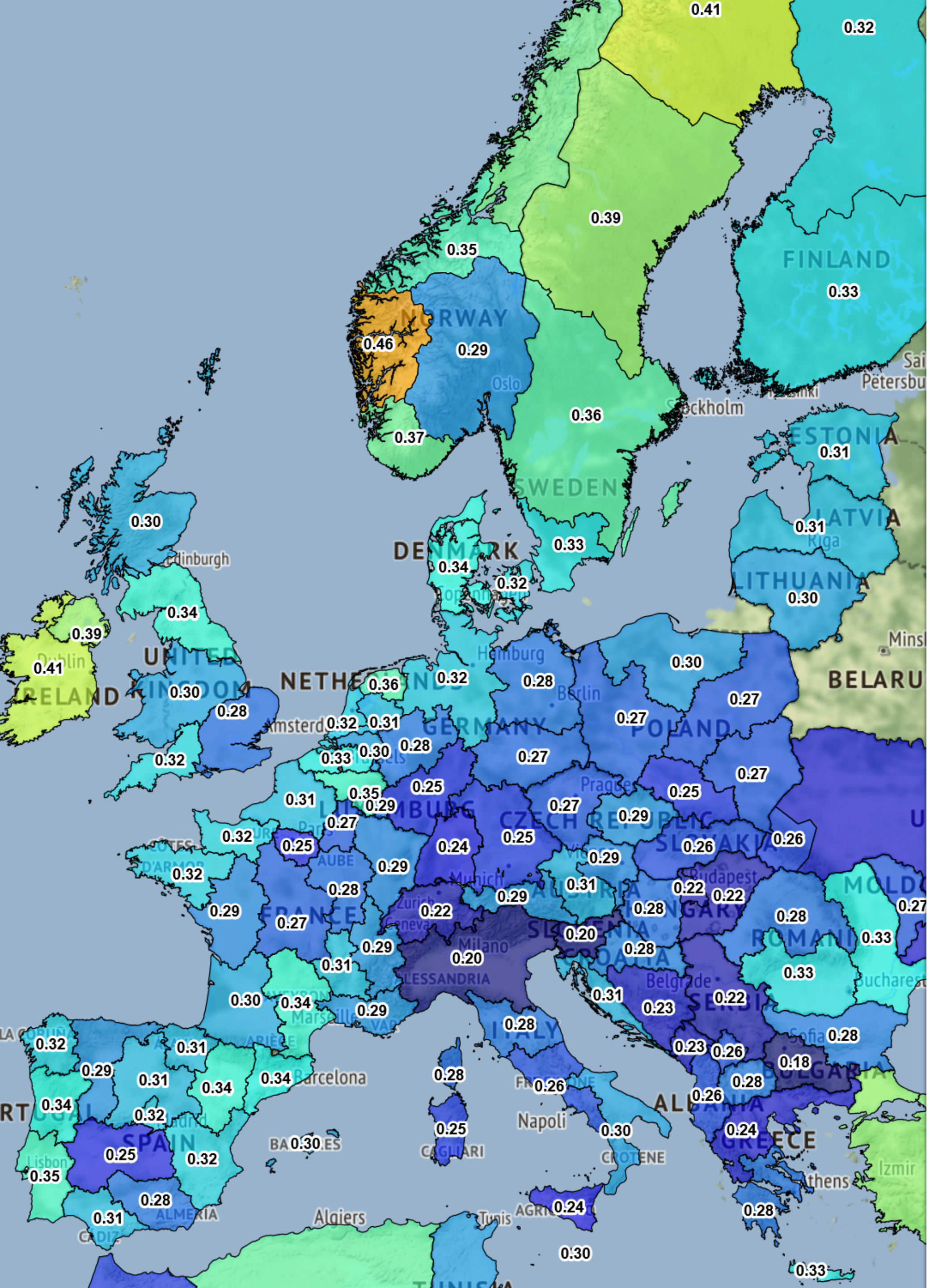
On the importance of modelling today's hub heights accurately:
M. Koivisto et al., "Large-scale wind generation simulations: From the analysis of current installations to modelling the future", *Journal of Physics: Conference Series*, vol. 1102, no. 1, 012034, 2018 (https://doi.org/10.1088/1742-6596/1102/1/012034)

The effect of specific power decrease: Example simulation for DE and DK

- Single wind power plant (WPP) simulated in this example
  - From today’s (average) power curve towards a low specific power PC
  - Same hub height (120 m) in all simulations

Resulting CFs

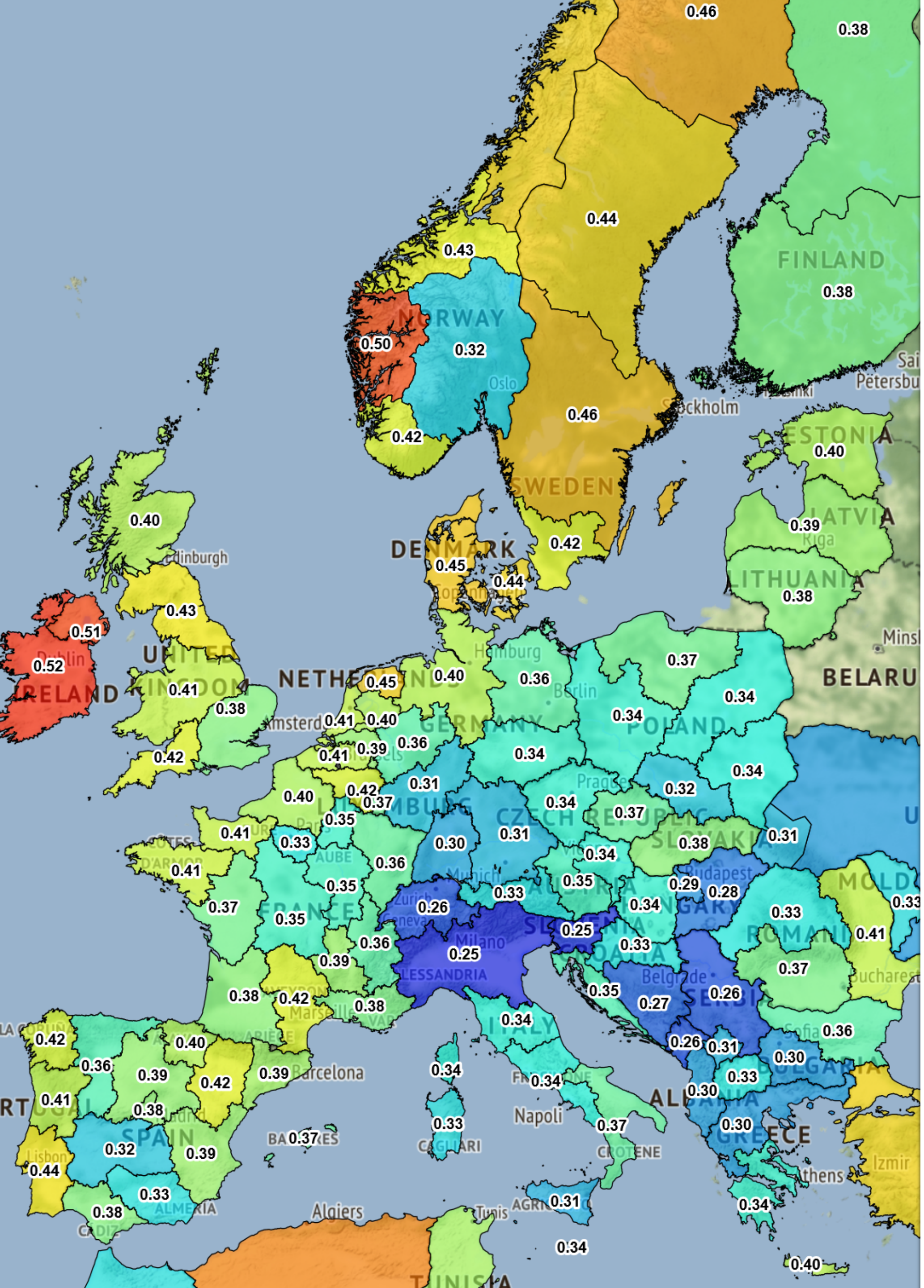
Power curve	DK	DE
Today’s average	0.35	0.28
30 % lower specific power	0.44	0.36



2030 scenario

Onshore wind

CFs are averages of 35 meteorological years



2050 scenario

Onshore wind

CFs are averages of 35 meteorological years

In 2050, all onshore regions are assumed to reach an average hub height of 120 m

Some things to be checked:

1. Swedish CFs are high
2. UK CFs (except NI) are a bit low

Minimizing variance in large-scale VRE generation

- Variance of VRE generation be minimized[1] considering
  - **A mixture of wind and solar PV**
  - **Geographical distribution of installations**

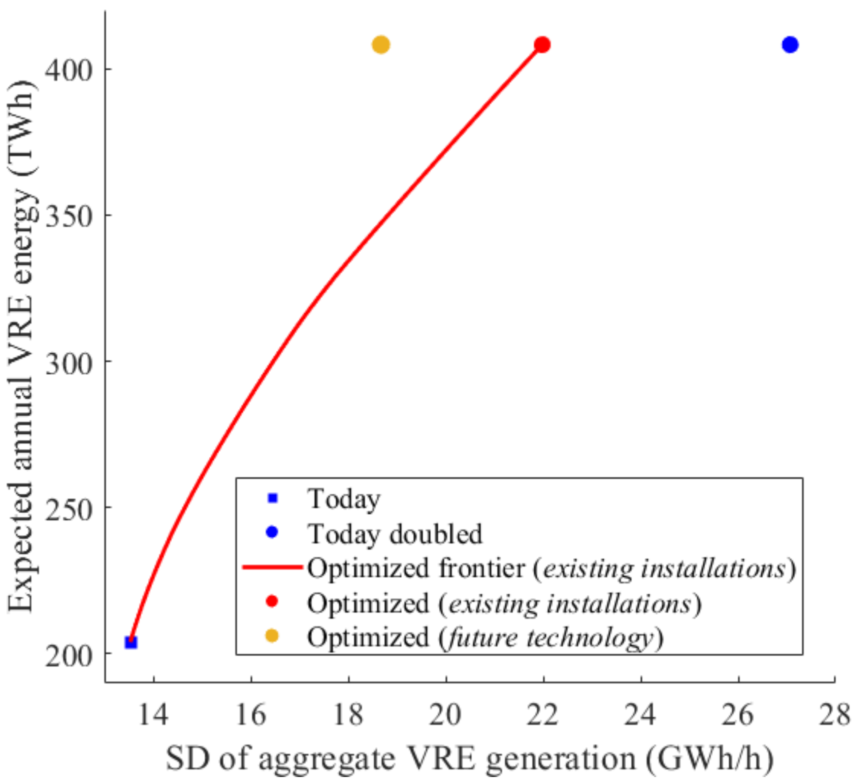
Map of the analyzed countries in[1]

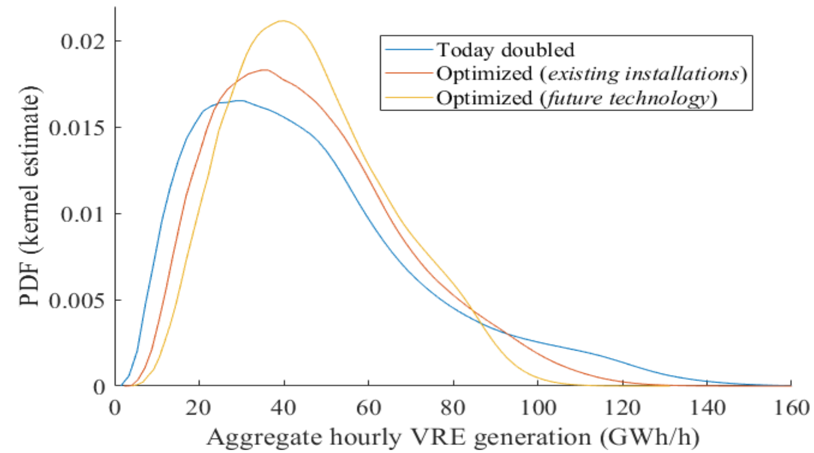
		Onshore wind										Offshore wind										Solar PV									
		DE	DK	EE	FI	LT	LV	NL	NO	PL	SE	DE	DK	EE	FI	LT	LV	NL	NO	PL	SE	DE	DK	EE	FI	LT	LV	NL	NO	PL	SE
Onshore wind	DE		0.66	0.25	0.14	0.40	0.35	0.80	0.26	0.69	0.36	0.72	0.61	0.21	0.11	0.37	0.34	0.67	0.07	0.50	0.32	-0.21	-0.22	-0.22	-0.23	-0.22	-0.22	-0.21	-0.21	-0.20	-0.23
	DK	0.66		0.26	0.18	0.39	0.39	0.52	0.45	0.56	0.57	0.73	0.86	0.25	0.16	0.36	0.35	0.53	0.14	0.54	0.43	-0.07	-0.11	-0.10	-0.13	-0.11	-0.10	-0.07	-0.11	-0.07	-0.12
	EE	0.25	0.26		0.56	0.55	0.72	0.19	0.26	0.37	0.54	0.19	0.23	0.82	0.48	0.54	0.63	0.16	0.16	0.36	0.47	-0.12	-0.14	-0.18	-0.19	-0.16	-0.16	-0.12	-0.15	-0.13	-0.16
	FI	0.14	0.18	0.56		0.25	0.36	0.11	0.37	0.18	0.58	0.12	0.16	0.46	0.87	0.26	0.33	0.10	0.29	0.18	0.49	-0.09	-0.11	-0.13	-0.17	-0.12	-0.12	-0.09	-0.14	-0.10	-0.13
	LT	0.40	0.39	0.55	0.25		0.86	0.26	0.22	0.68	0.51	0.29	0.35	0.56	0.22	0.86	0.76	0.23	0.08	0.63	0.40	-0.14	-0.15	-0.18	-0.18	-0.18	-0.18	-0.14	-0.16	-0.15	-0.17
	LV	0.35	0.39	0.72	0.36	0.86		0.24	0.26	0.57	0.59	0.27	0.34	0.74	0.32	0.81	0.88	0.21	0.13	0.57	0.48	-0.09	-0.11	-0.15	-0.16	-0.14	-0.14	-0.09	-0.12	-0.10	-0.13
	NL	0.80	0.52	0.19	0.11	0.26	0.24		0.25	0.42	0.27	0.72	0.50	0.15	0.09	0.25	0.24	0.84	0.08	0.32	0.24	-0.16	-0.19	-0.17	-0.19	-0.17	-0.17	-0.17	-0.18	-0.15	-0.19
	NO	0.26	0.45	0.26	0.37	0.22	0.26	0.25		0.22	0.52	0.35	0.41	0.24	0.35	0.20	0.22	0.28	0.70	0.21	0.32	-0.13	-0.17	-0.18	-0.22	-0.17	-0.18	-0.14	-0.23	-0.14	-0.20
	PL	0.69	0.56	0.37	0.18	0.68	0.57	0.42	0.22		0.49	0.47	0.53	0.35	0.15	0.63	0.54	0.36	0.07	0.78	0.42	-0.20	-0.20	-0.23	-0.23	-0.23	-0.23	-0.19	-0.20	-0.21	-0.22
	SE	0.36	0.57	0.54	0.58	0.51	0.59	0.27	0.52	0.49		0.37	0.53	0.56	0.55	0.49	0.53	0.26	0.32	0.52	0.77	-0.15	-0.18	-0.20	-0.23	-0.19	-0.19	-0.15	-0.21	-0.16	-0.21
Offshore wind	DE	0.72	0.73	0.19	0.12	0.29	0.27	0.72	0.35	0.47	0.37		0.78	0.18	0.10	0.28	0.26	0.86	0.11	0.43	0.31	-0.13	-0.16	-0.15	-0.16	-0.14	-0.15	-0.14	-0.16	-0.12	-0.17
	DK	0.61	0.86	0.23	0.16	0.35	0.34	0.50	0.41	0.53	0.53	0.78		0.22	0.16	0.36	0.34	0.57	0.13	0.54	0.43	-0.12	-0.15	-0.14	-0.14	-0.12	-0.14	-0.14	-0.17	-0.11	-0.16
	EE	0.21	0.25	0.82	0.46	0.56	0.74	0.15	0.24	0.35	0.56	0.18	0.22		0.41	0.54	0.65	0.14	0.15	0.35	0.47	-0.15	-0.16	-0.19	-0.20	-0.18	-0.18	-0.13	-0.16	-0.15	-0.17
	FI	0.11	0.16	0.48	0.87	0.22	0.32	0.09	0.35	0.15	0.55	0.10	0.16	0.41		0.24	0.33	0.09	0.29	0.16	0.47	-0.09	-0.11	-0.12	-0.15	-0.11	-0.11	-0.09	-0.13	-0.09	-0.13
	LT	0.37	0.36	0.54	0.26	0.86	0.81	0.25	0.20	0.63	0.49	0.28	0.36	0.54	0.24		0.80	0.22	0.09	0.64	0.41	-0.16	-0.17	-0.19	-0.18	-0.17	-0.19	-0.16	-0.18	-0.16	-0.19
	LV	0.34	0.35	0.63	0.33	0.76	0.88	0.24	0.22	0.54	0.53	0.26	0.34	0.65	0.33	0.80		0.22	0.13	0.54	0.44	-0.07	-0.09	-0.12	-0.11	-0.08	-0.11	-0.10	-0.11	-0.08	-0.11
	NL	0.67	0.53	0.16	0.10	0.23	0.21	0.84	0.28	0.36	0.26	0.86	0.57	0.14	0.09	0.22	0.22		0.09	0.30	0.23	-0.11	-0.15	-0.14	-0.15	-0.13	-0.13	-0.13	-0.15	-0.11	-0.15
	NO	0.07	0.14	0.16	0.29	0.08	0.13	0.08	0.70	0.07	0.32	0.11	0.13	0.15	0.29	0.09	0.13	0.09		0.07	0.18	-0.07	-0.10	-0.12	-0.14	-0.10	-0.11	-0.08	-0.16	-0.09	-0.13
	PL	0.50	0.54	0.36	0.18	0.63	0.57	0.32	0.21	0.78	0.52	0.43	0.54	0.35	0.16	0.64	0.54	0.30	0.07		0.43	-0.13	-0.14	-0.16	-0.16	-0.16	-0.16	-0.12	-0.13	-0.14	-0.16
	SE	0.32	0.43	0.47	0.49	0.40	0.48	0.24	0.32	0.42	0.77	0.31	0.43	0.47	0.47	0.41	0.44	0.23	0.18	0.43		-0.11	-0.13	-0.15	-0.17	-0.15	-0.14	-0.10	-0.14	-0.12	-0.15
Solar PV	DE	-0.21	-0.07	-0.12	-0.09	-0.14	-0.09	-0.16	-0.13	-0.20	-0.15	-0.13	-0.12	-0.15	-0.09	-0.16	-0.07	-0.11	-0.07	-0.13	-0.11		0.94	0.90	0.85	0.88	0.92	0.92	0.90	0.96	0.94
	DK	-0.22	-0.11	-0.14	-0.11	-0.15	-0.11	-0.19	-0.17	-0.20	-0.18	-0.16	-0.15	-0.16	-0.11	-0.17	-0.09	-0.15	-0.10	-0.14	-0.13	0.94		0.91	0.87	0.88	0.91	0.90	0.93	0.93	0.96
	EE	-0.22	-0.10	-0.18	-0.13	-0.18	-0.15	-0.17	-0.18	-0.23	-0.20	-0.15	-0.14	-0.19	-0.12	-0.19	-0.12	-0.14	-0.12	-0.16	-0.15	0.90	0.91		0.91	0.91	0.98	0.86	0.91	0.93	0.94
	FI	-0.23	-0.13	-0.19	-0.17	-0.18	-0.16	-0.19	-0.22	-0.23	-0.23	-0.16	-0.14	-0.20	-0.15	-0.18	-0.11	-0.15	-0.14	-0.16	-0.17	0.85	0.87	0.91		0.92	0.90	0.75	0.85	0.87	0.91
	LT	-0.22	-0.11	-0.16	-0.12	-0.18	-0.14	-0.17	-0.17	-0.23	-0.19	-0.14	-0.12	-0.18	-0.11	-0.17	-0.08	-0.13	-0.10	-0.16	-0.15	0.88	0.88	0.91	0.92		0.94	0.77	0.84	0.92	0.90
	LV	-0.22	-0.10	-0.16	-0.12	-0.18	-0.14	-0.17	-0.18	-0.23	-0.19	-0.15	-0.14	-0.18	-0.11	-0.19	-0.11	-0.13	-0.11	-0.16	-0.14	0.92	0.91	0.98	0.90	0.94		0.87	0.91	0.94	0.94
	NL	-0.21	-0.07	-0.12	-0.09	-0.14	-0.09	-0.17	-0.14	-0.19	-0.15	-0.14	-0.14	-0.13	-0.09	-0.16	-0.10	-0.13	-0.08	-0.12	-0.10	0.92	0.90	0.86	0.75	0.77	0.87		0.90	0.90	0.89
	NO	-0.21	-0.11	-0.15	-0.14	-0.16	-0.12	-0.18	-0.23	-0.20	-0.21	-0.16	-0.17	-0.16	-0.13	-0.18	-0.11	-0.15	-0.16	-0.13	-0.14	0.90	0.93	0.91	0.85	0.84	0.91	0.90		0.91	0.95
	PL	-0.20	-0.07	-0.13	-0.10	-0.15	-0.10	-0.15	-0.14	-0.21	-0.16	-0.12	-0.11	-0.15	-0.09	-0.16	-0.08	-0.11	-0.09	-0.14	-0.12	0.96	0.93	0.93	0.87	0.92	0.94	0.90	0.91		0.94
	SE	-0.23	-0.12	-0.16	-0.13	-0.17	-0.13	-0.19	-0.20	-0.22	-0.21	-0.17	-0.16	-0.17	-0.13	-0.19	-0.11	-0.15	-0.13	-0.16	-0.15	0.94	0.96	0.94	0.91	0.90	0.94	0.89	0.95	0.94	

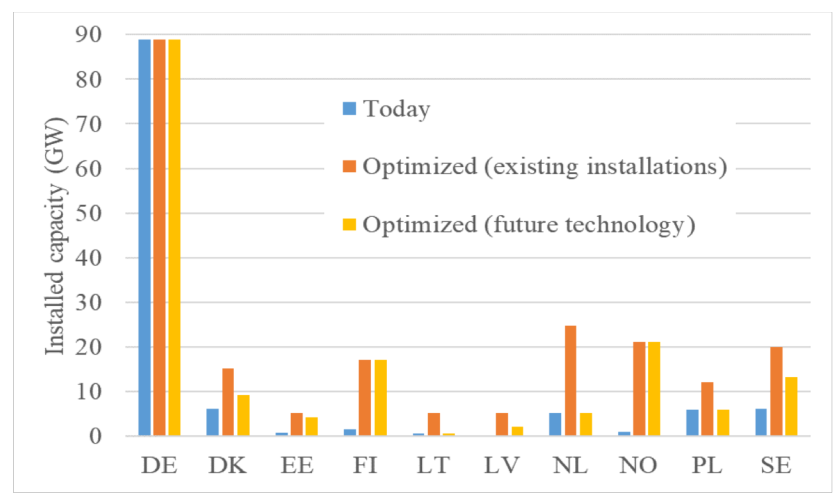
Correlations between the VRE sources[1]

[1]M. Koivisto et al., "Minimizing Variance in Variable Renewable Energy Generation in Northern Europe", *IEEE International Conference on Probabilistic Methods Applied to Power Systems*, Boise, Idaho USA, June, 2018 (https://doi.org/10.1109/PMAPS.2018.8440369)

Impact of wind turbine technology development on VRE variability







M. Koivisto et al., “Effects of Wind Power Technology Development on Large-scale VRE Generation Variability”, *IEEE PowerTech 2019* (accepted).

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Black start from offshore wind power plants

24.03.2020, IEAWind Task 25

Nicolaos A. Cutululis, Anubhav Jain, Jayachandra N. Sakamuri, Oscar Saborio-Romano, Ömer Göksu, DTU Wind Energy

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

- Why
- How
- Results
- Lessons learnt

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

PROMOTioN WP3 WTG-converter interaction

WP3 Partners

MHI VESTAS OFFSHORE WIND

DTU
Technical University of Denmark

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ENERGINET

ABB

SIEMENS

DNV·GL

FGH

University of Strathclyde

RWTH AACHEN UNIVERSITY

Ørsted

equinor

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Why black-start is (becoming) a topic for wind?

Less and less conventional power plants means need for services like BS from other sources

Increased share of RES in power systems also means changes in stability

- UK event, August 2019
- Canary Islands (Tenerife) event, September 2019

TSOs concerned about defence & restoration in systems with high RES

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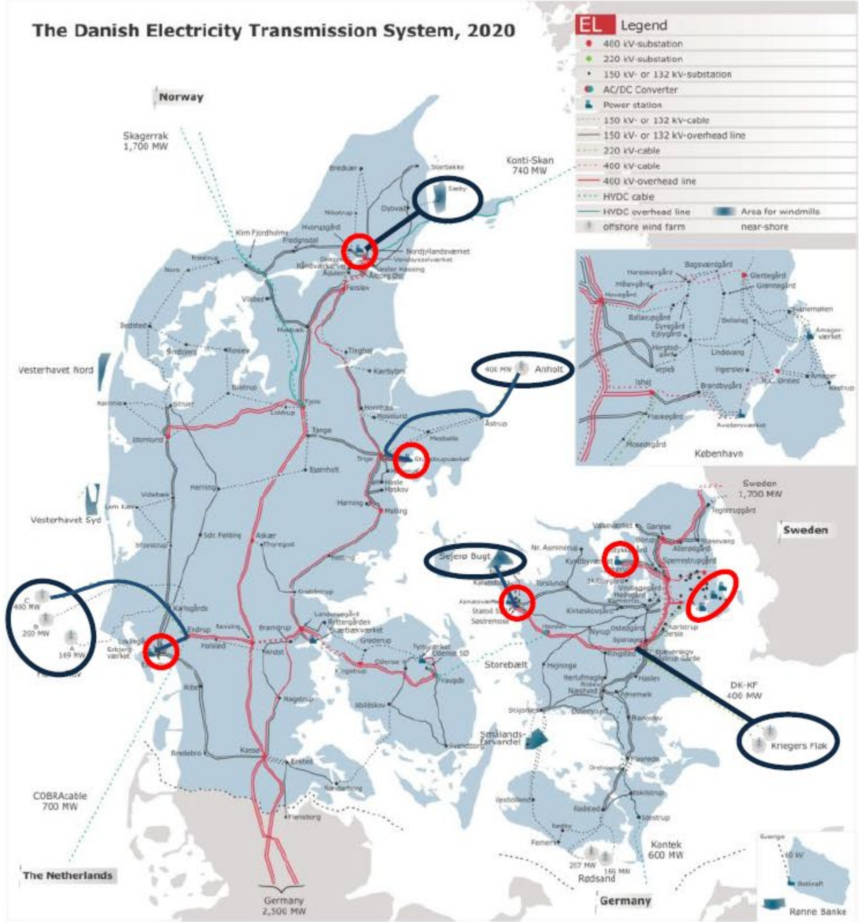
Suitability for black start operation from OWPP



OWPP are large and connected to substations where grid is reasonably strong = <u>close to traditional generators</u>

<u>OWPP can start much faster than traditional black-start units</u>

Slide courtesy of Prof. Blasco-Gimenez, UPV, Spain

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Black start from offshore wind – can we do it?

Business model → **Regulatory / Market hurdles**; **Black Start Capability for OWPP at low cost**

Wind Variability → **Flexible Availability Requirements**; **New Restoration Strategies**

Technical Capability → **Grid Forming Wind Power Plants**; **Aim to minimise modification to WTG Electrics / Mechanics**

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Slide courtesy of Prof. Blasco-Gimenez, UPV, Spain

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Black start from OWPP – how

Option 1 – Sequential hard switching:
all critical transmission system components (like cables and transformers) are connected and energized in sections (sequence) at rated voltage.

Option 2 – Soft start:
connect the different parts of the AC network like cables, reactors and transformers, together with the black-starting generator at low voltage and smoothly ramp-up the voltage of the entire network to energize it in one step.

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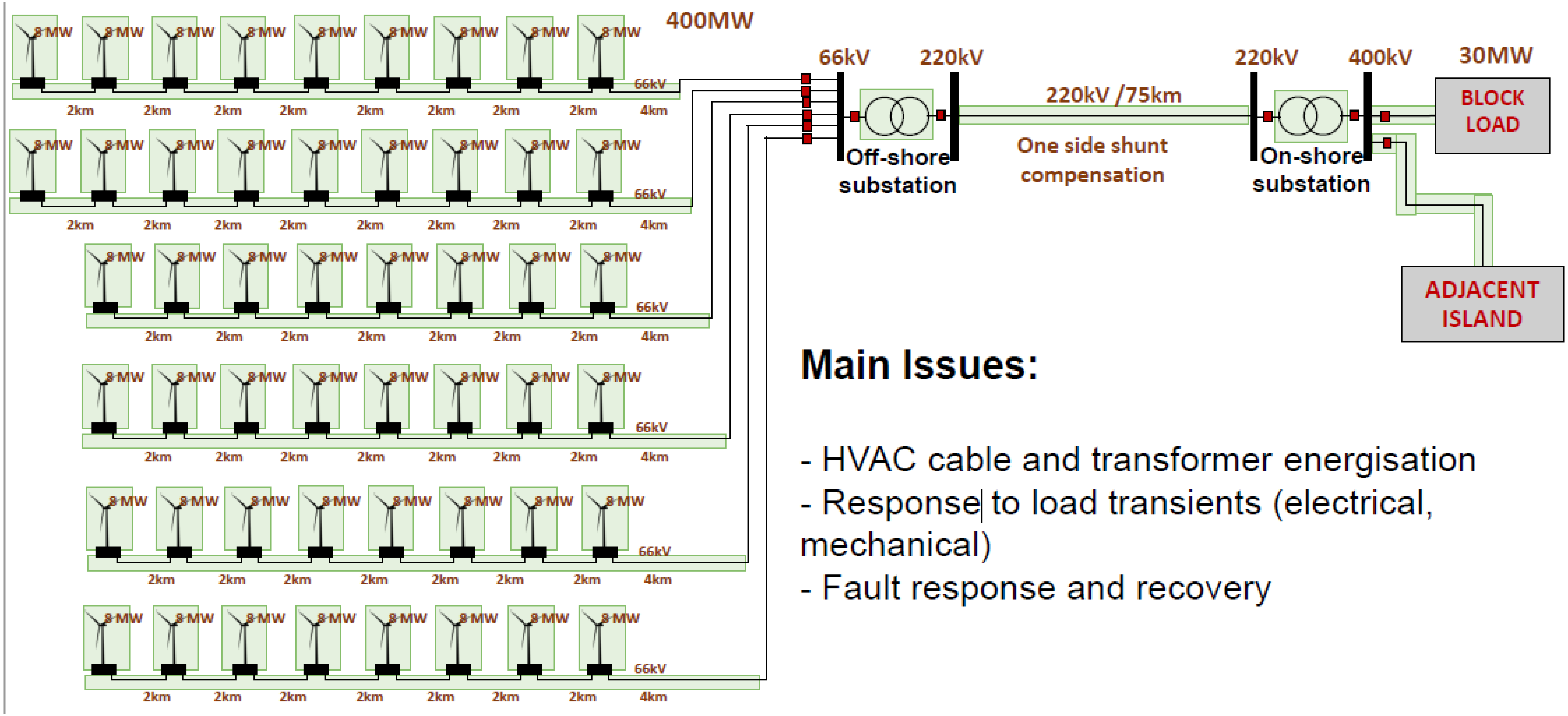
HVAC connected OWPP – hard switching



Main Issues:

- HVAC cable and transformer energisation
- Response to load transients (electrical, mechanical)
- Fault response and recovery

Slide courtesy of Prof. Blasco-Gimenez, UPV, Spain

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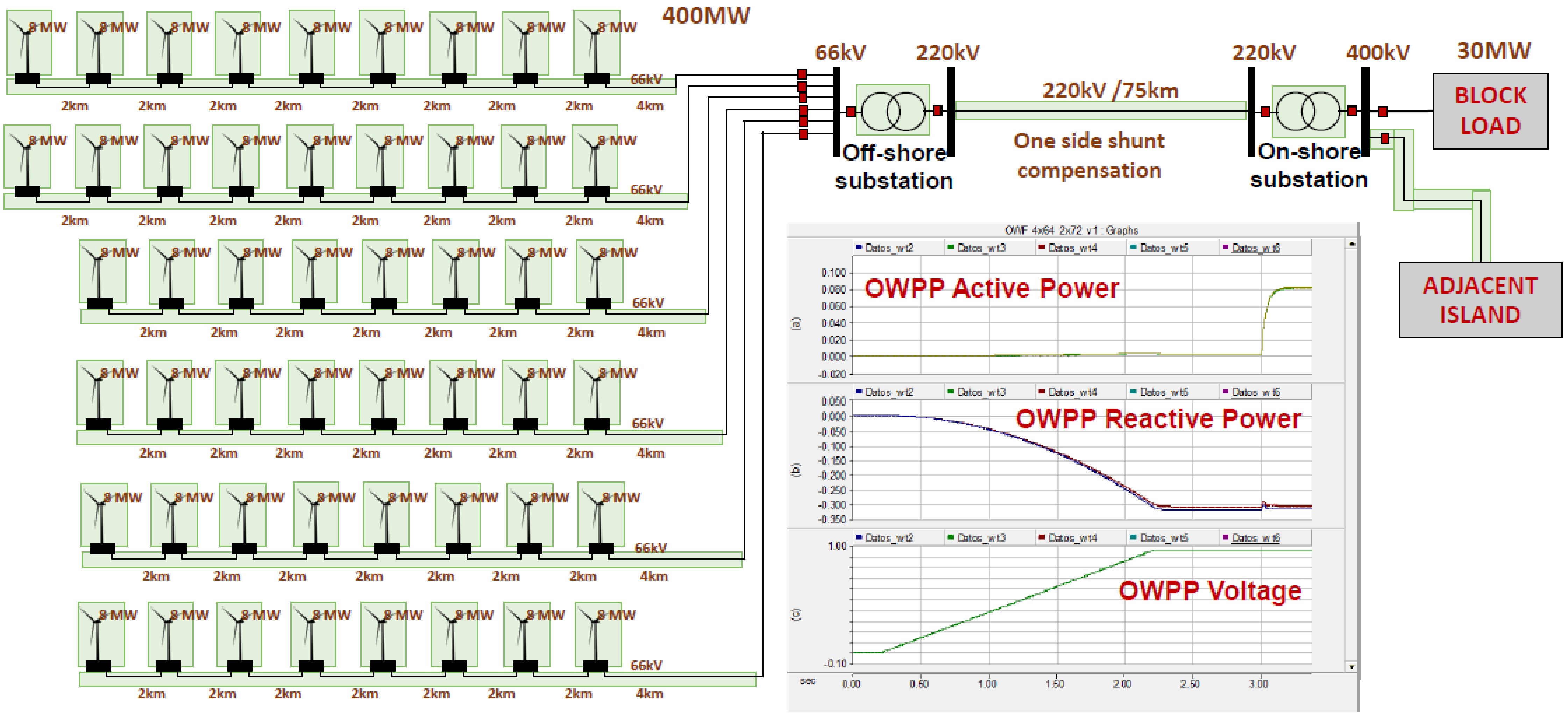
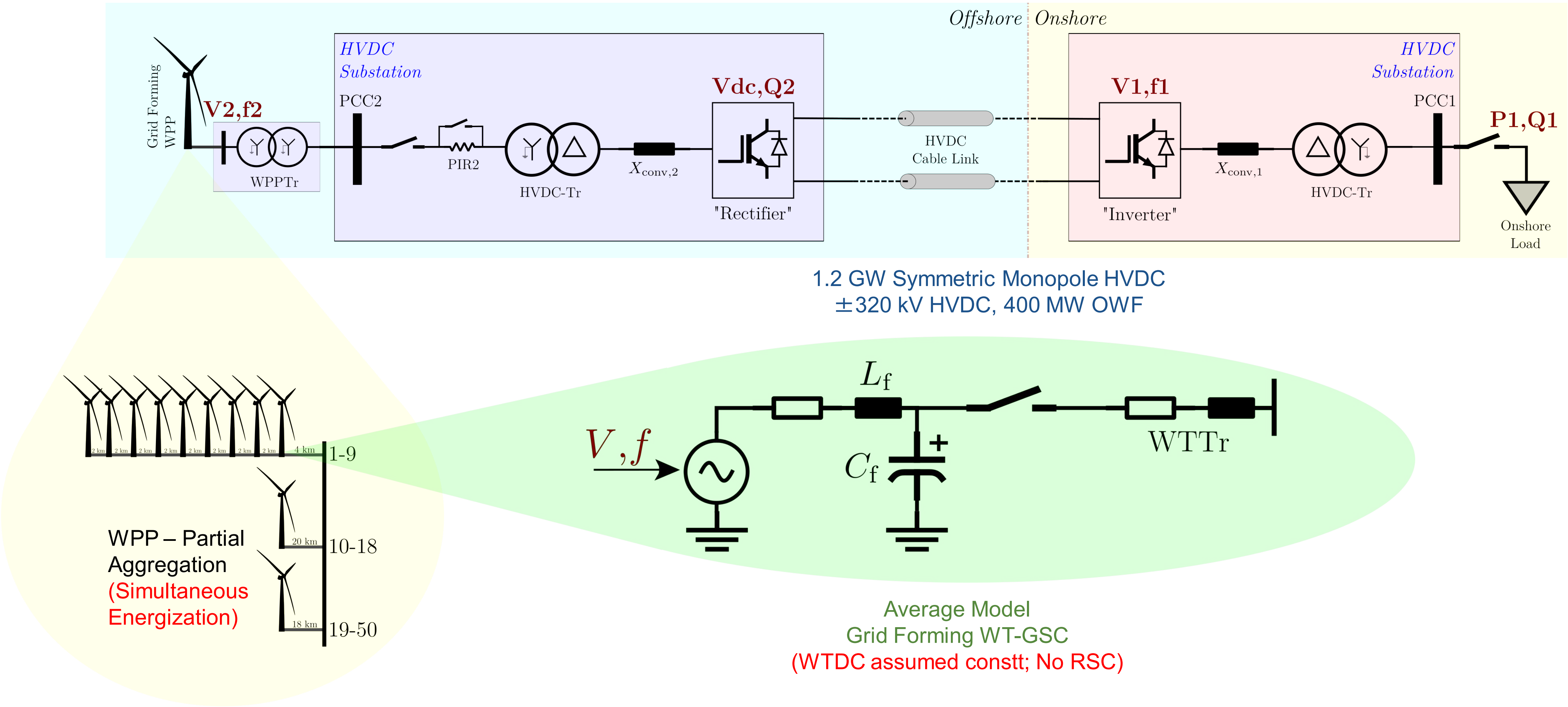
HVAC connected OWPP – soft start



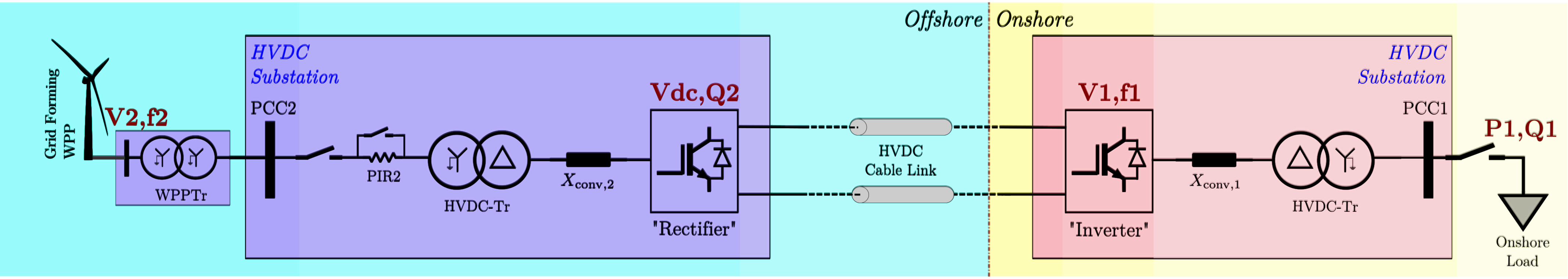
Slide courtesy of Prof. Blasco-Gimenez, UPV, Spain

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

HVDC connected OWPP – Model



Hard Switching



Stage	Time [s]	Event
I	0-	WPP Grid Forming
	1.3	PIR Inserted (Trafo Energization & Offshore MMC Precharging)
II	+0.3	PIR Bypassed
	2.1	Offshore MMC Deblocked (controls HVDC link)
	2.5	Onshore MMC Upper arm Controlled Precharging
	2.8	Onshore MMC Lower arm Controlled Precharging
III	3.1	Onshore MMC Precharging Ends (Both arms blocked)
	3.3	Onshore MMC Deblocked (controls Onshore V,f)
IV	4	Onshore Load Pick-up

Sensitivity
$f(\text{PIR}, \text{PIT})$

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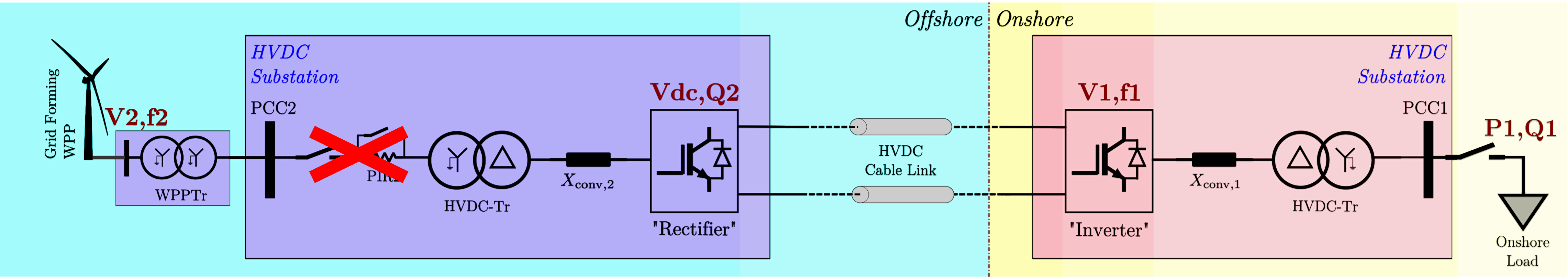
Soft Start



Stage	Time [s]	Event
I	0-1	Grid Forming WPP Ramp-up (Trafo Energization & Offshore MMC Precharging)
II	2.1	Offshore MMC Deblocked (controls HVDC link)
III	2.5	Onshore MMC Upper arm Controlled Precharging
	2.8	Onshore MMC Lower arm Controlled Precharging
	3.1	Onshore MMC Precharging Ends (Both arms blocked)
	3.3	Onshore MMC Deblocked (controls Onshore V,f)
IV	4	Onshore Load Pick-up

Sensitivity $f(\Delta t_{ramp})$

Same as Hard Switching (Stages II–IV)

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Hard Switching

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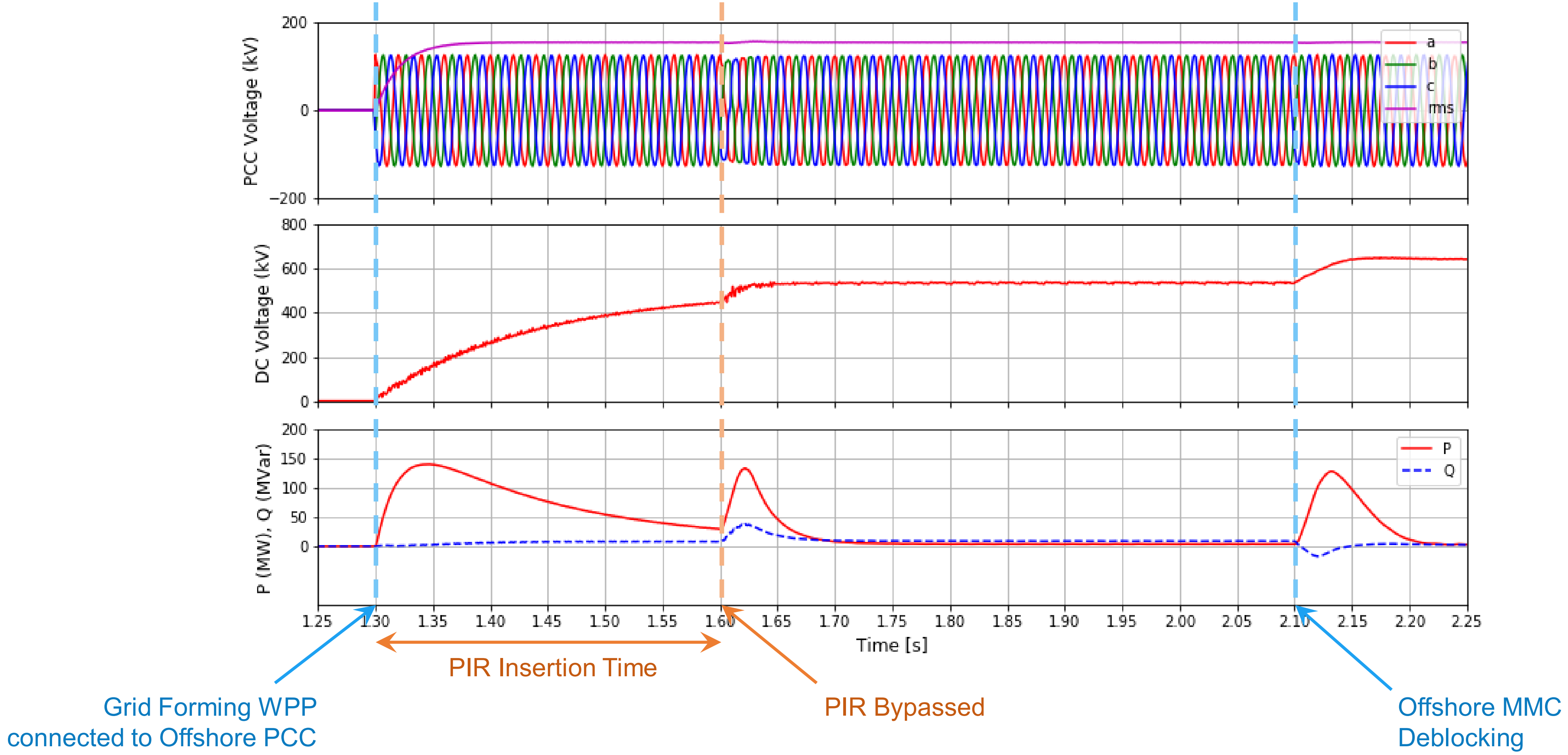
Hard Switching

Stages I-II



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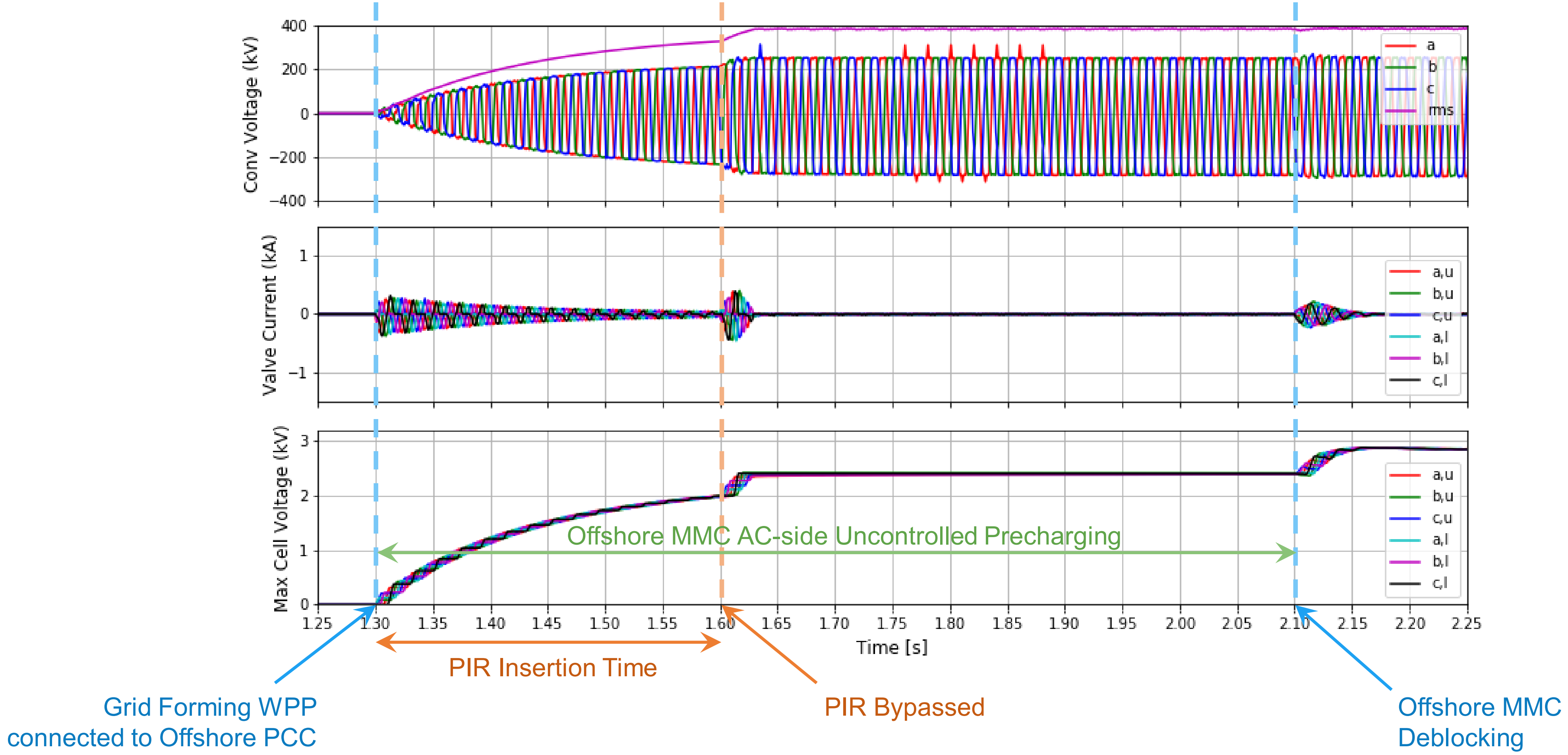
Hard Switching

Stages I-II



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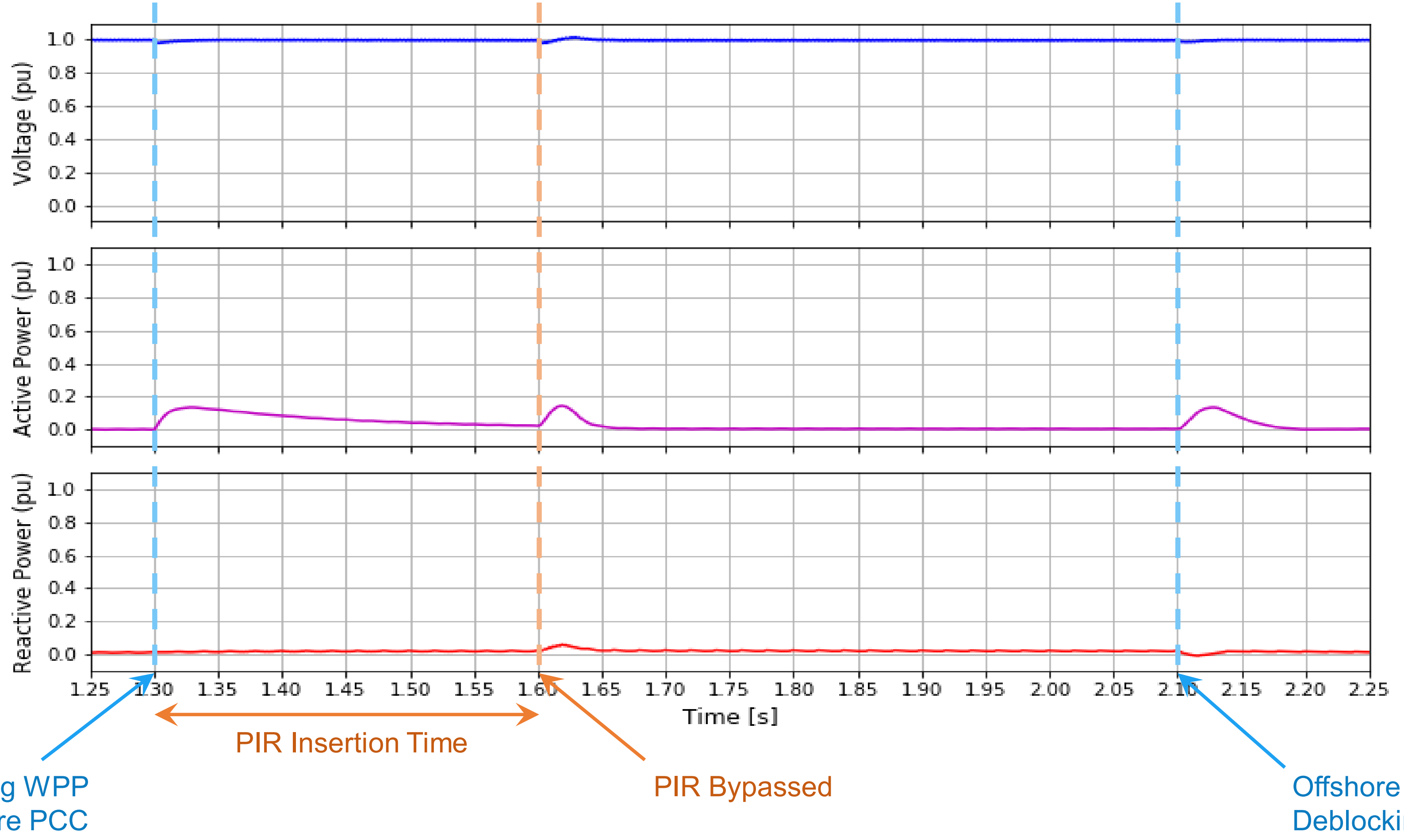
Hard Switching

Stages I-II

WPP
Response



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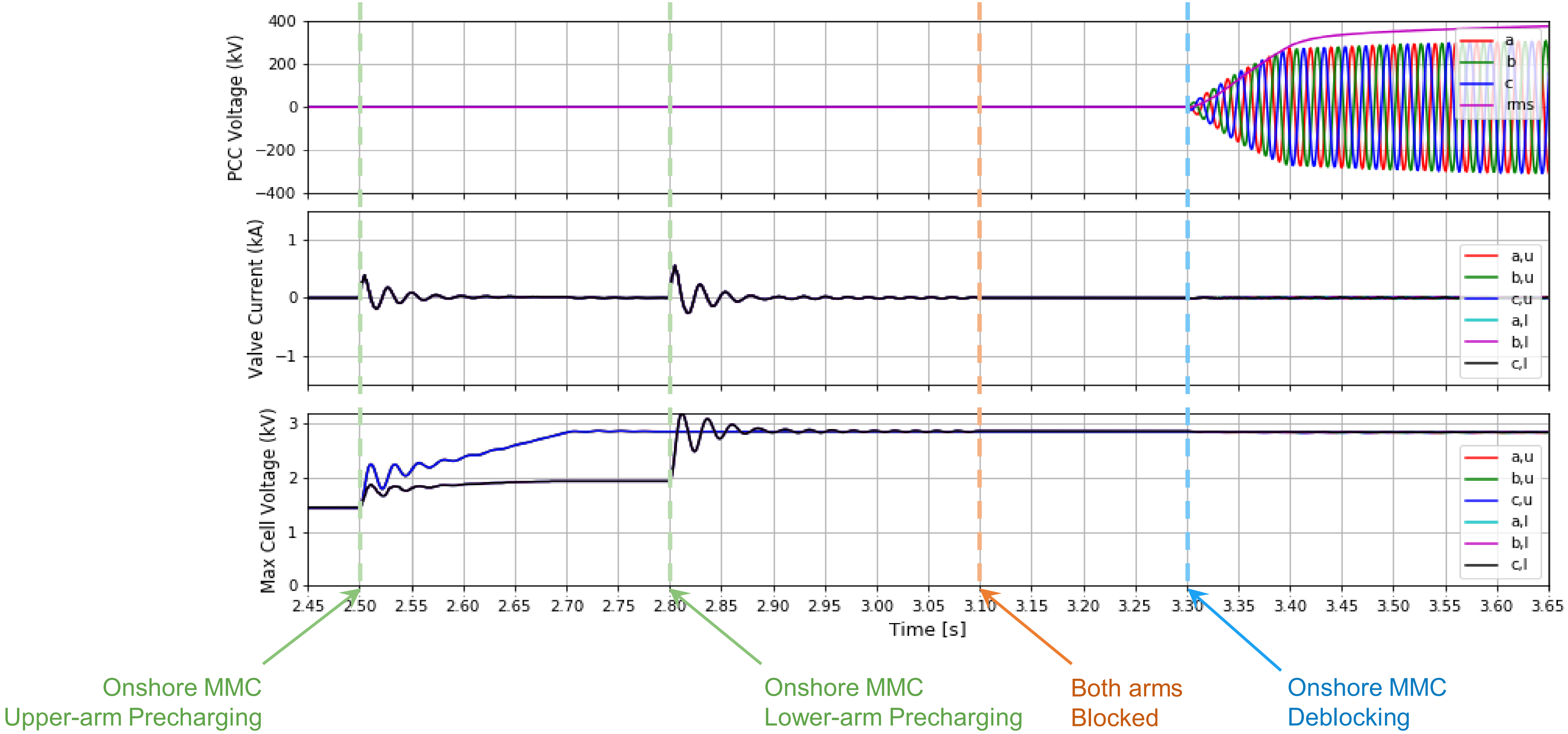
Hard Switching

Stage III



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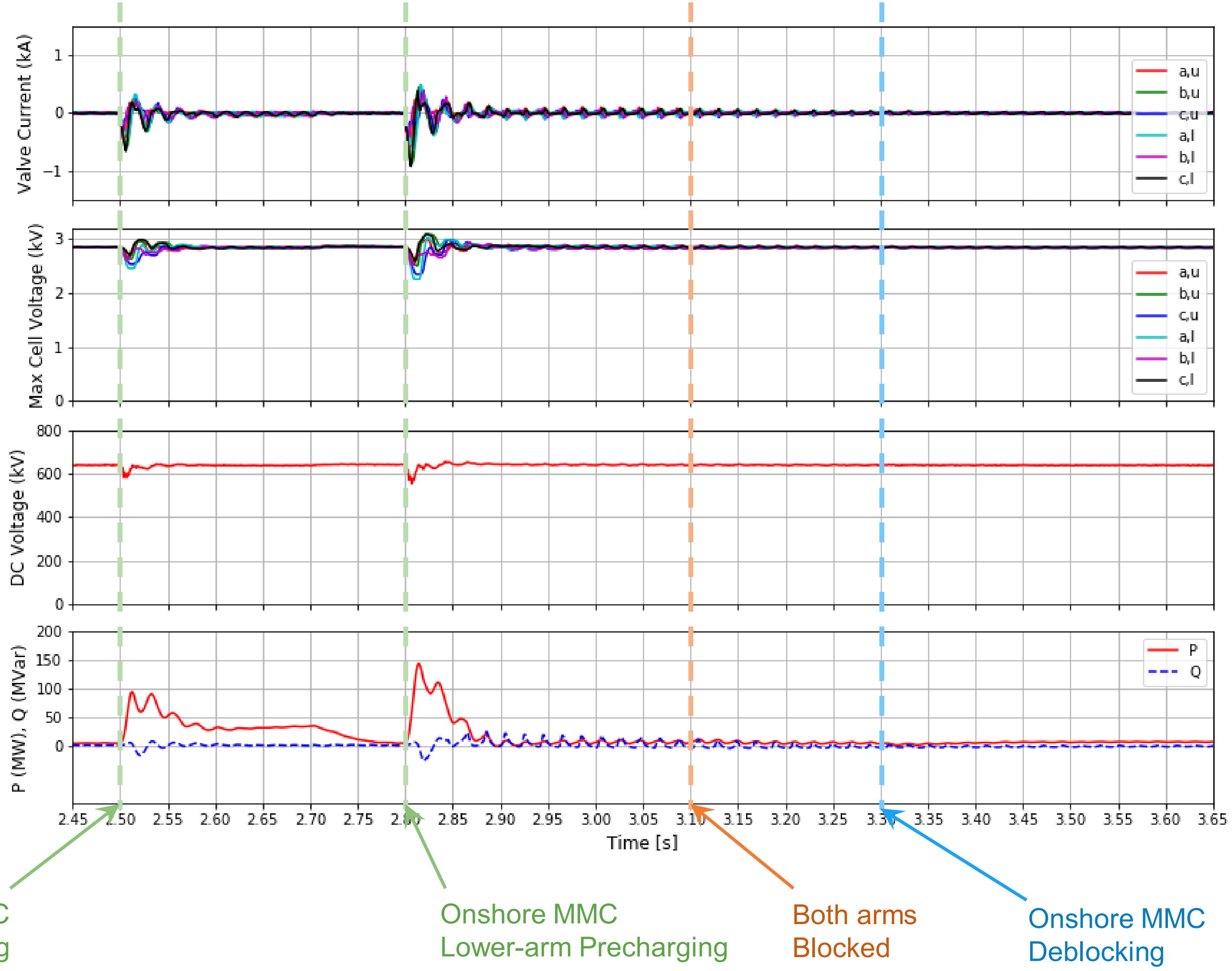
Hard Switching

Stage III

Offshore MMC Response



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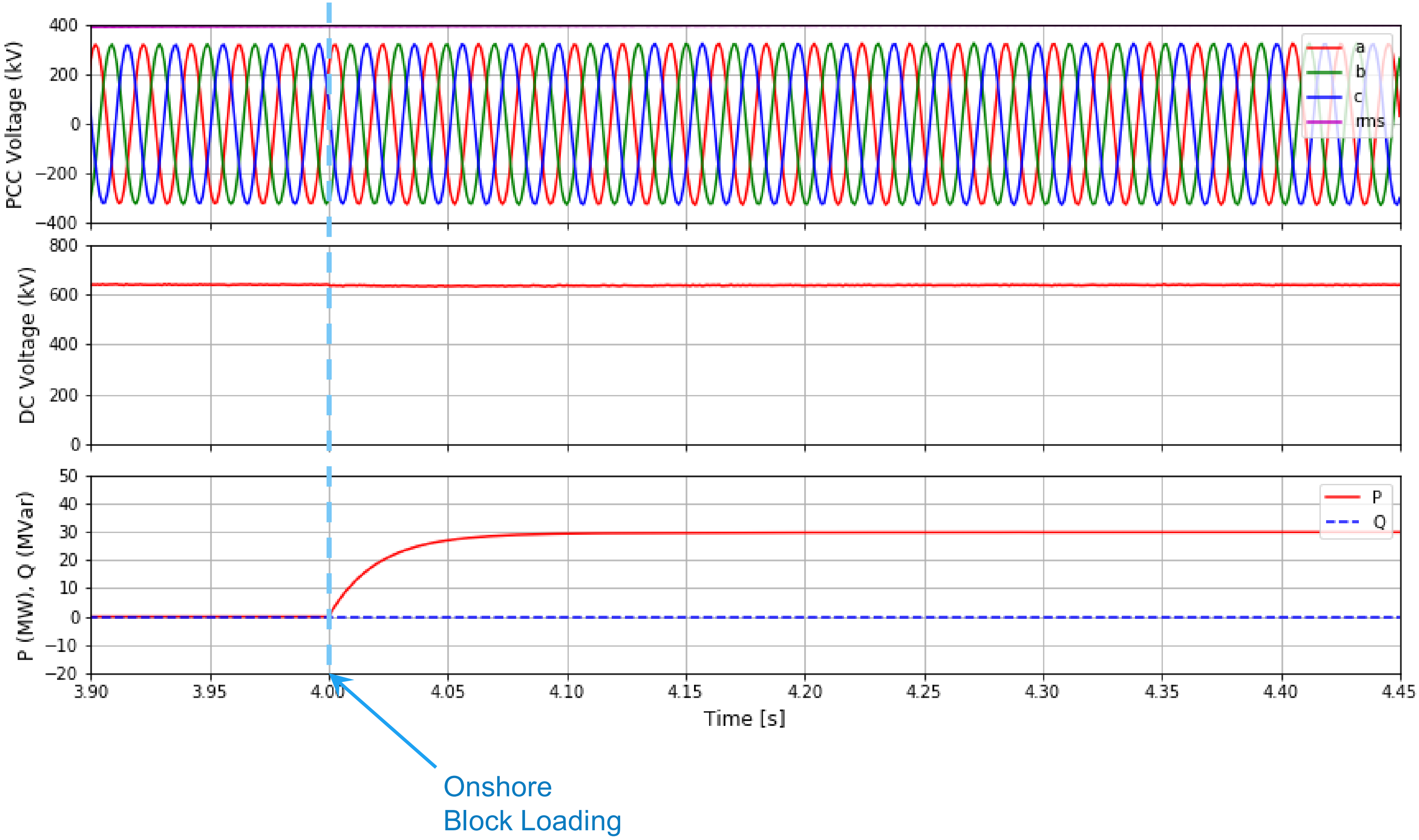
Hard Switching

Stage IV



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Soft Start

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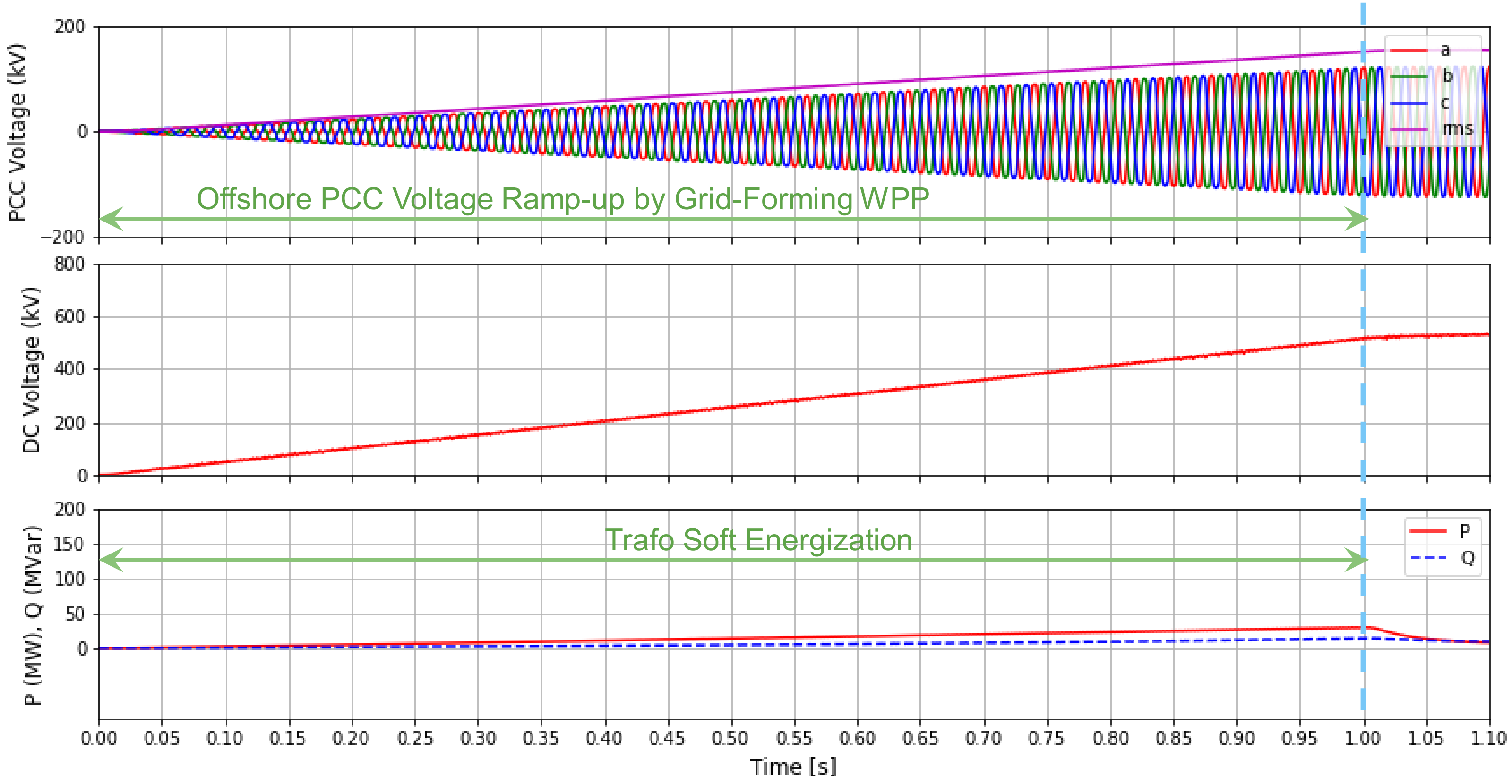
Soft Start

Stage I



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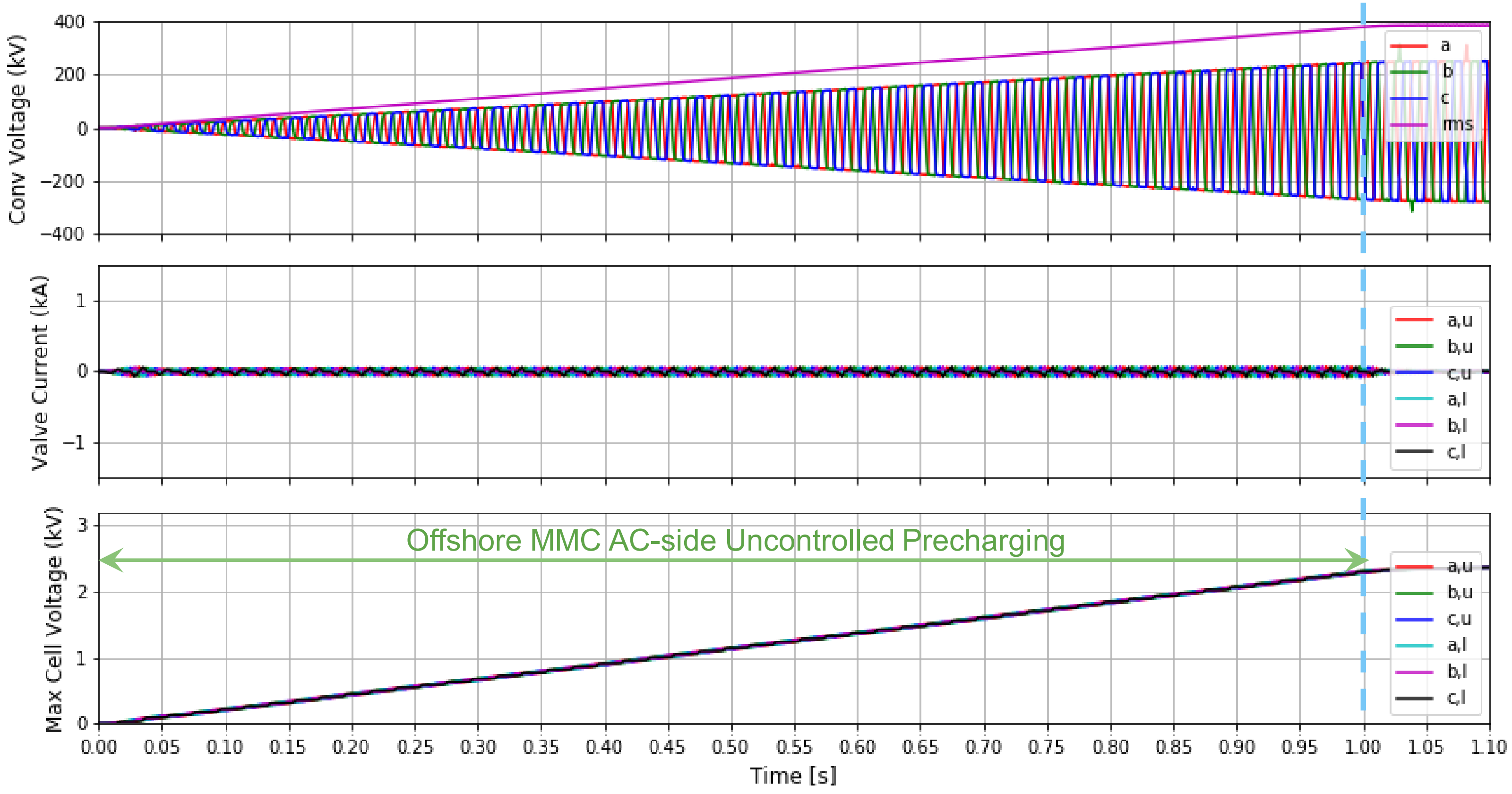
Soft Start

Stage I



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Sensitivity

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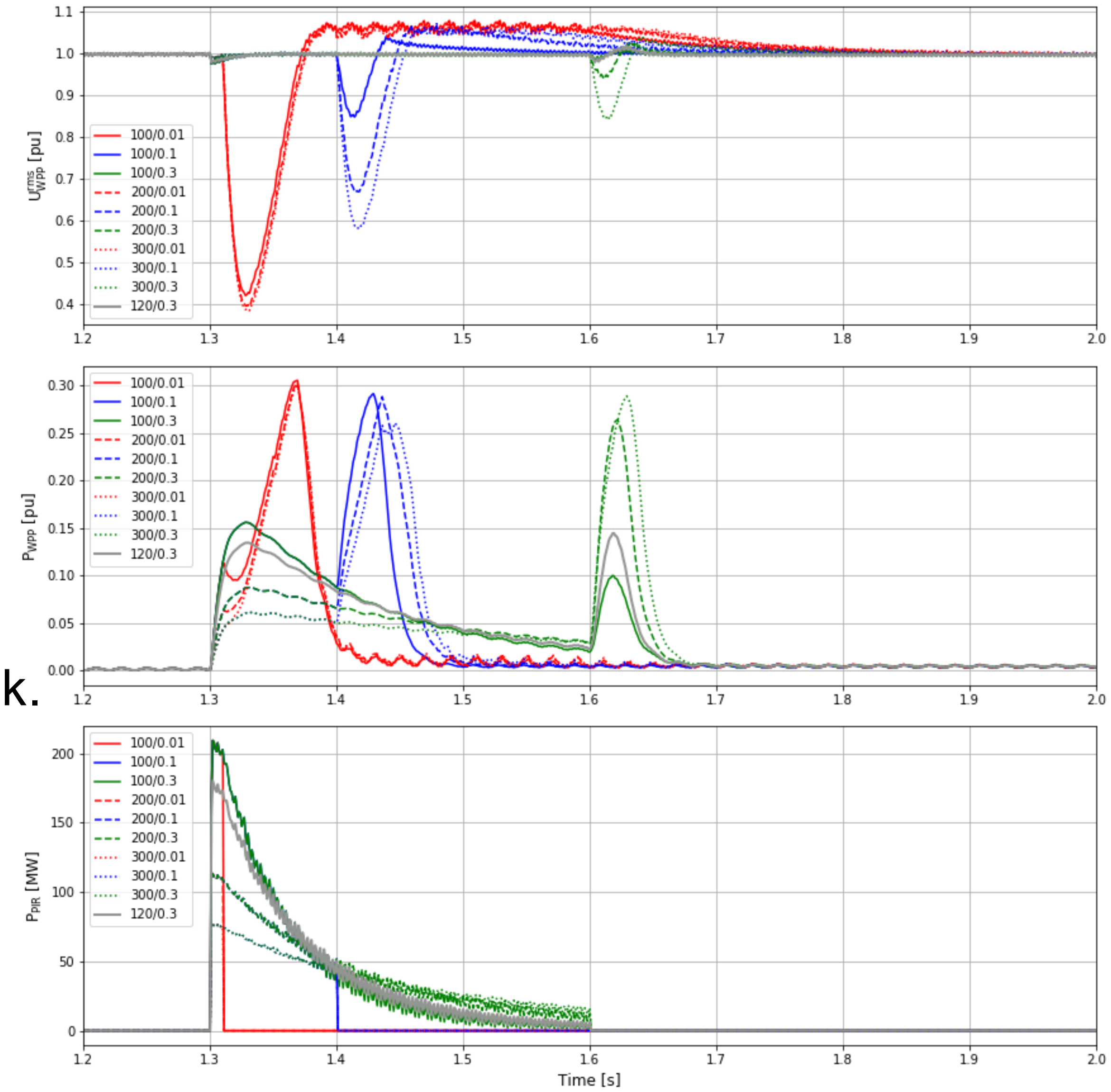
Hard Switching

PIR, PIT

PIR *inserted* at 1.3s
PIR *bypassed* at
- 0.01s
- 0.1 s
- 0.3 s

V-Dip or P-peak at PIR bypass.
- Lower PIT → PIR value doesn't affect peak.
- Higher PIT → lower peak for higher PIR.



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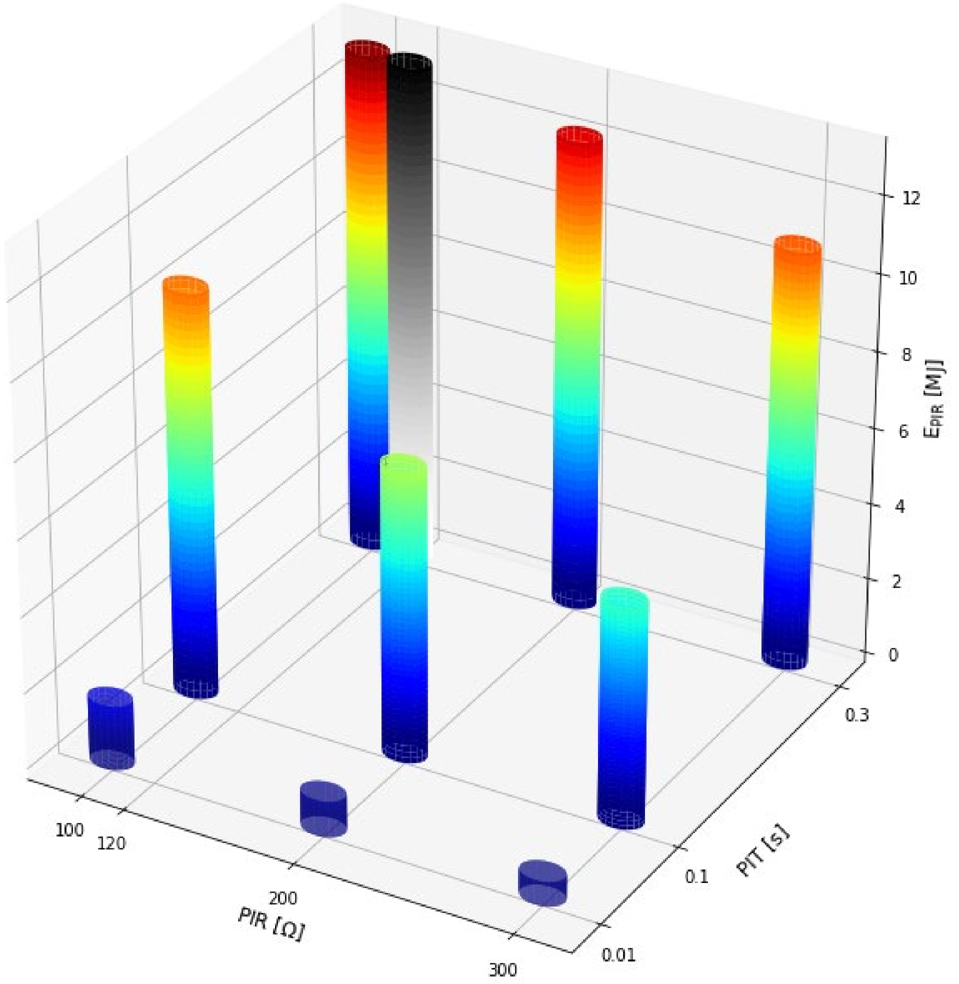
PIR, PIT

Sizing of PIR:

- Energy dissipated by PIR during PIT
- Duty Cycle → Heating/Cooling

Real estate is *costly* on the offshore platform.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

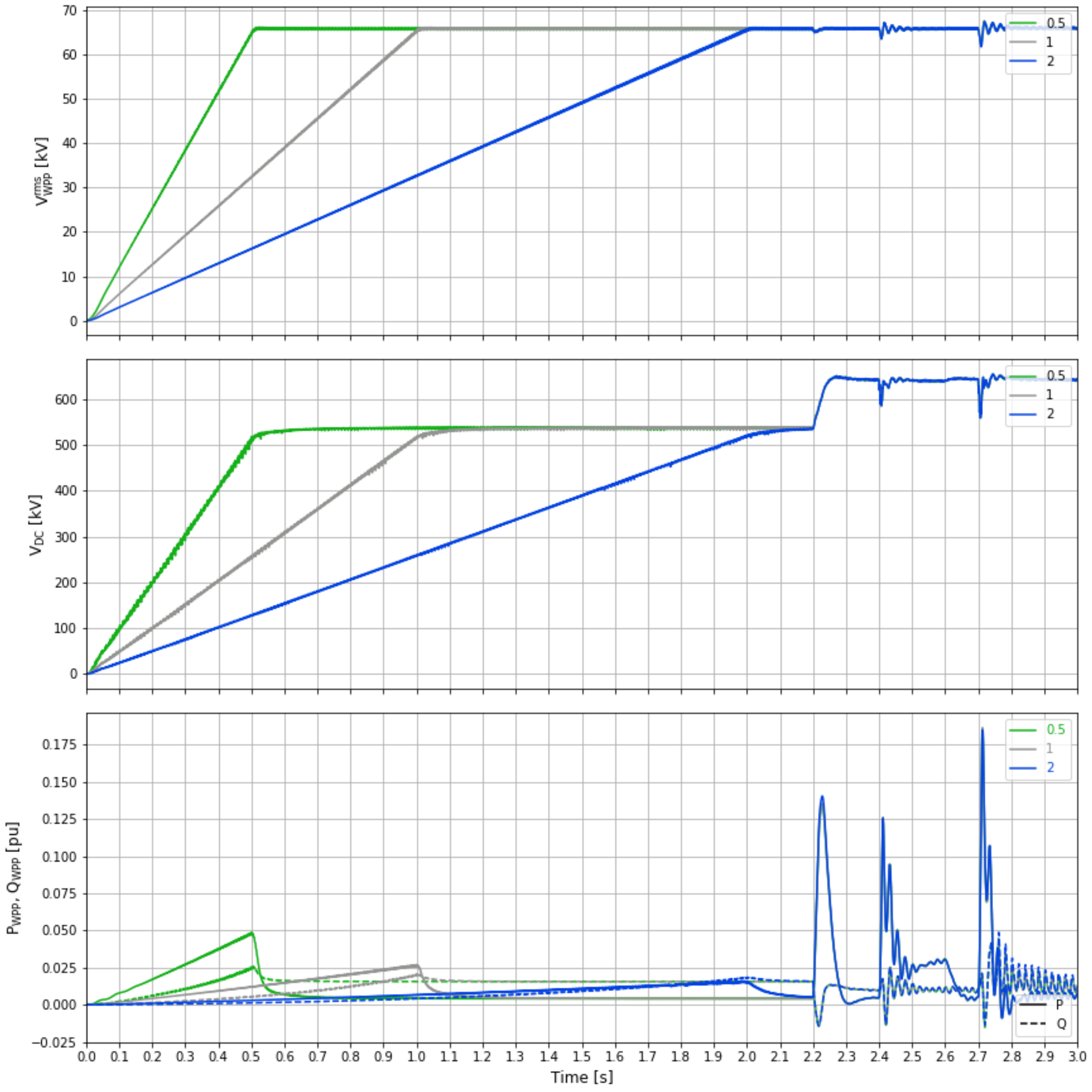
Soft Start

Ramp-time

1pu Ramp-time
- 0.5 s
- 1 s
- 2 s

Faster ramp → Higher charging peak.

Conclusion:
Soft Start preferred over Hard Switching.



Grid forming WTG/WPP Control Validation

Requirements

↓

Scenarios
HVAC, HVDC

↓

Test cases

↓

Validation based on simulations:
Generic Controllers
Vendor Specific Controllers

WP3 (Finished)

Validation based on Real Time Simulation

DNV·GL

WTG
Control Hardware in-the-loop

WTG
Power Hardware in-the-loop
1 MW WTG converter

UNIVERSIDAD POLITECNICA DE VALENCIA

Multiple WTG
Control Hardware in-the-loop

Multiple WTG+WPP
Control Hardware in-the-loop + protection relays

WP16 (On-going)

KTH · DTU Technical University of Denmark · RWTH AACHEN UNIVERSITY · UNIVERSIDAD POLITECNICA DE VALENCIA · Ørsted · DNV·GL

Slide courtesy of Prof. Blasco-Gimenez, UPV, Spain

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Conclusions/lessons learnt

- OWPP could provide black-start services with (mainly) changes in control (re-certification) (and possibly need for local storage at WT)
- Hard switching start might lead to overvoltage/overcurrent due to inrush currents, ferromagnetic oscillations and takes a relatively long time
- Soft start leads to much faster energization time and minimizes inrush current and oscillations
- Grid forming control has to be robust to interactions with other converters/generators in the area
- Large installed capacity of OWPPs might improve it’s availability for black-start operation

Thank You

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

APPENDIX

DISCLAIMER & PARTNERS

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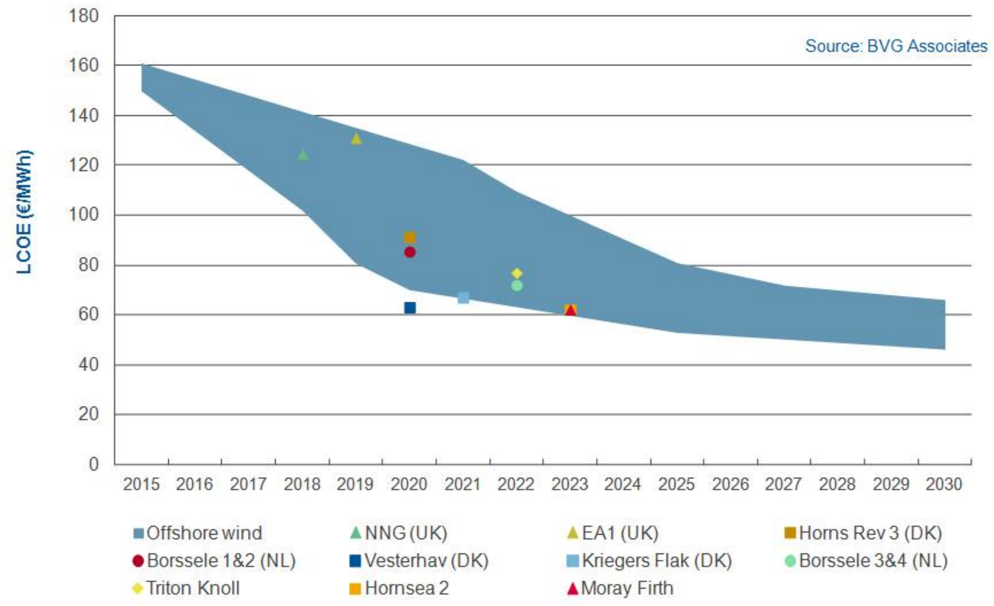
Juan-Andrés Pérez-Rúa & Nicolaos A. Cutululis

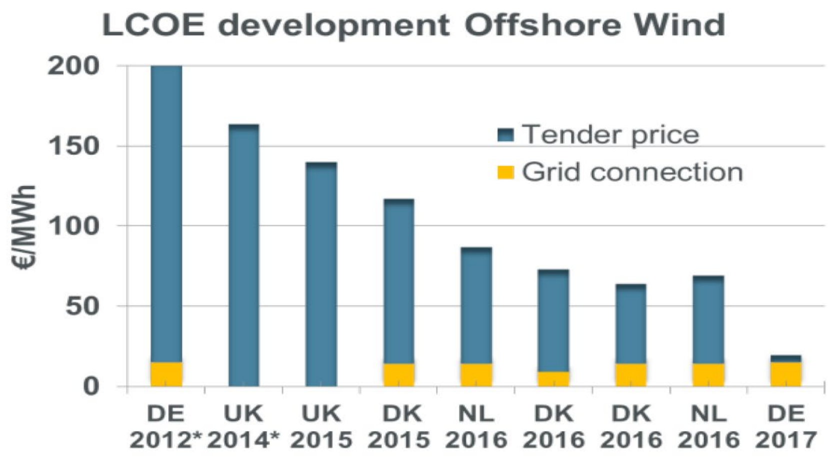
Electrical network design for offshore wind

Introduction

The LCOE of Offshore Wind Farms is decreasing steadily…



Offshore wind LCOE evolution



- **Limited cost reduction in grid connections.**
- **Longer offshore connections lead to increase in cost**

LCOE development of offshore wind

Tennet, "North Sea Energy Infrastructure: Status and outlook", Tech. Rep., 2019,pp. 1–29

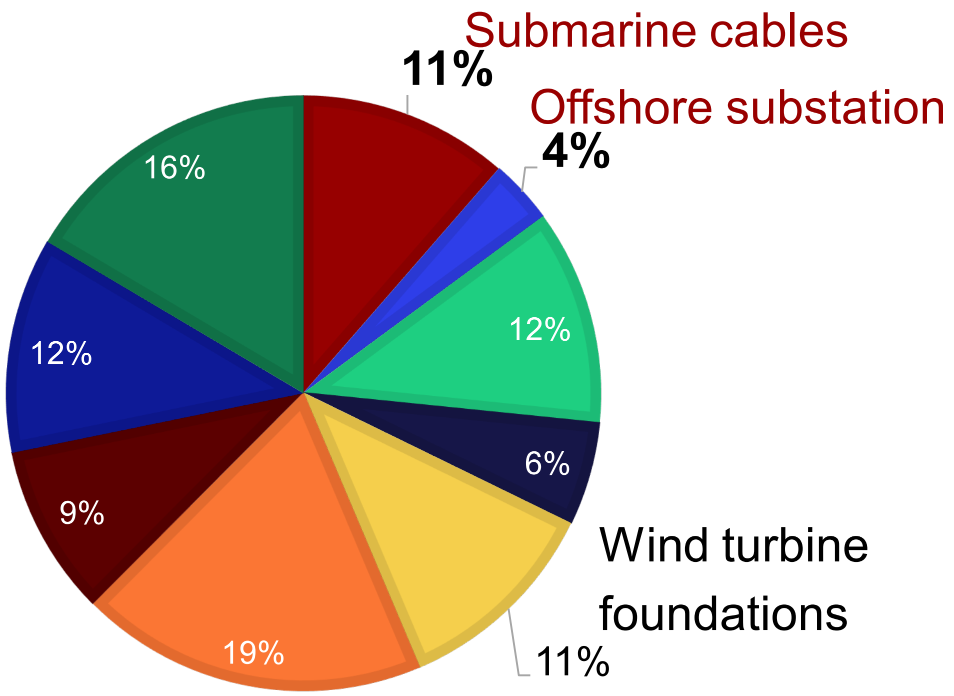
[…] *this is mainly from technology innovations in turbines and installation, and reductions in financing costs* […] WindEurope

Introduction

- **Cables (Capex + install.)**
- Nacelle
- Turbine foundation (Capex + install.)
- Operations
- Others
- **Offshore substation**
- Rotor
- Maintenance and service
- Turbine installation and others

Main drivers for grid connection

Total costs of submarine cables (**11%**) plus offshore substation (**4%**) represent the major cost component in the Balance of Plants (BoP) .



Offshore wind LCOE breakdown

ORE Catapult,Wind farm costs, 2020

Introduction

Cables, cables and more cables!

https://techstartups.com/2019/07/28/global-internet-powered-vulnerable-undersea-cables-end-cloud-know/

https://www.windpowermonthly.com/article/1434069/new-underwater-drone-cable-inspection-launched

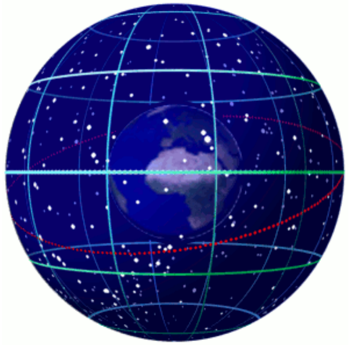
Submarine cables are the backbone component of the grid connection system and the main element for the BoP!

RenewableUK Project Intelligence

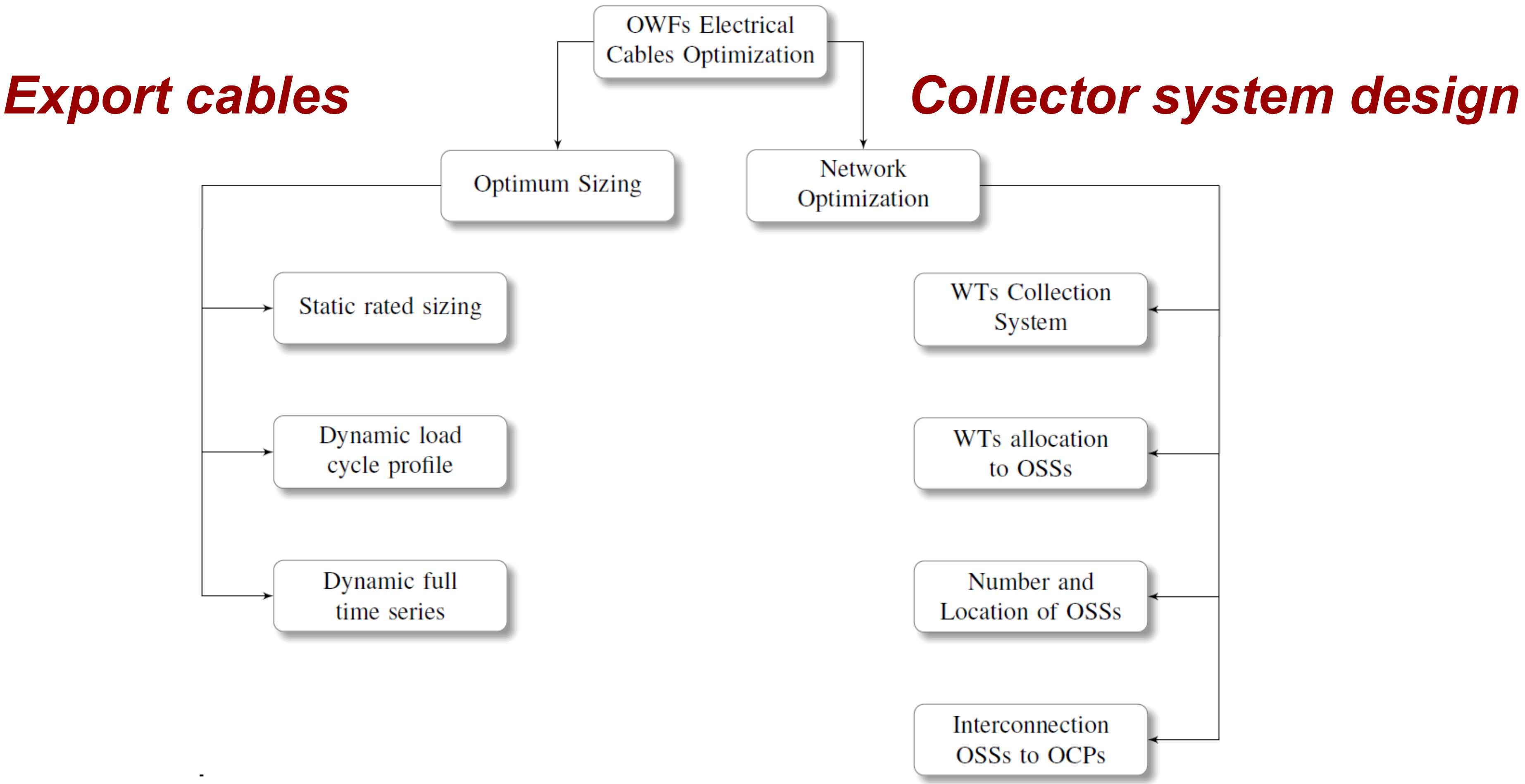
✓ Between 2018 and 2028 a total of **19 702 km** of array cables are forecast to be installed worth **£ 5.36 bn**.

✓ Between 2020 and 2024 a total of **6 750 km** of export cables are needed.

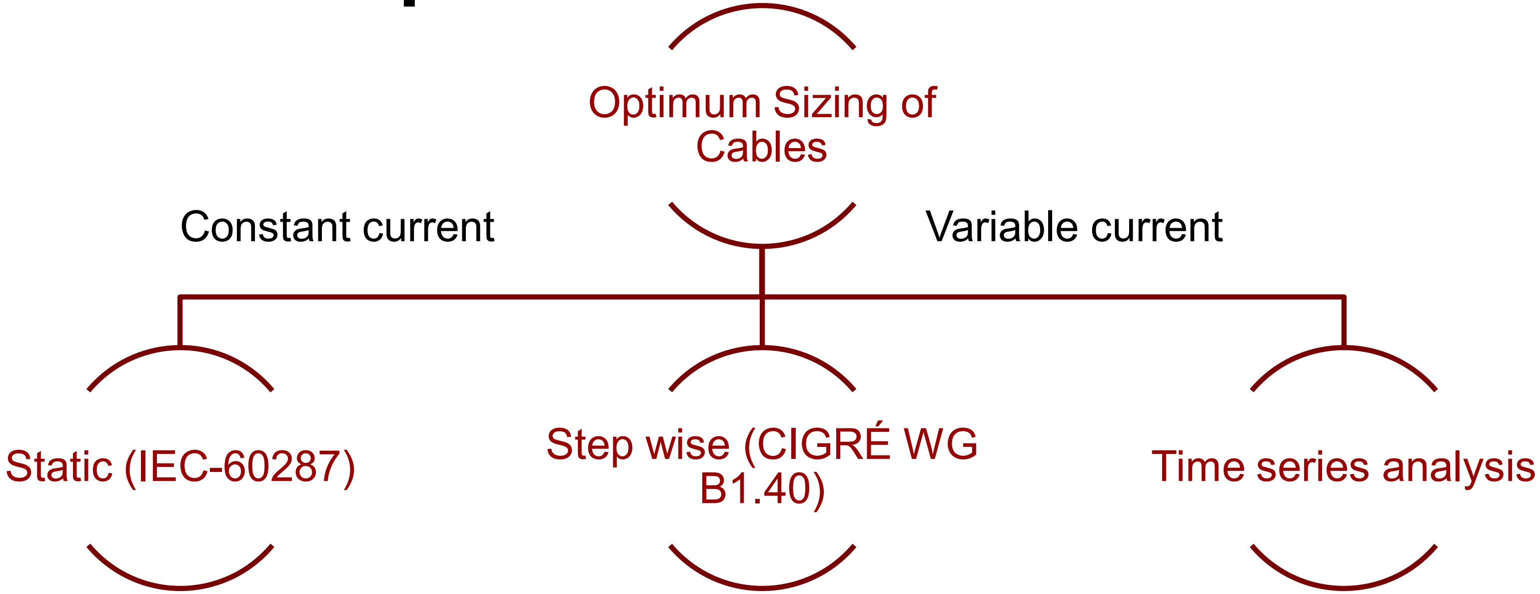
Imagine 450 GW of offshore wind!

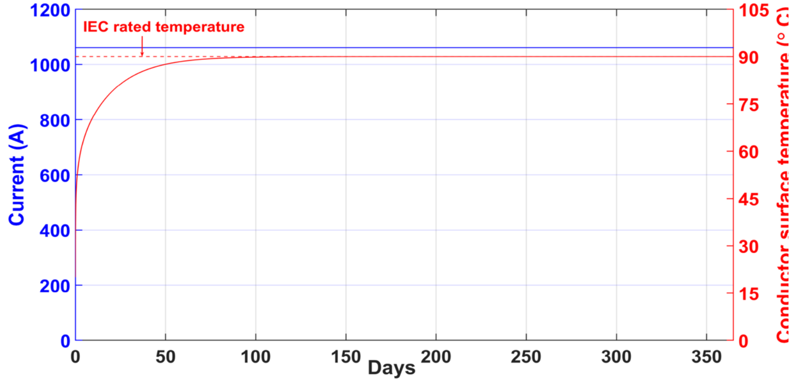


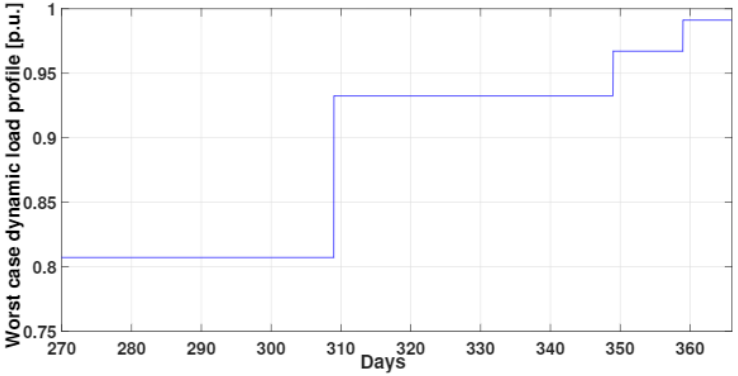
Electrical cables design

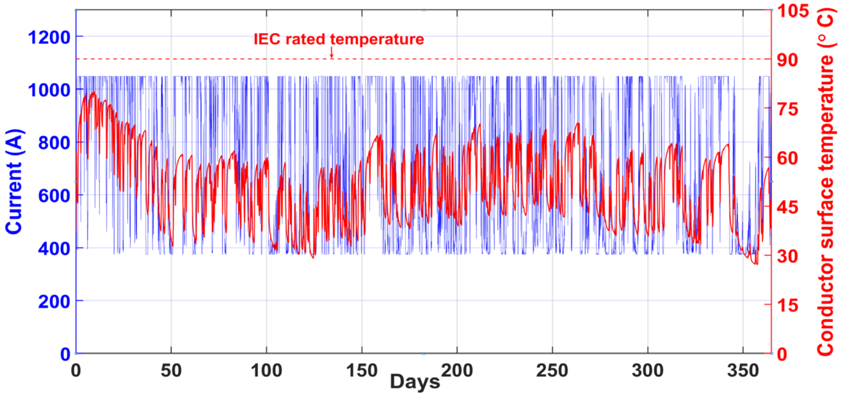


How to size export cables?

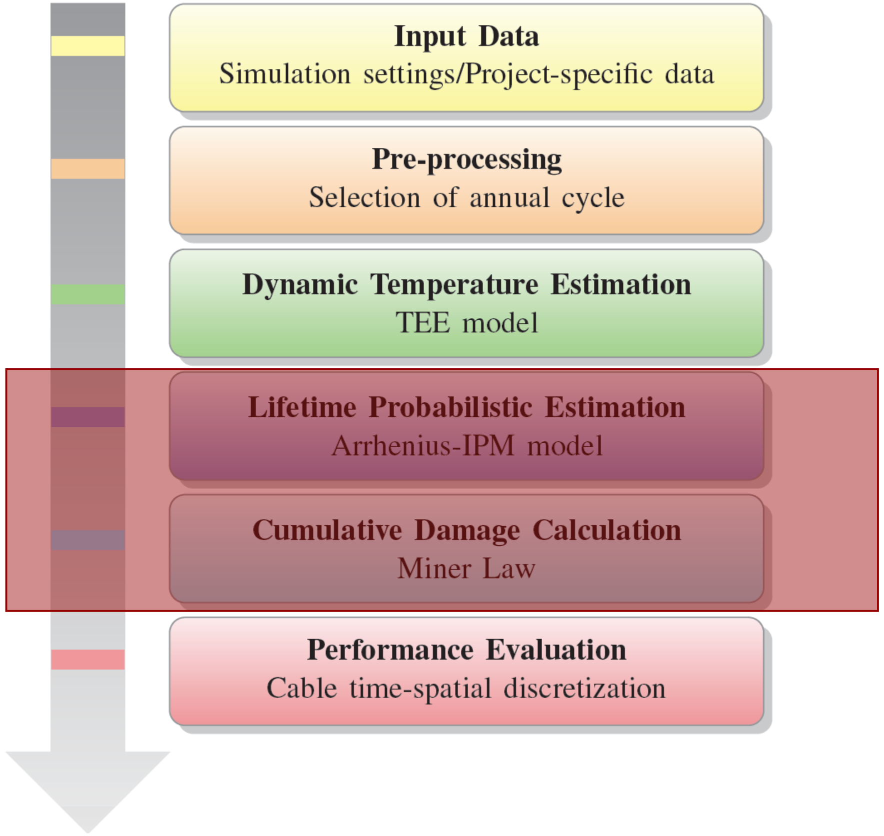


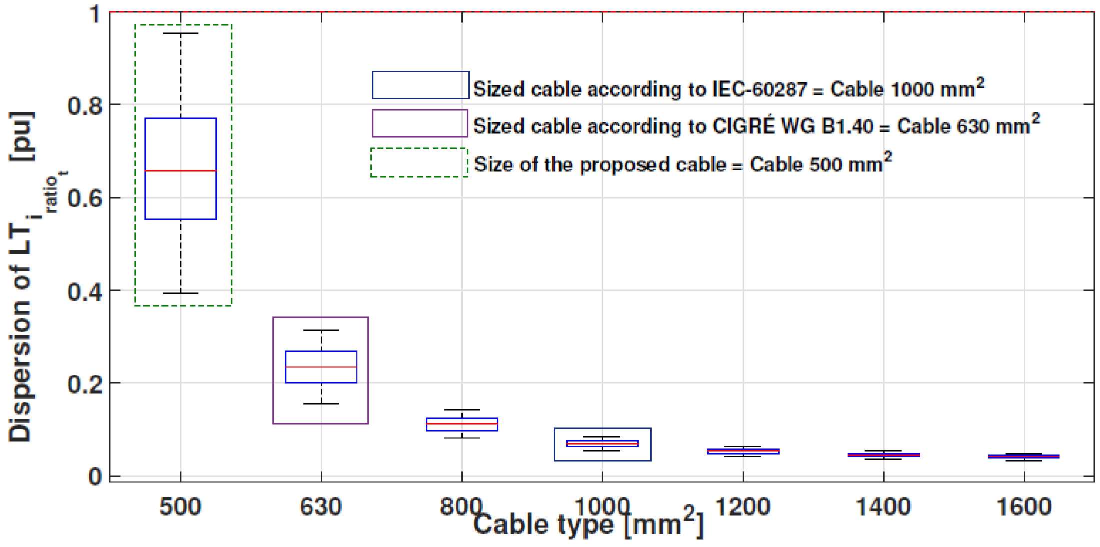






Sizing of export cables





Overall lifetime simulation results

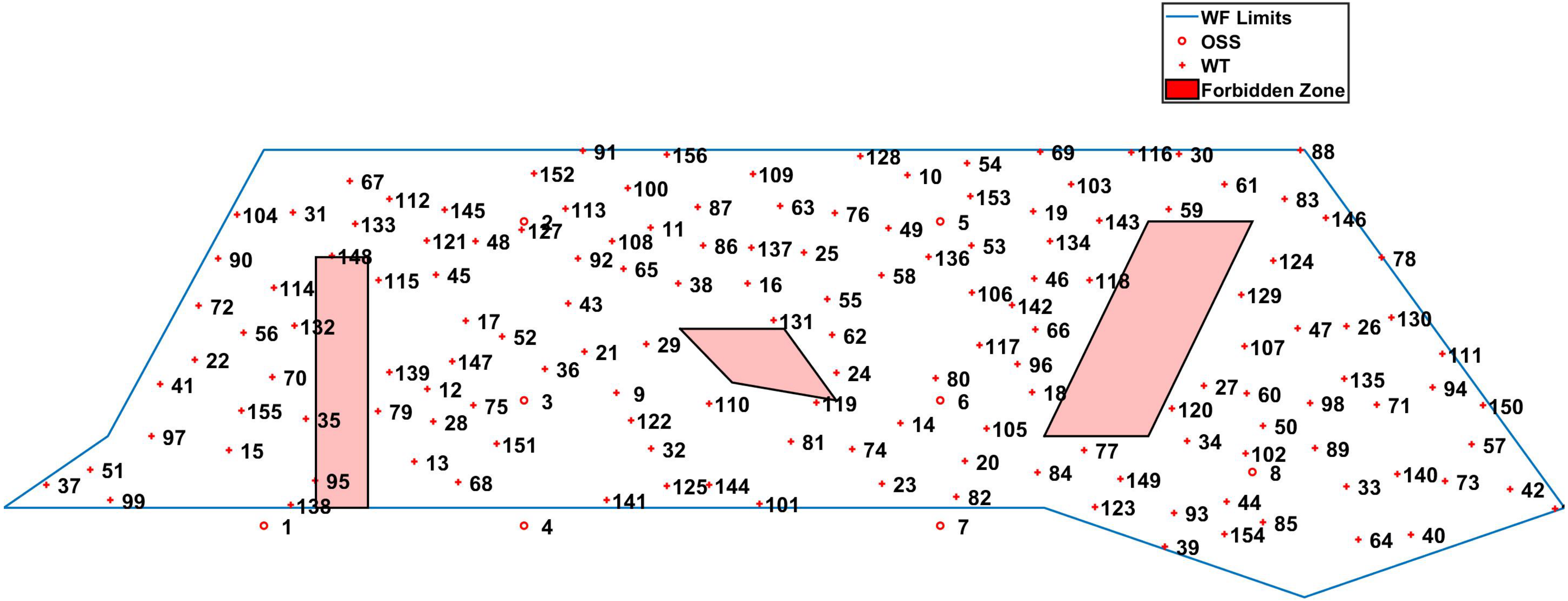
✓ Sized cable according to the proposed method: 500 mm².

Best balance between investment, losses and reliability by relaxing the ultimate strength limit.

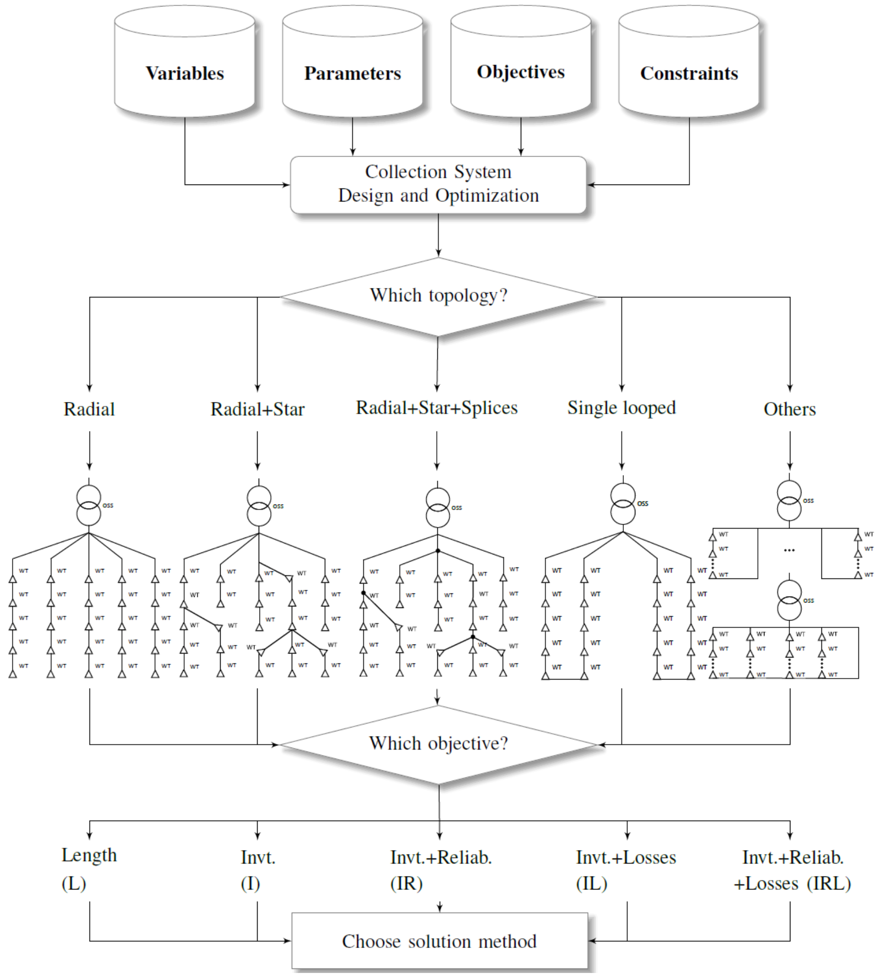
Reduction of 7% compared to IEC-60287 and of 2% compared to CIGRÉ B1.40 in LCOE-share.

Collector system design - problem definition

How to optimally join the points?



Collector system design – decision flowchart



Variables

Binary (actives arcs, cable selected per active arc, etc), **Continuous** (Number WTs per OSS, Current through active arc, etc).

Parameters

Costs (cables costs, cost of energy, etc), **Lenghts** (Distance between two WTs (Wind Turbines), to the Offshore Substation (OSS), etc), **Topological** (Maximum number of main feeders, maximum number of connections in WTs, etc), **Cables' specifications** (max current, resistance, reactance, etc), **Financial** (lifetime, discount rate, WACC, etc).

Objectives

Economic metric (LCOE, NPV, IRR, etc).

Constraints

Technical (Current limit, OSS power limit, etc), **Topological** (node degree, max number feeders, etc), **Planarity** (no-crossing cables, forbidden areas, seabed bathymetry, etc).

Computational optimization

Three main types of methods

Global optimization or exact formulation, metaheuristics and heuristics

Costs components **Investment** or CAPEX, **Reliability** (cables failures), **Electrical losses**. Combination between them defines different types of problems.

Stochastic collection system design

Problem definition

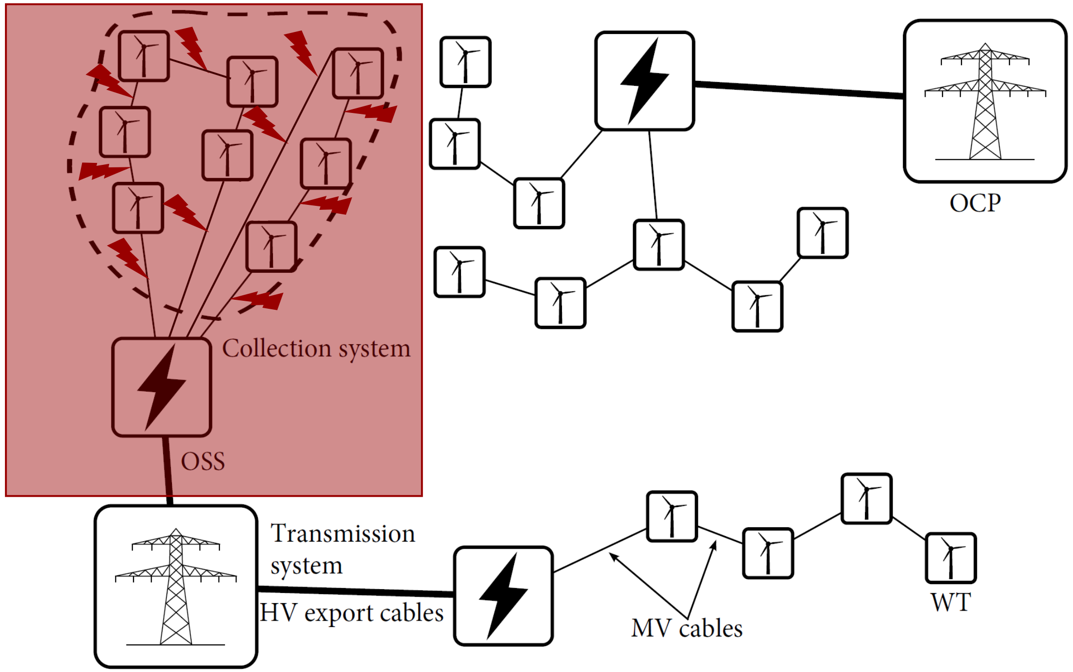
Design a closed-loop collection system network (cable layout) assuming:

✓Fixed position of the wind turbines.

✓Fixed position of single offshore substation.

✓A list of available cables sized using any of the methods previously described (capacity defined in terms of electrical current).

✓Cables are prone to fail according to a N-1 criterion.

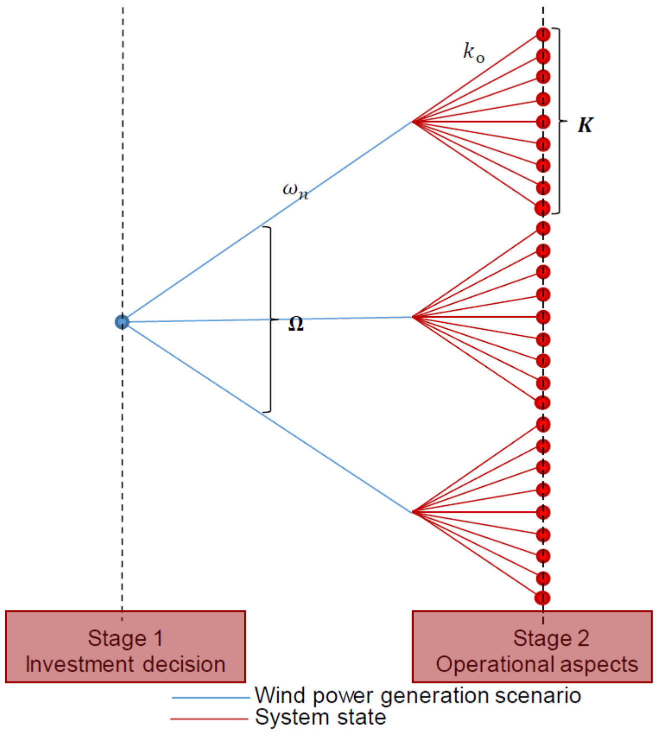


Scope of the collection system design problem with stochastic cables failures

Stochastic collection system design

Modelling the stochasticity

- ✓Two random parameters are considered: offshore wind power and cables failures.
- ✓A scenario numeration technique for probabilistic reliability analysis is implemented.



- ✓The scenario tree is presented in the left figure. It splits the problem into two stages where decisions need to be made; investment and operation.
- ✓The scenario tree expresses the different states of the random parameters, defining the system scenarios which affect the operation of the system. Blue is for wind power scenarios and Red for cables failures.
- ✓It expresses how to stochasticity develops over time and the non-anticipative nature of the first stage decisions.

STOCHASTIC COLLECTION SYSTEM DESIGN

Global optimization: Mixed Integer Linear Programming with stochasticity incorporated

Variables

First stage (Investment)

- y_{ij} → Binary. Active if edge $[ij]$ is selected
- $x_{ij,t}$ → Binary. Active if edge $[ij]$ uses cable type t

Second stage (Operation)

- $I_{ij}^{\omega,k}$ → Current through edge $[ij]$ during generation ω and system state k
- $\theta_{i}^{\omega,k}$ → Voltage phase at node i during generation ω and system state k
- $\delta_{j}^{\omega,k}$ → Curtailed current at WT j during generation ω and system state k

Cost coefficients

Investment

- c_t → Cost per unit of length of cable type t. May include cost of total electrical losses by pre-processing

Operation

- c_e → Cost of energy
- τ^{ω} → Duration of wind power scenario ω
- ψ^{k} → System state probability at k. From associated failed cable and calculated using a discrete Markov chain model

MTTR ↔ MTBF

(Mean Time To Repair) (Mean Time Between Failures)

STOCHASTIC COLLECTION SYSTEM DESIGN

Global optimization: Mixed Integer Linear Programming with stochasticity incorporated

Objective function

$$\min \overbrace{\sum_{[ij]\in \boldsymbol{E}} \sum_{t\in \boldsymbol{T}} c_t \cdot d_{ij} \cdot x_{ij,t}}^{\text{Investment}} + \overbrace{c_e \cdot \sum_{i\in \boldsymbol{N}_w} \sum_{\omega\in \boldsymbol{\Omega}} \sum_{k\in \boldsymbol{K}} \tau^{\omega} \cdot \psi^{k} \cdot \delta_i^{\omega,k}}^{\text{Operation/Reliability}}$$

➡ The objective is to minimize system costs: Simultaneously including *capital expenses* and *expected costs of curtailed energy*.

Constraints – First stage

$$\sum_{t\in \boldsymbol{T}} x_{ij,t} = y_{ij} \quad \forall [ij] \in \boldsymbol{E}$$

➡ To select only one cable type t if edge $[ij]$ is active.

$$\sum_{\substack{j\in \boldsymbol{N} \\ j\neq i}} y_{ij} = 2 \quad \forall l \in \boldsymbol{N}_w : l = i \vee l = j$$

➡ To ensure a closed-loop topology throughout the network.

STOCHASTIC COLLECTION SYSTEM DESIGN

Global optimization: Mixed Integer Linear Programming with stochasticity incorporated

Constraints – First stage

$$\sum_{i \in \boldsymbol{N}_\mathrm{w}} y_{ij} \leq \phi \quad j = 1$$

➡ To limit the number of main feeders.

$$y_{ij} + y_{uv} \leq 1 \quad \forall \{[ij], [uv]\} \in \boldsymbol{\chi}$$

➡ To force no-crossing cables in the solution.

Constraints – Second stage

$$\sum_{\substack{i \in \boldsymbol{N} \\ j \neq i}} \sum_{\omega \in \boldsymbol{\Omega}} \sum_{k \in \boldsymbol{K}} I_{ji}^{\omega,k} - I_{ij}^{\omega,k} + \delta_j^{\omega,k} = I_j^{\omega} \quad \forall j \in \boldsymbol{N}_\mathrm{w} \quad \forall \omega \in \boldsymbol{\Omega}$$

➡ Flow conservation. To ensure fully connected solutions.

STOCHASTIC COLLECTION SYSTEM DESIGN

Global optimization: Mixed Integer Linear Programming with stochasticity incorporated

Constraints – Tender: Linking the stages

$$I_{ij}^{\omega,k} - \frac{1000 \cdot V_n \cdot (\theta_i^{\omega,k} - \theta_j^{\omega,k})}{\sqrt{3} \cdot X_t \cdot d_{ij}} - M \cdot (1 - x_{ij,t}) - M \cdot r_{ij}^k \leq 0 \quad \forall [ij] \in \boldsymbol{E} \quad t \in \boldsymbol{T} \quad \forall \omega \in \boldsymbol{\Omega} \quad \forall k \in \boldsymbol{K}$$

➡ DC power flow.

$$-I_{ij}^{\omega,k} + \frac{1000 \cdot V_n \cdot (\theta_i^{\omega,k} - \theta_j^{\omega,k})}{\sqrt{3} \cdot X_t \cdot d_{ij}} - M \cdot (1 - x_{ij,t}) - M \cdot r_{ij}^k \leq 0 \quad \forall [ij] \in \boldsymbol{E} \quad t \in \boldsymbol{T} \quad \forall \omega \in \boldsymbol{\Omega} \quad \forall k \in \boldsymbol{K}$$

$$\sum_{t \in \boldsymbol{T}} u_t \cdot x_{ij,t} \cdot (1 - r_{ij}^k) \geq I_{ij}^{\omega,k}$$

➡ Cable capacity.

$$\sum_{t \in \boldsymbol{T}} -u_t \cdot x_{ij,t} \cdot (1 - r_{ij}^k) \leq I_{ij}^{\omega,k}$$

Stochastic collection system design

Strategies to simplify the problem

The presented MILP program presents a very complex structure: the binary investment and the continuous operation variables escalate exponentially in function of the problem size (WTs number, among others), and the scenario tree.

In order to simplify the problem, three strategies are adopted:

✓Exact: To reduce the number of system states $\boldsymbol{K}$, in order to find the representative system states set $\boldsymbol{K}'$.

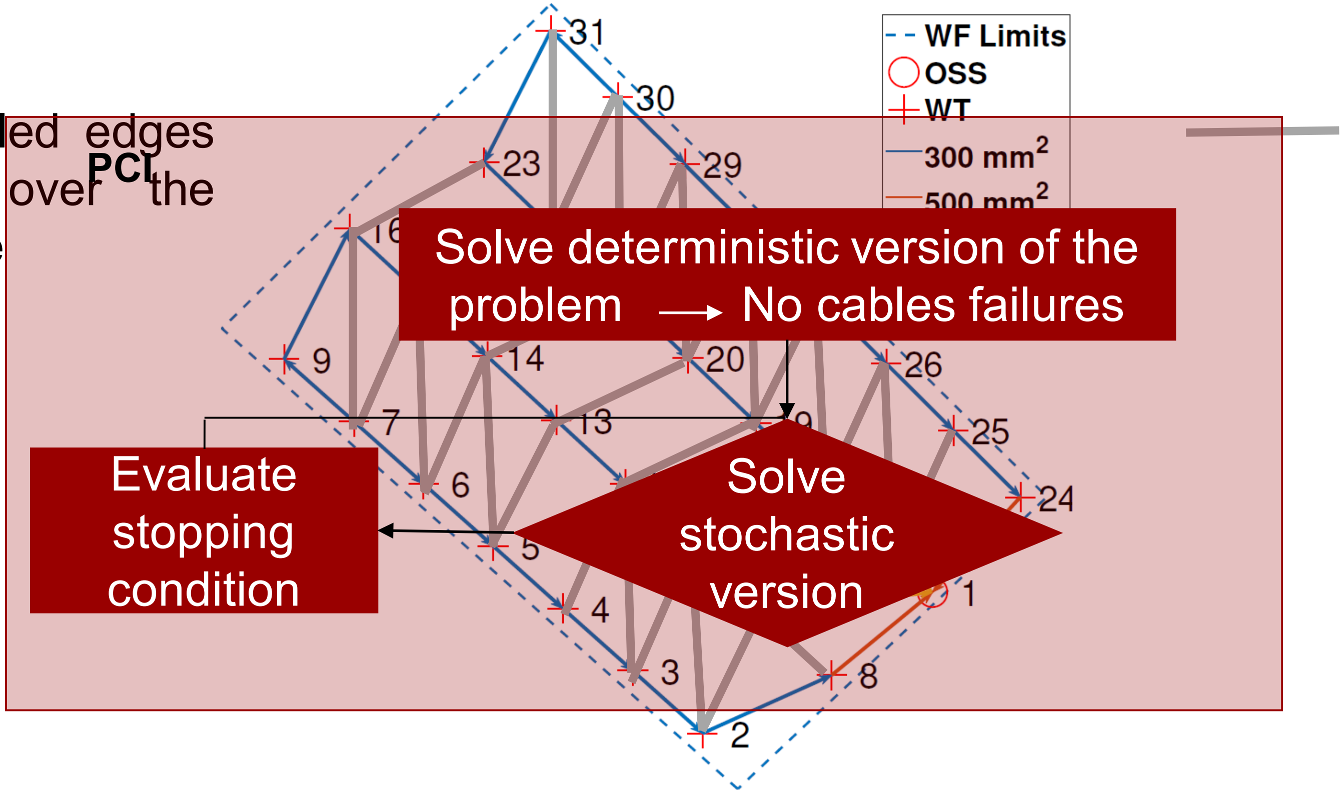
✓Approximate:

- Definition of the reliability level: Which edges subject to fail have a larger impact over the operation of the system?
- Relaxation of the DC power flow variables (voltages phases) and constraints. Implementation of a transportation power flow model.

Stochastic collection system design

Strategies to simplify the problem: Exact (Progressive Contingency Incorporation Algorithm)

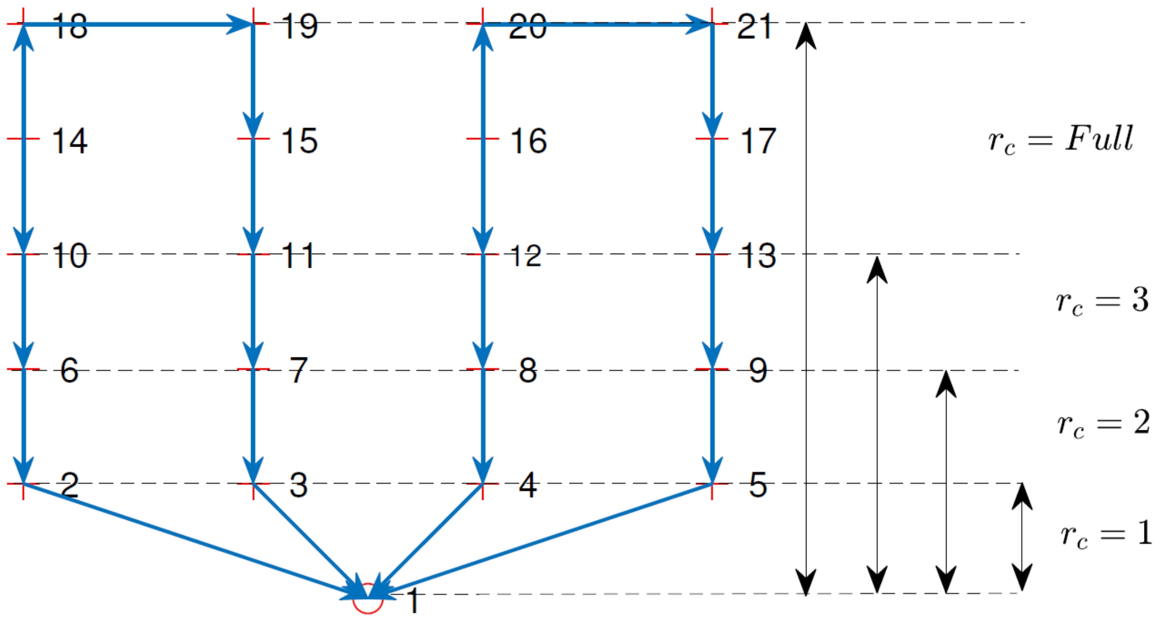
Failure of not-installed edges have no impact over the system performance



Not-installed edge

STOCHASTIC COLLECTION SYSTEM DESIGN

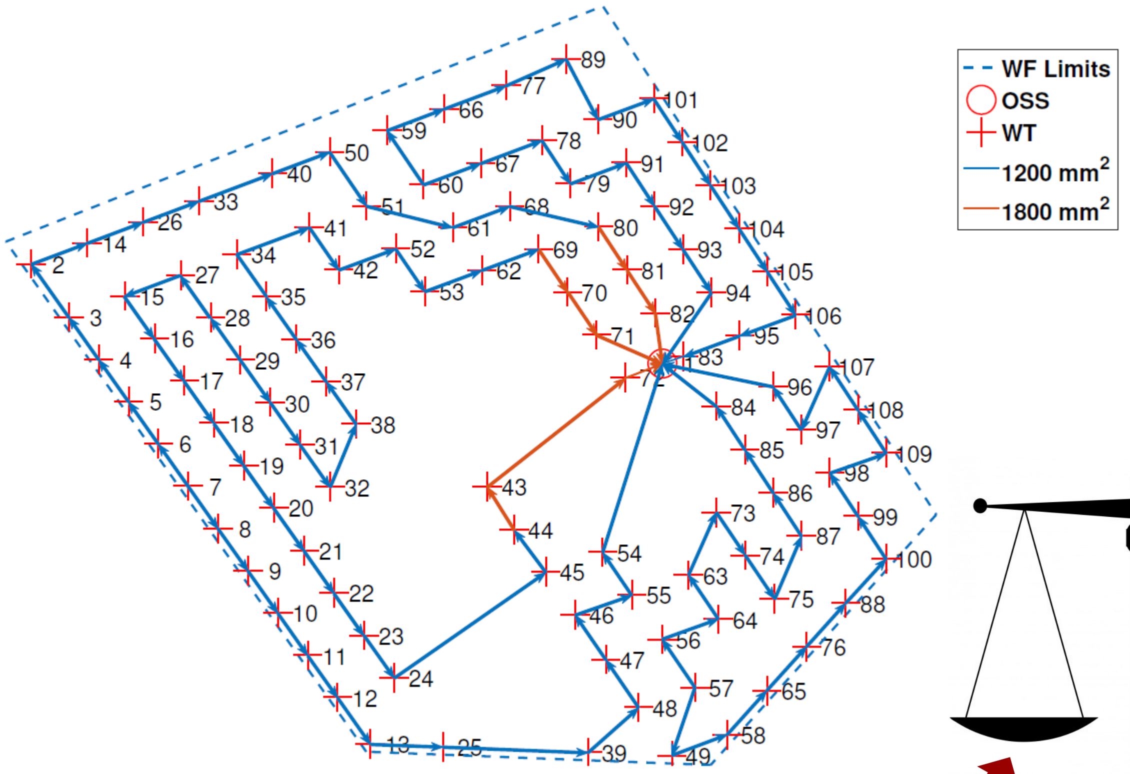
Strategies to simplify the problem: Approximate (Reliability level)



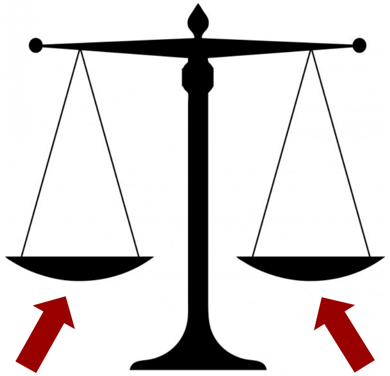
- ✓ Parameter r_c defines the degree of connection towards the OSS, so for example, r_c of 1 brings along the main feeders (rooted at 1) and r_c of 2 includes the last ones together with the feeders connected to the main ones, and so on for r_c>2.
- ✓ By means of this parameter, the model can be further relaxed for large instances. A reliability level equal to one would still represent at a large extent the consequences of all cables failures, as those main feeders are the one carrying the vast amount of energy compared to downstream connections.

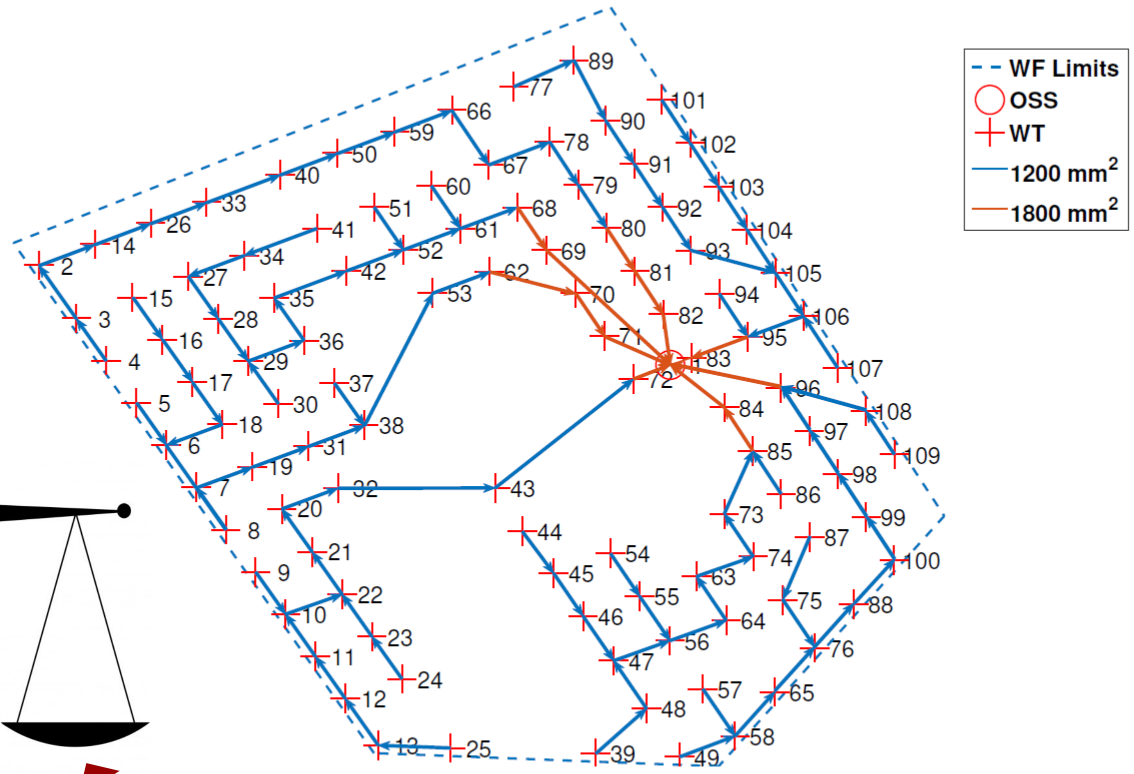
STOCHASTIC COLLECTION SYSTEM DESIGN

Radial+Star (Tree) vs Closed-loop solutions



(a) Closed-loop design for West of Duddon Sands with MTBF=178

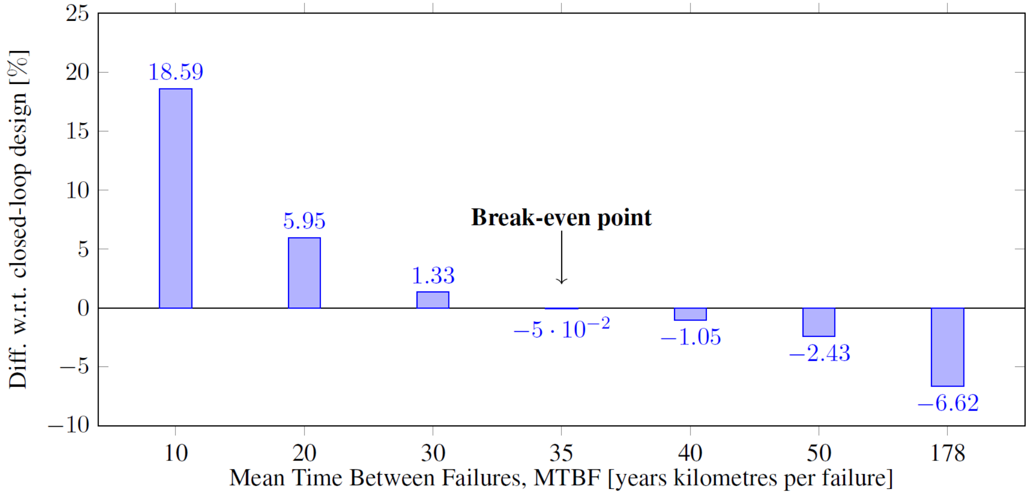




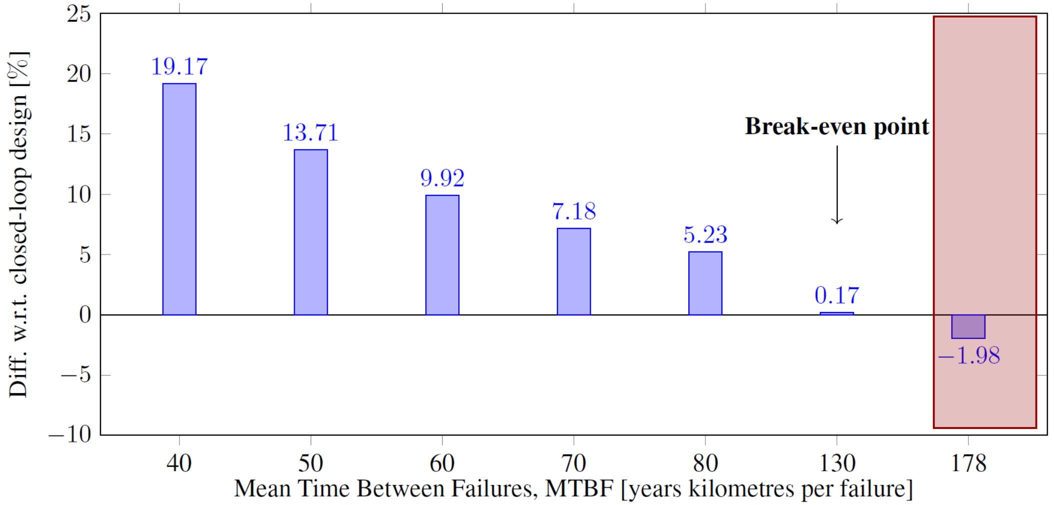
(b) Radial design for West of Duddon Sands

STOCHASTIC COLLECTION SYSTEM DESIGN

Results: Ormonde OWF (30 WTs @ 5 MW)



Comparison of topologies for $r_c = 1$



Comparison of topologies for full reliability

- ✓ The break-even point (where tree and closed-loop topology have same costs) moves to the right (higher MTBF) when considering full reliability level.
- ✓ For a MTBF of 178 (average value according to updated literature) and full reliability, a **tree** network is almost **2% cheaper** than a **closed-loop** network.

STOCHASTIC COLLECTION SYSTEM DESIGN

Results: Horns Rev 1 OWF (80 WTs @ 2 MW)

MTBF	Diff. in total expenses Eq. (1) [%]	Diff. in investment [%]	Diff. in operation [%]	Computing time closed-loop [min]
90	-0.80	-3.34	91.14	359
178	-2.01	-3.31	90.90	43

Comparison of topologies for $r_c = 1$

MTBF	Diff. in total expenses Eq. (1) [%]	Diff. in investment [%]	Diff. in operation [%]	Computing time closed-loop [h]
178	1.13	-3.43	83.01	2.47

Comparison of topologies for full reliability

✓For a MTBF of 178 (average value according to updated literature) and full reliability, a **tree** network is almost **1% more expensive** than a **closed-loop** network.

STOCHASTIC COLLECTION SYSTEM DESIGN

Results: West of Duddon Sands OWF (108 WTs @ 3.6 MW)

MTBF	Diff. in total expenses Eq. (1) [%]	Diff. in investment [%]	Diff. in operation [%]	Computing time closed-loop [h]
178	-0.67	-1.65	96.46	0.90

Comparison of topologies for $r_c = 1$

- ✓For a MTBF of 178 (average value according to updated literature) and $r_c = 1$, a **tree** network is only **0.67% cheaper** than a **closed-loop** network.
- ✓Additional experiments for full reliability and MTBF of 178 failed due to lack of computational resources (RAM memory).
- ✓One could reasonably expect that for full reliability the closed-loop topology pays off for this OWF given the trend presented in previous cases. More wind turbines with higher power ratings than HR1!

Summary

- Electrical network design for offshore wind at early stages of optimized design

- For **export cables**, given the stochastic nature of the wind power, a shift from deterministic to *stochastic* (with reliability analysis) design approach is needed
- An *optimization framework* for obtaining the best *trade-off* between *investment*, *losses* and *reliability* has been proposed.

- **Collector system design** will also move towards optimization methods that include stochasticity (reliability). This depends on the *availability of methods to perform computational optimization under uncertainty*.
- Results show that the profitability of either a tree or closed-loop topology *depends strongly on the project size and WT rating*.
- The paradigm of the electrical network design of (very large) OWFs needs to become more tailored upon the *stochastic nature of several involved aspects: wind power, components failures*. Optimization pushes designs to the limits, *reliable (and cheap) designs must be provided*.

Further readings

[J1] J.A. Pérez-Rúa, and N. A. Cutululis, “Electrical Cable Optimization in Offshore Wind Farms - A review”, in IEEE Access, Vol. 7, 85796–85811, July 2019, https://doi.org/10.1109/ACCESS.2019.2925873.

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[J3] J.A. Pérez-Rúa, M. Stolpe, K. Das, and N. A. Cutululis, “Global Optimization of Offshore Wind Farm Collection Systems”, in IEEE Transactions on Power Systems, Vol. 35, No. 3, 2256–2267, May 2020, https://doi.org/10.1109/tpwrs.2019.2957312.

[J4] J.A. Pérez-Rúa, M. Stolpe, and N. A. Cutululis, “Integrated Global Optimization Model for Electrical Cables in Offshore Wind Farms”, in IEEE Transactions on Sustainable Energy, Vol. 11, No. 3, 1965–1974, July 2020, https://doi.org/10.1109/TSTE.2019.2948118.

[J5] J.A. Pérez-Rúa, S. Lumbreras, A Ramos, and N. A. Cutululis, “Reliability-based Topology Optimization for Offshore Wind Farm Collection System”, Under Review in Wind Energy, April 2020.

[C1] J.A. Pérez-Rúa, K. Das, and N. A. Cutululis, “Lifetime estimation and performance evaluation for offshore wind farms transmission cables”, in Proceedings of the 15th IET International Conference on AC and DC Power Transmission (ACDC 2019), Coventry, UK, 5th–7th February 2019, https://doi.org10.1049/cp.2019.0062.

[C2] J.A. Pérez-Rúa, K. Das, and N. A. Cutululis, “Improved Method for Calculating Power-Transfer Capability Curves of Offshore Wind Farms Cables”, in Proceedings of the 2019 CIGRE International Symposium, Aalborg, Denmark, 4th–7th Jun 2019.

[C3] J.A. Pérez-Rúa, D. Hermosilla, K. Das, and N. A. Cutululis, “Heuristics-based design and optimization of offshore wind farms collection systems”, in Journal of Physics: Conference Series, Vol. 1356, 012014, 16th Deep Sea Offshore Wind R&D conference, Trondheim, Norway, 16th–18th January 201 https://doi.org/10.1088/1742-6596/1356/1/012014.

[C4] D. Hermosilla, J.A. Pérez-Rúa, K. Das, and N. A. Cutululis, “Metaheuristic-based Design and Optimization of Offshore Wind Farms Collection Systems”, in Proceedings of the 13th IEEE PES PowerTech Conference, Milan, Italy, 23rd–27th June 2019, https://doi.org/10.1109/PTC.2019.8810583.

[C5] J.A. Pérez-Rúa, S. Lumbreras, A. Ramos, and N. A. Cutululis, “Closed-Loop Two-Stage Stochastic Optimization of Offshore Wind Farm Collection System”, accepted in Journal of Physics: Conference Series, EAWE TORQUE 2020, Delft, Netherlands, https://arxiv.org/abs/2003.06598.