North Sea Energy Hub & multiDC - Large-Scale Offshore Wind Power Integration

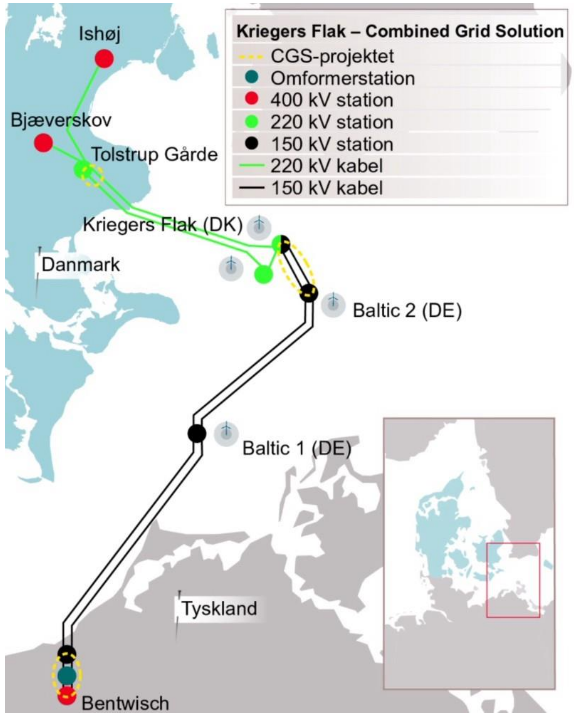
Tilman Weckesser

Three main drivers

- 100% renewables
- 100% inverter-connected devices
- HVDC Lines and Grids

New approaches for wind integration

Kriegers Flak: First interconnection in the world to integrate off-shore wind



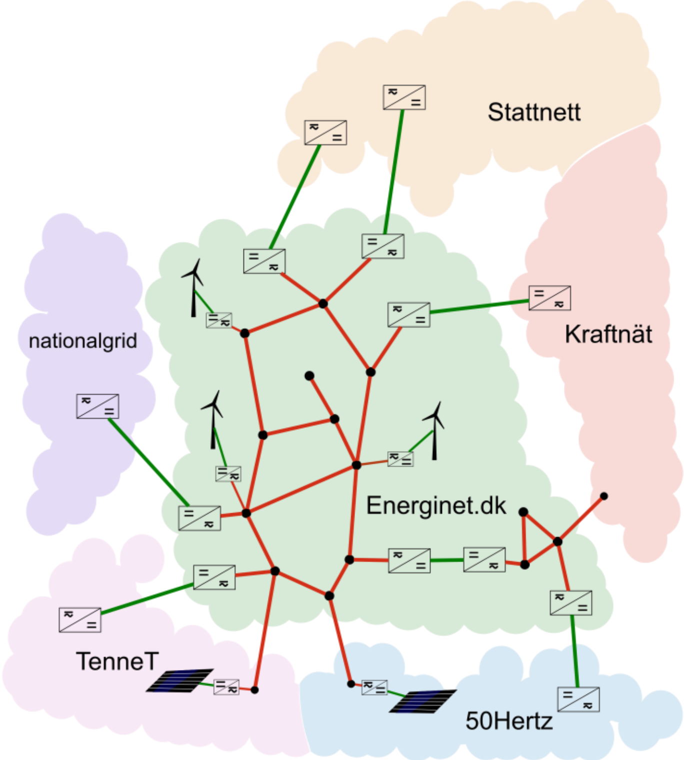
North Sea Wind Power Hub: First hub-and-spoke topology for offshore wind

Denmark is unique in being involved in two first-of-their-kind projects

multiDC

Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grids

- Innovation Fund Denmark Grand Solutions
- Partners:
  - **Two neighboring TSOs:** Energinet, Svenska kraftnät
  - **Three universities**: DTU, KTH, Univ. of Liege
  - **One major manufacturer**: Hitachi ABB Power Grids
  - Advisory Board: RTE, Nordic RSC
- **3.5 million EUR** (25.7 million DKK)
- **4 years**; Start May 1, 2017, ends in 2021



North Sea Energy Hub Feasibility Study (NSEH)

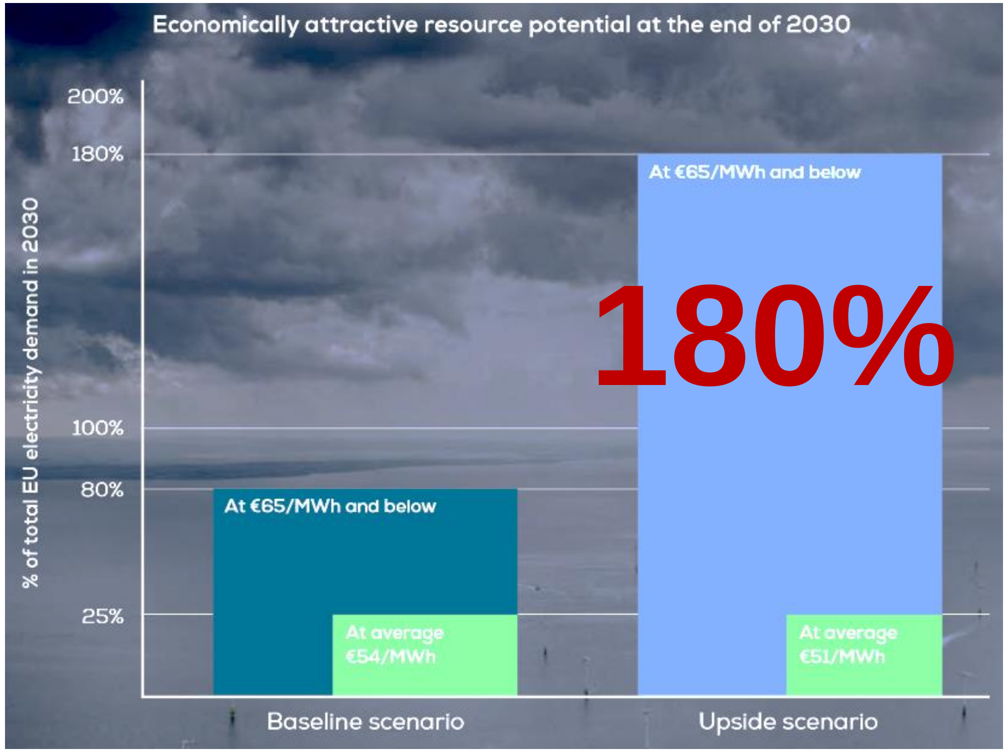
- **Funded by EUDP**
- **Partners:**
  - DTU
  - Energinet
  - Dansk Industri
- **2.2 million DKK**
- **1.5 years**

The Team

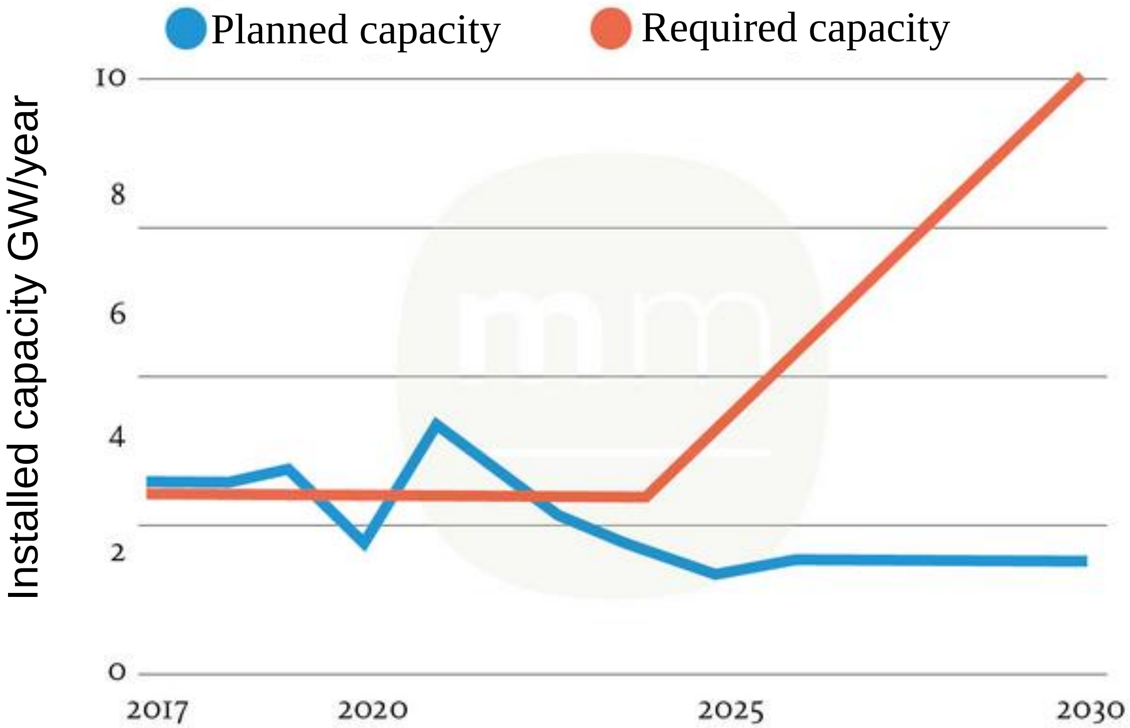
20 persons – 3 countries – 10 nationalities

What is the North Sea Energy Hub? (NSEH)

Europe has the potential and the need to add significant amount of offshore wind in the near future



Source: WindEurope. "Unleashing Europe's offshore wind potential A new resource assessment". June 2017. https://windeurope.org/wp-content/uploads/files/about-wind/reports/Unleashing-Europes-offshore-wind-potential.pdf



Source: Analysis by Ecofys for North Sea Wind Power Hub on offshore wind capacity additions required to meeting Paris Climate ambitions

Offshore wind development could significantly increase through hub concept

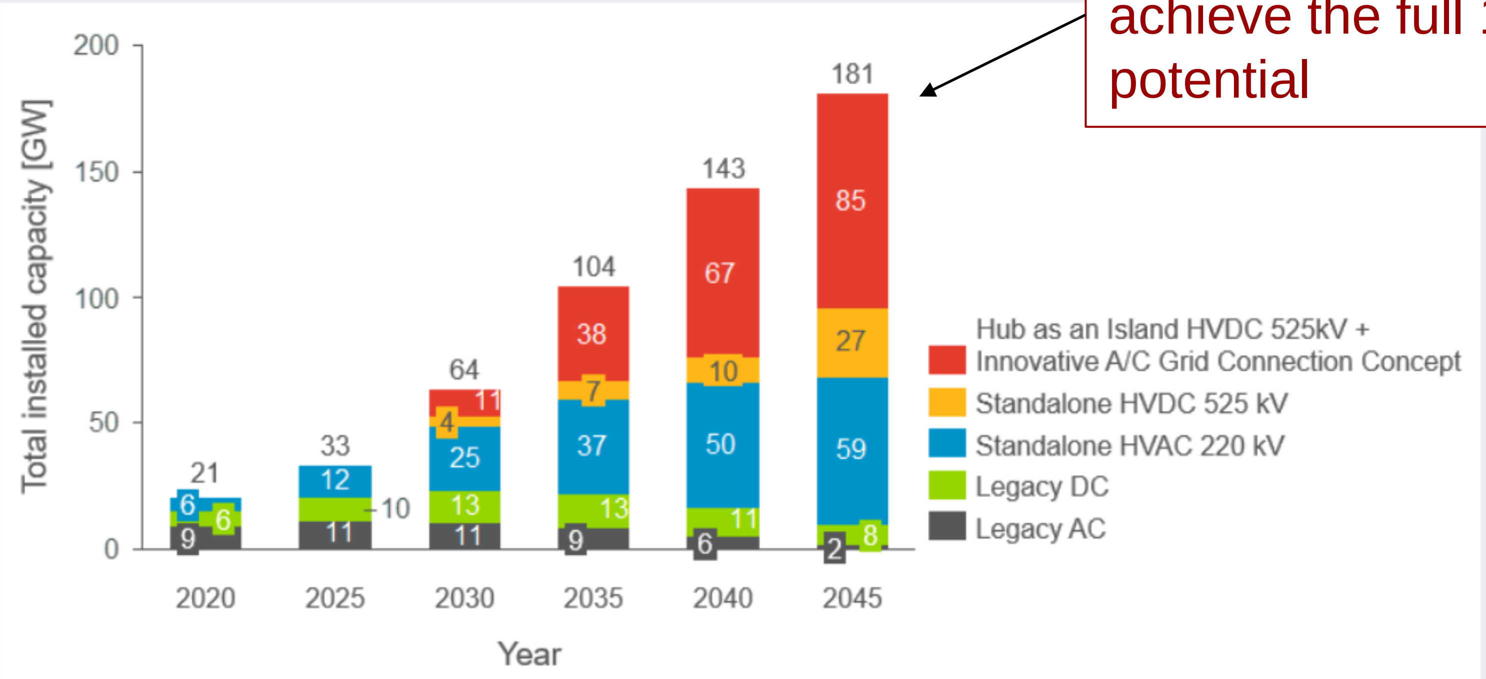


Figure 4 Installed wind power capacity in the North Sea broken down to the different transmission asset concepts for the ICRO approach. Legacy AC refers to currently operational and planned AC radially connected offshore wind farms. Legacy DC refers for currently installed and planned DC connected (German) offshore wind farms. The remaining grid connection concepts refer to Table 1

NSEH: necessary to achieve the full 180 GW potential

Hub-and-Spoke concept:
30% lower costs for electrical infrastructure compared with radial connections (AC or DC)

Sources:

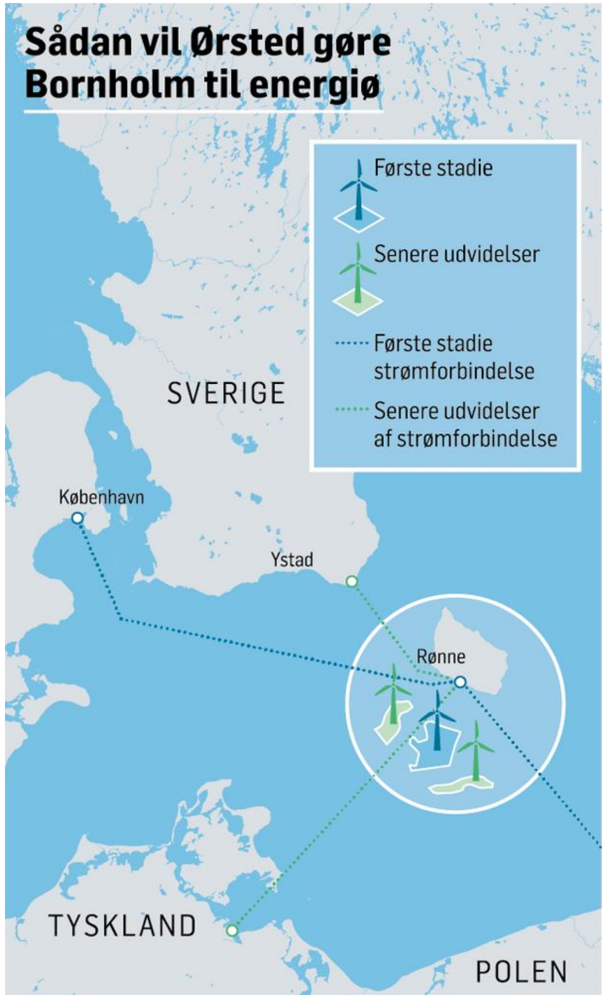
North Sea Wind Power Hub, “Modular Hub and Spoke” , 2017

North Sea Wind Power Hub, “Concept Paper 4 – The Benefits” , 2019, https://northseawindpowerhub.eu/sites/northseawindpowerhub.eu/files/media/document/Concept_Paper_4-The-benefits.pdf

North Sea Wind Power Hub

The Baltic Sea Energy Island

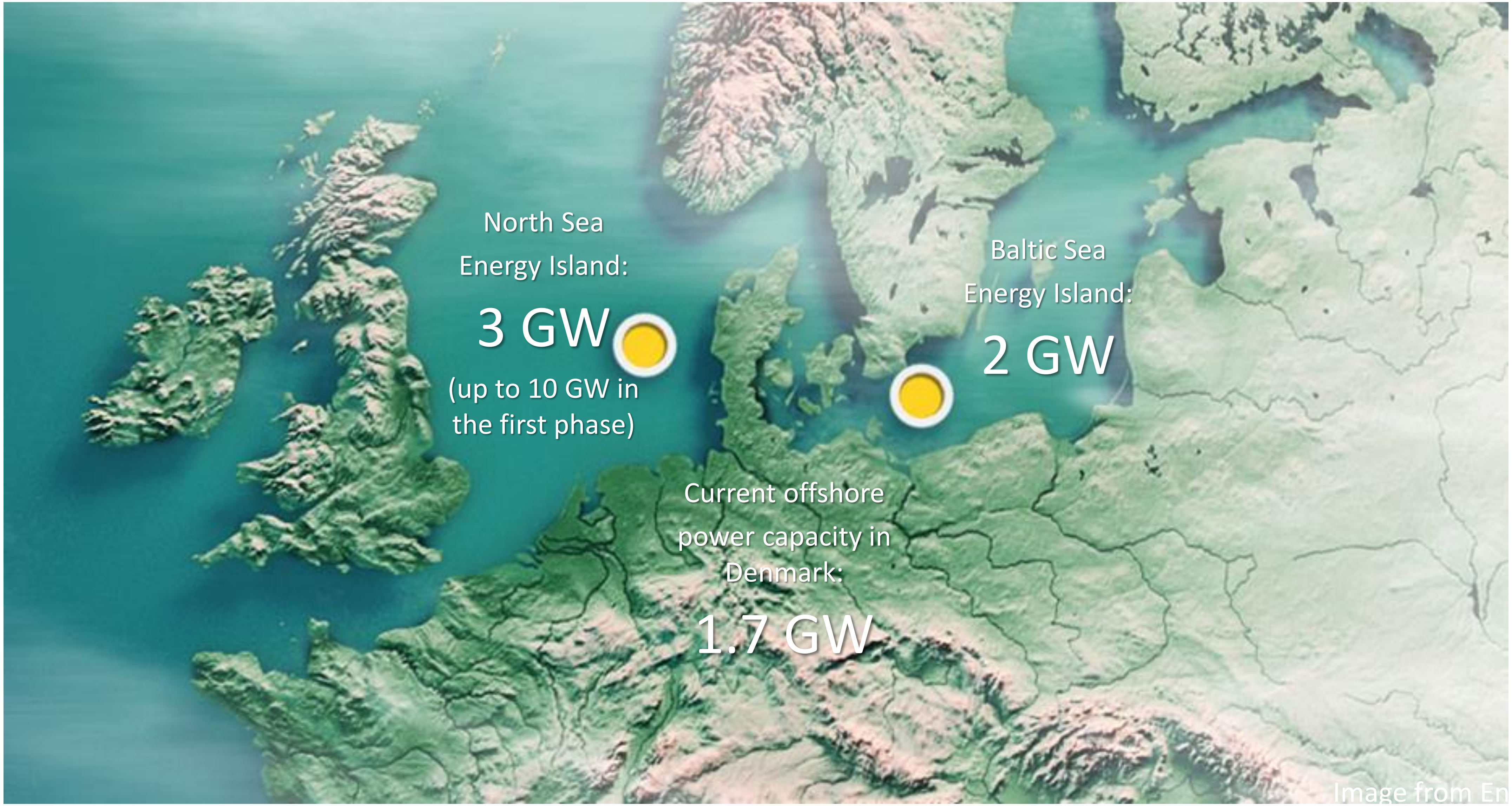
Proposal by Ørsted A/S



- **Bornholm: existing Danish island with approx. 40,000 residents**
- **Area equal to the size of Corfu (Kerkyra), Greece**
- **1 – 5 GWs offshore wind farms**
- **HVDC converters on the island (Bornholm)**
- **Power-to-Gas on the island**
- **Connection to Denmark, Sweden, Germany, and Poland**

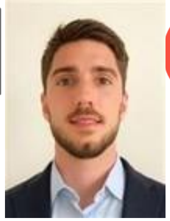
Source: https://politiken.dk/klima/art7512833/Gigantisk-vindmøllepark-ud-for-Bornholm-kan-blive-et-grønt-gennembrud-for-Danmark

Danish Energy Islands 2030



Offshore Energy Hubs: Open Questions


Georgios

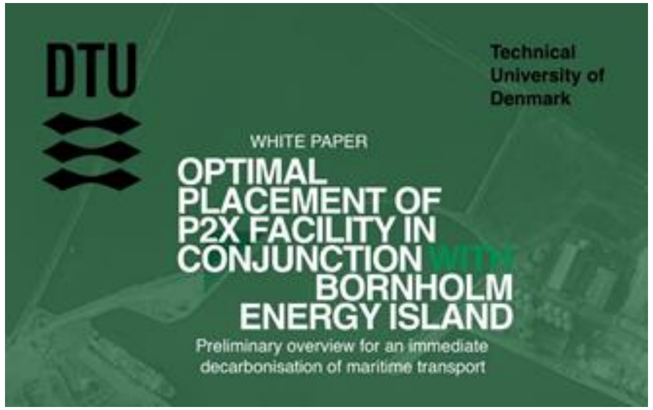

Andrea


Matas


Brynjar


Alessandro

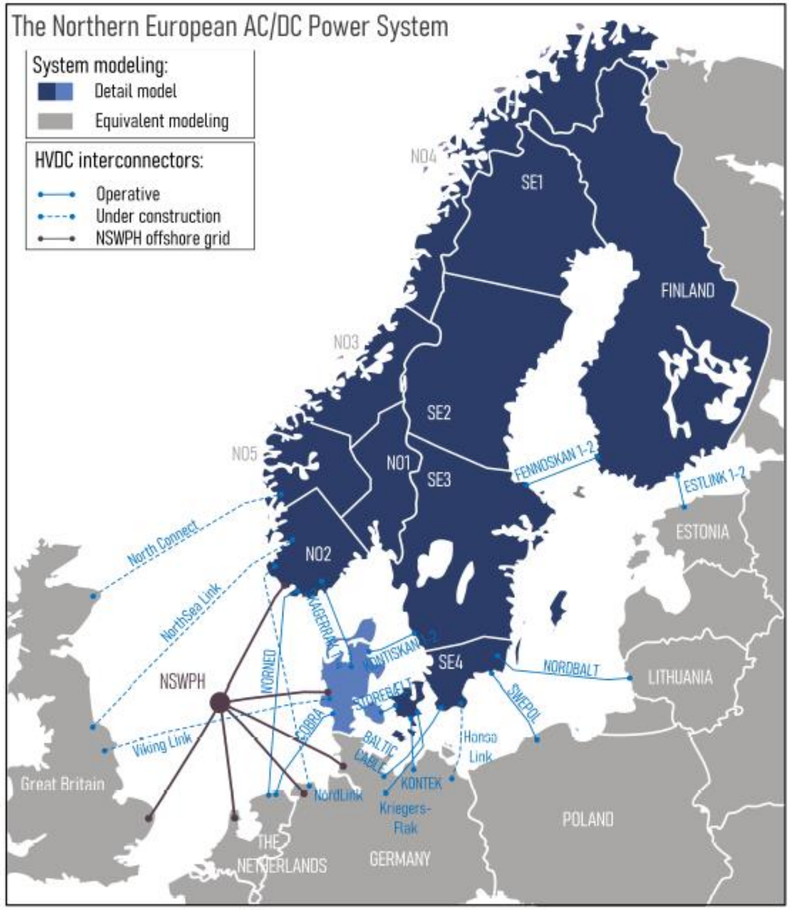
1. **What is the optimal topology for the Offshore Hub?**
   - DC vs AC grids
2. **How to ensure secure operation of the Offshore Hubs?**
   - Zero-inertia; requirements for grid forming converters to ensure stability;
   - RMS vs EMT
3. **Impact on Onshore Grids**
   - Dimensioning incident; sharing reserves among asynchronous areas (Nordics, Continental Europe, UK); Adaptive Frequency Droops; Hub Master Controller
4. **Impact on Electricity Markets**
   - How do prices evolve across Europe; how is the cycling of conventional generators affected
5. **Need for Storage: Hydrogen**
   - Optimal placement; technoeconomic assessment for the expected Levelized Cost of Electricity and Hydrogen

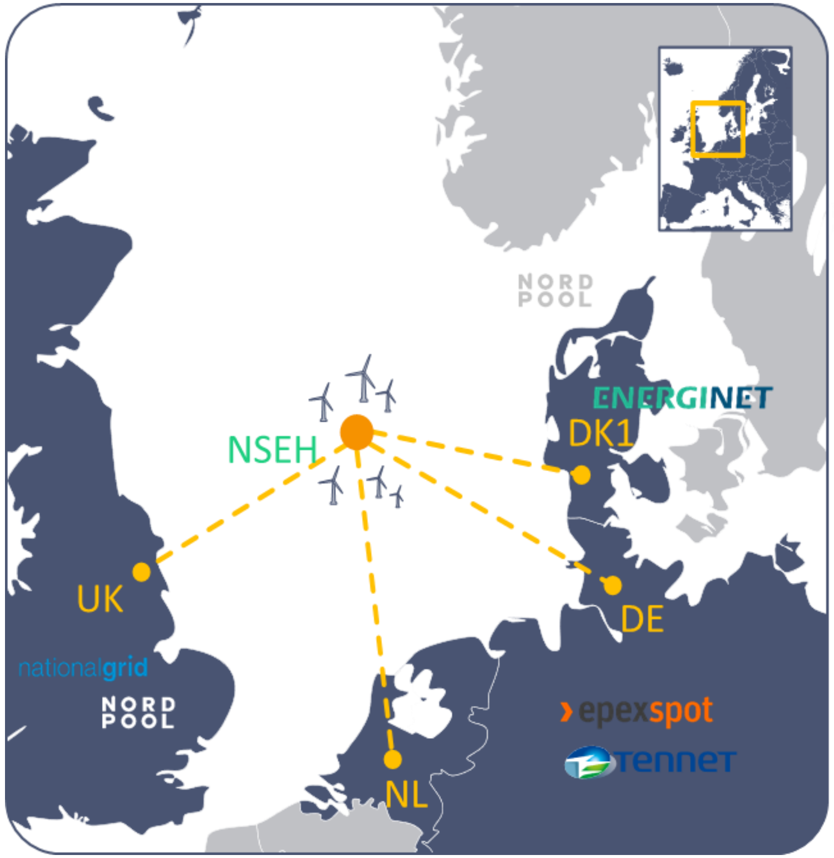


Open-source models

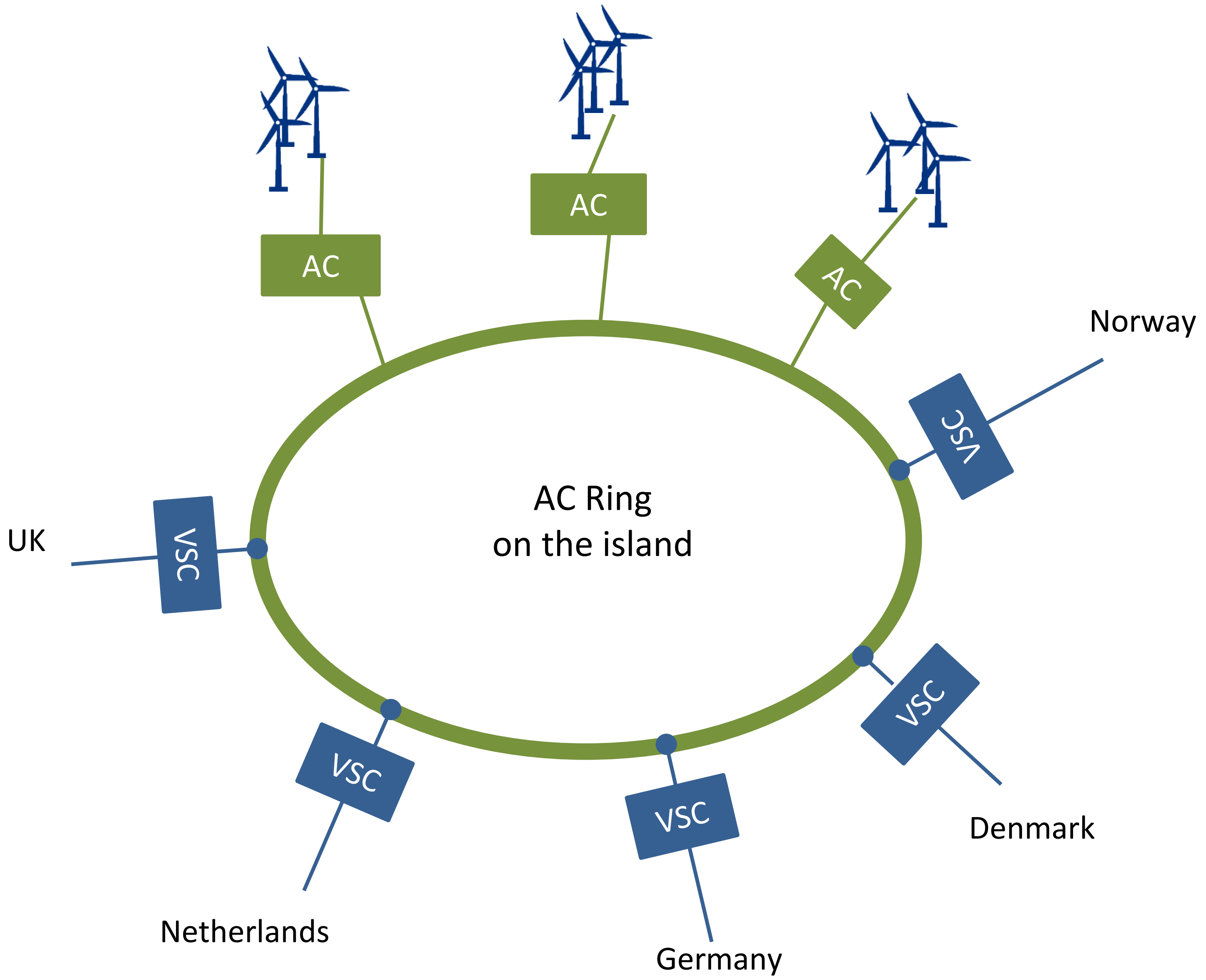
Georgios Andrea Matas Brynjar

- **Nordics+Continental Europe+UK/Ireland**
- **Dynamics**
- **Markets**
  - Andrea Tosatto. European transmission and market models. GitHub repository, 2021. Available: https://github.com/antosat/European-Transmission-and-Market-Models/.

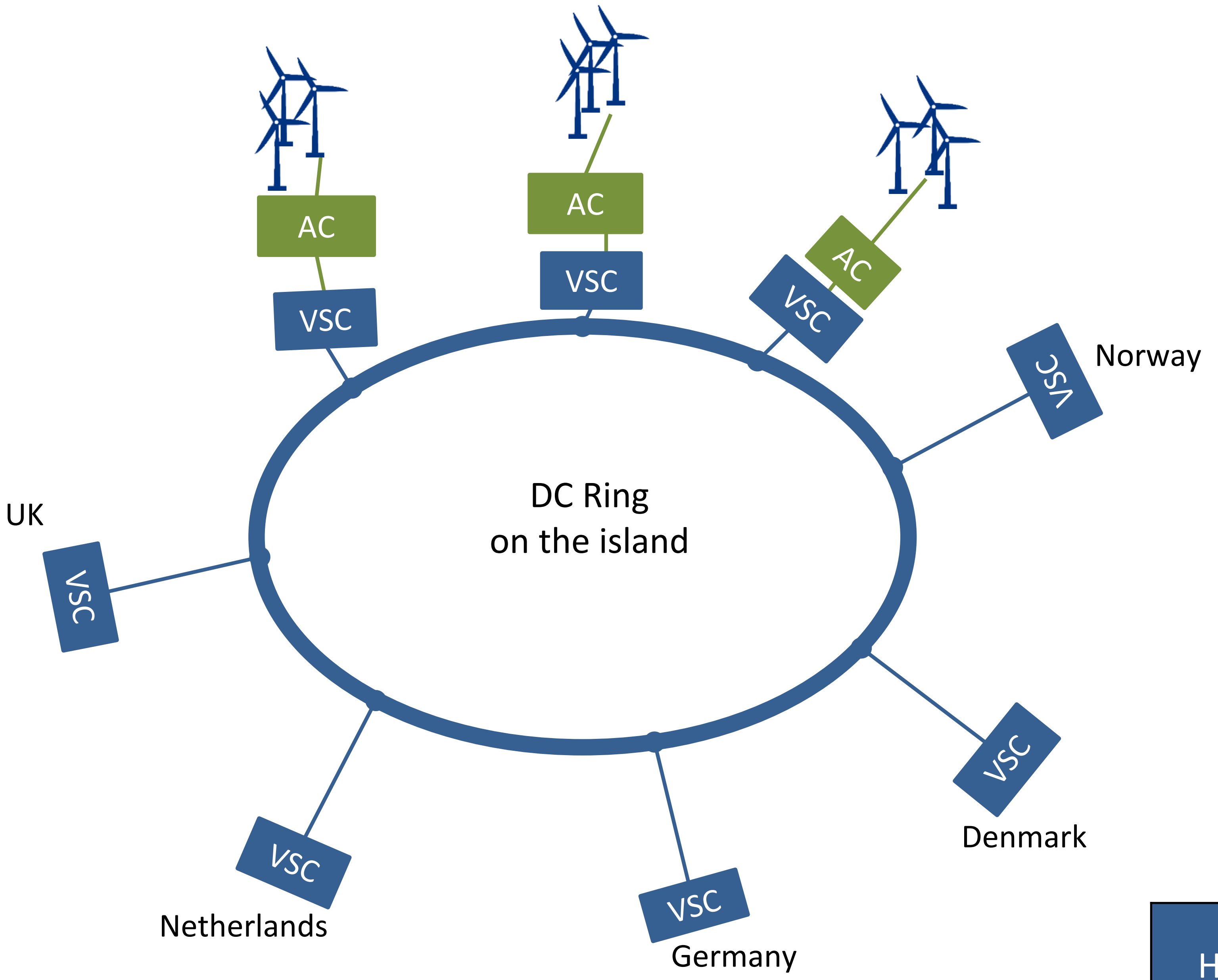




Question #1:
What is the optimal topology for the North Sea Wind Power Hub?



AC	50 Hz
	Low-frequency AC (16.67 Hz)
HVDC	Point-to-point HVDC



But: No commercial HVDC Breaker yet

Impossible to build a DC grid without protection

HVDC	Multi-terminal HVDC Grid

For now: Focus on the AC ring Challenges and Opportunities

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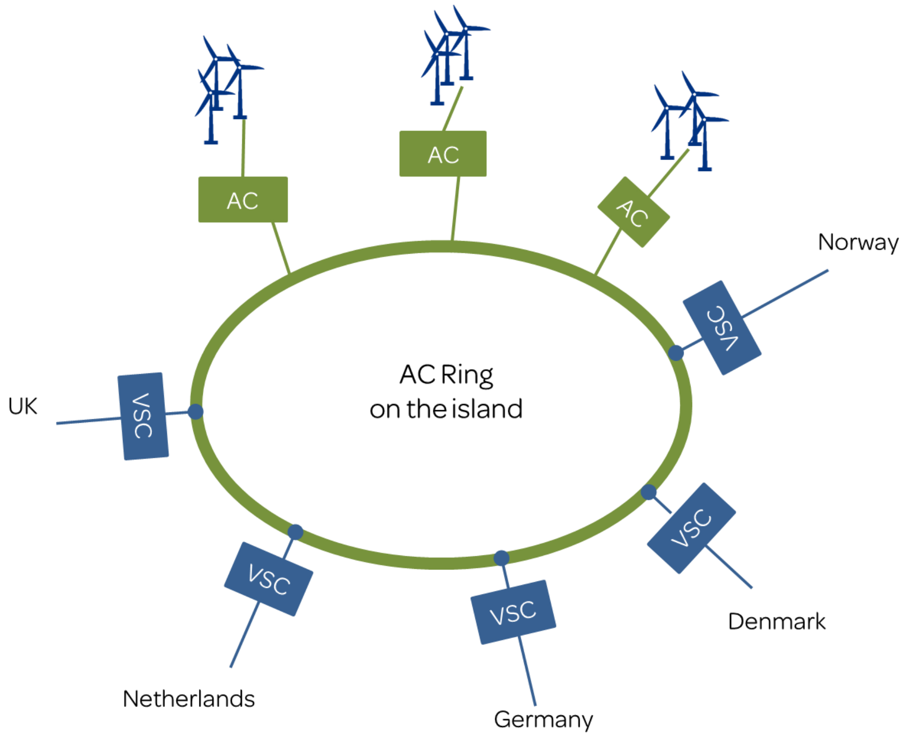
- **AC Ring configuration**
  - Zero- or Low-inertia
  - 50 Hz or Low frequency AC

- **How to guarantee N-1 security?**
  - Coordination of VSC converters
  - What controls are needed?

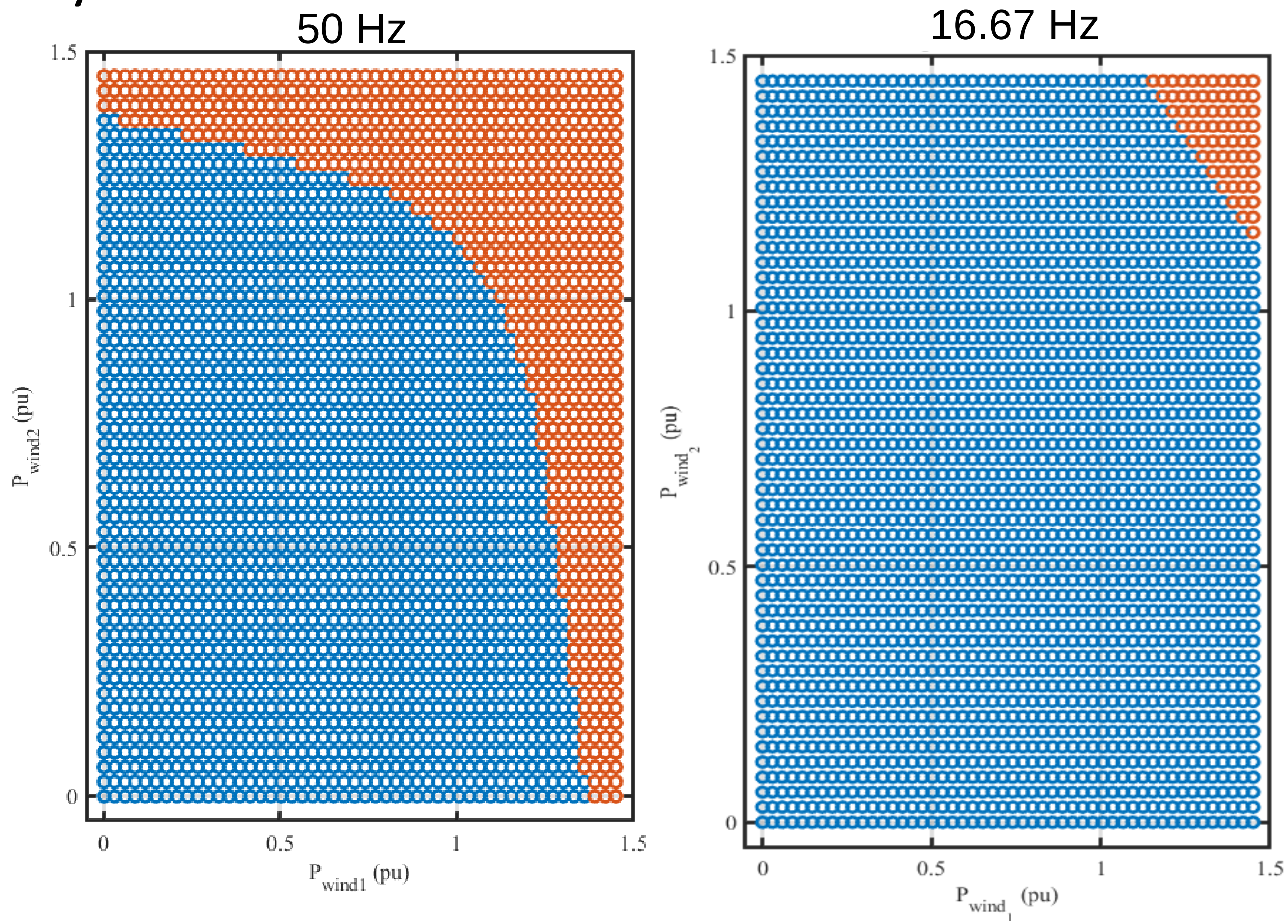


Insight #1: Low Frequency AC has a larger stability region and allows longer distances, but costs and weight of transformers may cancel out the benefits

- **16.67 Hz** leads to larger stability region than 50 Hz

But:

- The costs for 16.67Hz transformers are 3x higher
- The weight for 16.67Hz transformers is 3x higher



Further readings: Misyris, G., Van Cutsem, T., Moller, J., Dijokas, M., Renom Estragués, O., Bastin, B., Chatzivasileiadis, S., Nielsen, A., Weckesser, T., Ostergaard, J., & Kryezi, F. North Sea Wind Power Hub: System Configurations, Grid Implementation and Techno-economic Assessment. Proc. CIGRE 2020,

Zero-inertia vs low-inertia systems

multiDC

To different AC configurations

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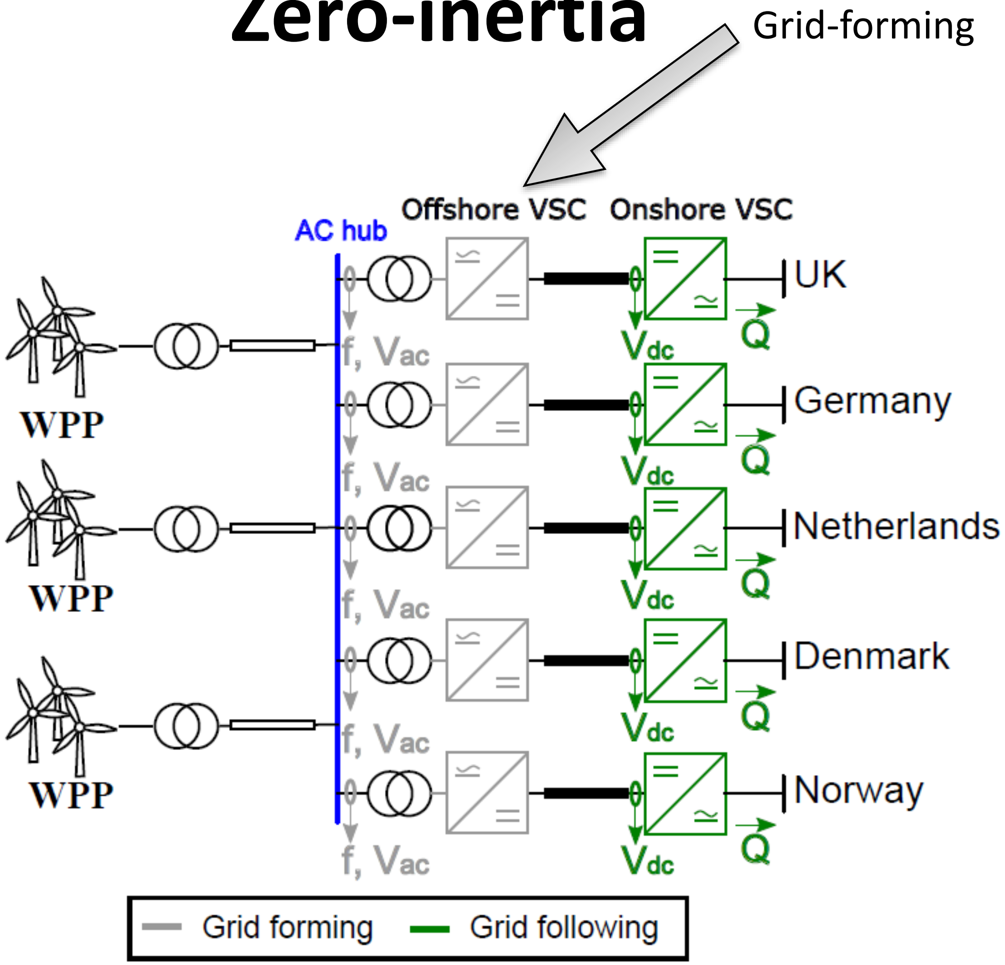
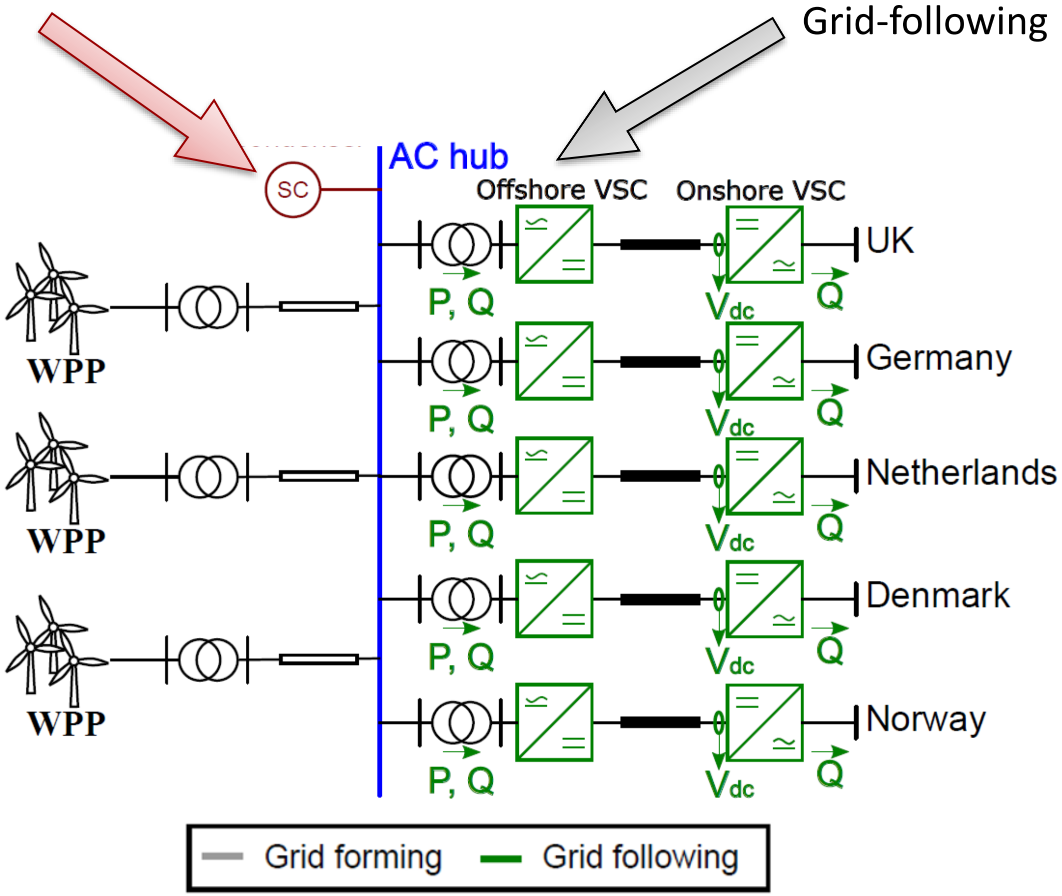
Zero-inertia



Low-inertia



Further readings: Misyris, G., Van Cutsem, T., Moller, J., Dijokas, M., Renom Estragués, O., Bastin, B., Chatzivasileiadis, S., Nielsen, A., Weckesser, T., Ostergaard, J., & Kryezi, F. North Sea Wind Power Hub: System Configurations, Grid Implementation and Techno-economic Assessment. Proc. CIGRE Technical Exhibition 2020,

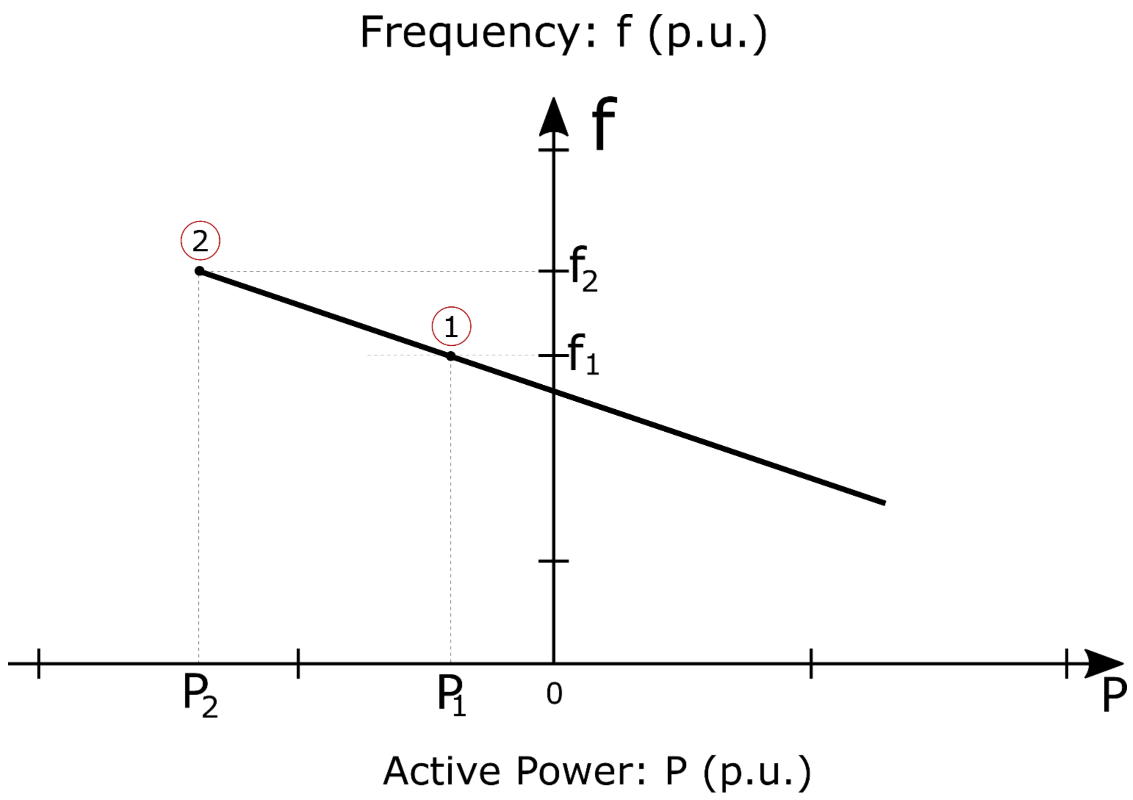
Question #2:

How to ensure secure operation of the offshore hub?

How to regulate the frequency in the offshore hub?

- **Frequency droop control for offshore converters**
  - Power transfer increases as the frequency increases

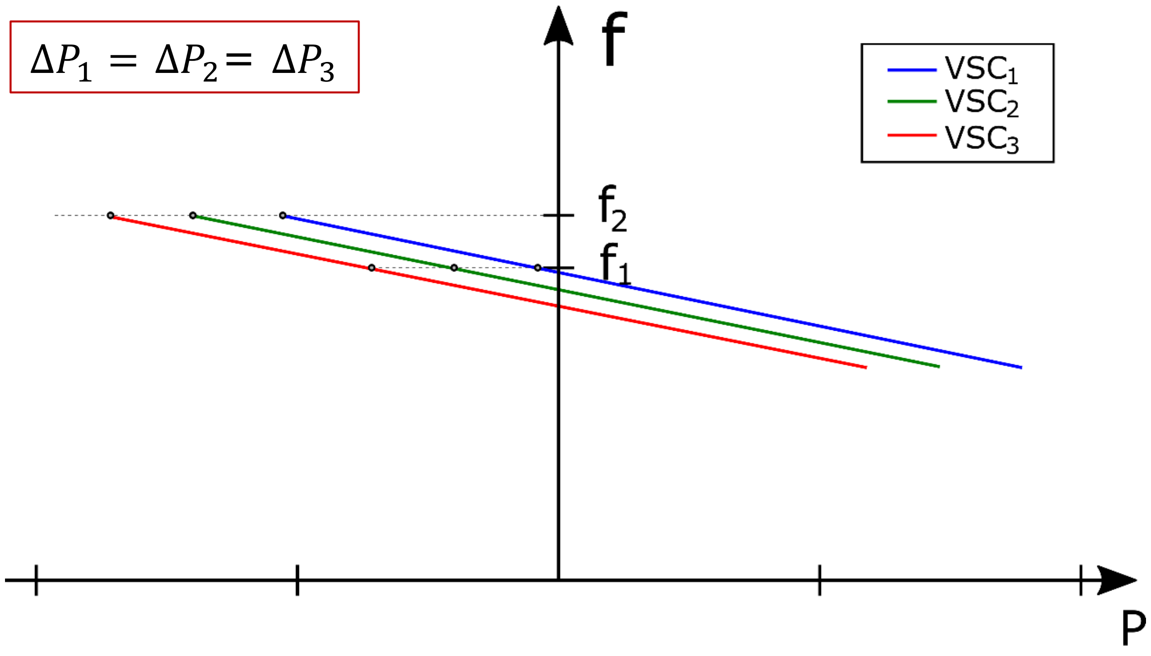
- **Allows multiple converters to operate in parallel**
  - Any power imbalance is shared among the converters
  - Ratio of frequency droops determine the power output of the offshore converters



Power sharing strategies in multiple VSC-HVDC systems

Equal frequency droops

$\Delta P_1 = \Delta P_2 = \Delta P_3$

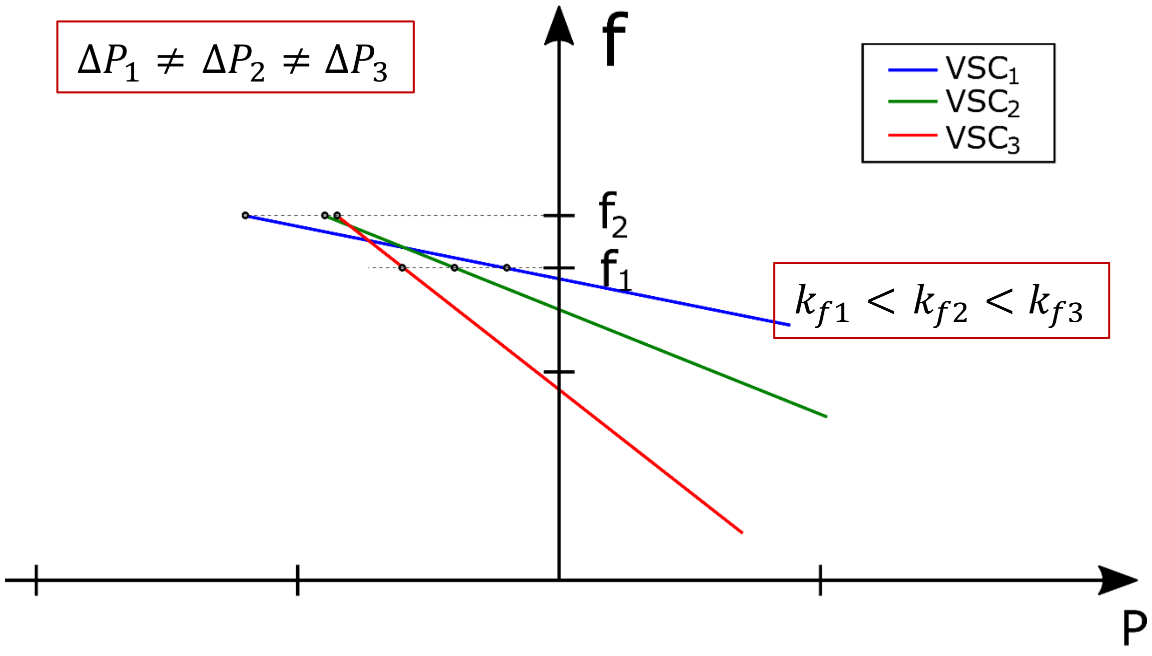


VSCs share equally any power imbalance in the offshore system

Different frequency droops

$\Delta P_1 \neq \Delta P_2 \neq \Delta P_3$

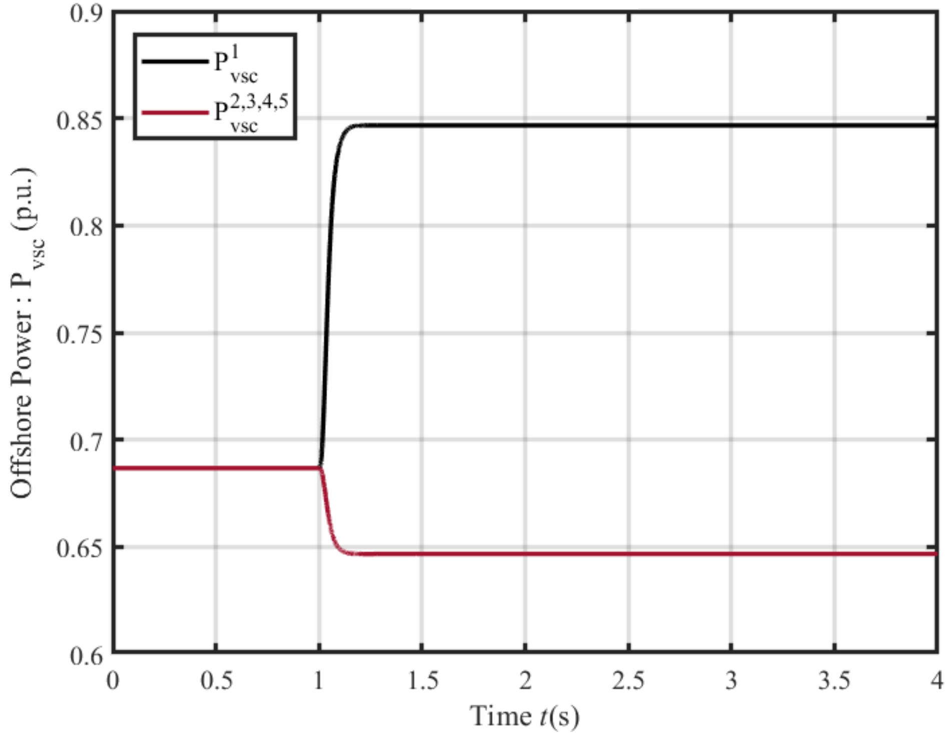
$k_{f1} < k_{f2} < k_{f3}$



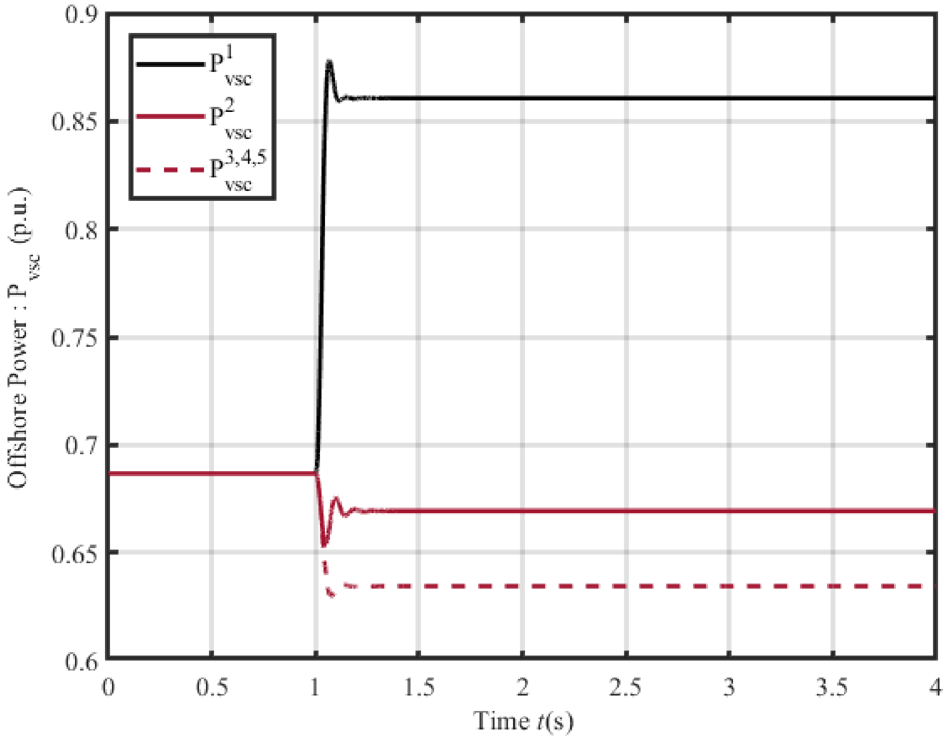
Different power sharing based on the frequency droop values

Insight #2: Equal frequency droops perform better

Equal frequency droops



Different frequency droops



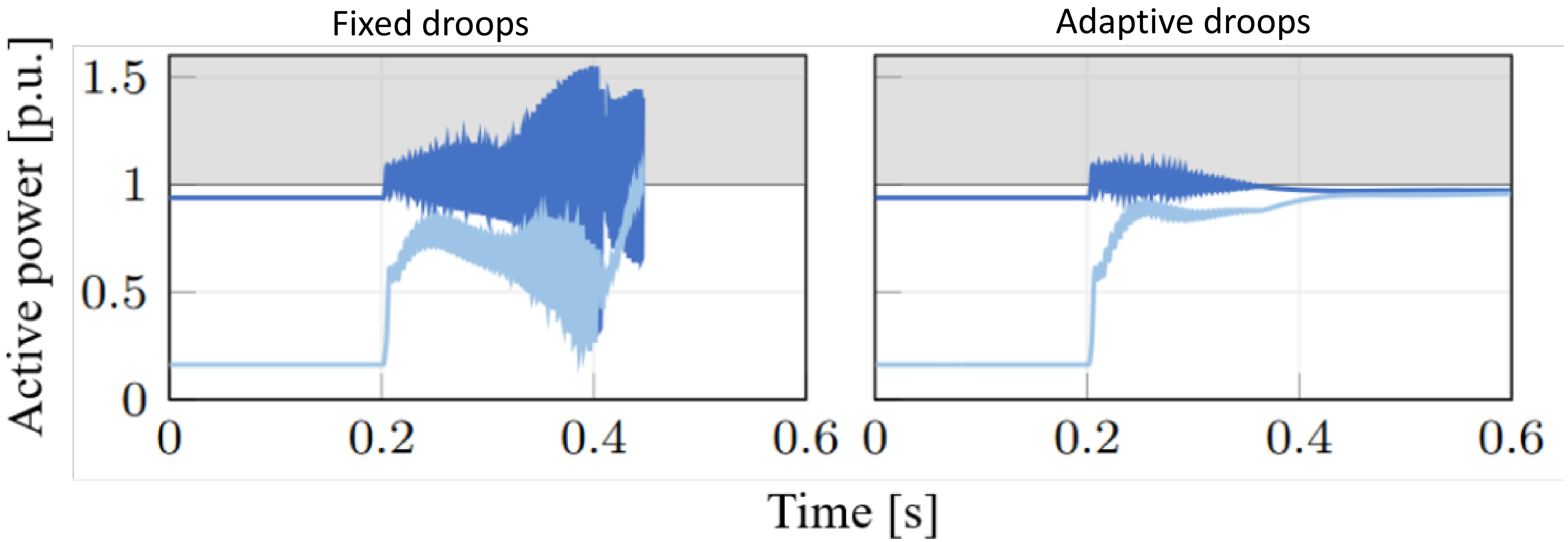
- Smooth power response – **No overshoot**
- Better power quality

Power oscillations between the offshore converters

Further reading: G. S. Misyris, A. Tosatto, S. Chatzivasileiadis and T. Weckesser, Zero-inertia Offshore Grids: N-1 Security and Active Power Sharing, . arXiv preprint arXiv:2009.11039. 2021.

Fixed or adaptive droops

- **Fixed droops:**
  - Frequency droops are set once and for all
  - When operating close to the limits of the converter a disturbance may lead to saturation of the converter → Loss of synchronism
- **Adaptive droops:**
  - Frequency droops are adjusted depending on the converters operating point
  - Generally equal droops are used
  - When converter close to its limit, an adaptive droop is chosen to avoid saturation in case of a disturbance



Insight #3: Adaptive droops to ensure N-1 security and improve utilization of wind power

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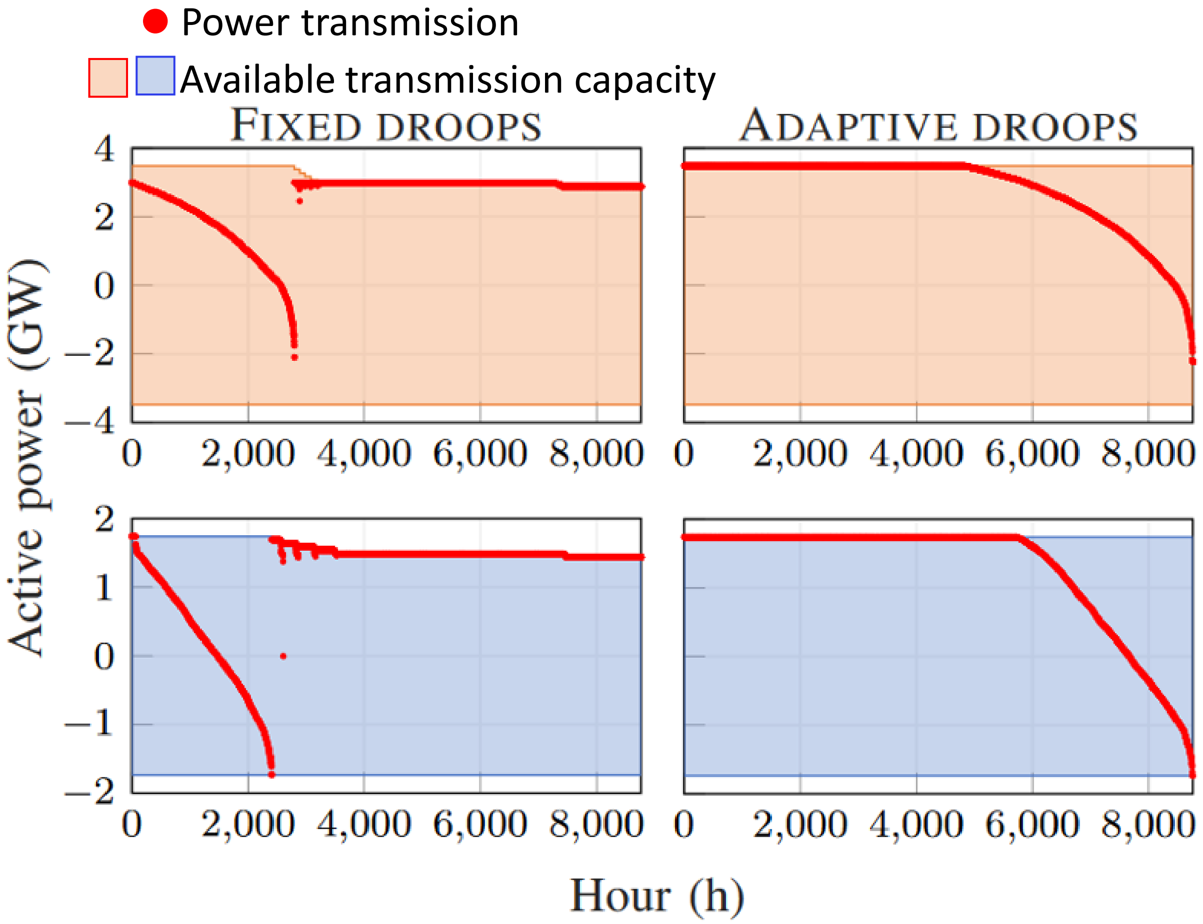
- **Fixed droops:**
  - To ensure N-1 security, during some hours, the available transmission capacity would need to be descreased (shaded area)
- **Adaptive droops:**
  - When a converters power transmission is close to its limit, the frequency droop is rescheduled to ensure N-1 secruity

→ Better utlization of the transmission capacity and the available wind power resources



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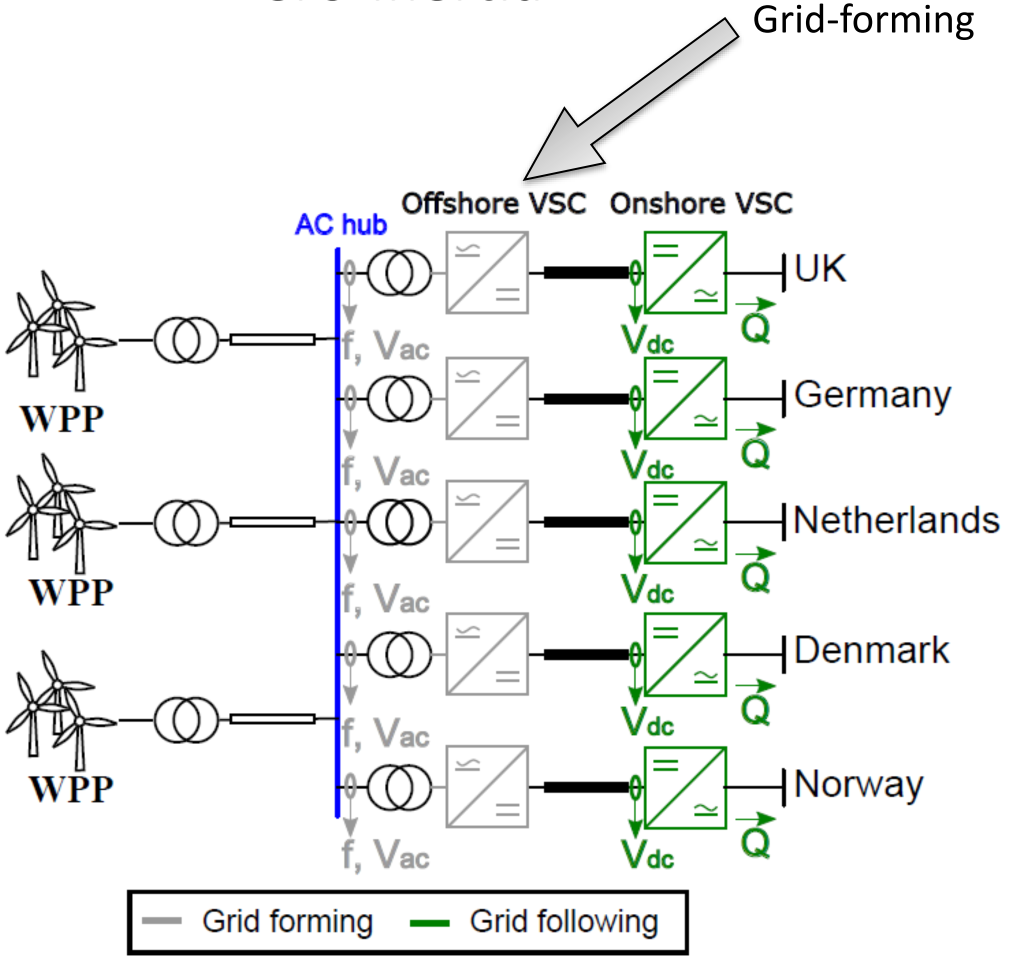
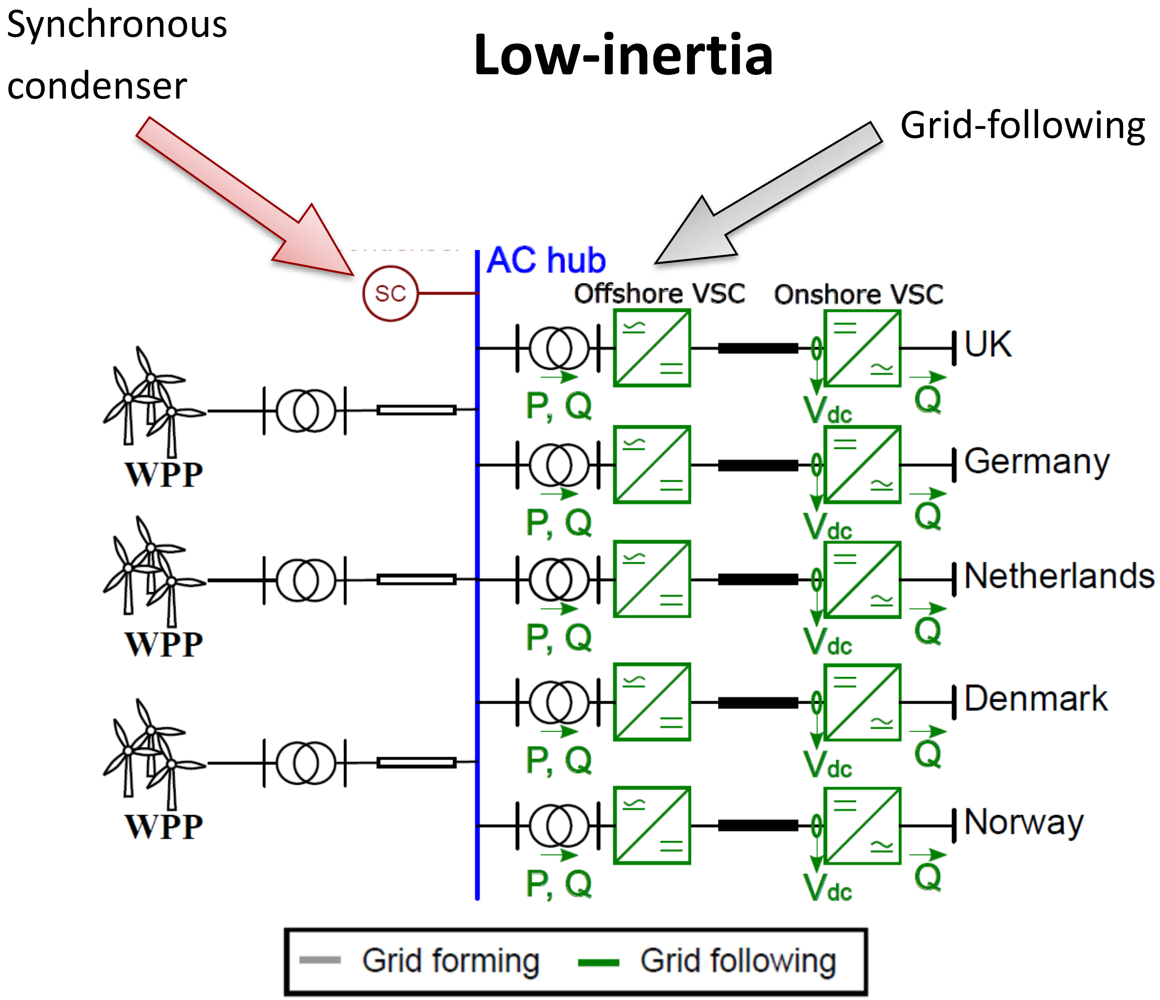
Zero- or low-inertia configuration

Zero-inertia

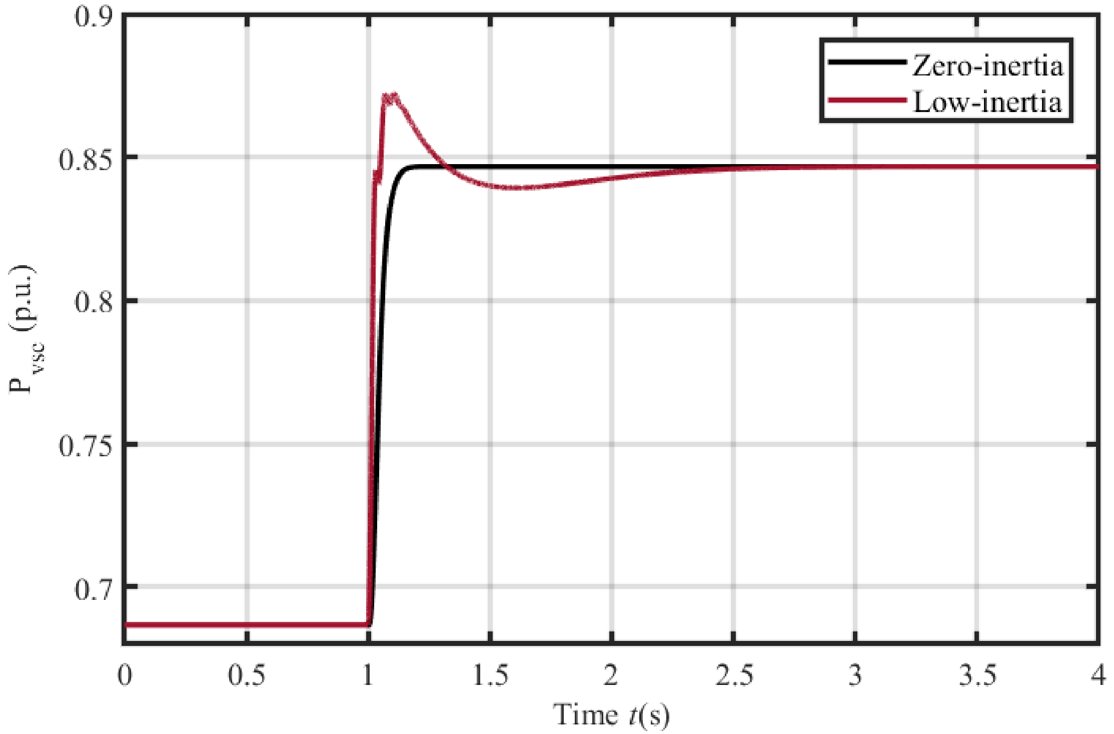


Low-inertia

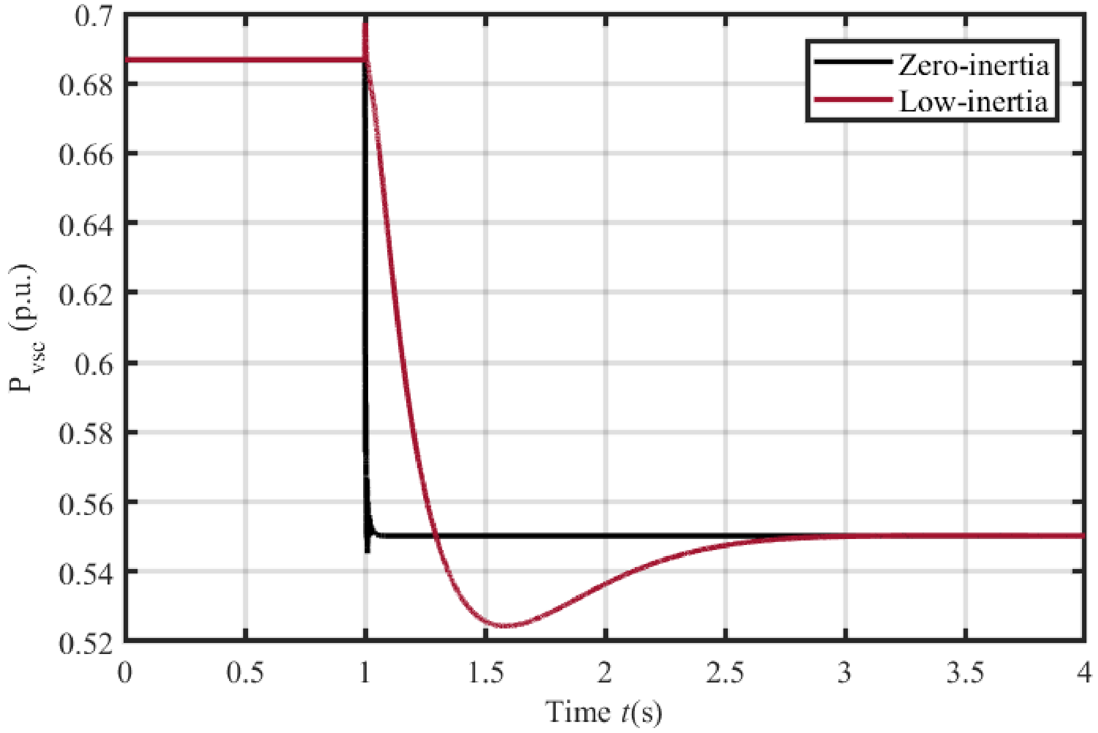


Insight #4: Zero-inertia topology has a faster response to requests and shorter settling time; but disturbances propagate faster

Scenario 1: Power request from one of the onshore systems



Scenario 2: Loss of a wind farm



Zero-inertia: shorter settling time. Preferable for fast frequency support.
Low-inertia: Overshoot of the power. May induce oscillations.

Zero inertia: Fast propagation of disturbance to the onshore grids
Low inertia: Smaller rate of change of power due to the kinetic energy stored in the synchronous condenser

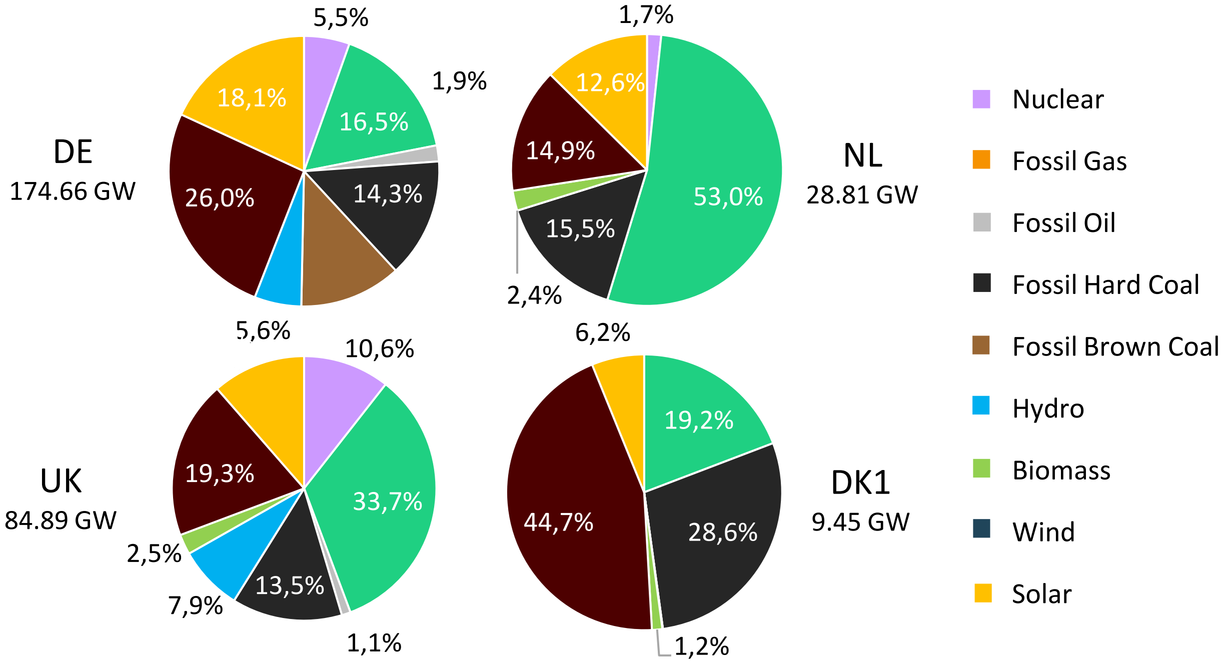
Further readings: G. Misyris, T. Van Cutsem, J. Moller, M. Dijokas, O. Renom Estragués, B. Bastin, S. Chatzivasileiadis, A. Nielsen,T. Weckesser, J. Ostergaard, & F. Kryezi. North Sea Wind Power Hub: System Configurations, Grid Implementation and Techno-economic Assessment. In Proc. CIGRE conference. 2020.

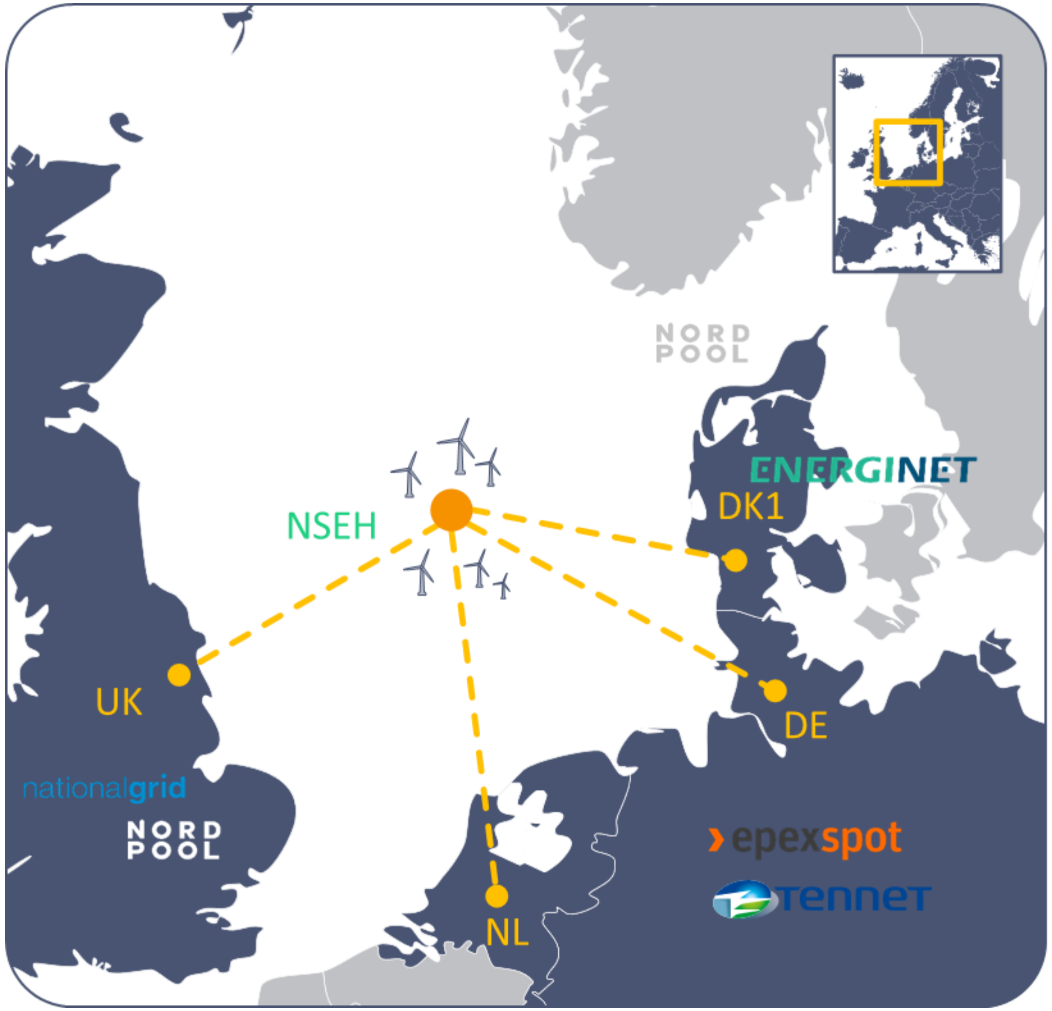
Question #3:

What is the NSWPH's impact on the electricity market?

Market model

- Market model of UK, NL, DE and DK1.
- Wind, solar and demand profiles from 2019 (real data).
- Neighboring non-NSEH zones included as positive or negative loads.

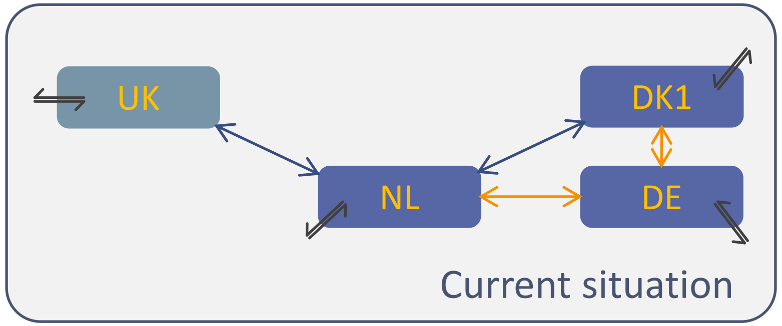


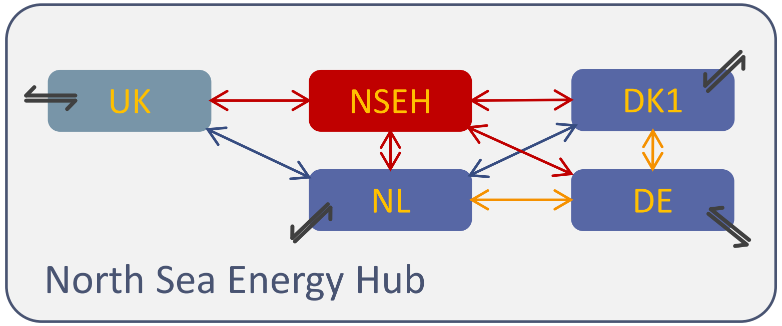


Resource: Andrea Tosatto. European transmission and market models. GitHub repository, 2021. Available: https://github.com/antosat/European-Transmission-and-Market-Models/.

Simulation setup

› Three cases, seven simulations:





#1: Base case

NO HUB
Reference case

North Sea Energy Hub

5 GW | 10 GW | 15 GW | 20 GW

#2: More transmission capacity

10 GW wind
10 GW
transmission

→

10 GW wind
15 GW
transmission

#3: Connection to Norway

10 GW wind
Connections to:
DE,DK,NL,UK

→

10 GW wind
Connections to:
DE,DK,NO,NL,UK

Case #1: 5-20 GW – Impact on prices

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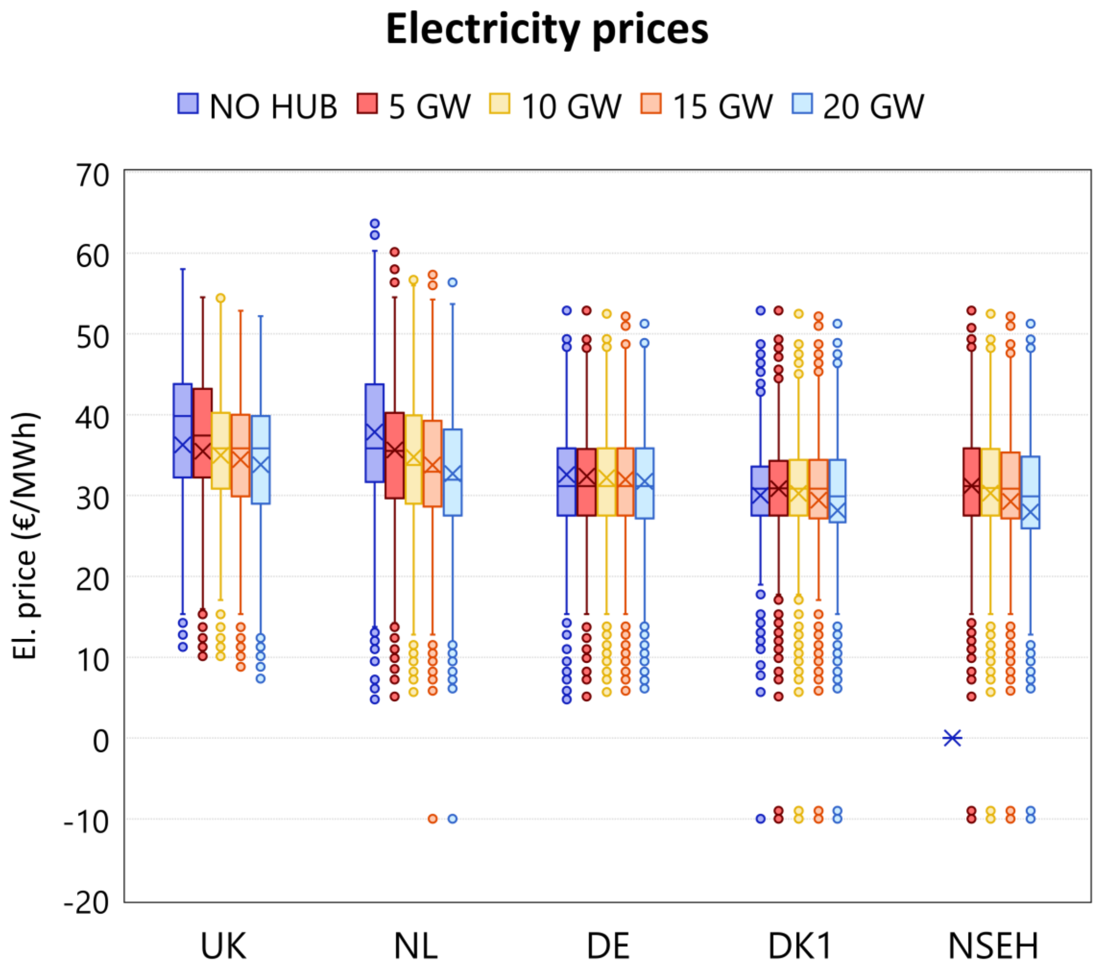
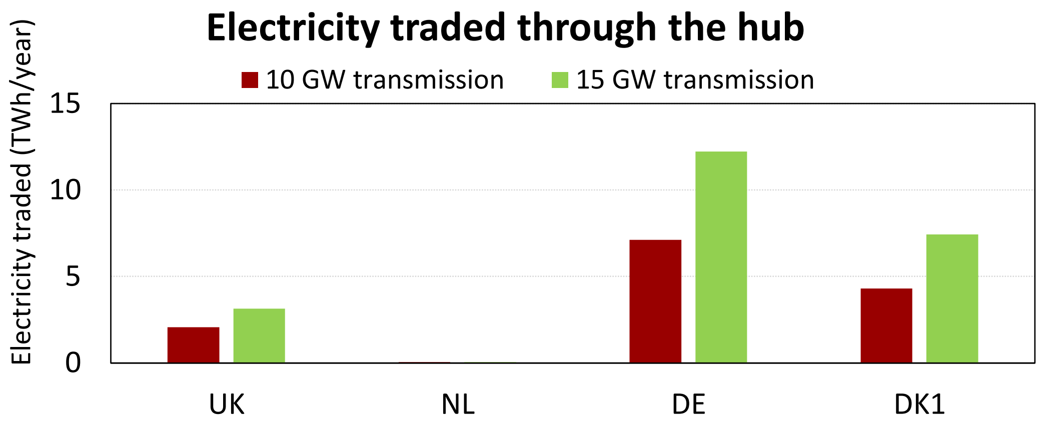
- Overall, electricity prices decrease.
- Prices decrease marginally in Germany because of the increased exports.
- The drop of prices is also related to the extra available transmission capacity.

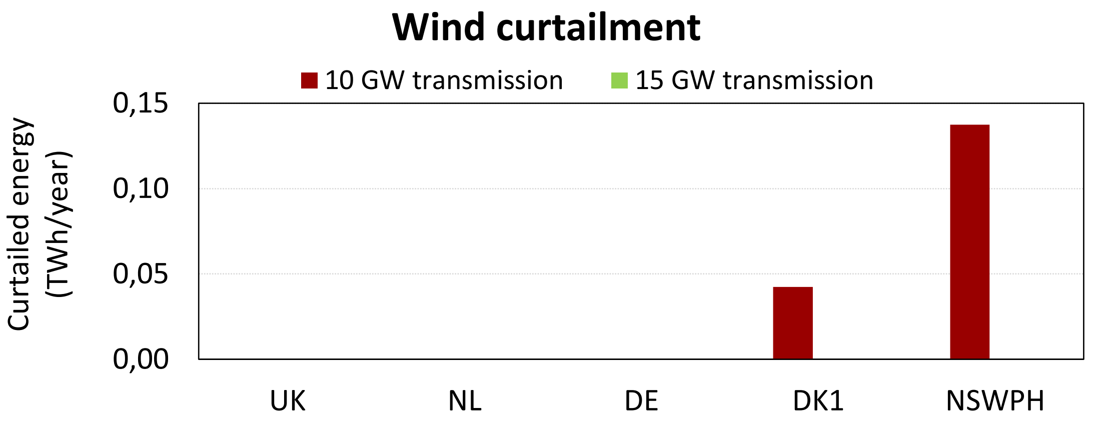
[€/MWh]	NO HUB	5 GW	10 GW	15 GW	20 GW
UK	36.29	35.49	34.97	34.46	33.81
NL	37.85	35.64	34.77	33.79	32.70
DE	32.58	32.39	32.20	32.01	31.76
DK1	30.00	30.83	30.27	29.43	28.16
NSEH	-	31.22	30.27	29.27	27.96



Case #2: More transmission capacity, more exchanges

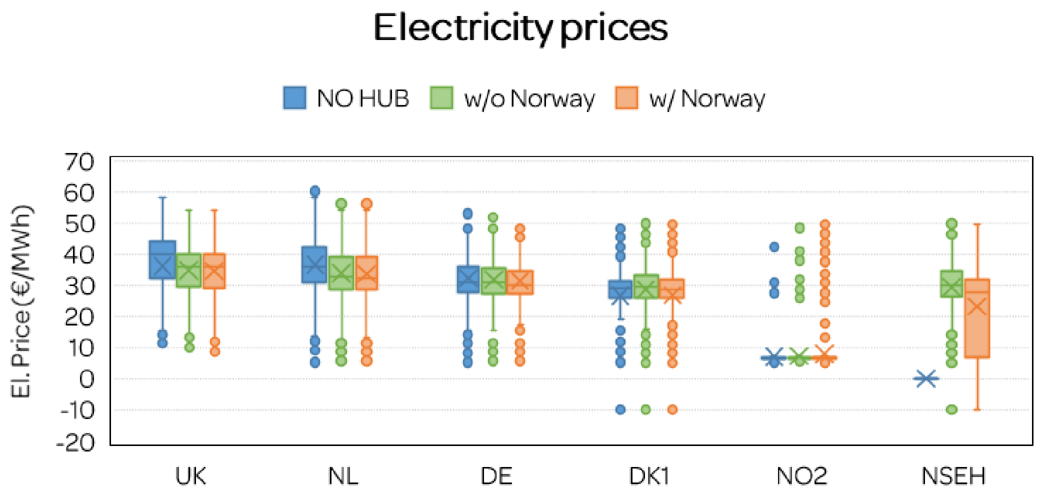
- With more transmission capacity, the exchanges between the countries increase.
- It is now possible to transmit all the wind power produced.



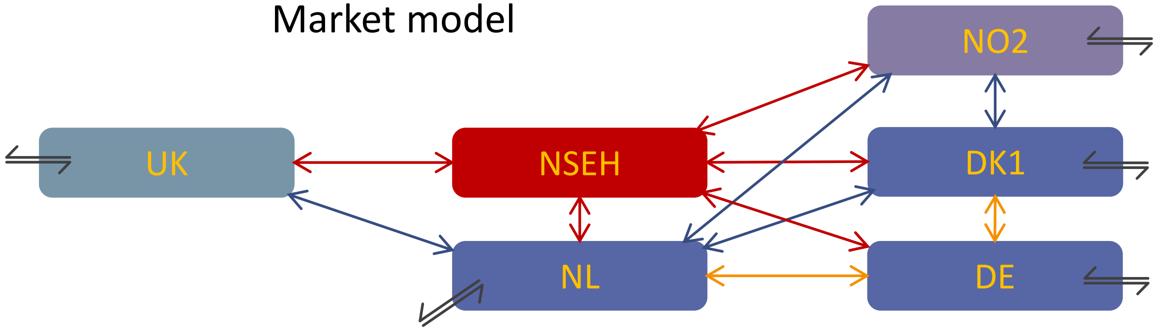


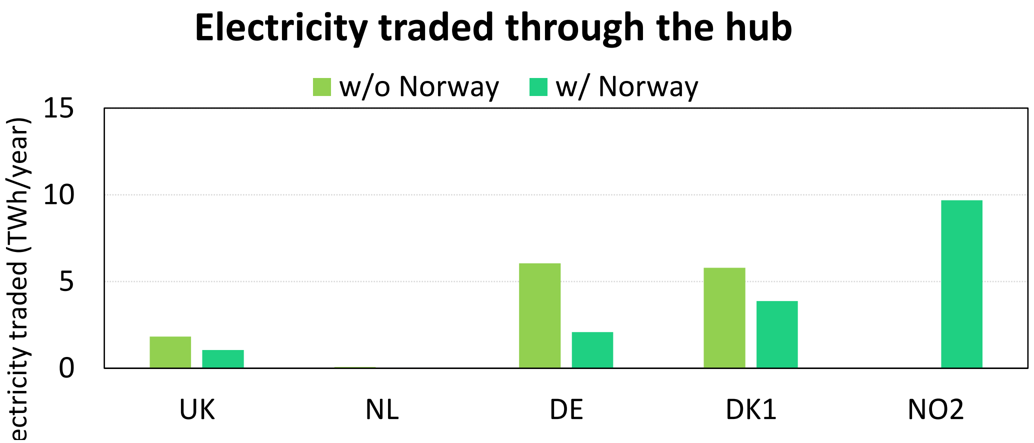
Case #3: Connection to Norway

- Norway has almost only hydro power plants: low cost electricity.
- With the connection to Norway, Germany becomes the main importer through the hub.
- Prices decrease also in Germany.



Market model





Insight #6: The NSWPH results overall in a decrease of the electricity prices

- Overall, electricity prices **decrease**.
- More transmission capacity means **more exchanges** and removes the need for **wind power curtailment**
- The connection to Norway alters the equilibrium between NSEH-connected countries, with **Norway becoming the main exporter**.

Further reading: A. Tosatto, X. Martínez Beseler, J. Østergaard, P. Pinson and S. Chatzivasileiadis, North Sea Energy Islands: Impact on National Markets and Grids, submitted to Energy Policy. arXiv:2103.17056

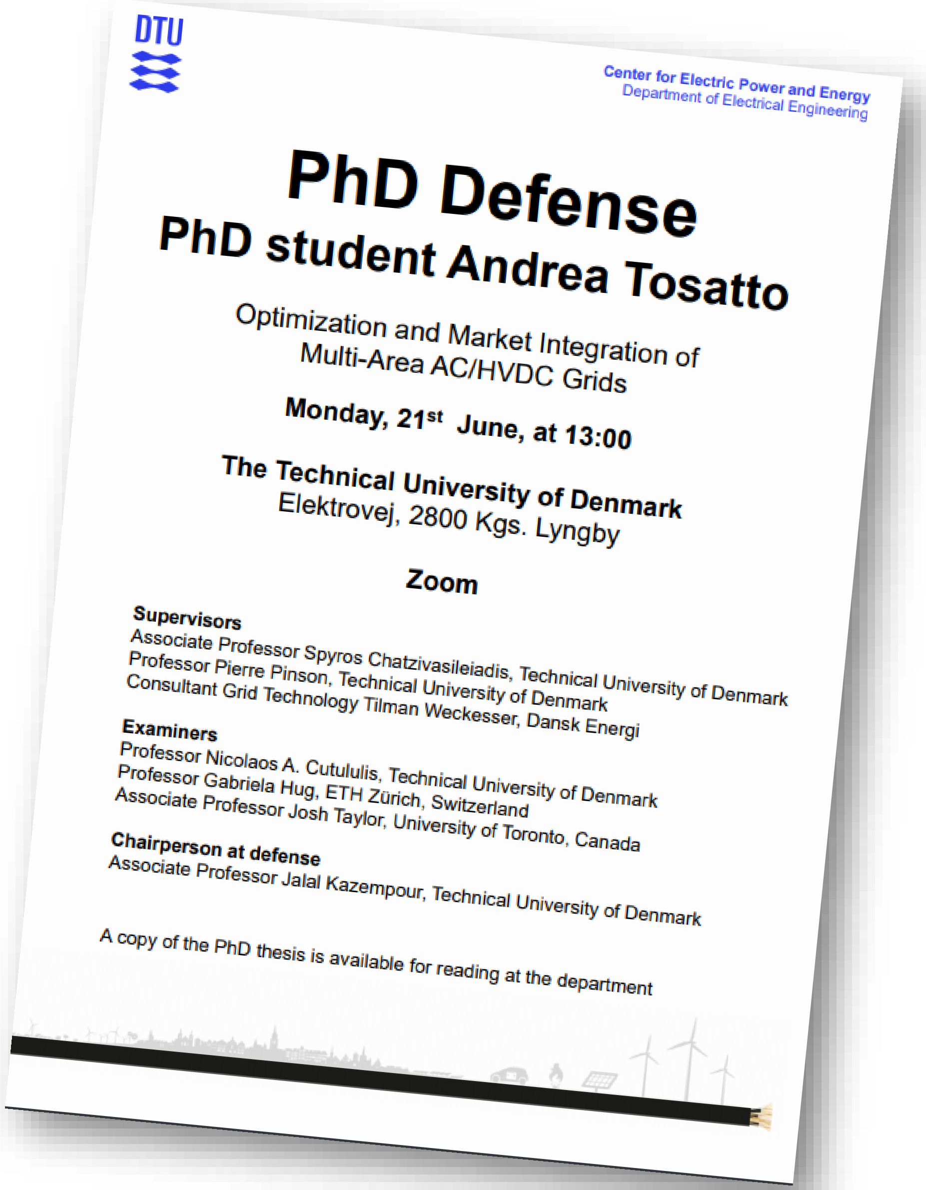
PhD defence

- **Optimization and Market Integration of Multi-Area AC/HVDC Grids**

- **Andrea Tosatto**

- **Monday 21st June, at 13:00**

- **On Zoom: https://dtudk.zoom.us/j/66243225081**



DTU

Center for Electric Power and Energy
Department of Electrical Engineering

PhD Defense

PhD student Andrea Tosatto

Optimization and Market Integration of Multi-Area AC/HVDC Grids

Monday, 21st June, at 13:00

The Technical University of Denmark
Elektrovej, 2800 Kgs. Lyngby

Zoom

Supervisors
Associate Professor Spyros Chatzivasileiadis, Technical University of Denmark
Professor Pierre Pinson, Technical University of Denmark
Consultant Grid Technology Tilman Weckesser, Dansk Energi

Examiners
Professor Nicolaos A. Cutululis, Technical University of Denmark
Professor Gabriela Hug, ETH Zürich, Switzerland
Associate Professor Josh Taylor, University of Toronto, Canada

Chairperson at defense
Associate Professor Jalal Kazempour, Technical University of Denmark

A copy of the PhD thesis is available for reading at the department multiDC

Thank you!

www.multi-dc.eu

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Innovation Fund Denmark
DTU
KTH VETENSKAP OCH KONST
LIÈGE université Sciences Appliquées
ENERGINET
SVENSKA KRAFTNÄT
ABB

Further readings

- A. Tosatto, T. Weckesser, S. Chatzivasileiadis, Market Integration of HVDC Lines: internalizing HVDC losses in market clearing, IEEE Transactions on Power Systems, 2019 10.1109/TPWRS.2019.2932184
- A. Tosatto, S. Chatzivasileiadis, HVDC loss factors in the Nordic power market. Electric Power Systems Research, 190, [106710].2021
- A. Tosatto, M. Dijokas, D. Obradovic, T. Weckesser, R. Eriksson, J. Josefsson, A. Krontiris, M. Ghandhari, J. Østergaard, S. Chatzivasileiadis, Market Integration of HVDC Lines: Cost Savings from Loss Allocation and Redispatching, In Proc. CIGRE conference. 2020.
- A. Tosatto, M. Dijokas, T. Weckesser, S. Chatzivasileiadis & R. Eriksson. Sharing reserves through HVDC: potential cost savings in the Nordic countries. arXiv preprint arXiv:2001.00664. 2020
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