North Sea Energy Hub 2030: Building artificial islands to cover Europe's electricity demand by Offshore Wind

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Associate Professor

Energy in DTU

DTU Photonics

Solar PV systems

DTU Wind Energy

Thermal systems

DTU Mechanical Engineering

DTU Electrical Engineering

DTU Energy Conversion

DTU Compute

Dynamic systems and smart cities

DTU Civil Engineering

Building energy, Solar thermal and District heating

DTU Management Engineering

Energy system analysis and policy

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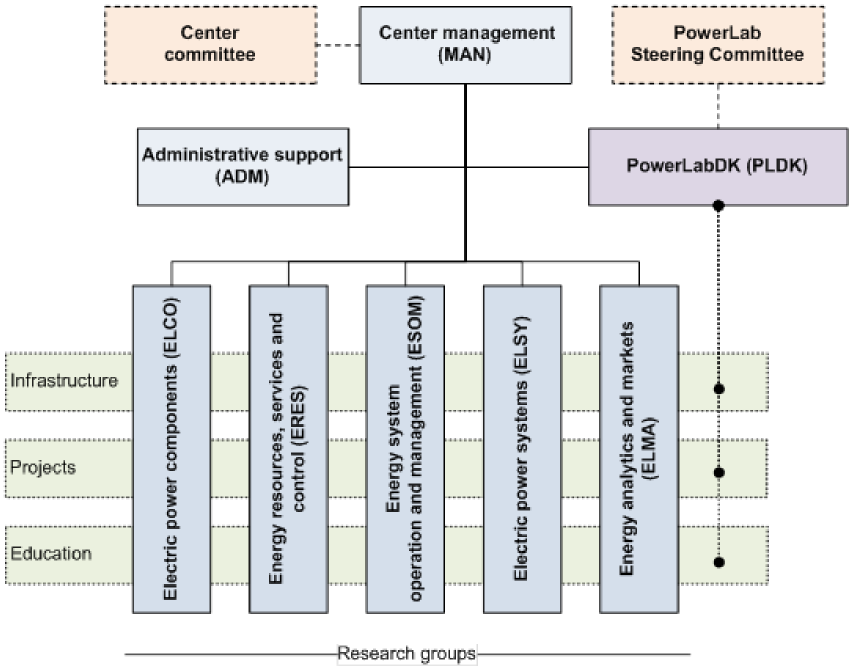
Center for Electric Power and Energy (CEE)

- Established 15 August 2012 by merging two existing units (Lynbgy + Risø)
  - Among the strongest university centers in Europe with approx. 110 employees and 12 faculty members
- **Bachelor and Master programs:** Sustainable Energy Design, Electrical Engineering, Wind Energy, Sustainable Energy
- **Direct support from:**

ENERGINET Ørsted SIEMENS Danfoss



DTU consistently ranks among the top 10 universities of the world in Energy Science and Engineering (Shanghai ranking, 2016, 2017, 2018)

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Strong National and International Collaboration

Selected collaboration partners

Academic partners:

- ETH Zürich (CH)
- EPFL – École Polytechnique Fédérale de Lausanne (CH)
- Nanyang Technological University (SG)
- Tsinghua University (CN)
- Stanford (US)
- Aalborg Universitet (DK)
- Nordic Five Tech: DTU (DK), NTNU Norwegian University of Science and Technology (NO), Aalto University School of Science and Technology (FI), Chalmers (SE), KTH Vetenskap och Konst (SE)
- University of Strathclyde Glasgow (UK)
- Berkeley University of California (US)
- University of Delaware (US)
- The Hong Kong Polytechnic University 香港理工大學 (HK)

>80 formal partners

Commercial and industrial partners:

- Energinet (DK)
- Ørsted (DK)
- Radius (DK)
- Siemens (DE+DK)
- elia – Powering a world in progress (BE)
- ABB (SE/DK)
- Bornholms Energi & Forsyning (DK)
- nationalgrid (UK)
- IBM (CH)
- Vestas (DK)
- Pacific Northwest National Laboratory (US)
- Danfoss (DK)
- Københavns Kommune (DK)
- seas nve (DK)
- ScottishPower (UK)
- Dansk Energi (DK)
- NKT (DK)

>100 formal partners

s:

- Smart Energy Networks – Research, Development and Demonstration (DK)
- Mission Innovation – Accelerating the Clean Energy Revolution (Global)
- EERA – European Energy Research Alliance (EU)
- iea Energy Technology Network; ISGAN – International smart grid action network (Global)
- IEEE PES Power & Energy Society™ (Global)
- EES-UETP Electric Energy Systems University Enterprise Training Partnership (EU)

Wind power in Denmark

In 2017 Denmark achieved a wind energy world record: **43,4 %** of the Danish power was produced solely by wind

January 2014:
Danish wind power generation: **63.3%** of the electricity consumption

December 21th 2013:
Danish wind power generation: **102%** of the electricity consumption

Single hour July 9th 2015:
Danish wind power generation: **140%** of the electricity consumption

March 11th 2014:
only 9 MW wind power generated out of installed 4,900 MW
but 480 MW out of 580 MW solar units supplied the grid

Ref.: Energinet.

North Sea Energy Hub and multiDC:
Controlling the Power Flows towards a Zero-Inertia System

Three main drivers

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

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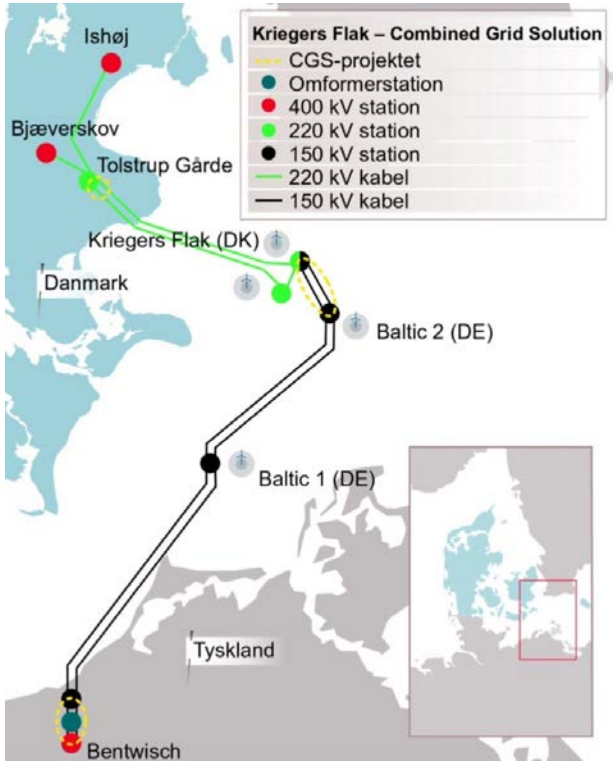
Denmark is unique in being involved in two first-of-their-kind projects

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



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

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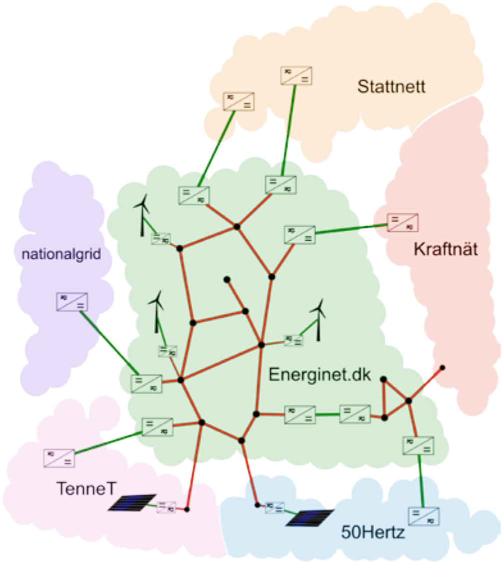
Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grids

- Innovation Fund Denmark Grand Solutions
- Partners:
  - **Two neighboring TSOs:** Energinet, Svenska kraftnät
  - **Three universities:** DTU, KTH, Univ. of Liege
  - **One major manufacturer:** ABB
  - Advisory Board: RTE, Nordic RSC
- **3.5 million Euros**
- **4 years**; Start May 1, 2017



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North Sea Energy Hub Feasibility Study (NSEH)

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

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Advisory Board – 13 industry members

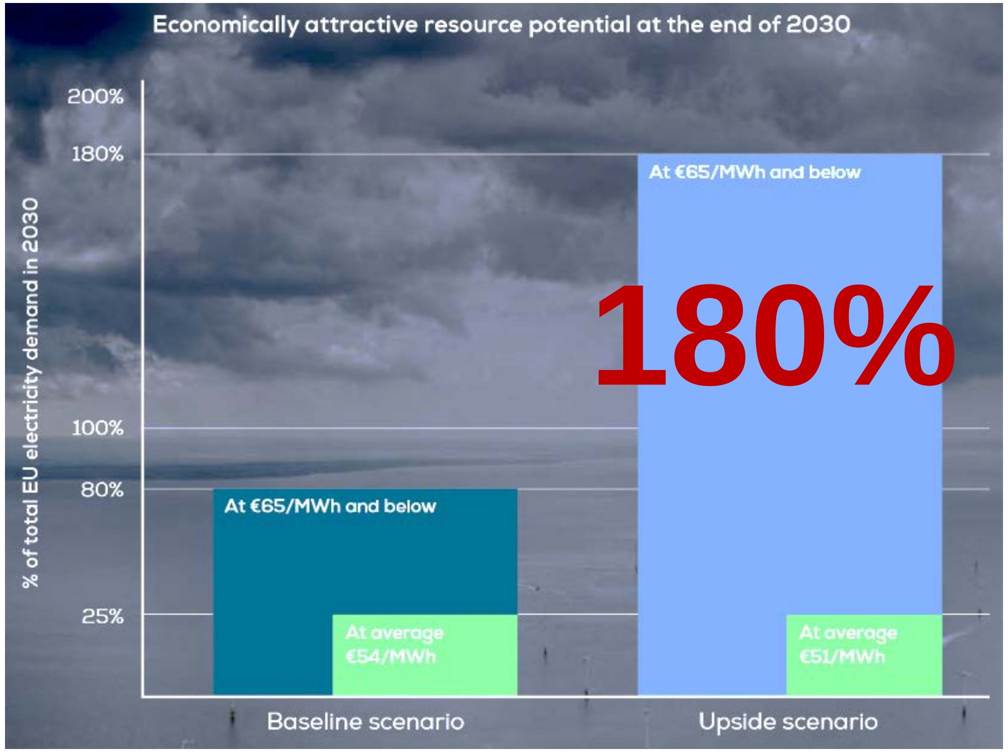
NKT
Siemens
Siemens-Gamesa
Vestas Wind Systems
MHI Vestas Offshore Wind
Ørsted
Energy Innovation Cluster
Semco Maritime
ABB
Wind Denmark
Dansk Energi
Haldor Topsoe

The Team

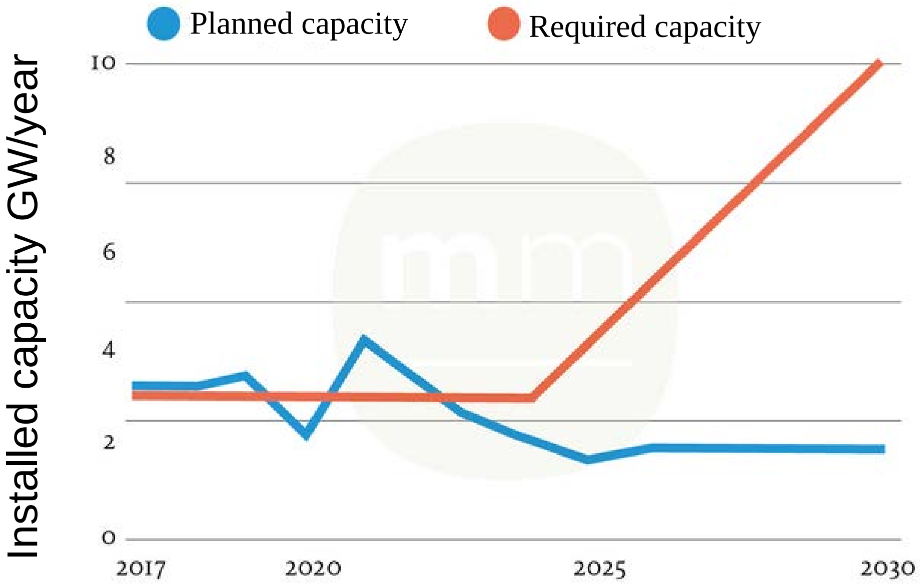
21 persons – 3 countries – 10 nationalities

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 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

Momentum in Europe and Denmark high

- North Sea Wind Power Hub cooperation (from 2017)

North Sea Wind Power Hub

Port of Rotterdam

gasunie

TenneT

ENERGINET

- **Danish Government** announced that they are exploring the possibility that **Denmark constructs the first "Energy Island"** in the North Sea with at least **10 GW** offshore wind by **2030**

Dan Jørgensen,
Danish Minister for Climate, Energy and Utilities

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Offshore wind development could significantly increase through hub concept

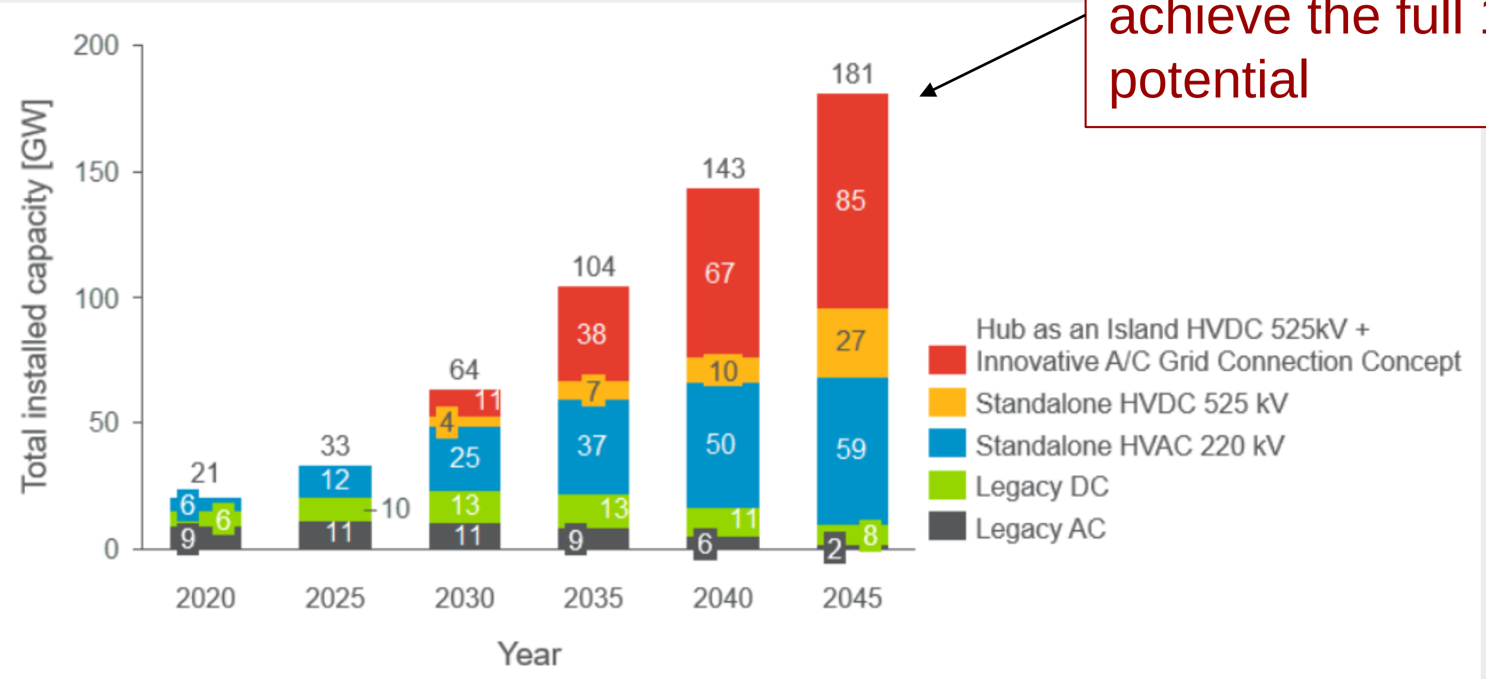


Figure 4 Installed wind power capacity in the North Sea broken down to the different transmission asset concepts for the ICRO approach. Legacy AC refers to currently operational and planned AC radially connected offshore wind farms. Legacy DC refers for currently installed and planned DC connected (German)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

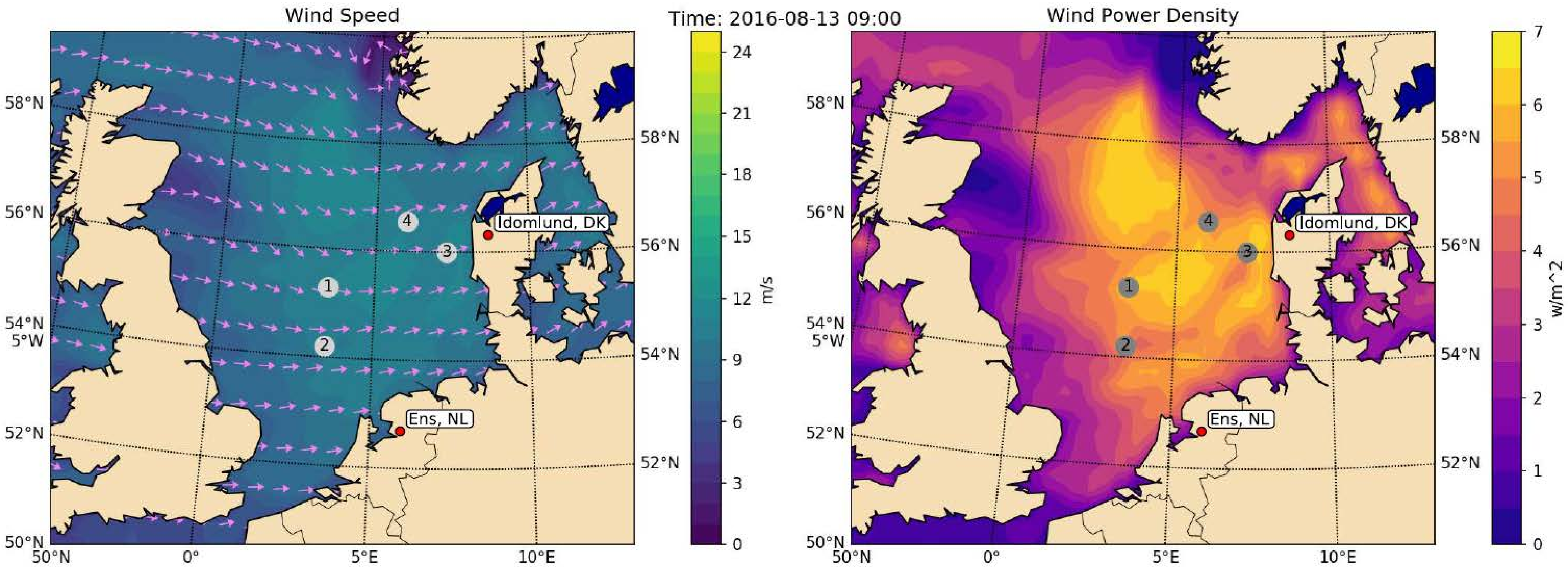
NSEH: necessary to achieve the full 180 GW potential

Hub-and-Spoke concept:

30% lower costs for electrical infrastructure compared with radial connections (AC or DC)

Source: https://northseawindpowerhub.eu/wp-content/uploads/2017/11/Concept-Paper-2-Modular-Hub-Spoke.pdf

North Sea Energy Hub: Wind Power Yield



- The NSEH will integrate approx. 10-30 GW of wind (probably closer to 10-15 GW)
- We need several islands to harvest the full 180 GW potential

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Data: ERA5, Copernicus, 2016

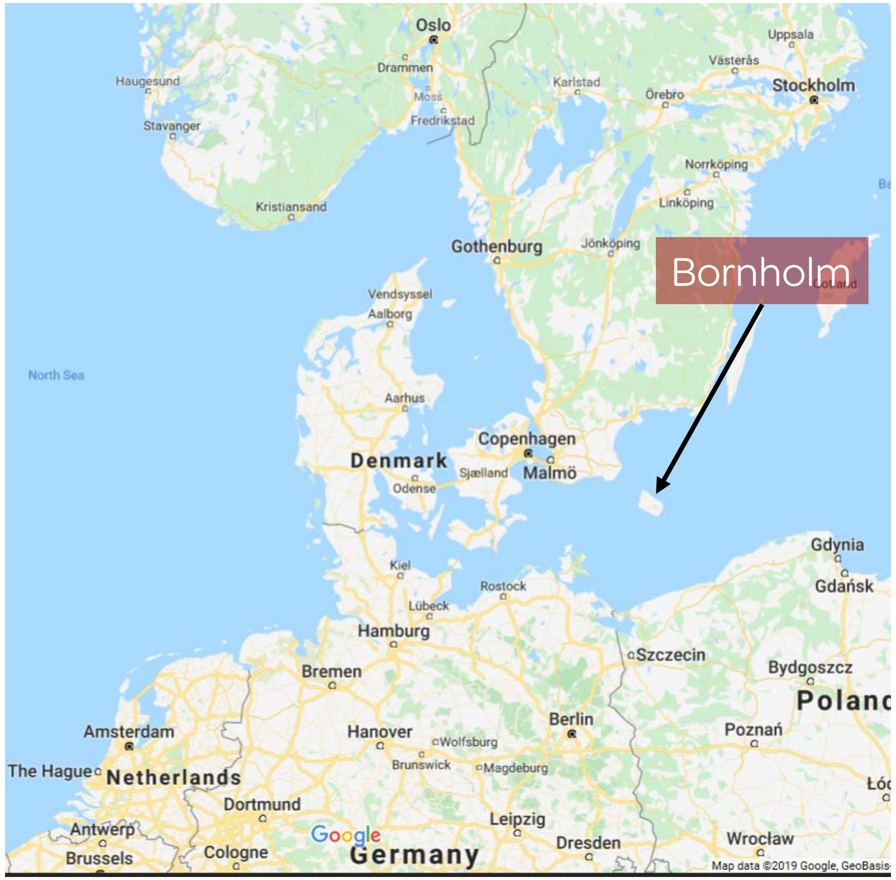
North Sea Wind Power Hub

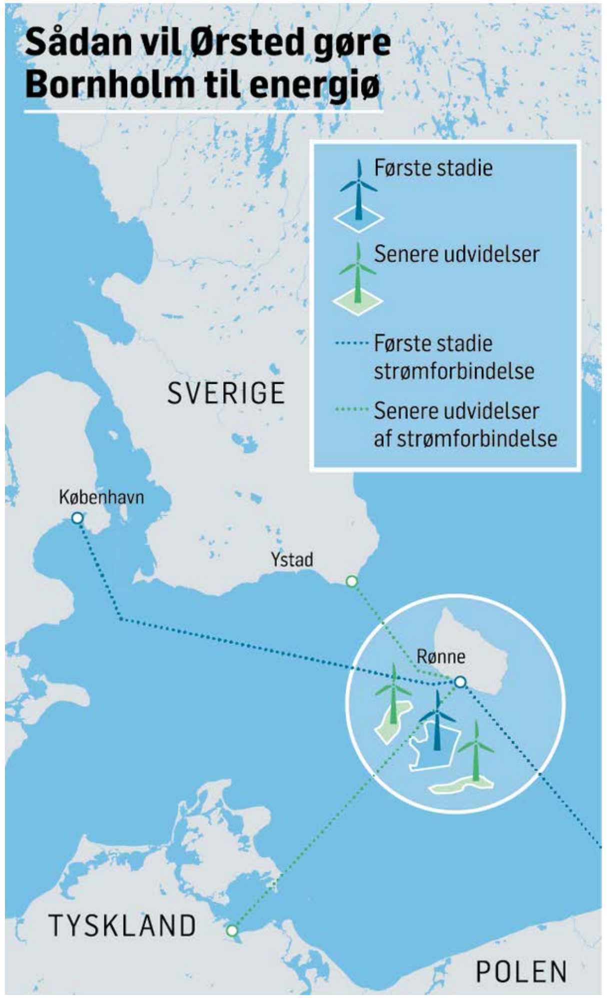
Several regulatory and political challenges

- Possible to develop a first Hub-and-Spoke project within the current regulatory framework
- Timeframe (<2030) ambitious
- Who will pay for the island to be built? International/national waters
- How can wind farm investors use the island facilities? Shall they be shareholders or lease part of the facilities, or…?
- Shall there exist an offshore TSO? Should we create a new price zone just for the offshore island?

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

Question #1:

What is the optimal topology for the North Sea Energy Hub?

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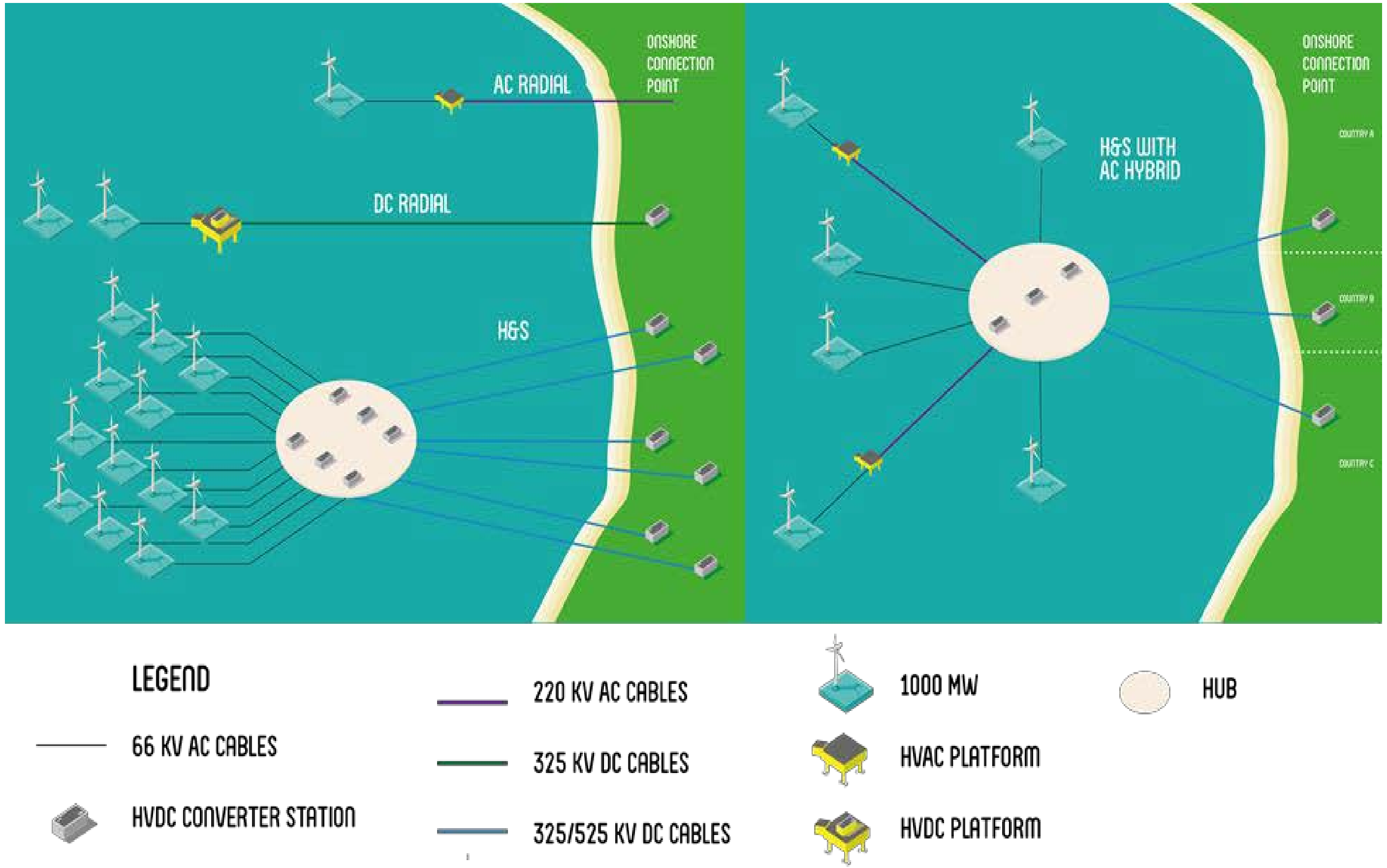
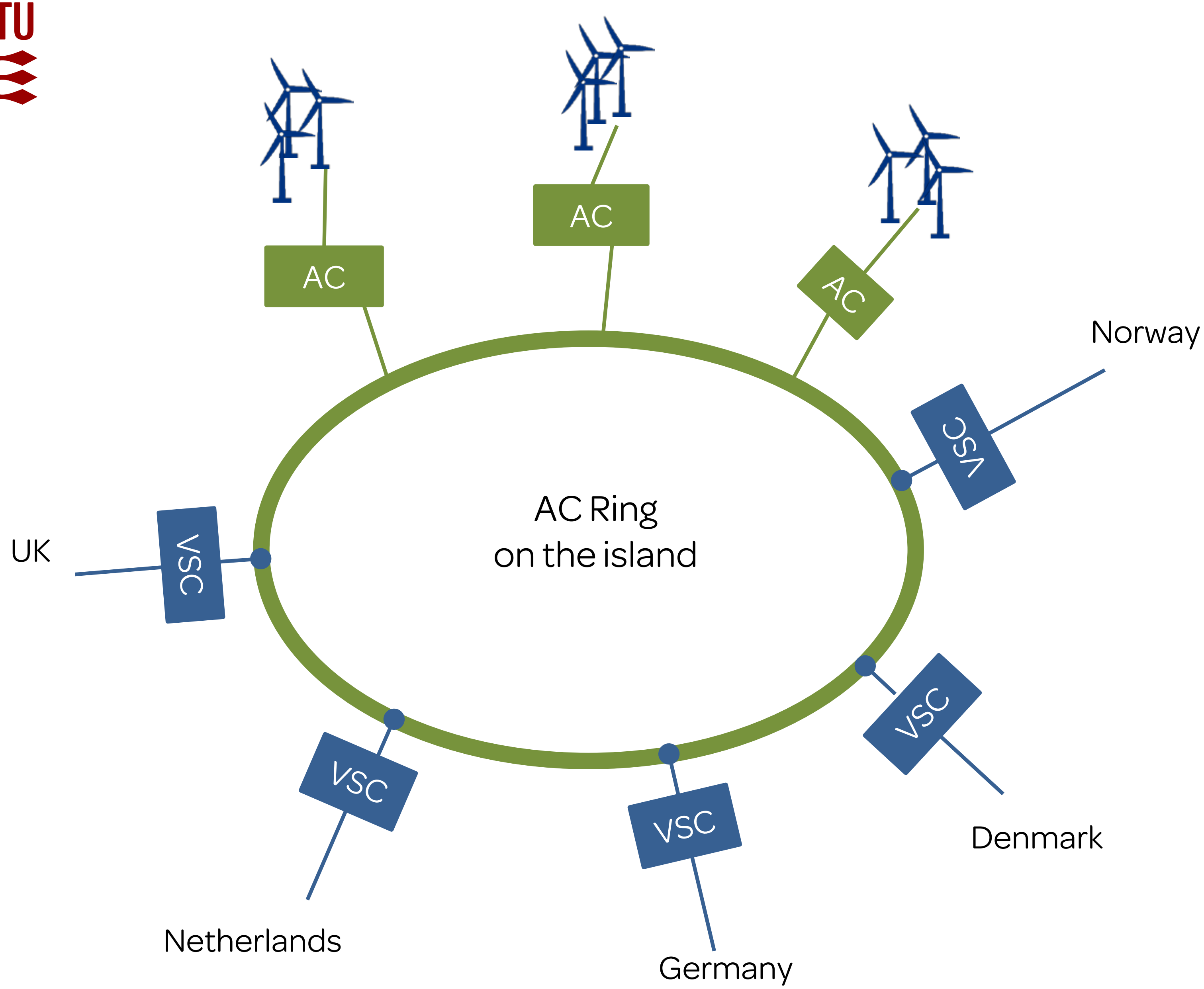


<30 km: 66kV AC

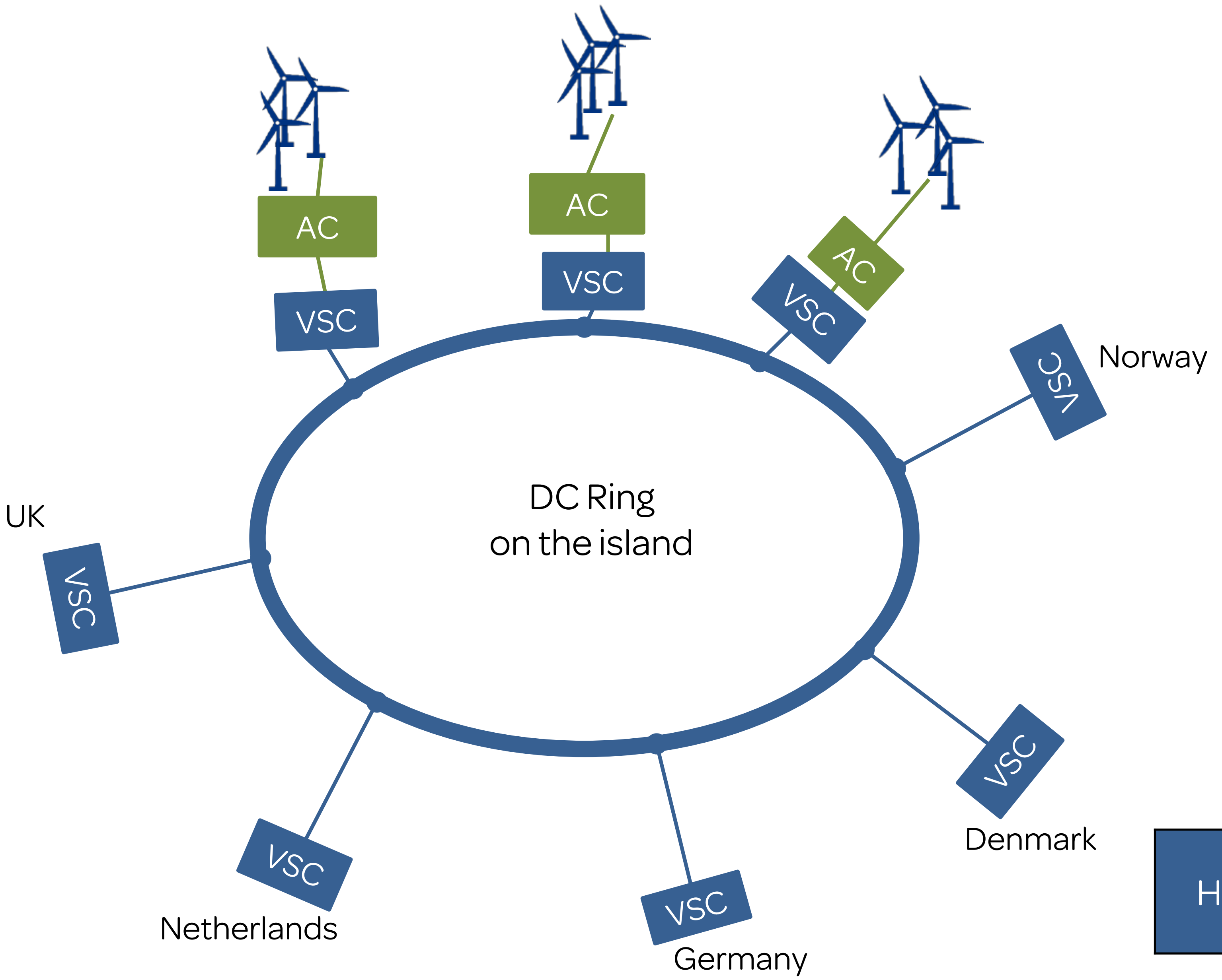
<80km: 220 kV AC

>80km: 325/525 kV DC

https://northseawindpowerhub.eu/cost-evaluation-of-north-sea-offshore-wind-post-2030-towards-spatial-planning/



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



HVDC	Multi-terminal HVDC Grid

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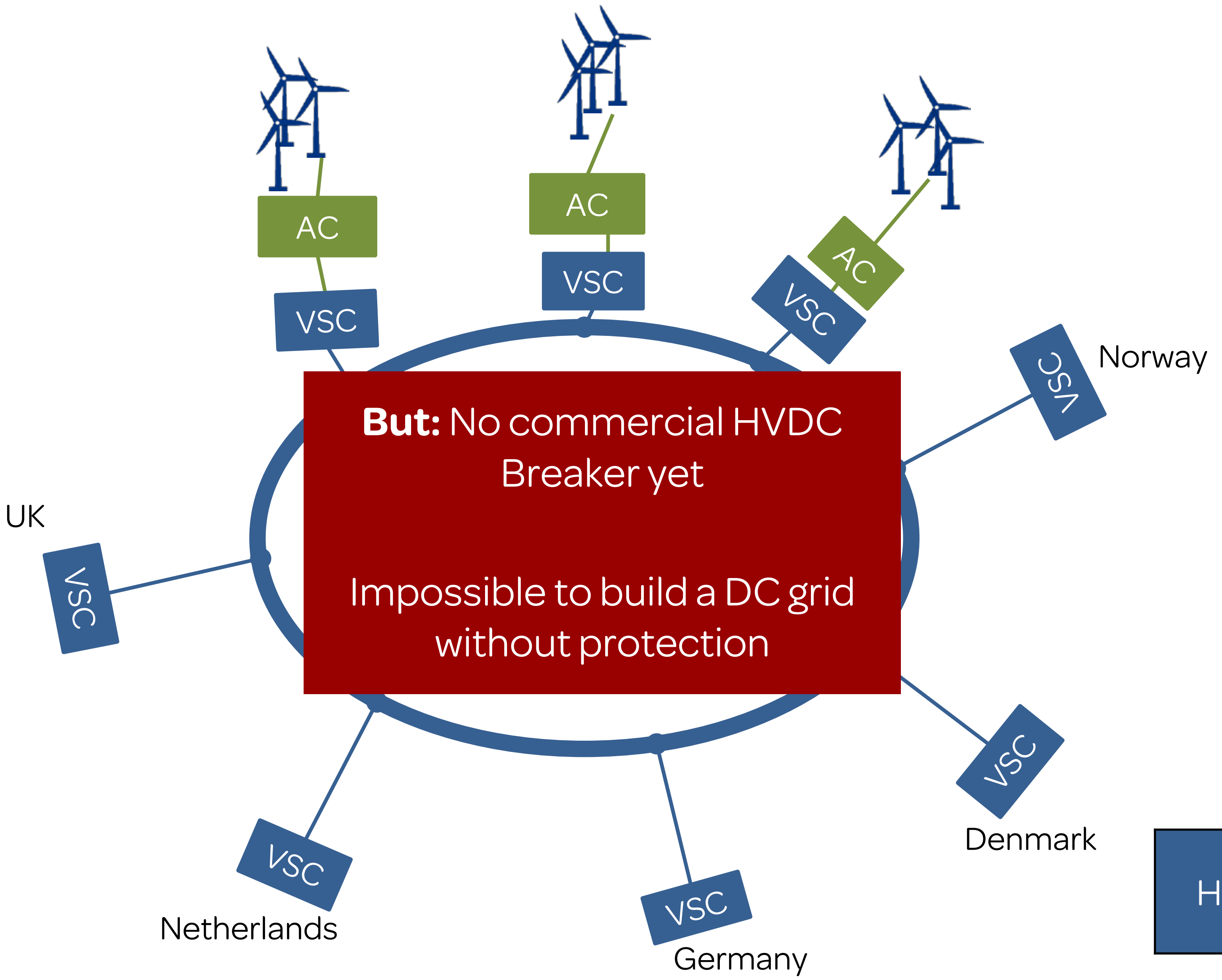
19 September 2019



But: No commercial HVDC Breaker yet

Impossible to build a DC grid without protection

HVDC	Multi-terminal HVDC Grid

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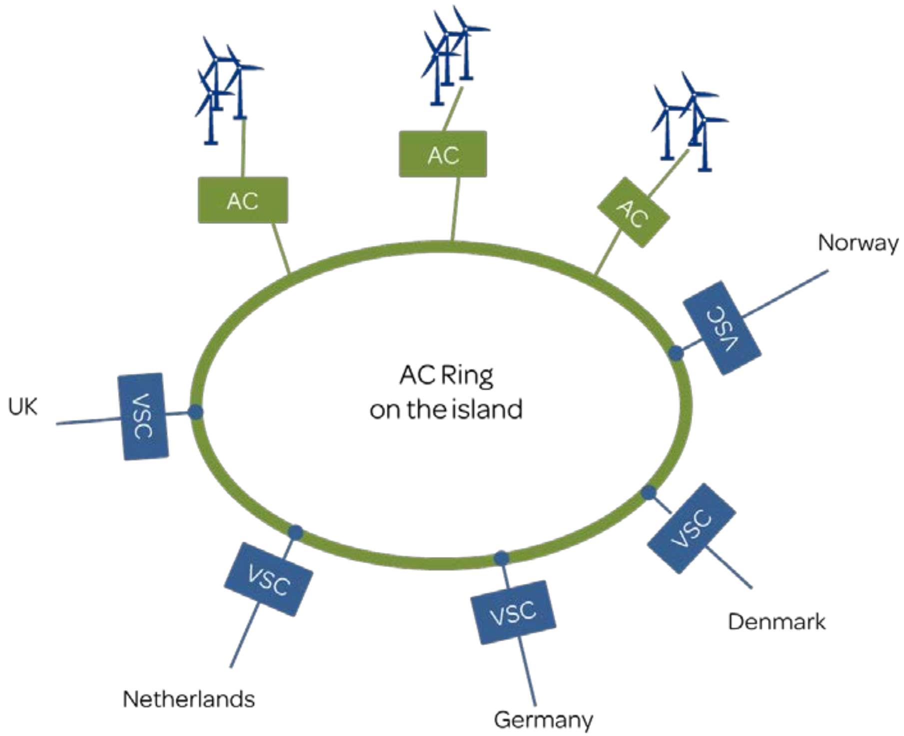
For now: Focus on the AC ring

Challenges and Opportunities

- Zero-inertia AC Ring
  - Fast transients
  - Possibly the first real zero-inertia power system in the world

- How to guarantee N-1 security?
  - Coordination of VSC converters



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19 December 2019

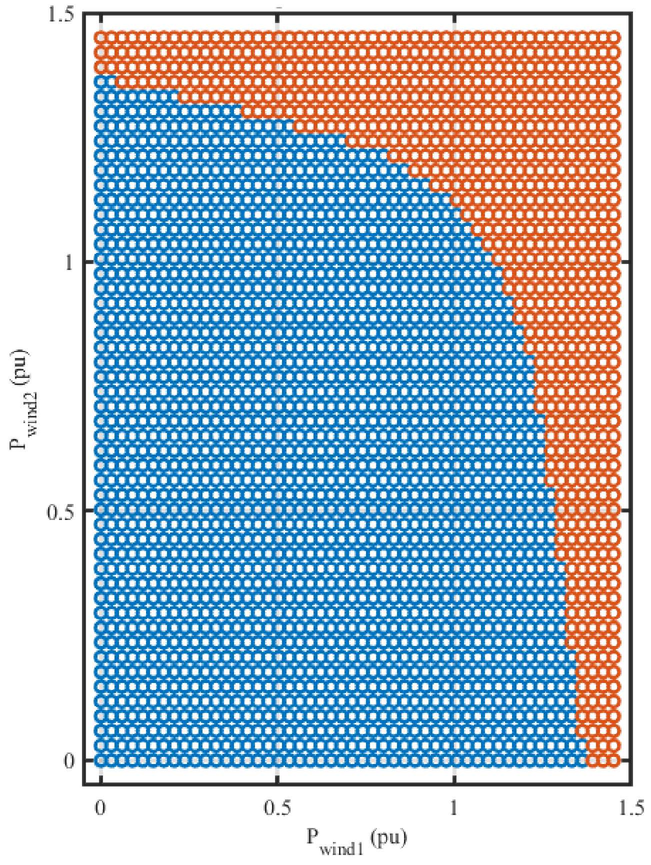
Insight #1: **Low Frequency AC** has a **larger stability region** and allows **longer distances, but costs and weight** of transformers **may cancel out the benefits**

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

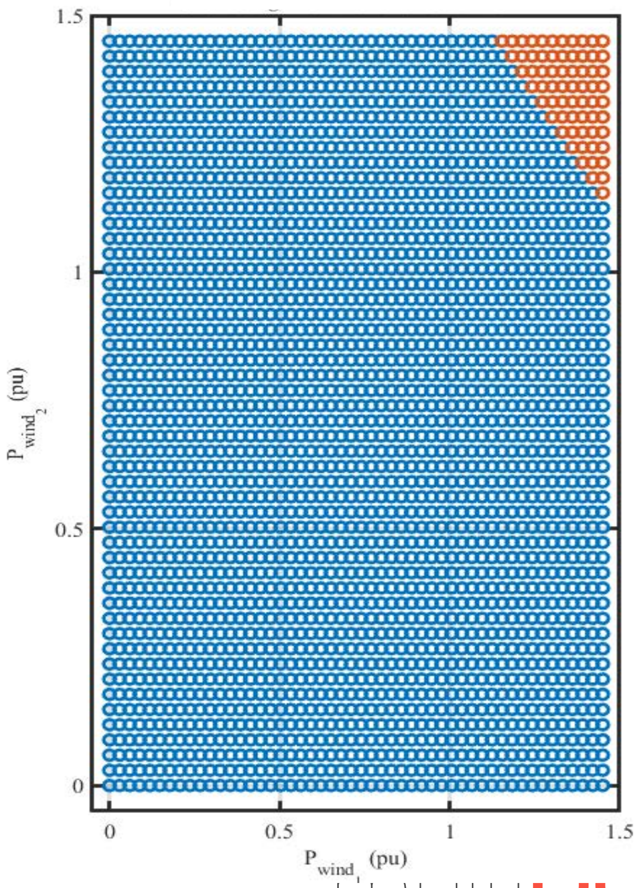
But:

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

50 Hz



16.67 Hz



Zero-inertia vs low-inertia systems

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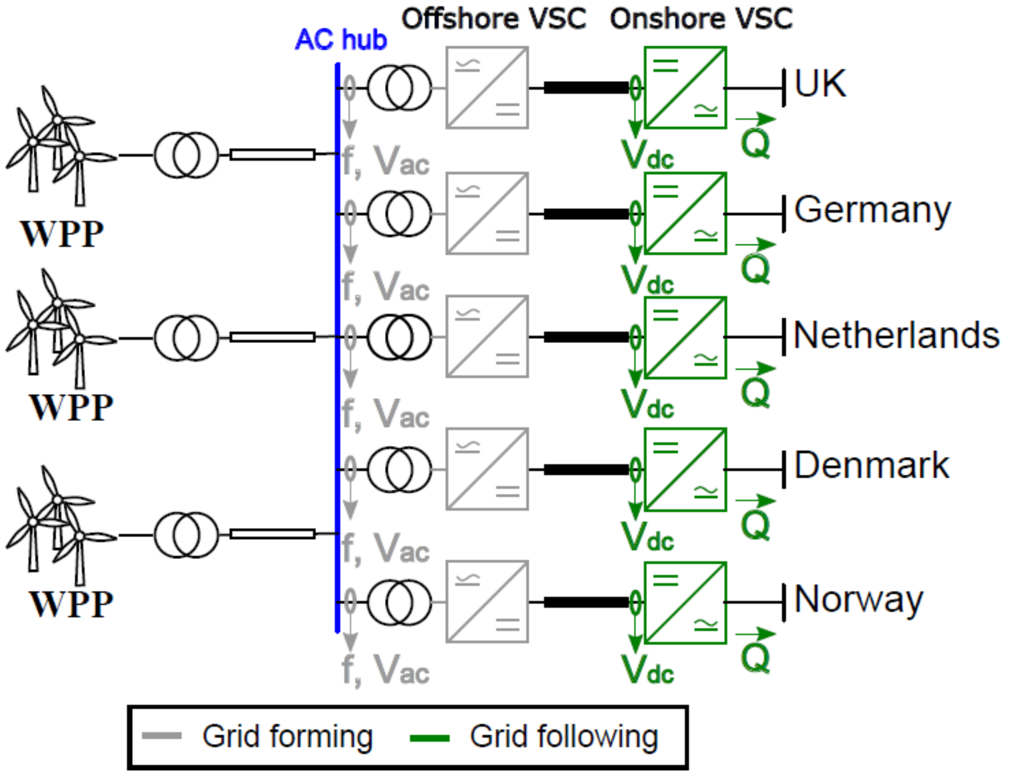
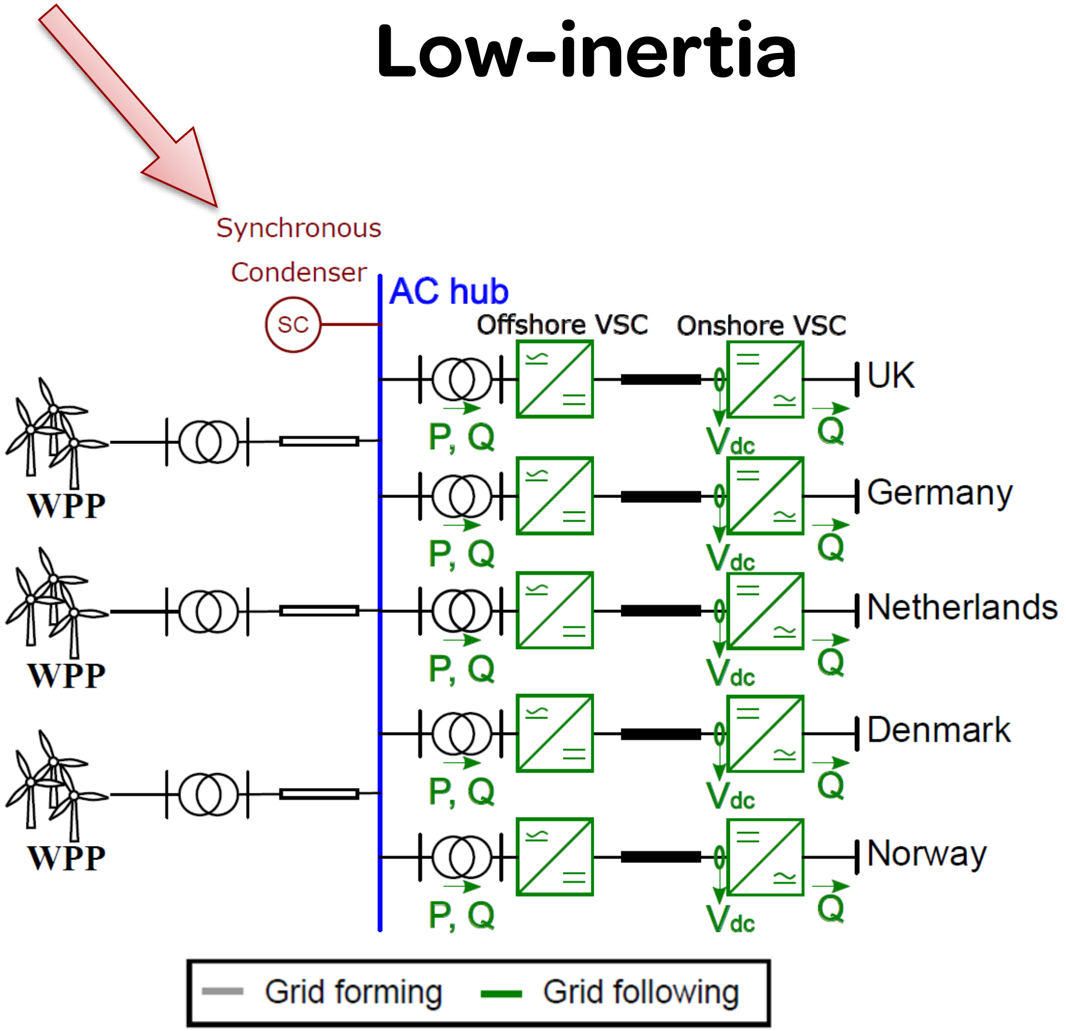
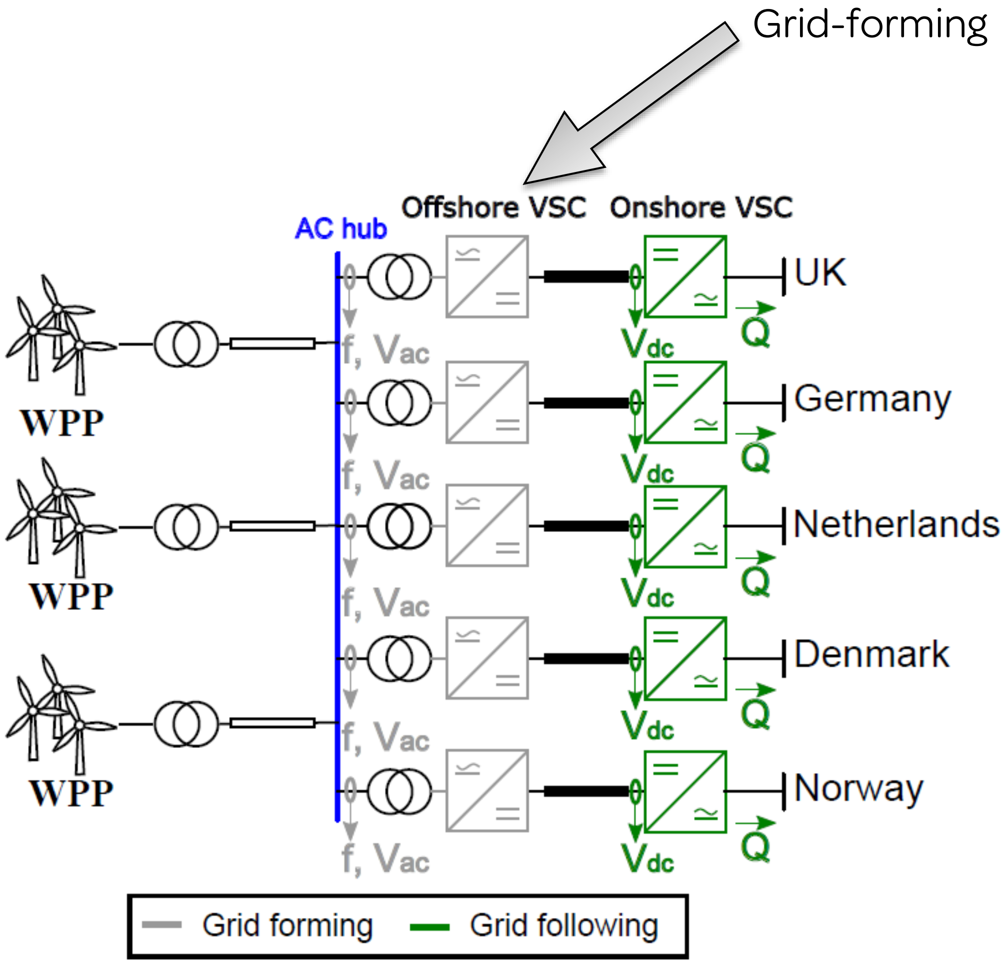
Zero-inertia



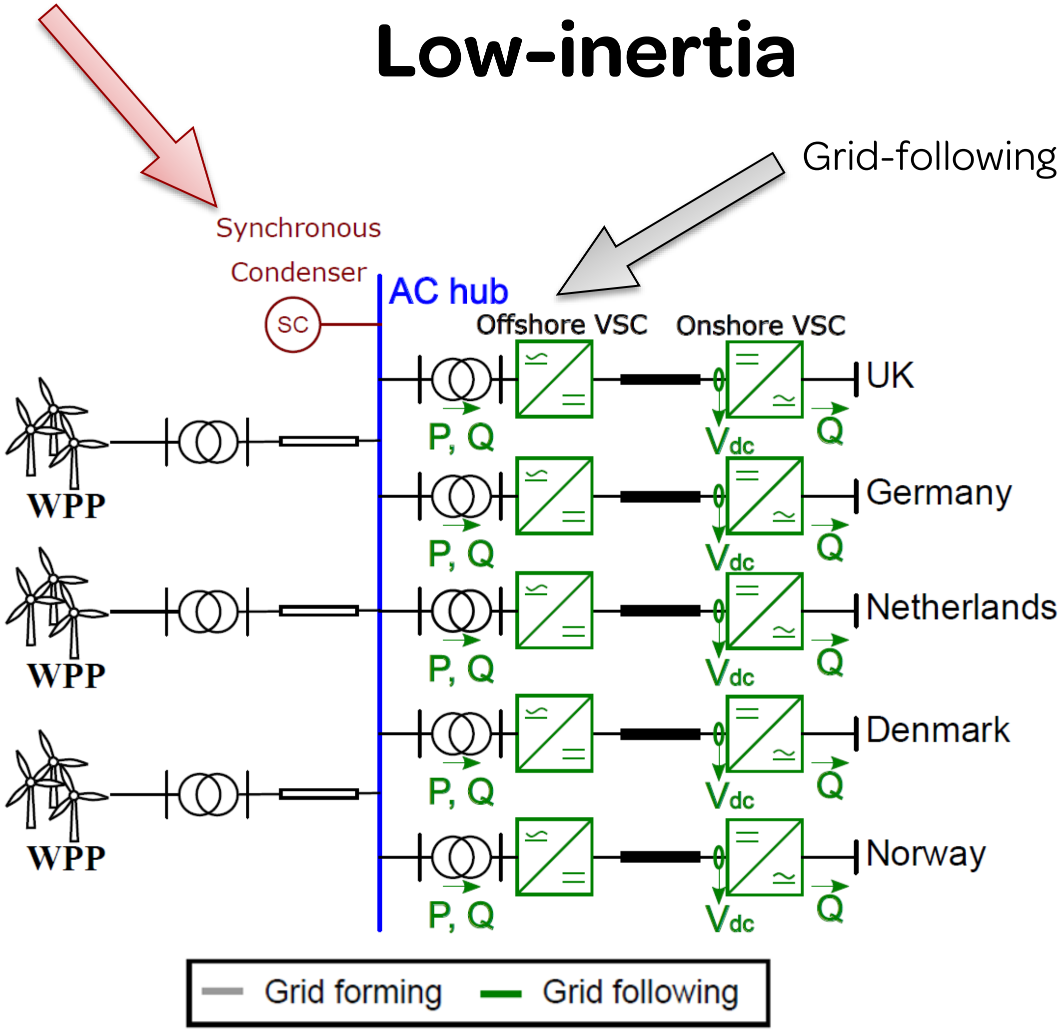
Low-inertia



Zero-inertia



Low-inertia



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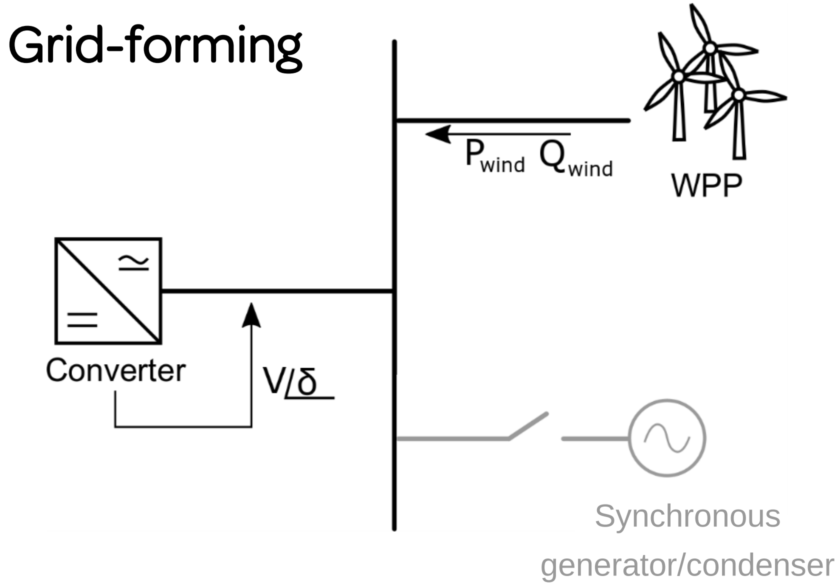
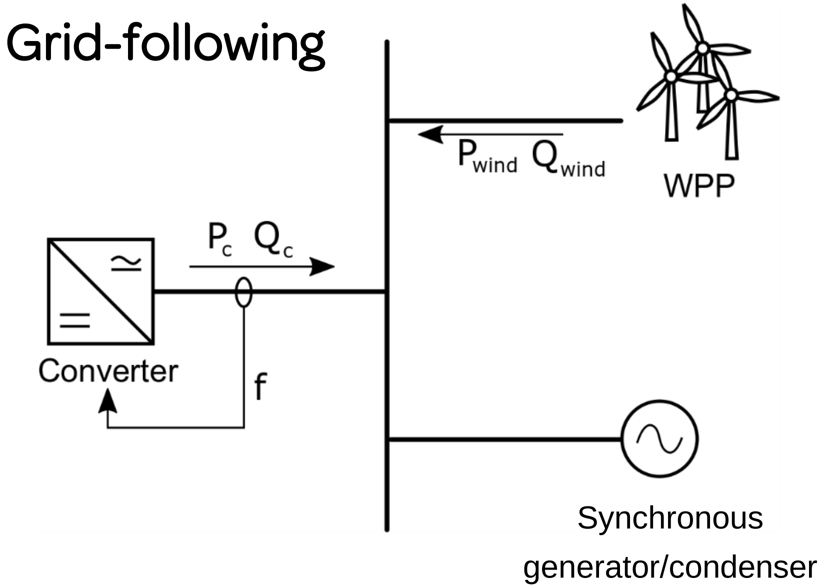
Grid-forming vs grid-following converters

Operating principles



- Wind generates the power
- Frequency generated by the converter
- Converter acts as a slack bus
- Converter sets V, δ



- Wind generates the power
- Requires synchronous machine (synchronous condenser) to set the frequency
- Converter acts as a PQ bus
- Converter sets P,Q

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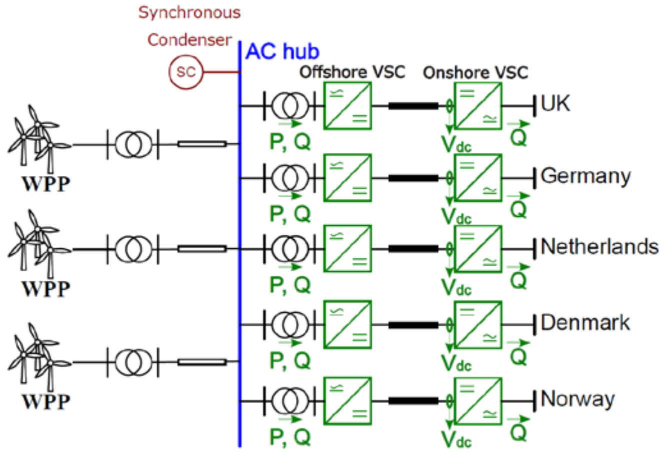
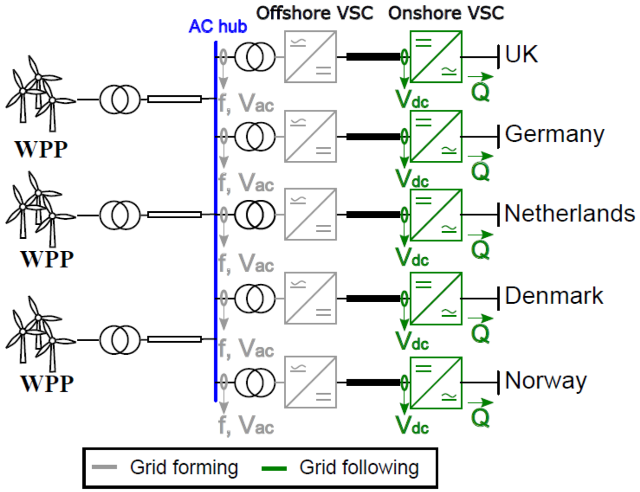
Zero-inertia vs. low-inertia configuration

1. **N-1 security – How** should the **converters share the control effort** to keep the frequency within limits on the island?

2. **Which** topology can **better withstand disturbances**?

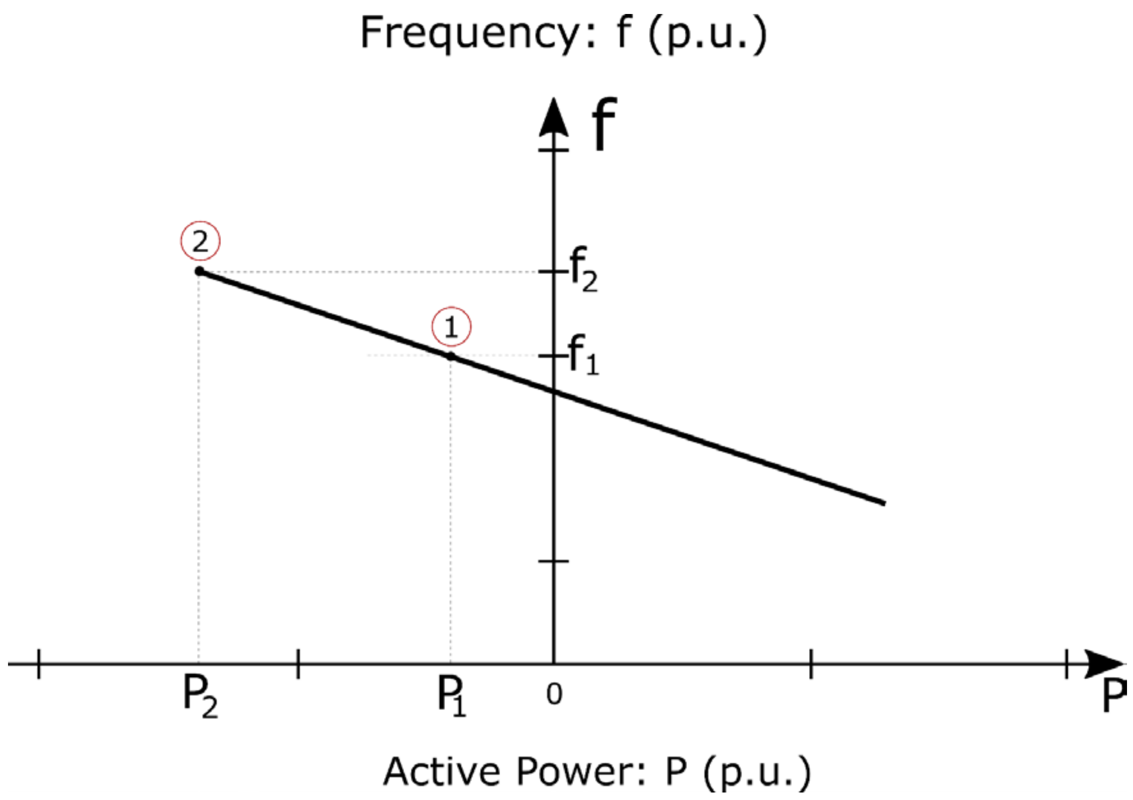




Regulate the frequency of the offshore system
Frequency droop

- Frequency droop control for offshore converters
  - Power output reduces as the frequency increases

- Allows multiple converters to operate in parallel

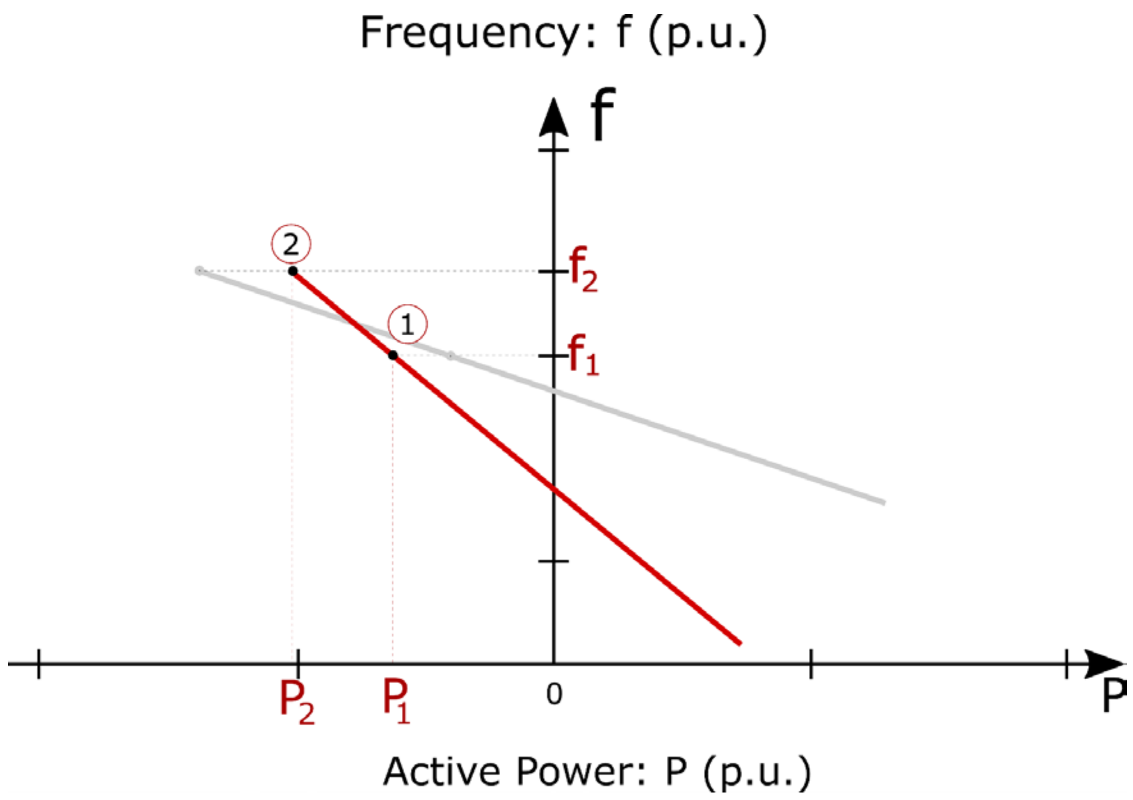


Regulate the frequency of the offshore system
Frequency droop

- Frequency droop control for offshore converters
  - Power output reduces as the frequency increases

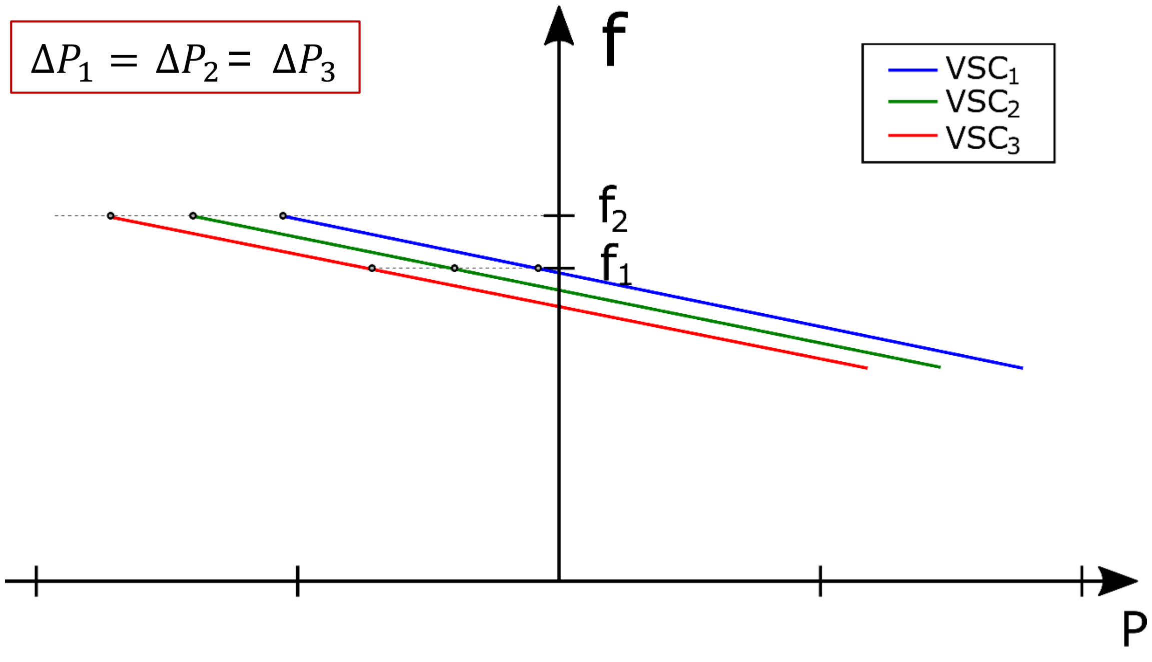
- Allows multiple converters to operate in parallel
  - Any power imbalance is shared among the converters
  - Ratio of frequency droops determine the power output of the offshore converters

- Offshore converters must operate with the same frequency at steady state



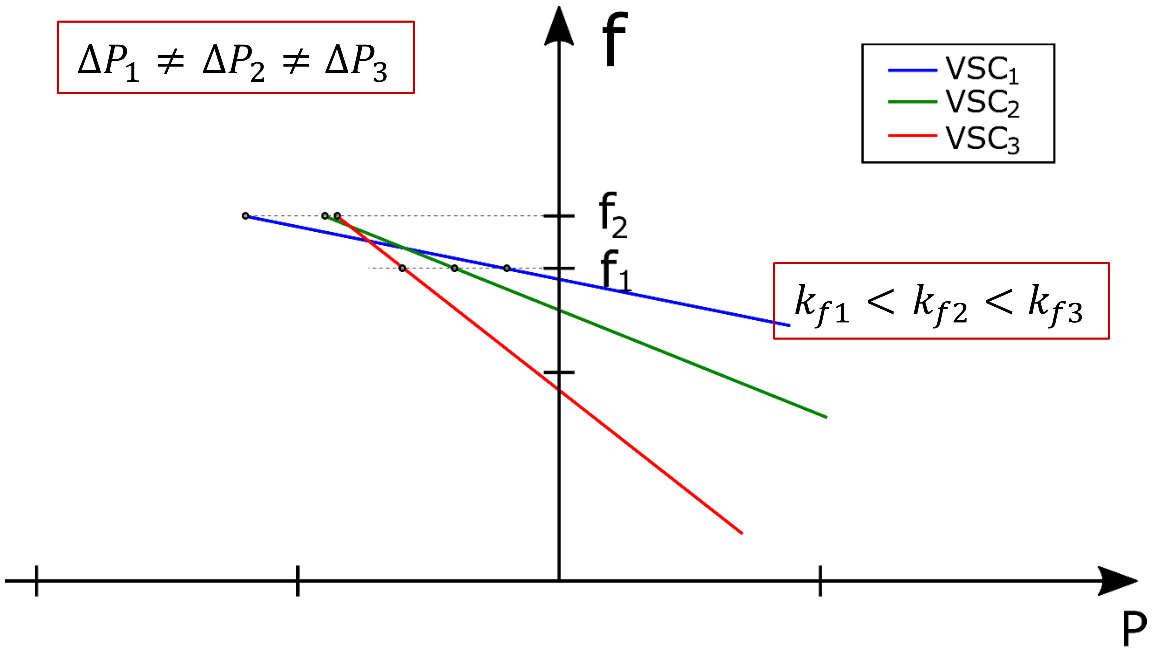
Power sharing strategies in multiple VSC-HVDC systems

Equal frequency droops



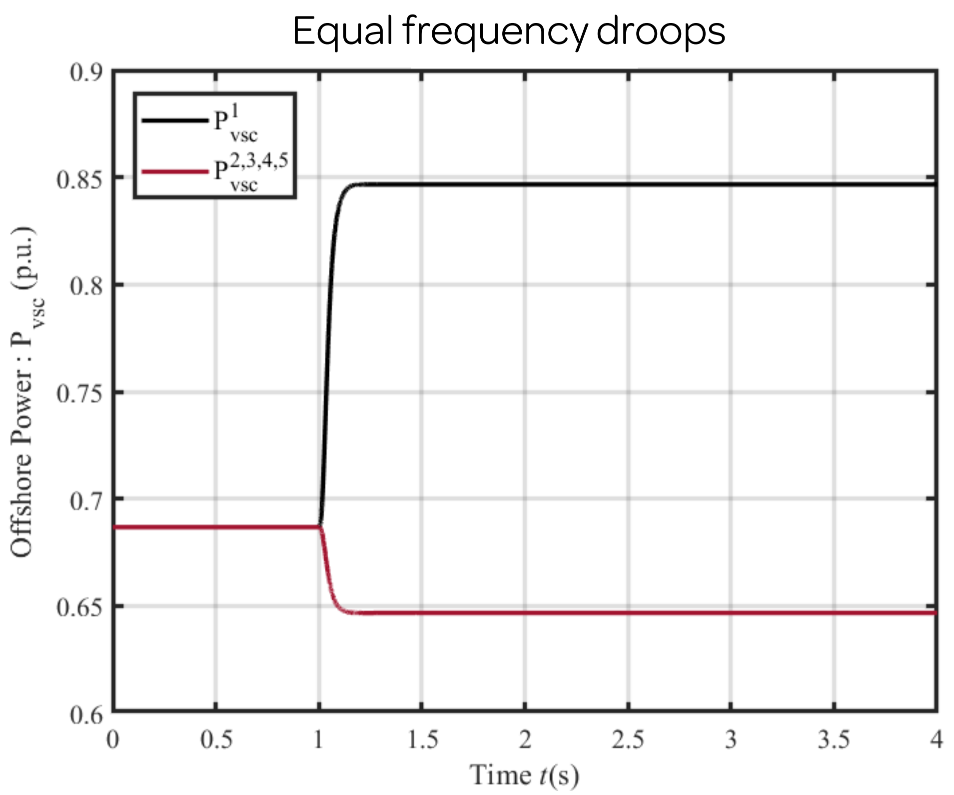
VSCs share equally any power imbalance in the offshore system

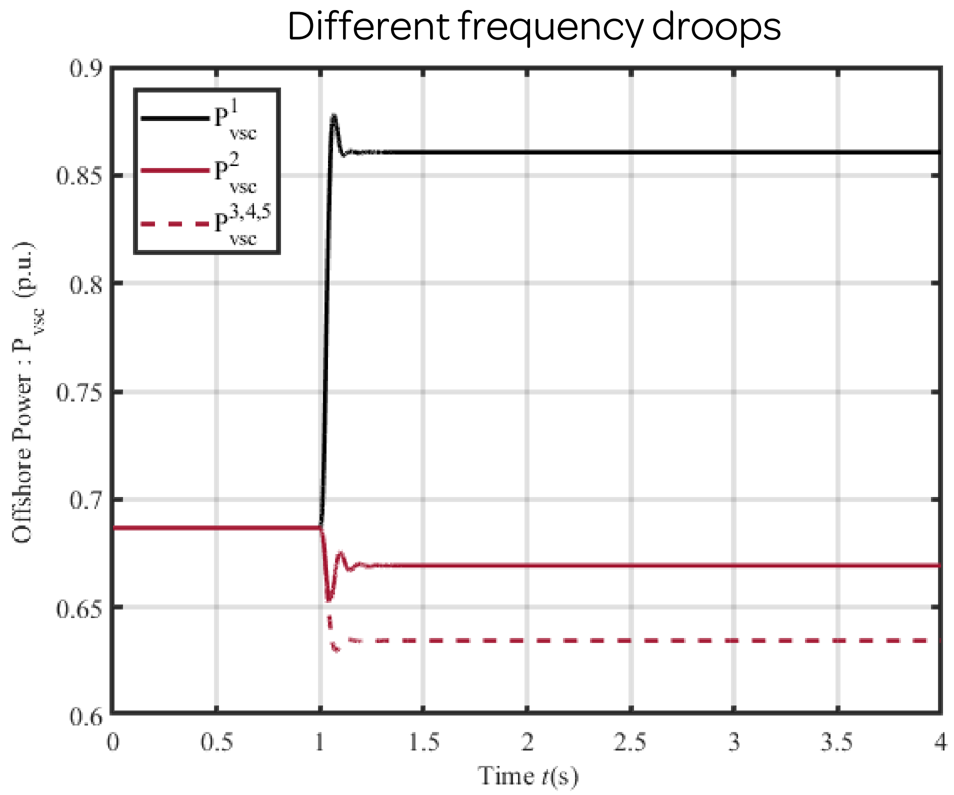
Different frequency droops



Different power sharing based on the frequency droop values

Insight #2: **Equal frequency droops perform better**



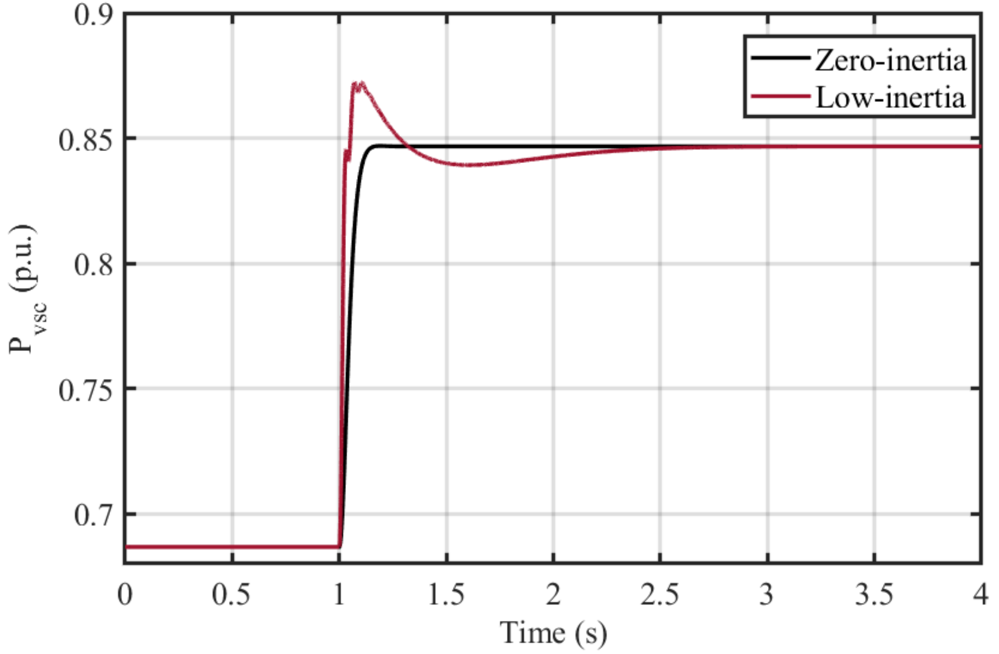


- Smooth power response – **No overshoot**
- Better power quality

Power oscillations between the offshore converters

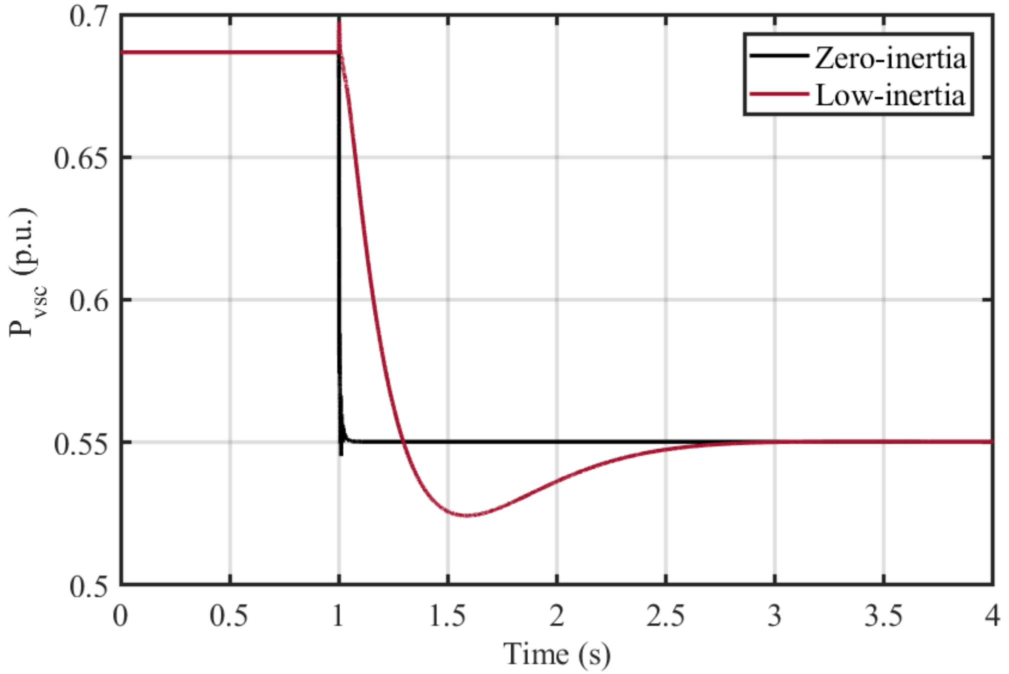
Response to disturbances

700 MW power request from one of the onshore systems



Insight #3: **Zero-inertia** configuration **preferable for providing frequency support** to the onshore grids

700 MW wind variation



Insight #4: **But,** in a zero-inertia configuration **disturbances propagate faster** to the onshore grids.

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RMS vs EMT simulations
for low- and zero-inertia systems
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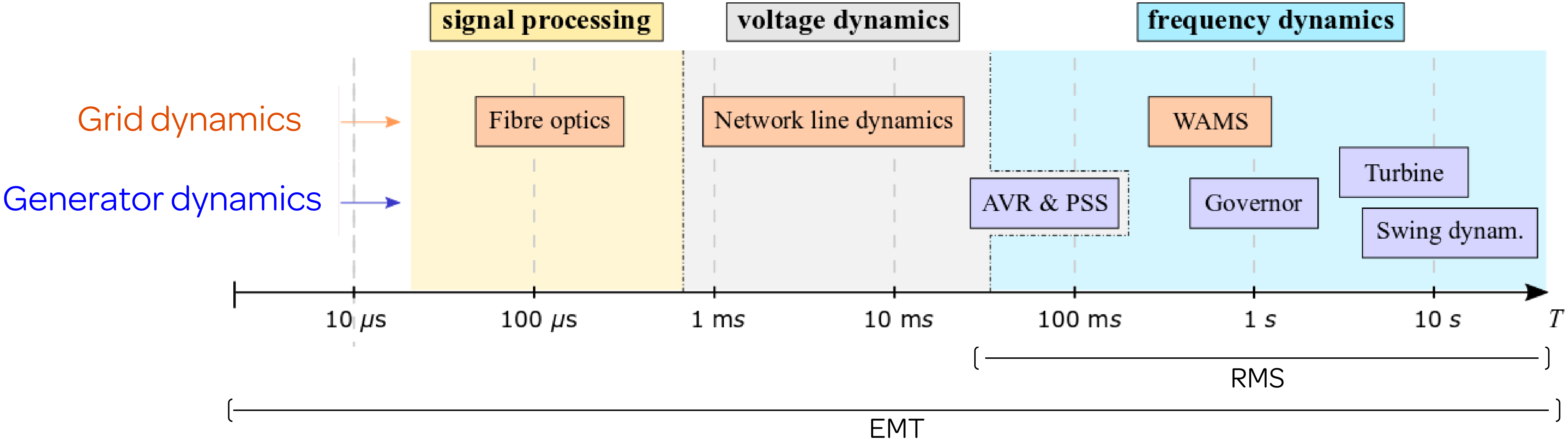
Synchronous generator-based system



- Distinct time scale separation between generator and network dynamics
  - Able to disregard the state equations describing the network dynamics
  - Network and generator dynamics are decoupled under normal operation
- EMT simulations mainly used under fault-conditions (line-switching , short-circuit fault, etc.)

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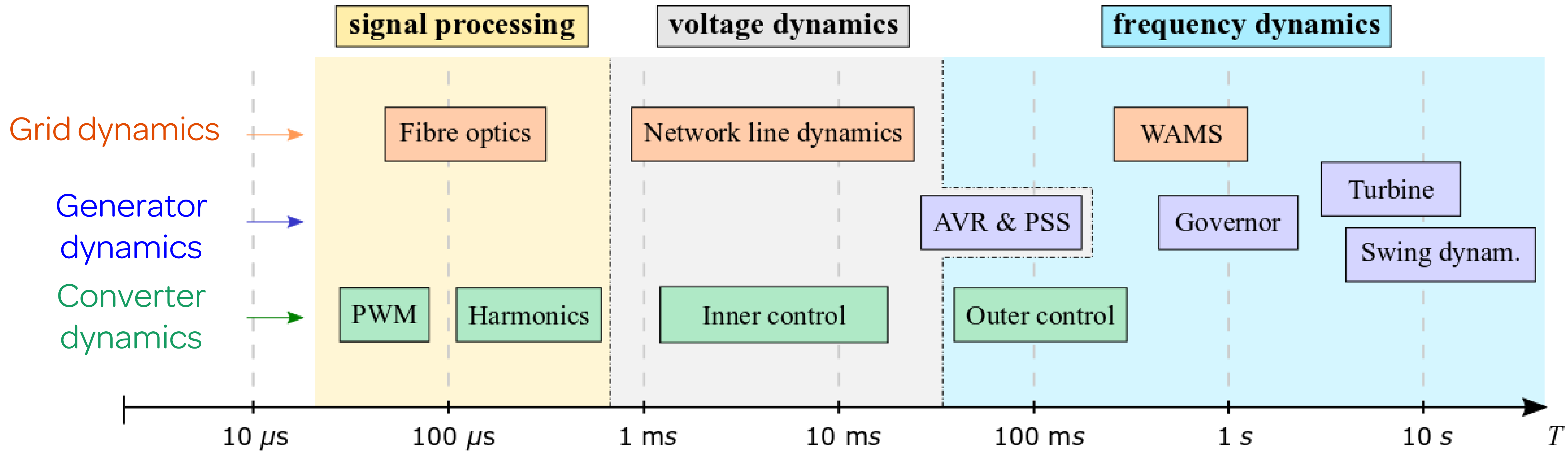
Inverter-based generation systems

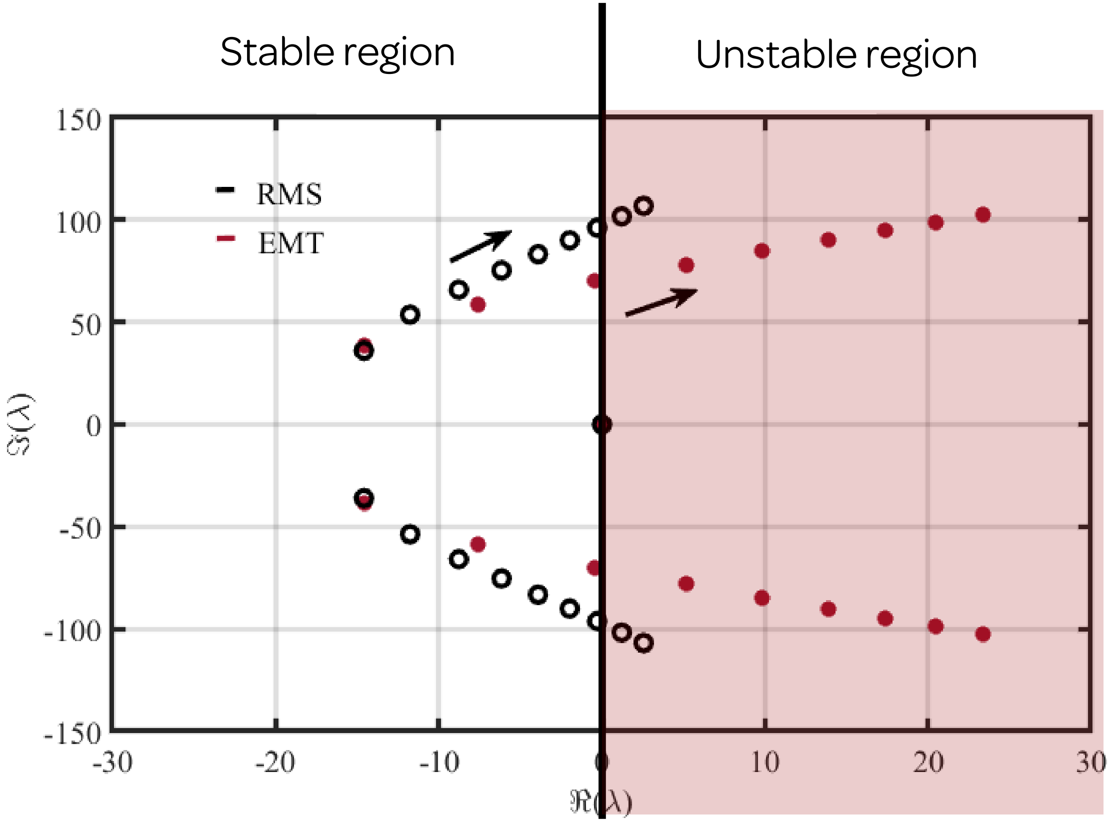


- Generation-units in zero/low inertia systems are too fast
- Overlapping of network dynamics with converter controllers

[1]: "Understanding Stability of Low-Inertia Systems", Uros Markovic, Student Member, Ognjen Stanojev, Evangelos Vrettos, Member, Petros Aristidou, and Gabriela Hug

Insight #5: **RMS simulations are not enough for zero- and low-inertia systems**

- The **dynamics** for zero/low inertia systems are **too fast**
- **RMS simulations, such as in Powerfactory, cannot capture all instabilities**
- **Need for EMT;** but EMT are very computationally intensive



The RMS model does not capture all unstable modes

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RMS simulations are not enough for zero- and low-inertia systems

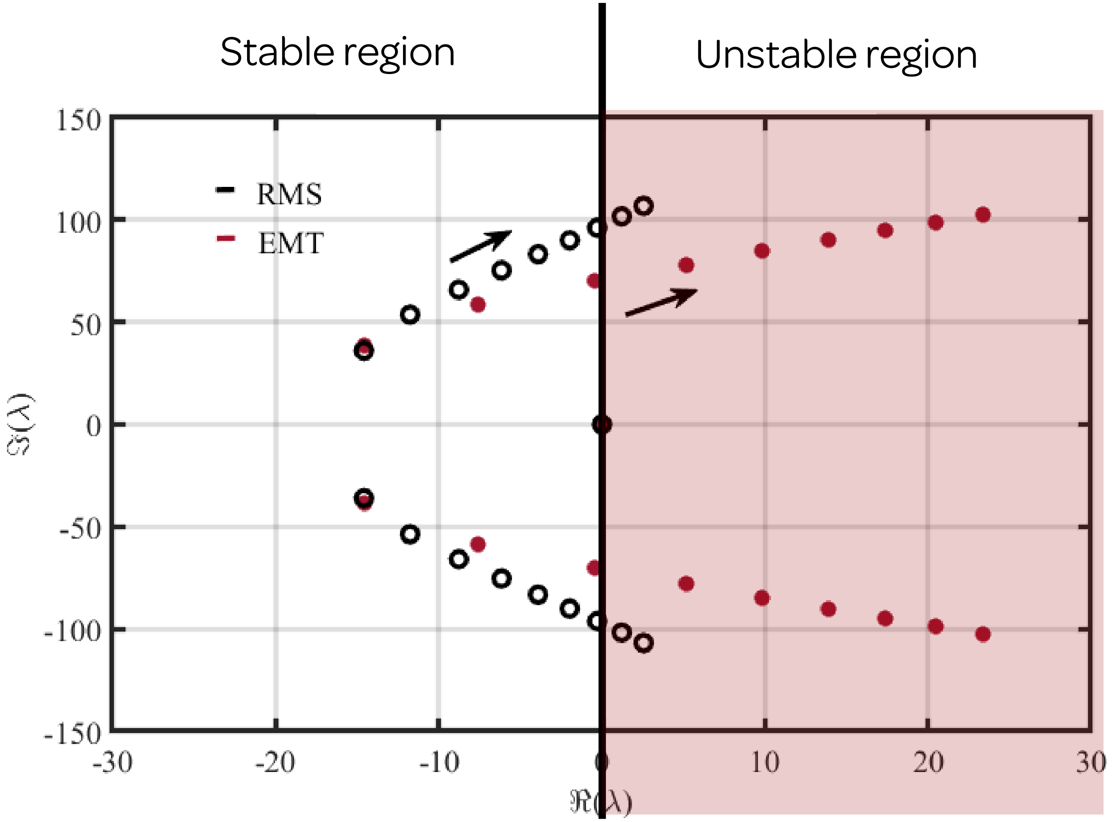
Zero-inertia systems

1. **For what** type of disturbances is **RMS still good**?

2. **For what** phenomena do we need **new simulation tools**?

Ongoing work:

RMS vs EMT: The need for new simulation tools



The RMS model does not capture all unstable modes

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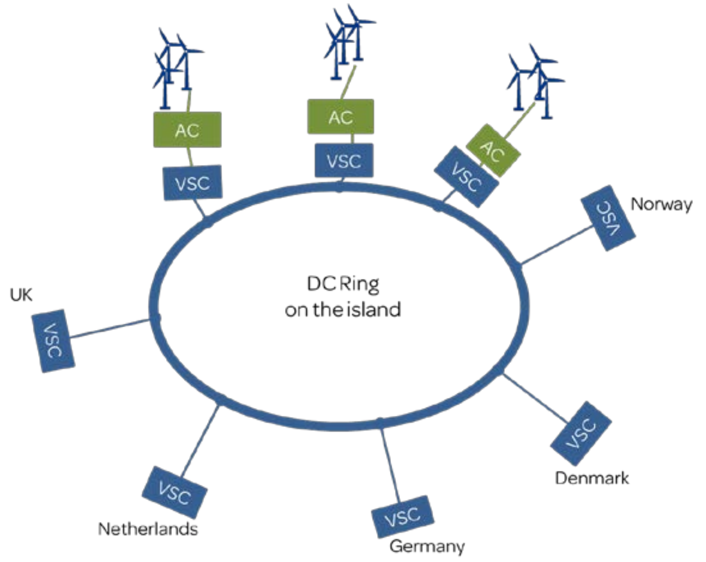
Planned Next Steps

- **North Sea Energy Hub as a "Live Lab" at PowerlabDK**
  - **RTDS:** Low inertia vs Zero inertia NSEH
    - Use of a **real controller** for the **Synchronous Condenser**
    - Use of real converters and storage



- **HVDC multi-vendor compliance with RMS-based tools**
  - Determine **requirements** for **HVDC converters** in low-/zero-inertia systems, so that **RMS tools capture all** important **transient phenomena**: Different vendors must comply with that

Coordination of HVDC (additional multiDC goals)

- HVDC corrective control as a market product
- Hopefully **test** the most promising functions **at Energinet and Svenska Kraftnät**!

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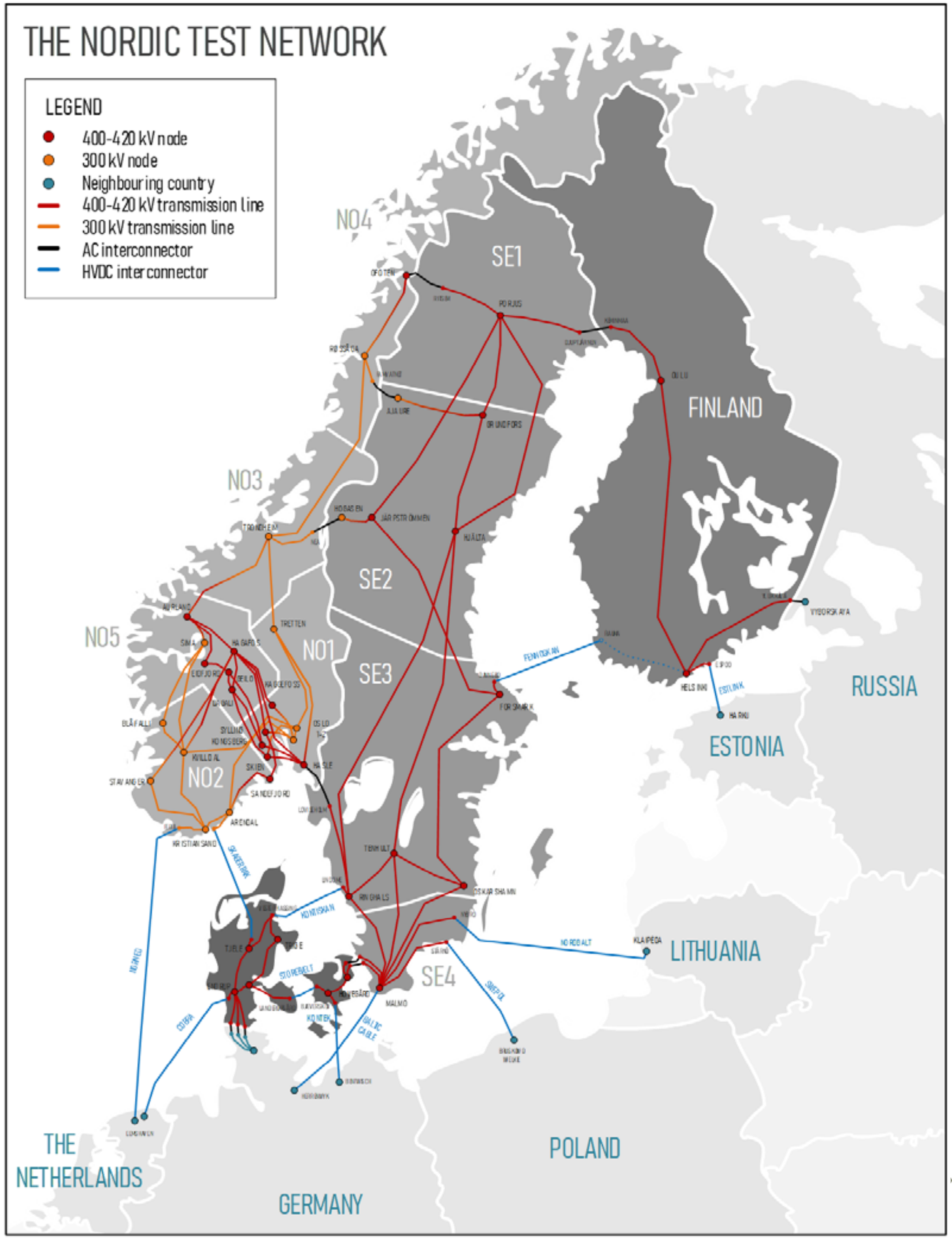
Open-source models

Nordic dynamic model

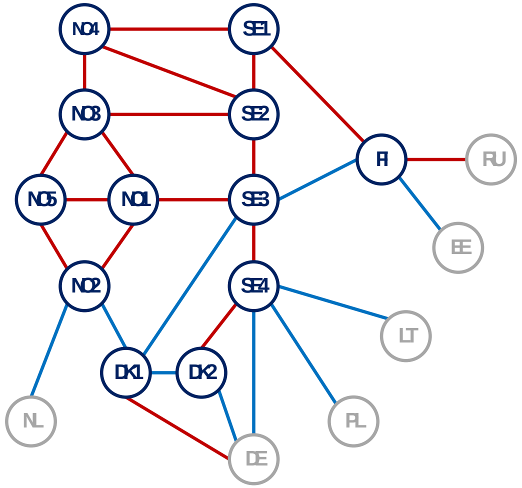
- 424 buses
- 80 synchronous machines
- 2 asynchronous areas
- **Open source** (including HVDC models)

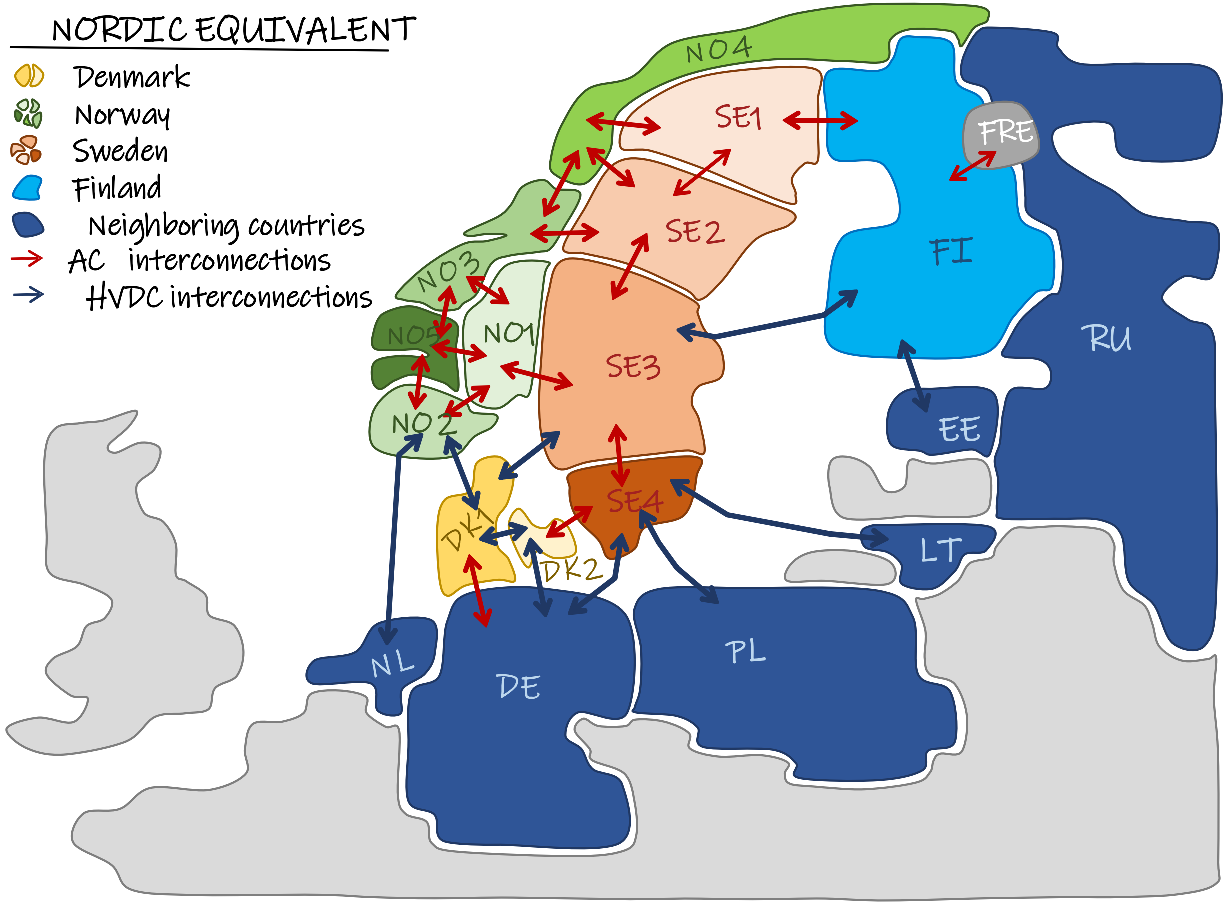
- Modeling both in RMS and EMT
- Powerfactory and RAMSES (U.Liege)



Nordic market model

- Both for **zonal and nodal** markets
- Grid reduction for flow-based market coupling
  - Estimation of the equivalent PTDF matrix





A. Tosatto, S. Chatzivasileiadis, HVDC loss factors in the Nordic Market. 2019. Submitted. https://arxiv.org/pdf/1910.05607.pdf

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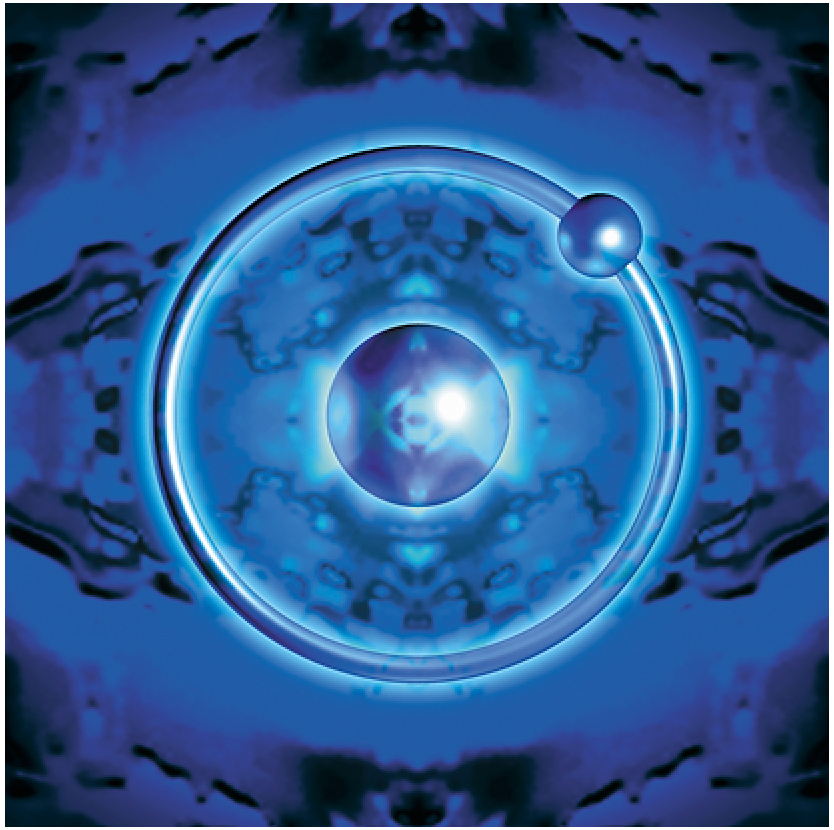
NSEH: Need for Storage?

What kind of storage makes sense for the NSEH?

- Still not clear:
  - How much do we need?
  - Should it be on the island or at the coast, distributed in different countries?

- The **most popular solution** at the moment is (possibly) a combination of:
  - **Power-to-Gas**
  - **Battery Energy Storage**

- Most popular Power-to-Gas: **Hydrogen**
  - much denser energy carrier than other options
  - but substantial losses in the conversion



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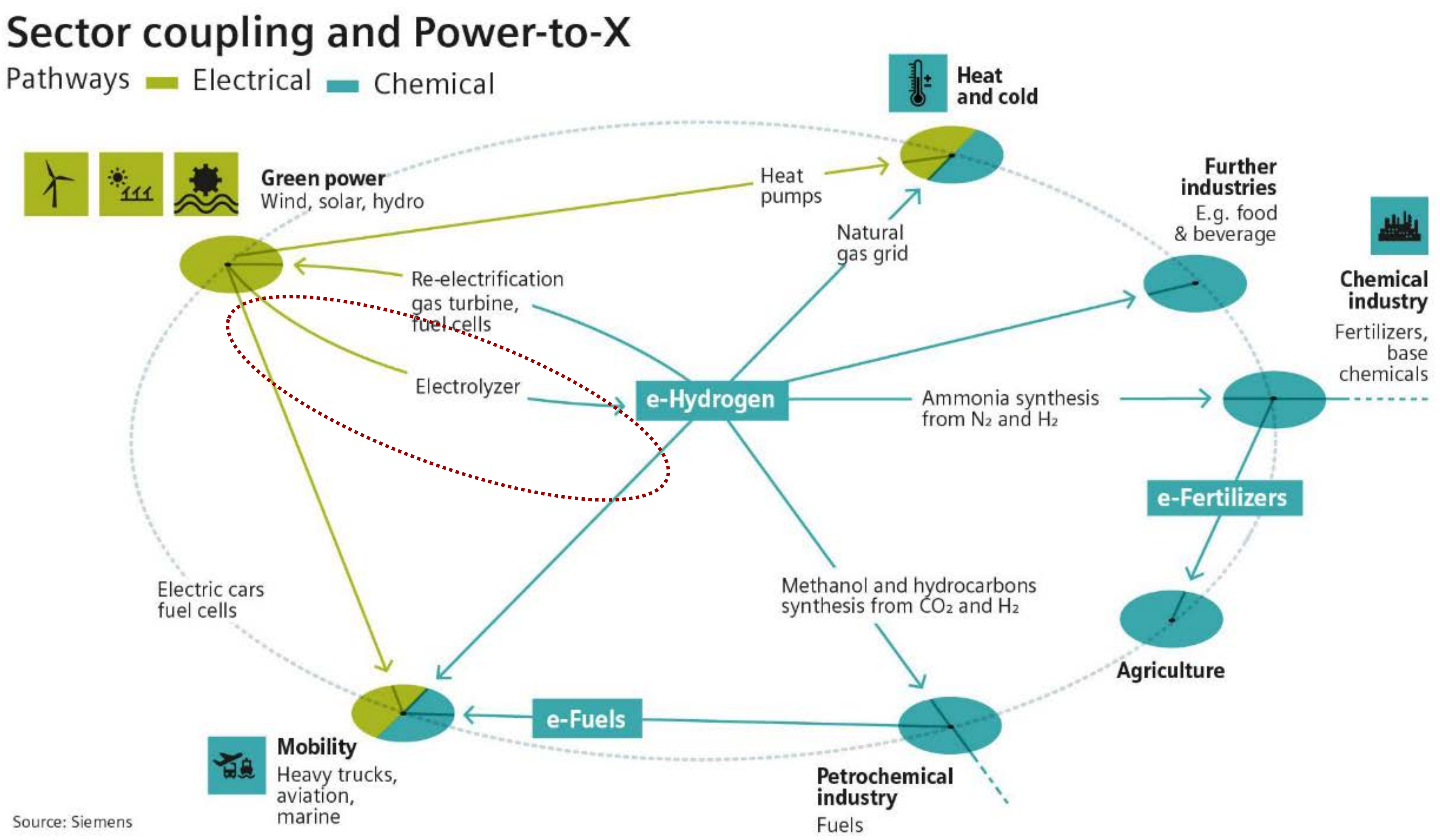
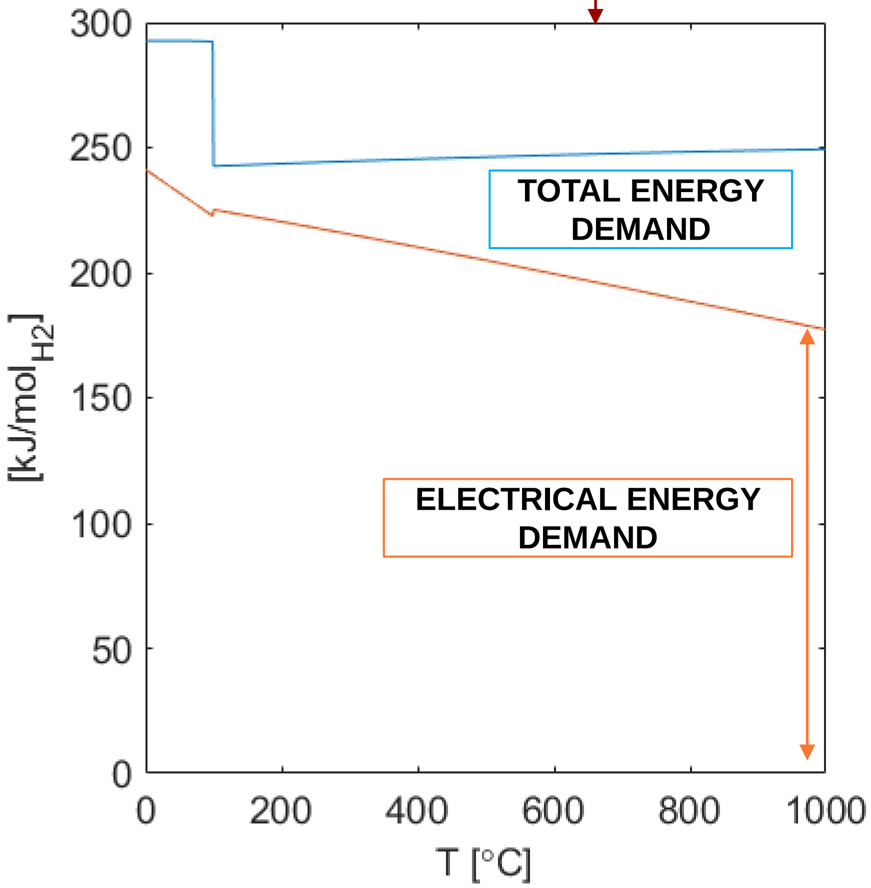
Power-to-X overview



[1]

Power-to-Hydrogen: Electricity is key

- *Electrolysis*: $2H_2O + E_{electricity} \rightarrow 2H_2 + O_2$



Power-To-Hydrogen: Technologies

	Alkaline electroliser AEL	Proton exchange membrane PEMEL	Solid oxide SOEL
Operation parameters			
Cell temperature (°C)	60–90	50–80	700–900
Typical pressure (bar)	10–30	20–50	1–15
Flexibility			
Load flexibility (% of nominal load)	20–100	0–100	−100/+100
Cold start-up time	1–2 h	5–10 min	hours
Warm start-up time	1–5 min	< 10 s	15 min
Efficiency			
Nominal system[b] efficiency (LHV)	51–60%	46–60%	76–81%
...specific energy consumption (kWh/Nm^3)	5.0–5.9	5.0–6.5	3.7–3.9

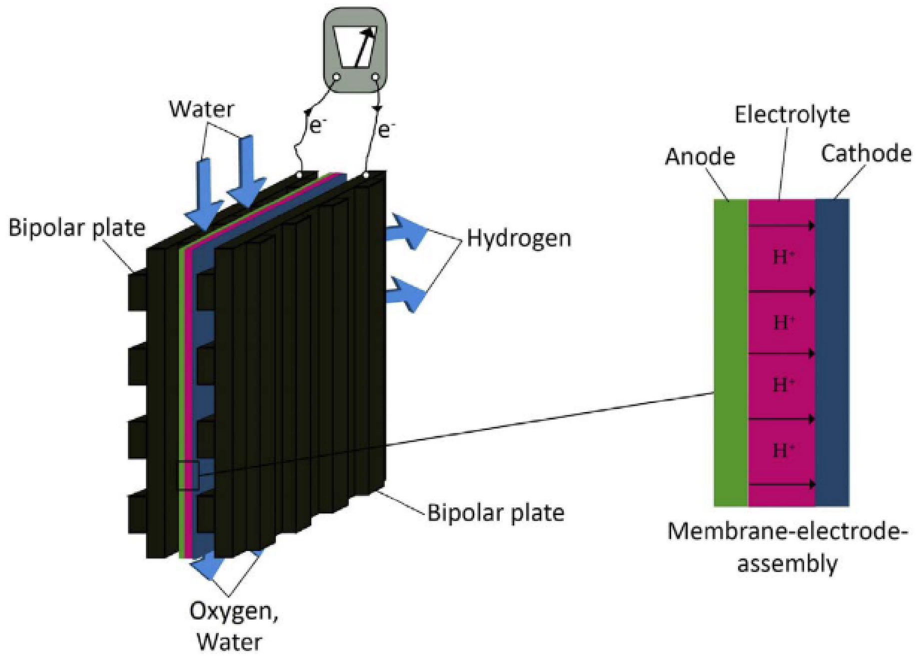


Fig. 5. Schematic representation of a PEMEL cell.

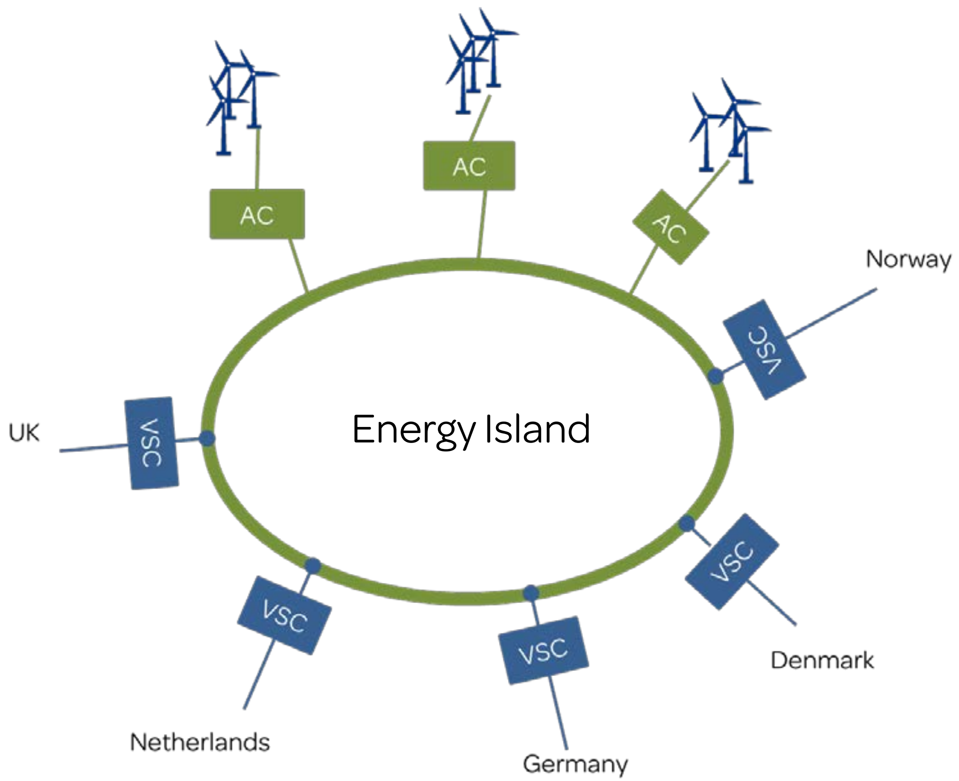
Problem statement

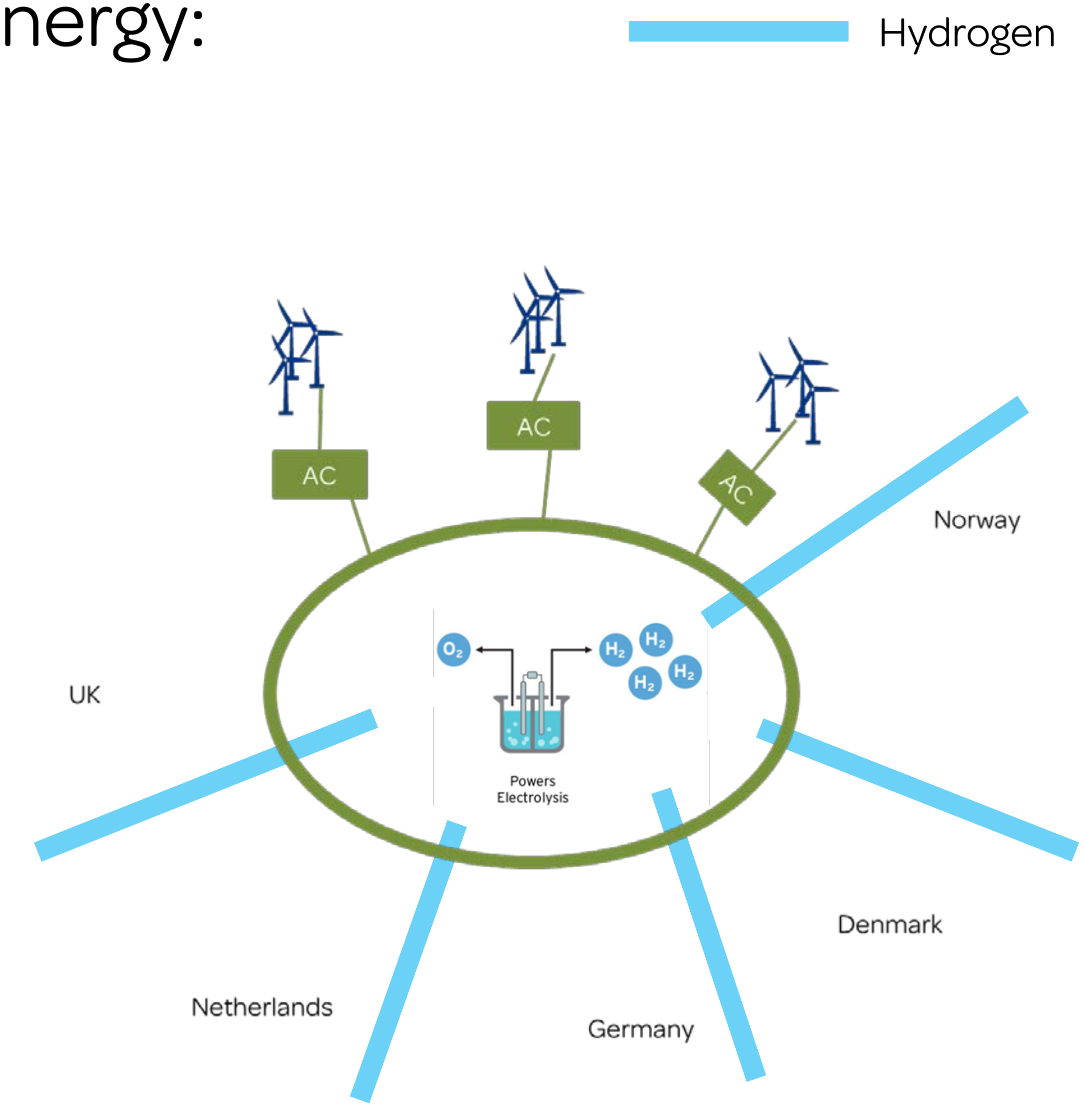
1. Investment cost comparison:

   HVDC transmission vs H_2 transmission pipelines

2. Investigation on the theoretical limits of the possible production of CH_4

Transferring the Offshore Wind Energy:
HVDC only vs HVDC+Hydrogen





Results: H_2 vs HVDC transmission

Green: H2 route

Red: HVDC

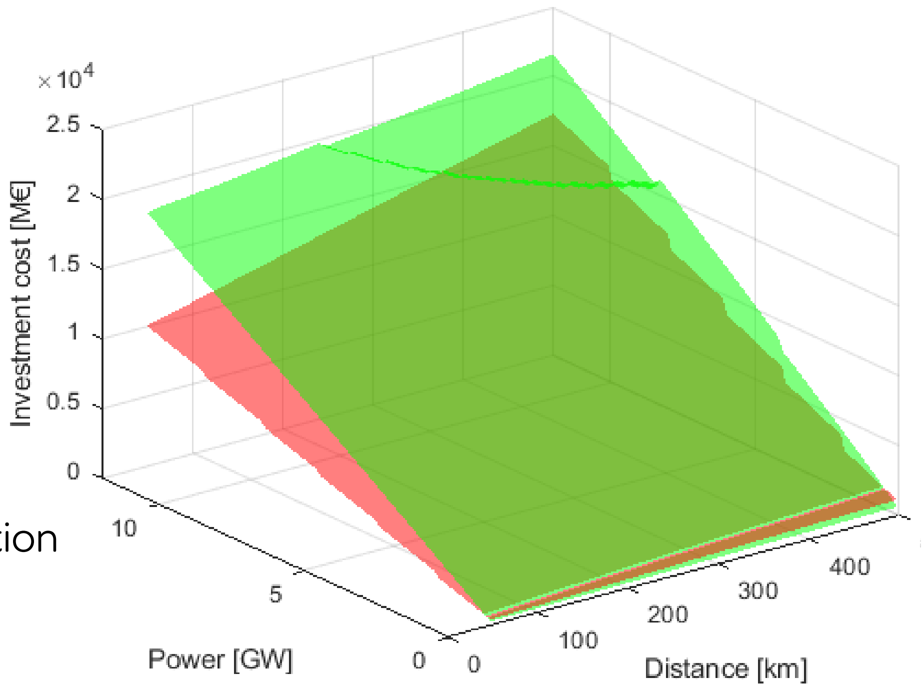
Average case scenario:

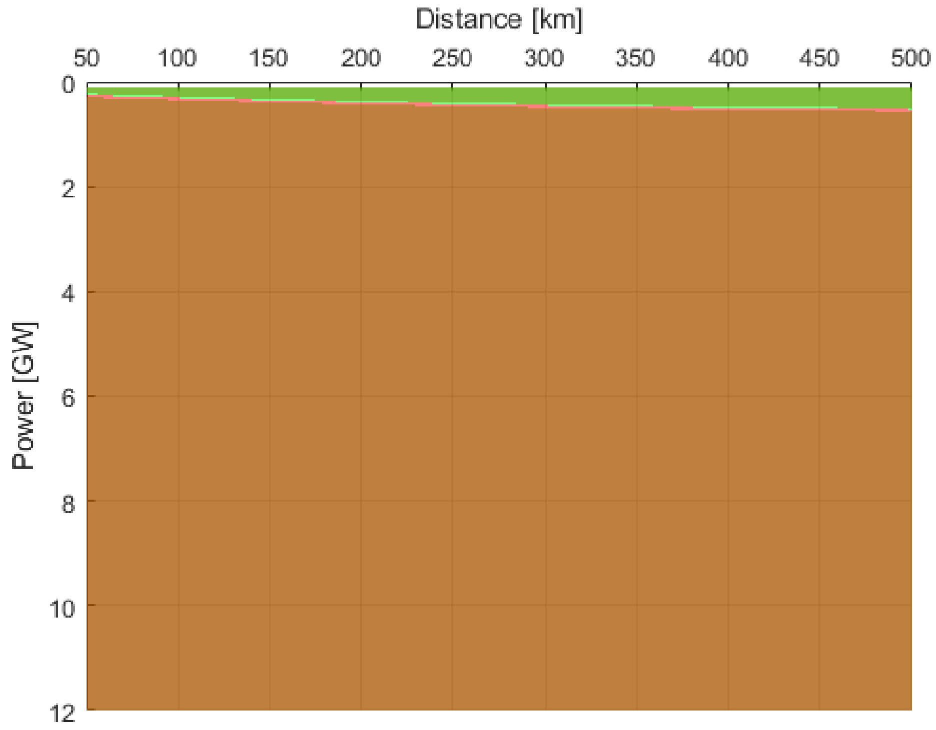
Specific Energy Consumption for Hydrogen Production

$\eta = 5.75\ kWh/Nm^3$

Investment Costs

Electrolyzer: 1,498 M€/GW





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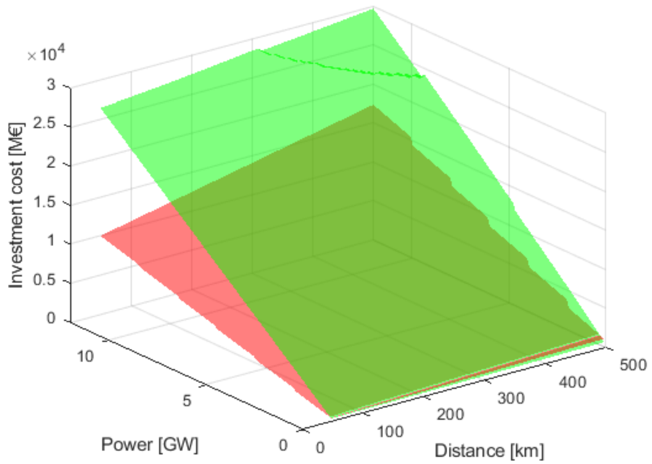
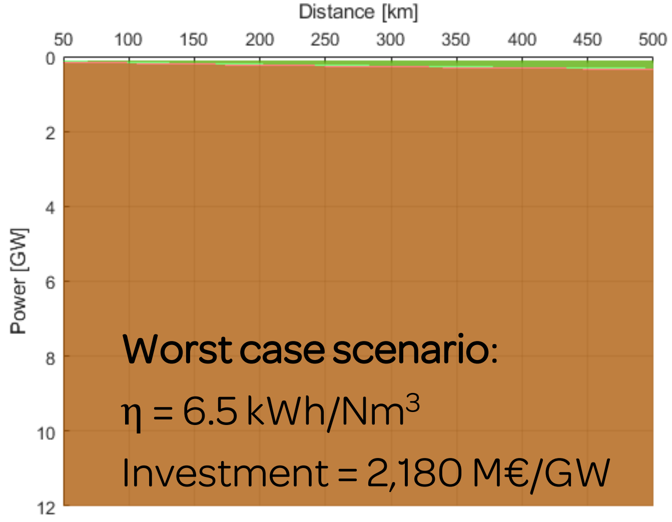
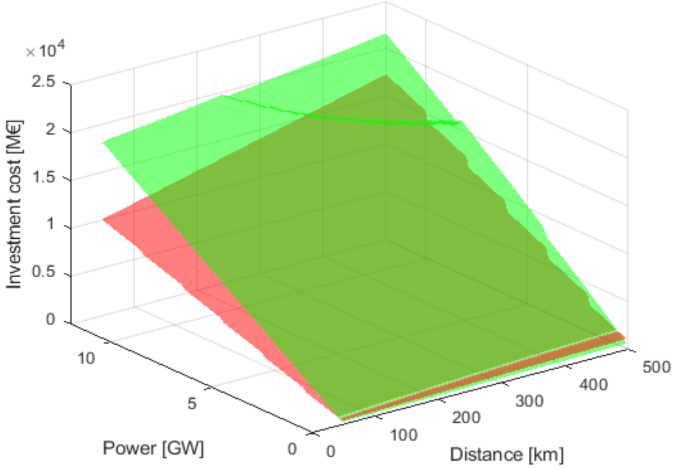
Scenario analysis

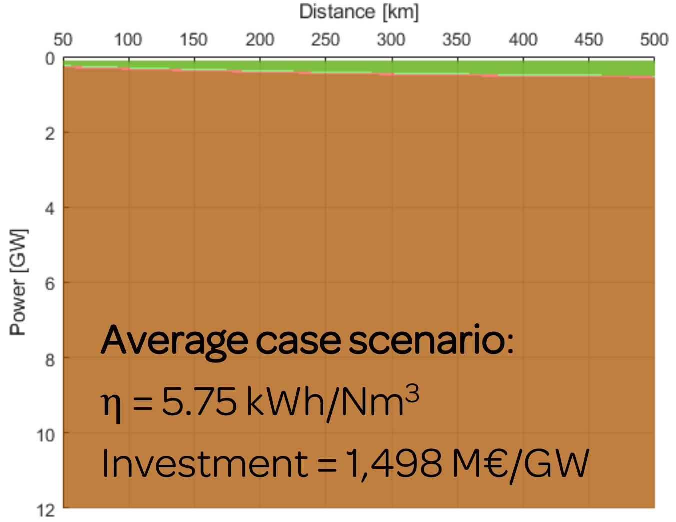
Green: H_2

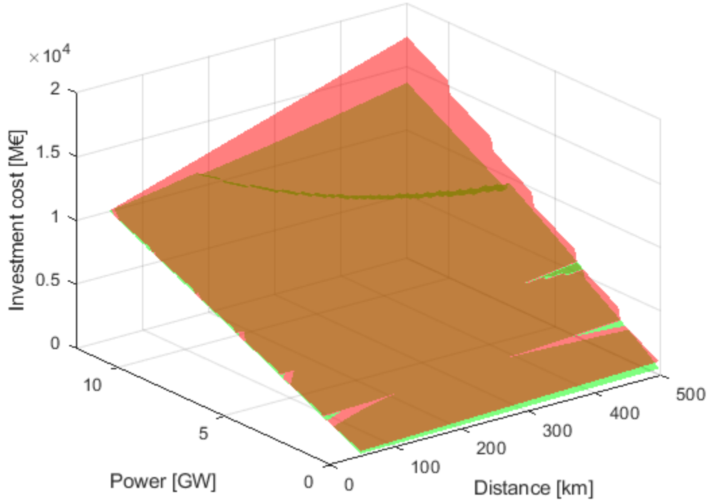
Red: HVDC

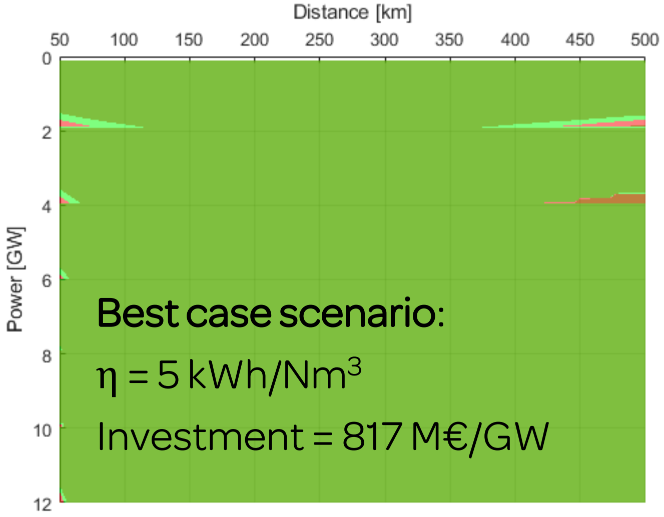












Hydrogen-to-X

X: generic product generated from H_2

C-Route

Methane (CH_4):

Sabatier:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Methanol (CH_3OH):

Methanolisation: $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Reverse water-gas shift: $CO_2 + H_2 \rightarrow CO + H_2O$

Hydrogenation: $CO + 2H_2 \rightarrow CH_3OH$

Other hydrocarbons…

N-Route

Ammonia (NH_3):

Haber-Bosch: $N_2 + 3H_2 \rightarrow 2NH_3$

In need of CO_2 and/or N_2 to have a full PtX conversion

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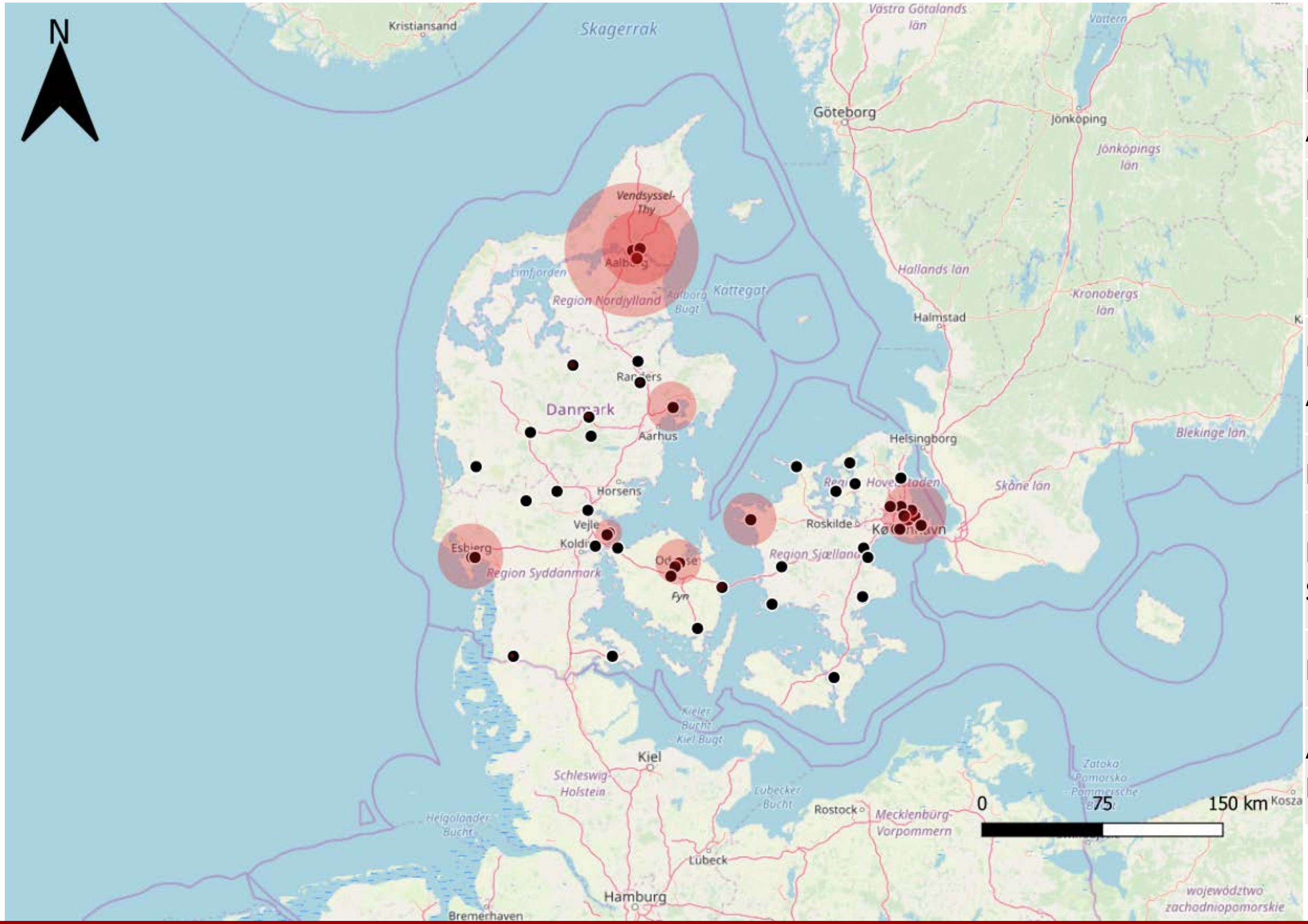
CO_2 Sources

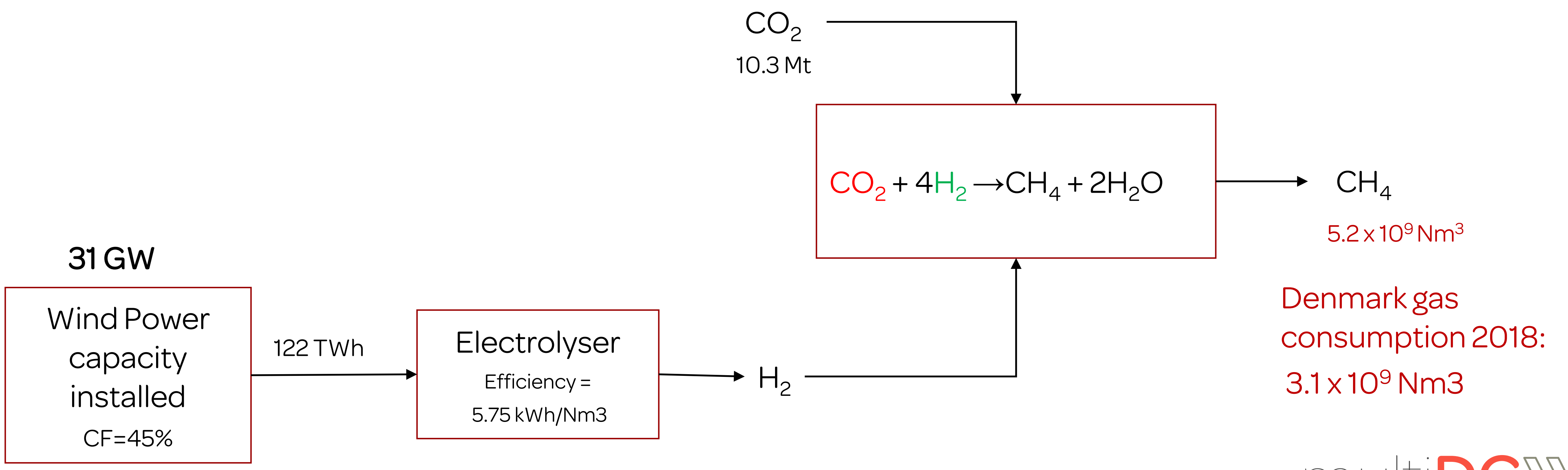
Total CO_2 Production in Denmark = 10.3 Mt/a



Name	Location	CO2 [Mt/a]
Aalborg Portland A/S	Aalborg Øst	2.19
Nordjyllandsværket	Vodskov	1.22
DONG Energy A/S – Esbjergværket	Esbjerg	1.07
HOFOR Energiproduktion A/S Amagerværket	København S	1.04
DONG ENERGY POWER A/S	Kalundborg	0.87
DONG ENERGY POWER A/S, Studstrupværket	Skødstrup	0.83
Fjernvarme Fyn Produktion A/S	Odense C	0.75
A/S DANSK SHELL SHELL-RAFFINADERIET	Fredericia	0.44

CH_4 production estimation

- **Converting the total CO2 production of Denmark to CH4**:
  - Needs **31 GW of offshore wind** (45% capacity factor)
  - Produces **enough CH4 to cover 1.7 times** the gas needs for Denmark



Conclusions

- Exciting times! A series of challenges ahead

- The North Sea Energy Hub breaks ground towards the massive integration of offshore wind energy
  - Potential coupling with Power-to-Gas technologies
  - A series of technical and regulatory questions seeking an answer!

- Operation of a zero-inertia AC system
  - How should we coordinate the operation of HVDC converters (N-1 security, droop-frequency control)
  - How does the zero-inertia system respond to disturbances?
  - The need for new simulation tools (RMS vs EMT)

- What is the impact of Power-to-Gas + Electricity Coupling?

Thank you!

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