Offshore Wind and Grids

Nicolaos A. Cutululis

Agenda

- Offshore wind
- Electrical concepts
- Transmission and grids
- Trends


Photo of Risø site of DTU Wind Energy

A little about me

- Wind power research since 1998, with PhD in wind turbine electrical control

- Professor in ”Offshore wind grid integration”, leading a
a group on offshore wind grid connection and integration

- Main research area is wind power integration:
  - Offshore wind technology, offshore grids, HVDC, electrical infrastructure design
  - Wind power control: wind turbine control, wind power plant control, capabilities for ancillary services
  - Modelling of wind power variability

- Principal investigator for EU, Nordic and Danish projects
- Supervision and Teaching at M.Sc and Ph.D level

Denmark as a wind energy nation

- From niche technology to a global leading, cost competitive industry
- In Denmark, 1 out of every 50 employees in the private sector is employed in the wind turbine industry
- Denmark is the country with the highest share of wind energy in its electricity demand (50% in 2020).

Danish wind sector had a 112.5 billion DKK revenue in 2017

Export worth 54.4 billion DKK in 2017 – 6.7 percent of the total Danish export income

More than 33.000 people are employed in the the Danish wind energy sector

Danish Wind Industry Association

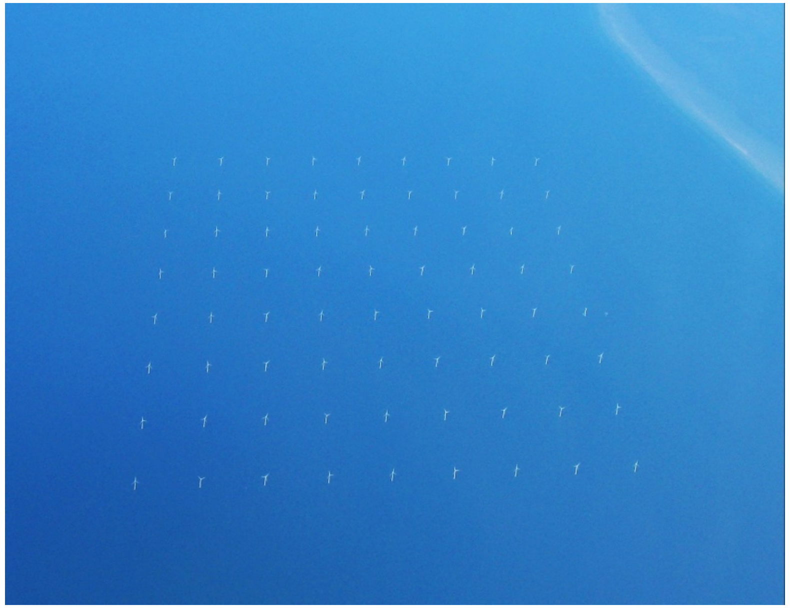
Denmark - a leader in offshore wind…

Vindeby, 4.65 MW, 1991 - 2017

Horns Rev 1, 160 MW, 2002

http://www.ecology.com/2012/04/12/fish-thrive-offshore-wind-farm/

Nysted 1, 166 MW, 2003



By Plenz - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=4222138

...DK home to the most shown picture ever!!

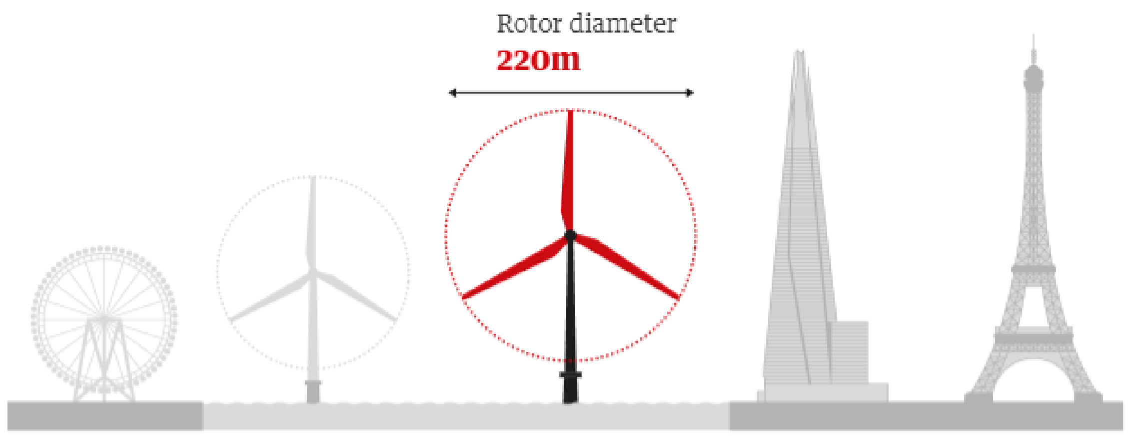
Horns Rev 1

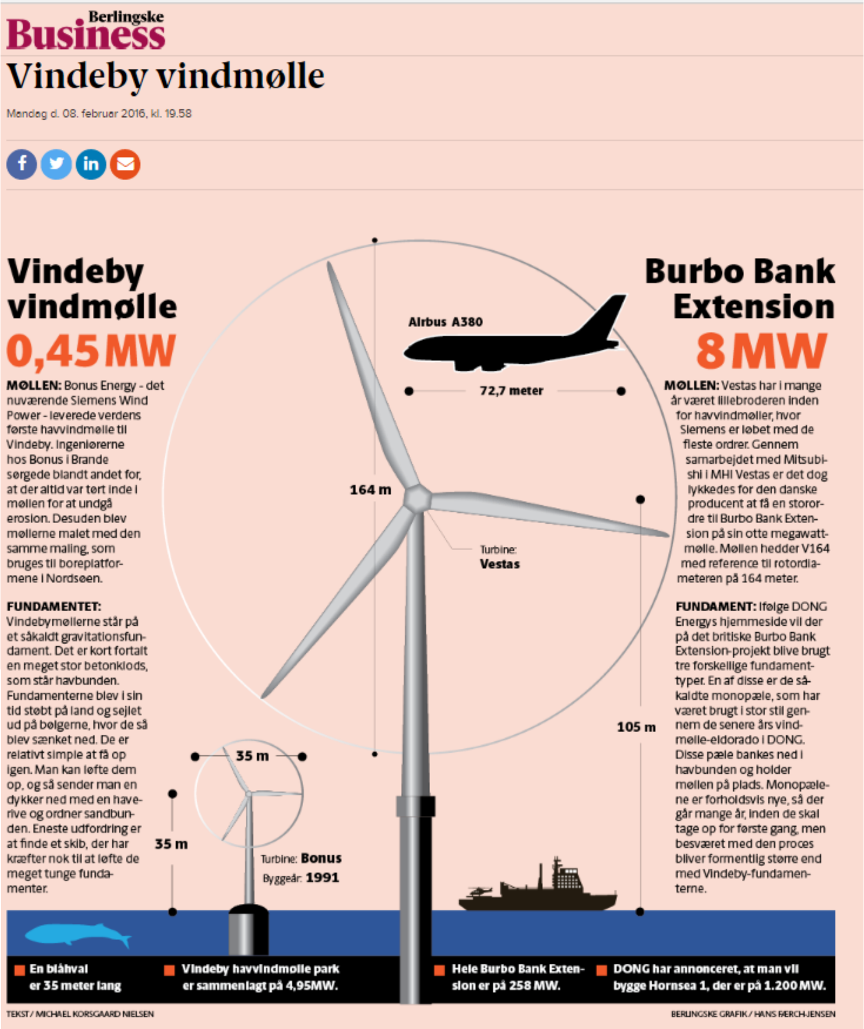
Horns Rev 2

Offshore wind – how big is big?

Ørsted to Use GE Haliade-X 12 MW on US Offshore Wind Farms

Ørsted has selected GE Renewable Energy as the preferred turbine supplier for two of its US offshore wind farms which marks the world's first commercial deployment of GE's Haliade-X 12 MW offshore wind turbine.





Berlingske Business

Vindeby vindmølle

Mandag d. 08. februar 2016, kl. 19.58

Vindeby vindmølle
0,45 MW

MØLLEN: Bonus Energy - det nuværende Siemens Wind Power - leverede verdens første havvindmølle til Vindeby. Ingeniørerne hos Bonus i Brande sørgede blandt andet for, at der altid var tørt inde i møllen for at undgå erosion. Desuden blev møllerne malet med den samme maling, som bruges til boreplatformene i Nordsøen.

FUNDAMENTET: Vindebymøllerne står på et såkaldt gravitationsfundament. Det er kort fortalt en meget stor betonklods, som står havbunden. Fundamenterne blev i sin tid støbt på land og sejlet ud på bølgerne, hvor de så blev sænket ned. De er relativt simple at få op igen. Man kan løfte dem op, og så sender man en dykker ned med en haverive og ordner sandbunden. Eneste udfordring er at finde et skib, der har kræfter nok til at løfte de meget tunge fundamenter.

Burbo Bank Extension
8 MW

MØLLEN: Vestas har i mange år været lillebroderen inden for havvindmøller, hvor Siemens er løbet med de fleste ordrer. Gennem samarbejdet med Mitsubishi i MHI Vestas er det dog lykkedes for den danske producent at få en stor ordre til Burbo Bank Extension på sin otte megawatt-mølle. Møllen hedder V164 med reference til rotordiameteren på 164 meter.

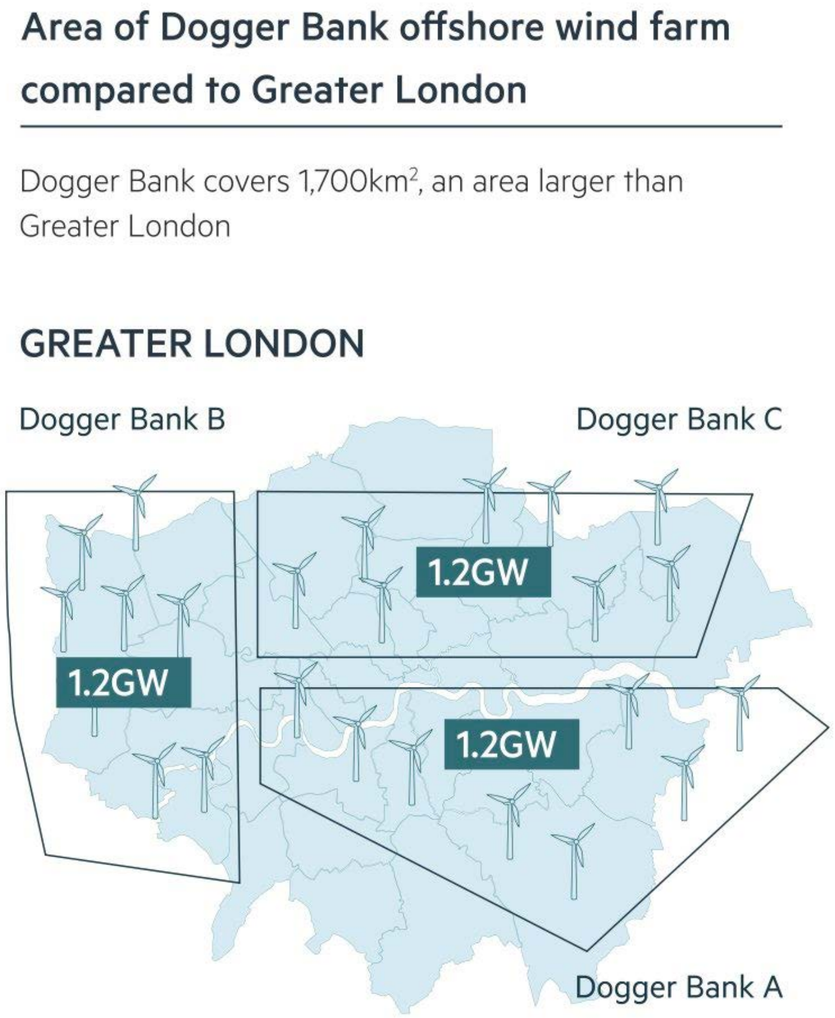
FUNDAMENT: Ifølge DONG Energys hjemmeside vil der på det britiske Burbo Bank Extension-projekt blive brugt tre forskellige fundamenttyper. En af disse er de såkaldte monopæle, som har været brugt i stor stil gennem de senere års vindmølle-eldorado i DONG. Disse pæle bankes ned i havbunden og holder møllen på plads. Monopælene er forholdsvis nye, så der går mange år, inden de skal tage op for første gang, men besværet med den proces bliver formentlig større end med Vindeby-fundamenterne.

- En blåhval er 35 meter lang
- Vindeby havvindmølle park er sammenlagt på 4,95MW.
- Hele Burbo Bank Extension er på 258 MW.
- DONG har annonceret, at man vil bygge Hornsea 1, der er på 1.200 MW.

TEKST / MICHAEL KORSGAARD NIELSEN

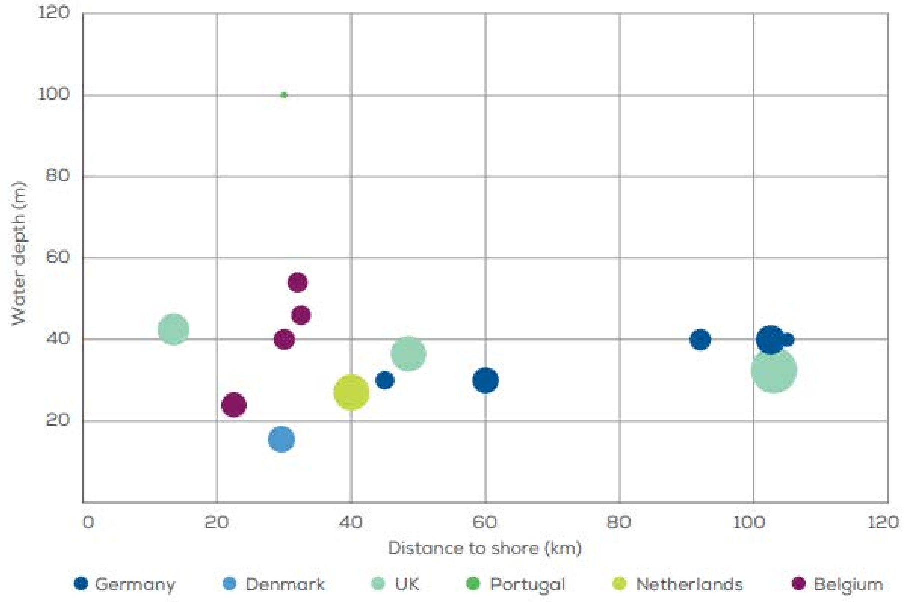
BERLINGSKE GRAFIK / HANS FÆRCH-JENSEN

Offshore wind – how large is large?



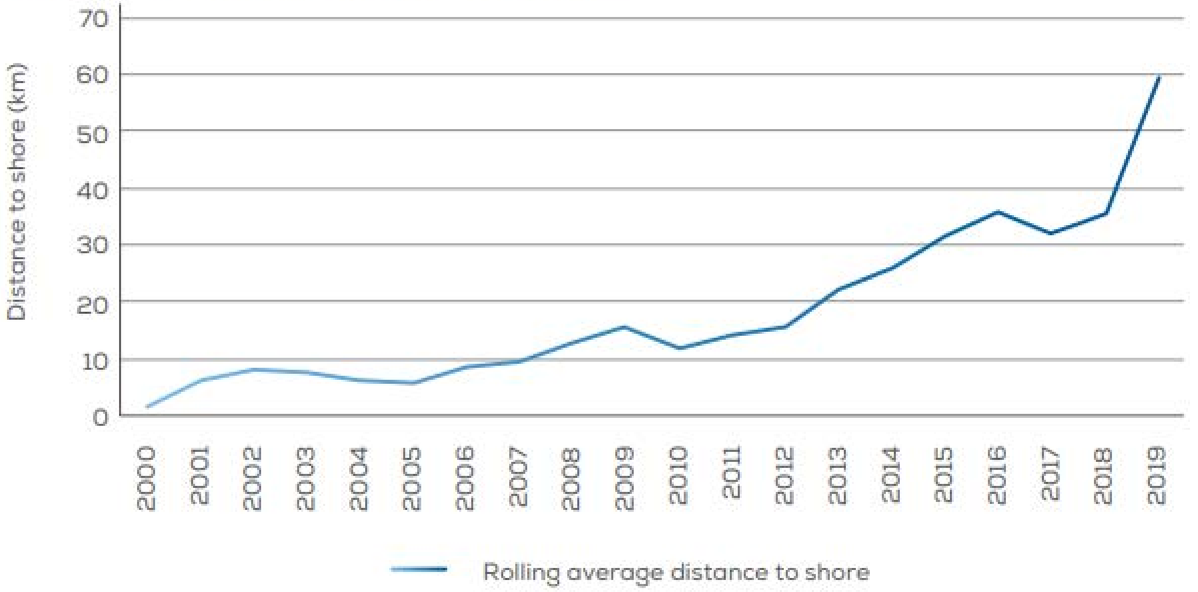
Offshore wind – how far is far?

FIGURE 8
Average water depth and distance to shore of offshore wind farms under construction during 2019. The size of the bubble indicates the capacity of the site



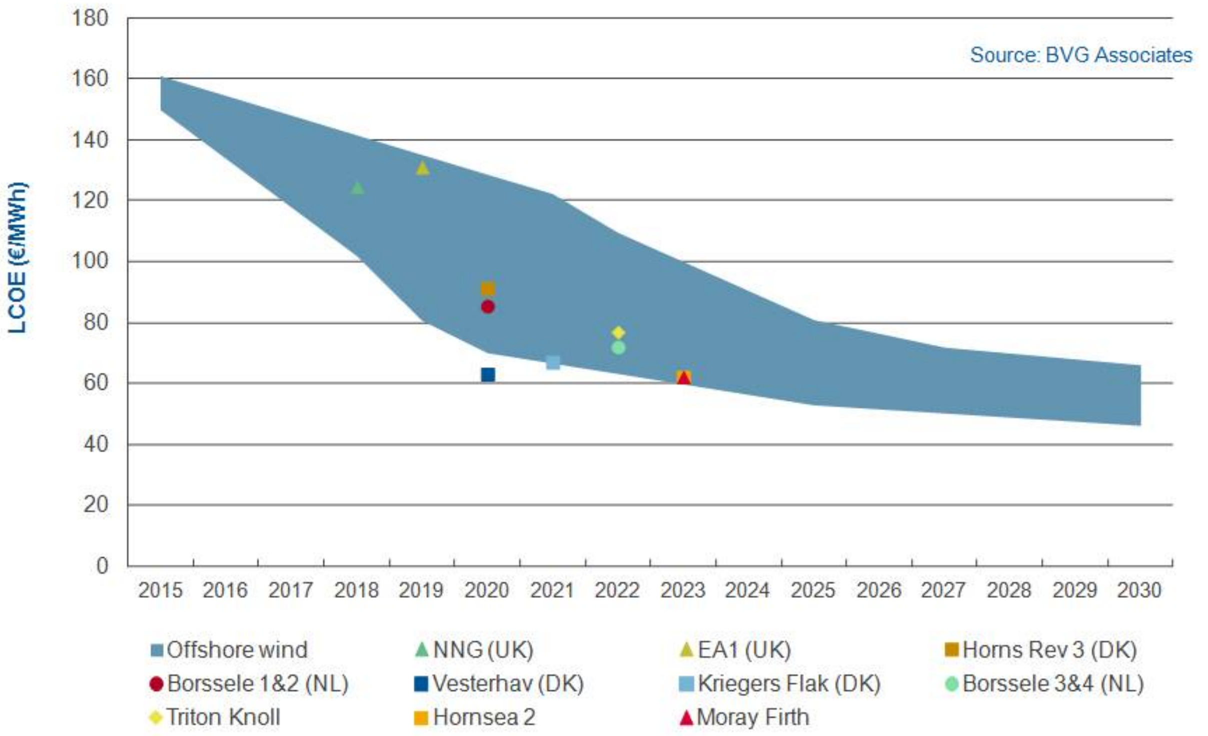
Source: WindEurope

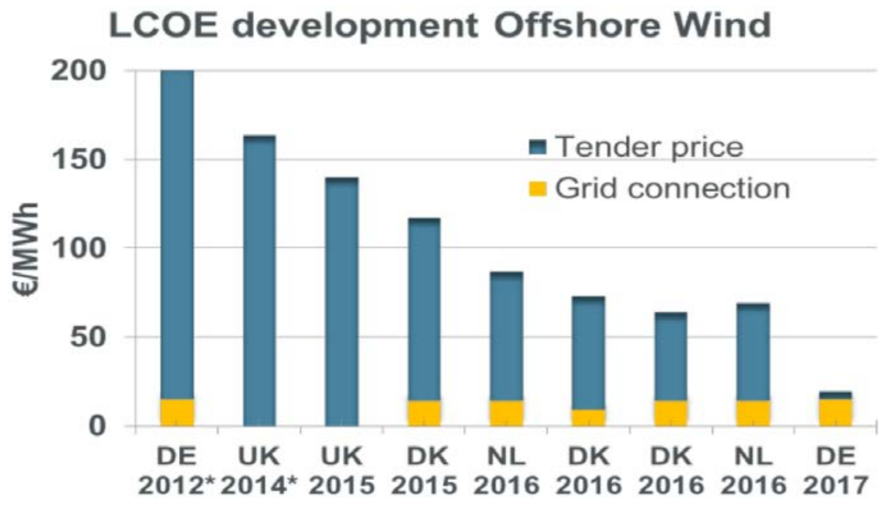
FIGURE 10
Rolling average distance to shore of online offshore wind farms



Source: WindEurope

Offshore wind cost reduction ....but





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

Source: North Sea Energy Infrastructure: Status and outlook, TenneT, Deepwind 2019

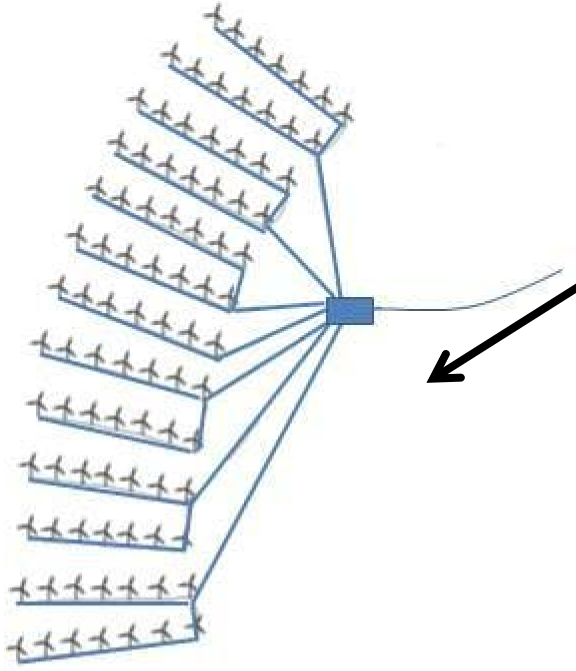
[...] *this is mainly from technology innovations in turbines and installation, and reductions in financing costs* [...]
WindEurope

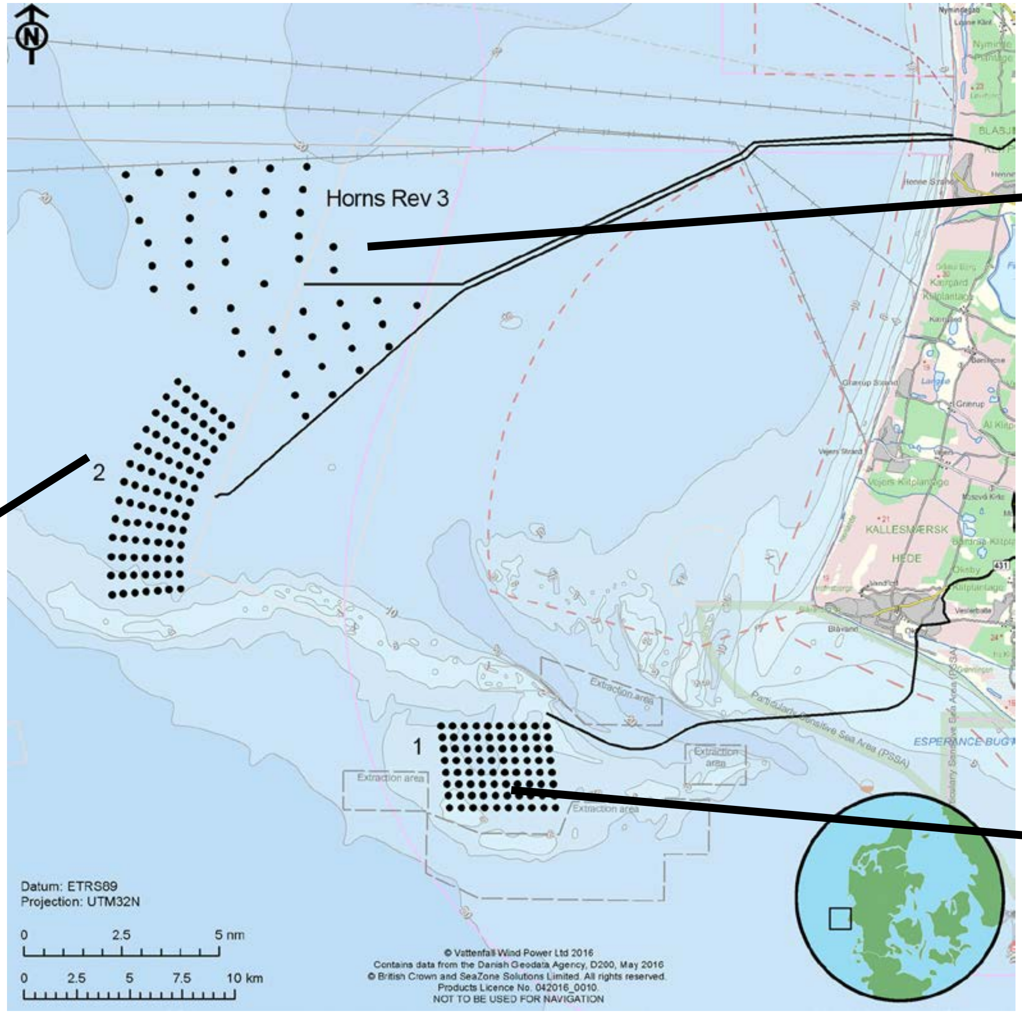
Wind farm layouts

Horns Rev 2

91 WT x 2.3 MW=209 MW

Operational 2009

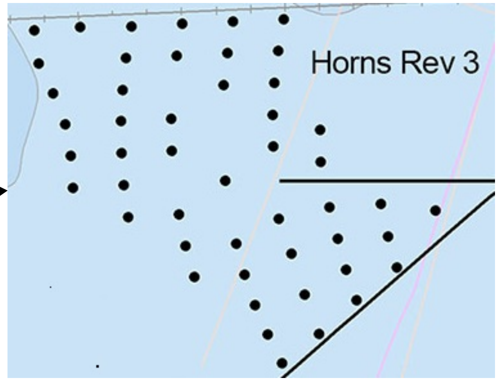




Horns Rev 3

49 WT x 8.3 MW=406.7 MW

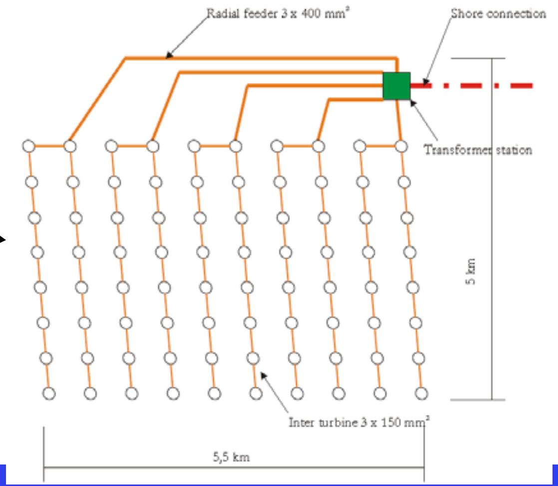
Operational 2019



Horns Rev 1

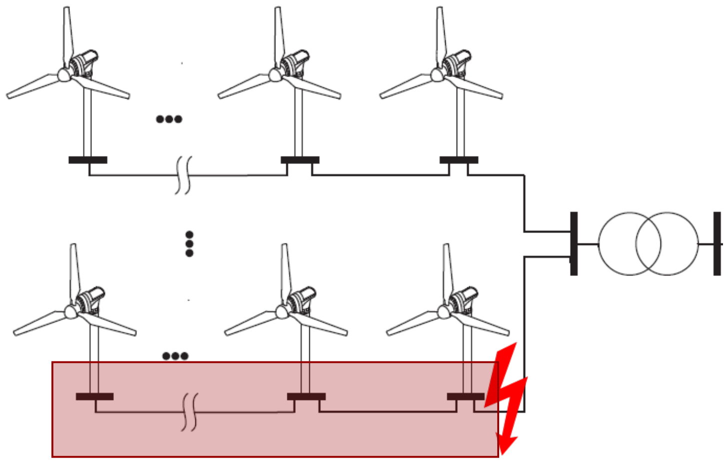
80 WT x 2.0 MW=160 MW

Operational 2003

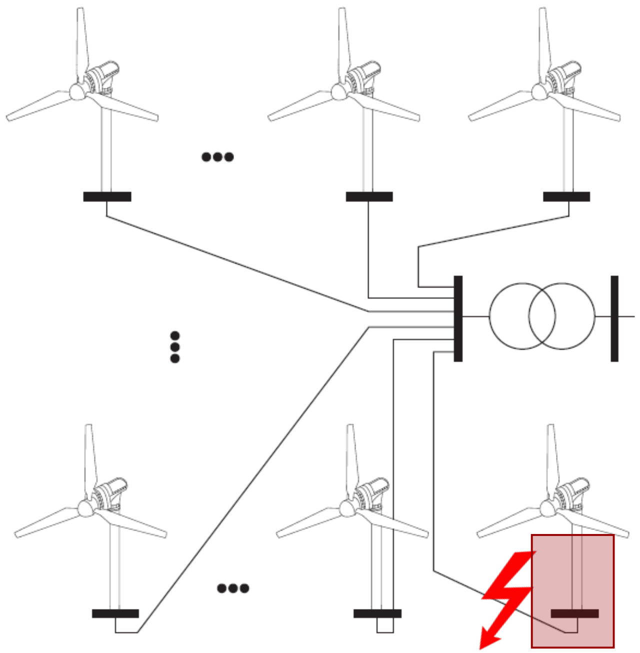


Collection system

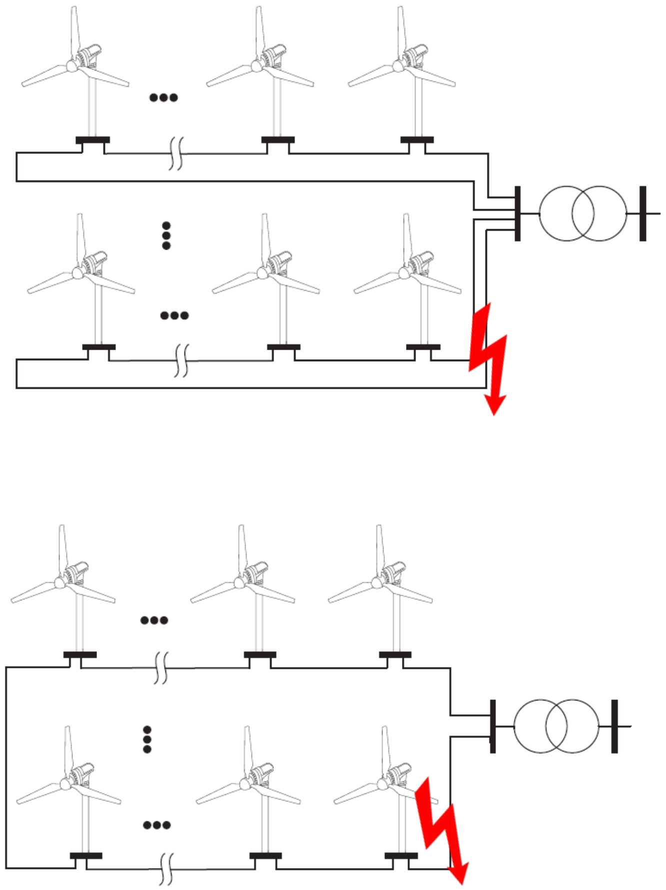
Radial



Star

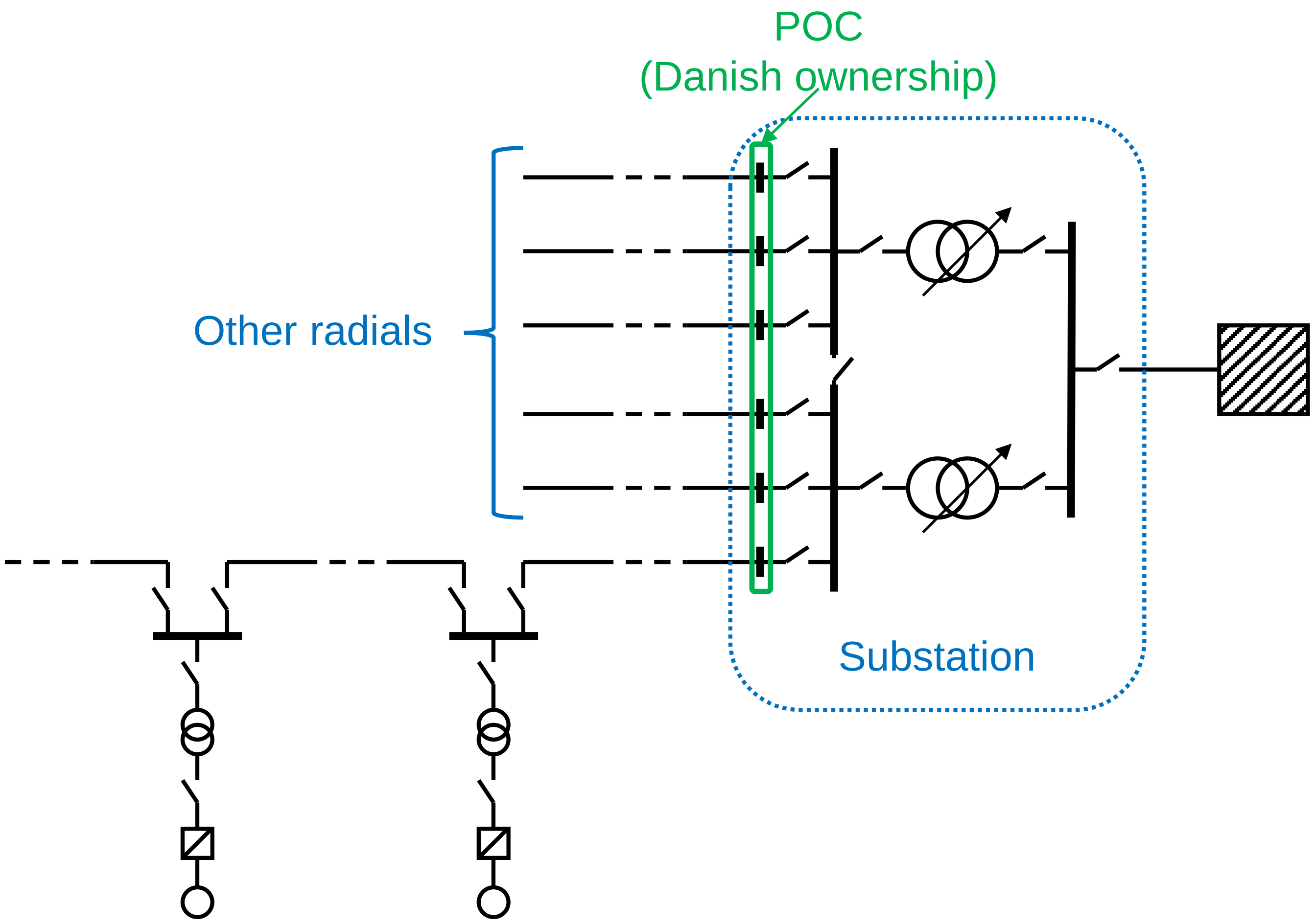


Ring



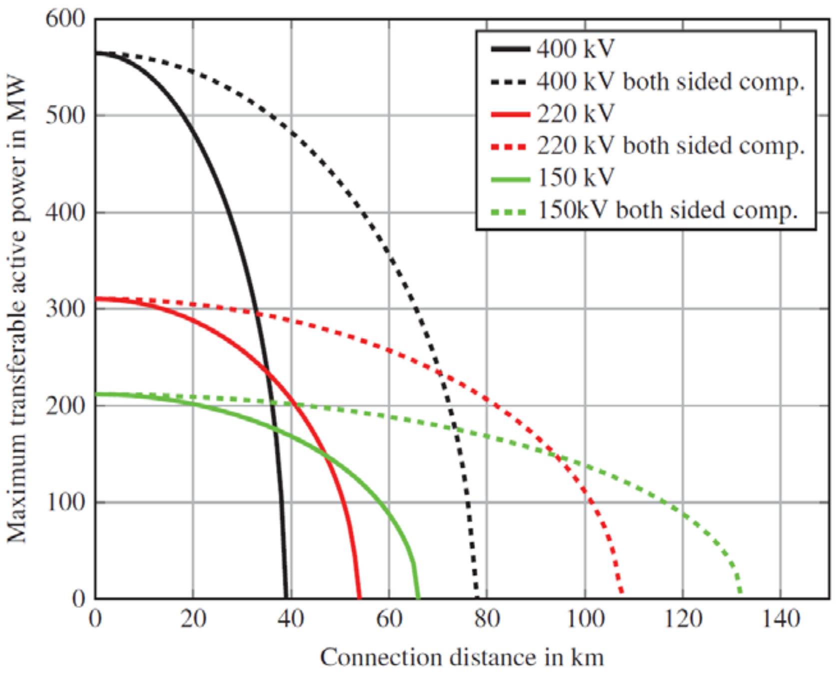
Wind power plant - single line diagram

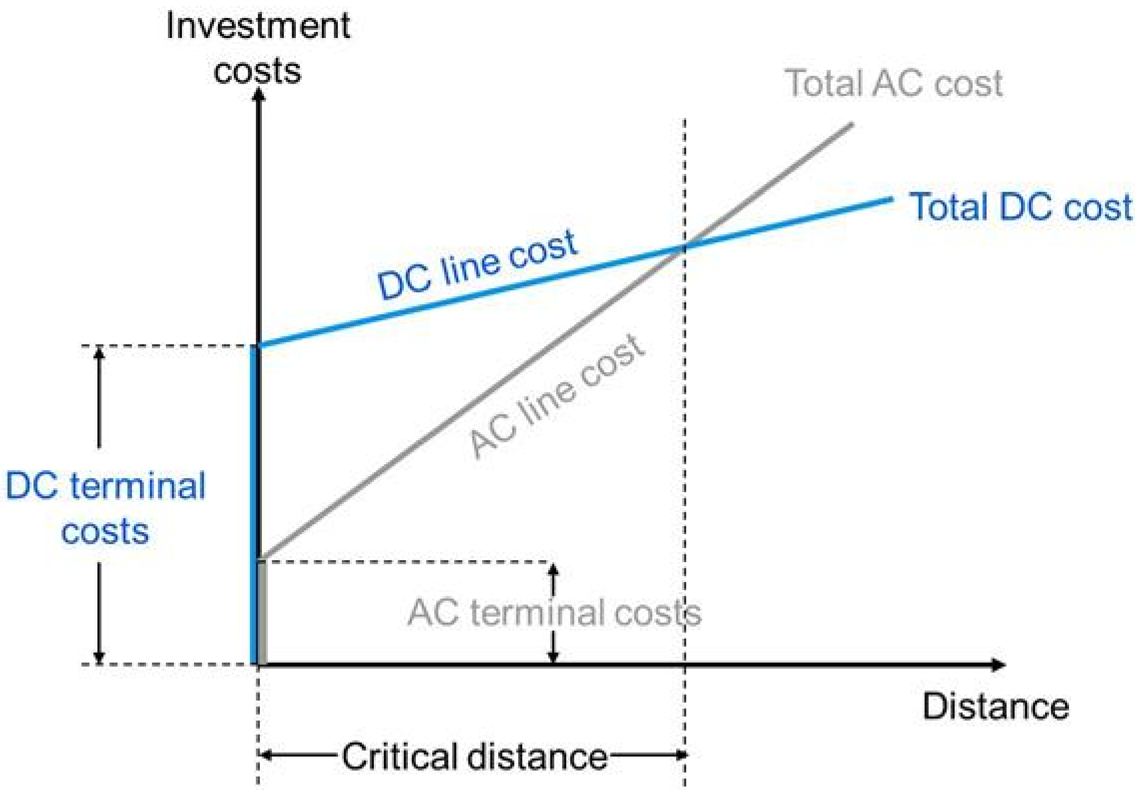
- Point of connection depends on ownership:
  - In DK substation owned by TSO
  - Strictly speeking POC is virtual (one for each radial)
- Redundant substation transformers (2 x 50%) can be required or simply feasible



Transmission – AC vs DC

- AC transmission limited by reactive currents – compensation needed

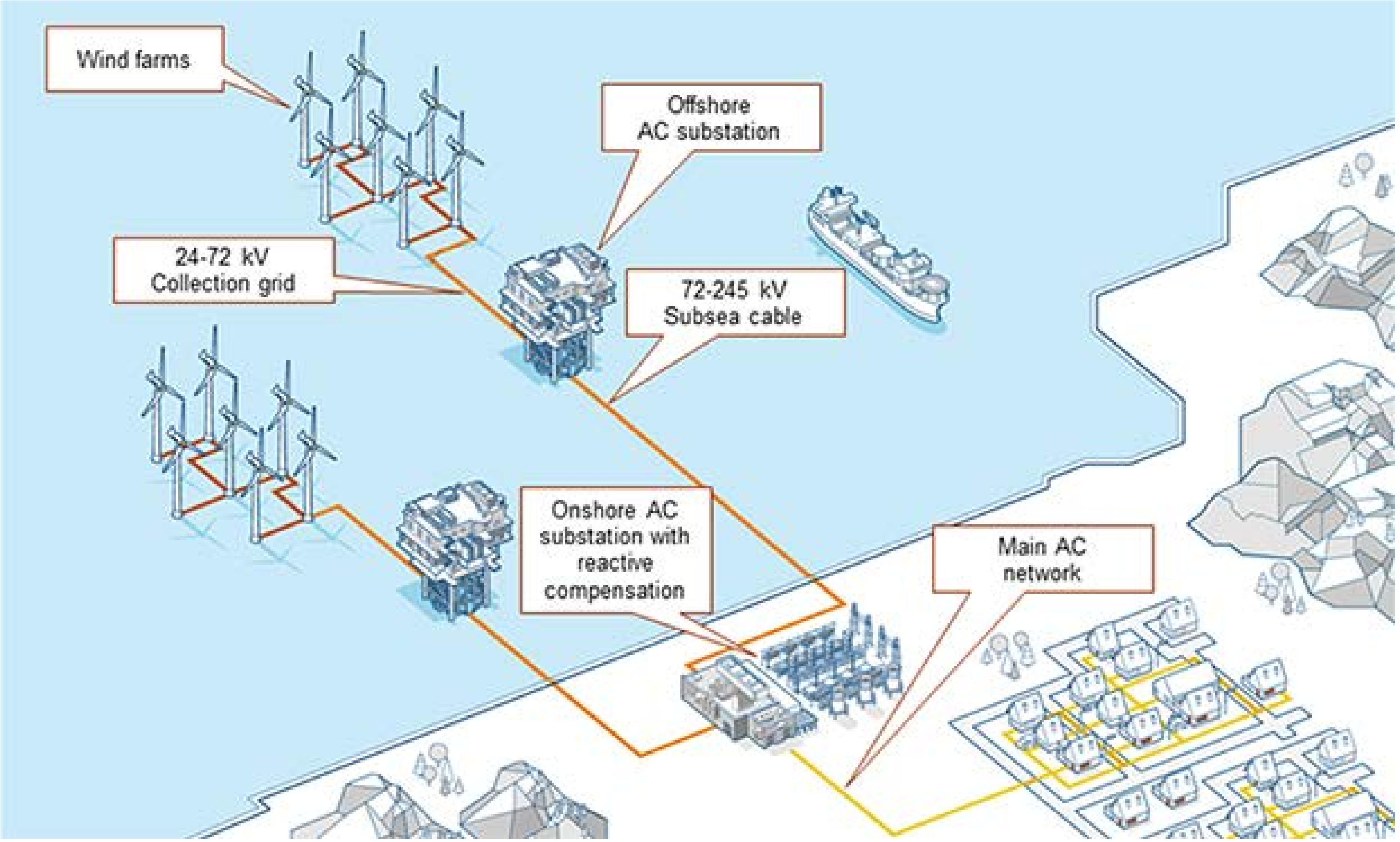




Source figure: ABB, online

Grid connection – main components

HVAC (High Voltage AC)



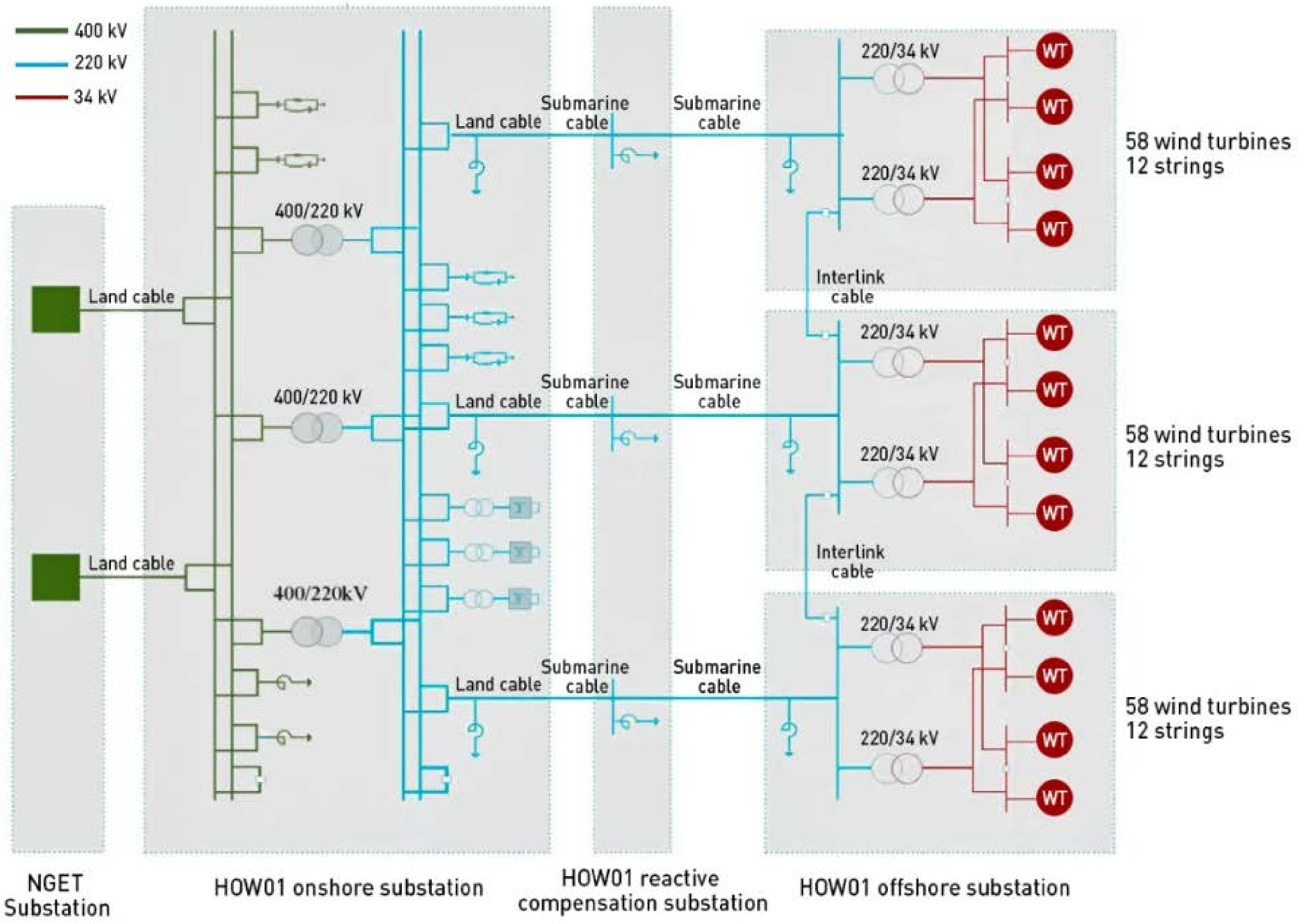
Source: ABB

HVAC transmission

Hornsea ONE WPP:

- 174 WTs X 7.0 MW → 1.218 MW
- Three clusters (58 WTs each, 12 strings)
- Export cables of app. 170-190 km

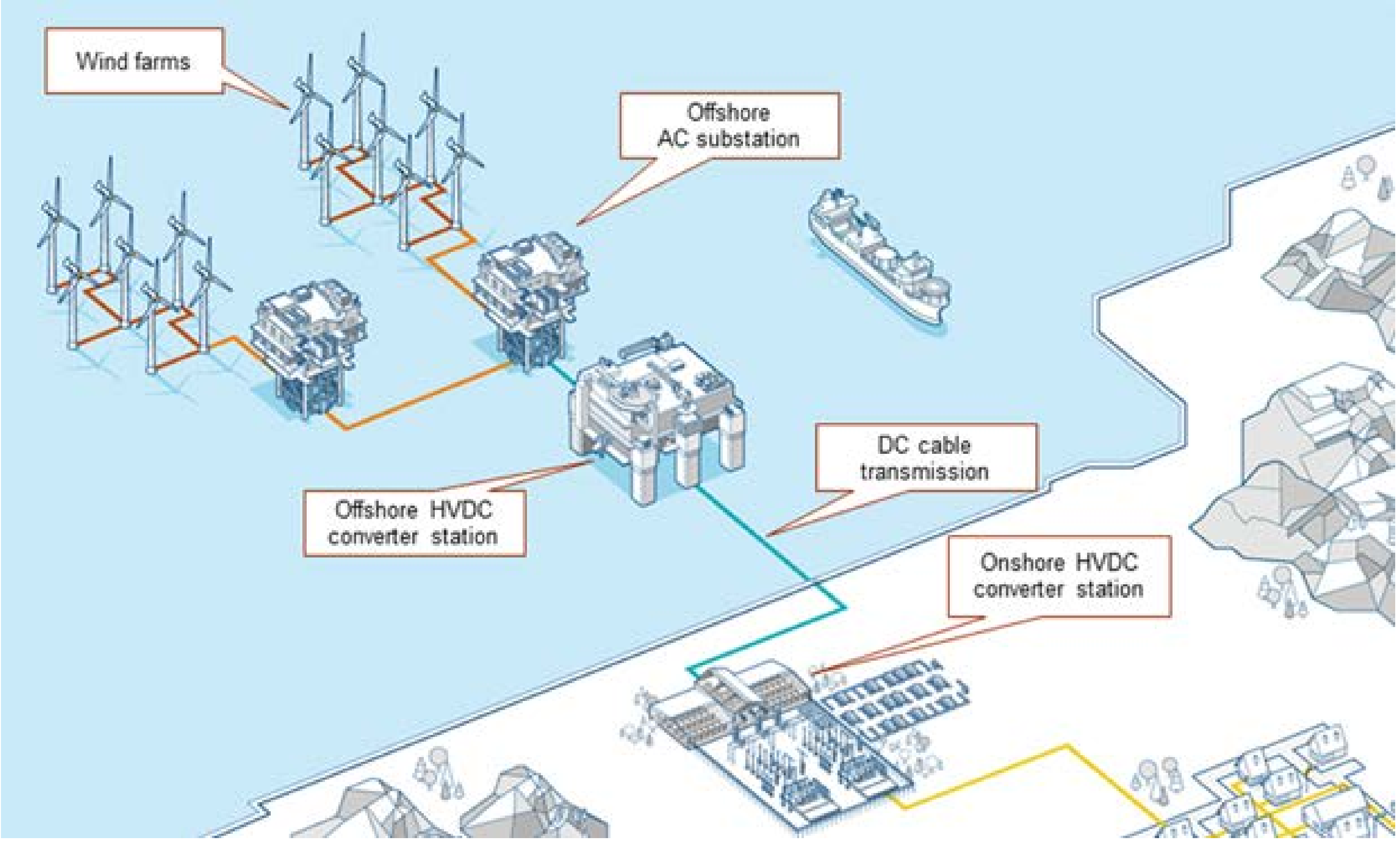
- Interlink cables
- Mid-point compensation (extra platform)
- Compensation units:
  – Passive - shunt reactors
  – Active – STATCOM
- Filters: C-type



Source: Active Filtering in a Large-Scale STATCOM for the Integration of Offshore Wind Power - Lehmann et al

Grid connection – main components

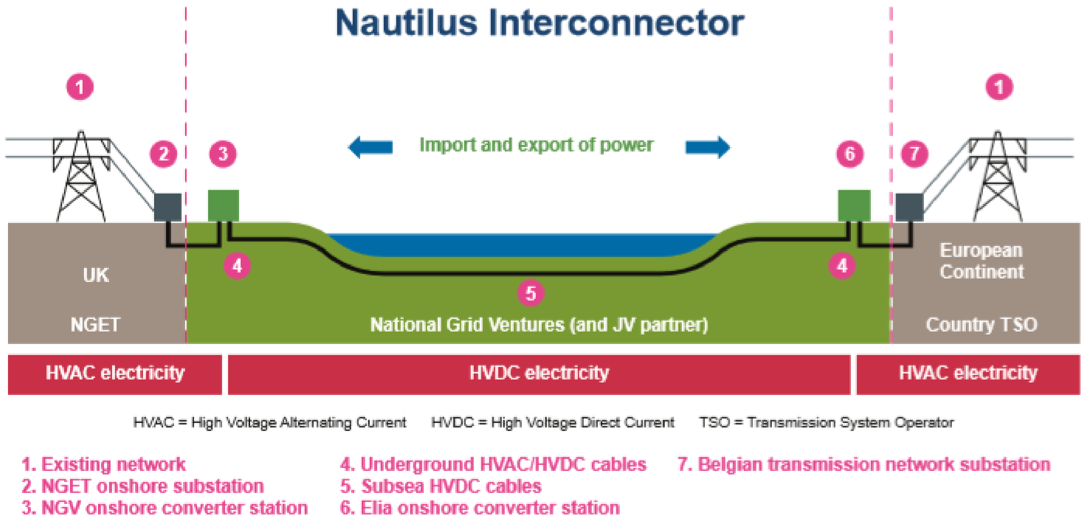
HVDC (High Voltage AC)



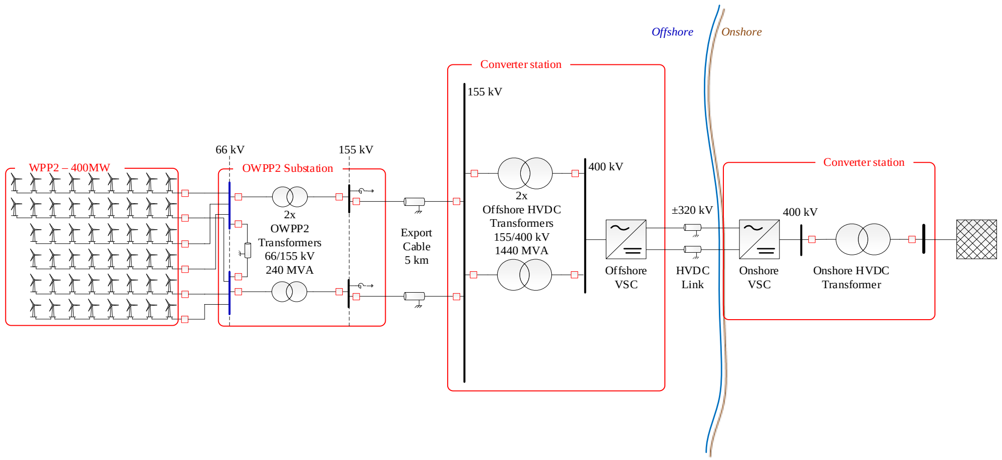
Source: ABB

HVDC transmission

Connecting two AC systems



Connecting OWPP to shore



HVDC properties

- Fewer cables needed for equal power transmission

- No reactive losses:
  – No stability distance limitation
  – No limit to cable length
  – Lower electrical losses

- No need for maintaining synchronism
  – Connecting asynchronous grids (UCTE-Nordic)

- Power flow can be fully controlled (enabling ancillary services provision)

HVDC technologies

HVDC Classic 300 – 10,000 MW

- Thyristor controlled
- Switched reactive power control
- Typical design: valve building plus switchyard
- Overhead lines or mass impregnated cables

HVDC Light 50 – 3,600 MW

- Transistor (IGBT) controlled
- Continuous reactive power control
- Easily expandable to more terminals
- Dynamic voltage regulation
- Black start capability
- Typical design: more equipment in compact building
- Extruded cables

LCC **VSC**

Source: ABB

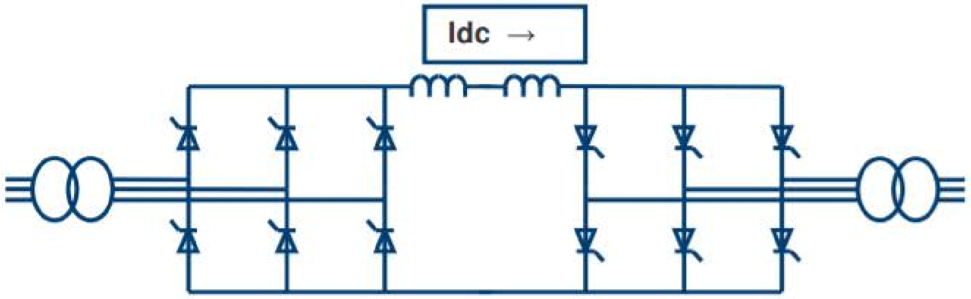
LCC vs VSC

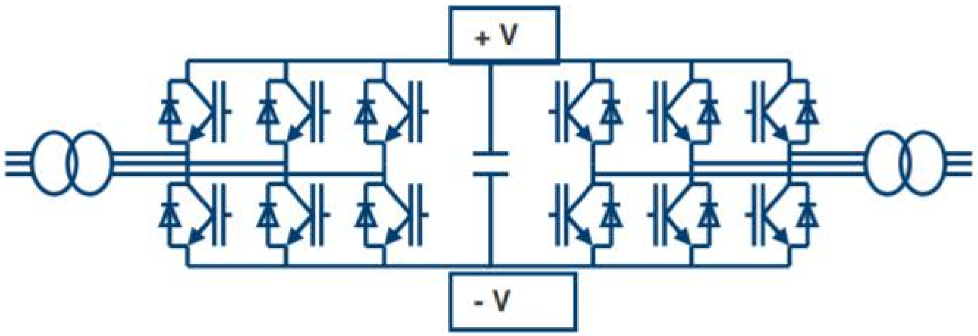
LCC

- Current Sourced
- **L**ine **C**ommutated **C**onverter

VSC

- **V**oltage **S**ourced
- Self Commutated **C**onverter





Source: Alstom (GE)

LCC Vs VSC

Technology	LCC	VSC
Semiconductor	Thyristor	IGBT
Control	Turn on only	Turn on/off
Current flow	Unidirectional	Bi-directional
Power Reversal	Output voltage polarity must be reversed and current reversal is not possible	DC current reversal is possible (The power can be reversed in few milli-seconds)
Energy Storage	Inductor (DC side)	Capacitor (DC link)
Power rating	High power (due to high current capability of thyristos)	Medium power (IGBT has limited current capability)
Reactive Power Control	Coarse Reactive power control	Fine reactive power control
Site	Large overall site area (dominated by Harmonic Filters)	Compact site area (60%)
AC filters	Yes	No (minimum)

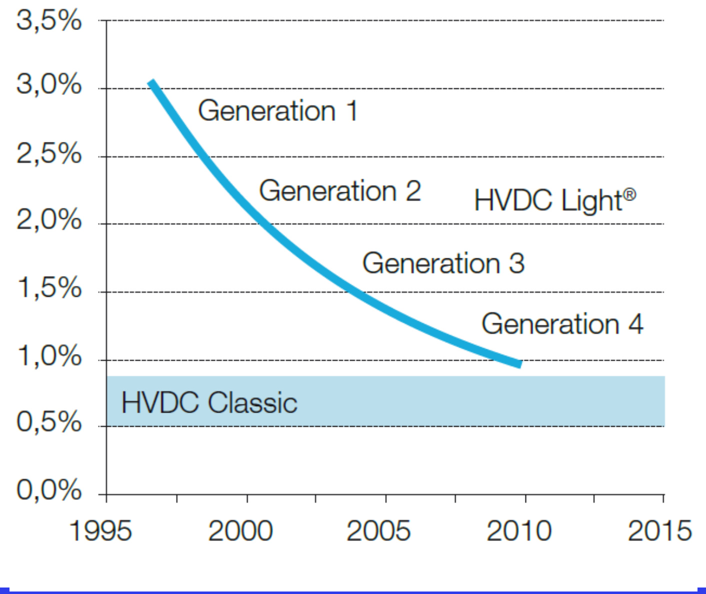
LCC Vs VSC

Technology	LCC	VSC
Minimum AC grid S.C. Ratio	>2	0
Black start capability/Islanded Operation	No	Yes
Losses	Lower power losses compared to VSC	Higher power losses
Foot Print	Large	Smaller

Loss Diagram of ABB HVDC Light (G1 to G4) Vs Classic

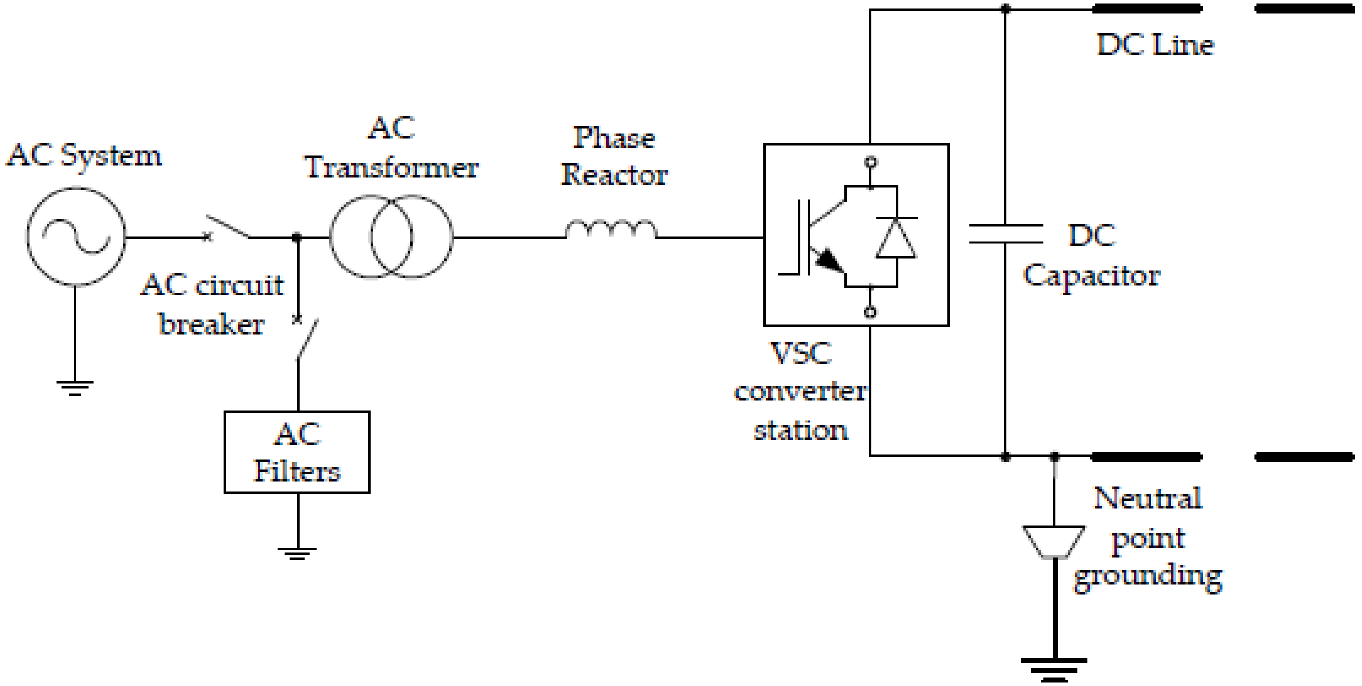
G1- 2 Level VSC

G4- Casceded Two Level Converter (MMC)



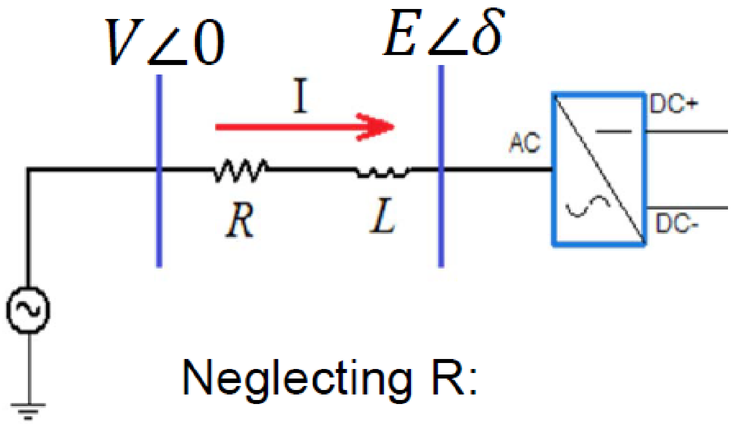
Source: ABB

VSC station layout



- Valves
  - Voltage rating
  - Current rating
- DC capacitors
  - dc capacitors
  - Ripple and energy
- Transformers
- Filters
  - Harmonics
- Reactors
  - Based on fault current
- Breakers
- Arresters

Operation principle of VSC



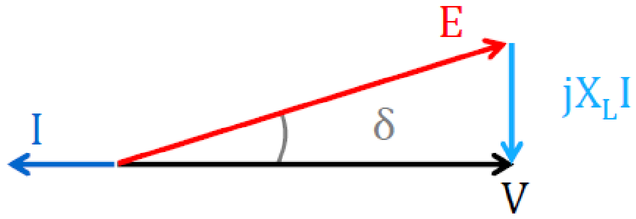
Neglecting R:

$$I = \frac{V\angle 0 - E\angle\delta}{jX_L}$$

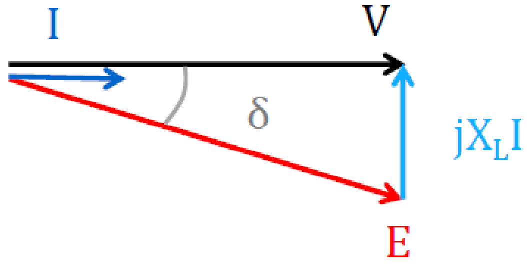
$$S = VI^* \Rightarrow$$

$$\begin{cases} P = -\dfrac{EV}{X_L}\sin(\delta) \\ Q = \dfrac{V^2 - EV\cos(\delta)}{X_L} \end{cases}$$

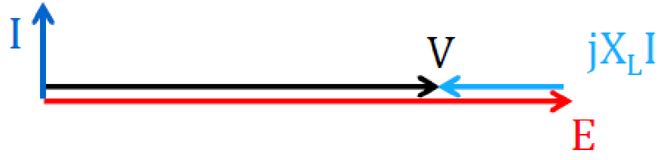
Supplying P:



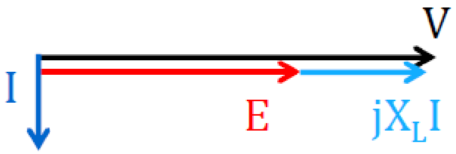
Absorbing P:



Supplying Q:



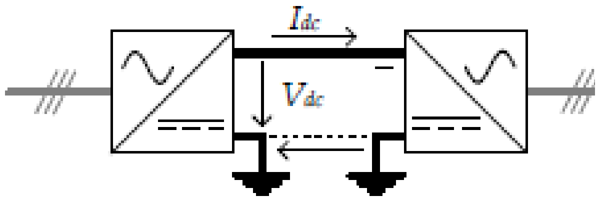
Absorbing Q:



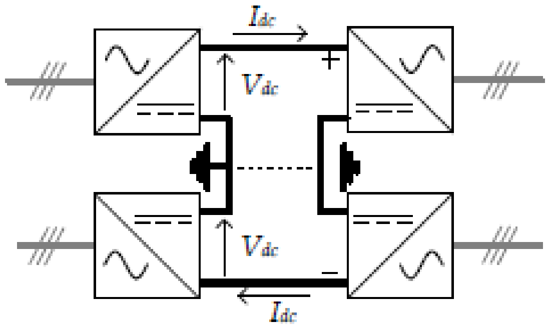
Source: Manitoba research

System configurations

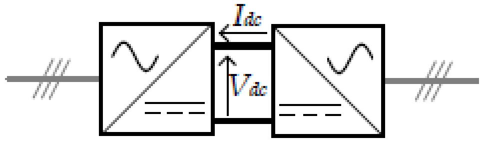
- Monopolar



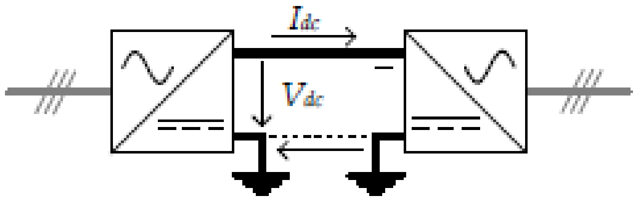
Bipolar



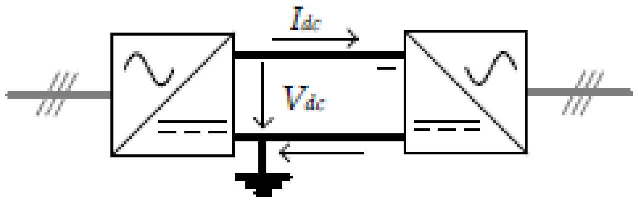
Back-to-back



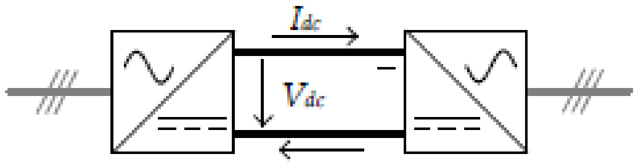
System configurations - Monopolar



(a) Ground return



(b) Metallic return

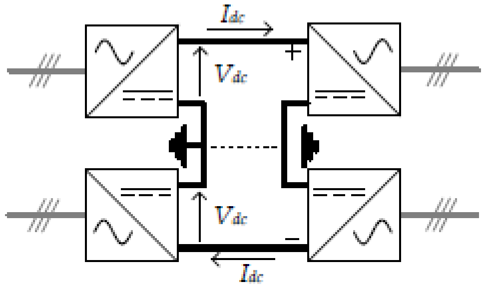


(c) Symmetric Monopole

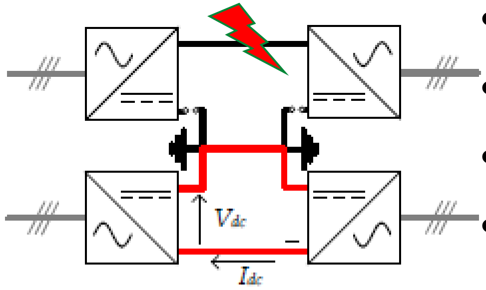
Characteristics:

- Most basic HVDC transmission system configuration
- Cost efficient
- Transformer with additional insulation required for asymmetric monopole, since it will be exposed to a DC offset in the valve side AC voltages,
- Symmetric monopole configuration can be utilized to avoid special transformers → two dc cables with full insulation are needed.
- If a cable or converter fault occurs the whole HVDC transmission becomes momentarily offline.

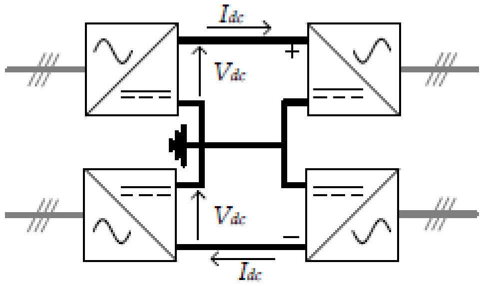
System configurations - bipolar



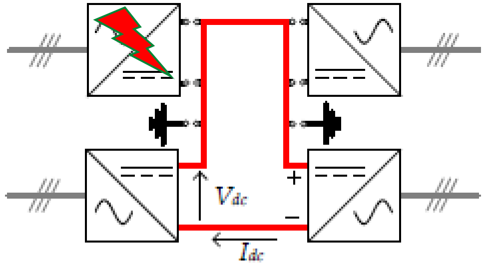
(a) Ground return



(a) HVdc cable fault



(b) Metallic return



(b) HVdc converter fault

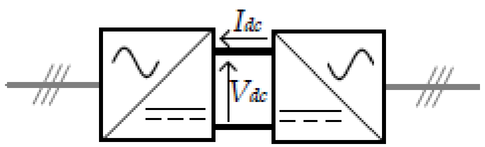
Characteristics

- Typically used at higher power ratings
- Different polarities, DC current in opposite directions
- Currents have same amplitude, no current in return path
- Higher costs
- Larger footprint

Faults:

- In case of cable fault, system still available with at least 50% capacity (depends on cable and overload capability of converter)
- In case of converter fault, it becomes monopolar operation

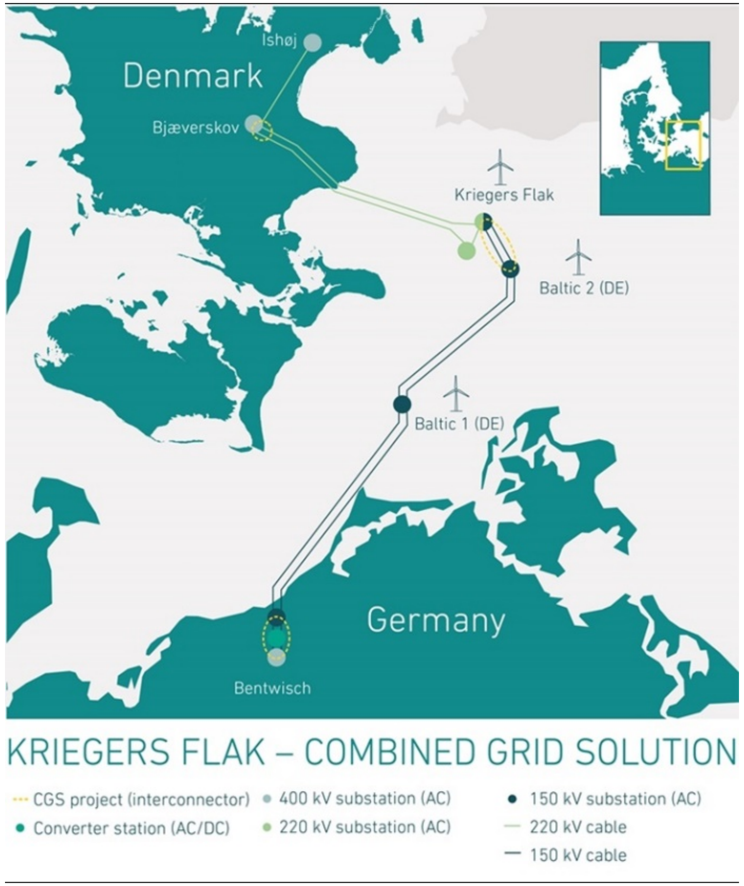
System configurations – back-to-back



Characteristics:

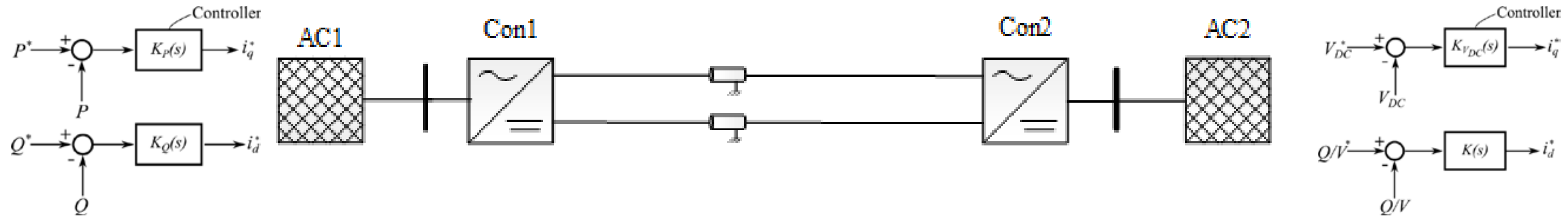
- Small footprint (both converter station in the same building)
- Low(er) voltage (HVDC valve costs are voltage dependent), high currents
- Can be either monopolar or bipolar
- No transmission, only coupling of asynchronous areas and controllability

Main data:	
Commissioning year:	2019
Power rating:	410 MW
No. of poles	2
AC voltage:	Germany side: 400 kV Offshore side: 150 kV
DC voltage:	±140 kV
Type of link:	Back-to-back station
Main reason for choosing HVDC:	Interconnecting asynchronous grids
Application:	Interconnecting grids

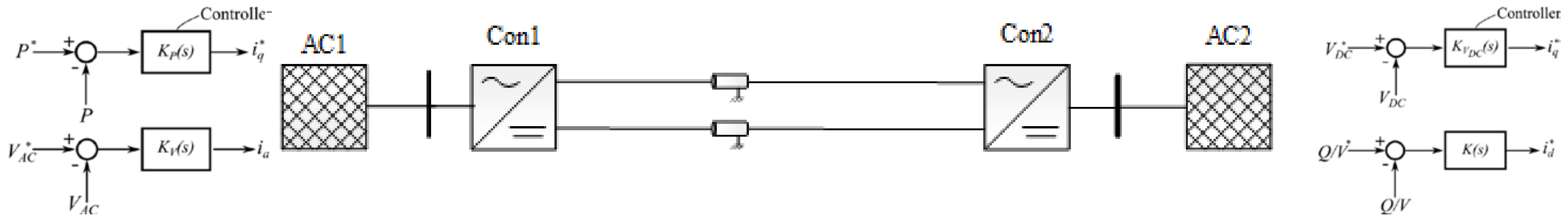


Control of P2P VSC HVDC link

- HVDC interconnector

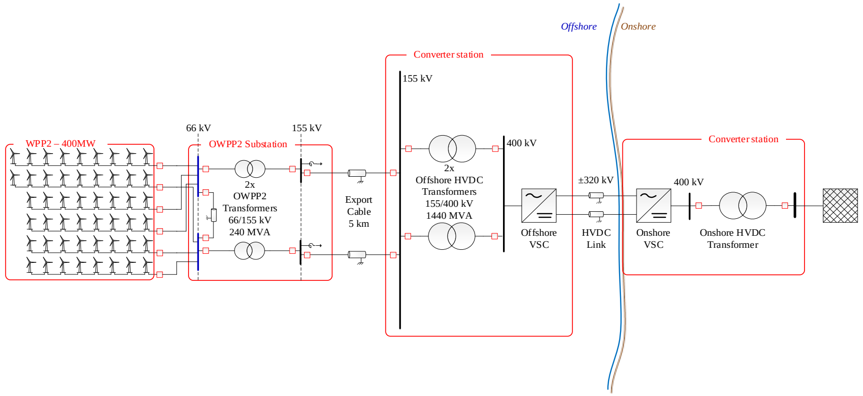


- HVDC transmission (AC1 → OWPP)



Offshore wind connected to HVDC

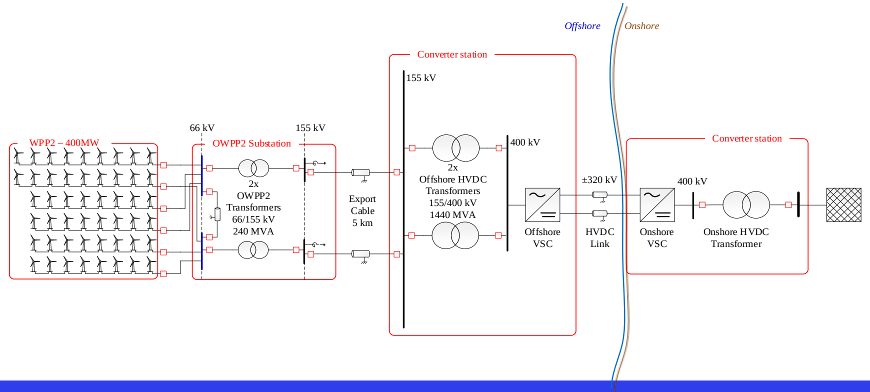
- OWPP connected to HVDC are not synchronous with the main terrestrial grid.
- Offshore HVDC VSC is in charge of maintaining the offshore AC network: controlling voltage magnitude and frequency with appropriate coordination with the WT converters.
- OWPPs also provide support to the HVDC transmission system and the onshore network(s) according to the relevant grid codes.



Offshore HVDC VSC (wind farm converter)

Operation modes:

- Normal operation
  - Power is injected into the HVDC grid by means of the HVDC VSC. Offshore grid voltage constant to absorb all the incoming WPP power. (Infinite bus)
  - Operating in Grid-forming mode
- Voltage droop mode
  - During onshore AC grid faults or loss of a grid-connected converter, the HVDC network may not be able to export all the power-> HVDC voltage increases -> Power reduction needed.



Offshore HVDC VSC (wind farm converter)

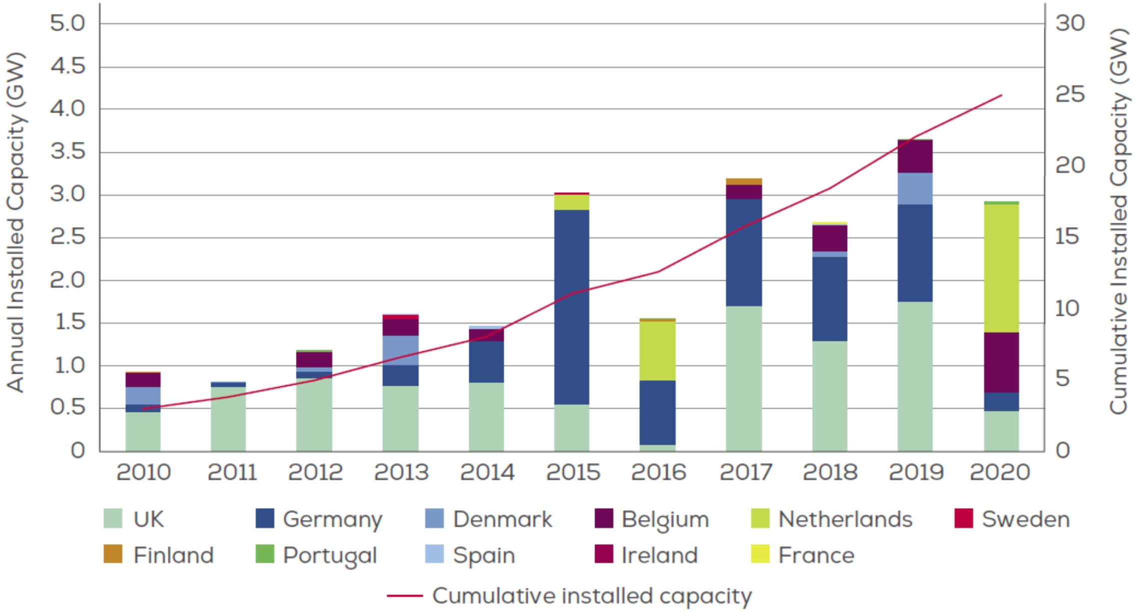
Grid-forming control mode

- The grid angle is imposed by the offshore HVDC VSC
- The voltage is regulated either in a **cascaded control scheme** or as **direct voltage control** (it forces the voltage, in some cases compensating the voltage drop in the transformer, and switches to current control when there is a fault)
- The controllers design is critical as there can be resonances between controllers (offshore HVDC VSC and WTs).
- Protections need to be carefully designed, considering the nature of the grid (no synchronous machine supplying short-circuit current).

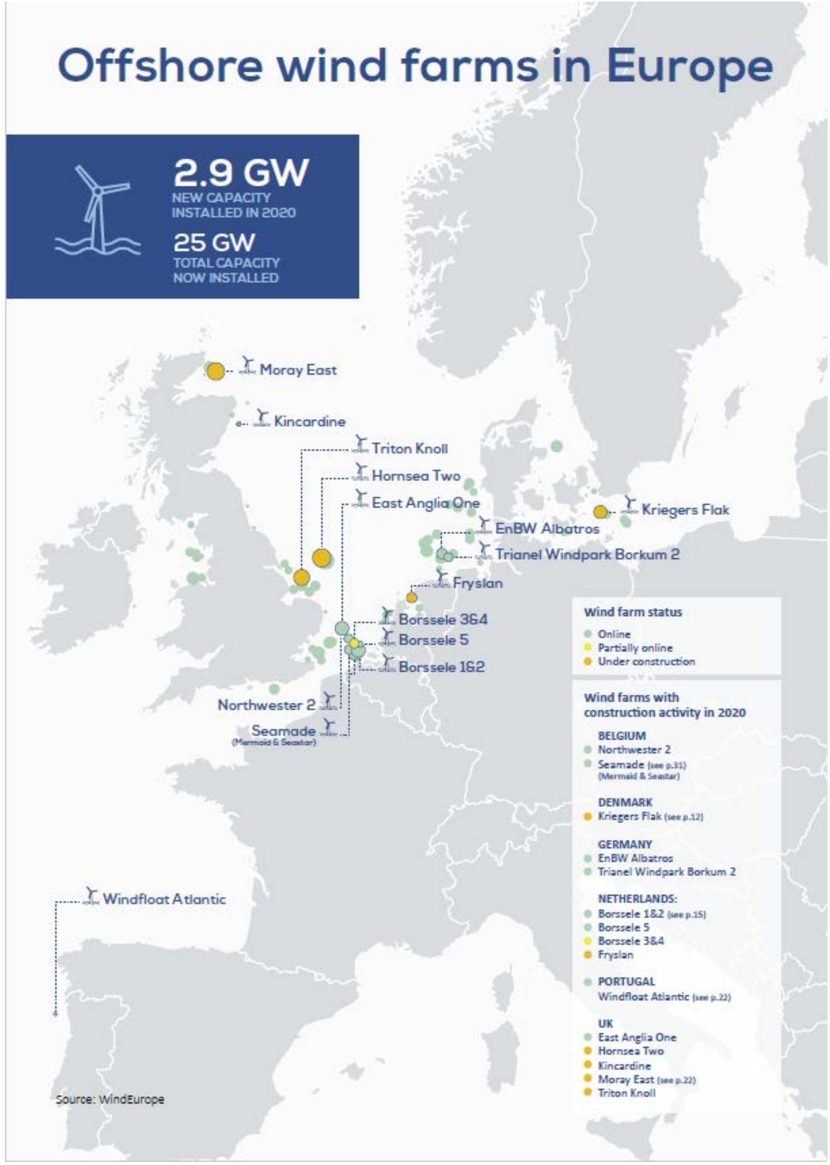
Offshore wind in Europe

FIGURE 1

Annual offshore wind installations by country (left axis) and cumulative capacity (right axis)

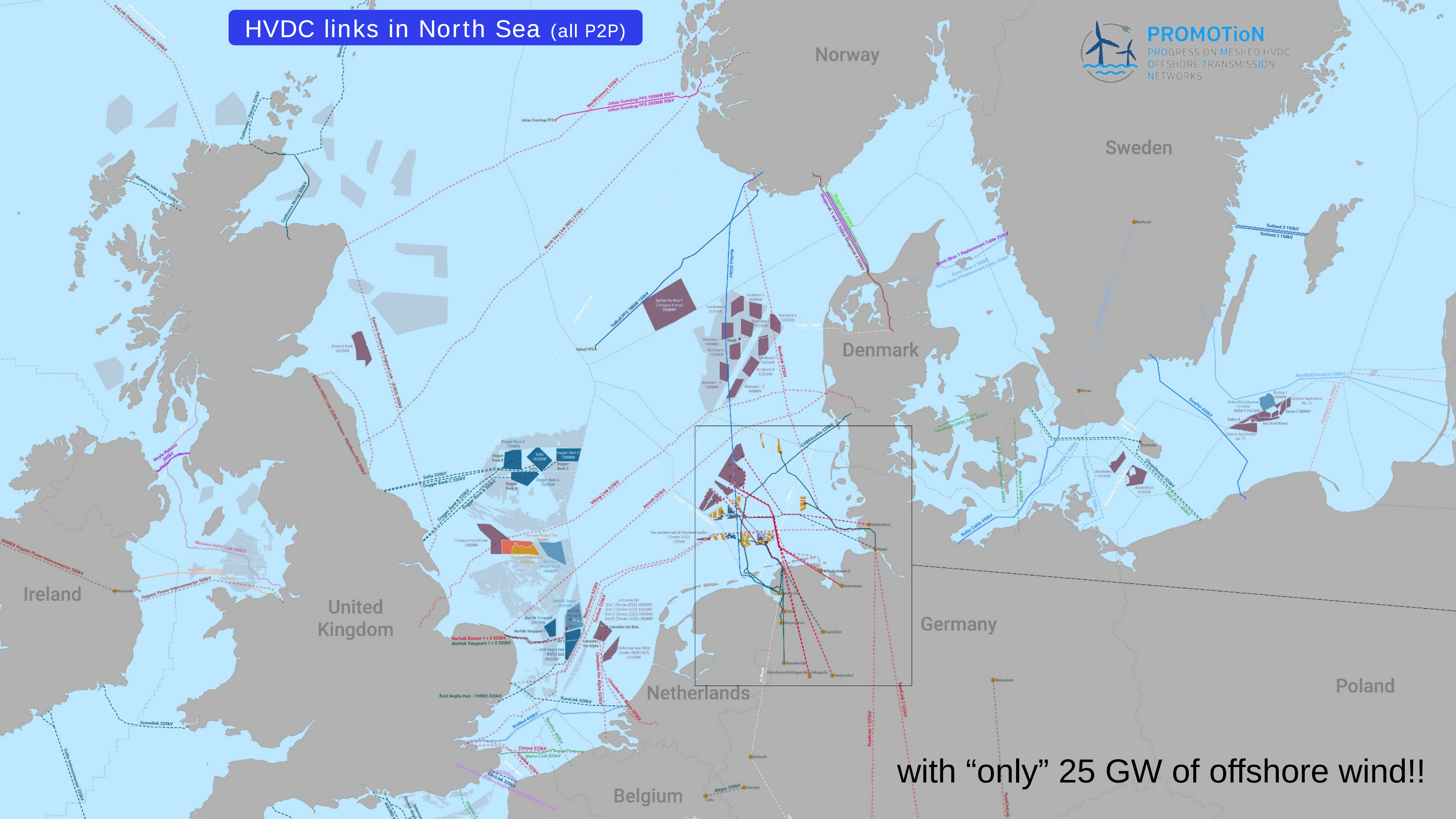


Source: WindEurope



HVDC links in North Sea (all P2P)

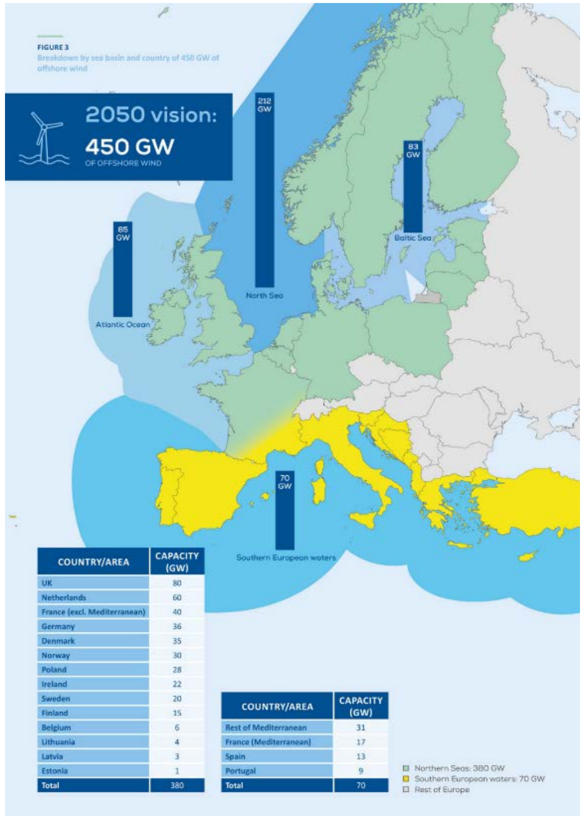
PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS



with “only” 25 GW of offshore wind!!

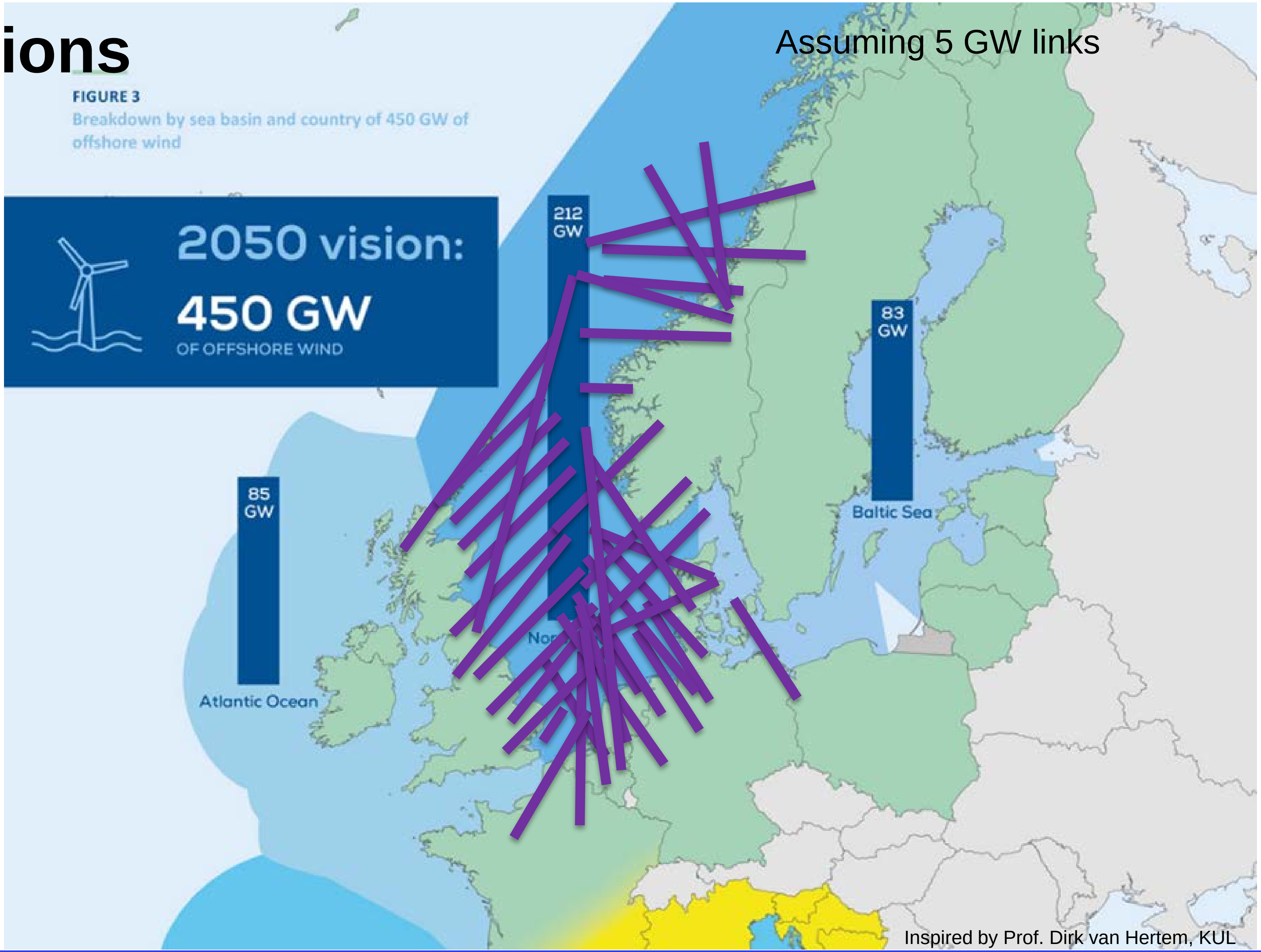
Very high ambitions

- Expectations for 100 GW by 2030 and 200 GW by 2050

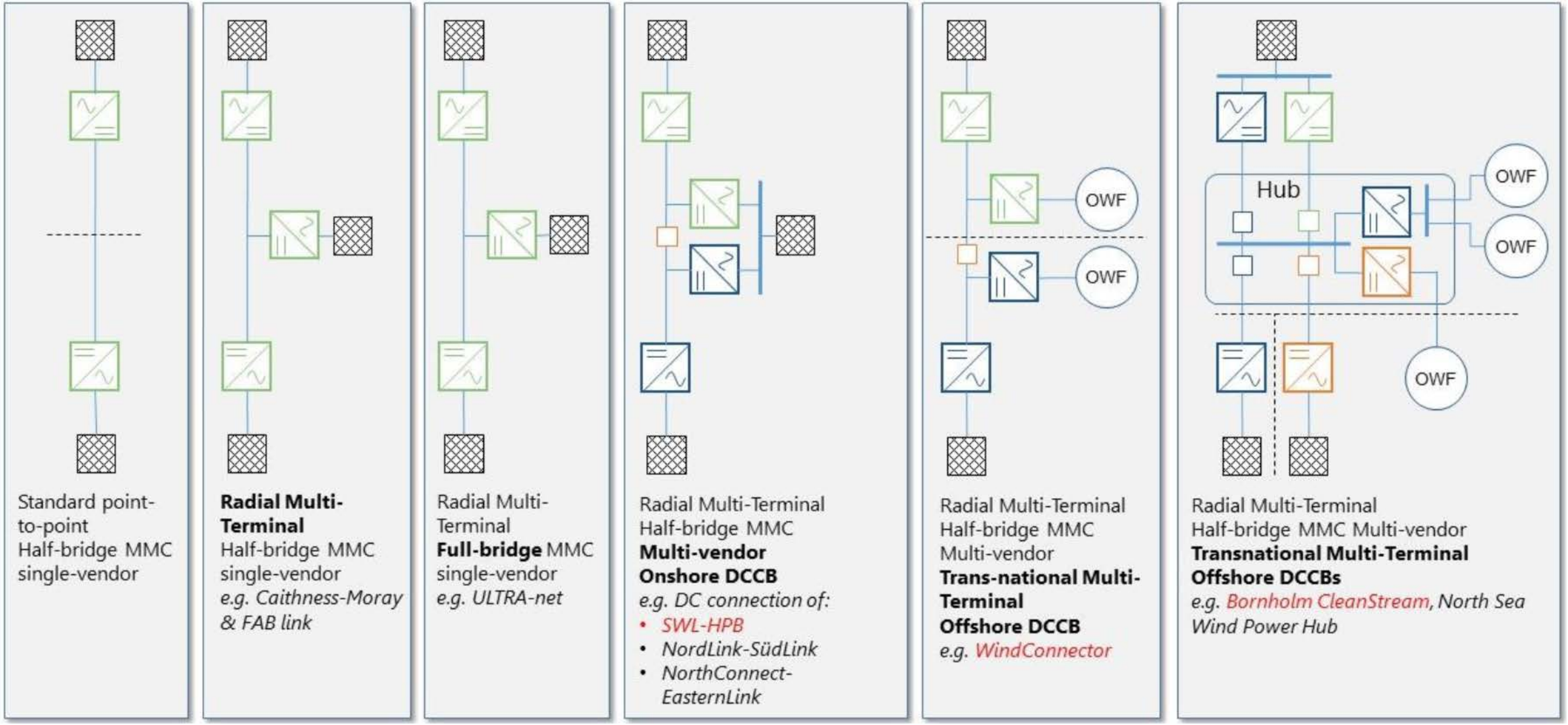


COUNTRY/AREA	CAPACITY (GW)
UK	80
Netherlands	60
France (excl. Mediterranean)	40
Germany	36
Denmark	35
Norway	30
Poland	28
Ireland	22
Sweden	20
Finland	15
Belgium	6
Lithuania	4
Latvia	3
Estonia	1
Total	380

COUNTRY/AREA	CAPACITY (GW)
Rest of Mediterranean	31
France (Mediterranean)	17
Spain	13
Portugal	9
Total	70



How to develop offshore grid?



Why offshore grids

Advantages:

– Reduce costs (reduce CAPEX & OPEX by 18% - UK study)

– Reduce environmental impact (fewer offshore platforms/converters)

– Increase availability and reliability (multiple paths to deliver energy)

Barriers:

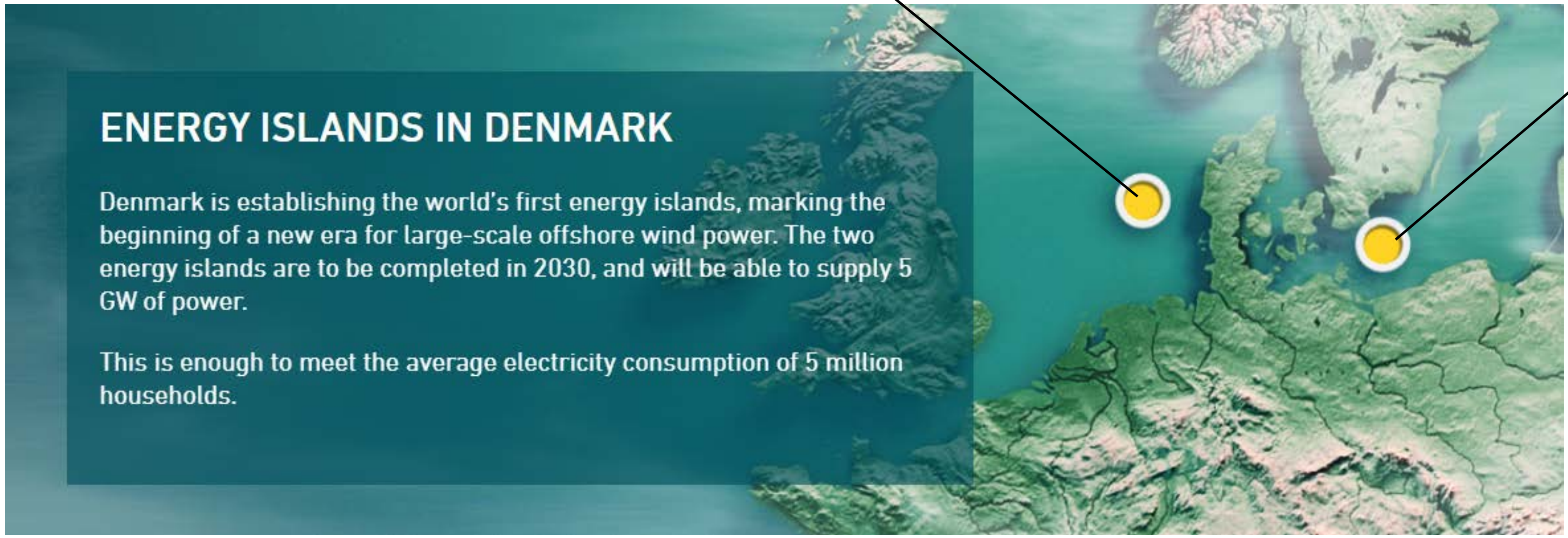
- Limited market (very large, but few, projects)
- HVDC converters interoperability (control is the main IP for vendors)
- Development of components – DC breakers (almost there)
- Regulatory and legal (hybrid and transnational assets)
- Operational – offshore TSO?

Danish Energy Islands

- In June 2020, Danish parliament decided […] the construction of two energy islands in Denmark – in the North Sea and in the Baltic Sea.
- Both islands will be connected to other countries

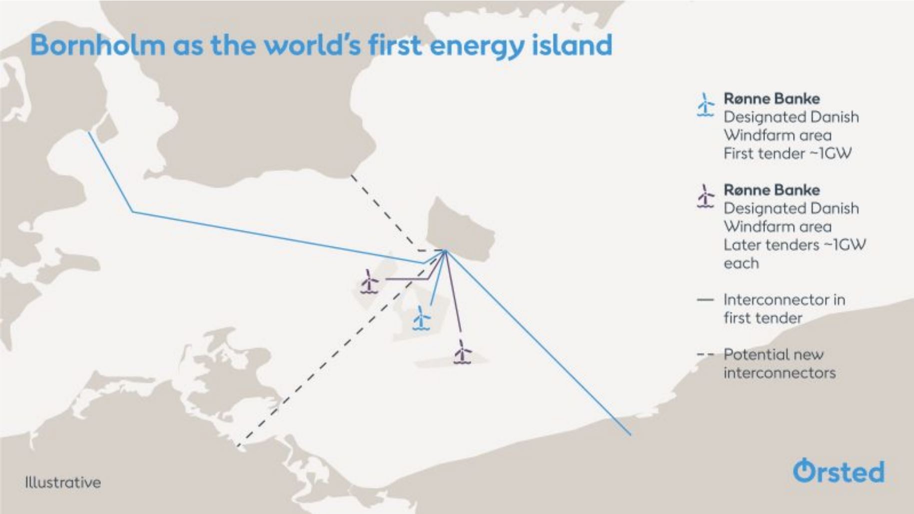
North Sea – 3 GW by 2030, aim for 10 GW by 2050

Bornholm island – 2 GW



Baltic Sea Energy Island

- Bornholm will function as the physical energy island
- Offshore wind south and south-west of Bornholm

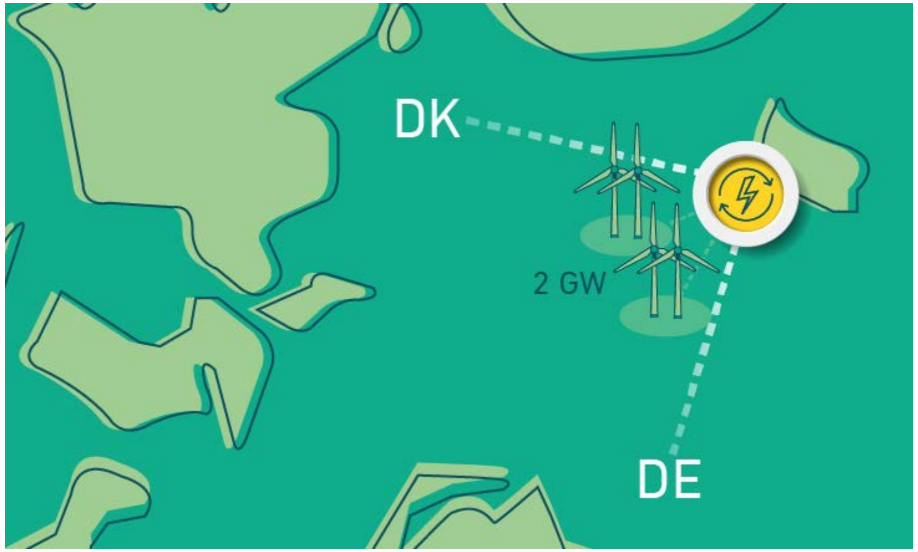


- Could be the first transnational MTDC grid; pre-feasibility study by EU PROMOTioN project:

D12.5 Short Term Project Bornholm Island CleanStream Energy Hub
https://www.promotion-offshore.net/fileadmin/PDFs/D12.5_STP_Supplement_Bornholm.pdf

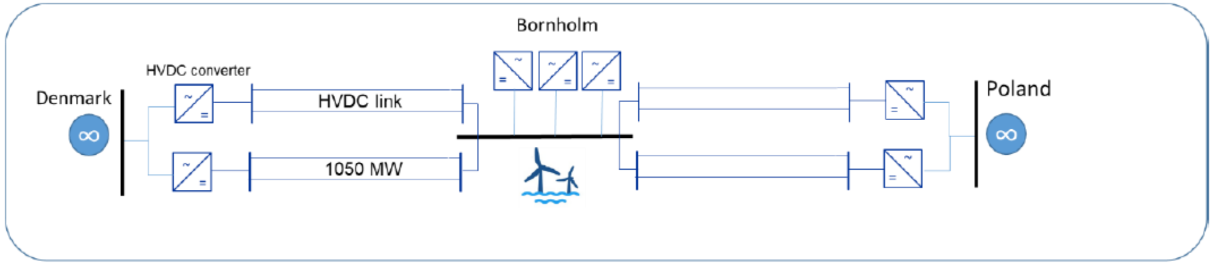
- Energinet (TSO DK) and 50 Hz (TSO DE) agreement MoU to study the construction of an electric cable connection between the two countries via Bornholm

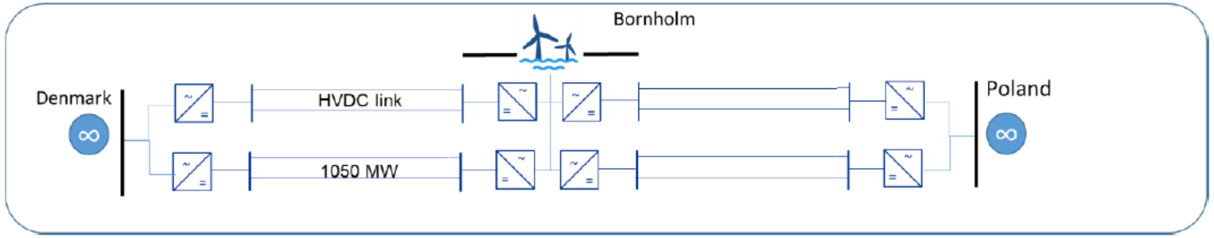
https://en.energinet.dk/About-our-news/News/2021/01/20/LoI-energy-island-baltic-sea

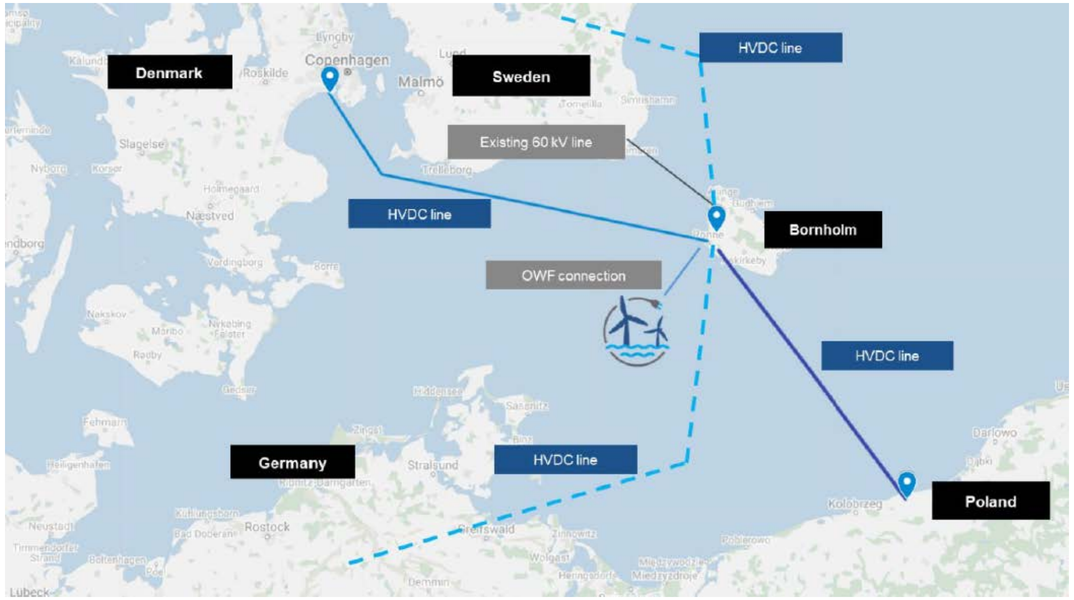


Baltic Sea Energy Island

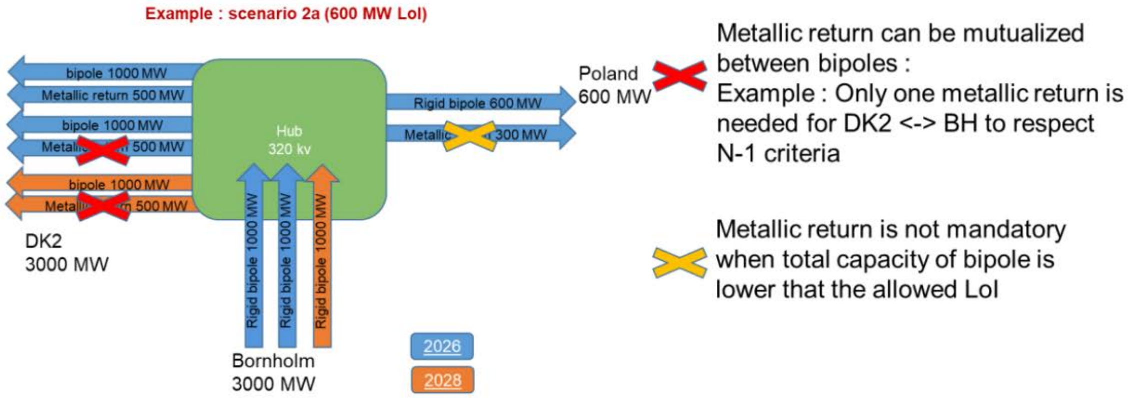
DC or AC hub?







Max loss of infeed – 600 MW for DK1



D12.5 Short Term Project Bornholm Island CleanStream Energy Hub https://www.promotion-offshore.net/fileadmin/PDFs/D12.5_STP_Supplement_Bornholm.pdf

Energy Islands/hubs

A step forward in development of offshore energy infrastructure

Characteristics:
- 100% inverted based system
- No inertia
- (extremely) Low system strength
- Multi-vendor environment (production & demand)
- Robust and seamless expansion

Electrical design & operation a challenge – never done before!

Future energy hubs are (extreme) versions of 100% inverter based systems

Summary

- Offshore wind power plants have complex electrical infrastructure
- Offshore transmission and grid connection important cost drivers
- Choice of technology mostly based on economic reasoning
- Offshore grids most likely to be developed incrementally
- Energy islands – extreme versions of 100% inverter systems

Thank you