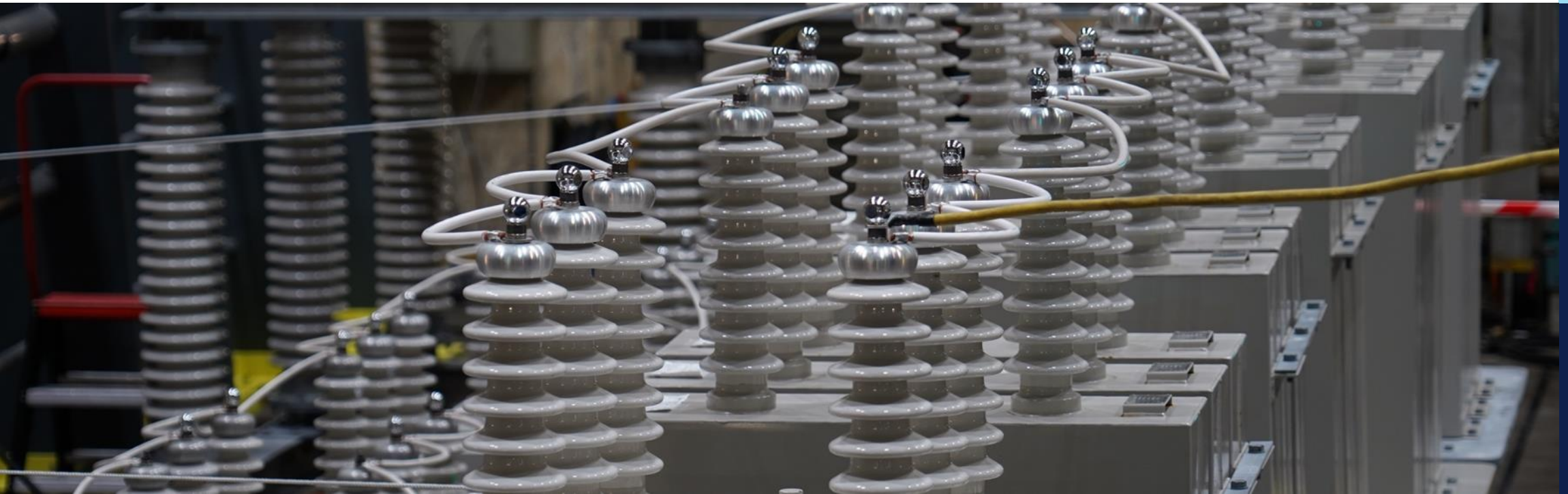
WHEN TRUST MATTERS

Multi-terminal HVDC Grid: Current Status and Next Steps

Power Systems Advisory

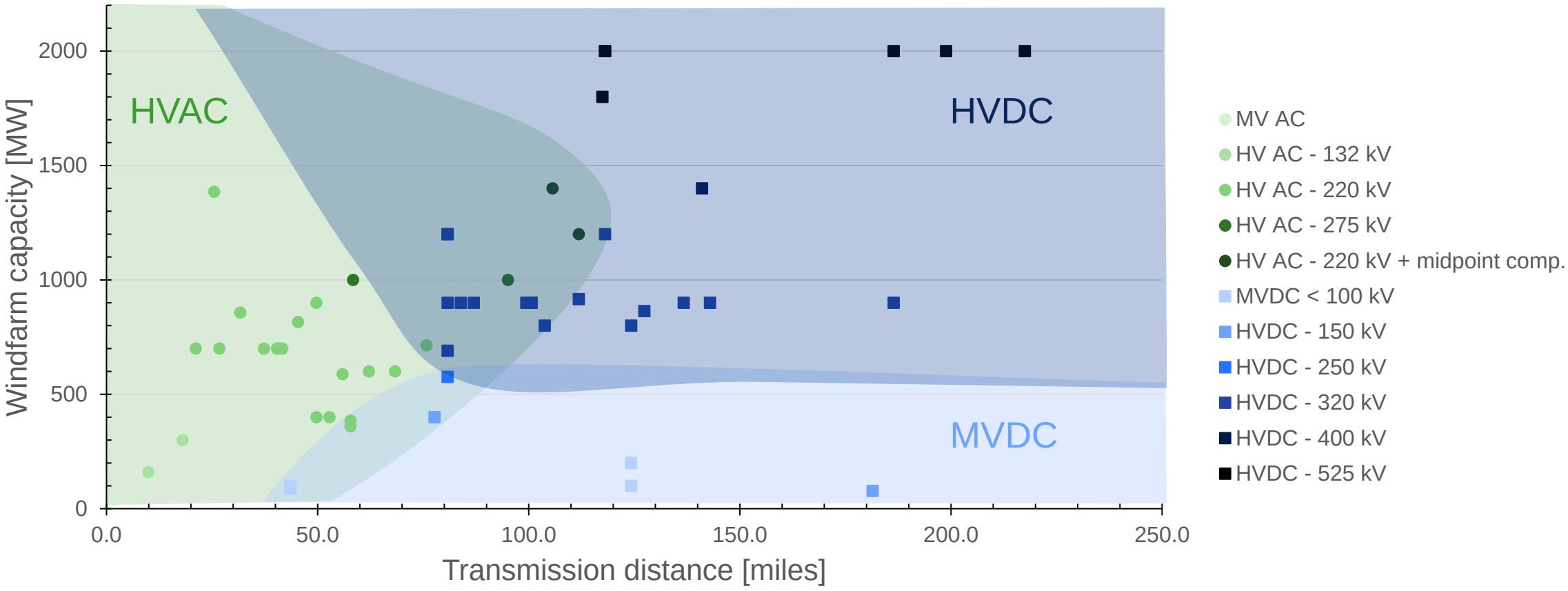
01 May 2024



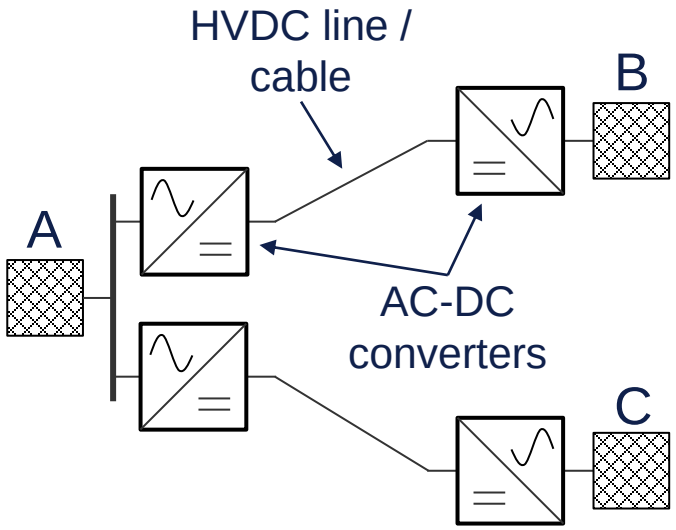
What is HVDC?

- High voltage direct current
- Cost-effective and low-impact technology for high capacity and long-distance transmission
- Fully controllable
- Grid integration of remote large-scale renewables
  - Hydro
  - Offshore wind
  - Solar
- Energy trade between countries / continents
- Reinforcement of existing onshore grids

When does it make sense to use HVDC?

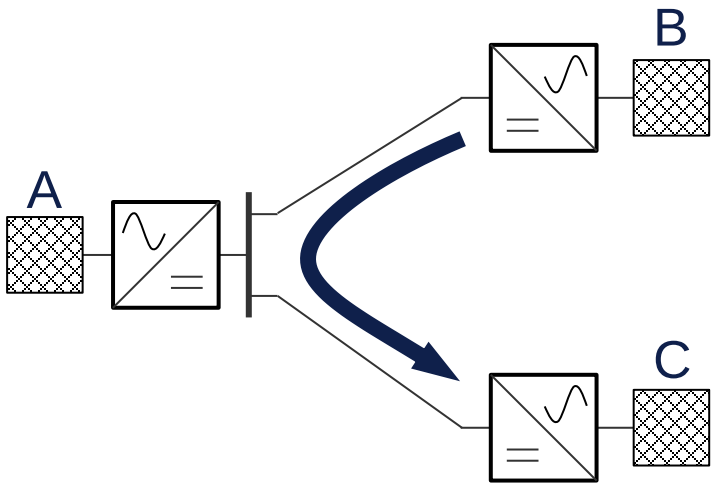


How can HVDC systems be used?



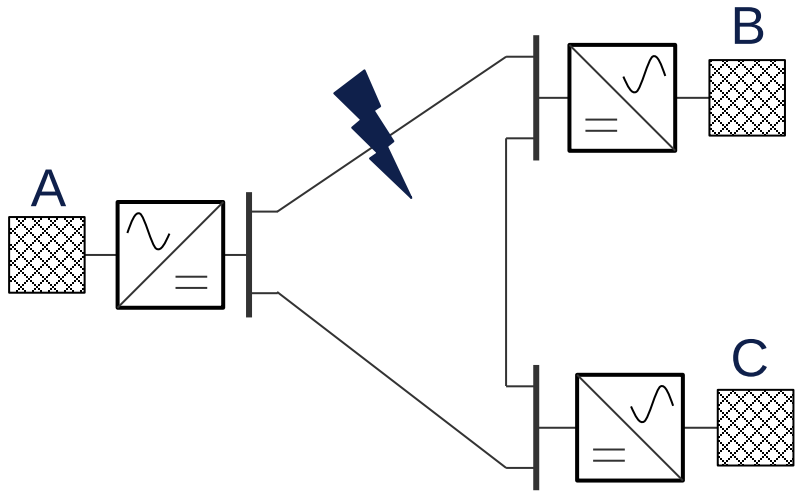
Point-point systems

- Bespoke projects
- Easier project development
  - Single vendor procurement
  - Single purpose
- Mature and widely applied



Radial multi-terminal system

- Multi-purpose
- Fewer converters
  - Lower cost
  - Lower footprint
  - Lower losses
- Requires compatibility



Meshed multi-terminal system

- Redundant paths
  - Increased availability
  - Reduced impact on AC grids
- Requires DC protection system

What is the difference?

Multiple point-point links

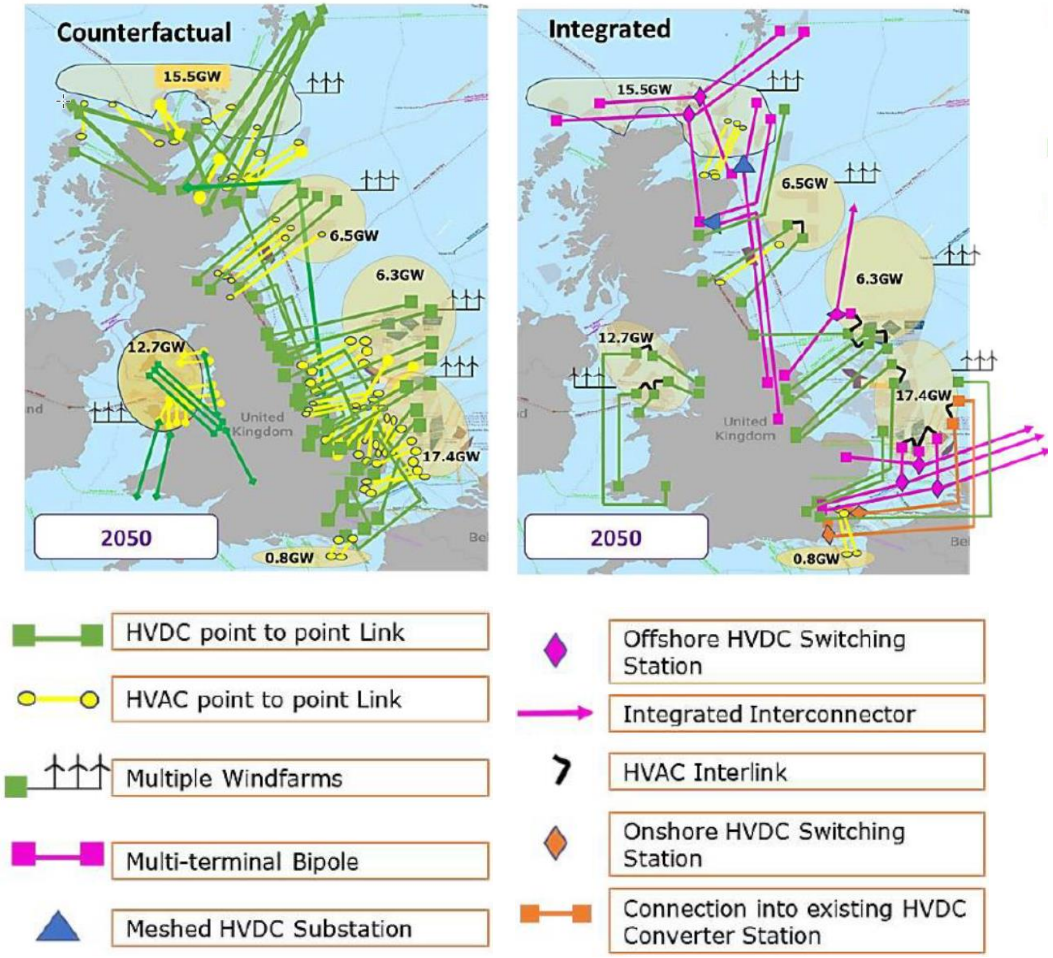
- Allows different technologies and voltage levels for each link
  - Optimise design & operation of each link
- Avoids project dependencies
  - Schedule
  - Terminal locations
  - Anticipatory investments for expandability
- Simplifies multi-vendor interoperability
  - Systems from different vendors coupled at AC side guided by AC grid codes
- Proven, accepted technology

Multi-terminal grid

- Better utilization
  - Multi-purpose use
- Fewer converters
  - Lower losses
  - Lower footprint
    - Lower socio-environmental impact
    - Lower permitting burden
  - Higher availability
- Fewer cables (for meshed systems)
  - Use redundant paths to satisfy most severe single contingency constraints

Multi-terminal HVDC grid benefits

- **UK as example**

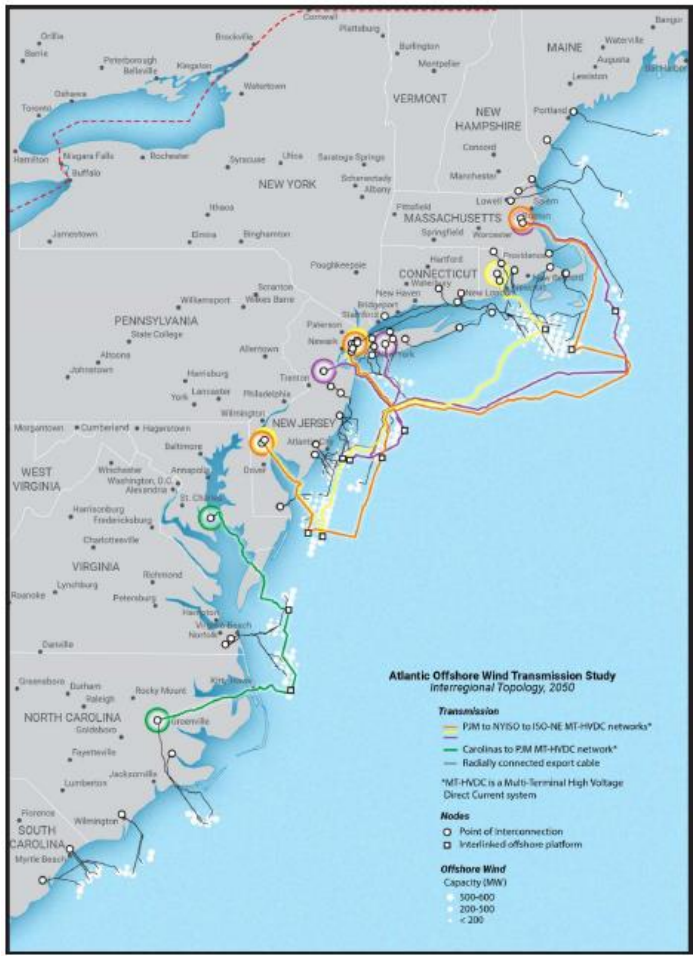


- 18% lower lifetime costs
- Significantly lower environmental impact
- Significantly lower local and social impact
- Improved security of supply

Ref: National Grid ESO Offshore Coordination Study, 2020

Multi-terminal HVDC grid benefits

- **US Example – Atlantic Offshore Wind Transmission Study**



- Benefits of networking comes from:
  - Reduced curtailment
  - Reduced usage of higher-cost generations
  - Contribution to reliability
- Benefits outweighs Cost, often by ratio of 2:1

Ref: NREL Atlantic Offshore Wind Transmission Study Report

Deck stacking in favour of multi-terminal HVDC grids

Increasing density of HVDC transmission links creates opportunities to realize multi-terminal synergies

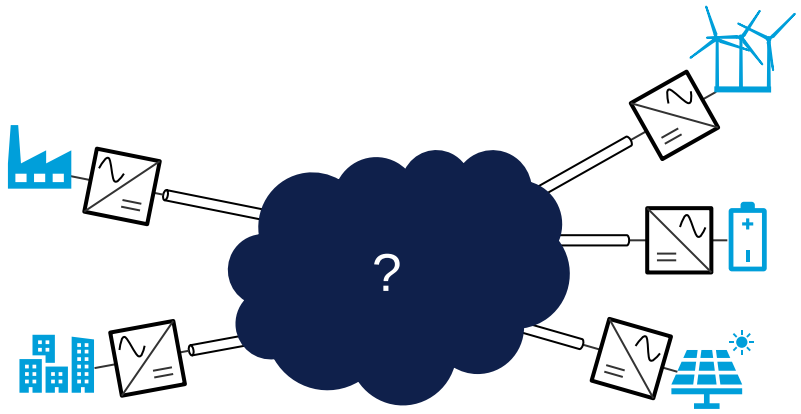
Offshore wind export	Onshore grid reinforcements	Onshore inter-regional links	Onshore renewable lead lines

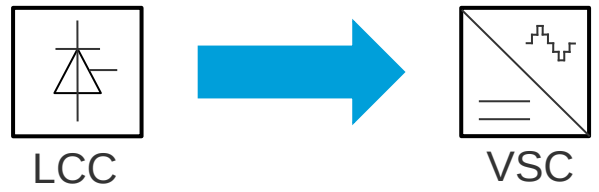
New HVDC projects use Voltage Sourced Converter technology whose control capabilities make it naturally suitable for multi-terminal connections

Changes current polarity to change power flow direction, but keeps voltage constant	Suitable for large, complex multi-terminal HVDC networks

Development of DC fault current clearing technologies enables large HVDC grids without jeopardizing AC grid frequency stability

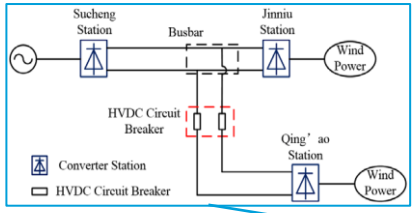
Full bridge converters	HVDC circuit breakers	Superconducting fault current limiters



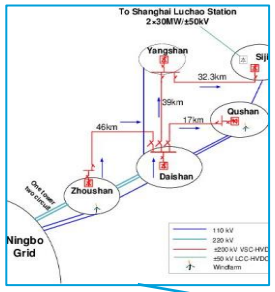


HVDC grids in operation > 30 years

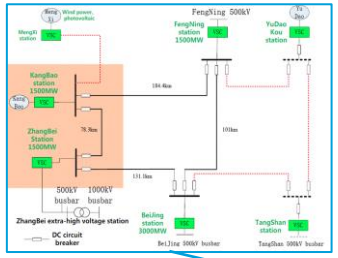
VSC technology



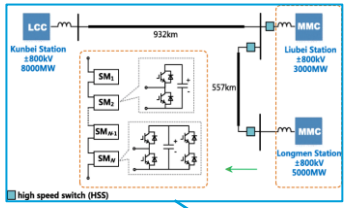
China, Nanao
240 MW, 160 kV
3 terminals



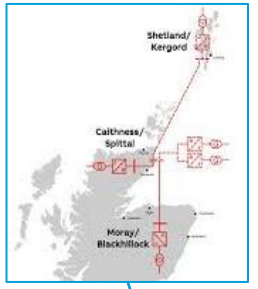
China , Zhoushan
400 MW, 200 kV
5 terminals



China, Zhangbei
3 GW, 500 kV
4 terminals



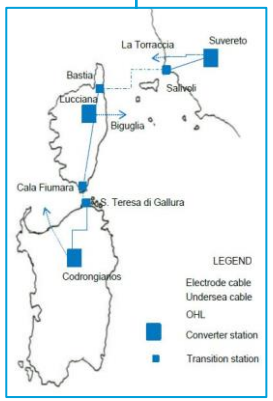
China, Wudongde
5 GW, 800 kV
3 terminals



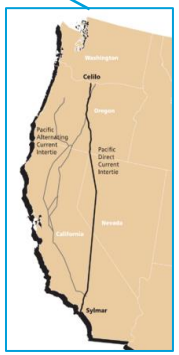
UK, CMS
1.2 GW, 320 kV
3 terminals

1985 1990 1995 2000 2005 2010 2015 2020 2025

LCC technology

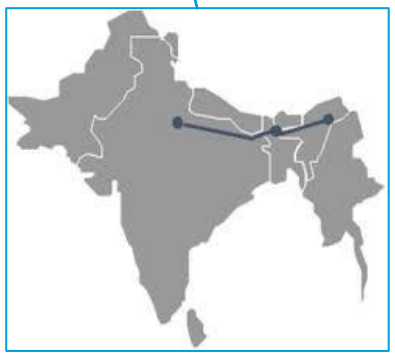


Italy, SACOI, 200 MW
200 kV, 3 terminals



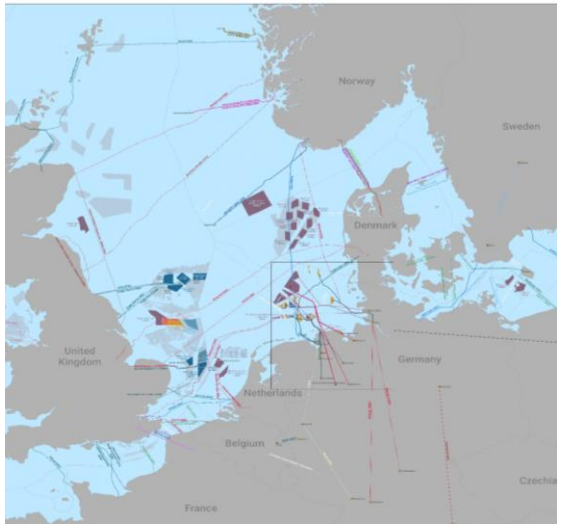
USA, Pacific Intertie
1.1 GW 500 kV, 4 terminals

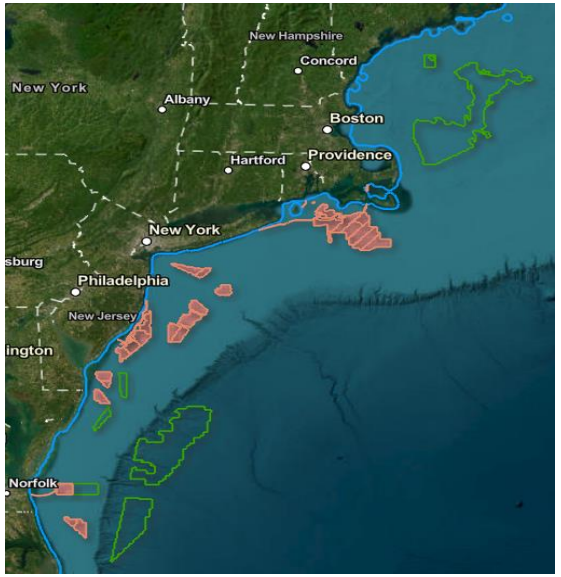
USA, Quebec - New England
2 GW, 450 kV, 3 terminals



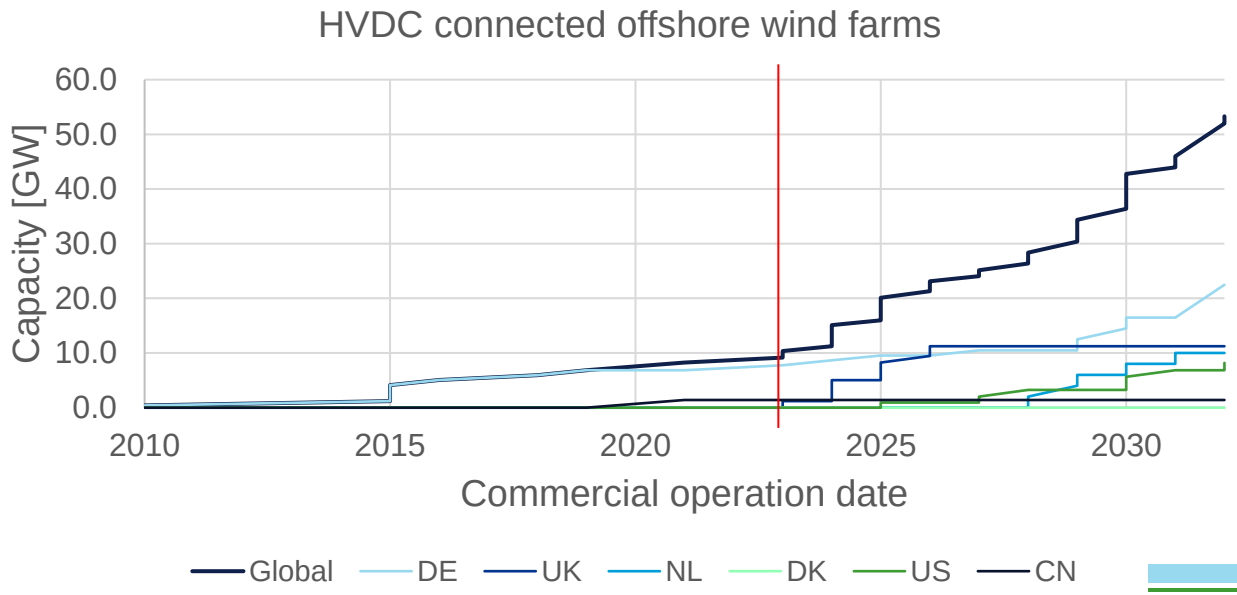
India, North East Agra
6 GW, 800 kV, 3 terminals

Where are we now?

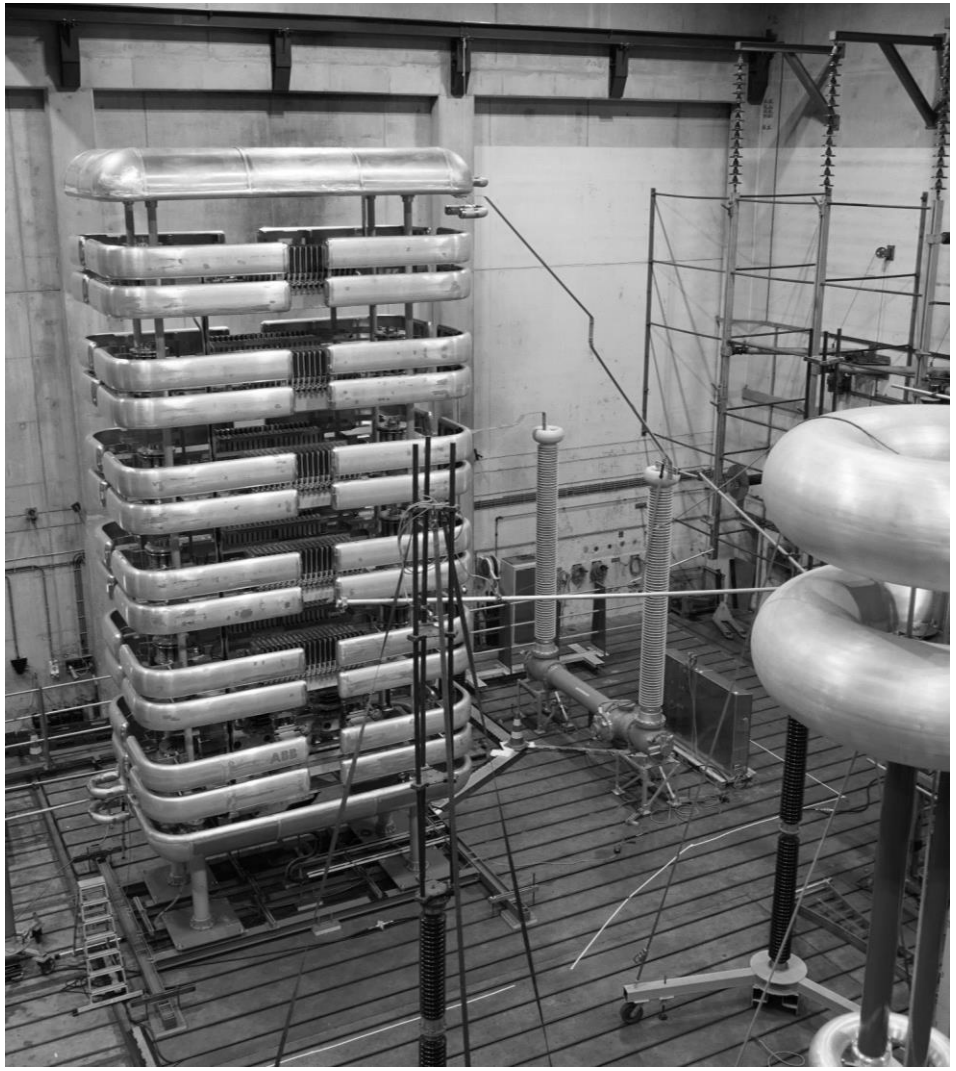




- Strong global growth expected
  - Both onshore & offshore
- First multi-terminal (radial) VSC-HVDC grids
- Multi-purpose HVDC infrastructure appearing
- Policy moving towards multi-terminal HVDC grids



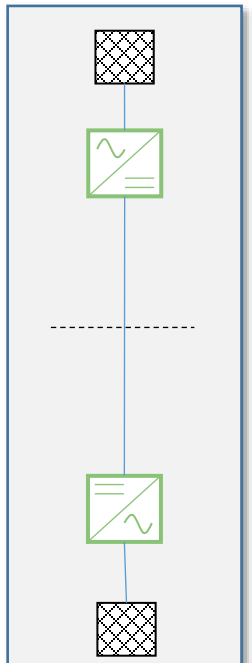
What are the main barriers?



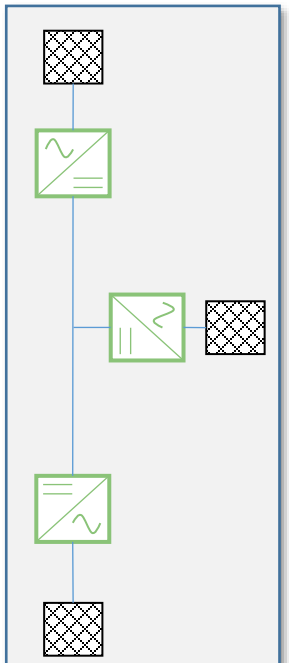
- Inadequate cross-jurisdiction coordination
  - Between states
  - Between ISOs and non-ISOs
  - Between countries
- Incompatible regulatory frameworks
- **Insufficient operational and Planning experience**
- **Proven protection and control strategy**
- **Lack of standardization**
- **Unsolved vendor interoperability issues**
- Limited supply chain
- Onshore AC grid constraints

Pilot projects

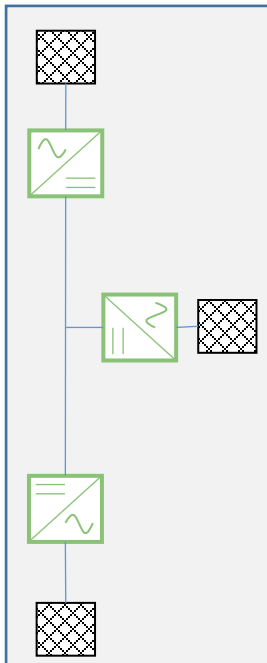
Full scale demonstrators of feasibility and benefits



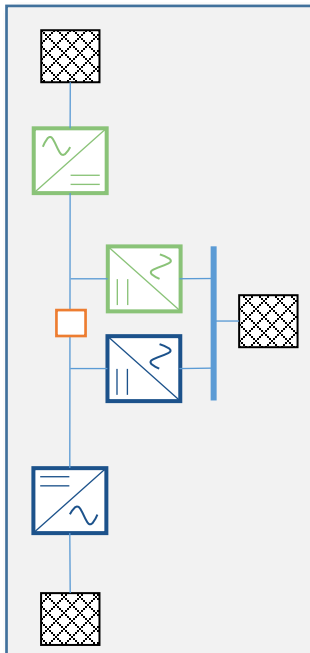
Standard
p2p
Half-bridge
MMC
single-
vendor



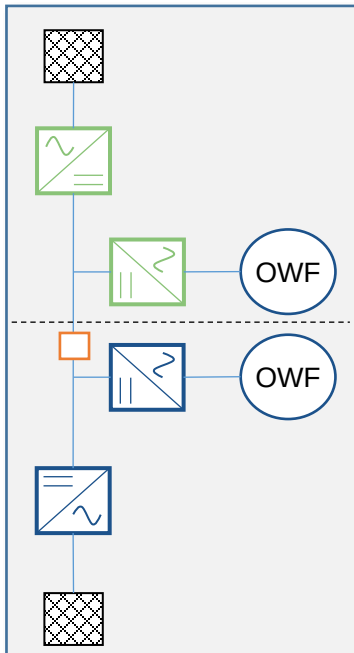
Radial MT
Half-bridge
MMC single-
vendor



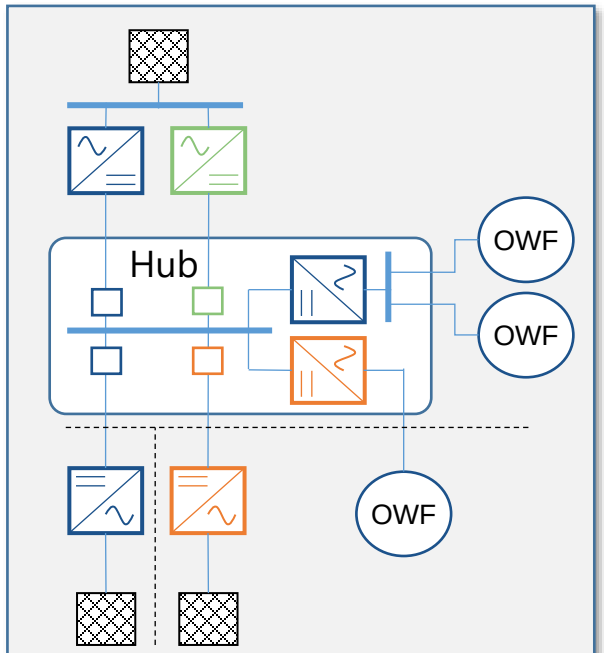
Radial MT
Full-bridge MMC
single-vendor



Radial MT
Half-bridge MMC
Multi-vendor
Onshore DCCB

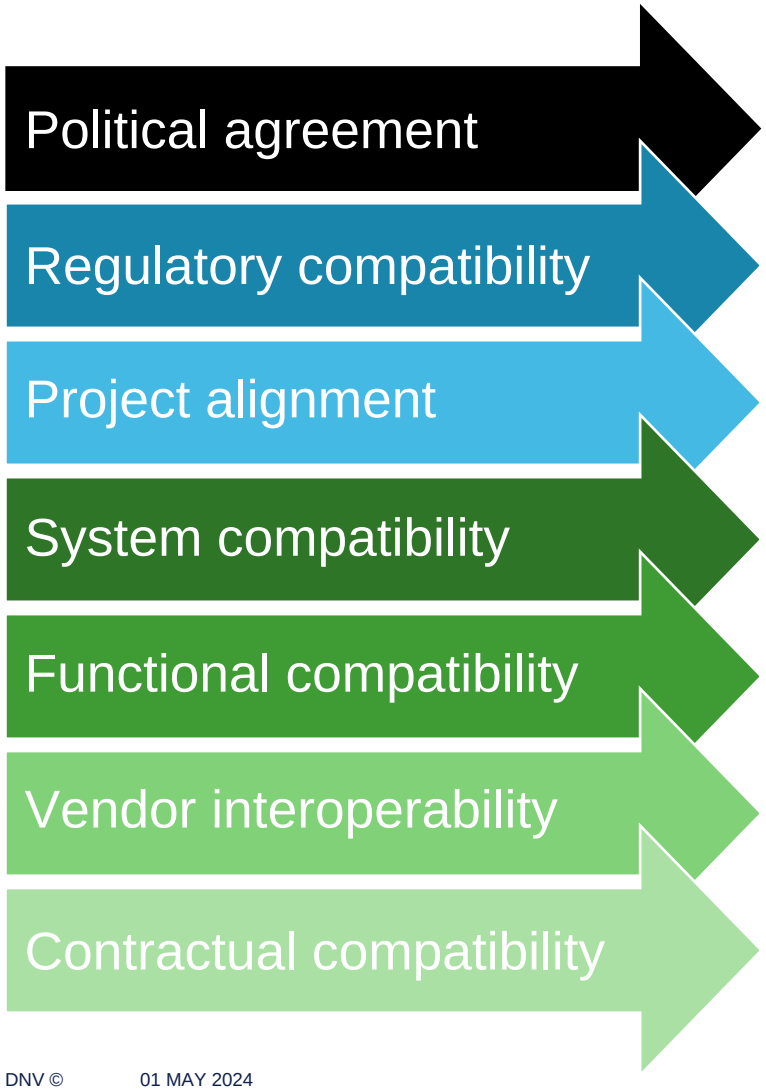


Radial MT
Half-bridge MMC
Multi-vendor
Trans-national MT
Offshore DCCB



Radial MT
Half-bridge MMC Multi-vendor
Transnational MT
Offshore DCCBs

Seven levels of compatibility



Coordination: Unlock project synergies and realize societal benefits

Standardisation: Enable technical compatibility

Future developments

Radial multi terminal China

Meshed multi terminal China

Radial multi terminal Europe

HVDC GIS Europe

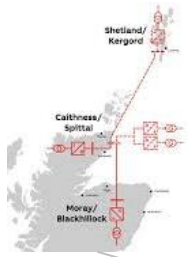
Full-bridge converters Europe

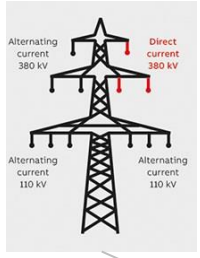
Standardization Modularization Coordination Europe

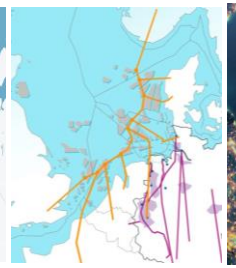
Multi-terminal grids & islands Europe

Combination with hydrogen Europe

Offshore & multi-terminal HVDC US







DC MultiHub

EUROBAR

North Sea Wind Power Hub

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

160 kV 240 MW
Three-terminal radial
Na'nao system
China

200 kV 400 MW
Five-terminal radial
Zhoushan system
China

500 kV 3 GW
Four terminal meshed
Zhangbei system
China

320 kV 1200 MW
Three-terminal radial
CMS system,
Scotland, UK

320 kV 900 MW
HVDC Gas insulated switchgear
Borwin 5 & Dolwin 6 projects
Germany

380 kV 2 GW
Three-terminal FB
ULTRANET, Germany

2 GW 525 kV
HVDC Multi-terminal
readiness & HVDC GIS
IJmuiden Ver, Netherlands

525 kV 3x2 GW
Wind Power Booster
Hub & Heide HVDC
hub Germany

DNV

Conclusions

Multi-terminal HVDC transmission grids:

Have **significant benefits** over multiple point-point links
Already exist → the **technology is ready**
Are a **key enabler of the energy transition**

North American **pilot projects** needed to demonstrate technical feasibility and project benefits

Cooperation and collaboration across all stakeholder levels needed to achieve:

Standardisation to enable **technical compatibility** and interoperability
Coordination to unlock **project synergies** and realize societal benefits

The **future is HVDC**, lets plan for it

Questions?

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