IERE HVDC webinar

The Direction of HVDC development in GB

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15 October 2025

The National HVDC Centre

Scottish & Southern Electricity Networks

Topics

- **Multi vendor Interoperability in VSC-HVDC systems.**
  - What we've done.
  - Demonstration and making it practical to deliver
  - How we've done this.
- **Growth of DC systems.**
  - What might they look like
  - How to get to a vendor agnostic DCCB specification.
  - Associated devices to enable DCCB.
- **Practical DC system interfacing- offshore**
  - INTOG, Hydrogen- anything else to come?
  - Load rejection management- practically.
  - Co-ordinated and staged allocations of offshore grid forming and damping controls.
- **Practical DC system interfacing- onshore**
  - HVDC as a network vs a resource connection interface.
  - Grid forming support from multi-terminal systems.
  - Black start and other support.
  - HVDC systems complementing resilience
  - HVAC & HVDC system cross-optimisation.

The Role of HVDC in Achieving Net Zero

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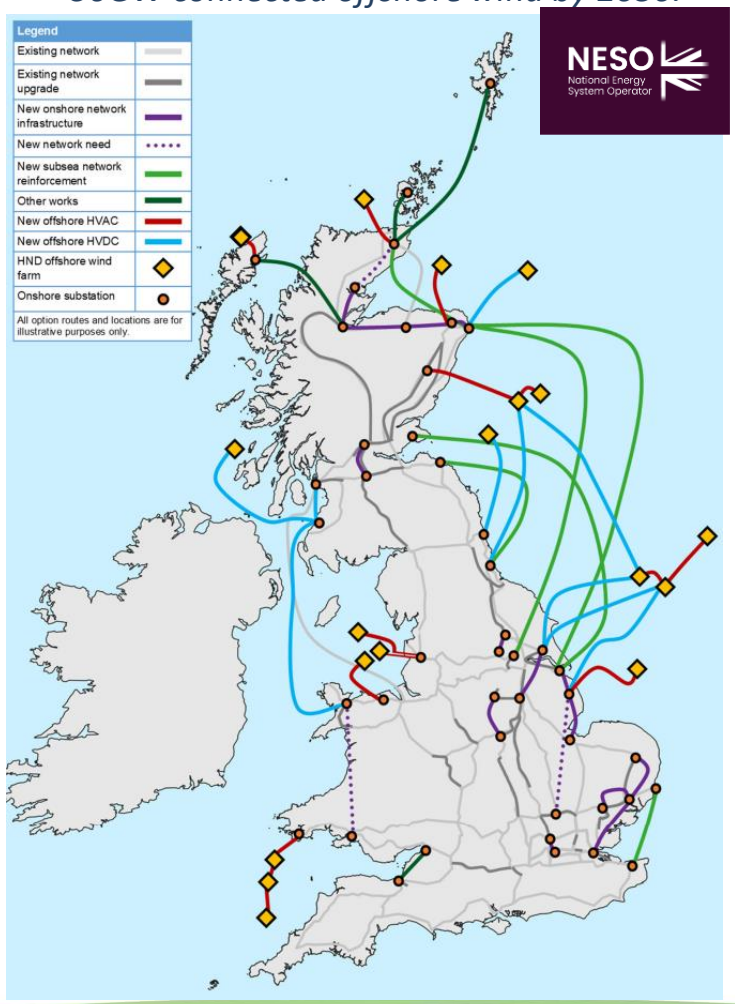
Holistic Network Design - Pathway to 2030
50GW connected offshore wind by 2030.



Beyond 2030 National Blueprint *Additional 21 GW offshore wind.*

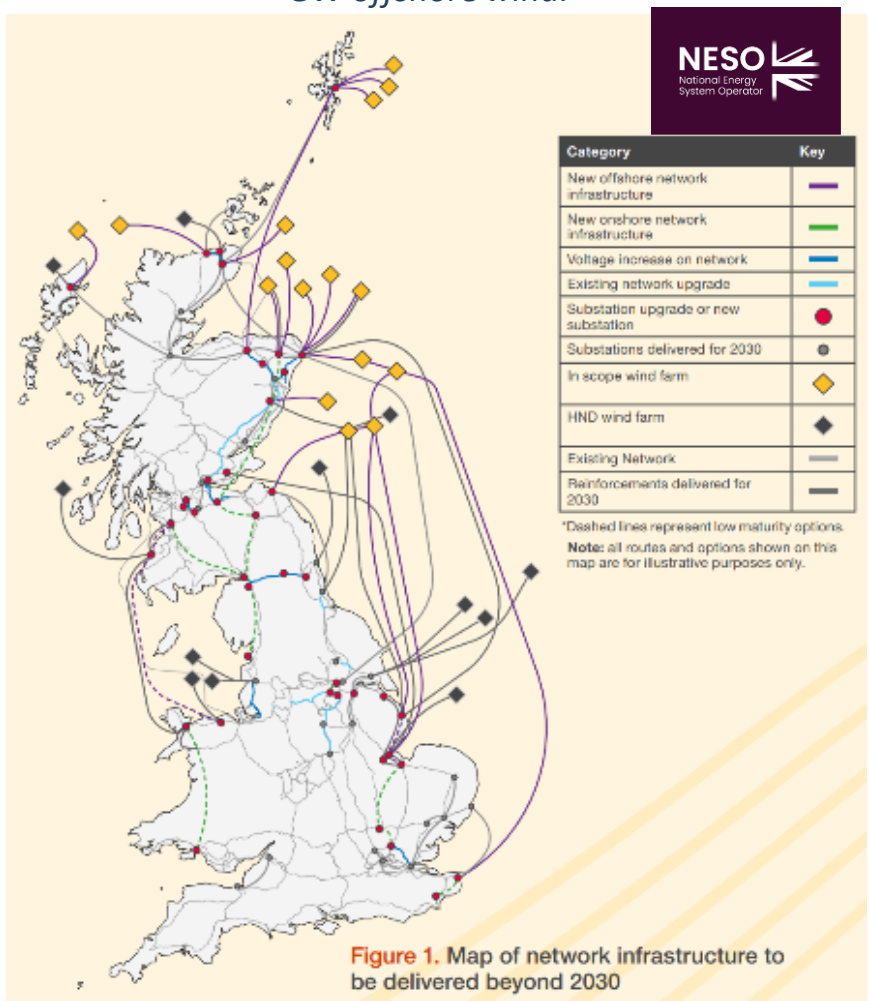
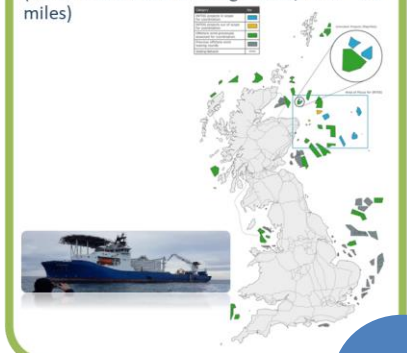


Figure 1. Map of network infrastructure to be delivered beyond 2030

We need HVDC to meet Clean Power 2030 *(and beyond)*:

1) To connect offshore Wind Farms
(AC cannot be use for long cables; over ~90 miles)

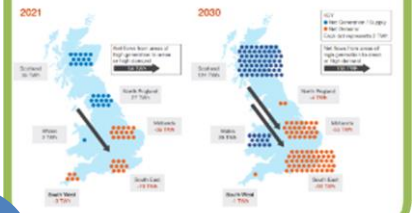


Connect OWF

2) To move electricity from North (where it is Generated) to South (where it is Consumed)

50GW connected offshore wind (by 2030).

Additional 21 GW offshore (beyond 2030).



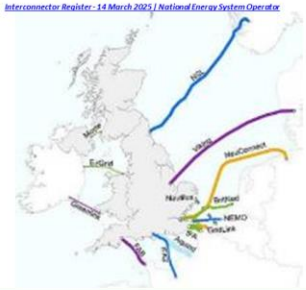
Network Reinforcements

CP 2030

3) To interconnect to asynchronous networks

Current: *11 GW (10 projects)*

Planned: *+29 GW (21 projects)*



Interconnections

We need a roadmap to get to here, and beyond

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A road map to get to the DC systems we need.

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Today

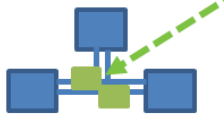
Radial AC (1.3GW max, 220kV)

Radial/ multi terminal HVDC (1.4GW max, 320kV)- max 5 ends

- Going beyond point- point
- DC Switching Stations (DCSS)

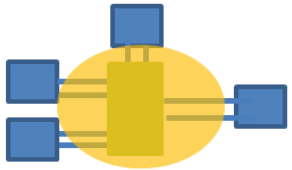
By 2030

Offshore DCSS (HND)



Radial/ multi terminal HVDC bipole (2x1.2GW max, 525kV)- max 5 ends

Project Aquila



HVDC DCSS hubs onshore (2x1.2GW max, 525kV)- multi-terminal multi vendor demonstration

- Specifying & operating DC networks
- Multi-terminal, Multi-vendor HVDC

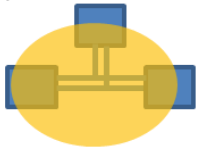
SIF Network DC

- **We are here!**

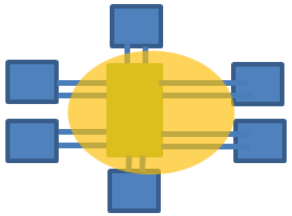
By 2035

Radial AC (2.1GW max, 275kV {using 400kV substation plant offshore})) HND proposed, if developed.

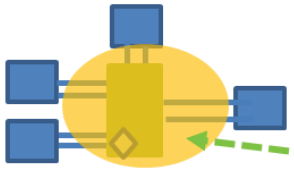
New higher ratings of HVDC- the next standard?



Radial/ multi terminal HVDC bipole (2x1.8GW max, 640kV)- no inherent limit to ends- if developed

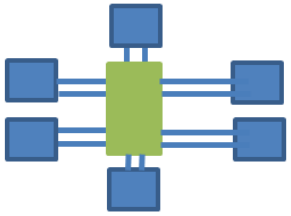


HVDC DCSS hubs onshore with DC generation connection BAU, small offshore DCSS being implemented.

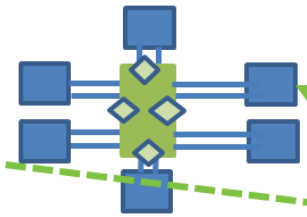


HVDC CB demonstration on existing hubs.

By 2040



Offshore large hubs



Onshore DCCBs at scale within big hubs >3600MW generation

DCCB use onshore

By 2050

Offshore DC networks

Offshore meshed network across north sea.

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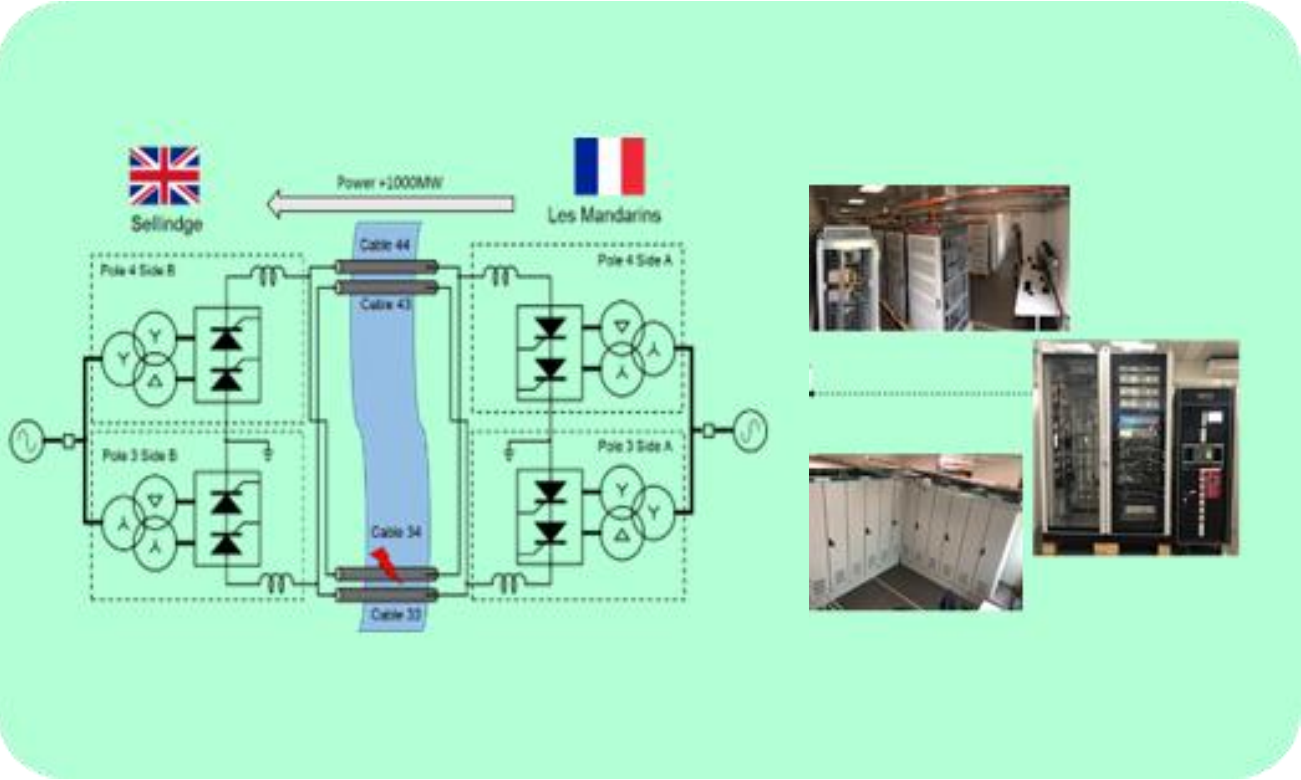
IFA 2000 project- We've been here before



- 1980s- Bi-pole LCC-type HVDC link- ABB convertor in UK, Alsthom convertor in France
- Both vendor C&P cubicles Tested together via CHiL, along with master control within ABB facility in Stafford UK at time-separated access to individual vendors to only view individual plant performance.
- Overall performance verified ahead of commissioning in 1986.
- LCC- HVDC range of functions and performance (and control time constants naturally more limited) than todays' VSC-HVDC, but that does not mean there is a problem with the test process!
- Rather, key challenge is identifying right tests- and right areas of specification to ensure acceptable Multi-vendor complexity- "trial and error" has not to date worked.

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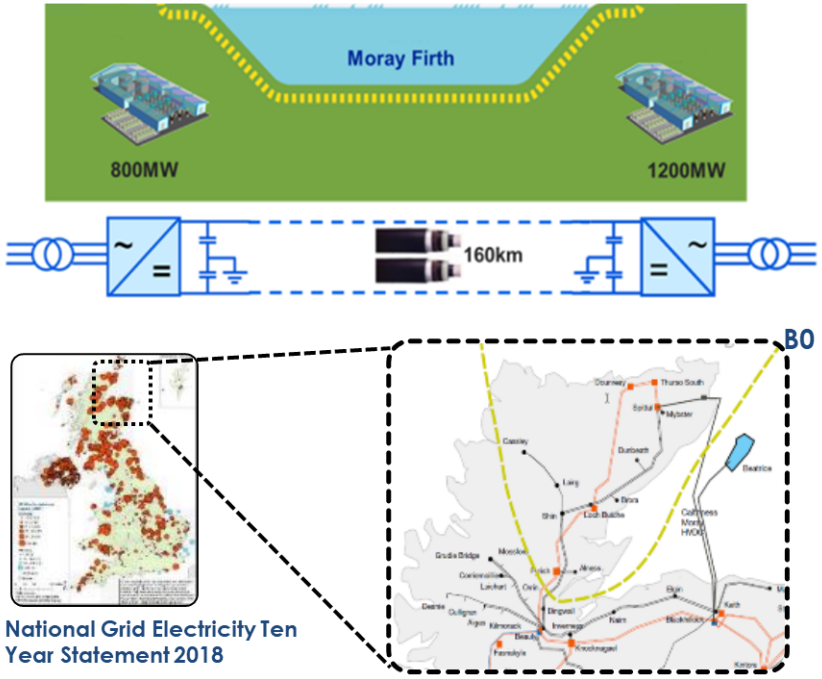
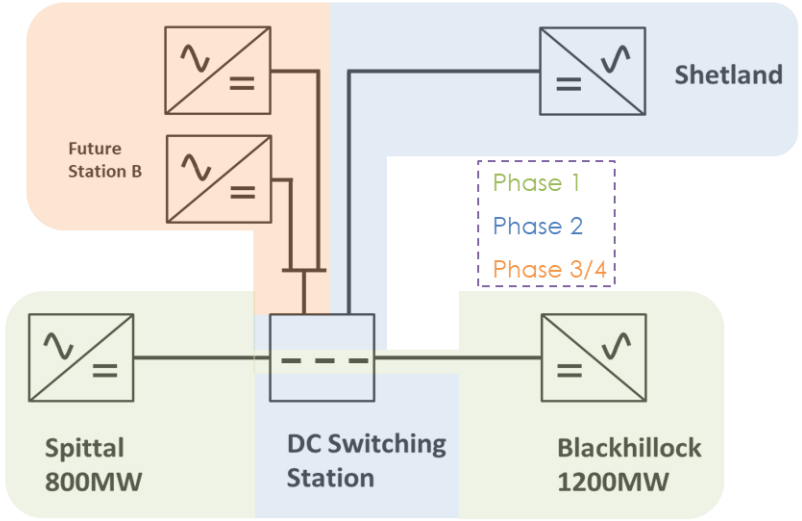
Europes first multi-terminal VSC-HVDC project

- Designed 3-terminal with (in principle)capability to include potential for 2 further terminals from any potential vendor.

- Phase 1 is a point-to-point HVDC link between Spittal (in Caithness) and Blackhillock (in Moray)



- Phase 2 is planned as an extension to Shetland and the introduction of a DC switching station
- Full design allows for further terminals to be incorporated



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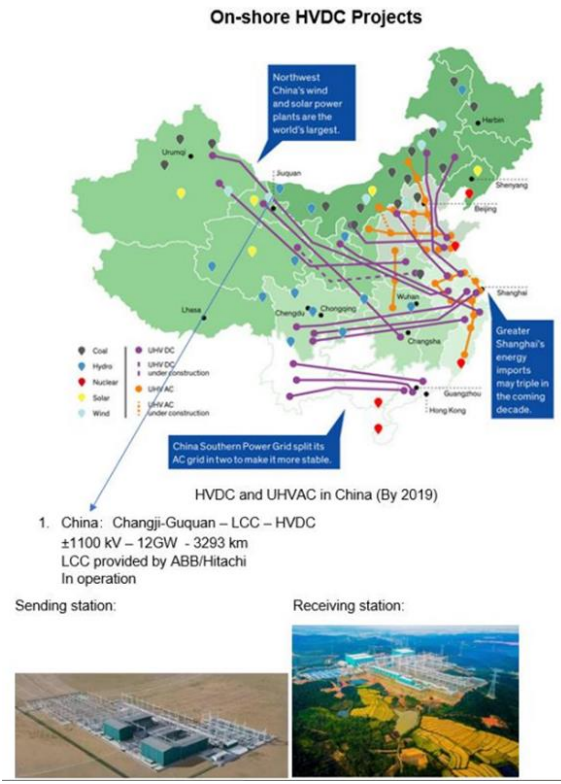
Interoperability in China

Why That's different….



HVDC and UHVAC in China (By 2019)

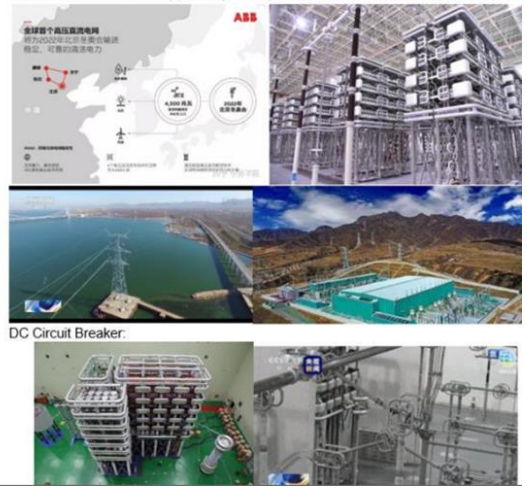
1. China: Changji-Guquan – LCC – HVDC
   ±1100 kV – 12GW - 3293 km
   LCC provided by ABB/Hitachi
   In operation

Sending station:

Receiving station:

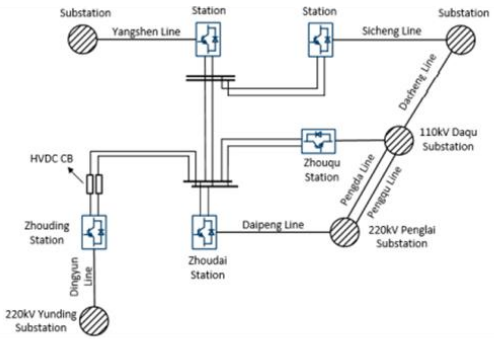
2. China: Baihetan (Sichuan-Jiangsu) Central China to east coast
   ±800 kV/8000 MW –
   Sending from LCC to LCC+VSC – 2172 km
   Under development

3. Zhangbei MMC 4-terminal ring network,MMC half bridge + DCCB
   ±500kV – in operation from 2020 June
   666 km in total, 3 GW supplied by multiple venders, ABB, Nari Electric, etc.

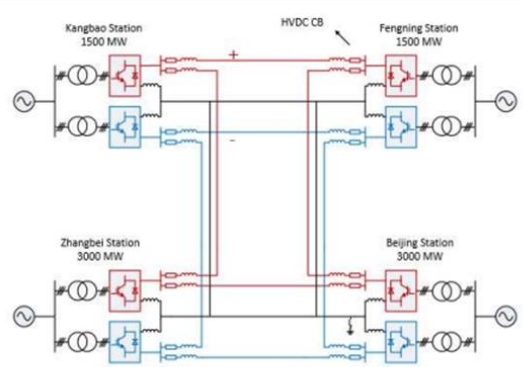


DC Circuit Breaker:

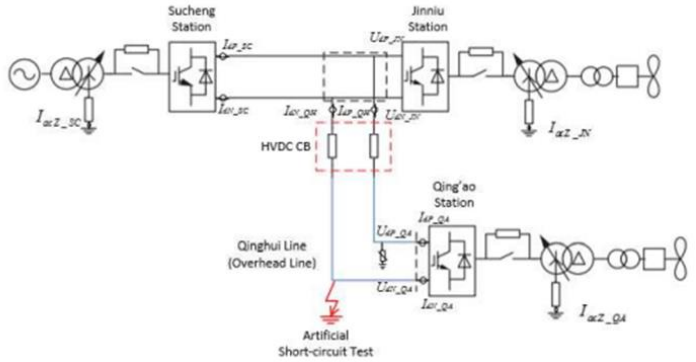
Zhoushan (China)- 5 terminal



Zhangbei (China)- 4 terminal



Nan'ao (China)- 3 terminal



- Different purposes & design principles
- Multi-vendor has been achieved within Chinese systems, but not in a sustainable approach outside of China

In each case- one point of direction in Control & Protection, delivery subcontracted to vendors to a common plan; at every stage one vendor takes responsibility for their and others work.

Multi-vendor control today VSC-HVDC

Approach	Control approach	DCCB consideration?	Data openness (multi vendor)	Role/ responsibility for MTMV success	Timeframes
CMS approach	Evolution of Master-slave concept	None	New vendor would need to share req'd data to support	Original Vendor & SSE Networks- Transmission	Commissioning in full 2024
Chinese approach	Similar	included	All vendors req'd to provide full openness of solutions	Last vendor in must take responsibility for their and re-design/ specification of others	Deployed on China state grid. Would struggle to follow this route elsewhere
Interopera approach	TBC	included	Levels of openness to support base design and new capabilities tbc	Integrator takes responsibility- vendors collaborate with integrator	EU innovation project completes by 2030- findings can then inform
Project Aquila	See next slides	For but not with- staged delivery	Vendor IP need not be exchanged. Approach is vendor agnostic.	TO (SSEN-Transmission) specifies relevant aspects, vendors deliver to specification	Projects deliver for real-world demonstration from 2030 onwards

- **More options**

= more vender approaches to achieve them,

= complementing unique vendor devices & topologies

- **Risk of more complexity and more ambiguity from "overspecification" interface ambiguity and access to functions subject to multiple levels of optimisation**
- **Important to define the network functional and operational needs first- in a way that generates clear specification which is "vendor-agnostic"**

Multi-vendor simulations in GB for EU Promotion project

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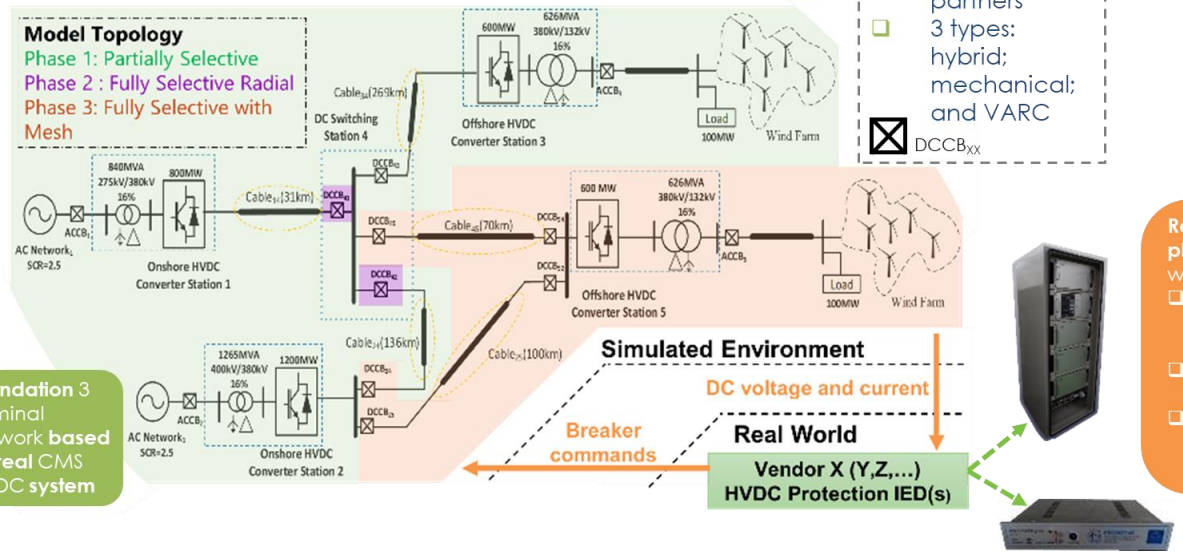
HVDC Cables
- Parameters from real project
- Travelling wave frequency-dependent phase model used giving accurate v, i response

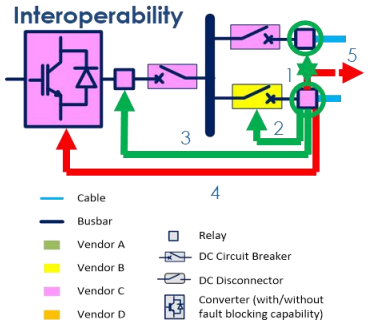
Converters
- Open-source
- Average HB-MMC
- Includes high and low level control

DCCBs
- Developed by WP6 in collaboration with industrial partners
- 3 types: hybrid; mechanical; and VARC

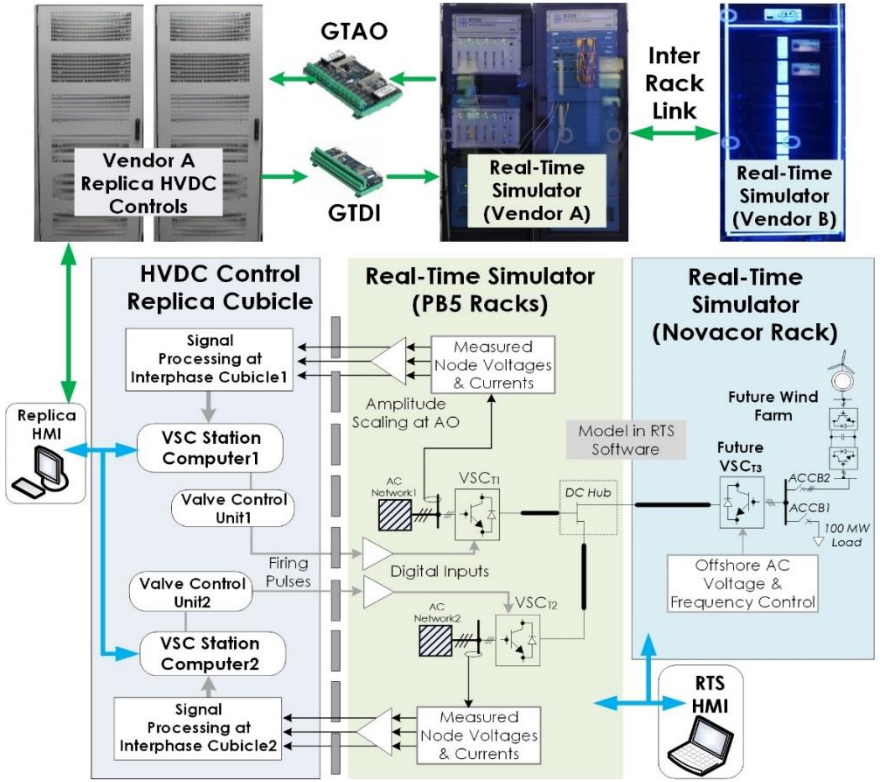
$DCCB_{XX}$



Foundation 3 terminal network **based on real** CMS HVDC **system**



Real time operation lets us **connect physical devices** in a **closed-loop** with the simulated environment
- Shows dynamic response of the system as test continues after action of the device.
- Test multiple devices simultaneously
- More detailed system representation than open-loop test provides



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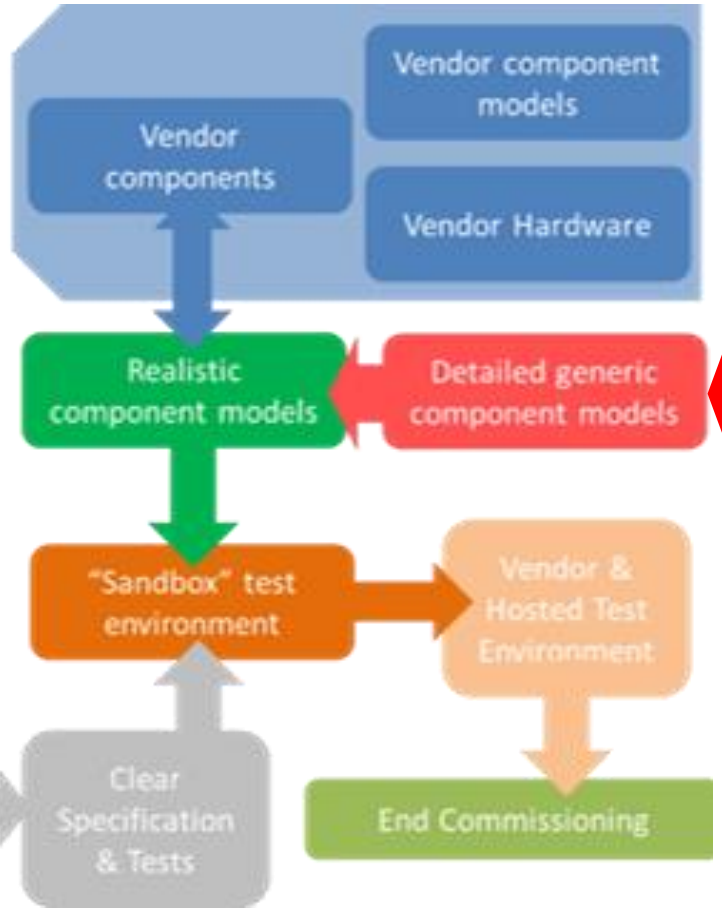
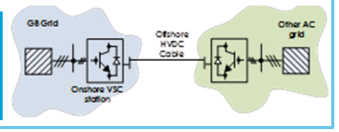
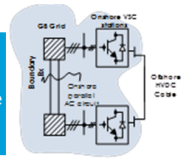
Centre work on Functional Designs for HVDC (2022-2023)



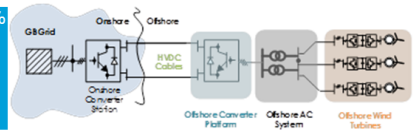
- **Interconnection**
  - Linking GB grid to other countries
  - Loading depends on price differential between different grids
  - Not always fully loaded



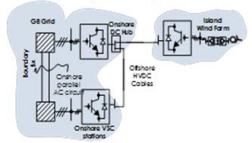
- **Grid Reinforcement**
  - Two converters located in same grid for reinforcement & boundary capability improvement;
  - Loading follows variable demand profile, renewable generation & plant dispatch - not always fully loaded.



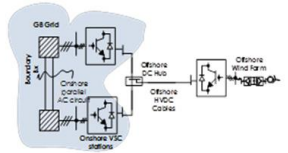
- **Offshore Wind Connections**
  - Load factor is about 50% in GB
  - GB projects under-construction with 7 existing in Germany



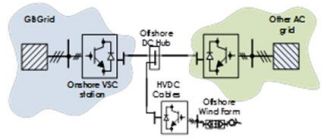
- **Multi-purpose HVDC**
  (Can be built in stages across different options)
  - Embedded link with onshore DC hub



  - Embedded link with offshore DC hub



  - Interconnector with offshore DC hub



We see this project as a critical component of enabling GB delivery:

- Providing a flexible 'test-bed' for TOs/ESO/Developers/ Manufactures to test their coordinated designs.
- Component, control and protection elements of DC systems
- Includes patent filed approaches to control

This enables:

- ***TOs;*** to test the technical performance of offshore network designs on onshore networks;
- ***ESO;*** to assess potential interaction risks and ancillary service capability of integrated solutions.
- ***Developers;*** to investigate technical feasibility and operability of shared transmission solutions; and
- **Manufacturers;** to verify performance of confidential 'black-box' models within offshore network designs comprising equipment from another supplier.

Project Aquila

•Net Zero targets for GB by 2030

• up to 50GW of Offshore wind, by 2030 at least 40GW

- Scotwind leasing- 25GW in Scottish waters alone.
- Drives multiple co-located high capacity HVDC projects, reinforcing network and connecting Net Zero resources.

•Drivers for Multi-terminal & Multi-vendor.

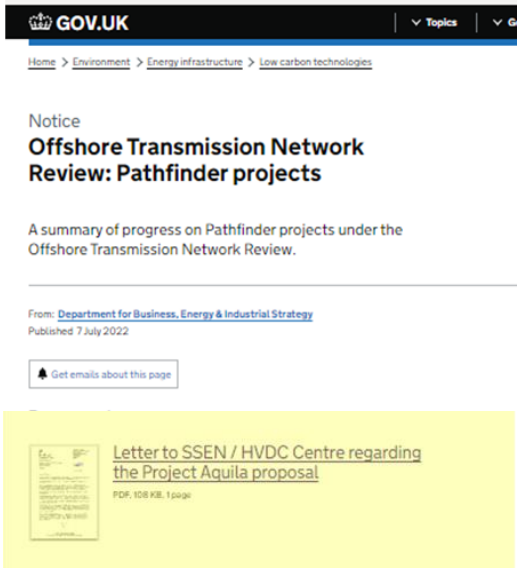
•Environmental, cost and network efficiency benefits in avoiding excessive converters, and managing power flow in multi-terminal.

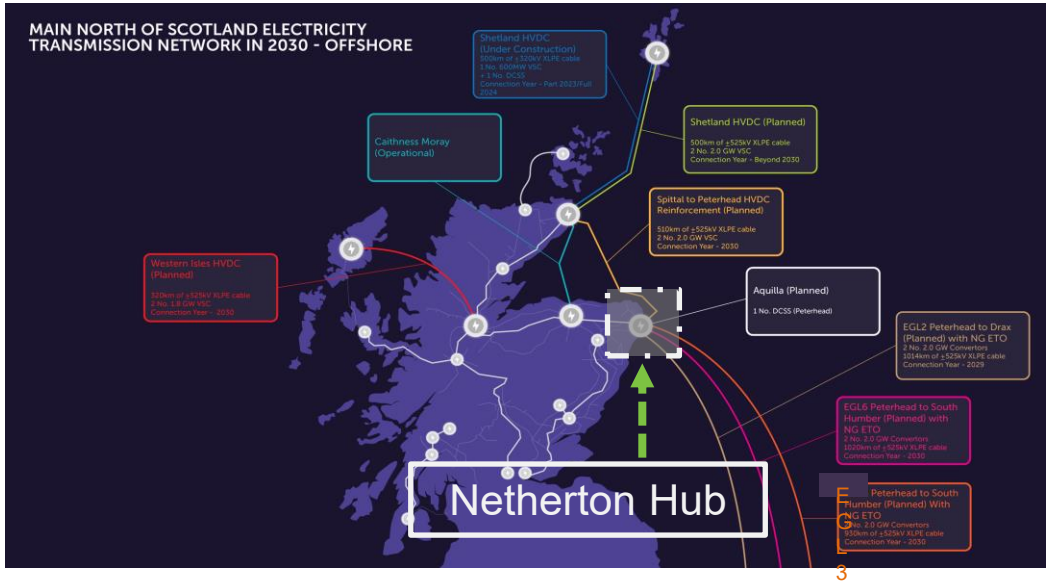
- Scale of simultaneous projects.
- Staged development of multi-terminal

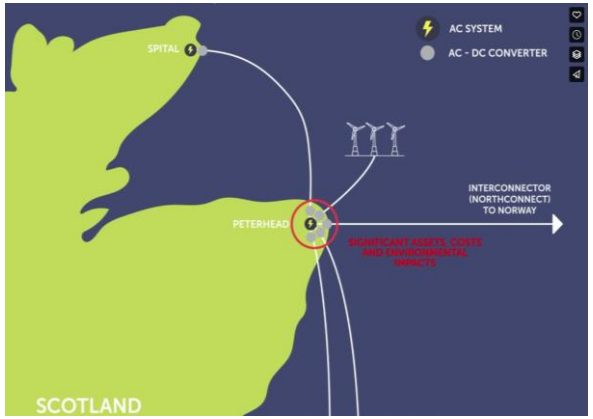
•Delivery under Business as Usual with Government commitments.

•Pathfinder approval- assures Government and regulatory support in removing blockers across policy, frameworks, codes to enable project delivery.

•Funded within the context of known available regulatory instruments, providing certainty.







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Multi-terminal Multi-vendor VSC HVDC demonstration.

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- **What we have done.**

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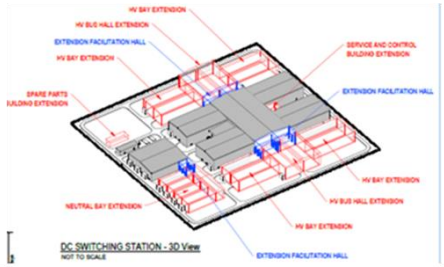
Specifications- layouts interfaces, data, design (Q2, 2024/5)



Enables contracting, consenting, delivery

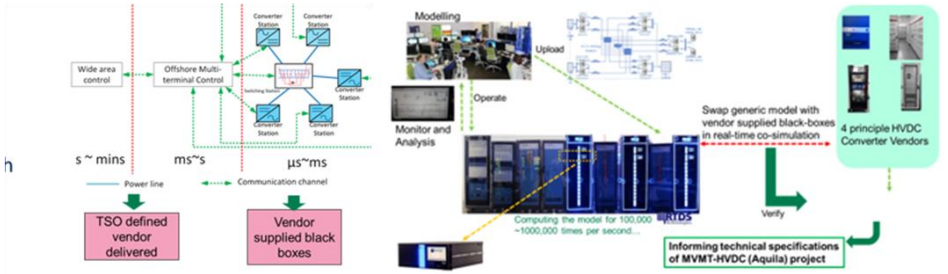
Patent protection, legal commercial review (Q4 2024/5)

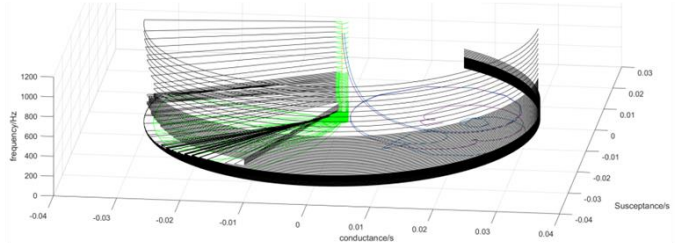
Multi-Vendor Multi-Terminal Control	This Patent covers an advanced control system for coordinating HVDC converters supplied by different vendors in a multi-terminal configuration. This enables smooth power flow orchestration between all terminals- prioritising stable operation intact and post-fault.
Multi-Vendor Multi-Terminal Operability	This Patent allows operation across unbalanced conditions across a range of configurations and outages to maximise the availability of an integrated HVDC grid.
Multi-Vendor Multi-Terminal Stability	This patent provides a mathematical proof of network stability that can then be monitored in real time- and provides a basis for clear specification of an vendors' convertor interface to a DC network

Enables legal & commercial space for interoperability

Hitachi Energy | SIEMENS energy

MTMV Control specification and testing (Q3 2024/5)





Enables clear roles& responsibilities, & assured performance

	Aquila Interoperability Package	DCSS hub and associated design and specification	Aquila Commercial and Legal package.
Who?	Lead by **HVDC Centre** (September 2021- April 2024)	Lead by **SSEN-T HVDC engineering** team (September 2021- April 2024)	Lead by SSEN-T Innovation, Comercial, legal and procurement teams in association with **University of Groningen** (April 24- April 25)
What?	**Vendor Agnostic** multi-terminal control, control interface specification, design input. Associated test & demonstration approach	Tender pre-engineering, **specifications, layouts, design** at vendor agnostic level.	**Requirements** at tender & contracting phase, **liabilities and responsibilities** allocations, how to manage "switch on" and lifecycle support thereafter.
Why?	Patented approach protecting vendor agnostic delivery. **Respects vendor IP** as in real industrial project. **Tested demonstration** across vendor replicas	Planning, tender and **contractual engineering documents enabling interoperability**	**Independent review** and **assessment of readiness** to contract and manage multi-vendor solutions.

- **More to come!**
  - **More Vendors**
  - **More projects (offshore hubs & onshore hubs- GB and continental Europe & beyond)**

Multi-terminal Multi-vendor VSC HVDC demonstration.

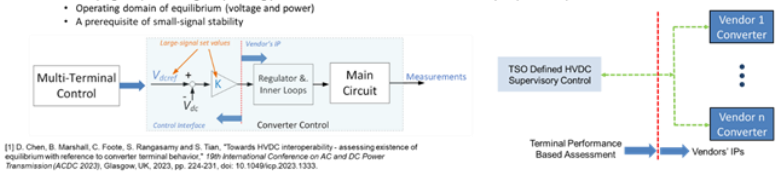
The National HVDC Centre

- **How we did this.**
- Four key principles to our approach-

Principle 0 – respect vendor IP

Characterise and inform performance at convertor island interface. NOT open up C&P

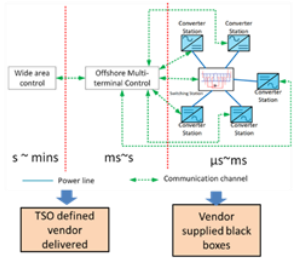
- Cascaded control architecture between MTC and converter
- Converter interfacing MTC via voltage reference value of V/I droop (K-factor refers to virtual conductance)
- Essential MTC Functions
  - Power Control
  - Global DC voltage control
  - Pole balancing control
  - Quantifying the positioning of operating point between no-load condition and collapse (CX-index)
    - Operating domain of equilibrium (voltage and power)
    - A prerequisite of small-signal stability



[1] D. Chen, B. Marshall, C. Foote, S. Rangasamy and S. Tian, "Towards HVDC interoperability - assessing existence of equilibrium with reference to converter terminal behavior," *19th International Conference on AC and DC Power Transmission (ACDC 2023)*, Glasgow, UK, 2023, pp. 224-231, doi: 10.1049/icp.2023.1333.

Principle 1- coherent robust DC network control

Stability over power flow efficiency. Across contingencies including loss of communication.

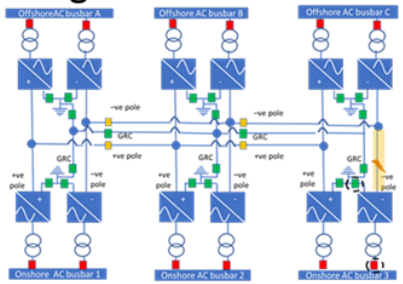


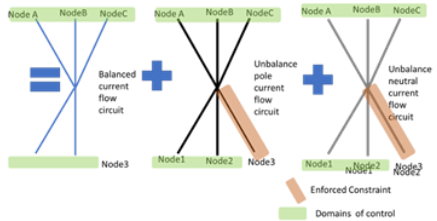
- ✓ Converter Control (µs ~ ms):
  - operate based on local measurement
  - respond to Multi-Terminal Control
  - sustainable when communications are lost
- ✓ Multi-Terminal Control (ms ~ s):
  - monitor
  - assess
  - optimize

The DC Grid should be sustainable when all communication channels or a single power line is lost.

Principle 2- enhanced DC network operation & availability

Unbalanced control to manage network outages/ faults, control hunting and Hybrid rigid & full bipole arrangements

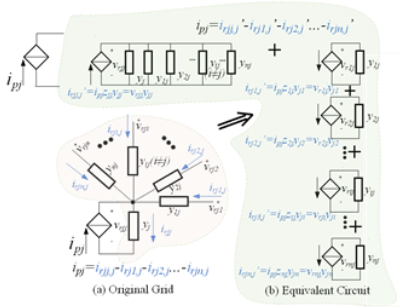


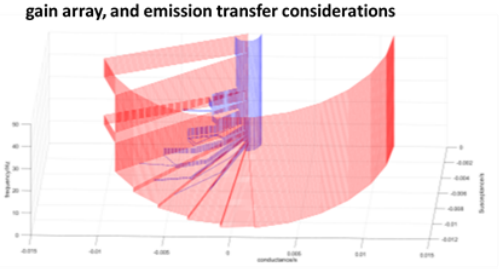


[2] Dong Chen and Benjamin Marshall, "Modelling Asymmetrical HVDC Transfer Network for Multi-Vendor-Multi-Terminal Interoperability," *IET Conference on Renewable Power Generation*, Glasgow, 2023, in press

Principle 3- assess and maintain stability in operation.

Ability to present emission limits at the DC converter terminal Interface supporting single terminal testing of a global set of DC network stability criteria. Based on small signal, relative gain array, and emission transfer considerations



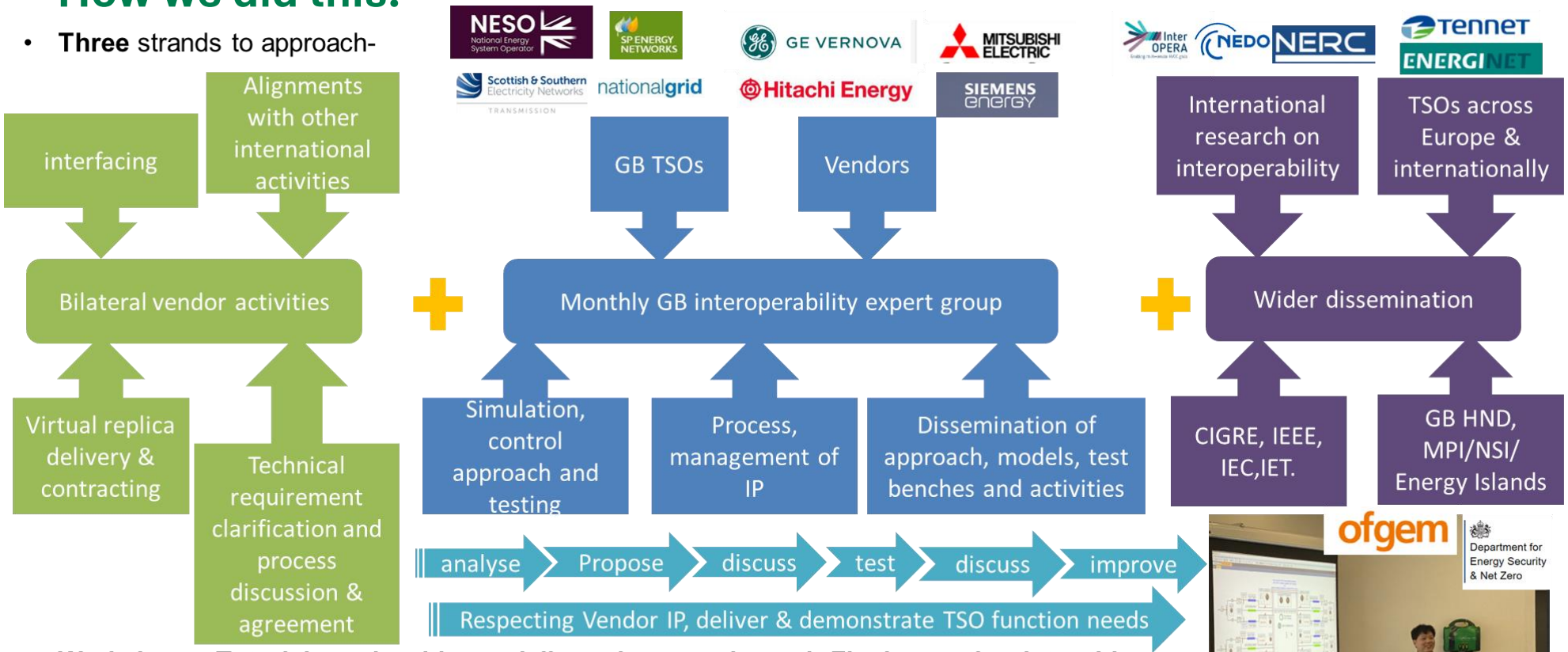


[3] Dong Chen and Benjamin Marshall, "Towards HVDC Interoperability – On Dominance of Nodal Impedance," *TechRxiv*, Oct, 2023

Scottish & Southern Electricity Networks

Multi-terminal Multi-vendor VSC HVDC demonstration.

- **How we did this.**
  - **Three** strands to approach-

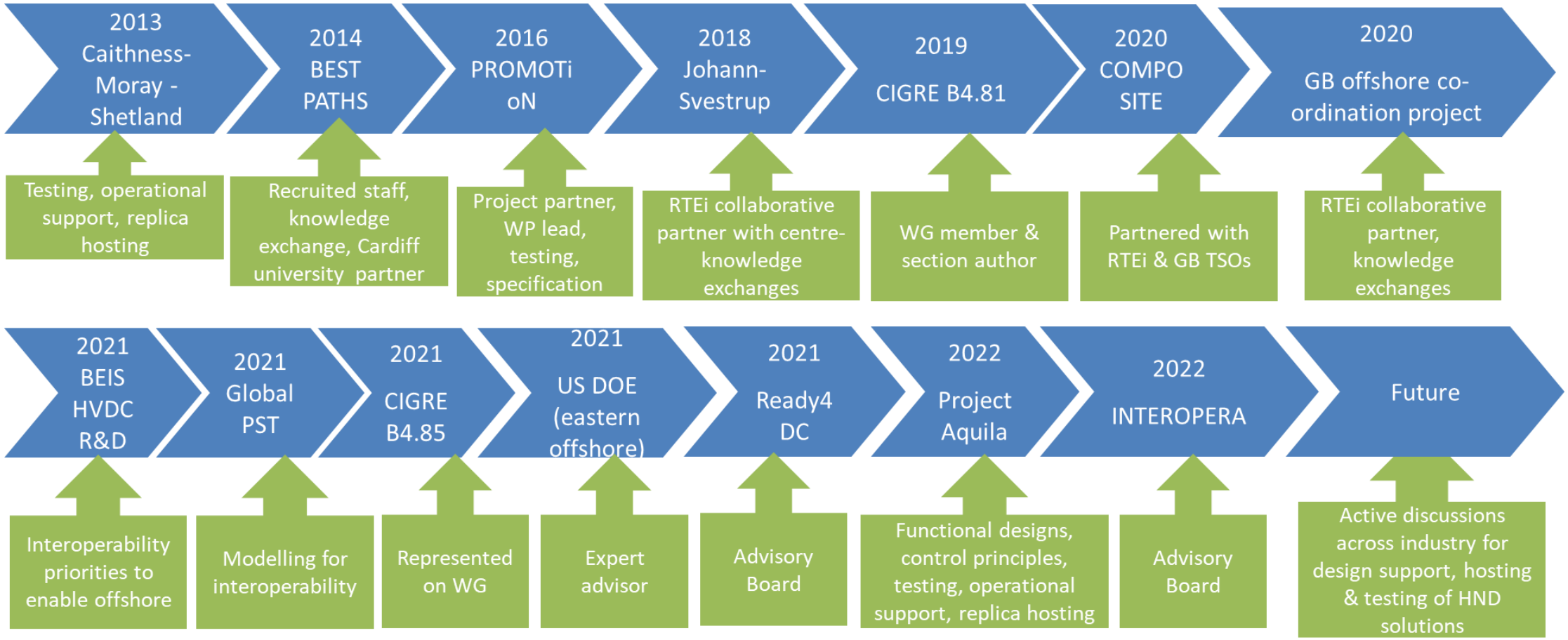


- **Workshops, Tutorials and webinars delivered- more planned. Final reporting later this year.**
- **Future work (Network DC et al) on a similar basis**

Multi-terminal Multi-vendor VSC HVDC demonstration.

The National HVDC Centre

- **How we got here.**



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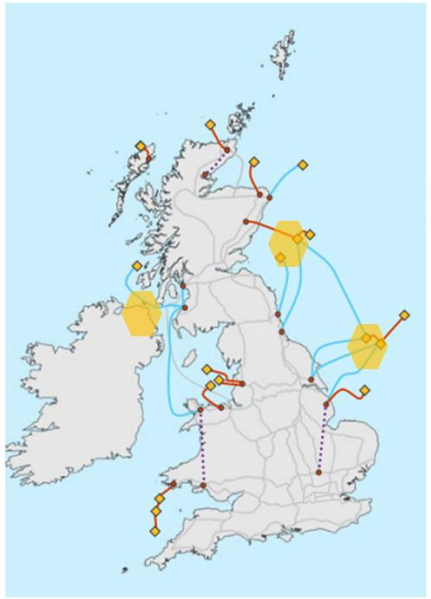
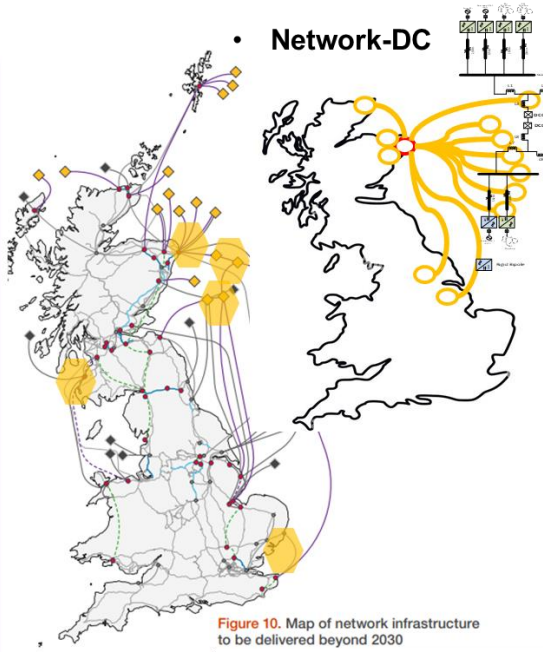
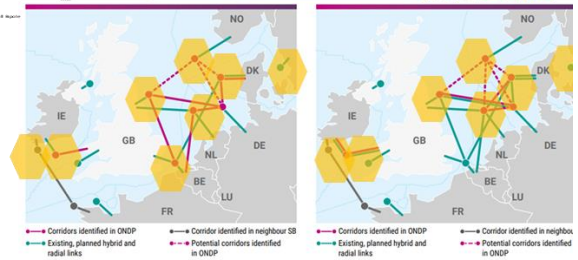
Growth of DC systems.

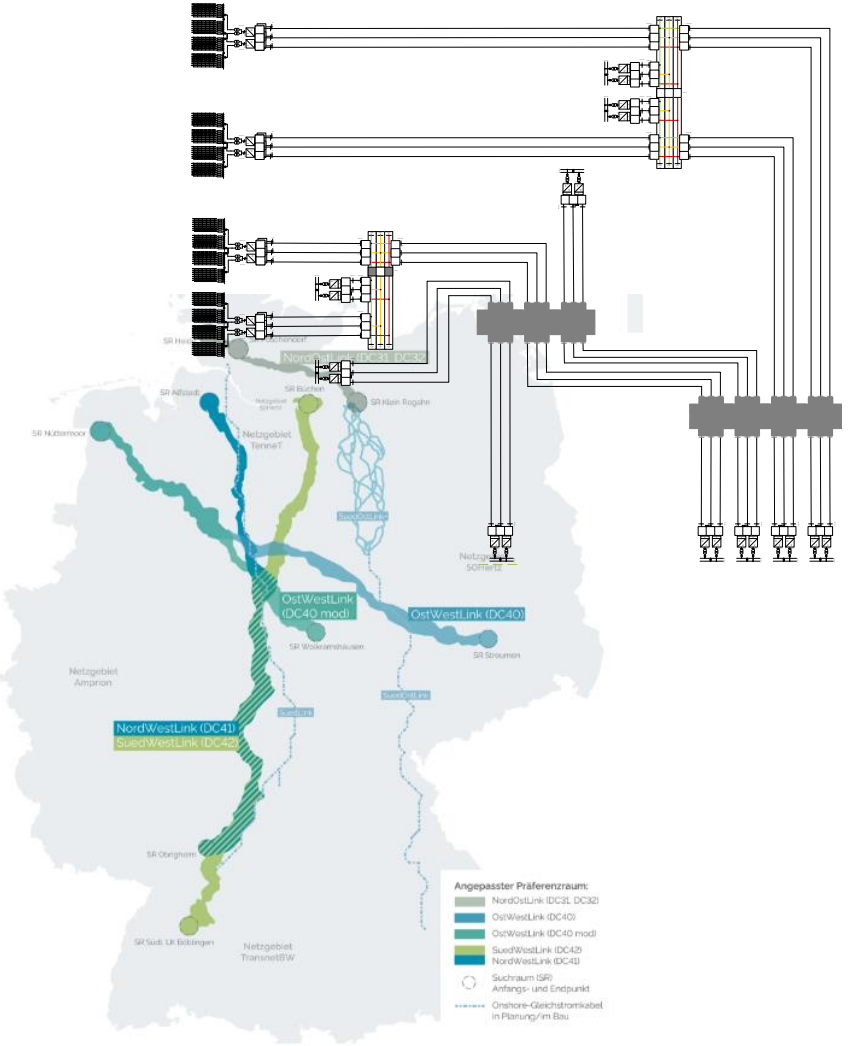
- The future is now!







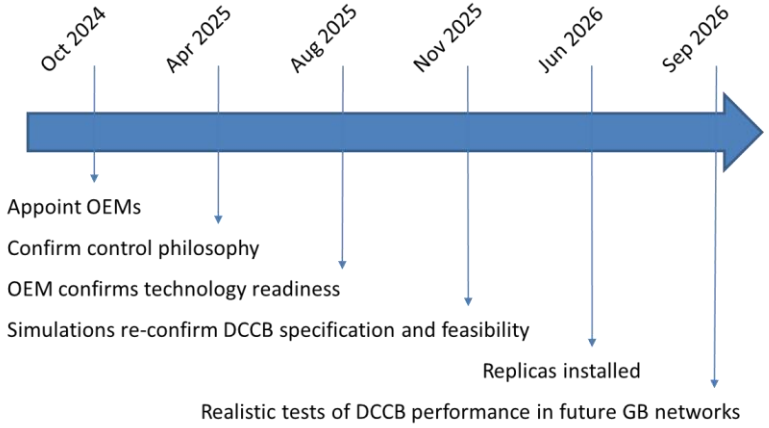
- HND phases----------→?
- DC Network reinforcements where **Project Aquila unlocks solutions**

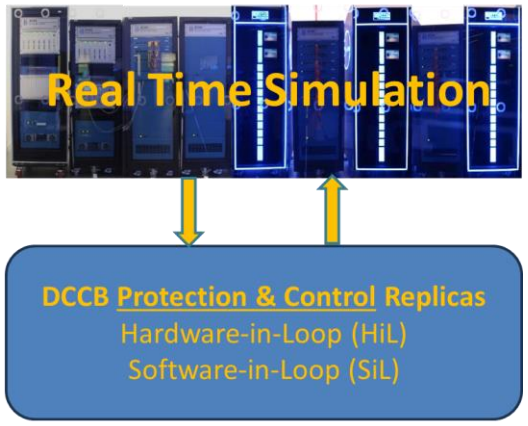


- Networks needing Multi-vendor & DCCB at scale

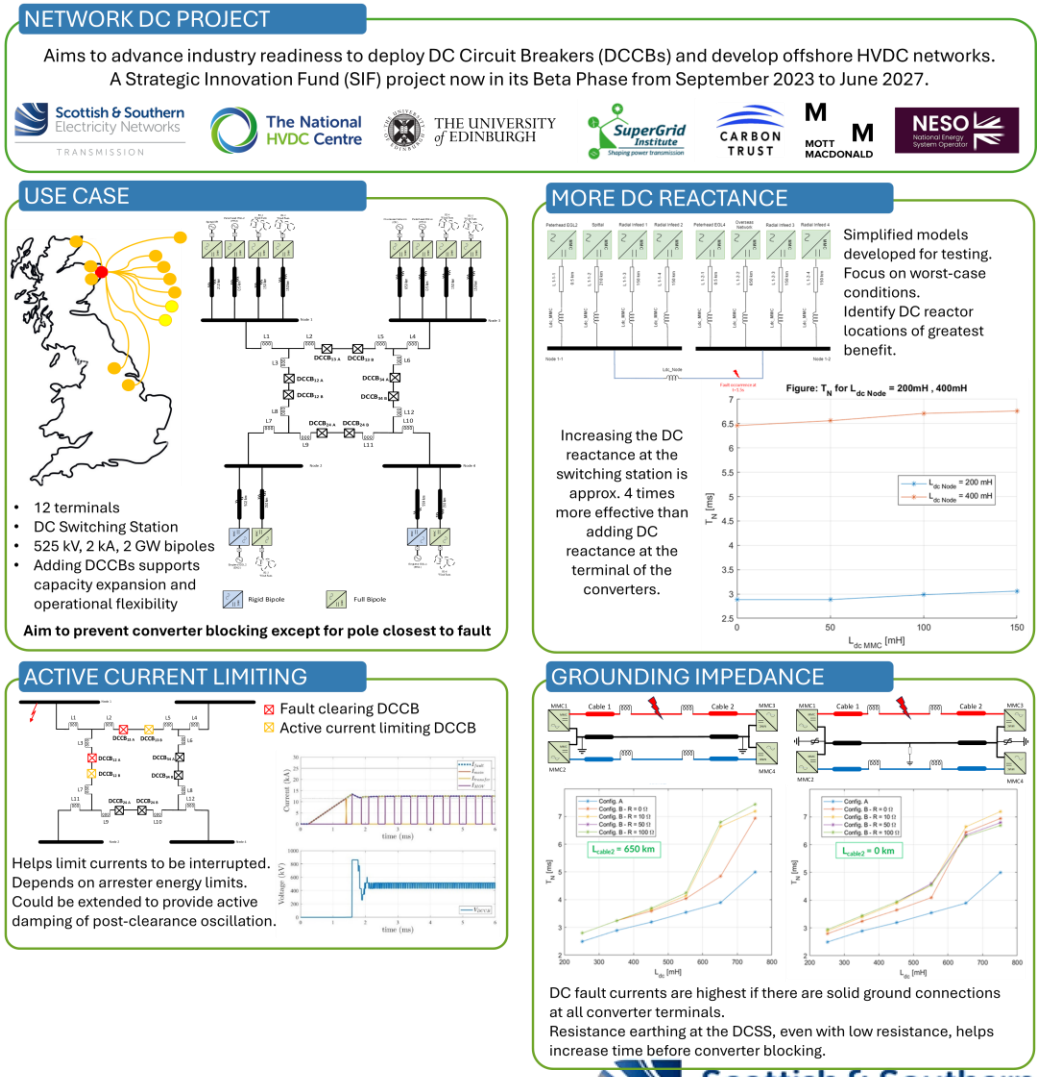
Growth of DC systems- DCCB.

- **The progress of Network-DC; vendor agnostic DCCB specification & integration as a network grows.**





- **Philosophy and testing process confirmed**
- **OEMs identified; contracting supports next steps**



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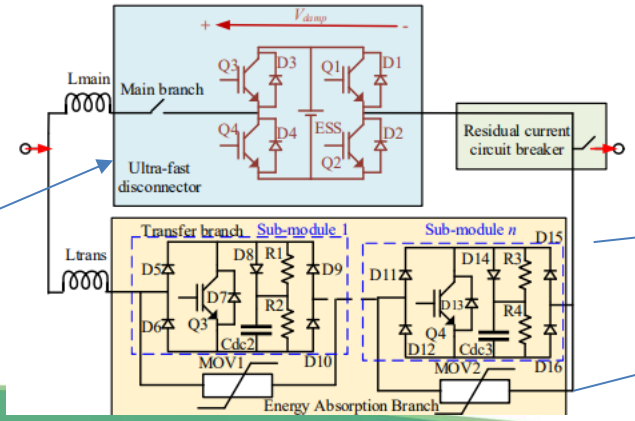
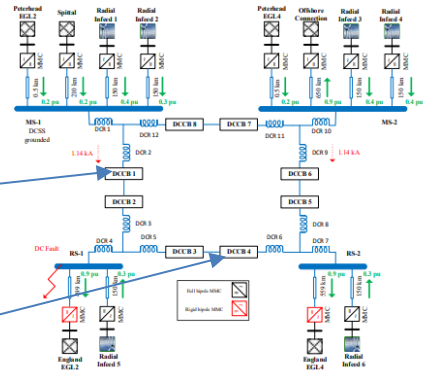
Growth of DC systems.

- Enabling DCCBs- related considerations.
- Protection IED capabilities
- Fault limiters
- Damping support

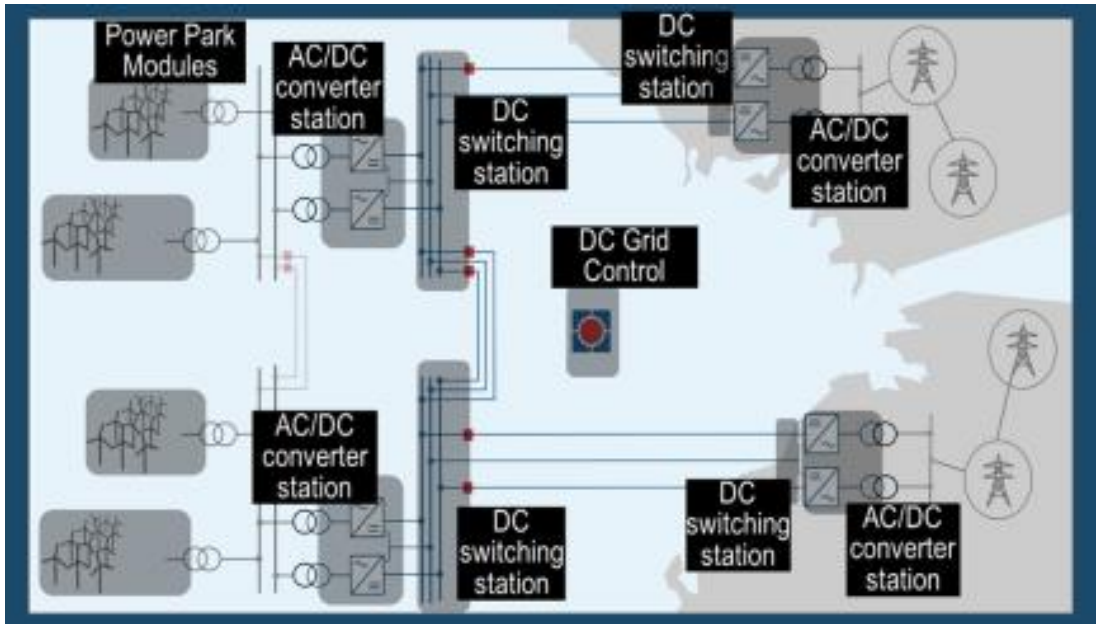
PROMOTioN IEDs

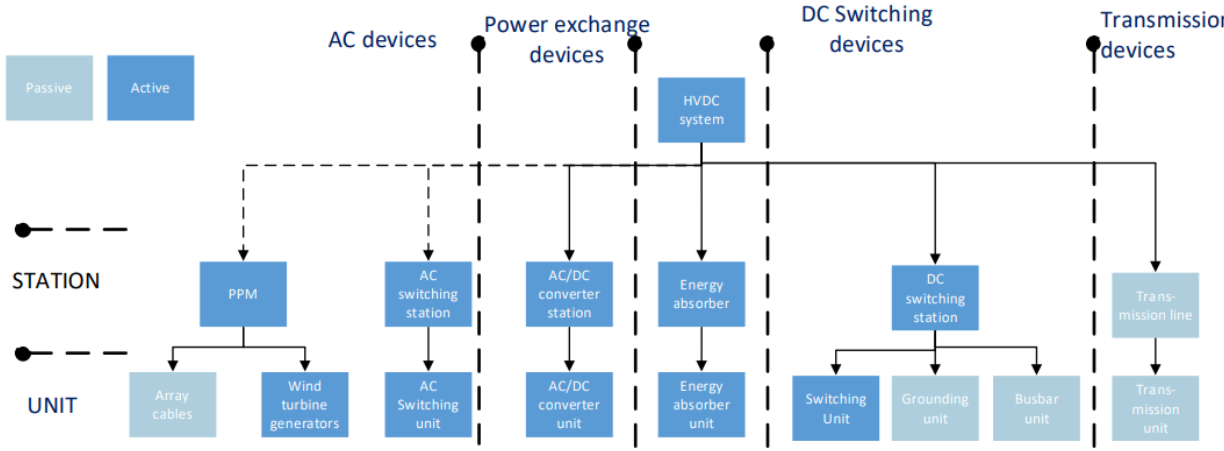




DC networks Components and specifications

- **InterOpera provides additional clarity on DC component functions and specification areas.**

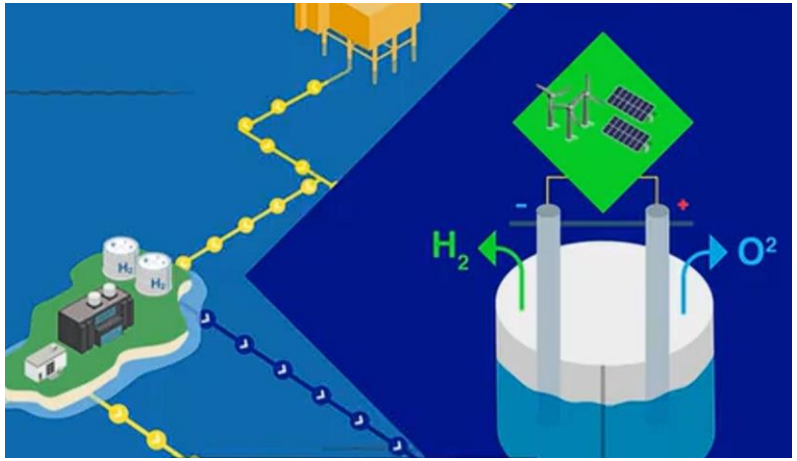


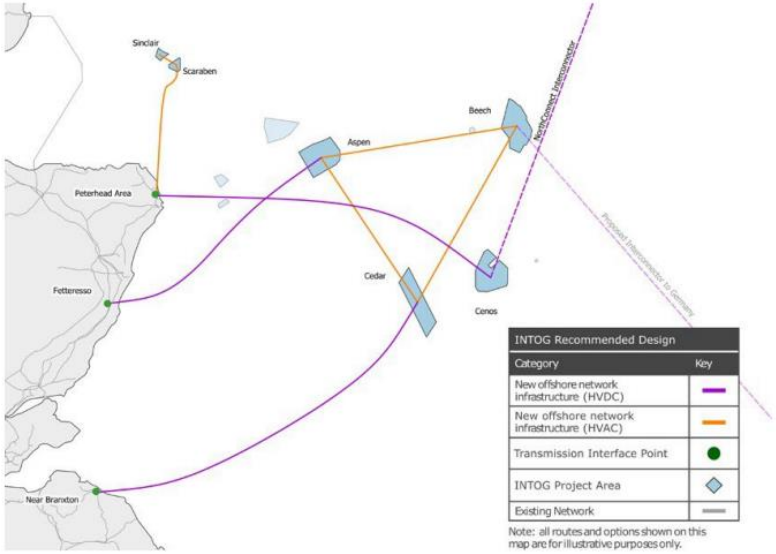


- **Standardised terminologies and implementation concepts**
- **Aquila and Network provide foundations for control and performance specification respecting IP. It all fits together.**

Practical DC interfacing- offshore.

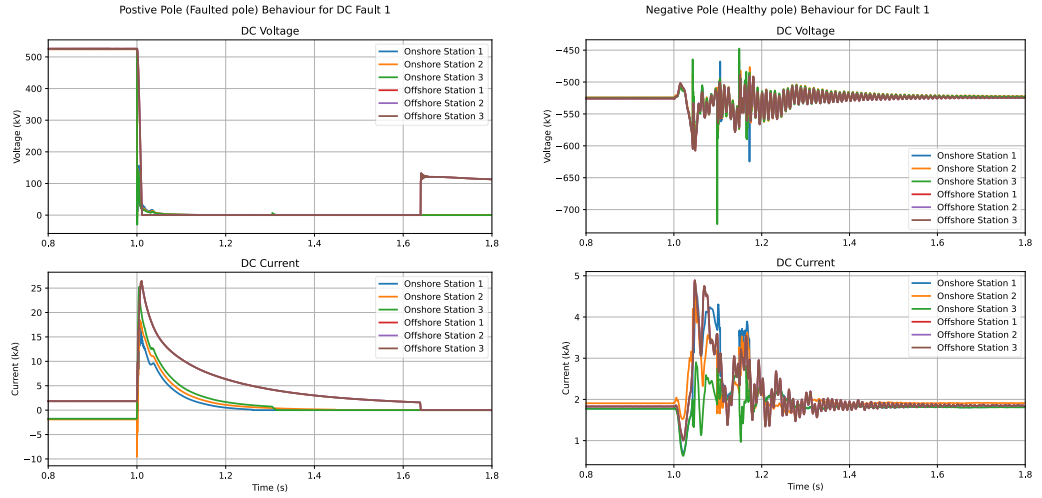
- Lots of new devices.
- Lots of new considerations-
  - Load security/ intermittency
  - Energisation/ impulse load management.
  - Legacy specification/interfacing (INTOG).

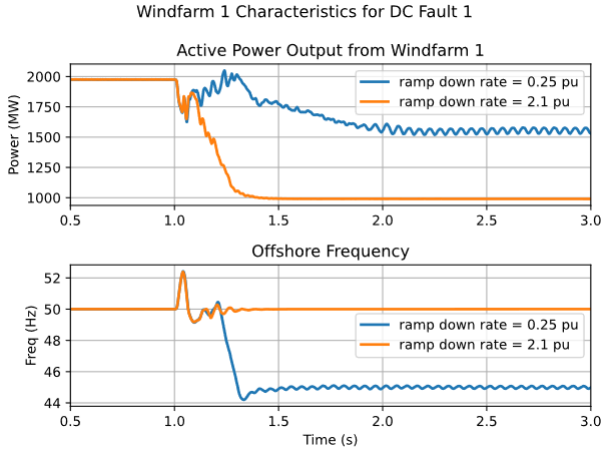


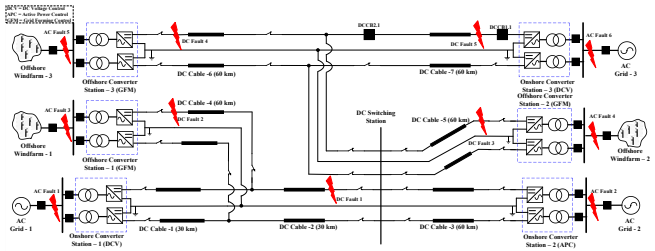


Practical DC interfacing- offshore.

- **Load rejection**
  - **WTG want slow ramping- e.g. 0.25p.u./ s**
  - **but can go faster with crowbar action (AC fault or intertrip)**
  - **Intertrips risk uncertainty across large arrays.**
  - **But this is not a reason for AC chopper specification- would WTG really want that?**
  - **Offshore AC Hf/ HV crowbar operation specification?**

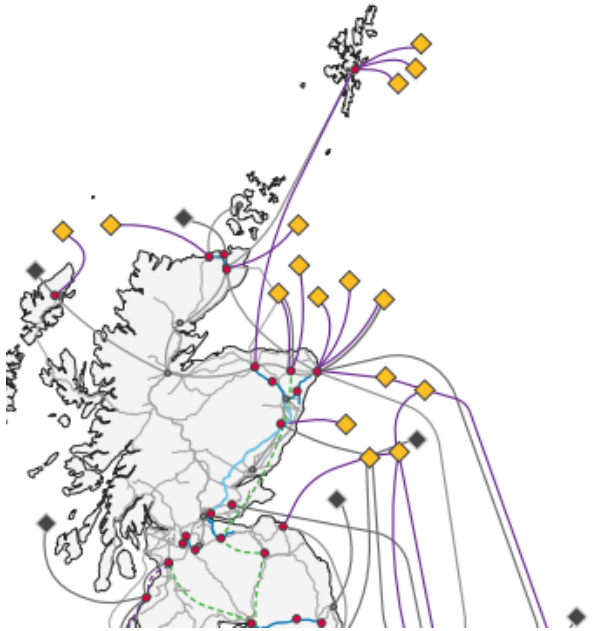






Practical DC network interfacing- offshore.

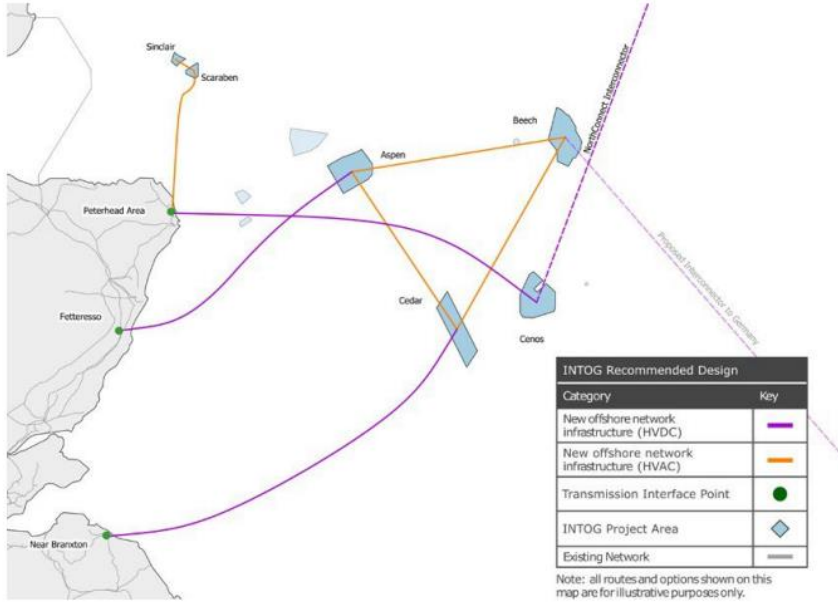
- Grid forming- across HVDC interfaces to common AC offshore islands
- Harmonic and inter-harmonic damping and allocations of roles.
- Code and standards issues- clarity needed



Category	Key
New offshore network infrastructure	
New onshore network infrastructure	
Voltage increase on network	
Existing network upgrade	
Substation upgrade or new substation	
Substations delivered for 2030	
In scope wind farm	
HND wind farm	
Existing Network	
Reinforcements delivered for 2030	

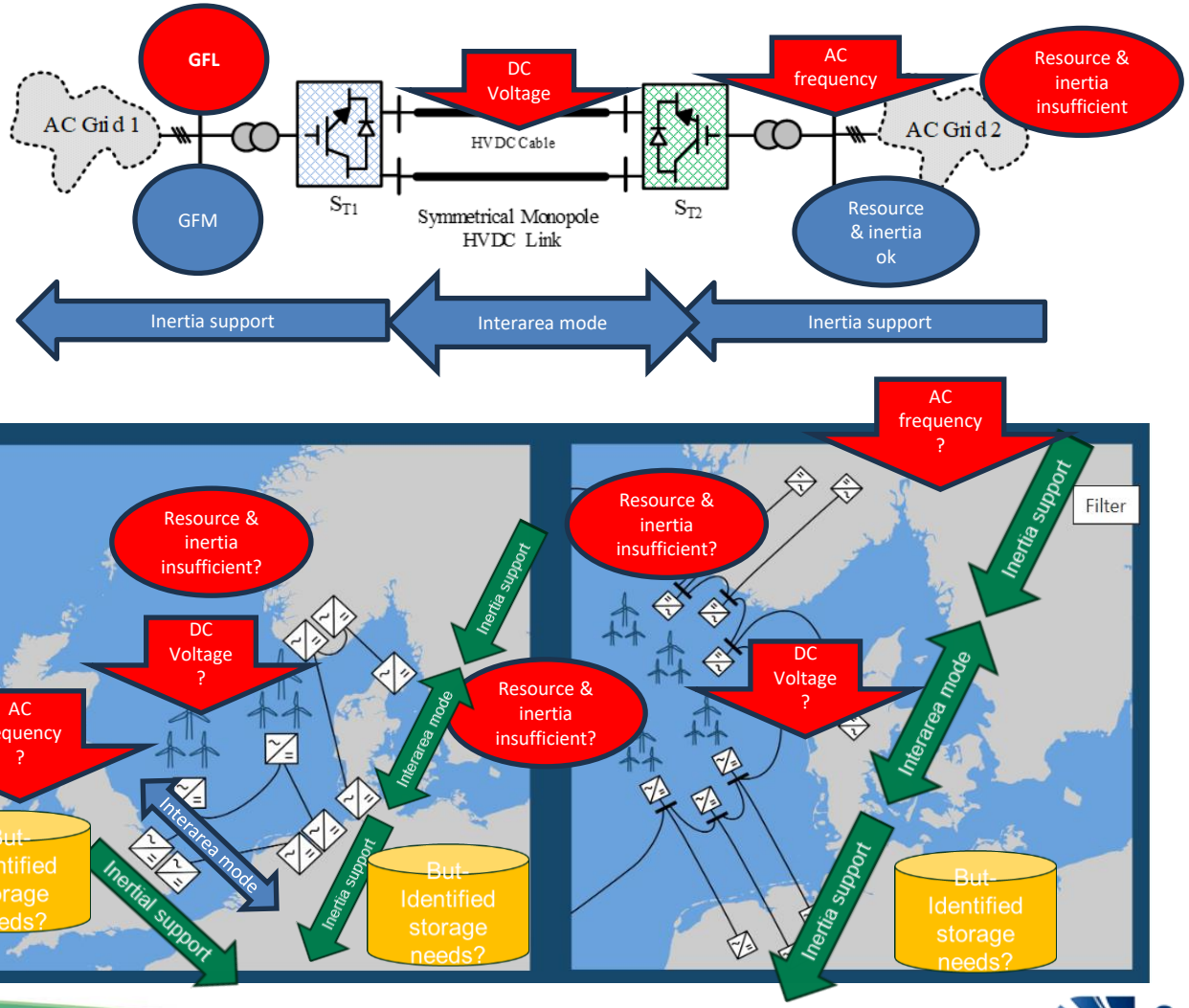
*Dashed lines represent low maturity options.

Note: all routes and options shown on this map are for illustrative purposes only.



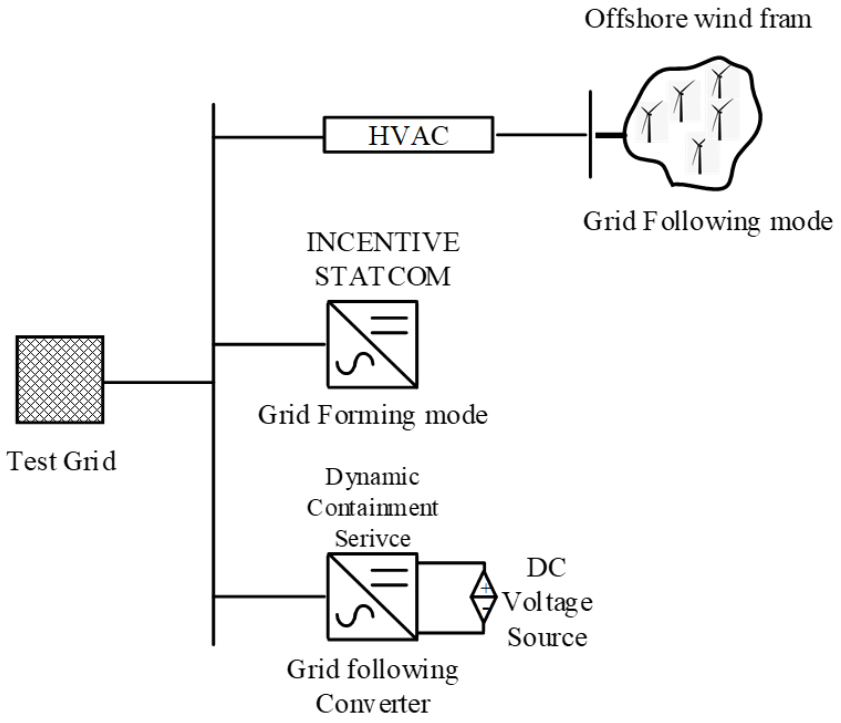
Practical DC network interfacing- onshore.

- **Resource connection vs transmission**
- **Energy buffers?**

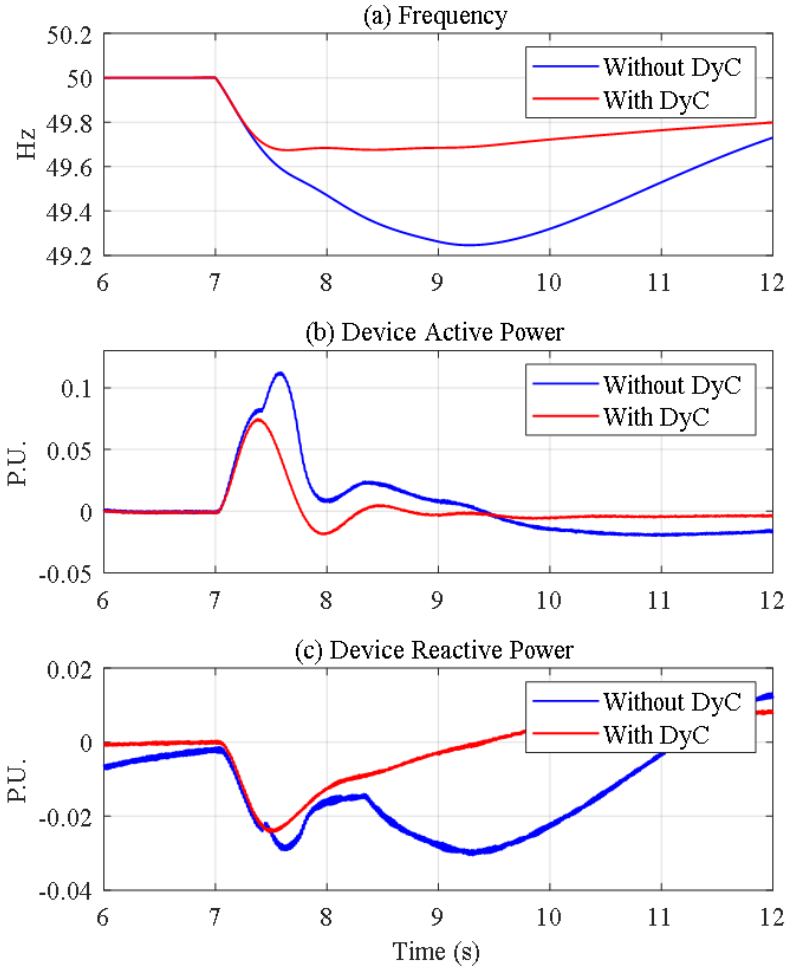


Practical DC network interfacing- onshore.

- **The INCENTIVE project**
- **The storage don't need to be that big!**
- **What else could (some of these..) Energy buffers be used for?**



❑ **INCENTIVE Device**



Black start, fault recovery, POD?

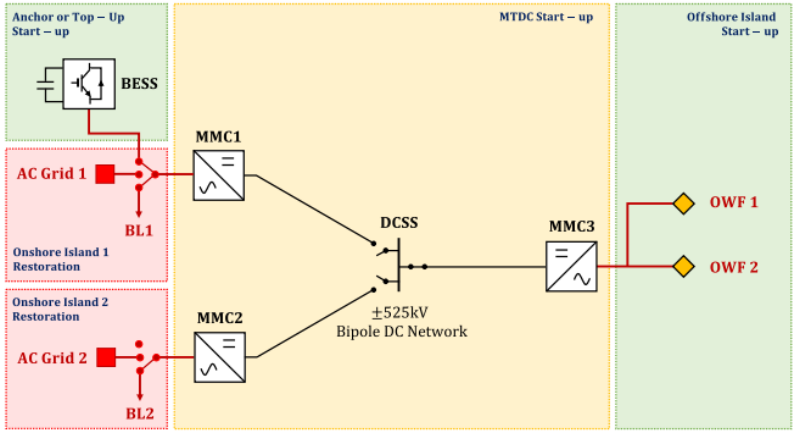
- One re-start asset can reconnect many offshore and onshore resources via the MTHVDC network.
- Many buffers can insulate HVDC network from a widespread AC system voltage depression.
- Energy buffer can be used for POD and other damping functions to avoid MTHVDC disturbance
- Just beginning to explore these applications.

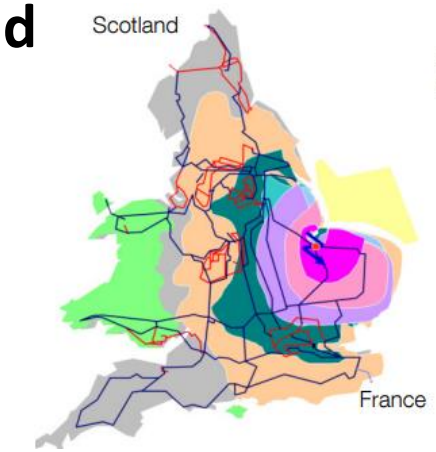
1. **Offshore island:** VSCs + AC assets
2. **MTDC:** MMCs, cables, DCSS
3. **Onshore system:** Supporting generation and block loads

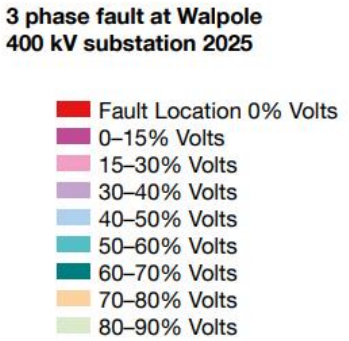
GC0156 Definitions: ESRS

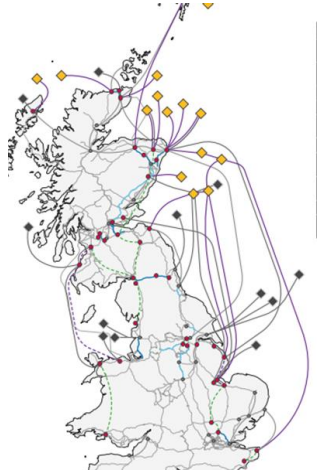
Anchor: Generator with the ability to start-up and support reenergisation of the NETS without need for external voltage source

Top-Up: Generator not required to self-start, but can be ready to connect on instruction once external voltage source becomes available, to support demand reconnection









Complimenting resilience, optimising AC & DC system

- **HVDC wise.**
- **Learning as we go.**

1. Large, highly-meshed network

HVDC embedded in single synchronous zone, operating in parallel with AC corridors. System remains AC-dominated.

Investigate HVDC overlay grids, interaction risks, impact of failure.

Large model enables testing of analysis tools.

2. Small or medium synchronous area

HVDC to transfer power from wind-rich zones onshore and offshore. Connection of large offshore wind plus embedded links forming multi-terminal networks.

Investigate hybrid AC/DC grid dominated by HVDC and converters.

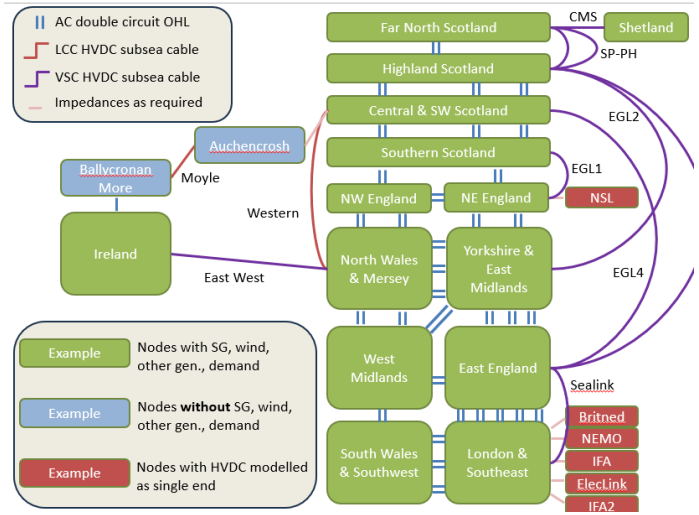
Smaller model enables analysis of whole system.

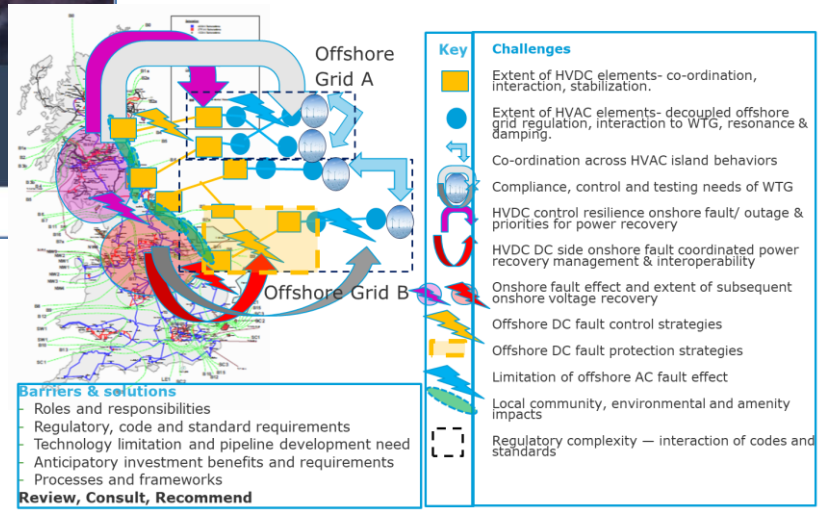
3. Multi-purpose offshore HVDC grid

Offshore wind integration and inter-area energy trading.

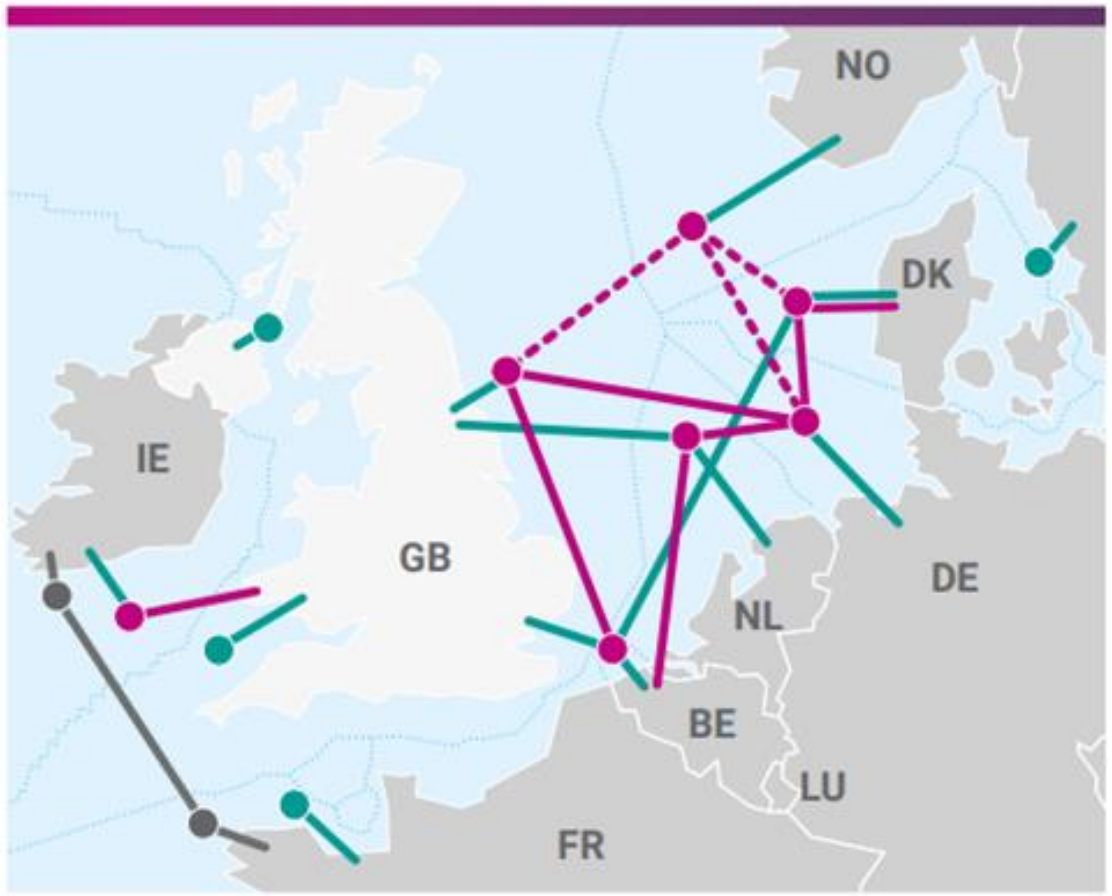
Interconnection of use cases 1 and 2. Need to respect requirements of different areas. Opportunity for new inter-area services while maintaining firewall.

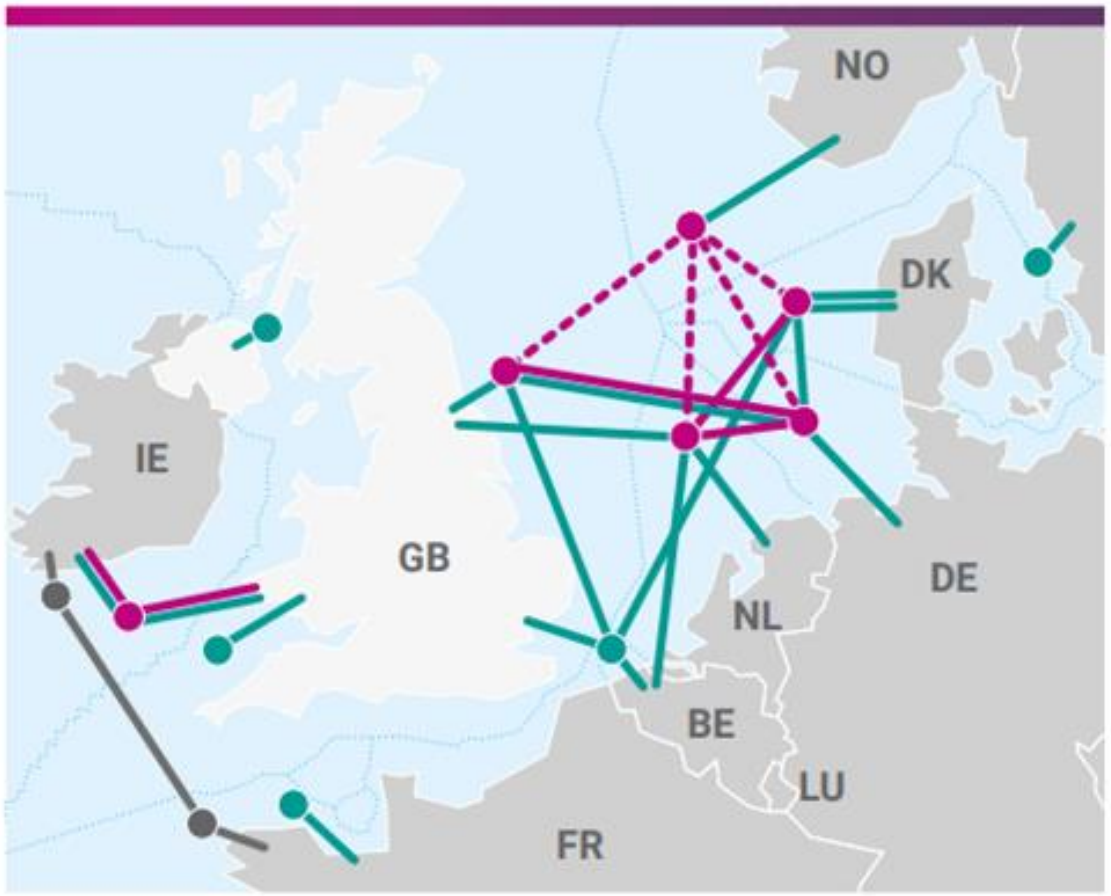
Model will interface to UC1 and UC2 models, or reduced equivalents.





The Future networks of Northern Europe- its not just GB.





Conclusions

- We have started a long journey.
- We have already made substantial progress
- There is a plan
- There is more to come
- There has never been a more interesting time to be an Electrical Engineer.
- Engage with the tasks ahead, and they will continue to be addressed

The Future is Now.

- ***We need to do this to address Climate change***. **DC networks are non-optional, we need to deliver & are doing so in GB *now*.**
- **Evolution vs revolution- find the steps, learn from the relevant earlier work.**
- **Plan-ahead to learn what you need next, from what you do now.**
- **Play the players where they best perform, not where you want them to be- *right tools* for *right job*.**
- **Learn from others- we're in it together.**

Enjoy this event and these unprecedented times- they won't come again in our lifetimes

Thanks for listening.

Any questions, please?

- For further information, please visit **www.hvdccentre.com** ; OR email: **info@hvdccentre.com**
- **https://www.hvdccentre.com/technical-films/**

The National HVDC Centre

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Overview of the HVDC Centre

The National HVDC Centre *part of* Scottish & Southern Electricity Networks TRANSMISSION *together with* SP ENERGY NETWORKS nationalgrid *and* nationalgridESO

The National HVDC Centre is Great Britain's simulation and training facility for HVDC; supporting the integration and successful operation of all HVDC schemes connecting to the GB Network (including Offshore Wind connections).

The Centre is also the National hub for HVDC knowledge exchange, expertise and innovation.