Building the European SuperGrid

Breakthroughs in Technology and Grid Design

April 2023

Executive summary

The concept of a European SuperGrid – an interconnected, continental scale electricity transmission system – has huge potential to benefit Ireland, in particular the ability of Ireland to maximise its capacity for offshore wind. The technical potential of offshore wind in Ireland is more than ten times the peak domestic energy consumption. Being able to export that energy to France, Britain, Germany, Denmark and beyond gives a pathway to utilise and export the country's exceptional offshore wind potential. Ireland would also benefit from access to diverse renewable energy resources across Europe, helping to mitigate the inherent variability of renewable generation through access to Southern European solar energy, Nordic hydro power and the differing winds across Europe.

Crucially, without a European SuperGrid of some description integrating with Ireland, the level of offshore wind that Ireland can sustain will be massively compromised. While it is also in the wider interests of Europe to gain access to the offshore wind potential that Ireland has to offer, we recommend that Ireland does not leave this alignment of needs (and associated timescales) to chance, and is proactive in driving the planning, timing, and progression of a European SuperGrid.

Collaborative, continent-spanning infrastructure on this scale can seem like science fiction, but the technology building blocks are all in place and being used in real projects around the world. In China, a single High Voltage Direct Current system carries 12 GW (twice the peak electricity demand of Ireland) across more than 3,000 km between Zhundong and Wannan. In Belgium the Princess Elisabeth Island - the world's first energy island – an electricity hub connecting Belgian offshore wind while acting as an interconnector is planned. In Denmark, an Energy Island in the North Sea is being planned, an artificial construction to act as a hub to connect offshore wind and interconnect with the energy systems of other North Sea countries. Denmark is also planning another Energy Island in the Baltic Sea for the early 2030's. In Scotland, the existing Caithness to Moray link is adding a 260km subsea extension to reach the remote Shetland Islands.

The European SuperGrid is hard to envisage in its final from. It is a concept whose details will naturally evolve over time as with any infrastructure project of this scale, it will grow organically, from the bottom up, rather than emerging fully formed, and those first steps that will define the pathway of its growth are already happening. While demonstrations of individual projects prove the theoretical viability of much of the technology, there are still key questions of co-ordination, planning, supply chains and international cooperation.

Ireland must act quickly and strategically to ensure its participation in this early stage of development and access the wide-ranging benefits this can bring. The first step must be to acknowledge that others are currently leading the way in terms of policy, technology, and project experience. Rather than trying to replicate that journey, Ireland should seek to learn as much as possible from existing successes and failures and seek to enter open collaboration, while focusing on the unique value they can bring to this journey. We recommend that Ireland:

1. Engages with the governments and transmission system operators of those countries leading the way, such as Belgium, Denmark, Germany, France, UK and China, as well as other neighbours less far down this path, to build continental and international consensus and co-ordination.
2. Expands the interconnectedness of a meshed Irish energy system with further links to the UK and France to ensure redundancy.
3. Integrates subsea transmission as a core element of future Marine Spatial Planning in Ireland, considering the possible environmental impacts of this technology on all ecosystems and ocean stakeholders.
4. Streamlines processes to create opportunities for demonstrator scale projects of SuperGrid technology in Irish waters.

Acknowledging that the supply chain of cable manufacture and cable-installation vessels is already well established (and is external to Ireland), we recommend that Ireland identifies high value areas of research, development, and manufacturing in the SuperGrid value chain where Irish academia and industry can compete globally (we suggest that DC-related protection and control systems are a key candidate). The other relevant supply chain area for investment is in existing cable installation, cable manufacturing, and maintenance services. Irelands target of

35GW is going to require significant lengths of cable infrastructure, and so, should be attracting cabling supply chain to meet these targets following suit to how the UK is attracting cable OEMs to set up bases.

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1. Introduction

1.1. Background

Decarbonising Europe's economies is a significant challenge. A key part of the strategy required to meet this challenge is the electrification of our economies through the widespread adoption of renewable energy. Renewable energy has grown in significance in Europe, but still only plays a minor role in meeting our energy demand. Focus on reducing the cost of renewable energy has resulted in wind and solar being the cheapest forms of electricity available in most areas of the world. The focus thus far has been on integrating renewables into the existing electricity grid, a grid that was designed and optimised for centralised fossil fuel-based generation. For efficient integration of ever-increasing amounts of distributed renewables-sourced electricity, change is needed in how we plan, and design our grid systems, and the technologies we use in developing new grids.

Europe's geography determines that much of the wind and solar resources are located at the periphery, often far away from the major demand centres. We require additional networks, storage, and consumer side participation, together with greater integration between existing regional and national transmission grids, to more efficiently address this geographical challenge. These "super grid" concepts are crucial to facilitating Europe's decarbonisation and long-term net-zero ambitions.

1.2. This work

Wind Energy Ireland (WEI) has engaged BVG Associates (BVGA) to investigate the technology landscape surrounding the concept of a European SuperGrid. This report aims to provide an overview of transmission technologies today including High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) technologies, as well as examining case studies where innovative technologies and architectures have been deployed.

The work consists of five work packages (WPs):

- WP1: An overview of the key differences between HVAC and HVDC
- WP2: Case studies of real-world projects utilising technology key to the delivery of a European SuperGrid
- WP3: Review of the key technology building blocks of a SuperGrid and the state of the art for each
- WP4: Investigation of the environmental impact of the deployment of a SuperGrid, and
- WP5: Key recommendations for how Ireland can lead the way on developing a European SuperGrid, focusing on technology innovation and planning.

1.3. The SuperGrid concept

A SuperGrid is an interconnected, transmission network spanning across multiple countries. It connects the most viable, large scale, renewable generation and facilitates the efficient trading of energy. It overlays the existing alternating current (AC) transmission networks of connected countries, to supplement and support the existing infrastructure acting like a cross-border motorway for the movement of power.

The concept of a European SuperGrid has been discussed for many years as a solution to help provide a low cost, sustainable and reliable energy system with a high penetration of renewable generation.

WEI published a position paper on the SuperGrid entitled "Ireland and the SuperGrid: Connecting an Energy Independent Europe"[i]. It highlights that Europe's best wind resources are in the north and west, its best solar resources are in the south, while the major demand is in the centre. A SuperGrid would allow Europe to install its

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[i] https://windenergyireland.com/images/files/supergrid-report-march2022-final.pdf

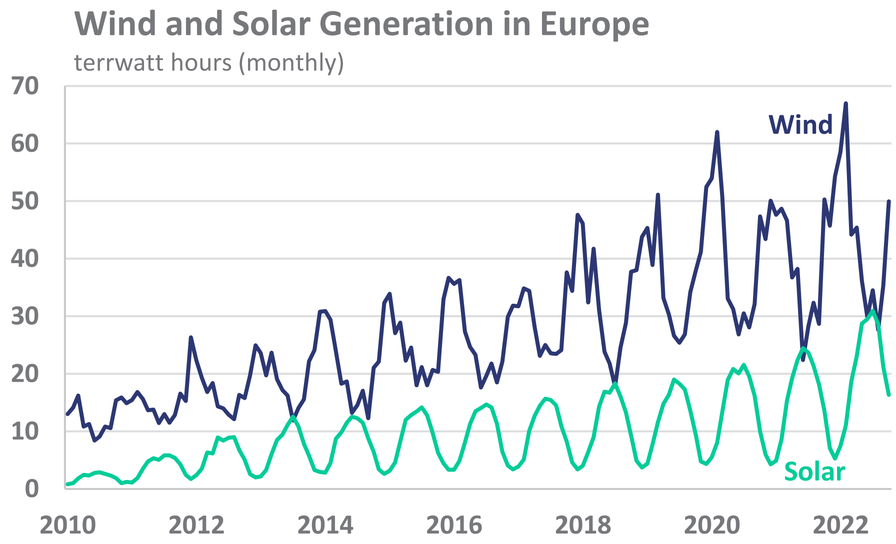
renewable generation capacity where the resources are strongest, efficiently moving that power over long distances to where it is needed.

Optimising the location of renewable generation will result in a lower cost of electricity, while a larger grid can reduce the levels of constraints and curtailment and facilitate a more stable and secure electricity system.

Within Europe, a SuperGrid could allow countries to more easily balance their supply and generation, by providing access to a wider market to buy and sell electricity. This allows the peaks and troughs in demand and renewable generation to be balanced across a larger area and facilitates a greater penetration of renewable energy across all connected countries, without being limited by domestic infrastructure and supply and demand profiles. This will facilitate a more stable and secure future electricity system that will also reduce the level of curtailment on the system.

The SuperGrid could be used to connect low-cost wind generation from the north and west, low-cost solar generation from the south (and potentially north Africa) with the main demand centres throughout Europe.

There is further benefit in this geographical spread when considering seasonal variations. The strong seasonal complementarity between wind and solar is shown in Figure 1, which illustrates the almost perfect negative correlation between solar and wind generation in Europe.



BVGA created the above graphic using data sourced from International Energy Agency's Monthly Electricity Statistics, January 2023. Data is for OECD Europe, updated October 2022.

Figure 1 Annual generation profile for solar and wind generation in Europe.

Even spreading identical generation technologies across a wider geographic area can help to create generation diversity and help smooth out the intermittency of these resources. In simple terms, it is likely to be sunny or windy somewhere across Europe and the larger the area connected to this SuperGrid, the greater the collective benefit and cost savings.

A study conducted by University of Strathclyde, University College Cork, and Queens University Belfast aimed to analyse the spatial and temporal correlation of wind power generation across several European Union countries to understand how wind 'travels' across Europe. Simply put, a weather front that passes over Ireland on a Sunday will probably pass over the UK within hours and over Denmark a few days later.

Having access to a wider market can also allow more reliable routes to market to sell power, with less risk of curtailment. A similar benefit can be seen in energy demand, with diverse countries across time zones, cultures and latitudes using energy at different times.

1.4. Ireland

The benefits of a SuperGrid are particularly relevant for Ireland. The highest peak electricity demand for Ireland was 5.1 GW in 2020, but the technical potential for commercially viable offshore wind is much higher, perhaps over 50 GW. If Ireland is part of an interconnected SuperGrid, it will have the ability to develop its offshore wind potential and become a significant net exporter of wind power.

Current capacity levels of interconnection do not provide a means to exporting the available level of renewables generation from Ireland. Without the ability to export excess wind energy to a large and diverse market, Ireland's wind industry will remain small, limited by domestic demand, and keep us dependent on imported fossil fuels. A connection into a wider, high capacity European SuperGrid would allow Ireland to install wind generation many times more than its national demand. For the rest of Europe, this grants consumers access to the highest average offshore wind speeds in Europe and the associated low-cost energy.

Climate change is not a national problem, but rather a challenge faced by us all. As WindEurope stated, "Countries with offshore wind resources have a geographical responsibility to lead Europe in this [the deployment of offshore wind]"[ii].

1.5. Technology

Offshore wind to date has been deployed using conventional point to point transmission systems, meaning that each wind farm has its own connection back to shore. This trend is changing, and planners are progressing towards a more coordinated approach to grid design, using architectures which share electrical infrastructure.

The technology required to implement such shared infrastructures is currently in development and there are challenges to overcome before it can be regarded as a proven solution. While many of the required technologies exist, they have not yet been deployed collaboratively at large scale across international markets. One of the key barriers to delivering this vision is the requirement for technological innovation.

In this report we present the technology landscape, identifying the key barriers and challenges to delivery of a SuperGrid. Point to point connections have been the architecture of choice to date but progressing towards a decarbonised system requires a step change in grid design. A SuperGrid will deploy meshed grid principles to facilitate a more secure and stable grid for the seamless movement of power from areas of high renewable resource in the peripheries of Europe to areas with high demand.

[ii] https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659313/EPRS_BRI(2020)659313_EN.pdf

2. WP1: Overview of technology

2.1. Economics of HVAC and HVDC

2.1.1 System Components

The following components make up the typical high voltage transmission system. More detail on state of the art and innovation for each technology and a range of supporting technologies is given in section 4 of this report. Common components:

- Cable – metal core with insulating sheath that conducts electricity to transfer power.
- Protection - circuit breakers act to isolate sections of the system in the case of a fault and act to protect the wider system.
- HVAC specific components:
    - Transformer – “passive” component made of a metal core with large number of coils of wire forming a primary and secondary coil. Electrical current flowing in one coil induces a magnetic field in the core, which in turn induces a current in the secondary. By varying the ratios of turns on the primary and secondary, voltage can be stepped up or down to a desired value. This only works in an AC system.
- HVDC specific components:
    - An HVDC converter station (or simply just “converter station”) is a specialised type of substation which forms the terminal equipment for a HVDC transmission line. It converts direct current to alternating current (or the reverse). In addition to the converter, the station usually contains:
    - DC Equipment: The direct current equipment often includes a coil (called a reactor) that adds inductance in series with the DC line to help smooth the direct current.
    - Converter Transformers: The converter transformers step up the voltage of the AC supply network.
    - Reactive Power: When line commutated converters are used, the converter station will require between 40% and 60% of its power rating as reactive power. This can be provided by banks of switched capacitors or by synchronous condensers. Voltage sourced converters can generate or absorb reactive as well as real power, and additional reactive power equipment is generally not needed.
    - Harmonic Filters: Harmonic filters are necessary for the elimination of the harmonic waves and to produce the reactive power at line commutated converter stations.
    - AC switchgear: It contains circuit breakers for overcurrent protection of the converter transformers, isolating switches, grounding switches, and instrument transformers for control, measurement, and protection.

2.1.2 Number of cables

A HVAC system requires three cables, one for each phase of the three-phase power. A HVDC system requires only two cables in a typical bipolar setup. There is an upper limit of power that can typically be transmitted over a single set of cables, with additional sets of cables, and converters required to transmit additional power.

For example, the Sofia Wind farm, rated at 1.4 GW will use one pair of cables[iii] for its HVDC transmission solution. The planned 3.6 GW Xlinks project from Morocco to the UK will use two pairs of cables, with each pair transmitting 1.8 GW of power. [iv]

[iii] https://sofiawindfarm.com/ - Accessed 14/12/22.

[iv] https://xlinks.co/- Accessed 14/12/22.

2.1.3 Overhead and underground cables

For onshore transmission systems, there is a choice between building overhead lines and underground cables. Undergrounding cables has some advantages:

- Less visual impact
- More resilient to extreme weather and “non-technical losses”

And some disadvantages:

- More expensive to install.
- Harder to reach for maintenance works.
- Higher variable losses

For transmission across sea, all systems are either laid on the seabed or buried in a trench in the seabed.

2.1.4 Losses

Losses in a transmission system are made up of two key parts:

- the static losses that remain the same regardless of distance and
- the dynamic losses in the cable that vary with distance.

For an AC system, static losses are predominantly caused by losses in the transformer. In a DC system, the static losses are caused by switching losses in the converter. Static losses in a HVDC system tend to be greater than those in an AC system.

The dynamic losses for each system also vary. For a DC system, these losses are dominated by resistive losses, but the AC system also introduces reactive losses. The inductance and capacitance of the line must be charged, causing additional losses in addition to the resistive losses observed in the DC system. This additional loss results in an AC system having greater variable losses per km.

Resistive losses can be reduced by increasing the voltage and reducing the current of the transmission system. This is achieved using step-up transformers in HVAC and converters in HVDC. As Power = Current x Voltage, the same power transfer can be achieved with lower current and high voltage.

Resistive losses are governed by the equation $P = \text{Current}^2 \times \text{Resistance}$. Losses can therefore be reduced by transmitting power at a higher voltage and lower current. This is the primary reason why all transmission systems, AC or DC, prefer to operate at higher voltages where possible.

2.1.5 AC or DC?

The key deciding factor for the deployment of a HVAC or HVDC for point-to-point connections is the lifetime cost of the system. Higher losses result in less revenue for the system with all else being equal.

Losses:

- HVDC has lower losses per km, but higher static losses.
- HVAC has higher losses per km and lower fixed losses. The dynamic losses – those per km - for an AC system are much greater if the cable must be undergrounded or subsea when compared to an overhead line. These dynamic losses area made up by a combination of resistive losses, present in both AC and DC systems and the reactive losses, only present in AC transmission

Capital costs:

- HVDC cables can carry more power in the same size cable and require less cables, resulting in lower cost per km than HVAC.

- HVDC substations tend to be more expensive than HVAC substations, due to more complex technology and the additional costs associated with having a lower global install base (with the implication that costs will reduce as HVDC systems are used more often).

For short distances, the higher fixed costs and fixed losses of a HVDC system make HVAC the lower cost option.

For longer distances, the lower variable losses and lower cable costs make HVDC the cheaper option.

The breakeven distance is the distance at which it is cheaper over the lifetime of the system to use HVDC than HVAC. This distance varies based on technology, changing costs and other project specific conditions, but is usually considered to be between approximately 50-120 km for offshore transmission projects, with this breakeven distance decreasing as the capacity of the project increases. This trend is shown in Figure 2.

This balance is changing quickly as project experience and greater demand gradually reduces the absolute cost of HVDC over time. This is further driven by the scale of offshore wind farms growing in capacity, which better suits HVDC, which can transmit more power through the same number of cables than the equivalent HVAC system. A change in planning towards shared transmission schemes, as seen in the German North Sea, also favours HVDC.

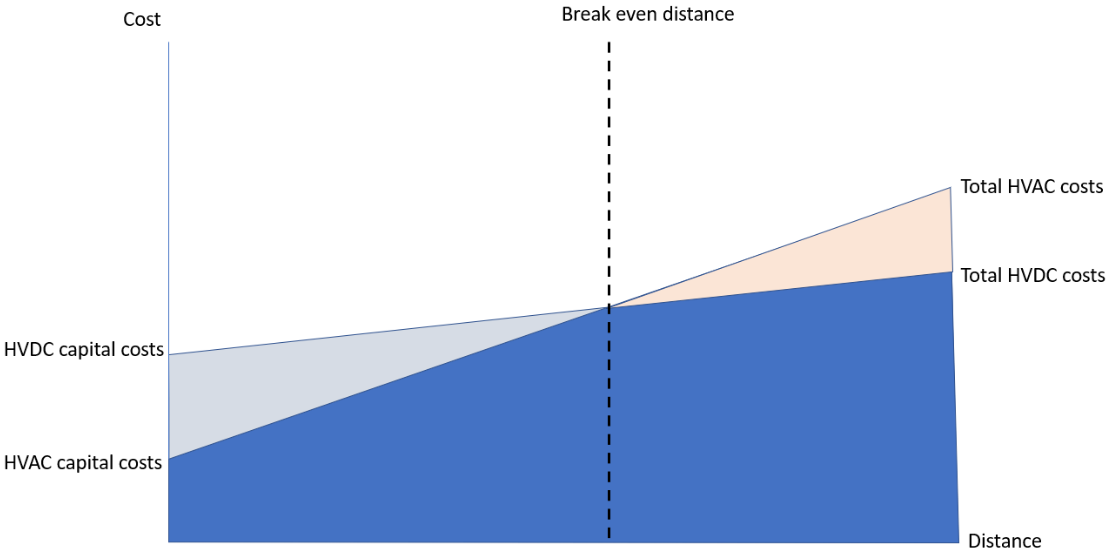


Figure 2 HVAC and HVDC break even distance.[v]

Hornsea One is a 1.2 GW offshore windfarm located in the North Sea that began construction in 2018. The transmission system is roughly 120 km long offshore, 155 km in total, and the project opted for a HVAC solution, using Mid-Point Reactive Compensation.

Dogger Bank A also has a capacity of 1.2 GW and a transmission system of 170 km. The project is located 130 km from shore in the northeast of England, making it a similar size and distance to Hornsea One. It began construction in 2022 and will use a HVDC transmission solution. Sofia windfarm, a 1.4 GW project 195 km off the northeast of England is due to begin construction in 2023 and will also use HVDC, demonstrating the transition towards HVDC technology offshore and business as usual.

DC technology is fundamental to facilitating cost effective transmission of power over the large distances required to develop a SuperGrid with acceptable power losses. This technology is still developing and while the different use cases, such as point-to-point DC connections for offshore windfarms, country to country interconnectors and network reinforcement are emerging as business-as-usual solutions, much innovation is still required to deliver a complex interconnected meshed system that can seamlessly connect multiple locations across national borders.

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[v] https://www.researchgate.net/figure/AC-vs-DC-transmission-cost-comparison_fig3_320957010

3. WP2: Case Studies

3.1. Introduction

Most transmission infrastructure deployed globally is HVAC, but a range of innovative HVDC projects have been deployed in recent years that have demonstrated different building blocks of a larger SuperGrid. These include two HVDC projects in Ireland - the East–West Interconnector and Celtic interconnector - both HVDC projects connecting the Irish and British electricity systems.

In this section we present a deeper look into eight other significant HVDC projects from around the world, examining the key technology options used and highlighting the key takeaways from a European SuperGrid perspective.

However, as welcome as these individual and country-specific projects are, it is the case that an operational meshed SuperGrid would benefit from being planned at a pan-European level, rather than as a combination of many individual point-to-point or multi-purpose interconnector projects taken in aggregate, which is the current practice.

3.1.1 Definitions

The following definitions are used for different system types of HVDC connection:

- Point to point – a link with a single dedicated converter station at each end of a cable.
- Multi terminal – A project connecting more than two locations. Could be a number of point-to-point connections or a meshed network.
- Meshed – a topology where a single converter station transmits power down more than one cable.
- Multi-purpose interconnector – a project built to facilitate both power transmission and connection of renewable generation.

3.2. Case Studies

3.2.1 Caithness-Moray – Scotland

The Caithness-Moray Link in Scotland was constructed to accommodate the growth of electricity generation from renewables in northern Scotland, particularly offshore wind. The link was designed and constructed to be able to accommodate an additional link to Shetland in the future. It is the first multi-terminal project in Europe. With the growth (current and future) in renewable generation in the northeast of Scotland, the link provides an efficient, high-capacity route to move energy generated in the northeast of high generation to the areas of high demand further south.

The link was commissioned in 2019 and constructed over four years by Scottish & Southern Electricity Networks (SSEN) a subsidiary of Scottish and Southern Energy (SSE)[vi]. The final cost of the project was €1.1 billion, having had an initial budget of €1.2 billion. €570 million of funding was provided by the European Investment Bank (EIB) (targeted at improving connections between renewable generation and the national power network). The remainder of the funding was provided by SSE.

The project has a total length of 160 km, with 113 km being 320 kV HVDC subsea cable. It runs between new converter stations at Spittal in Caithness and Blackhillock in Moray, shown in Figure 3. It has a capacity of 1.2 GW.

[vi] https://www.ssen-transmission.co.uk/projects/project-map/caithness---moray/

The modular nature of the Caithness-Moray link has allowed the installation of a second stage, connecting over 260 km to the Shetland Islands with a 600 MW link. This second stage is currently under construction and due to be in operation in 2024[vii]. This addition will make this into a three terminal HVDC system.

This system is innovative both from a technological perspective and a planning perspective. The system topology was designed to first be built as a point-to-point connection, but with capability to add in an additional connection to the Shetland Islands in the future. Although it does not currently operate as a multi-terminal system, the forethought to construct it with this capability demonstrates long term planning.

Figure 3 Caithness-Moray link and route of planned connection to Shetland.[viii]

3.2.2 Zhangbei HVDC Grid – China

The Zhangbei HVDC grid in China was built to accommodate the distribution of wind, solar and hydro energy produced in Zhangjiakou to Beijing, Tianjin and the Hebei region, as shown in Figure 4. It is owned and operated by the State Grid Corporation of China and cost €1.6 billion.

[vii] https://www.ssen-transmission.co.uk/projects/project-map/shetland/ - Accessed 14/12/22.

[viii] https://www.hitachienergy.com/about-us/case-studies/caithness-moray-hvdc-link

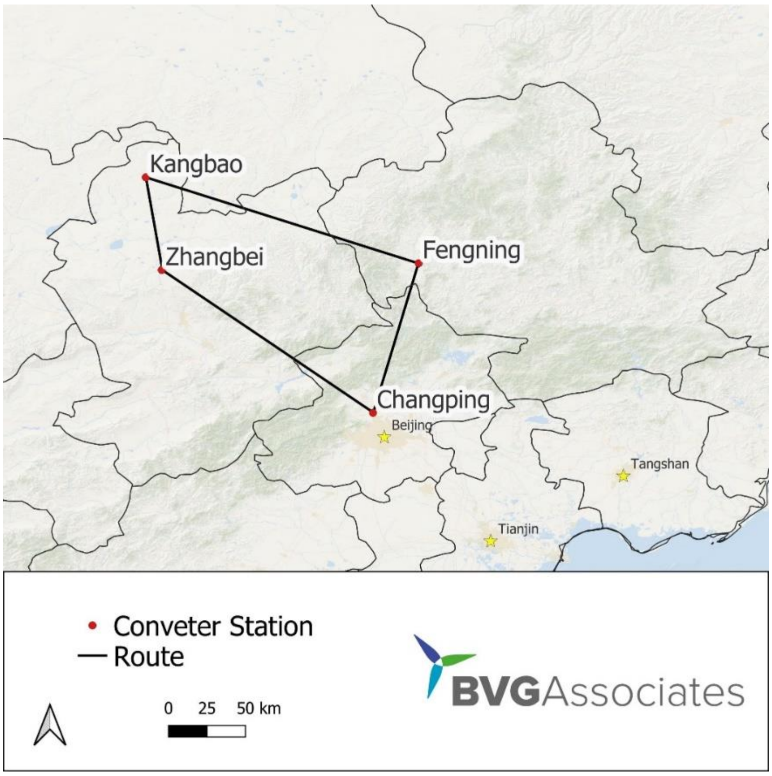

Figure 4 Zhangbei VSC-HVDC system topology[ix]

The transmission lines cover 227 km in Zhangbei, 126 km in Beijing, 219 km in Fengning and 66 km in the Kangbao region. It was the world's first HVDC system to utilise multi-level voltage sourced converter (VSC) technology, at a voltage of 500 kV. The transmission system consists of four terminals, each with connections to the existing AC grid.

The project is an operational meshed HVDC grid, operating four converter stations connected in a rectangular arrangement. Each supply terminal has a 500 kV flexible DC converter station featuring bipolar half-bridge modular multilevel converters (discussed further in 4.3).

The project innovates in several ways. It features a modular design, with the possibility of adding additional lines into the system to connect additional locations into the meshed grid as needs develop. There is a plan to expand the system to include three further locations, using the existing grid as a foundation for further expansion.

The project demonstrates the high technology readiness of a range of technologies, including multi-modular converters and HVDC breakers, each of which are discussed in more details in section 4 of this report. The project is also innovative for its size, being the highest capacity meshed DC grid in operation.

It demonstrates the required communications and control coordination to safely operate a meshed HVDC network at this power level, although it has only been operational for two years so information on the reliability of the system is limited at the time of writing.

3.2.3 Kriegers Flak Combined Grid Solution – Denmark and Germany

The Kriegers Flak Combined Grid Solution is the first offshore interconnector in the Baltic Sea, connecting Zealand in Denmark with Mecklenburg-Western Pomerania in Germany via the German Baltic 2 and Danish Kriegers Flak

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[ix] Image from "NR's VSC-HVDC Solution ±500kV Zhangbei DC Grid for boosting large scale hybrid renewables penetration", www.nrec.com\web\upload\2019/05/14, accessed 01/11/22.

offshore wind farms, shown in Figure 5. It allows energy to be shared between Germany and Denmark. It became operational in December 2020.

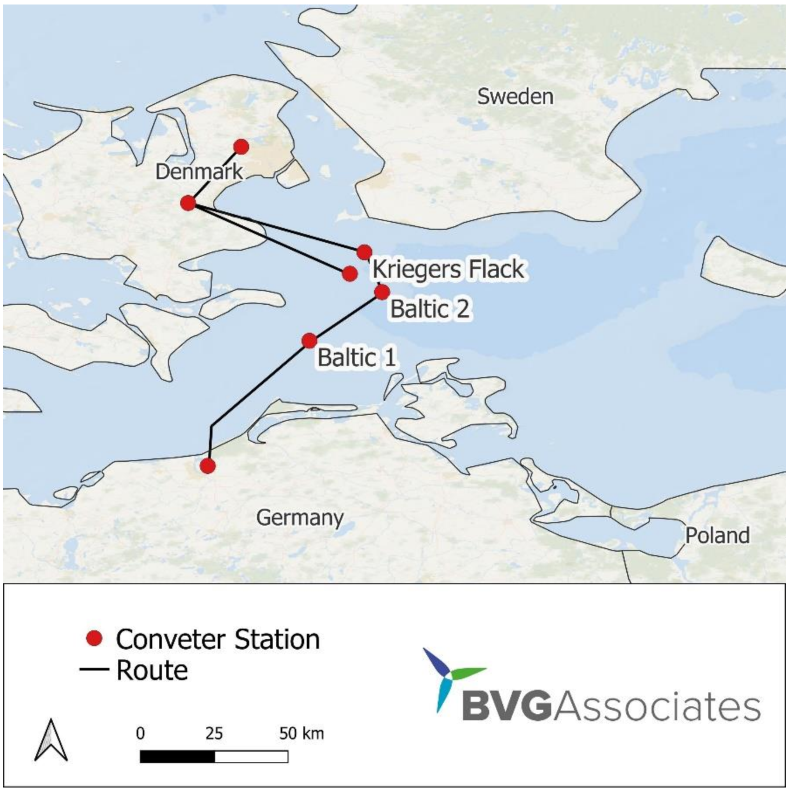

Figure 5 Kriegers flak-combined grid solution.[x]

The two wind farms are connected by two 30 km long 150 kV subsea cables with a transmission capacity of 400 MW. Due to phase and voltage differences between the Danish and German transmission systems, the project also incorporates two serial voltage source converters (a back-to-back converter) onshore, and a transformer on one of the Danish offshore platforms.

German transmission operator 50Hertz was responsible for the construction and operation of the German section of the interconnector project, with its Danish counterpart Energinet responsible for the Danish side. The Combined Grid Solution was granted a financial support of €150 million from the European Energy Programme for Recovery.

The project utilises existing offshore infrastructure, making use of the connections to shore for the existing wind farms connected to create multipurpose interconnector capable of cross boarder energy transfer.

Each converter station has multiple connections (the wind farm, the connection to shore and the interconnection) so the resulting solution is a meshed network, demonstrating how existing offshore infrastructure can be integrated into a larger system. This approach could be adapted to facilitate wider interconnection of offshore transmission infrastructure.

The project faced challenges in navigating the differing regulatory and environmental frameworks in Germany and Denmark, as well as the technical challenges of connecting two different electricity networks. [xi]

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[x] Marten, A.-K., Akmatov, V., Sørensen, T.B., Stornowski, R., Westermann, D. and Brosinsky, C. (2018), Kriegers flak-combined grid solution: coordinated cross-border control of a meshed HVAC/HVDC offshore wind power grid. IET Renewable Power Generation, 12: 1493-1499. https://doi.org/10.1049/iet-rpg.2017.0792

[xi] https://www.osti.gov/etdeweb/biblio/21594645

The two systems operate on different voltage levels and are asynchronous, a so back-to-back converter station was designed to facilitate the flow of power.

3.2.4 Northeast Agra – India

The Northeast Agra link is the world's first multi terminal ultra-high voltage DC (UHVDC) transmission link. It is used to transmit power from northeast India's hydroelectric generators to load centres in the west of India, particularly the city of Agra, a distance of 1,728 km, as shown below in Figure 6.

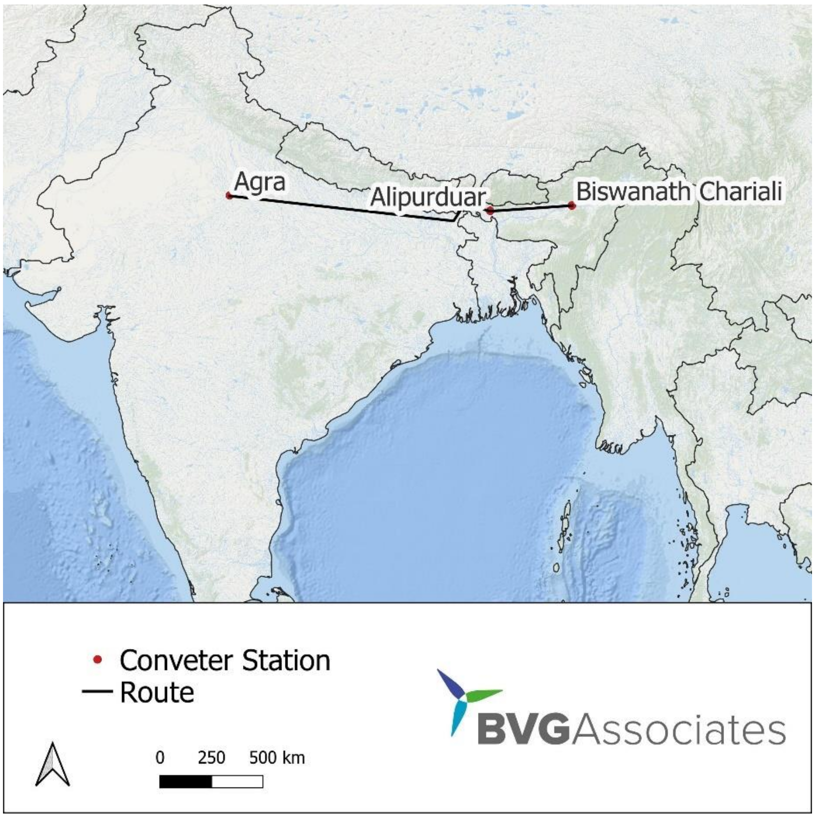

Figure 6 Northeast Agra link route.[xii]

India has an abundance of hydroelectric generation, but it is mostly located far from the demand. Therefore, the UHVDC link was conceived to exploit this resource. It has an 8 GW converter capacity, including a 2 GW redundancy, and a rating of 800 kV. The link is owned and operated by the state-run Power Grid Corporation of India. Hitachi Energy and Bharat Heavy Electricals Ltd had turnkey responsibility for the project, including engineering, design, supply and installation of the three converter stations and the link cost €1.5 billion to construct.

This project demonstrates the large scale of power transfer capable in a high voltage HVDC system. The capacity of this single link is greater than the entire peak electricity demand of Ireland. The length of this system also demonstrates the potential of HVDC connections to provide long distance power transfer.

For this SuperGrid, one challenge presented by the system is the size of the infrastructure required, due to its use of Line Commutated Converter HVDC technology, requiring large filter banks. The converter halls for this system are 75x75 meters each and two are present at each node of the link. For any SuperGrid infrastructure with converter stations located offshore, a lower footprint solution would be necessary due to size and weight limitations for offshore platforms.

[xii] https://www.hitachienergy.com/about-us/case-studies/north-east-agra

3.2.5 TenneT 2 GW

The TenneT 2 GW program is a standardised platform, shown in Figure 7, that will provide grid connections to Germany and the Netherlands offshore wind projects. TenneT, the transmission system operator for the Netherlands and the northwest coast of Germany, is aiming to build at least ten offshore grid connections with a capacity of 2 GW each in Germany and the Netherlands, starting commissioning from 2028 [xiii]. By standardising the design of these connections, TenneT hopes to reduce uncertainties for developers around grid connection and reduce CAPEX requirements.

The 2 GW program is the successor to the “Win” series of standardised offshore platforms, which presented standardised approaches to connecting wind farms with HVDC.[xiv] There are 9 “Win” series platforms in operation, each forming a point-to-point HVDC connection for an offshore wind farm.

The new 2 GW project is significant as the infrastructure for offshore generation will be built before the generation is in place, a planning approach different from the standardised approach to building offshore transmission in parallel with wind farm construction. TenneT plans to award the tender for the first of the Dutch grid connections in the beginning of 2023, and the tenders for three of the connections in Germany in Q3 2023. TenneT wants to enter into partnerships with companies that will deliver the offshore platforms, onshore substations and converters for a period of up to 8 years.

TenneT has estimated that they will eventually deliver 15 to 20 offshore grid connection systems, with the overall value estimated to be up to €30 billion.

Figure 7:Tennet 2 GW platform artist’s rendering.[xv]

The 2 GW program will use 525 kV HVDC cables which are already qualified, and tenders have been awarded. The standardised design of the substation platform will include flexibility of design as one of its key criteria, so that it can adapt to innovation in the future. The standardised approach is intended to reduce costs and provide more

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[xiii] https://www.youtube.com/watch?v=ccKw9-FQOqw

[xiv] https://www.tennet.eu/projects/borwin1

[xv] https://www.tennet.eu/2gw-program, image recreated with permission.

certainty around platform specifications to aid in future infrastructure planning. These platforms, or something similar, could form the nodes of the future SuperGrid as they are designed to be multi terminal ready. One of these platforms will be part of the WindConnector project connecting the Netherlands to the UK.[xvi]

3.2.6 Xlinks

This is a speculative project planned to consist of four 3,800 km HVDC subsea cables that connect the Guelmim Oued Noun region of Morocco to the UK. The cables will link to Britain's electricity network via two 1.8 GW connections at Alverdiscott in Devon. The cables will be buried at depths of between 100 and 250 m for most of the route.

Onshore wind and solar projects in Morocco will provide 10.5 GW, 3.6 GW of which is to be exported to the UK. Xlinks says this will provide 8% of the UK's electricity demand by 2030. The route is shown in Figure 8.

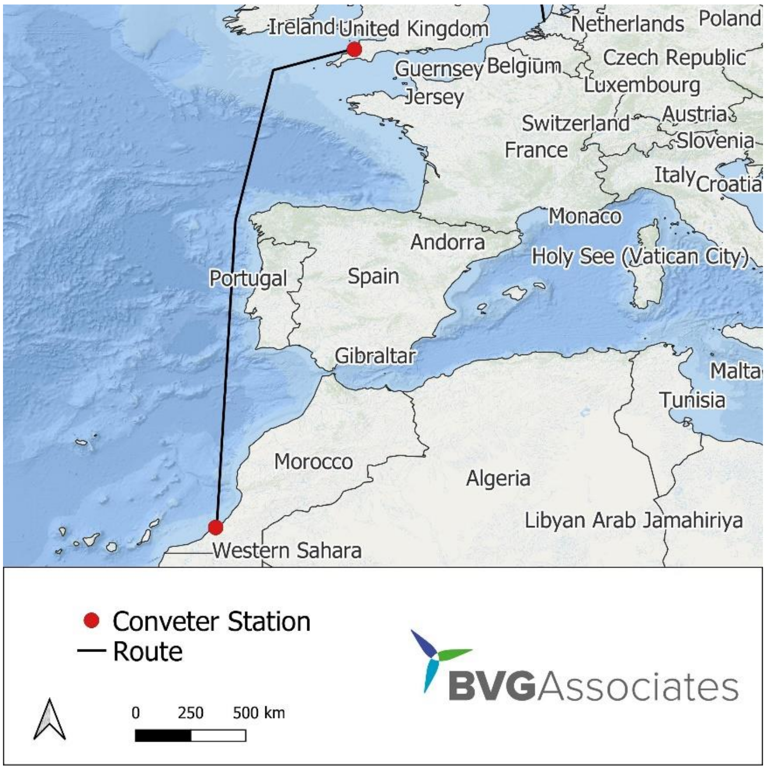

Figure 8: Map of the planned Xlinks project[xvii]

A 20 GWh lithium-ion battery storage facility onsite in Morocco will allow for smoothing of the energy delivered in periods of low production. The project will also involve the construction of new converter stations at both ends of the HVDC cables. The project is expected to cost around €16 billion.

- This project is the most ambitious pipeline project in Europe and its construction would make it the longest HVDC link in the world. Although the project is still only at the concept stage, it will offer a valuable case study regardless of success. If it is a success, it could pave the way for more very long distance and large scale HVDC projects in Europe, and if the project is unsuccessful, it will offer a valuable learning opportunity to aid in the future delivery of similar projects in Europe.

[xvi] https://www.tennet.eu/projects/offshore-projects-netherlands

[xvii] https://www.current-news.co.uk/news/octopus-invests-in-morocco-uk-power-project-xlinks-as-it-signs-strategic-partnership

3.2.7 Denmark’s Energy Islands

The Government of Denmark has approved plans for two artificial ‘energy islands’ in the Baltic Sea and North Sea. The North Sea Energy Island will be located between 80 and 100 km west of Jutland. The island is expected to have a footprint of between 120,000 and 460,000 m^2(around 20 – 80 football fields).

The islands will provide the infrastructure to form a green energy hub that can distribute renewable energy to areas of high demand, across several countries.

The Danish State will be the majority owner and own at least 50.1 % of the island. The initial phase of the North Sea Island will involve the connection of 3 GW of offshore wind farms to the island by 2033. However, this is expected to be extended to 10 GW by 2040, and possibly up to 40 GW overall. The Government of Denmark approved a total investment of €28 billion for the project. €1.4 billion of this is expected to be used to build the island itself, with the remaining money to be used to build the wind farms and electrical infrastructure.

The Danish Energy Agency plans to start the tendering procedure in autumn 2023, with the announcement of the winner of the tender in August 2025. Orsted, in partnership with Danish pension fund ATP, is preparing a bid for the tender.

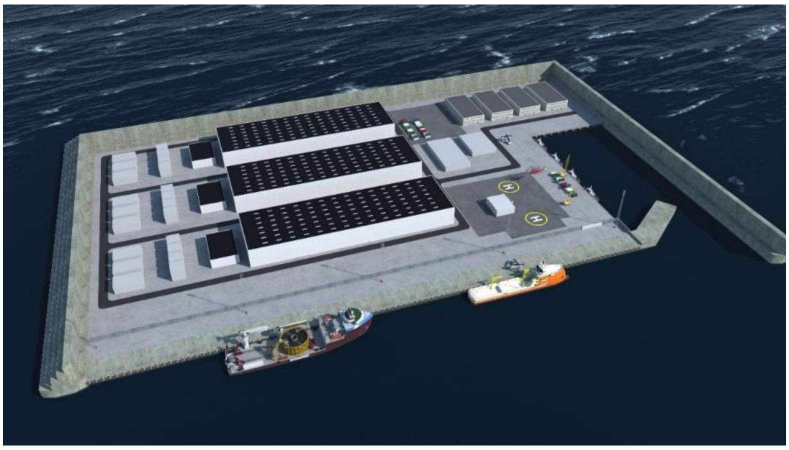

Figure 9 Artist’s impression of Danish Energy Island.[xviii]

This project is expected to be operational in 2033. The potential for such islands is significant, as they can overcome the limitations in size of offshore infrastructure imposed by the requirement to construct platforms in the ocean. This project is being built in coordination with planned wind generation to facilitate the cost-effective integration of energy and shows a joined-up approach to infrastructure planning that can help to reduce the cost of a renewables-dominated energy system.

This work on energy islands is gaining momentum, with multiple countries now investigating their potential. A coordinated roll-out with multiple energy connections between North Sea countries is much more efficient than just connecting every new wind farm to its home country by default. Figure 10highlights how these islands can be linked together to facilitate better energy flows between countries.

Denmark is not alone in considering the feasibility of energy islands. Belgium have announced their intentions to construct the Princess Elizabeth Island before 2030 to facilitate interconnectors with the UK and Denmark and connect to North Sea wind projects. [xix] Germany is investigating the feasibility of a similar project and has entered into an agreement to collaborate on interconnection into the German system from the Danish energy island.

[xviii] https://ens.dk/en/our-responsibilities/wind-power/energy-islands/denmarks-energy-islands, image recreated with permission.

[xix] https://www.rechargenews.com/wind/belgium-plans-worlds-first-artificial-energy-island-linked-to-offshore-wind-by-2026/2-1-1327950

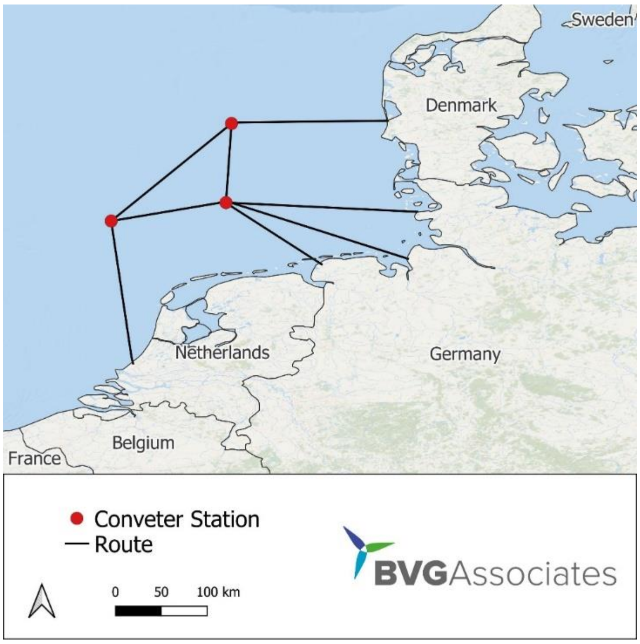

Figure 10 Illustrative map of energy island interconnection between Denmark, Germany, and the Netherlands.

3.2.8 Zhundong–Wannan HVDC link

China has a large number of operational HVDC projects, with 20+ HVDC projects in operation.

The Zhundong-Wannan UHVDC Link, also known as the Changji-Guquan UHVDC Link, is a 1,100 kV overhead line with a length of 3,324 km that stretches from Zhundong in the Xinjiang region of China to Wannan in the Anhui province. It is owned and operated by the state-owned State Grid Corporation of China and is used to provide energy security to the densely populated regions on the east of China, using wind and hydro generation in the relatively sparsely populated north-west.

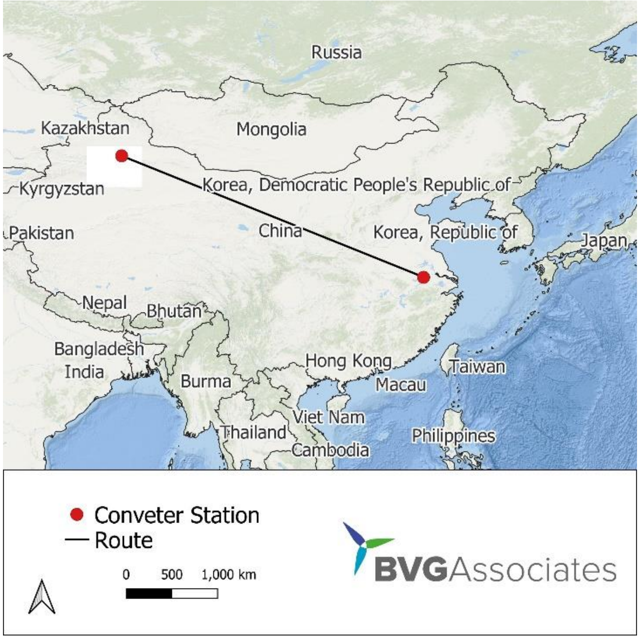

Figure 11 Route of Zhundong-Wannan (also known as Changji-Guquan) Link.[xx]

The line can transmit up to 12 GW. This project demonstrates the largest scale achieved to date for current HVDC technology. The pylons used are approximately 300 m tall, which is roughly the same height as the Eiffel tower in France.

Started in 2016, the project was completed in December 2018 and cost €5.3 billion.

3.3. Conclusions

While far from exhaustive, this section has given an overview of the key state of the art projects operational and/or under development globally that are of relevance to the development of a European SuperGrid.

A wide range of existing and planned infrastructure projects each demonstrate the deployment of technology elements that will be key to delivering a SuperGrid, but each have limitations. The largest projects, representing multi-GW long distance power flows are all constructed onshore and within single countries, minimising several challenges associated with offshore construction, planning and coordination. Those operating offshore are either smaller projects or point-to-point connections with possible future flexibility to expand into truly meshed systems. These projects demonstrate that the technology for high power transmission corridors exist today, along with innovative transmission architectures to increase the levels of renewables integrated into our systems.

[xx] https://www.modernpowersystems.com/features/featureconstruction-of-record-breaking-transmission-line-is-under-way-6097161/featureconstruction-of-record-breaking-transmission-line-is-under-way-6097161-492837.html

4. WP3: Building blocks

This section breaks down each enabling technology of a SuperGrid in more detail. It will focus on both existing state of the art and emerging innovations in technology.

4.1. Cables

4.1.1 Superconducting Cables

A superconductor is any material which when cooled below its critical temperature, operates with zero electrical resistance. Superconductors are often mistakenly considered in the same vein as fusion, but have been deployed in different applications for decades. Superconductors are an established technology and are used in various industries around the world. Superconductors have been used in MRI machines since the 1980's, and have since been deployed for electric motors, high power magnets, and generators. The EcoSwing project in Denmark saw a superconducting generator retrofitted into an existing wind turbine, and was found to be 40% lighter than the original generator, and 25% smaller in volume.

Superconducting cables for the transmission of electricity are made using materials known as either Low Temperature Superconductors (LTS) operating at approximately - 260°C and high temperature superconductors (HTS), which operate at approximately -200°C. Currently, there are numerous projects globally operating HTS power cables in electric grids. Given the very low temperatures that are required by superconductors, additional hardware is required to keep the superconductor within the required temperature range. This is usually achieved by using a very low temperature cryogenic fluid, such as helium or liquid nitrogen, which flows within the cable. Superconducting cables are designed to be no different to a conventional copper cable in transport, installation and operation.

There are three types of superconductors commercially available for AC or DC power cables:

- $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) with a critical temperature of –160°C
- $YBa_2Cu_3O_7$ (YBCO) with a critical temperature of –180°C
- MgB_2 with a critical temperature of –235°C

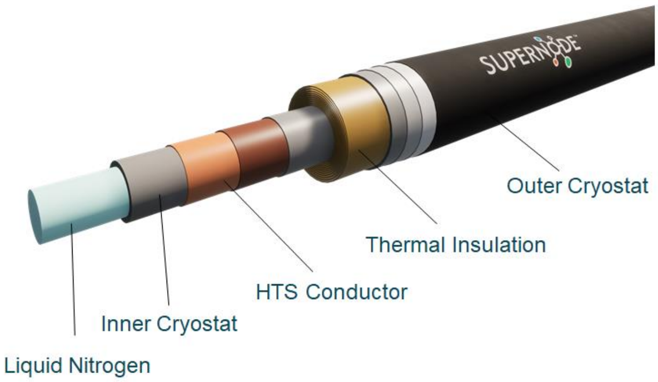

Figure 12 Layers of a HTS cable.[xxi]

[xxi] https://supernode.energy/

More recently, superconductors have seen deployment in the distribution grid. The distances covered by current existing operational HTS projects are between 200 m and 1 km, with planned projects continuing to increase in length. Their application has been seen worldwide, with the Ampacity project in Essen, Germany, which became operational in 2013[xxii], being one of the longest serving superconductors in the distribution grid. Their application for long distance, high-capacity transmission corridors is being developed today by companies such as SuperNode.

With a capacity of 3.2 GW, the 2018 Best Path's project has already demonstrated superconducting cables' high-capacity use case. It has a very compact installation footprint in the range of one meter in width for a dipole carrying 6.4 GW. In contrast, a traditional circuit based on XLPE insulated copper cables would typically be 10 meters wide. Meanwhile, the Superlink project currently being developed in Munich, Germany is pushing towards 500MW capacity and 12km in distance. This far exceeds what has been demonstrated today and will establish superconductors as a reliable, and more efficient solution for high-capacity use cases.

Table 1:Supercondcutor projects

Year of commissioning	Project Stage	Project Name
2013	Operational	Ampacity, Essen [40 MW]
2018	Demonstration	Horizon's 'Best Paths' Project [3.2 GW]
2019	Operational	Shingal, Seoul [50MW]
2021	Operational	REG, Chicago [62 MW]
Planned	Feasibility study phase	Superlink, Munich (1st phase) [500MVA, 110kV]

Key advantages of Superconductors include:

- **High Power carrying capacity:** Achieving higher levels of current density means that operational voltages can be reduced while still facilitating bulk power transfer as high as 10GW. Lower operating voltages reduces the size and volume of the electrical equipment required at both ends of the cable when compared to conventional HVDC.
- **Easier and shorter installation time:** Grid operators can benefit from shorter installation time as HTS cables are compact and can be routed underground through existing gas, oil, water or electric corridors or along highway or railway rights of way. Superconductors can be installed nearly side by side, which can drastically reduce the environmental footprint compared to conventional copper cables due to the fact that superconductors do not require spacing to reduce electrical interference or for heat dissipation. In addition, HTS cables are actively cooled and thermally independent of the surrounding environment, making them easier to operate. These aspects pave the way for higher capacity transmission corridors.
- **Low impact on the environment:** Reaching much higher levels of current density enables compactness in cable and electrical equipment and higher capacity power transmission compared to conventional cables. A superconductor system also has a smaller footprint in an underground installation as a result of not requiring

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[xxii] https://www.tdworld.com/overhead-distribution/article/20964180/the-ampacity-project

large separation between cables. Thus, a superconductor cable requires less space, materials and infrastructure, resulting in a smaller overall environmental footprint, and lower cost of supporting infrastructure. For example, a 4GW transmission need would be met by four 525kV copper cables whereas a superconductor could meet this task with just 2 cables.

HTS cables also offer significant advantages for high-capacity meshed grids. Due to the nature of Superconductivity, HTS cables offer inherent fault protection to the system in the event of a short circuit and can ‘firewall’ against fault propagation, enabling more advantageous approaches to meshed grid protection strategy and equipment and control. In contrast to copper cables, HTS cables can readily be designed to operate with multiples of spare power capacity, with minimal additional cost and no geometric impact, providing the ability to instantaneously re-route vast power capacities through to alternative nodes in the meshed network in the event of a localised issue.

The German Federal Network Agency stated in its Electricity Network Development Plan for 2035[xxiii] that:

> “This [superconductors] technology has great potential and grid deployment in the gigawatt range in 2030 is realistic if, for example, corresponding pilot projects are planned in the grid development plan.”

There are technical challenges to overcome but superconductors have been acknowledged by ENTSO-e (European association for the cooperation of transmission system operators) as a game changing technology with a high likelihood of realisation. ENTSO-e go further in their Technopedia to say

> "HTS DC Cables are well suited for long-distance high-power transmission and bulk energy transfer."

In summary, superconducting cables can carry huge amounts of power (2GW+) at much lower voltage levels, with a smaller footprint than conventional cables and require significantly less infrastructure, materials and space. The overall cost of installing superconductor cables will be lower than high-capacity, high voltage conventional cables such as those used offshore. This is due to the need for less infrastructure, primarily smaller collector stations. These properties make them an attractive technology for use in a SuperGrid, and for high-capacity transmission corridors.

4.1.2 Gas Insulated Lines

Gas insulated lines are used to transmit electricity at high power ratings over long distances in cases where overhead lines are not possible. The cables are housed in a metal container (most often aluminium), which is filled with an inert gas.

They have the advantage of not requiring compensation due to their capacitance when used for HVAC transmission. In addition, their electric fields are shielded, meaning no interference with external systems and lower environmental impact and they have a high fire safety.

Gas insulated lines have low power transmission loss and a large transmission capacity, which is highly applicable to large-capacity, long-distance power transmission, but are more suitable in applications where HVAC transmission is required, such as for connections between synchronous energy systems.

Common inert gasses used are 100% SF_6 or a mix of SF_6 (Hexafluoroethane) and N_2 (nitrogen). However, SF_6 is a potent greenhouse gas, so alternative synthetic gasses are currently under development to mitigate this issue.

[xxiii] https://www.netzentwicklungsplan.de/de/grid-development-plan-2035-2021

Current areas of research into gas insulated lines are concentrating on reducing construction time, cost, and assembly time on site, as the increased complexity of these cables compared to conventional cables makes them both more expensive to manufacture and build.

There are additional issues with supply chains, as most manufacturing facilities for cables both constructed and under development are equipped and designed primarily for the construction of conventional cables, discussed below. If gas insulated cables increase significantly in demand, supply chains could become a significant barrier at least for a while.

Gas insulated lines have been used in a number of operational projects, historically in the PALEXPO centre in Geneva, where it replaced an overhead line with an undergrounded line and at the Sai Noi substation in Bangkok, where the reduced losses of a gas insulated line allowed 3,800 MW to be transmitted through a single three phase system.[xxiv] More recently a gas insulated line was used for the river crossing component of the Huainan-Nanjing-Shanghai Ultra High Voltage (1000kV) HVDC project in China[xxv]. Most of the project was overhead lines, but the river crossing was unsuited to this. For the section beneath the river, GILs were used, to reduce electrical losses, making the project feasible.

SF_6 Alternatives

Alternatives under development include g3 gas, a trade name for a proprietary gas mix developed by GE [xxvi], AirPlus, developed by 3M and ABB[xxvii], but only g3 gas has been demonstrated to have appropriate properties to substitute for SF_6 at the higher voltages required for transmission voltages.

4.1.3 High Voltage Conventional Cables

Conventional high voltage cables are made up of conductors, an insulation system, and a protective outer layer. The conductors used for high voltage cables are most often copper or aluminium. Each conductor is separately wrapped in an insulator.

Figure 13: Cross section of a single core cable

Copper is more expensive than aluminium but is a better conductor so not as much material required. Aluminium is cheaper than copper but is a less efficient as a conductor, so more material is needed for the cable. It also exhibits weaker corrosion resistance. Aluminium also has a larger bend radius, making it harder to work with and to terminate at points of connection. Systems often use a combination of the two, with copper for the subsea section and aluminium for the land section to overcome this. Figure 14 and Table 2 show a typical HVAC high voltage cable. A HVDC cable would be similar, but with a pair of single core cables.

High voltage cables can either be suspended by pylons overhead or buried. Overhead lines are insulated by air, while cross-linked polyethylene (XLPE) is the most common insulator used for cables that are buried underground.

[xxiv] Experience with 2nd Generation Gas-Insulated Transmission Lines GIL, Hermann Koch

[xxv] http://en.goodeeis.com/news/8.html

[xxvi] https://www.gegridsolutions.com/hvmv_equipment/catalog/g3/

[xxvii] https://multimedia.3m.com/mws/media/1400591O/abb-airplus-flyer-with-3m-novec-5110-insulating-gas.pdf

Cables that are buried tend to retain heat because of their insulation and the surrounding environment. To compensate for this, buried cables are generally larger to reduce their electrical resistance and hence heat produced. The protective outer layer consists of a metallic sheath and a non-metallic outer covering. The outer covering is commonly made of extruded polyethylene or polyvinylchloride, which are anti-corrosive materials.

The metallic sheath can be used to carry the short-circuit current in case of failure and can optionally be equipped with temperature monitoring fibres. The metallic sheath is commonly made of copper or aluminium, although lead is used for cables that will come into contact with moisture or be submerged. However, given lead is toxic, future cables that must be in contact with water may be sheathed with other inert materials.

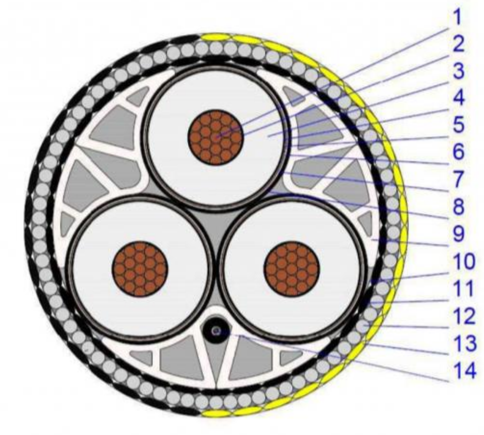

Figure 14: Cross section of a conventional cable

Table 2: Key for Figure 14

No .	Description	Details
1	Conductor	Copper, circular stranded, compacted, longitudinally water-blocked
2	Conductor screen	Extruded bonded semi-conductive compound
3	Insulation	XLPE
4	Insulation screen	Extruded bonded semi-conductive compound
5	Water-blocking tape	Semi-conductive water ‘swellable’ tape
6	Metal screen	Copper foil screen on each phase
8	Inner sheath	Extruded polyethylene on each core with semi-conductive skin
9	Fillers	Extruded plastic-shaped fillers
10	Binder tape	Synthetic tape to bound the assembled cores
11	Armour bedding	Polypropylene yarns
12	Armouring	One layer of galvanized steel wires
13	Serving	Polypropylene yarns
14	Optical fibre cable	1 x optical fibre cable, with 48 single-mode fibres

The main developments with HVDC cable technology have been towards ever increasing voltage levels. Projects being planned today, such as TenneT’s 2 GW platforms, are being designed for 525 kV cables. Beyond this, cable manufacturers have tested and qualified 640 kV extruded cables for use underground. These 640 kV cables are expected to carry 3 GW of power in a conventional bipole HVDC configuration. The UHVDC projects seen in China have shown that electrical equipment for higher voltages beyond 640 kV exist and are demonstrated commercially today. Developments for underground cables are focussed on increasing voltage levels to increase overall capacity.

4.1.4 Conclusions

Conventional cables have the advantages of established supply chains, and proven operation. Both GIL and superconducting cables offer the possibility of lower losses over long distances, but more demonstration projects and operational experience are required for both before they are mature enough to utilise in long distance subsea links.

The biggest challenge currently facing the manufacturing of high voltage cables is the supply chain including availability of raw materials (aluminium and copper). Several manufacturing facilities exist globally, in China, Japan, Europe and the USA capable of manufacturing both HVAC and HVDC cables, but there is a mismatch between growing future demand for HVDC cables and the manufacturing capacity. This is particularly true for HVDC cables, which require more specialised extrusion towers in their construction. Increased production capacity requirement in Europe for these cables could offer an opportunity for developing high value domestic manufacturing capacity in Ireland.

4.2. Cable Monitoring and Sensing Technology

Long distance subsea cables are vulnerable to damage and degradation from rusting, water penetration, anchors and fishing equipment, and other factors. Structural damage can jeopardise the ability of the systems to transmit power efficiently (or at all), which additionally brings in the threat of energy security.

There is significant interest in monitoring these cables to identify faults before they become system failures. Monitoring buried subsea cables presents several logistical challenges, so innovative remote sensing technologies are utilised to provide observation of cable condition without the requirement for physical investigation.

Both common forms of sensing, Distributed Acoustic Sensing and Distributed Temperature Sensing, mentioned below in sections 4.2.1 and 4.2.2 utilise a fibreoptic cable installed in the cable bundle. A light signal is transmitted down this wire and sensors at both ends detect the intensity, wavelength, and travel time of this light. Differences in this reflected (or backscattered) light can be used to derive information about the state of the cable bundle. The two common types of cable monitoring are often used in conjunction.

4.2.1 Distributed Acoustic Sensing

Uses a fibreoptic cable installed in the cable bundle to sense strain in a cable. As the cable bends, this will cause small variations in the “Rayleigh” backscatter of a pulse of light sent down the fibreoptic. This backscatter is measured in a manner like the reflected signals in radar systems, with a longer reflection time corresponding to a more distant part of the fibre. These changes are due to changes in the refractive index of the fibreoptic as it bends. The time taken for the backscatter to return along the fibre is measured along with its frequency, which can be processed to identify the location and magnitude of bends along the length of the cable. This can achieve a spatial resolution of 10 m.

4.2.2 Distributed Temperature Sensing (DTS)

Like DAS, DTS uses a laser light pulse in a fibreoptic integrated into the cable bundle. DTS measures the “Ramen” backscatter, which varies with the temperature of the fibre rather than the bend of the fibre. This can achieve a spatial resolution of 1 m and a temperature resolution of 0.01°C.

4.2.3 Conclusions

A combination of DAS and DTS allows cable temperature and magnitudes of bends along the entire cable to be accurately measured over many hundreds of kilometres. The key areas of innovation in this area are using machine learning and data analytics with the data, to predict and identify developing faults in cables and intervene with proactive maintenance before faults develop into failures. This is increasingly important when considering large scale SuperGrid technology, where a single cable could be carrying many GW of power.

4.3. HVDC converters

The power electronic converter uses controllable power electronic devices to step up voltage for transmission, convert from AC sources to DC and control the flows of power on a line. Several different technologies are used under a range of different trade names, and each has different advantages and disadvantages.

4.3.1 Line Commutated Converters

Line commutated converters (LCCs, sometimes known as HVDC Classic), are the most common form of HVDC converter in operation. They have been used since the 1970s, when they originally used mercury valves as switches. More modern LCCs utilise thyristors as controllable power electronic switches in place of mercury valves. LCC based converters output a constant current.

Thyristors can only be turned on in a controlled manner, but their switch off cannot be controlled via an external control signal. An LCC converter must be connected to an existing AC grid to provide the required signal to control the device switch off. This limits the ability of an LCC converter to imitate an AC waveform.

LCCs are commonly used for point-to-point connections to convert three phase AC to HVDC for transmission and then back to AC for injection into an AC grid. They are not suitable for use in more complex topologies, like those likely to emerge in a DC SuperGrid, as they lack the controllability to operate in a back-to-back DC to DC mode at a node where a number of DC lines would be connected in a SuperGrid, as these nodes will not have a synchronous AC waveform available to control the switch off of the thyristors.

They require large output filters to smooth the output waveform, as the switching process creates a large amount of harmonic content. This results in a large footprint for LCC converter stations, limiting the power capacity that can be constructed on offshore platforms.

4.3.2 Voltage Source Converters

Voltage Source Converters (VSCs, sometimes known as HVDC Lite) use Insulated Gate Bipolar Transistors (IGBTs) as the switching devices, rather than the thyristors used in LCC converters. These devices can be more directly controlled than thyristors, with the switching device able to be switched on and off by control signals. This allows a VSC to AC output without the need for an existing synchronous grid. This flexibility and controllability makes VSC converters capable of creating the complex and dynamic meshed topologies required for a SuperGrid.

The uptake of VSC converters was initially limited due to the availability of IGBT devices capable of blocking the high voltages required when switched off, but technological development has led to devices capable of blocking higher voltages and topologies allowing multiple devices to be controlled in a co-ordinated manner allowing stacks of lower rated devices to block higher voltages.

VSCs require less space to operate, due to less requirement for harmonic filtering. This is due to the use of pulse width modulation (PWM), enabled by the controllability of the IGBTs. Each device can be switched on and off for varying periods of time and the output filtered to create a waveform closer to an AC sine wave on the output. This makes them a preferable choice in locations where space is constrained, such as on offshore platforms.

4.3.3 Multi Modular Converters

Multi Modular Converters (MMCs) are a popular topology of VSC that utilises a larger number of smaller rated switching devices to create a stepped waveform. Rather than all devices on each leg operating in synchronization, the IGBT switches in each leg of an MMC are controlled independently, allowing a range of output voltages to be achieved.

The increased controllability can allow MMCs to create waveforms that more closely resemble a sine wave and need less filtering before injection into an AC grid than the outputs of conventional VSC converters, further reducing the footprint of converter stations. This could be a significant advantage for facilitating higher power converters on space constrained offshore platforms.

MMCs can also utilise flexible topologies to supplement or even remove the need for circuit breakers, by configuring their switching devices to block fault current and break a circuit, although this application has not been demonstrated at the voltage levels required for SuperGrid applications.

4.3.4 DC to DC converters

Although a SuperGrid could be constructed from a network of independent bipolar DC links, it is also possible to create a meshed topology with DC-DC conversion required to connect systems of differing voltage level.

MMC converters could be utilized with some small modifications to convert from DC to DC. This seems the most effective solution as it would utilise the same components found in MMC AC/DC converter stations.

The key innovations in this area are around reduction of losses by using new devices and topologies and size reduction, achieved by operating at higher frequencies resulting in smaller required transformers.

DC-DC converters can also facilitate fully DC wind turbines and array cables. Most existing wind farms use 66 kV AC cables to connect between wind turbines (although this is expected to increase to 132 kV by the end of the decade), but efficient and cost effective DC to DC converters could allow this to shift to DC, reducing the losses in the array cables and create more efficient wind farms.

4.3.5 Conclusions

The three key designs of HVDC converters each have distinct advantages and disadvantages, making them more suitable for use in a future SuperGrid.

LCC converters can achieve high voltages and power transfers and have low on-state losses, making them well suited for large scale, point to point connections, but for HVDC SuperGrids, the lack of flexibility and controllability of LCC converters makes them unsuitable for the deployment of meshed systems, creating a significant limitation in their ability to form the kind of flexible building block required to plan and deploy a European SuperGrid under uncertainty.

VSC converters have larger on state losses, the losses in power due to voltage drops across switching devices, than LCC converters, but can offer the flexibility required to operate in meshed mode, and have been proven operationally in a number of deployed projects. They also have a smaller footprint, making them more appropriate in space constrained applications such as offshore platforms.

MMCs are a source of innovation, using the same approach as VSC converters, but with multiple devices working together. Future developments in MMCs could further reduce the size requirements for converters, achieve lower losses and facilitate higher voltage VSC links, but further research and development is required to achieve commercial readiness for MMC converters.

4.4. HVDC Protection

Another limiting technological factor for HVDC meshed grids is the availability of appropriate circuit breakers. The role of a circuit breaker is to isolate part of the power system in the case of a fault, to ensure the safety and stability of the wider power system. This is particularly important in the allocation of multi-terminal HVDC systems, where faults can quickly propagate across a large number of converters if not isolated immediately.

Traditional mechanical circuit breakers used in high voltage AC applications operate by creating an air gap, physically separating two parts of the circuit and preventing current from flowing.

The large voltage present across this air gap can cause the air to ionise, creating an arc between the terminal of the breaker. In order to quench this arc, a breaker is designed to create an air gap as large as possible as quickly as possible, to increase the impedance of the path of the arc. This requires high speed operation and reliable operation of the mechanical arms at the breaker.

HVDC breakers present a unique challenge, due to the nature of the DC waveform compared to an AC waveform.

- In an AC breaker, the waveform is a sinusoid and has zero crossing points. At these points the voltage across the air gap will be zero which can aid in quenching the arc in the ionised air.
- In a DC system there are no “zero crossing points” in the voltage wave form, as there are in the sine wave of an AC system. To mechanically break the circuit and prevent an arc the breaker must create a large enough gap in the air as quickly as possible to increase the impedance of the air gap and prevent the formation of an arc or quench an existing one.

4.4.1 Mechanical Breakers

DC mechanical breakers are required to operate reliably at a very high speed, to quickly create a large air gap. Designing high speed and reliable circuit breakers for safety critical applications creates a range of technical challenges. It is desirable for the breaker to be as light as possible to allow it to move as fast as possible but must also be able to withstand repeated use without becoming damaged.

A range of techniques are used to either quench the arc or increase the impedance of the medium between the breaker arms, including:

- Using a medium other than air to insulate the air gap and prevent the formation of an arc. These include:
  - Insulating oil
  - Insulating gas such as CF6 (Hexafluoroethane)
  - Vacuum
- Air burst to deflect the arc, creating a longer path with larger impedance.
- Magnetic deflection to deflect the arc, creating a longer path with larger impedance.
- Resonant electrical circuitry to superimpose a negative current by discharging a recharged capacitor. This is commonly used in all mechanical circuit breakers for high voltage applications.

4.4.2 Solid State Circuit Breakers

Solid state circuit breakers approach the challenges of DC circuit breakers by utilising power electronic devices to break the circuit rather than a mechanical switch. The lack of moving parts in a solid-state breaker means they can operate much more quickly than mechanical alternatives.

A power electronic device is placed in series with the converter and can switch off in the case of a fault.

This approach has two key disadvantages.

- Some voltage is dropped across the protection device while it is conducting, resulting in “on state” losses.

- The voltage that can be blocked is limited by the available devices, making solid state breakers currently unsuitable for very high-power applications.

Further developments in HVDC solid state circuit breakers will focus on these two limitations, developing devices with lower “on state” losses and devices with larger voltage blocking capability suitable for higher power applications.

4.4.3 Hybrid Circuit Breakers

Hybrid circuit breakers use both high-speed mechanical breakers and a solid-state device in parallel. This overcomes the limitation of high “on state” losses for the solid-state device by bypassing them during normal operation, while maintaining the high speed of operation associated with solid state breakers.

During a fault, the following will occur:

- Power electric breaker in series with the mechanical breaker opens, increasing the impedance of that path and redirecting power to the alternative branch. Energy absorption circuits on the alternative branch temporarily absorb excess energy.
- The mechanical breaker opens, without risk an arc as current is directed through the alternative branch.
- The solid-state breaker then operates as in a standard solid-state breaker.

4.4.4 Conclusions

While there is a wide range of innovation in HVDC circuit breakers, developing a solution with low costs, low losses and reliable operation is a significant technological challenge. Hybrid solutions, utilising both solid state and mechanical elements are likely the best solution in theory but need to be developed and tested for high power applications.

4.5. HVDC Topology

A HVDC grid could follow a range of topologies and approaches. Rather than a co-ordinated, top-down design, it is likely that any system will be built over time from a range of building blocks including energy islands and cross border interconnectors. Therefore, it is key to consider how these building blocks could be developed and how planning and design can ensure flexibility of these assets under planning uncertainty.

4.5.1 Energy Islands

Energy islands are physical islands, either natural or artificial, that are used as hubs for offshore infrastructure. In addition to housing converter stations, and the associated equipment, energy islands can also house crew quarters for construction and maintenance staff and could have moorings for maintenance vessels to reduce the need for return trips to port during offshore operations. They could also be hubs for the production and distribution of green hydrogen or e-fuels, with the increased footprint compared to offshore platforms allowing for greater scale of production.

Energy islands could also be connected to shore by very large capacity multi-GW connections to facilitate the export of energy from multiple connected windfarms. This can also help to facilitate lower cost deployment of offshore wind, by sharing the transmission costs between multiple projects, rather than each project constructing its own radial connection to shore.

Energy islands provide one route to overcome the challenges associated with size limits for offshore platforms, allowing far more infrastructure to be constructed in a single location. This could prove vital to achieve the scale of power transfer required to make a SuperGrid viable.

The deployment of energy islands presents significant challenges for planning and deployment, including questions of sovereignty in some locations along with a potentially huge impact on local ecosystems.

4.5.2 Hybrid and Multi-Purpose Interconnectors

A hybrid or multi-purpose interconnector is a project designed to both provide interconnection within or between national energy systems, and connect other offshore demands or generation capacity. This model allows sharing of resources between various projects, rather than requiring individual retail or point-to-point connections for each project.

Multi-purpose interconnectors may be constructed with a range of purposes or connections in mind or may simply be designed to be flexible to evolving future needs. For example, by ensuring platforms, onshore facilities or energy islands have sufficient space to expand by adding new facilities such as hydrogen and e-fuel production, new converter stations or battery storage.

The design and standardisation of these interconnectors is an area with significant potential for innovation, with the challenging balance of standardisation, flexibility, and cost. The TenneT 2 GW program proposes a standardised size of 2 GW for offshore multipurpose interconnectors and intends to deploy many these as building blocks for its future offshore infrastructure.

Although multi-purpose interconnectors are a step in the right direction, they are merely a short-term solution. In the medium to long term, multi-purpose interconnectors may deter cross border trading by limiting interconnector capacity. Connecting an offshore wind farm to an interconnector contributes power into that interconnector thereby restricting the capacity of that interconnector and diluting the efficacy of the interconnector's primary purpose.

Rather than limiting interconnector capacity, more interconnector capacity should be created to carry vast amounts of solar and wind to the consumers. The way to achieve this is not through radial point-to-point interconnections but through larger, high-capacity, meshed grids.

If we are to move around the power that is targeted in Ireland (35 GW offshore), UK waters (50GW by 2030) and the North Sea (North Seas Energy Cooperation targets at least 260GW by 2050), we need to rethink our approach to grid planning. Any radial point-to-point interconnectors will be required to transfer massive amounts of power, 5-10GW. It is too great a risk for this level of power to be point-to-point with no alternate routes to supply.

A truly meshed grid must have built in redundancy with multiple routes to market, while also having fewer landing sites and require less infrastructure.

4.5.3 Conclusions

It is likely that energy islands and multipurpose connectors represent the building blocks of a highly interconnected European SuperGrid. The specific needs of Irish projects should be considered carefully, from both the planning and technological perspective. These two needs should be coordinated as the design of this infrastructure will be driven by several planning considerations, including requirements for capacity, water depth, number, and location of likely nodes, wider energy system considerations such as the locations of onshore windfarms and onshore connections and demand centres.

4.6. Energy Storage and Offtake

For grid systems that will be based more on intermittent renewable generation, batteries and hydrogen/e-fuel can store energy from renewables in high-supply, low-demand scenarios, and provide energy to the grid in low-supply, high-demand scenarios, smoothing differences between supply and demand on short timescales (up to a few hours).

While a SuperGrid could theoretically mitigate the issues of variable renewables by increasing diversity of demand and generation, there is significant potential for the integration of storage technologies and alternative offtake.

In particular, the use of storage and offtake integrated with energy islands in strategic locations could offer significant benefit to the ability of these assets to be utilised to their maximum potential.

Power-to-X (P2X) refers to systems in which electricity is converted to some form of stored energy. The storage medium can include batteries, hydrogen, e-fuels, heat, etc. Storage enables electricity generation to continue during periods of no grid-based demand, but introduces the challenges of lower efficiencies (converting to the storage itself introduces losses) and extra infrastructure.

4.6.1 Batteries

The most common battery technology is currently the lithium-ion battery. They have a high energy density, which allows energy needs to be met with smaller and lighter batteries. Their high energy density makes them highly applicable to hard-to-electrify areas, such as transport. However, they are reliant on scarce materials and harmful mining practices. Another concern is fire safety, with thermal runaway of the batteries leading to fires.

Vanadium redox batteries are less energy dense than lithium-ion, but have a higher number of cycles and therefore a longer life, as well as high intrinsic safety. They are regarded as easier to scale, but the technology is not as mature, especially at grid scale.

4.6.2 Hydrogen and Power-to-X

Green hydrogen is made through electrolysis using renewable electricity.

The production of green hydrogen produces no carbon dioxide as it is produced by an electrolyser that uses energy from renewable power sources.

For a grid based on variable renewable energy, green hydrogen or e-fuels could be used as longer-term storage of power. The expectation is that wind farms will be constructed dedicated to the production of hydrogen/e-fuels, with electrolysers sized to ensure a higher capacity factor,

Therefore, green hydrogen and e-fuels should primarily be used for hard to decarbonise sectors where direct electrification is not possible, such as the steel industry, fertiliser industry, and the shipping and aviation industries.

The main innovations in this area will come from the demand side, which could increase the need for hydrogen, ammonia or e-fuels, and therefore increase demand for P2X systems.

A wider range of innovative technologies are being explored for the effective production storage and transportation of hydrogen, and e-fuels. Integration of these technologies could further supplement the benefits of a SuperGrid, providing flexible demand centres for the use of excess renewable generation on the system.

4.7. Cable installation vessels

Cable installation vessels are used to install cables on the seabed. They house equipment used to handle the cables and large carousels that store the cables as a reel and unwind them as they are laid. The current capacity of carousels is of up to 10,000 tonnes. Some contractors offer vessels with a double carousel which can increase carrying capacity.

The same vessels may be used for export and array cable installation, although export cable-laying vessels will typically have larger carousels to accommodate longer cables. The main suppliers of cable-laying vessels are Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Jan de Nul, Seaway 7 and Van Oord.

Cable laying vessel designs are standardised and well understood, so innovations are minimal. The only key recent development that can be seen in cable-laying vessels is that newer vessels have larger carousels so they can carry more cable.

If alternative cable laying techniques are developed, such as those utilising subsurface drilling to reduce impact to seabed ecosystems, then vessel innovation will be required.

The largest challenge is the supply of these specialised vessels. And if demand quickly outstrips supply, then costs could significantly increase, alongside wait times for vessels. This can be mitigated to some extent by sending high confidence signals to industry though the use of credible long term marine spatial planning.

5. WP4: Environmental impacts

5.1. Potential impacts and mitigation strategies

A European SuperGrid would require tens of thousands of km of new subsea cables to be deployed. While the impacts of installing and operating these cables are considered to be relatively small compared to other oceanic activity in isolation, the aggregate effects must be taken into consideration during the planning and design stages. In addition, the impacts of extracting and mining raw materials for copper and aluminium based HVDC and HVAC technology are not insignificant, and it is worth noting that maintaining a business-as-usual approach to connecting renewables would result in a system requiring more cables. Coordinating grid infrastructure has been found to be more beneficial from an environmental perspective vs the current point to point approach.

Despite this, there is a lack of research detailing the long-term impacts of HVDC subsea cables on marine ecosystems. Supporting research and testing sites to improve understanding of these long-term impacts should be a key objective, alongside supporting mitigations for known impacts.

Several mitigations can be put in place to reduce these impacts:

- Consider marine ecosystems holistically in marine spatial planning and during planning and consenting for offshore infrastructure, to reduce or remove the length of cables passing though ecosystems of sensitivity.
- Ensure the needs of all ocean stakeholders, including shipping, renewable energy, fishing and tourism, alongside the protection of habitats and biodiversity are considered early in the planning process.
- HVDC rather than HVAC transmission can reduce heat, noise and EMF emissions.
- Using HVDC can reduce the number of cables required to transfer equivalent power. This would result in fewer cables, reducing impact on ecosystems.
- Armouring of cables can be designed to reduce the emissions of noise and EMF.
- Installation techniques can be developed to reduce disturbances to ecosystems, such as subsurface drilling to minimise direct disturbance to surface sediment or sensitive ecosystems.

6. WP5: Ireland

A European SuperGrid is essential if Ireland is to achieve its politically agreed offshore wind targes and the ambition to become carbon neutral. Likewise, a SuperGrid will enable the rest of Europe to benefit from the rich wind resource available in Ireland. It is vital that the speed of progress on both sides is aligned.

In this section, we examine the key considerations that Ireland should focus on in order to maximise the likelihood of a SuperGrid being realised at the required rate for Ireland's needs, and for Ireland to maximise the collateral benefits arising.

The pathways and recommendations in this section aim to avoid replicating work already undertaken by other international stakeholders. We seek to identify how Ireland can both learn from the work of others and contribute to the wider international pool of knowledge and expertise, taking advantage of the unique opportunities on offer.

6.1. Collaboration

The concept of a SuperGrid is inherently collaborative, and it is in this spirit that government, industry, academia, network operators and other key stakeholders should engage in the important work of bringing about an interconnected, renewables driven European energy system.

Within Europe, a wider range of governments and TSOs have greater experience than Ireland of deploying and developing this technology, and this presents an opportunity to benefit from the learning of others. Dialogues should be prioritised with Danish, German, Belgian, French, and UK policy makers and TSOs, to further understand the systems and processes they have put in place to facilitate technology development.

All the example projects in the document are projects that either take place in a single country or between two countries. A true European SuperGrid will require multilateral collaboration between many countries to reach its true potential, and Ireland should seek to build relationships with TSOs, governments and industry across Europe, including wider engagement with other countries not leading the way, to lay the foundations for these future collaborations.

On 12th September 2022 the Joint Statement on the North Seas Energy Cooperation (NSEC) was published, establishing non-binding targets for the entire region and individual members for 2030, 2040 and 2050. Irelands target under this framework are – 7 GW by 2030; 15-20 GW by 2040; 37 GW by 2050, representing a significant proportion of the 260-290 GW total target by 2050 (excl. UK).[xxviii]

Article 14 of the revised EU TEN-E Regulation 2022/869 of 30 May 2022 commits identified Member States, for each of the five Sea Basins identified in Annex I, to enter into "a non-binding agreement to cooperate on goals for offshore renewable generation to be deployed within each sea basin by 2050, with intermediate steps in 2030 and 2040, in line with their national energy and climate plans, and the offshore renewable potential of each sea basin". Ireland is part of two of the five sea basins. The same article 14 commits ENTSO-E to develop and publish high-level strategic integrated offshore network development plans for each sea-basin, for 2030, 2040 and 2050, in line with the non-binding agreements. This must happen before January 2024.

The Irish government should work to ensure that ENTSO-E and the European Commission apply a truly pan-European approach to planning the future meshed SuperGrid and that it reflects the 2030, 2040 and 2050 ambitions on offshore renewables communicated by the EU Member States, while ensuring effective cooperation with the UK and Norway.

[xxviii] Joint Statement on the North Seas Energy Cooperation – 12 Sept 2022 https://energy.ec.europa.eu/system/files/2022-09/220912_NSEC_Joint_Statement_Dublin_Ministerial.pdf

6.2. Test sites and demonstrator projects

Commercial test sites for new technologies, which emulate real world conditions, are vital for the commercialisation of new technology. While Ireland has existing test sites, there is a need for larger scale, real world trial projects and demonstration sites to provide the nature of testing required. Examples should be taken from projects like the Scottish Hywind[xxix] demonstrator, a 30 MW floating wind demo site using full scale floating wind turbines.

We recommend Ireland identifies and progresses one or more demonstration projects with similar scale and ambition. This is likely to attract international attention to Ireland in this space and may also lead to further investment (see section 6.5). Any demonstration site should combine testing SuperGrid specific technology, such as energy islands and superconducting cables with other renewable energy technologies, such as floating wind to derive greater value.

6.3. Marine spatial planning

Delivering large scale subsea infrastructure in the oceans around Ireland will require a strategic approach to engagement with a wide range of stakeholder. This is best achieved though integration with the ongoing process of Marine Spatial Planning (MSP) in Ireland.

The National Marine Planning Framework for Ireland, last updated in June 2022, sets out an approach for ensuring all ocean stakeholders are considered in all uses of Irish waters and that these activities are efficient and sustainable[xxx]. WEI should work to communicate the importance of including subsea SuperGrid infrastructure as a key element of any future updates to the National Marine Planning Framework for Ireland.

The Offshore Renewable Energy Development Plan II (OREDP II) is a document currently under development by the Irish Government focusing more directly on the implications of energy infrastructure in the Irish Exclusive Economic Zone (EEZ).[xxxi]

It is also vital for the success of a European SuperGrid to consider the consequences of infrastructure development beyond just the EEZ. Ireland is part of the North Seas Energy Cooperation (NSEC) group, comprising Belgium, Denmark, France, Germany, Ireland, Luxembourg, Sweden, the Netherlands, Norway, the UK, and the European Commission on behalf of the EU. Ireland held the presidency of this group during 2021 and signed a Political Declaration in 2021, laying out the process for cooperation on deployment of offshore energy infrastructure.[xxxii] This group offers a platform to develop wider Marine Spatial Planning approaches toward the entire North Sea basin, considering the subsea infrastructure required of the developing SuperGrid infrastructure. The member countries have an aggregate target of 76 GW of offshore wind by 2030, and 193 GW by 2040.

The European Commission, in its EU Strategy on Offshore Renewables (COM/2020/741) estimates that for every Euro invested in offshore renewable generation assets, two Euros would need to be invested in offshore grids. To step up offshore renewable energy deployment in a cost efficient and sustainable way, it states, more rational grid planning and the development of a meshed grid is key.

On 18 May 2022, the Prime Ministers of Belgium, the Netherlands, Denmark and Germany signed the Esbjerg Declaration on The North Sea as a Green Power Plant of Europe and the Energy Ministers of the same nations signed the Declaration of Energy Ministers. “To pave the way for the further expansion of offshore wind,” they “decided to jointly develop The North Sea as a Green Power Plant of Europe, an offshore renewable energy system

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[xxix] https://www.equinor.com/energy/hywind-scotland

[xxx] https://www.marei.ie/marine-spatial-planning/

[xxxi] https://www.gov.ie/en/publication/71e36-offshore-renewable-energy-development-plan-ii-oredp-ii/

[xxxii] https://commission.europa.eu/news/north-seas-countries-ministerial-meeting-2021-12-02_en

connecting Belgium, Denmark, Germany and the Netherlands and possibly other North Sea partners, including the members of the North Seas Energy Cooperation (NSEC)".

In 2022, the NSEC became the facilitating body for the task of delivering the North Seas Offshore Grids (NSOG) priority offshore corridor sea basin, under the revised Trans-European Energy Infrastructure framework of the European Union. A. On 19 January 2023, the members of the NSOGC (Belgium, Denmark, Germany, France, Luxembourg, Netherlands and Sweden) published their first non-binding agreement on goals for offshore renewable generation in 2050 with intermediate steps in 2040 and 2030 for priority offshore grid corridor Northern Seas offshore grids (NSOG). The corridor's combined offshore renewable capacities are 60.3 GW in 2030, 134.9-158 GW in 2040, and 171.6-218 GW in 2050.

Ireland should use their place in this body to encourage greater collaboration and planning coordination in the Marine Spatial Planning Space, with a particular emphasis on Ireland's place in the North Seas Offshore Grids framework, the North Sea as a Power Plant of Europe initiative and seek out other international bodies with similar aims to learn from and contribute to.

6.4. Ports

Port infrastructure requirements for cable-installation vessels are less onerous than those for wind turbine installation vessels, but considerations must still be made for the location and specification of port infrastructure in Ireland.

Wind Energy Ireland published a national ports study in September 2022 which detailed the requirements for Irish ports to serve the growing domestic and international wind energy market.[xxxiii]

Even though the requirements for cable vessels are less strenuous than turbine installation, with many cable vessels being loaded at the location of manufacturing and traveling directly to the installation route. Consideration should still be made to ensure that the appropriate ports have capacity for marshalling of cable install vessels for subsea transmission infrastructure.

Ports themselves can also act as hubs for the development of skills and supply chain. The capacity to load cable installation vessels could also be a vital part of a future value proposition, particularly if Irish cable manufacturing was ever realised.

Foundation installation vessels may also be necessary if projects feature offshore platforms, but the relative number of vessel trips and days required to install a single platform is far less than those associated with an entire wind farm of dozens of turbines, making the cost savings of local port infrastructure a less urgent factor.

6.5. Supply chain

There are a range of opportunities for high value manufacturing within the ecosystem of SuperGrid technology, including cables, cable lay vessels, and DC-specific protection and control systems. It is, however, a global industry, with little driving locational manufacture (as cables are relatively easy to transport). The UK has shown that attracting supply chain is possible, and with such significant targets in place, Ireland should be pushing to attract supply chain, in particular on electrical infrastructure, which will be urgently needed to connect 35GW of power to the energy system.

The exception to this may be found in innovative small-scale development of high-value protection equipment for DC networks.

[xxxiii] https://windenergyireland.com/latest-news/7110-new-report-not-enough-irish-ports-to-deliver-offshore-wind-energy-target

Ireland does have existing expertise in onshore cable installation and maintenance, and by extension above water on offshore substations and energy islands, in companies such as:

- RES
- Omexon
- M&M Contractor
- Farrans

6.6. Interconnection policy

Cross border interconnection between energy systems is a key building block of a SuperGrid. On the island of Ireland there are currently two HVDC interconnectors, the East-West Interconnector, a 500 MW HVDC connection to the British energy system, and the Moyle Interconnector, a 500 MW HVDC link between Scotland and Northern Ireland. In June 2022, the Department of the Environment, Climate & Communications held a consultation on the Irish Electricity Interconnection Policy, published in 2018.[xxxiv]

WEI responses highlight the following key messages:

- The EU's target of 15 % interconnection by 2030 is not ambitious enough, and a number of member states already meet or surpass this target.
- 30% interconnection by 2030 would require 4 GW of interconnectors in Ireland.
- Current and pipeline interconnectors result in 2.2 GW of interconnector capacity by 2030.
- The proposed MARES Interconnector may add an additional 750 MW to this; however, this would still leave Ireland with a shortfall to reach 30%.
- Expanding interconnection to Ireland presents challenges, as the onshore grid is already heavily constrained. The location of interconnection must be considered carefully to not cause further constraint issues.

6.7. Key Recommendations

Our key recommendations to Ireland are:

1. Engage with the governments and transmission system operators of those countries leading the way, such as Belgium, Denmark, Germany, France, the UK and China, as well as other neighbours less far down this path, to build continental and international consensus and co-ordination.
2. Expand the interconnectedness of the Irish energy system with further links to the UK and France.
3. Integrate subsea transmission as a core element of future Marine Spatial Planning in Ireland, considering the possible environmental impacts of this technology on all ecosystems and ocean stakeholders.
4. Streamline processes to create opportunities for demonstrator scale projects of SuperGrid technology in Irish waters
5. Identify high value areas of research, development, and manufacturing in the SuperGrid value chain where Irish academia and industry can compete on a global scale.

[xxxiv] https://www.gov.ie/en/consultation/ca3b4-electricity-interconnector-policy-technical-consultation/

7. Summary

In this report we have presented:

- An overview of the SuperGrid technology
- Eight different case studies from around the world, each showing a unique application of a subset of SuperGrid technology options.
- A deeper explanation of some of the key building blocks of SuperGrid technology, and
- A summary of the key environmental impacts caused by the installation and operation of HVAC and HVDC cables

Our key takeaway for Ireland is that Ireland will need to align its offshore wind growth plans with the planning, design, and deployment of a pan-European SuperGrid. The implementation of this grid will happen organically, with the early foundations being small but significant infrastructure projects within single countries or between two neighbouring countries. For Ireland, this means close collaboration with both the UK and France, and we would strongly encourage Ireland to proactively lead discussions with these two partners to further develop interconnectivity in the short term while helping drive the wider vision (at EU level) within the current context of REPowerEU and A Green Deal Industrial Plan for the Net Zero Age, published by the European Commission on 1st February. It is in Ireland's interest to drive these discussions as it is likely that overall progress at a European level will be slower than what Ireland needs to maintain momentum in its domestic offshore wind market.

The longer-term ambitions for interconnectivity within Europe are currently driven by the revised EU TEN-E Regulation 2022/869 of 30 May 2022 committing identified Member States, for each of the EU's five Sea Basins identified in Annex I, to enter into "a non-binding agreement to cooperate on goals for offshore renewable generation to be deployed within each sea basin by 2050, with intermediate steps in 2030 and 2040. These must be in line with their national energy and climate plans, and the offshore renewable potential of each sea basin". The same article commits ENTSO-E to develop and publish high-level strategic integrated offshore network development plans for each sea-basin, for 2030, 2040 and 2050, in line with the non-binding agreements.

It is important that Ireland is an active participant with high ambition and determination to enable a future pan-European SuperGird. It must also seek to ensure that the UK is included in the planning and deployment of the infrastructure.

A Memorandum of Understanding was signed between NSEC and the UK on December 18th 2022, establishing a framework for further collaboration between the UK and NSEC countries, including Ireland.[xxxv]

Other conclusions we can draw from the analysis presented in this report are:

1. DC technology is closing the cost gap on AC technology. It is already the preferred choice for simple point to point transmission infrastructure for large wind farms far from shore. As demand grows, prices of DC technology will fall further. For the various scenarios envisaged for an Irish/European SuperGrid, it is hard to envisage situations where AC technology will be preferred to DC.
2. There are increasing examples from around the world which demonstrate SuperGrid technology at large scale (long distances, high capacity/voltage, meshed networks, etc.). The focus for building the Irish/European SuperGrid should be to build on these examples, seeking to innovate only in the areas that fill the gaps in experience and glue the pieces together.
3. In the short to medium term commercial projects are likely to use either high voltage "conventional" cables or gas insulated cables. The use of superconducting cables over long distances (i.e. more than one or two

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[xxxv] https://energy.ec.europa.eu/news/north-seas-energy-cooperation-and-uk-establish-cooperation-framework-facilitate-development-offshore-2022-12-18_en

kilometres) are being developed and proven, and will play a role beyond 2030. Gas insulated lines have lower power transmission loss and larger transmission capacity (compared to conventional cables) but are more suitable in applications where HVAC transmission is required.

4. Remote sensing of cable condition is relatively advanced, with hotpoints in both cable temperature and curvature able to be detected to 10 m accuracy or better on cable runs of over 100 km.
5. There are a number of different converter technologies available for DC systems, each offering a different balance of pros and cons. We do, however, expect that VSC technology will be suitable for the majority of SuperGrid DC implementations, as it offers the greatest level of flexibility across the majority of known use cases.
6. Circuit breaker technology for DC systems remains a weak area and one for concern at this stage. DC systems are at higher risk of flash overs due to their sustained voltage levels (compared to AC alternatives), and both mechanical and solid-state circuit breakers have the limits. We expect that hybrid technology, which seeks to combine the best part of each of these solutions, will be able to address these shortcomings, but this is still in early phases of development at the time of writing.
7. HV lines present some environmental challenges that need to be addressed for any type of installation. These are mostly associated with noise, vibration, localised heating and seabed disruption. These impacts are fairly well understood and are not specific to either DC technology or the notion of SuperGrids. There are some aspects of SuperGrid design options which may exacerbate the issues, but on the other hand the use of DC technology, compared to AC, and the meshed nature of a SuperGrid, compared to business as usual radial connections, generally have the effect of reducing the impacts. Ecology and environmental impacts will remain a key focus for any significant transmission development, SuperGrid or otherwise.
8. The Irish government should use its ambitious offshore wind targets, its skilled and highly educated labour force, and innovative drive to attract innovative cable manufacturing to Ireland. There could also be the opportunity to create (through academic collaboration and investment) an innovation and manufacturing opportunity in high value engineering components for DC network protection and control.
9. Ireland does have existing expertise in onshore cable installation and maintenance, which could be extended to above water activities on offshore substations and future energy islands.