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Topologies of the North Sea Supergrid

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***Abstract*-The development of the North Sea Supergrid is closely linked to three main topological ideas: (i) Business as Usual; (ii) Local Coordination; and (iii) Fully Integrated. In this paper, the three proposed topologies were simplified, analysed and compared for power export from offshore wind farms unto onshore grids. A review on the state-of-the-art HVAC and HVDC offshore transmission technologies was carried out. The national offshore network development strategies of the six countries surrounding the North Sea were summarised. The number of HVAC and HVDC assets required for all three topologies were calculated. It was evident from calculations that, by 2030, the Fully Integrated Topology will achieve approximately 8% asset savings than the Local Coordination Topology.**

***Index Terms*— High voltage direct current, Multi-terminal HVDC, MTDC, Offshore grids, Voltage Source Converters.**

I. INTRODUCTION

The deliverability of the EU's targets for renewable energy is closely linked to the development of an offshore grid in the North Seas. To realise the North Sea Supergrid (NSSG), the European Network of Transmission System Operators for Electricity (ENTSO-E) have proposed three main topological ideas[1]: (i) Business as Usual; (ii) Local Coordination; and (iii) Fully Integrated. The reference year for the Business as Usual Topology is 2020. Both the Local Coordination and Fully Integrated Topologies are defined for 2030. The intellectual framework for the proposed topologies is illustrated in Figs. 1-3.

Although no meshed DC grid has been built as of now, the authors in [2] investigated the case of a continental overlay HVDC-grid. The analysis of costs and benefits of different proposals for the pan-European offshore grid was examined in [3]. Test benchmark sub-systems of the North Sea Grid have been proposed by [4] and [5]. In [6], an economic study of the NSSG's proposed topologies was carried out. The main contribution of this paper is to simplify, analyse and compare the three main topological ideas of the NSSG.

The method adopted was to calculate the number of high voltage alternating current (HVAC) and high voltage direct current (HVDC) assets that would be required for each topology. Based on this, the topology that will offer the most significant savings on overall transmission asset volume was determined.

II. TECHNOLOGY STATUS

The NSSG will be implemented using both HVAC and HVDC offshore transmission technologies. The HVAC transmission technologies are well understood and several offshore wind farms (OWF) including Greater Gabbard and London Array have successfully implemented 3 phase HVAC cables to transmit generated power to onshore substations at 132kV and 150kV [7]. However, since the Supergrid will both serve to connect offshore wind farms and interconnect countries across the sea, at distances beyond 90km from shore, HVDC technology becomes more appropriate[8–10].

A. HVDC state-of-the-art

The two HVDC technologies are the Voltage Sourced Converter (VSC-HVDC) and Current Sourced Converter (CSC-HVDC). It is expected that the proposed North Sea Supergrid will be implemented using multi-terminal, multi-vendor HVDC technology. VSC-HVDC technology and subsea cables will play a key role in the transmission of generated offshore wind power unto terrestrial grids. CSC-HVDC will enable bulk power transmission over long distances. Table I is a summary of the state-of-the-art HVDC technology status for offshore and onshore transmission[11].

The major assets are: VSC-HVDC offshore platforms and onshore stations; CSC-HVDC onshore stations; Cross-linked Polyethylene (XLPE) cables; and Mass Impregnated (MI) cables. In future, MI cables will be used with Paper Polypropylene Laminate (PPLP) insulation to achieve higher power transfers.

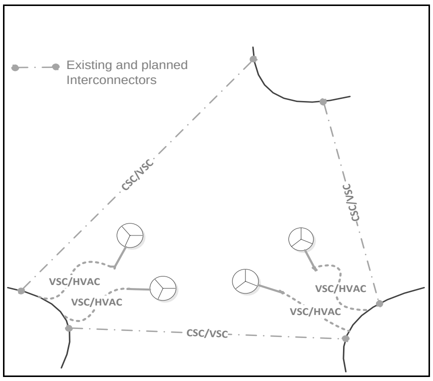

Fig. 1. Business as Usual Topology

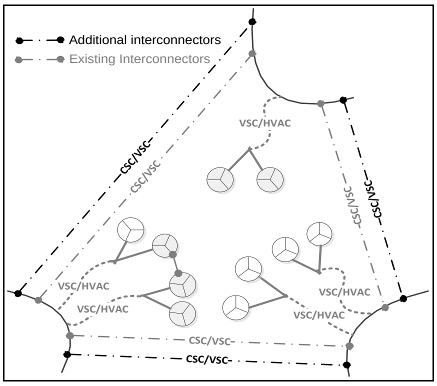

Fig. 2. Local Coordination Topology

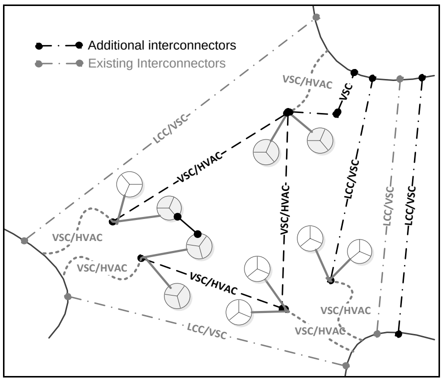

Fig. 3. Fully Integrated Topology

TABLE I
HVDC TECHNOLOGY STATUS

Technology	Maximum Installed	Maximum Currently Installed/Planned	Maximum Achievable rating (Near Term–2020)
VSC Converters	0.5GW;±200 kV	1 GW; ± 320 kV 0.7 GW; 500 kV	2 GW; ±500 kV
CSC Converters	7.2GW;±800 kV	7.2 GW;±800kV	7.2 GW;±800 kV
XLPE Cables	0.25 GW/Cable; 200 kV	0.5 GW/Cable; 320 kV	1 GW/Cable; 500 kV
MI Cables	0.6 GW/Cable; 500 kV	0.8 GW/Cable; 500 kV	1.5 GW/Cable; 600 – 650 kV (PPLP Technology)

XLPE – Extruded Cross Linked Polyethylene
MI – Mass Impregnated; PPLP – Paper Polypropylene Laminate

1) *Converters:* in China, the Jinping-Sunan point-to-point interconnector, which is being built, will use CSC-based technology rated 7.2 GW, ±800 kV via overhead lines. For VSC–HVDC technology, the maximum currently installed East-West Link (Ireland-UK), is rated 500 MW and ±200 kV. However, recent developments have been incremental – from 800 MW Dolwin1, to 900 MW Sylwin1 and maximum planned 1000 MW for the France-Spain link all at ±320 kV Bipole[1]. Notably, record VSC pole voltage at 500 kV was awarded in 2011 for monopolar 715 MW, Skagerrak 4 (Norway-Denmark) project. This new link, when completed, would be operated as the first hybrid-bipole in combination with the existing CSC-based pole of Skagerrak 3. In future, manufacturers foresee VSC–HVDC power ratings to double up to 2000 MW per bipole at ±500 kV.
2) *Cables:* there are two major cable technologies. On the one hand, conventional Mass Impregnated (MI) cable rated 660 MW and 500 kV is installed in Neptune RTS, USA. Upon completion, the highest planned Fennoskan 2 (Finland-Sweden) would deliver 800 MW per cable at 500 kV. Emerging mass impregnated technologies would use Paper Polypropylene Laminate (MI-PPLP) as insulation to achieve ratings of 650 kV and 1500 MW per cable. In this manner, the recently awarded Scottish-English Western link will use the MI-PPLP cable technology rated at 600 kV and 1100 MW per cable.

On the other hand, Extruded Cross Linked Polyethylene (XLPE) cable technology is fairly new and still being actively developed. In October 2012, the highest installed East-West (Ireland-UK) interconnector, rated 250 MW per cable at ±200 kV bipole, was put into service. Currently, the XLPE HVDC market supplies equipment at maximum voltage of ±320 kV for the planned 500 MW per cable (i.e. 1 GW per bipole circuit) France-Spain link. In future, it is envisaged that 500 kV XLPE cables would deliver bulk power up to 2 GW per bipole circuit[12].

B. HVAC cables

Table II is a summary of HVAC cable maximum data. Paper Insulated Self Contained Fluid Filled (SCFF) cable and XLPE cable technologies could be used in offshore transmission up to 500 kV and 1000 MW[13].

TABLE II
HVAC CABLE MAXIMUM DATA [16]

	SCFF	XLPE
Maximum nominal operating voltage	500 kV	500 kV
Maximum continuous conductor temperature	85 – 90 °C	90 °C
Conductor material	Copper/Aluminum	Copper/Aluminum
Maximum power installed	1.2GW/three phase	1GW/three phase
Maximum water depth	830 m	400 m
Maximum length	50 km	50 – 125 km

C. DC breakers and Supernode concept

DC breakers are a key enabler for multi-terminal HVDC (MTDC) grids. Recently, Alstom announced the results of DC breaker prototype tests in which currents exceeding 3 kA was interrupted in less than 2.5 ms. In addition, ABB announced 320 kV, 2 kA hybrid DC breakers. This device prototype has a fault current breaking capability of up to 9 kA within less than 3 ms and the next step is to deploy same into real HVDC networks[14].

The Supernode concept is basically an islanded AC network which mainly requires development of effective frequency control, fault detection and fault clearing strategies[13]. Here, the black-start capability of VSC-HVDC is highly required to regulate voltage in the AC hub. The Supernode facilitates multi-terminal HVDC grid operation and thus eliminates the requirement for DC circuit breakers. However, the cost of additional converter platform and extra power losses associated with such DC interconnections could be prohibitive. In future, it is envisaged that the Supernode concept will be combined with DC breakers toward the realisation of continental MTDC offshore grids.

III. NATIONAL STRATEGIES

The North Seas Countries' Offshore Grid Initiative (NSCOGI) fosters regional cooperation for developing electricity grid infrastructure in the North Seas[6]. In particular, the focus is on the six countries surrounding the North Seas. In Table III, a summary of expected offshore wind capacities in the North Seas (including Skagerrak and Kattegat)[1] is presented together with corresponding national Frequency Control Reserves (FCRs) [15].

The frequency control reserve (FCR) value is the level of instant response and reserve that Transmission System Operators (TSO) hold ready to replace energy lost through a fault, either through the failure of a circuit or shut down of a power station[15].

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TABLE III

EXPECTED WIND CAPACITIES AND FREQUENCY CONTROL RESERVES

Country	Wind Capacity 2020[1] (GW)	Wind Capacity 2030[1] (GW)	FCR[15] (GW)
Great Britain [16]	18.5	38.5	1.8
Belgium	2	4	3
Denmark [17]	1	4	*1.36
The Netherlands	2	12	3
Germany	10	24	3
Norway	0	1	*1.36
Total	**33.5**	**83.5**	

*Nordel countries of Sweden, Norway, Finland and Denmark combine to provide FCR of 1.16 GW against infeed loss risk of 1.36 GW

A. Great Britain (GB)

Fig. 4 is the GB transmission system for the 2030 Accelerated Growth Scenario defined by the National Grid[11]. Notably, Rounds 1 and 2 offshore wind projects mostly utilised HVAC export cables having rated voltage of 132 – 150 kV. However, few projects used 33 kV medium voltage alternating current (MVAC) export cables for transmission to shore, and these have been discounted in this work. For Round 3 projects, wind farm arrays are aggregated using 500 MW HVAC hubs; and intra-zonal connection between offshore HVAC transformer substations is achieved using HVAC cables. Furthermore, the power aggregated by two HVAC hubs is transmitted to shore via 1 GW and ±320 kV offshore converter platforms with 1 GW, 320 kV bipole cable circuits (BCC)[11].

B. Belgium (BE), Denmark (DK) and the Netherlands (NL)

In Belgium (BE), the national Transmission System Operator (TSO), Elia, plans to export offshore wind power in the North Seas to shore via two HVAC aggregator platforms. These two HVAC platforms (alpha and beta) are inter-tied via a 220 kV AC cable and have combined rated capacity of 2.3 GW. Both platforms can aggregate cables operating at 66 kV and 220 kV. The nominal export voltage is 220 kV and the schematic diagram is presented Fig. 5[18].

The CSC-based interconnector between Great Britain and Belgium (i.e. NEMO project) is expected by 2018[11]. Add to this, there is a planned international offshore HVDC platform to facilitate power exchange with neighbouring countries. This HVDC converter platform could either deliver power directly to shore via the planned HVDC-DOEL transmission cable or via the HVAC connectors to the alpha and beta platforms.

In Denmark (DK) and the Netherlands (NL), OWF locations are close to shore (i.e. less than 90 km). Offshore wind power will be exported to shore using offshore MVAC and HVAC transmission technologies.

C. Germany (DE)

In the German North Sea, offshore wind farms have been grouped into 13 clusters as illustrated in Fig. 6[19]. Each cluster has between 1-3 offshore VSC-HVDC platforms mostly rated 900 MW and ±320 kV. Connection of wind farm array to VSC platforms is via 150 kV HVAC cables.

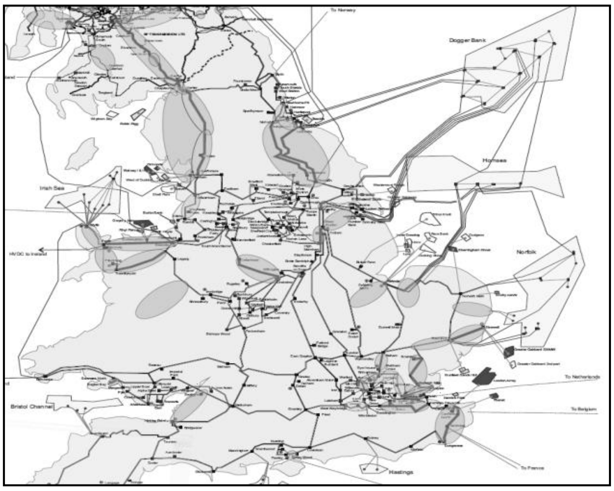

Fig. 4. GB Transmission System by 2030 [11]

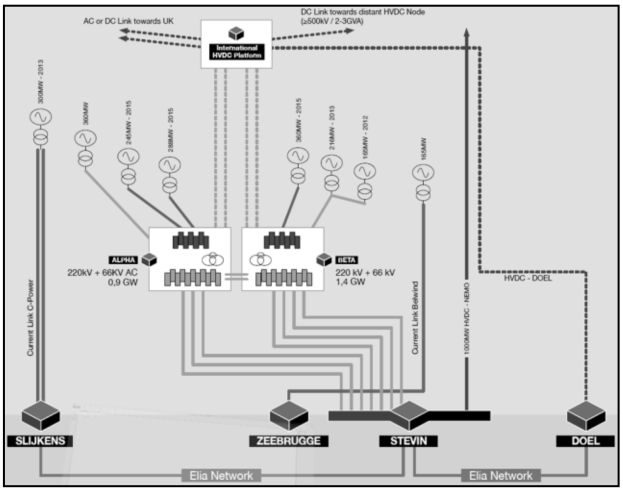

Fig. 5. Belgium North Sea High Voltage Grid, Source: Elia [16]

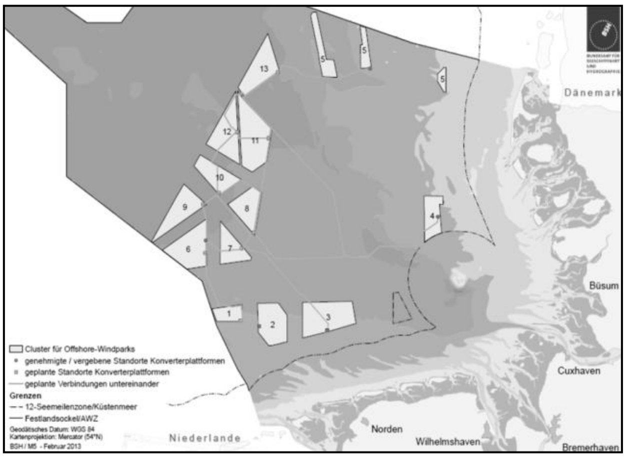

Fig. 6. Offshore Wind Farm cluster connection in Germany [17]

Furthermore, where separation distances are less than 20km, 150 kV HVAC cables will be used for cluster-to-cluster connections so as to improve flexibility. These inter-cluster connections are evident in Fig. 6. Markedly, the planned uniform voltage and power ratings across the German North Sea development zone would allow vendor-independence[19].

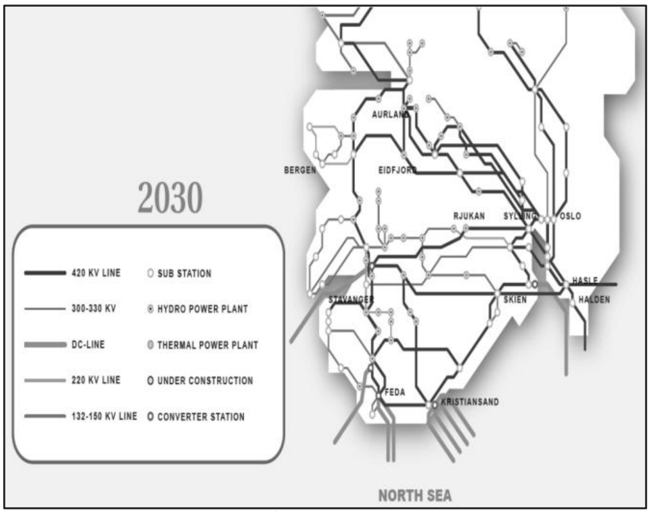

Fig. 7. Grid Development Plan for Southern Norway [18]

D. *Norway (NO)*

In southern Norway, the underlying mainland grid that will connect the planned onshore converter stations is currently operated at 330 kV. By 2030, Statnett plans to upgrade this inland grid network to 420 kV so as to allow further HVDC interconnections to the EU. Following from the 2011 Grid Development Plan, Fig. 7 illustrates the North Sea interconnectors that are expected by 2030[20].

IV. SIMPLIFICATION OF THE TOPOLOGIES OF THE NSSG

A. *Business As Usual Topology*

The Business as Usual Topology is typified by point-to-point (P2P) connection of offshore wind farms (OWF) to national shores with international shore-to-shore subsea interconnectors. With 2020 as the base year, installed North Sea offshore wind capacity (including Skagerrak and Kattegat) is 33.5 GW. There are eleven shore-to-shore subsea interconnectors expected by 2020, of which, all but two are based on CSC-HVDC technology. The VSC-based COBRA interconnector offers unique capabilities and will exploit the use of a single cable for both interconnection of countries and integration of renewable sources. The total cross-border exchange capacity is calculated to be 8.6 GW as in Table IV.

TABLE IV
INTERCONNECTORS FOR THE BUSINESS AS USUAL TOPOLOGY

Country	Project Name	Date	Capa-city (MW)	Voltage (kV)	Length (km)	Tech-nology
[21] NO-DK	Skagerrak 1-2	1976 1977	500	250	230	CSC
	Skagerrak3	1993	440	350	230	CSC
	Skagerrak4	2014	700	500	230	VSC
NO-NL	NorNed 1	2009	700	450	580	CSC
	NorNed 2	-	700	450	580	CSC
GB-NL	BritNed 1	2011	1000	450	250	CSC
DK-NL	COBRA	2016	700	320	350	VSC
GB-BE	NEMO	2017	1000	250	135	CSC
NO-GB	NSN	2018	1400	500	800	CSC
NO-DE	NordLink	2018	1400	500	600	CSC
Total			8600			

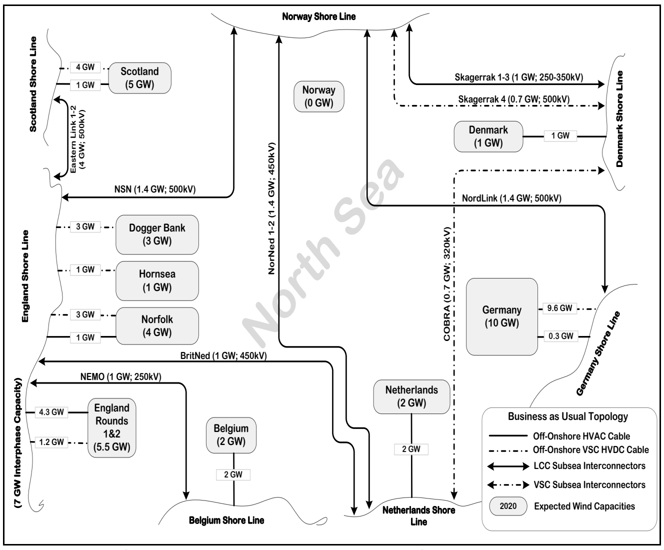

Fig. 8. Simplified Business as Usual Topology of the NSSG by 2020

Fig. 8 is the simplified Business as Usual Topology of the NSSG, illustrating existing and planned subsea export cables and interconnectors to 2020. Information available from various countries revealed offshore-to-shore export cables will be implemented using both HVAC and VSC-HVDC technologies.

B. *Local Coordination Topology*

By 2030, the installed offshore wind capacity in the North Sea will be 83.5 GW. The Local Coordination Topology will be typified by continuation of point-to-point offshore-to-shore connections with additional shore-to-shore cross-border subsea cables. The offshore-to-shore cables have total capacity of 83.5 GW. Relative to year 2020, there are seven extra shore-to-shore subsea cables anticipated by 2030. The power transfer capacity of each cross-border cable was estimated based on: planning information available from TSOs, futuristic technology and Frequency Control Reserve (FCR) of the interconnected countries.

It was assumed that all additional interconnectors are CSC-based with the exception of Skagerrak N, owing to the learning experience that the VSC-based Skagerrak 4 project under construction would have provided. In Demark, the proximity of OWF locations to shore (i.e. less than 50km) allows for continuation of offshore-to-onshore transmission via HVAC export cables. Hence, in Table V the extra cross-border exchange capacity was estimated to 10.6 GW.

TABLE V
INTERCONNECTORS FOR THE LOCAL COORDINATION TOPOLOGY

Country	Project Name	Capacity (MW)	Voltage (kV)	Length (km)	Tech-nology
NO-GB	NorthConnect	1400	500	800	CSC
NO-DE	NorGer	1400	450	600	CSC
DK-DE	-	≤1400	320	-	CSC
GB-BE	-	≤1800	≥250	135	CSC
NO-BE	-	≤1400	≥500	-	CSC
NO-DK	*Skagerrak N	≤1400	≥500	230	VSC
GB-DE	*BritGer	≤1800	≥500	-	CSC
Total		10600			

*project names are imaginary;

Fig. 9 is the simplified Local Coordination Topology of the NSSG by 2030. In general, where information was unavailable, it was assumed that power generated offshore was aggregated using 500 MW HVAC platforms for onward transmission to shore via two three-core HVAC export cables.

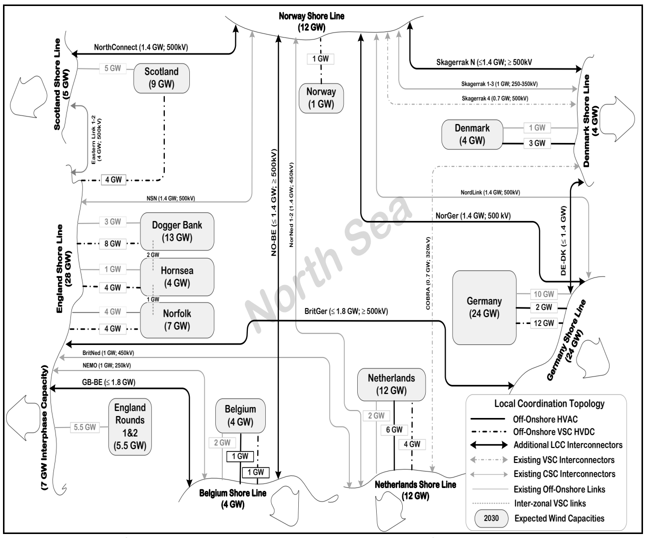

Fig. 9. Simplified Local Coordination Topology of the NSSG by 2030

C. *Fully Integrated Topology*

The Fully Integrated Topology has same offshore wind and interconnector capacities as the Local Coordination Topology. The total offshore power generated is 83.5 GW and the additional cross-border cable capacity is 10.6 GW as in Table VI. Fig. 10 is the simplified Fully Integrated Topology of the NSSG by 2030.

TABLE VI
INTERCONNECTORS FOR THE FULLY INTEGRATED TOPOLOGY

Country	Capacity (MW)	Voltage (kV)	*Length (km)	Parallel Bipole Circuit	Technology
GB-BE	≥400	320	100	1	VSC
GB-DE	1800	320	300	2	VSC
GB-NO	≥400	320	500	1	VSC
DE-NO	1800	320	400	2	VSC
DE-DK	1400	320	200	1	VSC
DK-NO	1400	320	200	2	VSC
NO-BE	1400	≥500	-	2	VSC
BE-NL	667	400	70	-	HVAC
NL-GB	667	400	70	-	HVAC
NL-DE	667	400	70	-	HVAC
Total	10600				

*cable lengths have been estimated

V. DETERMINATION OF ASSET VOLUME FOR THE NSSG

The asset volume is defined as the number of transmission equipment that is required to realise the NSSG proposed topologies. The HVAC and HVDC assets under consideration were calculated using published data from TSOs and offshore wind databases[17–19], [22–24]. The result obtained for the HVAC asset volume is presented in Fig. 11. It was evident from Fig. 11 that by 2030, the Fully Integrated Topology will achieve about 9% savings on overall HVAC asset compared to the Local Coordination Topology.

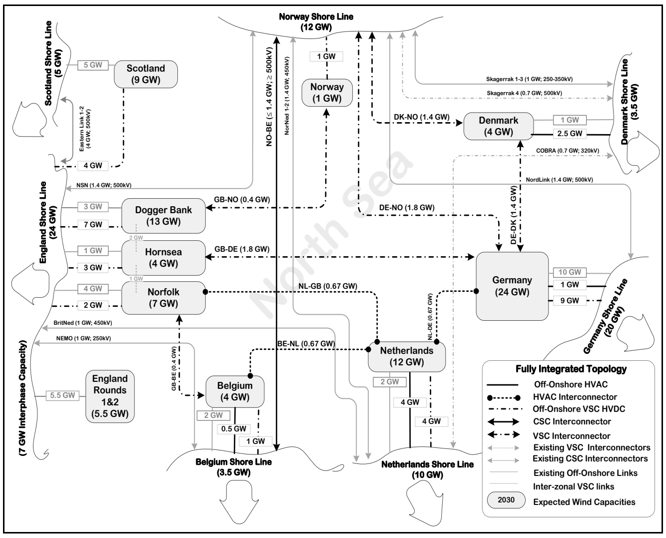

Fig. 10. Simplified Fully Integrated Topology of the NSSG by 2030

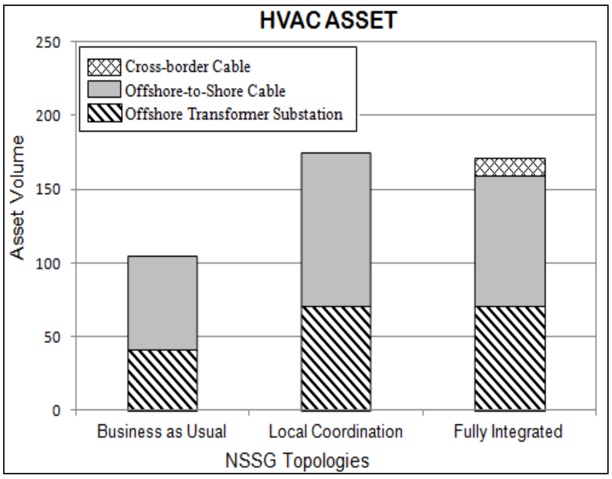

Fig. 11. HVAC asset volume for the NSSG Topologies

In Fig. 12, the result of the HVDC asset volume is presented. Notably, by 2030, the Fully Integrated Topology will achieve approximate savings of 14% on the number of onshore converter station and 7% on overall HVDC asset volume than the Local Coordination Topology.

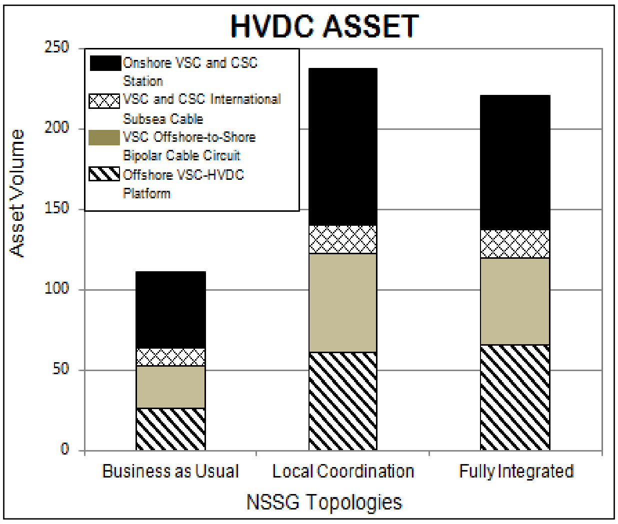

Fig. 12. HVDC asset volume for the NSSG Topologies

VI. CONCLUSIONS

The realisation of the EU's targets for renewable energy has become a topical subject. This study has examined the three main topological ideas of the North Sea Super Grid (NSSG) proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E). Building upon this, the authors have reviewed the state-of-the-art HVAC and HVDC offshore transmission technology status. Furthermore, the national offshore network development strategies of the six countries surrounding the North Sea have been summarised. Therefore, the proposed topologies of the NSSG were simplified, analysed and compared. The required HVAC and HVDC assets were calculated for all three topologies. It was evident from calculations that by 2030, the Fully Integrated Topology will achieve approximately 8% asset savings than the Local Coordination Topology.

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