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Comparative Assessment of Topologies for an Offshore Transnational Grid in the North Sea

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***Abstract*—In this paper, three topologies of transmission grids in the North Sea with different feasible structures for scenario 2030 are defined. Each of these topologies is optimized towards the objective of minimum total cost (i.e. the sum of investment and operational costs, including the costs of fuel, CO2 emission and load shedding, throughout the lifetime). The topologies are compared through a cost benefit analysis within the scope of six countries surrounding the North Sea. Sensitivity analysis is performed to investigate the implications of each topology against a wide range of uncertainties. As a result, the optimized North Sea Infrastructure in a hub-and-spoke structure with the North Sea Wind Power Hub located at the Dogger Bank leads to the lowest total cost among all compared topologies.**

***Index Terms*-- cost benefit analysis, HVDC transmission, power system planning, sensitivity analysis**

I. INTRODUCTION

This paper considers the possible implementation of a North Sea Infrastructure (NSI), of which the core is the North Sea Wind Power Hub (NSWPH) located at Dogger Bank. The surrounding wind farms, far out at sea where wind speed is relatively high, are connected to the hub using inexpensive AC connections, as these can be considered as “near shore” to the hub. High-Voltage Direct Current (HVDC) interconnectors are built from NSWPH to the surrounding countries: the Netherlands (NL), Germany (DE), Denmark (DK), Norway (NO), Great Britain (GB) and Belgium (BE). According to TenneT, the “wind-connector” (as the design combines the wind farms with HVDC interconnectors) design is expected to enable higher system efficiency, while the hub-and-spoke concept is expected to facilitate optimal energy transmission and further European market integration [1]. The location is chosen at Dogger Bank because of several advantages: shallow water (which contributes to cost reduction), high wind speed far out at sea, and central location which is important for a European-coordinated roll-out.

Cost benefit assessment of possible topologies has been performed before in [2]-[5]. However, a comprehensive comparative analysis is needed to properly and simultaneously consider different aspects like optimization (e.g. following a cost-related objective) of different topology structures within the scope of the six surrounding countries, and sensitivity analysis regarding uncertainties (e.g. meteorological conditions, load, or industry development).

In this paper, three topologies are considered (i.e. hub-and-spoke, point-to-point and meshed without a central hub) and optimized towards the objective of minimum total cost (i.e. the sum of investment and operational costs throughout the lifetime). A cost benefit analysis is performed to compare the topologies, while a sensitivity analysis investigates the effects of a range of uncertainties. Within this paper, NSI only refers to the specific design of “wind-connector” structure with NSWPH at Dogger Bank. Other topologies are not indicated with NSI. Besides, “six countries” refers to the six countries surrounding the North Sea, i.e. BE, DE, DK, GB, NL and NO.

The remainder of this paper is organized as follows. In section II, the baseline model and initial designs are presented. The methodology of topology optimization is then discussed in section III. Section IV describes the cost-benefit analysis as performed in this study. Some other results are discussed in section V. General conclusions are presented in section VI.

II. BASELINE MODEL AND INITIAL DESIGNS

A. Baseline Model

Before designing topologies of the HVDC grid, it is necessary to create a baseline model of the European power system for scenario 2030. The baseline model is used as: i) background/environment for further design of HVDC grids in the North Sea; and ii) a reference to quantify performance (e.g. total cost) of the designed topologies. The model is built in PowerGAMA (Power Grid And Market Analysis) [6], [7].

1) Data Sources

The grid topology of the European power system is comprised of three separate models: the continental European network [8], the GB 29-bus network [9], and the Nordic 44-bus network [10]. For the continental Europe and GB parts, the sources also provide information about the geological distribution of generation capacity per type of technology.

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This is scaled to the value of the year 2030 according to the Ten Year Network Development Plan (TYNDP) 2016 by ENTSO-E [11], considering 4 Visions.

For the Nordic power system, geological distribution of generation per type is taken from [10] and [12]. The percentage of hydro power with reservoir and run-of-river is taken from [13], and reservoir energy capacity (in MWh) from [14]. The generation capacities are also scaled to scenario 2030 according to [11]. Geological distribution of consumers is based on [8]-[10], and scaled to scenario 2030 as well [11].

2) *Assumptions*

The values for cross border power transmission capacity are taken from [11]. It is assumed that the cross-border transmission capacities are the same in both directions.

When considering the year 2030, compared to the topology from the original data sources, HVDC links (to be) commissioned from 2009 to 2022 are added based on [11] and [15]. Between GB and NO, both the North Sea Link and NorthConnect are considered, for the advantages of Nordic reservoirs in helping integrating wind power. Between GB and DK, Viking Link is not considered due to its overlapping with the NSI design. Instead, Viking Link is considered as part of another candidate design, which is elaborated in section IV.B.

Because of prediction difficulty, the development of energy storage systems (e.g. batteries) from scenario 2014 to scenario 2030 is neglected.

3) *Operation Simulation of Baseline Model*

The initial baseline model, built by integrating the three models (i.e. continental Europe model, GB model and Nordic model), has a size of more than 1500 nodes. For the sake of reducing computational effort, aggregation is used in the continental Europe model, except for the models of the countries surrounding the North Sea. After aggregation, the baseline model is reduced to 387 nodes. The model still remains at high resolution for the six countries surrounding the North Sea, and its simulation efficiency is significantly increased. The baseline topology is shown in Fig. 1.

Within this paper, when calculating the operational expenditure (OPEX) of the 6 countries throughout the lifetime, this is done by simulating the whole year 2030 and, taking this as a representative year, multiplying the one-year OPEX by the annuity factor, see (1) and (2).

$$OPEX_{lifetime} = OPEX_{2030} \times annuity\ factor \tag{1}$$

$$annuity\ factor = \sum_{n=1}^{lifetime} \frac{1}{(1+r)^n} \tag{2}$$

where n is the number of years from the year 2030 and r is the annual interest rate. Within this paper, the lifetime of the equipment is assumed to be 30 years and the annual interest is 5%. The annuity factor therefore is 15.37245. The 30-year OPEX of the six countries is shown in Table I.

TABLE I. OPEX OF SIX COUNTRIES IN BASELINE MODEL FOR 4 VISIONS

Visions	**Vision 1**	**Vision 2**	**Vision 3**	**Vision 4**
NSI	17.3	14.4	16.1	18.2

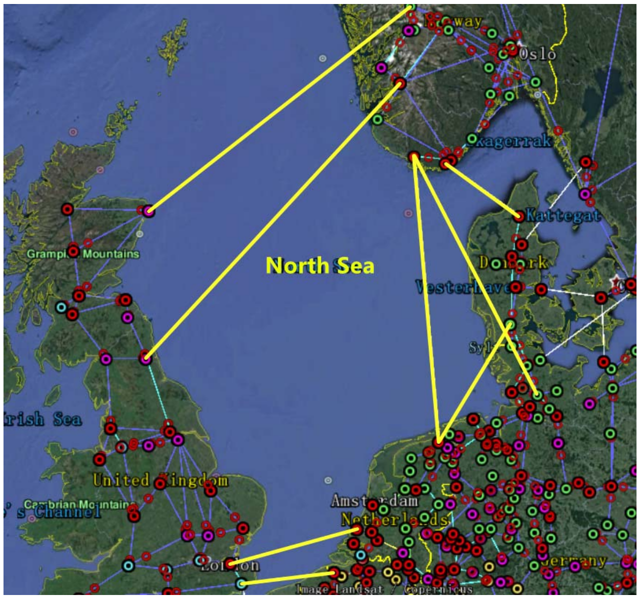


Figure 1. Baseline model for European power system 2030 (based on [16]).

B. *Initial Designs of Offshore Transmission Network*

The baseline model provides the starting point for the offshore transmission network designs. The initial designs of three topologies are defined in this subsection. The NSI in hub-and-spoke structure is based on [1]. The point-to-point topology is comprised of only direct DC interconnections, like Viking Link [15]. Inspired by [17], a meshed topology without central hub is defined. According to the development timeline in [1], it is assumed that 15000 MW wind capacity around NSWPH at Dogger Bank is connected, while the same total wind capacity is removed from the nodes in the surrounding countries. This keeps the total wind capacity in the different topologies constant. The locations of wind farms in the point-to-point topology are the same as in the baseline. For the meshed topology, the 15000 MW wind capacity is connected to five new nodes, as shown in Table II. The installed capacity of 15000 MW is constant for all 4 Visions.

Based on the budget described in [1], the budget for an HVDC transmission network to be installed in the North Sea is assumed 30 billion Euros. The wind power inflow factor at Dogger Bank is assumed 1.3 times the inflow factor of other offshore wind farms, based on the wind atlas of annual average wind speed [18], [19], and wind power output models (i.e. quadratic model [20], and cubic model [21]).

TABLE II. DISTRIBUTION OF WIND FARMS IN THE MESHED TOPOLOGY

Country	GB	NL	DE	NO	NO
Name	Dogger Bank	IJmuiden	Gaia	Ægir	Idunn
Node	N1	N2	N3	N4	N5
Longitude (°)	1.66	4.2	6.08	5.12	3.5
Latitude (°)	54.5	52.5	54.68	56.75	56.5
Capacity (MW)	7568	1137	4230	149	179

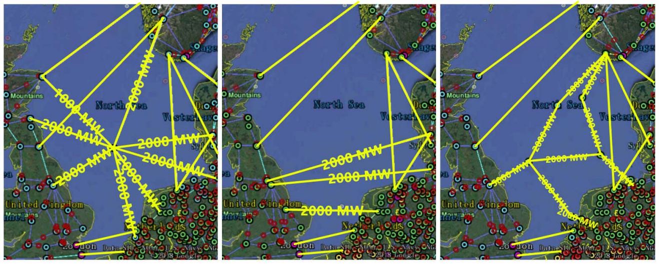


Figure 2. Initial design of NSI *(left)*, point-to-point *(middle)* and meshed topology *(right)* (map based on [16]).

The initial designs of NSI, the point-to-point and the meshed topology are shown in Fig. 2, with capital expenditure (CAPEX) of €14B, €11B and €14B, respectively.

III. METHOLOGY OF TOPOLOGY OPTIMIZATION

The optimization procedure is presented in Fig. 3. Both PowerGAMA and PowerGIM (the usage of which can be found in [22]) are used for the optimization. PowerGIM, in this step, is mainly used for giving investment advice and calculating the CAPEX of the system. Mixed-Integer Linear Programming (MILP) in PowerGIM is of high computational complexity. In order to obtain useful results within acceptable time duration, an aggregated model is needed. Aggregation is performed regarding both grid topology and time profiles.

In the aggregated model, the onshore nodes of each country are merged into one or a few representative nodes. In addition, the corresponding intra-area onshore AC branches, which are generally of infinite capacity in the full-size model, are neglected. At last, only six countries surrounding the North Sea are kept in this model. The cross-border AC branches and the HVDC branches (between the six countries) are kept as before aggregation. Only connections with a utilization rate larger than 50% are considered, as the risk of stranded assets is a potential risk in the development of offshore grids [23].

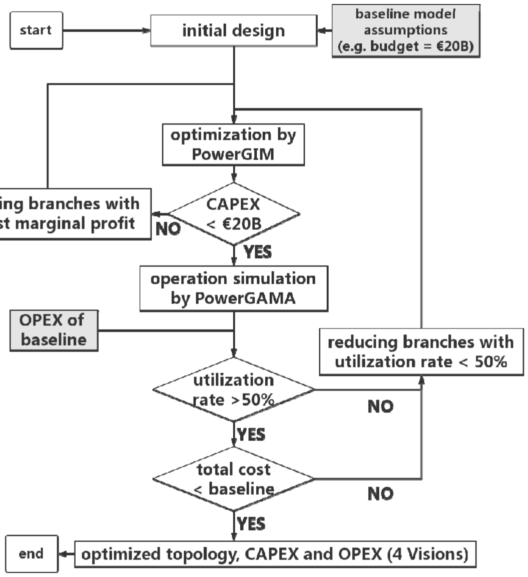


Figure 3. Topology optimization procedure.

As for the aggregation of time profiles (for the generation output and load of each hour), 1200 out of 8760 hours are randomly sampled. The aggregation of time profiles leads to severe deviations up to ± €20B, as large as the budget of the HVDC branches in the North Sea. Therefore, the OPEX results from PowerGAMA, rather than PowerGIM, are used in the final topology comparisons. Nevertheless, although the deviations in OPEX results between different simulations are large, PowerGIM provides consistent (and useful, as tested in Section V) investment advice.

IV. COST-BENEFIT ANALYSIS OF ALL TOPOLOGIES

A. Results of Topology Optimization

Following the procedure of optimization by PowerGIM and PowerGAMA, the optimized NSI, point-to-point topology and meshed topology are developed (see Fig. 4), with a CAPEX of €20B, the same as the budget. The baseline model is used as starting point for the designs and to quantify the absolute value of the economic benefit of each topology.

The cost-benefit comparison of the three topologies is shown in Table III. It is clear that the proposed NSI design with NSWPH outperforms the two other optimized topologies. However, the investment costs of the nonelectric parts of the power hub, e.g. earthwork, is ignored in the calculation. It is recognized that the smallest difference between NSI and other

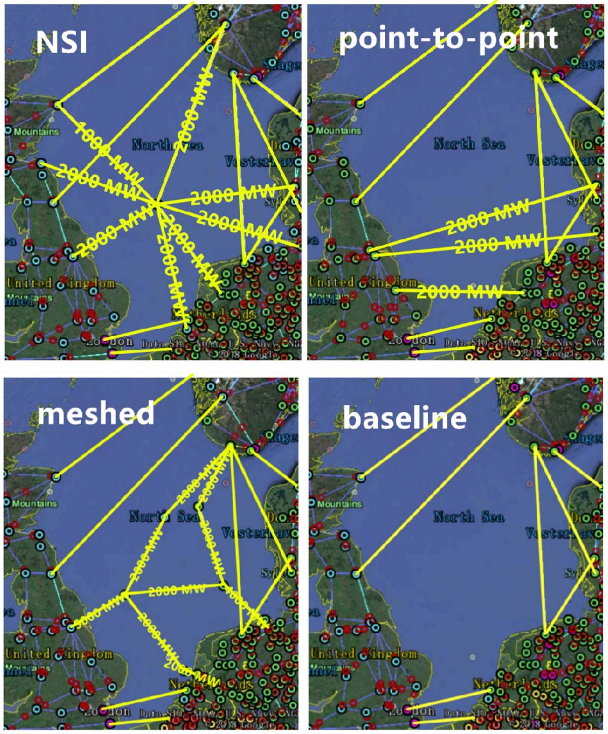


Figure 4. Optimized topologies and baseline (map based on [16]).

TABLE III. TOTAL COST (BLN EUROS) OF TOPOLOGIES AND VISIONS

Total cost	NSI	Point-to-point	Meshed	Baseline
Vision 1	578	598	594	593
Vision 2	429	447	442	448
Vision 3	597	624	612	628
Vision 4	731	755	746	760

topologies (for Vision 2, between NSI and meshed topology), €442B - €429B = €13B, is the maximum investment cost for the nonelectric constructions of the NSWPH without influencing the topology preference. The approximate investment cost of needed nonelectric construction is €1.5B [1] to €4.5B, which is only about 11.5% to 35% of the acceptable difference. Therefore, it can be concluded that the proposed NSI design provides the best cost benefit performance among all developed topologies.

B. *Results of the Sensitivity Analysis of Uncertainties*

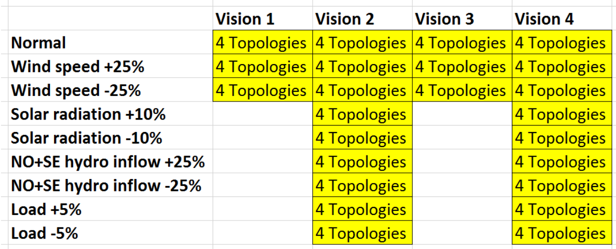
Whether the preference of NSI remains when the system is operating under a wide range of uncertainties w.r.t. RES (Renewable Energy Sources) inflow and load conditions, is tested in this subsection. The performed sensitivity analyses are listed in Table IV, where each yellow cell represents a simulation for all four topologies (i.e. the three HVDC grid designs plus the baseline).

As extreme (in annual mean value) wind conditions are important for the design of the North Sea HVDC grid, all 4 Visions of all 4 topologies are simulated. For other weather conditions, only Vision 2 and 4 are simulated as examples. Vision 2 is of special interest because it is where the lowest total cost difference appears (between NSI and meshed) and it is regarded as most likely to happen, while Vision 4 is chosen because of the highest proportion of RES in the energy mix, which makes it likely to be sensitive to RES inflow changes.

The considered extreme conditions include:

- Wind power inflow: according to [24], [25], within this century in Europe, the multi-year annual mean wind speed could be under the change of ±25%. The changes in wind speed can be converted to changes in wind power inflow by using the aforementioned quadratic or cubic model. The results are shown in Table V.
- Solar power inflow: basically, PV cells' power output is proportional to the solar irradiance (W/m2), and is negatively and linearly correlated to temperature [26]. According to [27], in Europe, the maximum annual mean solar irradiance deviation during 1939-2012 is ±10% from the 1971-2012 average. While influence of temperature change is neglected, the deviations of solar irradiance lead to ±10% of solar power inflow.

TABLE IV. SIMULATIONS PERFORMED FOR CRITICAL SCENARIOS



	Vision 1	Vision 2	Vision 3	Vision 4
Normal	4 Topologies	4 Topologies	4 Topologies	4 Topologies
Wind speed +25%	4 Topologies	4 Topologies	4 Topologies	4 Topologies
Wind speed -25%	4 Topologies	4 Topologies	4 Topologies	4 Topologies
Solar radiation +10%		4 Topologies		4 Topologies
Solar radiation -10%		4 Topologies		4 Topologies
NO+SE hydro inflow +25%		4 Topologies		4 Topologies
NO+SE hydro inflow -25%		4 Topologies		4 Topologies
Load +5%		4 Topologies		4 Topologies
Load -5%		4 Topologies		4 Topologies

TABLE V. WIND POWER INFLOW UNDER EXTREME WIND CONDITIONS

Change in wind speed	-25%	+25%
Change in wind power inflow	-59.514%	+92.308%

- Hydro power inflow: according to [28], from 1950 to 2002, the extreme deviation of annual hydro inflow of Norwegian and Swedish hydro power stations is ±25%. Only deviations of NO and SE power inflow are considered in the simulations in this study since the capacity of Norwegian and Swedish hydro power is 3 times the sum of hydro power of the other countries surrounding the North Sea.
- Load condition: the annual load of Europe from 1990 experienced a process of increasing and has been slightly fluctuating since 2008 [29]. In this paper, besides considering the load difference given by 4 Visions, a deviation of ±5% is considered according to the extreme deviation in [29] from 2008.

Within a year, the correlation among different parameters is inherently presented in the time profiles. However, when considering multi-year trends, no aforementioned parameters are considered correlated within this paper. There are mainly three reasons: i) weak correlation, e.g. correlation between wind and solar power inflow [30]; ii) minor influence, e.g. the multi-year temperature change in PV output [31], [32]; and iii) unclear influence, e.g. influence of temperature change in hydro inflow [33], [34]. Extreme deviations in wind, solar and load conditions are considered the same for all countries in the model, while for extreme conditions in hydro power, only changes in the Norwegian and Swedish area are considered. The result of the sensitivity analysis w.r.t. ±25% annual mean wind speed is shown in Fig. 5.

Variable RES generation (wind, solar and hydro) is of much lower fuel cost (0.5 €/MWh) compared to conventional generation (e.g. fuel cost of gas turbines is 83.3 €/MWh). Also, no CO2 emission is considered for RES generation. This leads to the situation that generally, the higher the RES penetration in the power system, the lower the system OPEX.

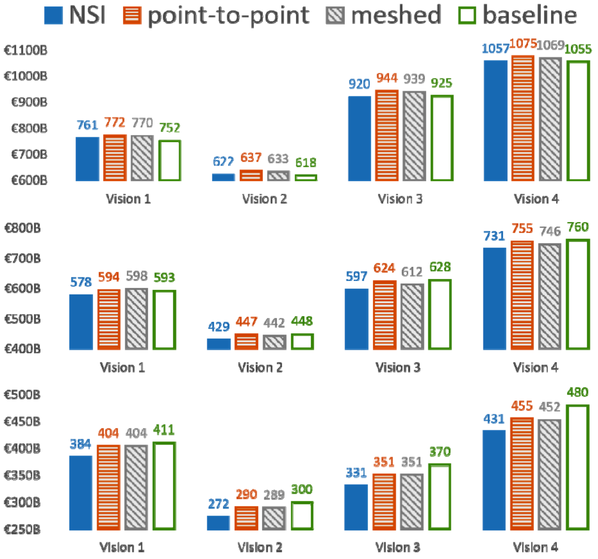


Figure 5. Total cost (billions of Euro) under -25% *(upper)*, normal *(middle)* and +25% *(lower)* annual mean wind speed condition

Under the condition of wind speed -25%, the wind power inflow drops almost 60%. Although the three proposed HVDC topologies lead to lower OPEX for the 6 countries compared to the baseline, their influence in helping integrate variable RES becomes so weak that when CAPEX is added, they cannot be paid back within a lifetime of 30 years (except for NSI in Vision 3). Nevertheless, NSI still brings lower overall cost in all Visions compared to the two competitors (point-to-point and meshed). Under the condition of wind speed +25%, the system with proposed HVDC topologies presented great benefit compared to the baseline. NSI ranks first for all Visions, followed by the meshed topology; their performances not only due to the optimized HVDC topology, but also to the higher wind speed at Dogger Bank (where there is a node for both NSI and meshed topology). In all other performed sensitivity analyses (i.e. extreme solar, hydro and load), NSI stays the most economically preferable topology. The investment of NSI can be paid back in all performed scenarios (except the aforementioned mean wind speed -25% situation).

V. OTHER RESULTS OF THE SIMULATIONS

A. *Other Advantages of the North Sea Infrastructure*

Besides the advantage in cost-benefit, it can be proved that the optimized NSI design can realize the expected functions:

- Transmission of renewable energy: Table VI shows that, compared to the baseline, when NSI is installed, the 15000 MW wind capacity can generate more energy, while the 6 countries surrounding the North Sea suffer from less renewable energy spillage. Providing more generation and less waste, NSI's ability to transmit renewable energy is verified.
- Price convergence: comparing NSI with the baseline, NSI presents satisfactory price convergence performance (see Fig. 6). There are two main features: convergent prices (for NSI, the differences of prices between different countries become smaller) and lower overall price (on the whole of all 6 surrounding countries, the price becomes lower, from €62.798 in the baseline situation to €62.492 with NSI).

TABLE VI. ANNUAL GENERATION OF 15000 MW WIND CAPACITY AND ANNUAL RENEWABLE ENERGY SPILLAGE OF 6 COUNTRIES

Generation (TWh)	**Vision 1**	**Vision 2**	**Vision 3**	**Vision 4**
NSI	65	56	59	57
Baseline	50	47	46	45
Spillage (TWh)	**Vision 1**	**Vision 2**	**Vision 3**	**Vision 4**
NSI	15	31	46	49
Baseline	19	39	55	58

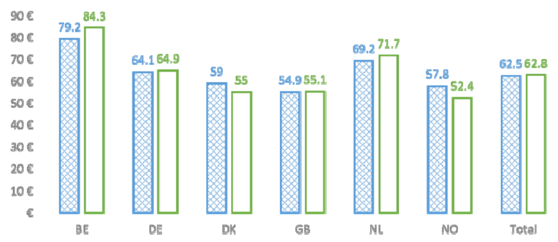


Figure 6. Comparison of annual average nodal price by area between NSI and baseline (Vision 2).

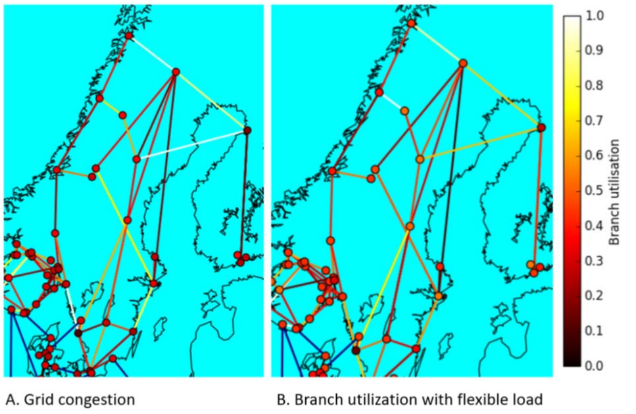
TABLE VII. EENS (TWH) OF SIX COUNTRIES THROUGHOUT THE LIFETIME

Visions	**Vision 1**	**Vision 2**	**Vision 3**	**Vision 4**
NSI	17.3	14.4	16.1	18.2
Baseline	39.0	29.6	29.4	28.2

- Enhancement of security of supply: calculating the EENS (Expected Energy Not Supplied) of 30 years, for NSI and the baseline case, the comparison is as shown in Table VII. Although the absolute value of EENS in TWh might not be reliable (due to aggregation and approximation), the relative comparison between NSI and the baseline design clearly shows that NSI strongly improves the system's security of supply.

B. *Challenges brought by the North Sea Infrastructure*

- Grid congestion: congestion is often encountered when large-scale variable RES is integrated into the system (see Fig. 7A). Grid reinforcement and demand-side response are regarded as possible solutions of grid congestion. As shown in Fig. 7B, when implementing flexible load (in this paper, 10% demand is flexible and 20% of the total time flexible demand can be used) in the Nordic power system, grid congestion is relieved.
- Benefit asymmetry: from Fig. 6, when installing NSI, although the overall nodal price is lower, for specific countries, such as DK and NO, the nodal price becomes higher. Table VIII clearly shows the direction and value of annual average power flow in all NSI HVDC branches. It can be seen that the flow from NO to the Dogger Bank (DB) is higher than the flow in the opposite direction. The solutions for this asymmetry, for instance a scientific side payment mechanism, need to be developed to better incentivize the investment from all the surrounding countries, as the free-rider problem is indicated as one of the challenges in the development of international offshore grids [23].



A. Grid congestion

B. Branch utilization with flexible load

Figure 7. Branch utilization (pu) before and after application of flexible load.

TABLE VIII. Annual Average Power Flow in all HVDC Branches of NSI (MW) from Doggerbank (DB)

From	To	Capacity (MW)	Positive (MW)	Negative (MW)	Total (MW)
DB	NL	3000	2400	254	2654
DB	DE	3000	1585	1071	2656
DB	DK	1000	573	363	936
DB	NO	4000	1608	1645	3252
DB	GB-16	3000	2061	661	2722
DB	GB-7	2000	1037	760	1796
DB	BE	2000	1972	3.5	1976
DB	GB-2	1000	348	491	839

VI. CONCLUSIONS

In this paper, three topologies were defined, namely hub-and-spoke North Sea Infrastructure (NSI), point-to-point and meshed. Each topology was optimized using PowerGAMA and PowerGIM software, following the objective of minimizing total cost, i.e. CAPEX + OPEX (for 30 years from 2030, for 6 countries). NSI, compared to the competitors, is the most economically preferable topology (i.e. leading to the lowest total cost for the six countries involved) when simulated under a wide range of uncertainties (e.g. selected critical scenarios reflecting differences in RES inflow condition, load condition, industry progress and international cooperation). Advantages of NSI, besides the lowest total cost, are the transmission of renewable energy, price convergence and enhancement of security of supply. On the other hand, it brings challenges like grid congestion and benefit asymmetry. It is recommended that in future research, the development of power system flexibility (e.g. ancillary services market), compliance with future expansion when designing NSI, and solutions for benefit asymmetry are considered.

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