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Integrated offshore transmission
综合海洋传输

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Abstract - **Electricity generated from offshore renewable energy sources is expected to make an important contribution towards the UK achieving its renewable energy targets by 2020. The government's Renewable Energy Roadmap (2011) suggests that there could be 11 to 18 GW of offshore wind capacity by 2020. There is also substantial scope for further growth beyond this, with the Crown Estate Round 3 zones representing up to 32GW of additional offshore generation. Achieving such levels will require a timely, cost-effective and secure offshore electricity transmission network to transfer electricity generated offshore to the onshore network.**

Up until now, offshore transmission assets have been developed as single, standalone connections to shore ("radial" connections). However, the Round 3 offshore wind projects are larger, more complex and at a greater distance from the shore than those that have been developed to date, and as a result there could be greater potential for network efficiencies through offshore asset integration. This could include integration between connections and coordination between the strategic development of the onshore and offshore networks through offshore reinforcement projects.

This paper will present the benefits of integrated and coordinated offshore designs to help improve boundary capability while incorporating flexibility into the existing transmission network, and providing offshore options to avoid potential delays usually associated with onshore reinforcements. This aims to achieve efficient reinforcement of the wider and local system boundaries for timely connection of offshore projects, helping to meet the government renewable targets while presenting the most economic and efficient outcome for UK consumers. The proposed methodology for optimal offshore integrated design will be applied to offshore connections of Round 3 on the East Coast in Great Britain.

Keywords – **National Electricity Transmission (NETS) System Security and Quality of Supply Standards (SQSS), Local System Boundaries, Wider System Boundaries, Integrated Offshore Design, Required Transfer (RT), Boundary Capability (BC)**

I. PLANNING OF TRANSMISSION SYSTEM FOR OFFSHORE WIND GENERATION

The government has set an ambitious target for the deployment of renewable energy over this decade culminating with 15 % of the UK's total energy needs being met from renewable sources by 2020. This means that around 30 % of electricity in Great Britain (GB) may come from renewables. To achieve this substantial deployment of green energy the government has established a policy framework to support investment in renewable generation. Within this framework, offshore wind is recognised as being an important source of renewable energy with financial incentives to encourage further investment. In particular three very large offshore wind power plants are planned for connection on the East Coast of GB namely Dogger Bank, Hornsea and East Anglia.

Connection of these offshore wind power plants will have a significant impact on the development of the transmission network. For the power generated to reach homes and businesses in Great Britain the existing electricity networks must be developed to reflect the change in generation location. A step change in network investment of this kind calls for a more dynamic approach to the development of transmission networks: an open, competitive approach that is built on encouraging innovation and new sources of technical expertise and finance.

National Grid has a statutory duty under the Electricity Act 1989 to develop and maintain an efficient, co-ordinated and economical system of electricity transmission. NGET also has a duty to facilitate competition in the supply and generation of electricity and must offer a connection to any proposed generator. The National Electricity Transmission System (NETS) is designed in accordance with the requirements of the Security and Quality of Supply Standard (SQSS). The standard sets out the minimum requirements for both planning and operating the NETS so that a satisfactory level of reliability and power quality is maintained. Thus any modification to the transmission system, for example new offshore generation connections, external connections and/or changes to demand must satisfy the requirements of the NETS SQSS. The NETS SQSS is applicable to all GB transmission licensees including National Grid, Offshore Transmission Owners (OFTOs) and the Scottish Transmission Owners.

In this paper the concept of Integrated Offshore Transmission is presented to assess the benefit of coordinating onshore and offshore transmission development. Using the concept of Planned Transfer and assessing Boundary Capability, the effectiveness of integrated onshore and offshore solutions are examined for generation scenarios which reflect the potential build-up of offshore wind power plants at Dogger Bank, Hornsea and East Anglia.

The remainder of this paper is organised as follows: in section II the Methodology and General assumptions are introduced. Section III elaborates the Offshore Integrated Designs. Section IV, the last Section presents the concluding remarks.

II. Methodology and generation assumption

A. General Methodology

The concept of Required Transfer and Assessment of Boundary Capability is used to identify the need for reinforcement on the Wider System Boundaries and East Coast Local System Boundaries, following this, design options are developed to provide the required capability.

1.1 Boundary Assessment in Transmission Planning

The NETS SQSS specifies separate methodologies for local boundaries and wider boundaries analysis. The differences between both are in the level of generation and demand modelled, which in turn directly affect the level of boundary transfer to be accommodated.

Local Boundaries: The generation is assumed at its registered capacity and the local demand is assumed to be that which may reasonably be expected to arise during the course of a year of operation. Local boundaries must be able to accommodate any generation to be connected without being constrained by the local network in the year of operation.

Wider Boundaries: In the case of wider system boundaries the overall generation is selected and scaled according to the Security and Economic criteria described below and assessed against peak demand, which result is a Planned Transfer' level. For each system boundary an interconnection or boundary allowance is calculated and added to the 'Planned Transfer' level to give a 'Required Transfer' level. In this way the standard seeks to ensure that peak demand will be met, allowing for variation in both generator location and demand forecast.

1.2 Wider Boundaries: Security and Economy Criteria

The 'Planned Transfer' of a boundary, as defined by the NETS SQSS, is based on the balance of generation and demand on each side of the boundary and represents the natural flow on the Transmission system for a given demand and generation background and is determined by the geographic location of demand and generation, as well as the impedance of the interconnecting circuits. The 'Required Transfer' of a boundary is the Planned Transfer value with the addition of an interconnection or boundary allowance based on an empirical calculation defined in the SQSS.

The full interconnection allowance is applied for single circuit losses and half the allowance is applied for two circuit losses. A shortfall in Boundary Capability compared with the Required Transfer indicates a need for reinforcement of that boundary. The SQSS specifies two separate criteria upon which transmission capability should be determined. These are described below and are based on Security and Economic factors respectively.

The Security Criterion:

The object of this criterion is to ensure that demand can be supplied securely, without dependence on intermittent generators or imports from interconnectors. The generation background is set by:

Determining from a ranking order, the conventional generation required to meet

- 120% of peak demand, based on the generation capacity.
- Scaling the output of these generators uniformly to meet demand (this means a scaling factor of 83%).

This selection and scaling of surplus generation takes into account generation availability. Based on this the Planned and Required Transfer values are calculated in the usual way. This criterion determines the minimum transmission capability required, ensuring security of supply. This is then further assessed against the economic implications of a wide range of issues such as safety, reliability and the value of loss of load.

The Economic Criterion:

As increasing volumes of intermittent generation connect to the GB system, the Security Criterion will become increasingly unrepresentative of year-round operating conditions. The Economy criterion provides an initial indication of the amount of transmission capability to be built, so that the combined overall cost of transmission investment and year-round system operation is minimised. It specifies a set of deterministic criteria and background conditions from which the determined level of infrastructure investment approximates to that which would be justified from year-round cost benefit analysis.

In this approach scaling factors are applied to all classes of generation such that the generation meets peak demand. Based on this the Planned and Required Transfer values are calculated in way explained above. If a comparison with the Economy Criterion identifies additional reinforcements, a further cost benefit analysis should be performed in order to refine the timing of a given investment. In networks where there is a significant volume of renewable generation it is expected that the application of the Economy Criteria will require more transmission capacity than the Security Criteria to ensure there is sufficient transmission capacity.

B. East Coast Specific Assumptions

The North Sea has some of the largest proposed offshore generation projects, including the Dogger Bank, East Anglia

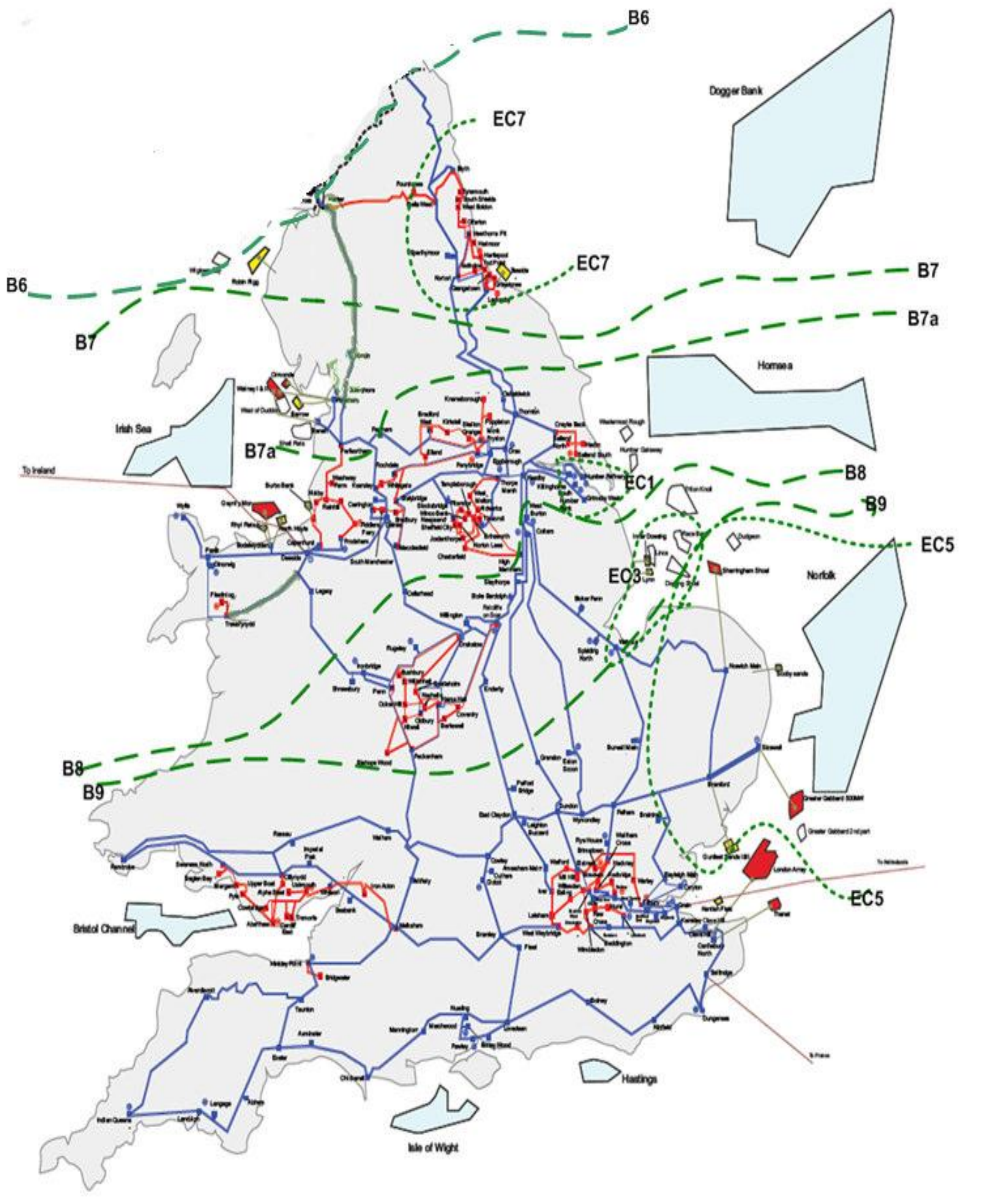

Figure 1. Illustration of Local and Wider System Boundaries

and Hornsea. To assess the impact of offshore wind power plants planned to be connected on East Coast, the following generation contracted Transmission Entry Capacity (TEC) data are taken into consideration:

- Dogger Bank 6 GW but considered up to 9GW
- Hornsea 4.8 GW
- East Anglia 7.2 GW

A sensitivity scenario is developed that takes into account both the TEC data as well as the published future energy scenarios such as the Gone Green Scenario. Overall there is the potential for over 25 GW of capacity from the East Coast and East Anglia (from the Crown Estate Round 1, 2 and 3 offshore wind farm projects). Connection of these projects to the wider transmission network involves multiple transmission connections all along the East coast from Teesside to the Thames Estuary including areas around Humberside, Lincolnshire and the Wash.

2.1 East Coast Local System Boundaries

These smaller areas of the NETS, which typically contain a large imbalance of generation and demand leading to heavy loading of the circuits crossing the boundary. As demand is not predicted to change significantly over the period, the local boundaries see significant growth generation and high boundary transfers. The local boundaries (see Figure 1) for the three large East Coast offshore wind power plants are:

• Dogger Bank connecting to local boundary EC1, EC3 and EC7
• Hornsea connecting to local boundary EC1 and EC3
• East Anglia connecting to local boundary EC5

2.2 East Coast Wider System Boundaries

Wider system boundaries are those that separate large areas of the GB transmission system containing significant quantities of demand and generation. With a predominant power flow toward the demand centre of London and the South East, connection of all three wind power plants impact directly boundaries B7, B7a and B8 and indirectly boundaries B6 and B9, presented in Figure 1. These wider system boundaries are analysed to ensure the SQSS requirements are maintained.

Each generation scenario has a corresponding boundary requirement from which the boundary reinforcement needs can be identified.

2.3 East Coast Boundaries Overview

The East Coast transmission network consists of a number of generation groups (Teesside, Humber, and East Anglia) which are connected to the main 400kV system via a strong 400kV spine from Lackenby through Creyke Beck, Keadby and Walpole to Pelham.

Teesside Group (EC7): In addition to the offshore wind, the North East could see the connection of multiple HVDC links from Scotland and an interconnector with Norway. These would result in increased power injections into this region.

The Humber group (EC1) consists of two 400kVdouble circuit lines running from Keadby towards Killingholme, with one continuing toward Grimsby on the coast. These lines gather outputs of power stations on the south side of the Humber and feed it into the main system at Keadby. From Keadby transmission circuits link the East Coast system via West Burton, Spalding North, and Bicker Fen into Walpole. There are also significant generation connections at West Burton and Keadby, adding to the power requiring throughout.

The transmission system in the East Anglia area (EC3, EC5) is characterised by a double circuit ring that links Walpole, Norwich, Bramford, Pelham and Burwell Main substations. Pelham substation provides additional interconnection between the East Anglia region and other sections of the transmission system.

C. Boundary Capabilities

For every boundary, the future capability necessary under each scenario is calculated by the application of the security standards and methodology explained above. The network at peak system demand is used to outline the minimum require transmission capability for Economy criteria. The years for consideration are 2021 and 2030.

3.1 Local System Boundaries

3.1.1 Boundary EC1

Boundary EC1 is an enclosed local boundary in the Humber group, consisting of four circuits that export power to the Keadby substation. The maximum power transfer out of this boundary is currently 5.5 GW which is limited by thermal overloads on the boundary circuit. The boundary is at its local limit and any further generation injections would require onshore reinforcement.

3.1.2 Boundary EC3

Boundary EC3 is a local boundary surrounding the Walpole substation and includes the six 400kV circuits out of Walpole. Walpole is a critical substation in supporting significant offshore generation connections and high North-South network power flows along the East Coast network. The maximum boundary transfer capability is currently limited to 3.2GW by thermal overloads on the boundary circuits. Following the Walpole re-build, Walpole will be able to accommodate up to a further 2GW before reaching its limit.

3.1.3 Boundary EC5

The local boundary EC5 covers the Eastern part of East Anglia including the substations of Norwich, Bramford and Sizewell. There is mainly generation enclosed by the boundary so that power is typically exported out of the enclosed zone, predominantly along the southern circuits. The maximum boundary transfer capability is currently limited to 3.4 GW due to thermal overload on the boundary circuits. Several onshore reinforcements are planned to facilitate the rapid build-up expected from East Anglia.

3.1.4 Boundary EC7

Boundary EC7 is a local boundary that encompasses the north east of England, predominately a 275kV ring serving local demand but crossed by one of the two of the 400kV North-South export routes from Scotland. This area is constrained by north-south power flows with the 400kV circuits at the southern end of the boundary. This boundary is already at its limit for further generation and would require onshore reinforcement to facilitate additional generation.

3.2 Wider System Boundaries

3.2.1 Boundary B7

Boundary B7 bisects England south of Teesside. It is characterised by three 400kV double circuits, two in the east and one in the west. The area between B6 and B7 is traditionally an exporting area, and constrained by the power flowing through the region from Scotland towards the South with the generation surplus from this area added. In 2021, the required transfer exceeds boundary capability by about 600MW, increasing to about 2.3GW by 2030. This represents the level reinforcement required for compliance across B7 (see Figure 2).

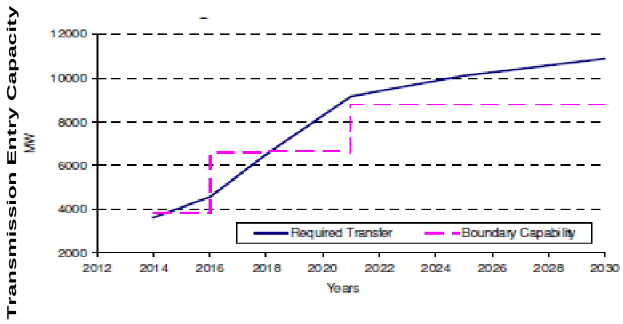

Figure 2. Reinforcement requirement B7

3.2.2 Boundary B7a

Boundary B7a runs parallel with boundary B7, sharing the same path in the east, but encompassing Heysham, Hutton and Penwortham in the west. The region between Boundary B7 and B7a includes more generation than demand, further increasing the transfers from north to south. In 2021, the shortfall in boundary capability is about 600MW, rising to over 2.5GW by 2030 (see Figure 3).

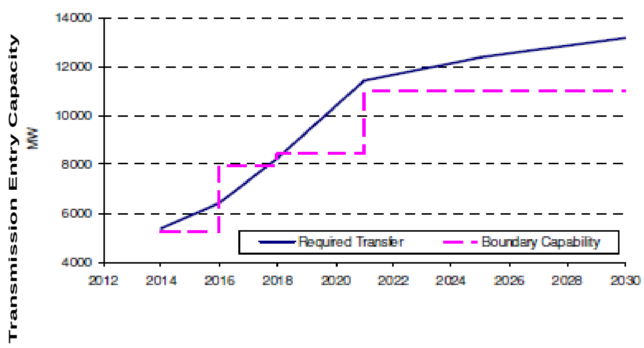

Figure 3. Reinforcement requirement B7a

3.2.3 Boundary B8

The North to Midlands boundary B8 is one of the wider boundaries that intersects the centre of Great Britain, separating the northern generation zones including Scotland, Northern England and Northern Wales from the Midlands and Southern demand centres. The east of B8 is traditionally a congested area due to the large amount of existing generation in the Humber and Aire valley regions. The current boundary capability is expected to drop between 2018 and 2021 due to changes in the generation background that reduce reactive capability. The shortfall in boundary capability in 2021 is about 3.5GW, rising to over 4.5GW by 2030 (see Figure 4).

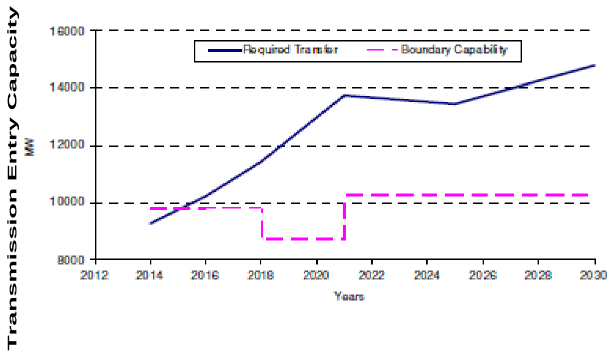

Figure 4. Reinforcement requirement B8

III. OFFSHORE INTEGRATED SOLUTIONS

From the results above it is clear that the connection of large scale offshore generation will require major network reinforcements either onshore or offshore for the wider system boundaries B7, B7a and B8. All the local system boundaries are close to their limit in capacity except Walpole area (Boundary EC3) which has spare capacity for up to 2GW before triggering further reinforcement. All these reinforcements will require extensive planning, consenting and construction programmes.

From past experience, National Grid would expect that planning and environmental issues for large scale onshore reinforcement activities would put delivery within the required timescales at significant risk. Therefore, a coordinated and integrated onshore and offshore development would lead to significant advantages to all parties.

Integrated offshore designs have been developed for two snapshot years; 2021, when the three large wind power plants may be reasonably considered as being 50% complete and 2030, when all wind farms are expected to be fully developed. The proposed designs employ a combination of:

- Offshore integration utilizes offshore AC interlinks within projects or HVDC links between offshore zones and onshore local boundaries, so as to provide boundary capability, while minimising onshore works and optimizing asset sizes based on available technology.

- Onshore reinforcements include all possible works to provide capability onshore such as line upratings, reconductoring, development of new onshore circuits and the use or installation of Quadrature Boosters.

The use of larger sized assets (e.g 2GW) has been assumed for projects connecting after 2019 so as to take advantage of anticipated advances in technology.

A. DESIGN FOR YEAR 2021

In 2021 the study results show a reinforcement requirement for B7 and B7a of about 600MW. Using the Economic Criterion, the wind scaling factor is assumed to be 70% and thus 1GW radial links to the shore will be utilised to only 700 MW. By installing AC links between the individual platforms within the Dogger Bank zone, the spare capacity on the two circuits that cross boundaries B7 and B7a (2 x 300MW) would provide the required boundary reinforcement.

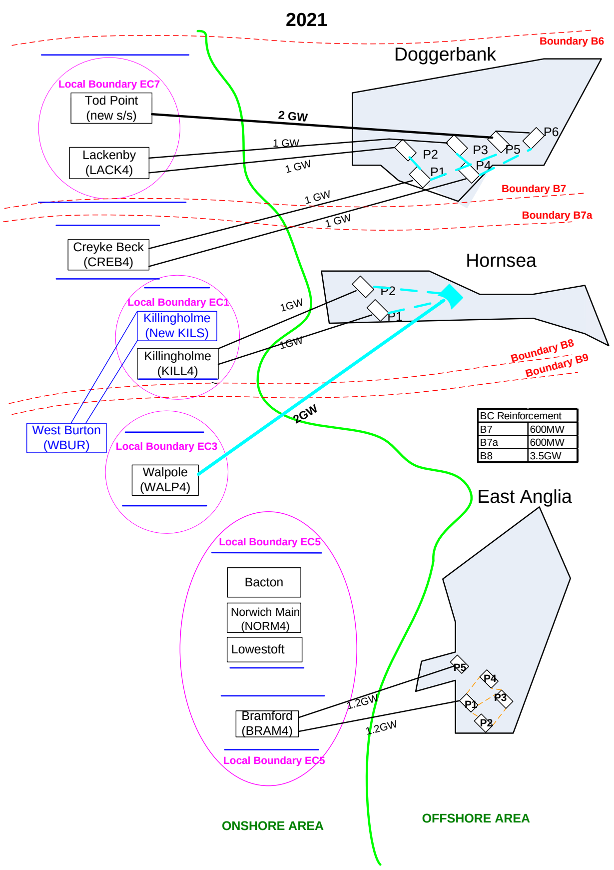

Figure 5. Offshore Integrated Design for 2021

In 2021, the reinforcement required across B8 is about 3.5GW. Offshore this could be achieved by integrating the two Hornsea platforms (P1, P2) with a new offshore platform which connects to Walpole via an HVDC link of 2GW capacity. The remaining 1.5GW capacity required across B8 can be achieved by an onshore reinforcement, Killingholme South – West Burton. The combination of onshore and offshore reinforcement minimizes offshore cables and onshore converters, avoids onshore reinforcements at Walpole and facilitates the build-up of future connections by providing onshore capability in EC1. Figure 5 shows the proposed design alternative boundary reinforcements;

- Bootstrap Option: Two HVDC bootstraps between EC1 and EC3 with total capacity up to 3.5GW. These would not only trigger onshore reinforcements in both local boundaries but would also require multiple onshore converters.
- Onshore Option: To provide 3.5GW across B8 would require the Killingholme South – West Burton Upgrade, new circuits from Drax to Creyke Beck and Keadby as well as circuit re-conductoring.
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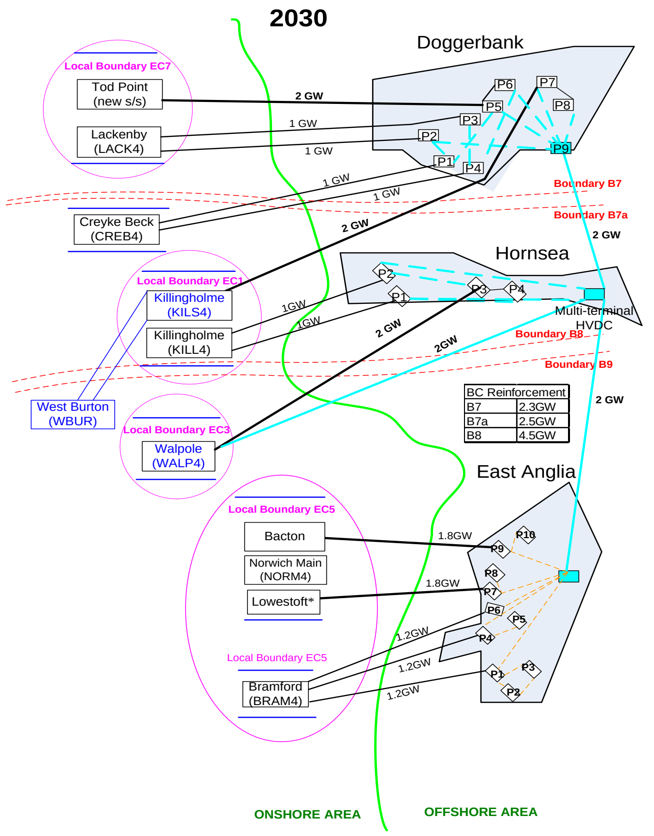

Figure 6. Offshore Integrated Design for 2030

B. DESIGN FOR YEAR 2030

By 2030 it is expected that the full capacity of Dogger Bank, Hornsea and East Anglia offshore wind farms will be connected to the system. At this time, B7 and B7a have a capacity shortfall of 2.3GW and 2.5GW respectively, while the B8 will require a reinforcement of about 4.5GW. The proposed design is presented in Figures 6.

This design provides a multi-terminal HVDC connection between Dogger Bank, Hornsea and East Anglia, and connects onshore at Walpole. Offshore integration between all platforms within the Dogger Bank zone provides 1.5GW of boundary capability across B7 and B7a using the economic criteria as discussed earlier.

The platform for project P9 is oversized to 2GW to accommodate both the 1GW project (P9) and also provide an additional 1GW of boundary capability to help provide 2.5GW capability across B7 and B7a (1.5GW plus 1 GW oversize of asset). This 2GW platform connects to a platform in Hornsea via a 2GW HVDC link. Capability is provided across B8 via offshore links towards Walpole and East Anglia.

From the multi-terminal HVDC platform, one HVDC link rated at 2GW connects to Walpole. AC links connect to this platform from the Hornsea projects to provide capability across B8 and connect Dogger Bank P9 to Walpole. Integrating P3 and P4 provides an additional 600MW capability. Also, the Killingholme South – West Burton onshore reinforcement provides some capability across Boundary B8. Using the economy criteria described earlier, spare capacity within East Anglia region can be taken advantage of by providing an HVDC platform that integrates with AC links from the East Anglia projects. This provides 2GW boundary capability by connecting a 2GW HVDC link from the multi-terminal HVDC to the platform in East Anglia. This provides a total capability of 4.5GW across B8.

This design requires onshore reinforcements at Walpole EC3 to accommodate the additional 2GW. Dogger Bank Projects 7 and 8 take advantage of the capability provided at Killingholme South.

Alternative boundary reinforcements;

- Bootstrap option: Two HVDC bootstrap links would be required as shown in Figure 7, one between EC7 and EC3 zone to provide 2.5GW across B7, B7a and B8. A second 2GW link would be required between EC1 and EC5 to bring the total capability to 4.5GW. However, significant onshore constraints of both capacity and space would limit connections to boundaries EC7, EC3 and EC1, also, technology limitations could increase the number of cables required.
- Onshore Option: To provide 2.5 GW across B7, and B7a requires a new AC Circuit from Norton-Padiham (over 100km), reconductoring Lackenby-Norton and Pewortham South circuits as well as completing the Mersey ring upgrade. To provide 4.5GW across B8 requires the Killingholme South – West Burton Upgrade, new circuits from Drax to Creyke Beck and Keadby as well as circuit re-conductoring. Also, Unified Power Flow Controllers (UPFC) would also be required at four substations to control power flows and voltage in the region.

The proposed integrated design will minimize onshore reinforcements and converter footprint onshore. It will increase the utilisation of the existing assets, by taking advantage of the spare capability within Dogger Bank, Hornsea and East Anglia zones.

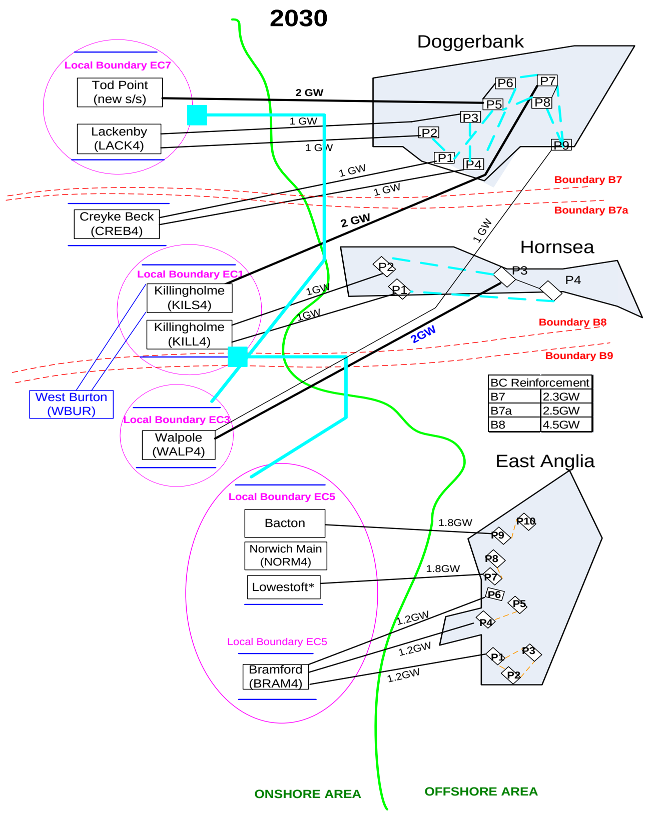

Figure 7. Coastal interconnection design for 2030

IV. Conclusion

The growth of offshore wind will raise several challenges in planning and operation of the GB transmission system. Integrating the offshore wind power plant networks and co-ordinating with onshore transmission works will decrease the environmental impact, improve the utilisation of assets and minimise wind power constraints.

The designs presented in this paper demonstrated the benefits of interconnecting offshore wind power plants to enhance wider system boundary capabilities. The connection of large offshore wind power plants at Dogger Bank, Hornsea and East Anglia both drive the need for reinforcement of system boundaries B7, B7a and B8 and offer, through offshore interconnection of their individual offshore networks, the solution.

The offshore interconnection adds North-South boundary capability to multiple boundaries from the North-East, through the Humber region and further South to East Anglia as well as relieving the local boundaries around the direct connection points onshore. During fault conditions it becomes possible to

reduce the power injection into stressed areas from the offshore wind power plants without constraining the offshore wind generation, assuming it is not operating at 100% output at this time. The benefits of onshore transmission development with interconnection of individual offshore networks demonstrate the need for inclusion of offshore interconnection into existing NETS SQSS Chapter 4. While the case for integrating onshore and offshore transmission design have been demonstrated in this paper the financial framework to incentivise commercial wind power plant developers to include these offshore interconnections in their projects has yet to be worked out.

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