Support grid integration of offshore wind power

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Abstract. China has a cumulative installed offshore wind capacity of 6.8 GW, making it the third largest in the world. Compared with Europe, which is the largest offshore wind power market, there are still gaps to substantially tapping the offshore wind potentials of China. This paper aims to investigate advanced experience of offshore wind power, and explore innovative approaches for offshore wind deployment and grid integration in China. Development and issues caused by offshore wind power in UK, Germany and Denmark have been investigated, including technological progress, curtailment, and network congestion and redispatch needs. The grid integration approaches to re-enforcement of network to accommodate offshore wind power are also analysed. Contrastive analysis is taken about stakeholders and planning process of offshore wind among UK, Germany, and Denmark. Construction suggestions are proposed for the development of offshore wind power in China during the 14th Five Year Plan period.

1. Introduction

The offshore wind resources offer a great potential for clean energy supply and tackling climate change challenges. Between 2010 and 2019, the global offshore wind market grew over nigh folds, benefitting from the rapid technology improvements and costs reduction[1, 2], and according to International Renewable Energy Agency (IRENA) projections, global offshore wind installed capacity will reach 228 GW by 2030 [3]. The major drivers include innovations in wind turbine technology, installation and logistics, economies of scale in operation and maintenance (O&M), and improved capacity factors from higher hub heights, better wind resources and larger rotor diameters. The charge for global offshore wind expansion has been led by European countries, notably UK, Germany and Denmark. China has leapfrogged in building-up its offshore wind power capacity over the last five years [4-7].

The development of offshore wind power will become an important strategic support for China's energy structure transformation. China is vigorously developing renewable energy, especially offshore wind power. As a rising star, China will become the largest offshore wind power market in the next few years. International Energy Agency (IEA) predicts that by 2040, China's offshore wind power installation will reach 175 GW, which is equivalent to the scale of the Europe, and the offshore wind power generation will account for 3%–5% of the total power generation [8, 9].
With a coastline of over 18,000 km, China has more than 1,000 GW of technical potential for offshore wind at the hub height of 90 meter which is great growth potential in offshore wind market, the economy target of 5 GW grid-connected offshore wind by 2020. By the end of 2019, China has a cumulative installed offshore wind capacity of 6.8 GW, making it the third largest in the world. Guangdong plans to build 30 GW offshore wind by 2030, followed by Jiangsu (15 GW), Zhejiang (6.5 GW) and Fujian (5 GW). Other coastal provinces namely Liaoning, Hebei, Shandong, Shanghai, Guangxi and Hainan, also have their own offshore wind development plans. Targets close to 60 GW by 2030 provides long-term visibility and scale for offshore wind power development [10, 11].

In order to draw on the advance experience of European offshore wind power, this paper choose UK, Germany and Denmark as research countries, to fully investigate its planning and operation achievements of offshore wind power, especially re-enforcement of network to accommodate offshore wind power [12].

2. Development and issues caused by offshore wind power

2.1. Technological progress

Offshore wind technology has advanced significantly across Europe over the last decade. The general technological trend has seen turbines become bigger with higher power outputs. Over the past 5 years turbines have increased from around 3 MW, up to between 7–10 MW. This progress is anticipated to continue and by 2050 offshore wind turbines are expected to be around 20–25 MW. The rise of larger turbines will also likely result in wind farms with fewer turbines, thus increasing array efficiency and leading to higher load factors. The sector expects further developments into optimizing foundation design which will enable turbine sizes to increase even further [13-15].

Technological progress has also led to wind turbine rotors increasing in size across Europe. Operational offshore wind turbine rotors are typically around 150–170 m in diameter, with this expected to rise to over 200 m. For example, General Electric’s most recent offshore wind turbine, expected to be operational mid-2020s, has a rotor diameter of 220 m.

Figure 3(a) shows the energy volume of offshore wind over the past five years for each of the studied countries. The graph shows the volume of offshore wind in the UK and Germany has increased significantly. During the same period, whilst still increasing, the volume of offshore wind in Denmark is still lagging behind the other studied countries. Figure 3(b) shows the total installed offshore wind capacity for each country. The graph shows the UK and Germany have significantly increased their capacity since 2015, whilst in Denmark only a minor increase has occurred. Figure 3(c) shows a comparison between the capacity factors of each of the countries over the past 5 years. The graph shows that broadly capacity factors have remained relatively steady since 2015 in all three countries.
2.2. Curtailment

Table 1 below has been provided to compare curtailment across the three countries, covering trends, the reasons for these trends, the associated costs and best practice.

| Trends                  | UK                                               | Denmark                                          | Germany                                          |
|-------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
|                         | • Curtailment rates for wind have marginally increased in the UK. | • Increased role for offshore wind turbines to offer balancing flexibility by downregulation | • Volumes of curtailed offshore wind energy have increased sharply over the last years from 0 GWh in 2014 to 1345 GWh in 2018. |
|                         | • However, offshore wind curtailment remains low, with annual rates of less than 1%. | • By downregulating Danish wind turbines, they provide a flexibility service to the German grid. | • The same trend can be observed for curtailed onshore wind energy, which makes up the majority of wind power in Germany. |
|                         | • Curtailment costs are increasing but this is expected to stop once new transmission projects are completed. | • Due to Denmark’s export possibilities to Norway, Sweden and recently the Netherlands, there has been hardly any curtailment of onshore and offshore wind energy. | • The transmission grid is continuously reinforced, but at the same time more wind power is added. |

| Reasons                 | UK                                               | Denmark                                          | Germany                                          |
|-------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
|                         | • Curtailment levels have been increasing for network thermal management and due to network constraints. | • Main drivers for increased demand for curtailment are congestion in the Danish and German transmission grids at times of high sun and wind energy production, combined with low demand. Especially over production in Northern Germany is a trigger. | • 83 % of the time transmission grid constraints were the reason for curtailment in 2019. |
|                         | • The limited curtailment of offshore wind is partially due to the higher compensation received compared to onshore wind farms. | • If it is necessary for maintaining security of supply, the Danish Transmission System Operator (TSO) Energinet.dk can reduce or fully curtail output of prioritised electricity production. | • The major constraint is the transmission capacity from northern Germany to southern Germany. |
|                         | • The compensation costs are higher due to higher previous CFD (contracts for difference) values awarded to offshore wind projects. | • By offering regulating power during hours with negative spot prices, wind power producers can still receive income while helping to mitigate the negative price effect on the spot market. | • Most of the wind power is produced in northern Germany, where there are less people and industry. The electricity needs to be transported to the more densely populated south with more industry. |
|                         | • With offshore wind project CFD values decreasing this may result in more curtailment for newer offshore wind projects. | • With offshore wind project CFD values decreasing this may result in more curtailment for newer offshore wind projects. | • With offshore wind project CFD values decreasing this may result in more curtailment for newer offshore wind projects. |
|                         | • Curtailment is a localised issue in the UK with network bottlenecks due to a lack of grid capacity. | • Curtailment is a localised issue in the UK with network bottlenecks due to a lack of grid capacity. | • Curtailment is a localised issue in the UK with network bottlenecks due to a lack of grid capacity. |

Figure 3. Energy volumes, installed capacity and capacity factor for studied country. (Source: Deutsche Wind Guard 2020, BEIS, Dukes 2020 for U.K., DEA, 2020 for Denmark)
Cost

- Curtailment costs have increased considerably over the past decade.
- The developer is compensated for any curtailment.
- Curtailment for offshore wind projects often take place in the Balancing Market.
- TSO issue developers and suppliers a Balancing Services Use of System (BSUoS) charge which covers any network balancing actions.
- In case of curtailment, the TSO carries an obligation to fully compensate the curtailed generation for loss of revenue.
- In case the demand for down regulation comes from Germany, the owners of the wind turbine generation receive compensation from Energinet, while Energinet receives a price for netting. This has been profitable for Energinet last years, with an average cost of down regulation of 8-12 EUR/MWh and average 19-38 EUR/MWh in netting in the balancing market [16].
- Significant cost due to feed-in tariff scheme. Curtailed offshore wind farms are still paid the agreed tariff for the wind power which could have been produced.
- In 2018 and 2019, the cost for this was €M 264.0 and €M 237.5, respectively.
- 95% of this cost is reimbursed by the respective TSO, the rest is not reimbursed and hence borne by the operator of the wind farm.
- Curtailing offshore wind is comparatively expensive.

Best Practices

- Ofgem, National Grid and the Committee on Climate Change recognise a collaborative and extensive approach that enhancing transmission grid capacity is required to avoid potential curtailment issues.
- Improving the network will enable offshore wind projects to be bigger and further ashore.
- Energinet has established tools being strong grid and interconnections, international electricity, and gas markets.
- Energinet recognizes that these tools are not sufficient. The new tools added are sector coupling (electricity, gas, heating, transport), flexible consumption, digital business models and new players and partnerships
- Transmission grid capacity is now the most important criterium when determining sites that are to be auctioned and the order in which they are auctioned.
- Network reinforcements will help to limit curtailment of offshore wind

2.3. Network congestion and redispatch needs caused by offshore wind

2.3.1 UK. The planning process considers network congestion and redispatch needs annually through Electricity System Operator (ESO)’s Electricity Ten Year Statement (ETYS). The process starts with the offshore wind power estimation on ESO’ Future Energy Scenarios (FES). The FES data is applied to simulation models of the National Electricity Transmission System (NETS) to analyse their impact on the network and assess its performance. The Security and Quality of Supply Standards (SQSS) set out the criteria and methodology for planning the NETS. 2019 ETYS highlighted the potentially high growth of up to 8GW in generation coming from offshore wind on the east coast connecting to East Anglia, which could increase the need for reinforcement in this region of the network.

2.3.2 Denmark. The congestion of the Denmark system happens on the interconnectors between East Denmark and West Denmark, and with the neighbouring countries Norway, Sweden and Germany. A low share of congested hours suggests that the interconnector capacity is too large, while a high share might suggest that the capacity is too small. For some links and some years, congestion has occurred for about 50% of the hours.

2.3.3 Germany. The needs of redispatch caused by offshore wind will be assessed by the Transmission System Operator within the network development plan process.

3. Network reinforcement to accommodate offshore wind power

3.1. General principles
Grid integration refers to re-enforcement of network to accommodate offshore wind power. They are normally part of the Transmission System Operator (TSO) operated transmission grid, not direct connection of offshore wind farms.
Table 2. Comparison of stakeholders and planning process across the three studied countries.

| Key stakeholders | UK | Denmark | Germany |
|------------------|----|---------|---------|
| **UK** | | | |
| National Grid ESO is responsible for publishing ETYS and NOA which provide an overview of planning requirements and reinforcements in the foreword 10 years. | | | |
| The regulator Ofgem approves the NGESO plans. | | | |
| Onshore TOs - SHETL, SPT, NGET – build the required upgrades in their networks, maintain the networks, provide technical guidance to generators. For planning the necessary reinforcement, the three TO develop their own ten-year plans which inform the ESO when developing the ETYS. This is a process where the TOs work in close collaboration with the ESO. | | | |
| Planning authorities: Some types of new energy infrastructure might require planning permission from local planning authorities. For the long-term planning processes (e.g. ETYS), local authorities can provide their view during stakeholder engagement activities, organised by the ESO. | | | |
| **Planning process** | | | |
| Development and publication of the Future Energy Scenarios | | | |
| Determine the British National Electricity Transmission System (NETS)’s requirement in the Electricity Ten Year Statement (ETYS) | | | |
| Evaluate network development options and publish investment recommendations in the NOA report. | | | |
| **Denmark** | | | |
| Energinet – TSO. Energinet has a duty to take the initiative to examine the socio-economic benefits of new initiatives, including expansion of interconnections with neighbouring countries, to integrate renewable energy, develop market competition, maintain security of supply and optimise operation over the long term. | | | |
| According to the legislation, Energinet is responsible for maintaining the specified level of security of electricity supply and to monitor changes. | | | |
| DUR – the Danish Utility Regulator, monitoring, analysis and regulate price of services of utilities. | | | |
| Wind developers | | | |
| DEA – Denmark Energy Agency, manages the legislation on the electricity market in Denmark. Specifically, the Danish Energy Agency develops the legal framework for production, transmission, and distribution of electricity, and for competition, consumer protection and security of supply. | | | |
| **Germany** | | | |
| The responsibility for onshore upgrades lies principally with Energinet. The grid planning process includes: | | | |
| The ENTSO-E Union-wide ten-year network development plan is published biennially (TYNDP). A separate regional investment plan for the Baltic Sea region is also published. In addition, the European Commission publishes BEMIP focusing on the Nordic and Baltic Sea region. | | | |
| The Nordic Grid Development Plan describes the ongoing and future investments in the Nordic grid. The plan is published by the Nordic TSOs at the request of the Nordic Council of Ministers. | | | |

The following stakeholders are involved in the German grid development process:
- BSH – Federal Maritime and Hydrographic Agency
- BNetzA – Federal Network Agency
- German TSO’s: 50Hertz Transmission, Amprion, TenneT and TransnetBW

The overall RES targets were set by the European Union. The German RES targets are defined within the Energy law, the renewable energy act and the Offshore wind act. The TYNDP – created by European TSO’s provides a future plan with all relevant electricity line (offshore and onshore) in the European Area. The German Network development plan (NDP) – created by the German TSO and approved by the Federal Network Agency provides a framework for grid extension in Germany.
3.1.1 UK. In the UK, the National Grid ESO as transmission system operator, and all onshore and offshore Transmission Owners (TOs) in GB are transmission licensees. This means that Ofgem (the regulator) has provided them with a license to operate.

The responsibility for onshore upgrades lies principally with NGESO and the three onshore TO’s, and the key documents are the System Operator Transmission Owner Code (STC) and the SQSS.

The process that TOs and the ESO follow with regard to planned network reinforcements to support offshore wind projects, is the same as for the other planned network reinforcements.

3.1.2 Denmark. According to the new legislation, Energinet is responsible for maintaining the specified level of security of electricity supply and to monitor changes. The responsibility for onshore upgrades lies principally with Energinet. The grid planning process includes:

The ENTSO-E Union-wide ten-year network development plan (TYNDP) is published biennially. A separate regional investment plan for the Baltic Sea region is also published. In addition, the European Commission publishes Baltic Energy Market Interconnection Plan (BEMIP) focusing on the Nordic and Baltic Sea region.

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Energinet develops the national electricity grid development plan for Denmark.

3.1.3 Germany. In Germany there are six steps used for the process of transmission grid extension.

- Federal Spatial Plan
- General development strategy (Scenario framework)
- Definition of extension demand (Grid development plan)
- Definition of projects (Federal Requirements Plan)
• Determination of corridors (Federal sectoral planning)
• Detailed routing (Planning Approval)

3.2. Stakeholders and planning process
Stakeholders and planning process across the three studied countries are analysed in Table 2.

3.3. Design strategies applied

3.3.1 UK. Traditionally the ETYS and Network Option Assessment (NOA) provide the planned level of reinforcements of the onshore grid to accommodate offshore connections (which to date have been radial connections connecting to a single onshore substation). Relevant planning process is shown in Table 2. The Project will make recommendations for potential changes to how offshore wind connects to the onshore network. This will be underpinned by: A set of conceptual integrated designs which are technically feasible, compliant with grid requirements. A cost benefit analysis of the different designs, considering the benefits for consumers and communities, with the key parameters informed by stakeholder engagement. Identification of the barriers to implementing the recommended approaches. These are likely to include the regulatory regimes, policy frameworks, network codes and the roles and responsibilities of different participants in the processes.

3.3.2 Denmark. Onshore integration and grid connection points will be determined by Energinet within the framework network development plan as well as the regional/European level grid development plan. Technically, onshore integrations are implemented as HVAC cables or overhead lines. Any grid reinforcement between the two systems (East Denmark and West Denmark) has to be implemented as HVDC cables as they belong to two different synchronous zones.

The technology choice of interconnectors to other countries will be determined by: Whether both sides belong to the same synchronous zone. The transmission distance for submarine cables and power rating of the interconnector. The planned grid reinforcement projects in Denmark are illustrated in Figure 4 and further detailed in Table 3.

Figure 4. Planned grid reinforcement projects in Denmark to facilitate the integration of offshore wind farms. (Source: Statnett, FINGRID, Energinet, Svenska Kraftnät, 2019)

| PROJECT | STATUS | DESCRIPTION |
|---------|--------|-------------|
| DK1 Endrup-Idomlund | Decided, Expected in operation 2023 | All projects are 400 kV domestic transmission lines. The purpose of the investments is to integrate ongoing and planned connections of renewable generation (offshore wind farms) and to connect new interconnectors (COBRA, Viking Link, DK West - |
### 3.3.3 Germany
The offshore development and grid connection strategies were defined by the Federal Maritime and Hydrographic Agency – within the Federal Spatial Plan “Flächenentwicklungsplan”. The choice of technology is clearly defined with Federal Spatial Plan where 320 kV HVDC is set for German North Sea (due to long distance to shore) and 220 kV HVAC for the German Baltic Sea. The onshore integration and grid connection points will be determined by the German TSO’s with the network development plan.

### 4. Summary
This paper analyses the development of offshore wind power in UK, Germany, Denmark. It can be seen that, the volume and capacity of offshore wind in the UK and Germany has increased significantly in the past five years. Network congestion is main reason for curtailment in these studied countries. Grid integration approaches to reinforcement of network to accommodate offshore wind power is essential. Although stakeholders and planning process of offshore wind power is different in UK, Germany and Denmark, coordination design is key to improve offshore wind power access to power grid. China promises to get peaking carbon dioxide emissions before 2030. It can predict that during the 14th Five Year Plan period, China is set to lead in new capacity of offshore wind power. Learning from the advance experience of European offshore wind power, some suggestions can be formed for the development of offshore wind in China.

- Strengthen the coordinated development of network and offshore wind. National energy department should reasonably arrange the construction of offshore wind and supporting power grid projects.
- Accelerating the improvement of power grid capacity. Power grid enterprises should dynamically adjust power grid construction planning according to the development of offshore wind power.

| Country | Offshore Wind Farm | Status | Connection Details |
|---------|-------------------|--------|---------------------|
| DK1     | Bjæverskov-Hovegaard | Under evaluation, expected in operation 2023 | Germany to the domestic grid. |
| CB2     | Kriegers Flak CGS, 400 MW Denmark East – expected in operation 2023 | Under construction, in operation 2020 | Secure connections to shore are vital for the Kriegers Flak offshore wind farm. An offshore interconnector is being developed in collaboration with the German TSO (50Hertz Transmission GmbH). The new interconnector will take advantage of the proximity of Danish and German wind farms by adding short cables and thus connecting the wind farms to both Germany and Denmark. |
| CB3     | COBRA 700 MW Denmark West – Netherlands | Commissioned in 2019 | The project from Endrup in Denmark West to Eemshaven in Holland was commissioned in Q3 2019. |
| CB7     | Viking Link 1,400 MW Denmark West – the UK | Expected in operation 2023 | The project aims at integrating the electricity markets of the UK and DK to increase the value of wind power as well as improving security of supply in the UK in the long term. |
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