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Integrated Baltic Offshore
Wind Electricity Grid Development

Market Analysis of the Offshore Wind Energy Transmission Industry

Overview for the Baltic Sea Region

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Market Analysis of the Offshore Wind Energy Transmission Industry

Overview for the Baltic Sea Region

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List of Abbreviations

Al	Aluminium
AC	Alternating current
AUV	Autonomous underwater vehicle
B2B	Back-to-back
BOP	Balance of plant
BSR	Baltic Sea Region
Cu	Copper
CAPEX	Capital expenditure
CGS	Combined grid solution
CSC	Current-source Converter
DC	Direct current
ENTSO-E	European Network of Transmission System Operators
EPC	Engineering, procurement, and construction
EPR	Ethylene propylene rubber
EWEA	European Wind Energy Agency
GGOWL	Greater Gabbard Offshore Winds Ltd.
GW	Gigawatts
GSU	Generator step-up transformers
HTS	High-temperature superconductor
HV	High voltage
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IKTS	Fraunhofer Institute for Ceramic Technologies and Systems
IRENA	International Renewable Energy Agency
kA	Kiloampere
kV	Kilovolt
LCC	Line-commutated converter
LCOE	Levelized cost of electricity
MW	Megawatts

MI	Mass-impregnated
MTDC	Multi-terminal HVDC
MVA	Megavolt-ampere
MVAC	Medium-voltage alternating current
OFTO	Offshore transmission owner
OLTC	On-load tap-changer
O&M	Operation and management
OMS	Operations and maintenance services
O-NEP	Offshore network development plan [*Netzentwicklungsplan*]
OPEX	Operating expenses
OTM	Offshore transformer module
OWE	Offshore wind energy
OWF	Offshore wind farms
PE	Polyethylene
PST	Phase-shifting transformer
PTV	Personnel transfer vessel
PVC	Polyvinyl chloride
R&D	Research and development
RD&D	Research, development, and demonstration
ROV	Remotely operated vehicle
SCADA	Supervisory Control and Data Acquisition
SHM	Structural health monitoring
SME	Small and medium-sized enterprises
SOV	Service operation vessel
T&D	Transmission and distribution
TSO	Transmission system operator
UUV	Unmanned underwater vehicle
VSC	Voltage-source converter
WPP	Wind power plant
WTG	Wind turbine generator
XLPE	Cross-linked polyethylene

Summary

The Baltic InteGrid project is an interdisciplinary research initiative designed to facilitate transnational cooperation and optimise offshore wind development in the Baltic Sea Region (BSR). The following analysis provides project stakeholders with up-to-date information on current market conditions for the development of a regional meshed grid. The report highlights relevant findings from the market analysis of the offshore wind energy transmission industry, with a particular focus on Europe and the Baltic Sea. It first provides a general overview of the European offshore wind energy industry, including information on relevant regulatory regimes, installed capacity, and technology trends. It then presents component-specific market overviews for high-voltage alternating current (HVAC) cables, high-voltage direct current cables (HVDC), converters, transformers, and substation foundations, as well as for the main operation, maintenance, and service (OMS) activities.

The offshore **HVAC subsea-cable** market is mature, with most of the supply provided by three main actors. European manufacturers are dominant, but new players are likely to enter the market as demand grows. New suppliers face barriers to entry, including high capital intensity, the need for high-level expertise, and the increasing importance of delivering turnkey solutions. Manufacturers have thus far expanded their production capacity to meet the increasing demand. There are no major bottlenecks in the supply chain for HVAC subsea cables, although the availability of installation vessels could prove problematic as demand rises.

HVDC technology has emerged as a solution to the limitations of HVAC technology. The European market for HVDC cables is growing due to increased demand for long-distance transmission. In the long run, the use of HVDC technology is likely to increase and become more common in the offshore wind energy (OWE) industry, provided that prices reduce to competitive levels. For now, however, uncertainty and risk associated with the technology make it difficult to forecast demand.

OWE converter demand in Europe is mainly driven by the deployment of HVDC technology. For now, the market is concentrated in the German part of the North Sea. As farms are built farther from shore, demand for HVDC technology is expected to grow if prices decrease to competitive levels. No major bottlenecks are foreseen at this point.

OWE transformer efficiency, rating, weight, and dimensions have improved significantly, driven by increased offshore wind farm (OWF) capacity and changing requirements. As the market continues to grow, further moderate innovations are expected. The competitive landscape for OWE power transformers is characterised by the dominance of a few well-established suppliers. Tap changers supply is a potential bottleneck in the future supply chain, along with copper windings. Further improvements in power density

are expected, but no significant reduction in capital expenditure is anticipated.

There is a high level of competition among **OWE substation foundation** manufacturers. Thus far, most suppliers on the European market have been locally based, with significant players in the BSR. Some industry experts predict an increase in non-European supply. Segments like engineering, installation, logistics, and subcomponents are examples of potentially competitive areas for SMEs. No major bottlenecks are anticipated.

The **operations and maintenance service (OMS)** sector is still relatively immature because OWFs have been operating for less than two decades and activities are still being adapted to changing parameters. Condition monitoring, forecast improvements, and technological innovations have allowed OMS to transition from a reactive to a more proactive approach, reducing costs and increasing energy generation. There is space in the OMS market for new companies to compete, provided that they offer cost reduction solutions (e.g. underwater drones).

1. Introduction

Offshore wind energy (OWE) is expected to play an important role in the future European energy mix. The European Union currently has 86 per cent of the total global OWE installed capacity in its waters, making it the world leader in offshore wind deployment.[1] Although most of the installed capacity is located in the North Sea, the Baltic Sea Region (BSR) offers good conditions for offshore wind development. This report supports the objectives of the transnational Baltic InteGrid project by offering stakeholders up-to-date information on relevant conditions for the development of a regional meshed grid. Specifically, it highlights relevant findings from the market analysis of the OWE transmission industry, with a particular focus on the European and BSR markets.

The first section of the report provides an overview of OWE in Europe by identifying the installed capacity, regulatory regimes, and technologies currently in place in the Member States of the BSR that are part of the European Union (EU). Section 2 outlines the methodology and assumptions used in creating the market development scenarios and market demand forecasts. Sections 3–8 present component-specific market overviews of the following offshore wind transmission components: high-voltage alternating current (HVAC) cables, high-voltage direct current (HVDC) cables, converters, transformers, and substation foundations; the main operation, maintenance, and service (OMS) activities are also described.

In this report, market analyses for offshore wind transmission components are based on information gathered from the technology catalogue,[2] relevant literature, and semi-structured interviews. Each section briefly describes the function of each component in offshore wind transmission infrastructure; estimates component-specific demand through 2030 on the basis of market scenarios, outlines market characteristics (e.g., with regard to the competitive landscape, manufacturing bottlenecks, and price trends); highlights major technological developments; and identifies the main barriers to market entry for new manufacturing entities.

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[1] WindEurope (2017): *Local impact, global leadership, The impact of wind energy on jobs and the EU economy*, p. 17

[2] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems, and HVDC systems*, DTU, prepared for the Baltic InteGrid project, Work Package 3

2. Offshore Wind Energy in the European Union

In 2017, the net additional offshore wind installed capacity in Europe increased by a record of 3,148 megawatts (MW). This capacity corresponds to 560 new offshore wind turbines across 17 offshore wind farms (OWFs). The same year, the European total installed capacity reached 15,780 MW, which corresponds to 4,149 grid-connected wind turbines across 11 countries. Currently, 11 OWFs are under construction. Once commissioned, those projects will increase the total grid-connected capacity by 2.9 gigawatts (GW), bringing the cumulative European installed capacity to 18.7 GW. By 2020, WindEurope expects the total European capacity to grow to 25 GW.[3]

The average size of installed offshore wind turbines in 2017 was 5.9 MW, which corresponds to a 23 per cent increase compared to 2016. The average capacity of OWF was 493 MW in 2017, which is 34 per cent higher than the previous year. WindEurope expects the wind farm capacities to rise to up to 900 MW in the upcoming years.[4] Figure 1 indicates the water depth and distance to shore of OWF completed or partially completed in 2017, where averages of 27.5 m and 41 km respectively are observed.[5]

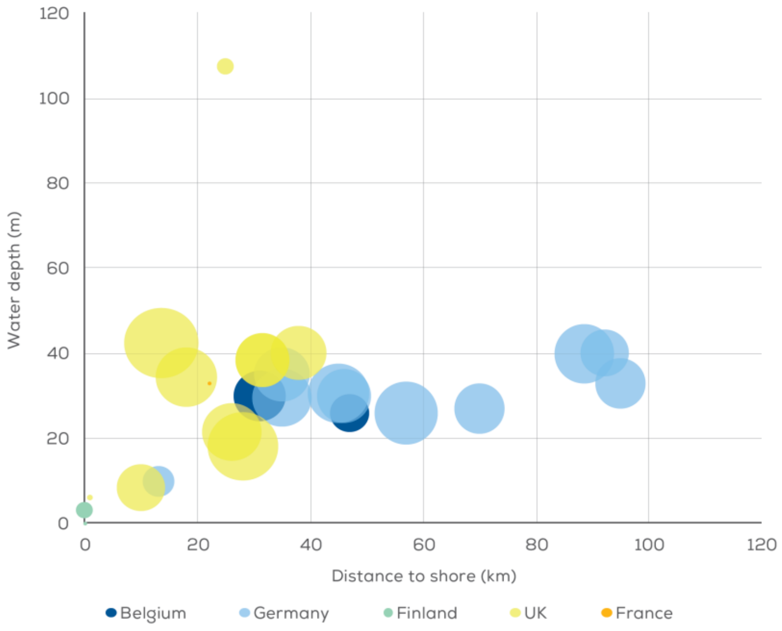

Figure 1. Water depth and distance to shore of OWFs fully or partially completed as of 2017.[6]

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[3] WindEurope (2018): *Offshore Wind in Europe, Key trends and statistics 2017*

[4] Ibid.

[5] Ibid.

[6] Ibid.

2.1 Regulatory regimes for offshore wind connections

The choice of a grid investment model is important because it determines grid development responsibilities (e.g. the wind farm connection), which ultimately distributes costs and risks. There are currently three main regulatory regimes for connecting OWFs to the onshore grids in Europe: the transmission system operator (TSO) model, the OWF generator model, and the offshore transmission owners (OFTO) model. For offshore interconnectors, the investor can be private investors or the national TSOs for the interconnected countries.

The **TSO model** is dominant in most European countries developing offshore wind. Here, the responsibility for the connection of the OWF to the onshore grid falls to the national TSOs. Because the grid connection requires substantial CAPEX, this model lowers costs for OWF investors. In addition, when the TSO is responsible for the grid connection, an early and more holistic connection planning can be created, such as the offshore grid development plan (Offshore Netzentwicklungspläne, O-NEP) in Germany.

In some countries and under certain conditions, the **OWF generator model** is used for OWF grid connections (see section 1.3). Under this model, generators (e.g. OWF owners, including utility companies) are responsible for the financing and/or development of OWF grid connections to the shore.

Under the **OFTO** model, which is applied in the UK, offshore wind transmission operates under a third-party. OFTO systems function separately from the onshore transmission system, although they are regulated by the same entity (Ofgem) and paid for by the national TSO. The current UK regulatory regime, known as the Enduring Regime, provides tenders for both generator-build and OFTO-build projects. Generators decide between these two options.[7]

2.2 Grid connection technology

Most existing OWF are connected via single lines using HVAC technology. This solution favours wind farms close to shore, because the technology has proven to be reliable and generally lowers costs. Due to the increase in OWF capacities, distance to shore, and the number of OWFs under development, the concept of OWF clusters has emerged to facilitate connections. These cluster connections link several OWFs via a transformer station, using HVDC technology for the connection to the mainland. HVDC technology offers many advantages but requires converter stations both offshore and onshore, which significantly increases the grid connection cost. HVDC is therefore used in cases in which OWF or clusters are located far offshore. The ‘break-even’ distance to shore decreases

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[7] OFGEM (2011): UK’s Offshore Transmission Regime: A case study for financing a low carbon future

with technological advancements, leading to a corresponding decrease in cost.

2.3 OWE in the BSR

According to WindEurope, 12 per cent of Europe's total installed capacity was located in the BSR as of 2017. The same year, a total of 405 MW was added in the region, corresponding to the commissioning of the Wikinger (Germany) and Tahkuoloto (Finland) wind farms. The North Sea Region dominates OWE development and accounts for 71 per cent of the total European offshore wind capacity (see Figure 2).[8]

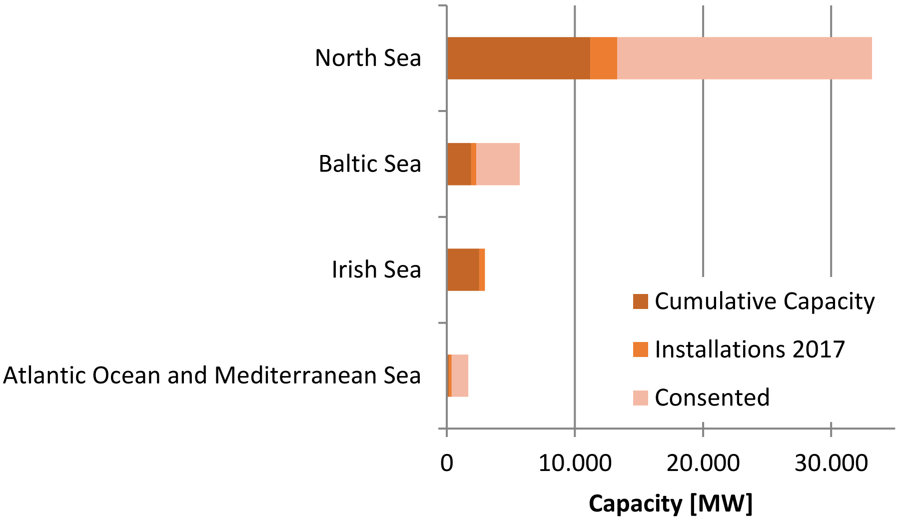

Figure 2. Share of cumulative capacity, installations in 2017, and consented capacity per sea region.[9]

Most of the installed capacity in the BSR is in Denmark (880 MW) and Germany (693 MW). Only two other BSR Member States, Sweden and Finland, have initiated offshore developments thus far. Figure 3 shows the average wind farm sizes in BSR countries with offshore wind infrastructure (only wind farms with more than 3 MW of capacity). The largest wind farms were constructed in Germany, where the average size is 230 MW, followed by Denmark, where the average is 100 MW.

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[8] WindEurope (2018): *Offshore Wind in Europe, Key trends and statistics 2017*

[9] Own figure based on data from WindEurope (2018): *Offshore Wind in Europe, Key trends and statistics 2017*

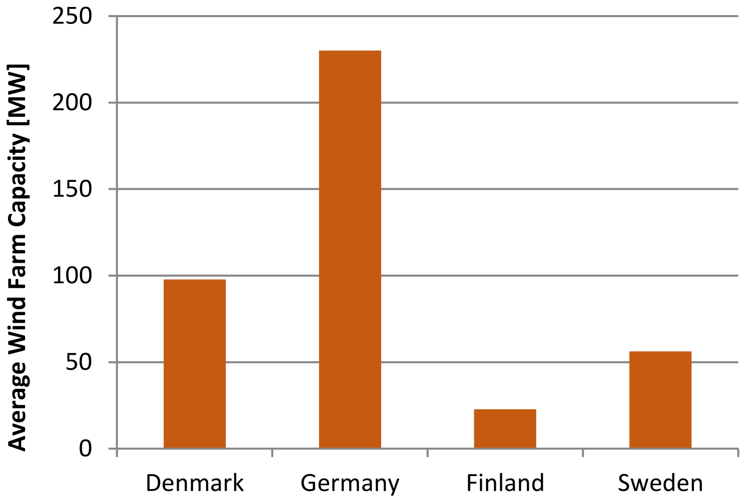

Figure 3. Average national wind farm capacities in BSR countries.[10]

Figure 4 shows the installed capacity projections through 2030 for all BSR Member States, based on high and low development scenarios developed in the Baltic InteGrid project.11 Based on the high scenario calculated in the context of the Baltic InteGrid, the total offshore wind installed capacity could reach up to 9.5 GW by 2030.

In both high and low scenarios, installed capacity in the Baltic Sea near the German coast is expected to increase significantly in 2025 and 2030. The high scenario indicates that three new offshore wind markets could emerge by 2030 (i.e. Poland, Estonia, and Lithuania). Figure 17 and Figure 18 (Appendix A) present maps of expected offshore wind development in the BSR through 2030 based on the high and low scenarios, respectively. More details on the assumptions and calculations for the high and low scenarios can be found in section 2 of this report ('Methods').

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[10] Ibid.

[11] The Baltic InteGrid project uses a different definition of the BSR than does WindEurope. While the WindEurope definition encompasses offshore wind projects located along Denmark's eastern coast, the Baltic InteGrid follows maritime spatial planning boundaries and thus excludes wind farms located in the Kattegat area. As a result, the offshore wind status quo capacity presented in figure 4 is lower than that reported by WindEurope for 2017 (i.e. 1.4GW and 1.8GW, respectively).

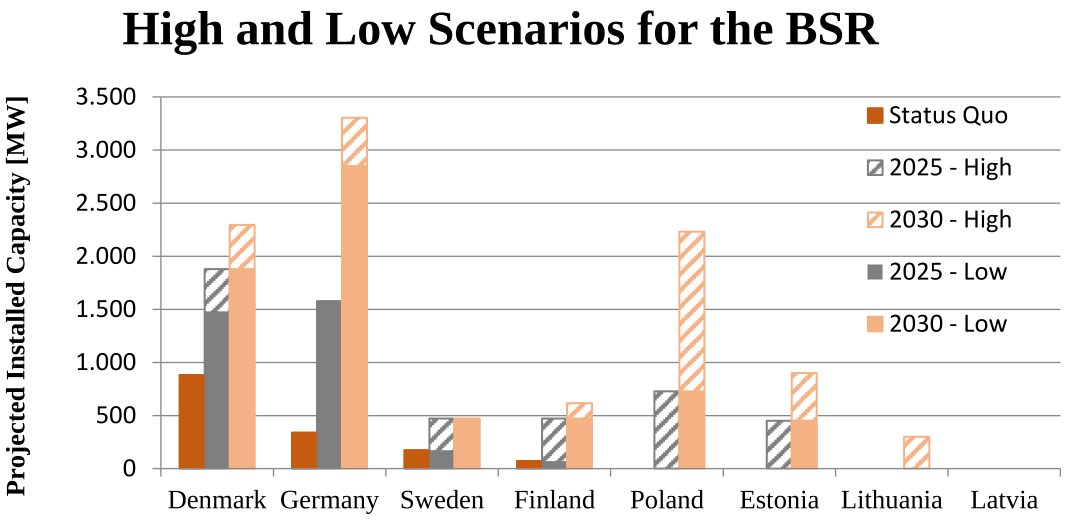

Figure 4. Projected offshore wind installed capacity, low and high scenarios through to 2030.[12]

Regarding the regulatory regimes for offshore wind connections in the BSR, the TSO model is the main grid connection regime in the Member States with the greatest offshore wind capacity (i.e. Germany and Denmark). However, even in these countries, the OWF generator model can sometimes be observed. For instance, for nearshore wind farms in Denmark, generators finance the grid connection to the shore. In Sweden and Finland, developers are responsible for the design, financing, and development of the grid connection to shore. Alternative connection models are however currently under consideration in Sweden. With regard to grid connection technology, all Baltic Sea wind farms in operation have been connected via AC lines. Germany plans to use cluster grid connections with DC technology for parts of future grid connection projects.

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[12] WindEurope estimates for offshore wind capacity in the BSR include wind farms located along the eastern coast of Denmark. In this report, the BSR is defined on the basis of maritime spatial planning and excludes wind farms located in the Kattegat area. Due to the variance in these definitions, the offshore wind status quo capacity shown in figure 4 is thus lower than that reported by WindEurope (1.8 GW versus 1.4GW, respectively).

3. Methods

The component-specific market analyses presented below provide a brief description of the component in the context of offshore wind transmission infrastructure; forecast component-specific demand in the BSR through 2030, based on offshore wind scenarios developed for the Baltic InteGrid project; describe market characteristics, including the competitive landscape, manufacturing bottlenecks, and price trends; outline major technological trends; and identify any barriers to entry for new manufacturing entities. Information used in this report was collected using multiple methods, which are described in this section.

3.1 Component-specific descriptions

Offshore wind transmission systems are technically complex endeavours. They often involve a large number of components at varying levels of technological maturity. This prompted the creation of a 'technology catalogue', which covers all of the main components needed for OWE and transmission projects. The technology catalogue was produced in the context of Work Package 3 of the Baltic InteGrid project and published *as Technology Catalogue: components of wind power plants, AC collection systems, and HVDC systems.*[13] Its main purpose is thus to serve as a common source for the techno-economic assessments performed in the project. The component-specific descriptions presented in the following chapters are derived from this catalogue.

3.2 Baltic InteGrid offshore wind development scenarios

The Baltic InteGrid project developed scenarios estimating potential offshore wind deployment through year 2030. Existing OWE development scenarios were used as a baseline for comparison and analysis. Deployment scenarios developed by the European Wind Energy Agency (EWEA) in 2015, WindEurope in 2017, as well as the European Network of Transmission System Operators (ENTSO-E) in 2017 were considered.[14] Some of these scenarios do not differentiate between North and Baltic Sea coastlines of Member States that border both seas; in these cases, capacity assumptions are based on the historical development and actual political frameworks of the respective countries. Baseline capacities were also compared to a project database created as part of the Baltic InteGrid project.

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[13] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems, and HVDC systems*, DTU, prepared for the Baltic InteGrid project, Work Package 3

[14] EWEA (2015): Wind energy scenarios for 2030; WindEurope (2017): Unleashing Europes Offshore Wind Energy Potential; WindEurope (2018): WindEurope: Offshore Wind in Europe, Key trends and statistics 2017

The Baltic InteGrid scenarios also incorporate the offshore wind deployment forecast through to 2030 in the Case Studies developed in Work Package 4. The objective of Work Package 4 is to conduct two pre-feasibility studies for two cases involving Polish-Swedish-Lithuanian and German-Swedish interconnections to planned OWFs. For portions of the sea and Member States that are not included in the case studies, additional capacity assumptions have been made by comparing the existing scenarios, findings from a literature review, and the project database.[15] Figure 5 provides an overview of the high and low scenarios for the entire Baltic Sea alongside other forecasts from industry representatives. Detailed scenarios for each BSR Member State can be found in the Appendix B (Figure 19).

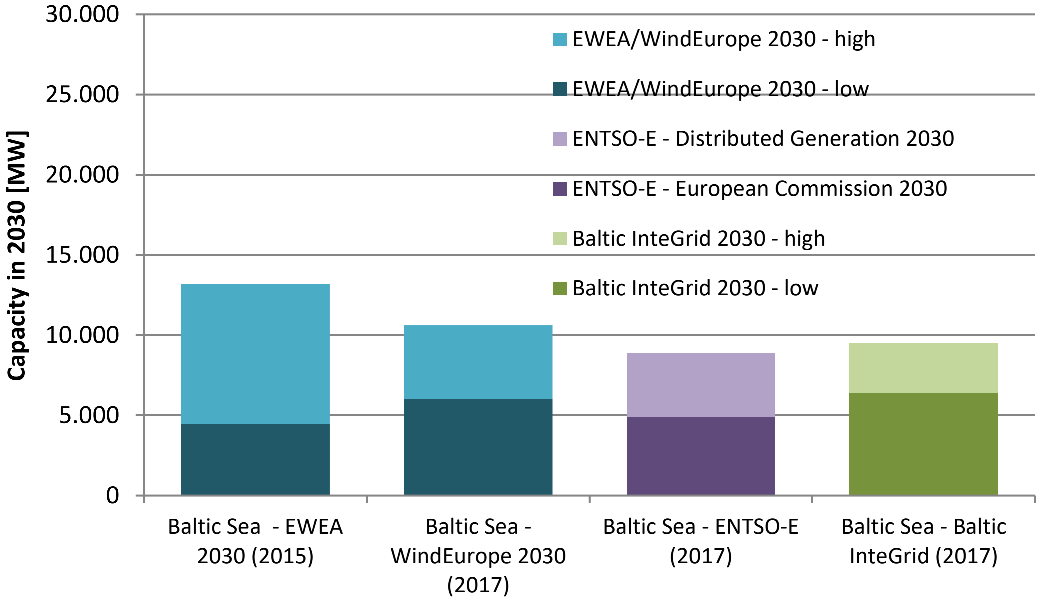

Figure 5. Low and high scenarios for offshore wind development in the Baltic Sea.[16]

3.3 Component-specific demand calculations assumptions

The Baltic InteGrid offshore wind development scenarios were the basis for estimations of future offshore component-specific demands for HVAC and HVDC export cables, transformer stations, converter stations, and substation foundations in the Baltic Sea through to 2030. The same clustering of wind farms presented in Work Package 4 is

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[15] The alignment with the offshore wind development scenarios used within the Case Studies was necessary to ensure consistent results throughout the project. However, the Case Study scenarios were designed to meet other requirements and adopted a long-term meshed grid development perspective, not necessarily in line with current development scenarios.

[16] EWEA (2015): Wind energy scenarios for 2030; WindEurope (2017): Unleashing Europe's Offshore Wind Energy Potential; WindEurope (2018): WindEurope: Offshore Wind in Europe, Key trends and statistics 2017

applied, using partial integration scenarios. (See Appendix C for further details on the forecasted cluster locations.)

In the case studies, the Kriegers Flak OWF is assumed to be connected to both the Danish shore and the Baltic 2 substation. For the other wind farms forecast, no clustering has been assumed through 2030 because very few to none of these wind farms are considered suitable for clustering, i.e. their installed capacity and distance to shore are limited, with large distances between farms. Radial connections are assumed for the OWFs outside Work Package 4 case study areas; Kriegers Flak is the only exception. Further details on the assumptions made in the design of the case studies of clusters can be found in Work Package 4 deliverables.

The cumulative substation rating in megavolt ampere (MVA) was calculated considering an additional ten per cent of total installed capacity to account for the potential reactive power produced in the electrical equipment between the wind turbine generator (WTG) and the transformer(s). Where the cumulative substation rating exceeded 500 MVA, two transformers were included, with the rating divided equally between them. All values for the distance to shore used in calculations were extracted from the 4C Offshore database. When the distance to shore were less than 9 km, the wind farm was assumed to be connected via MVAC[17] cables; in this case, no substation was considered.

The approximate export cable length was calculated by multiplying the estimated distance to shore by a predefined template value. The template value refers to the relationship between the distance from the centre of the wind farms to shore (extracted from 4C Offshore), using the designed cable route lengths defined in Case Study 1 of Working Package 4. The cable route design was mapped in GIS, accounting for general maritime spatial planning obstacles. The same export link voltage was assumed for all high HVAC export cables. The cross-sectional area of export cables was determined based on the amount of power transferred by the cable(s). The conductor material was assumed to be aluminium; copper could also be used, though ideally with smaller cross sections.

3.4 Semi-structured interviews and literature review

A review of relevant literature and semi-structured interviews with various industry actors were conducted to examine additional aspects, such as market characteristics (e.g. competitive landscape, manufacturing bottlenecks, and price trends), technological trends, and high entry barriers for new companies entering the market. Four types of respondents were targeted for interviews: components manufacturers, consultancy firms, market analysts, and wind energy associations. Interviews were conducted over the phone and in person during the WindEurope Summit 2016 in Hamburg, the Offshore Wind Energy 2017

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[17] MVAC cables are not included in the scope of this study.

in London, and the WindEurope Conference & Exhibition 2017 in Amsterdam. All findings were validated with respective experts to form an overview of component-specific market characteristics and trends. Further details on the companies interviewed during events and phone interview respondents can be found in Appendix D.

4. Overview and analysis of HVAC cables market

4.1 Component description

Of the various types of HVAC subsea cables on the market, the most prevalent are those made from cross-linked polyethylene (XLPE). High Temperature Superconducting (HTS) cables are also a mature technology, but their use in electricity highways can be limited due to the constraints of cryogenic systems.[18]

4.1.1 Cross-linked polyethylene cables

XLPE cables belong to the class of extruded cables, as do ethylene propylene rubber (EPR) and polyethylene (PE) cables. XLPE cables have good electrical properties, such as low dielectric loss factor, which makes it more feasible to operate at higher voltage than other kinds of material, including cables insulated with Poly Vinyl Chloride (PVC). PE is a thermoplastic material used as cable insulation, but its applications are limited by thermal constraints. Cross-linking is performed in XLPE through the process of ‘vulcanisation’ or ‘curing’. Chemical additives are introduced into the polymer in small quantities, which enable the molecular chains of the polymer to form a cross-linked lattice structure. An example of XLPE cable design is shown in Figure 6.[19]

Extruded insulation cables consist of many layers. Surrounding the conductors are an inner semi-conducting screen layer, the insulation compound, and an outer semi-conducting insulation screen, extruded simultaneously. Semi-conducting water swelling tape separates the outer semi-conducting screen and the metallic sheath to limit water propagation along the cable core in case of cable damage. A layer of polyethylene compound is extruded over the lead alloy-based metallic sheath. XLPE cables are used for HVAC and Medium Voltage Alternating Current (MVAC).[20]

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[18] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems*, p.7

[19] Ibid.

[20] Ibid., p. 8

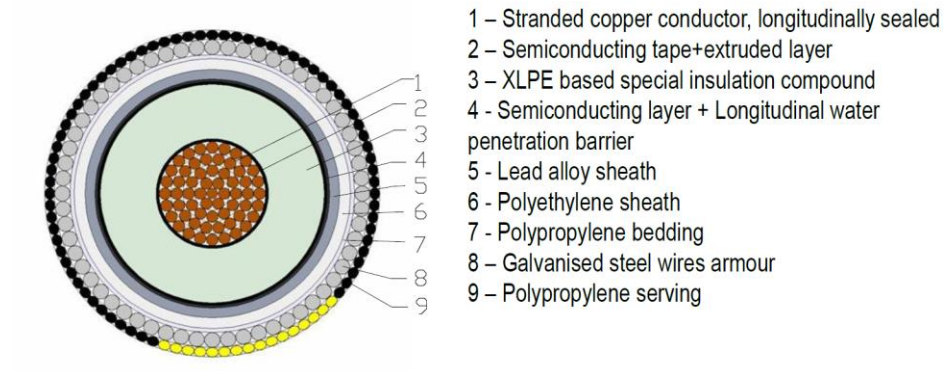

Figure 6. Example of XLPE cable design.
Source: *Technology Catalogue*, Baltic InteGrid.

4.1.2 High-temperature superconducting cables

Because HTS transmits power without resistance loss, utilities can increase power density by a factor of 2–8. Benefits of HTS Power Cables include its increased current-carrying capability; prevention of resistive electrical losses; use of liquid nitrogen as an environmentally benign coolant; its ability to be installed within existing conduit infrastructure; requirement of less space than conventional cables; satisfaction of the increased power requirements of existing substations; operation at high current levels with much lower losses; and requirement of less voltage transformations (reducing the cost of transformers).[21]

4.2 Current demand

Over the last decade, there has been a steady increase in demand for both offshore and onshore HVAC transmission cables.22 Within the European offshore wind industry, 46 export cables were energised in 2016, including HVDC and HVAC subsea cables.[23] The technical benefits of offshore subsea cables include high power transferability, high transmission efficiency, high reliability, competitive prices, compatibility with current infrastructure, and ability to provide offshore connections at medium to long distances.[24] Figure 7 shows the demand forecast for HVAC subsea export cables in the

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[21] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems,* p. 9-10

[22] Europacable. “Electricity transmission of tomorrow underground and subsea cables in Europe”. 2016. http://www.europacable.com/books/electricity_transmission_2016_06/assets/common/downloads/Electricity%20Transmission%20of%20Tomorrow.pdf (Accessed 11 September 2017)

[23] WindEurope. “The European offshore wind industry - Key trends and statistics 2016”. Brussels. 2017 https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf (Accessed 11 September 2017)

[24] N. Helistö and V. Tai, *OffshoreDC: Electricity market and power flow impact of wind power and DC grids in the Baltic Sea* (Oulu: VTT Technical Research Centre of Finland, 2015).

Baltic Sea for the high and low scenarios developed in the context of the Baltic InteGrid project. In the high scenario, the demand for HVAC cables for offshore transmission in the Baltic Sea is expected to reach nearly 1,900 km in 2030.

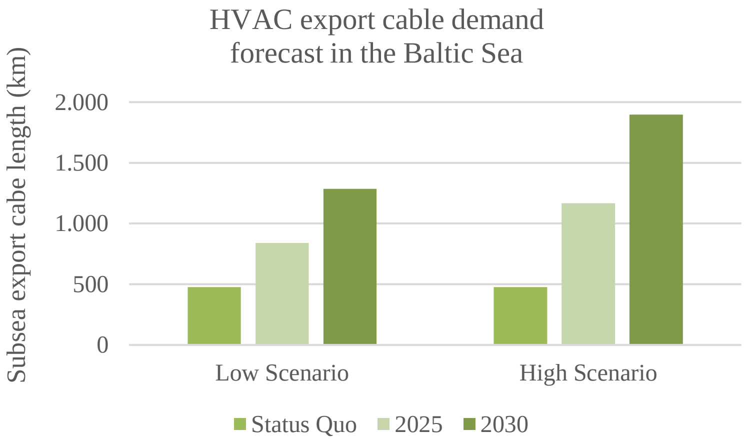

Figure 7. Cumulative demand for HVAC export cables in the Baltic Sea.[25]

4.3 Market characteristics

The market for offshore HVAC subsea cables is mature. HVAC cables are widely used, and the technology is well understood within the onshore transmission network. To date, HVAC subsea cables have been the preferred technology for connecting OWFs to shore. Experience with the technology has increased since the first European wind farms were installed in the early 2000s.[26]

4.3.1 Competitive landscape

The European market for HVAC subsea cables is dominated by three main actors: Prysmian Group, Norddeutsche Seekabelwerke (NSW), and the NKT Group (formerly NKT Cables). Figure 8 shows the European market shares of export subsea cables in 2016, including HVAC and HVDC technology. Because most export cables installed are HVAC cables, the figure also indicates the market shares for this segment. As shown in the diagram, Prysmian Group is by far the largest supplier, with a market share of over 50 per cent. In spring 2017, NKT Cables acquired the high voltage (HV) cable segment of ABB, increasing their market share significantly; the company changed its name to NKT after the acquisition.[27]

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[25] Own figure.

[26] WindEurope, *The European offshore wind industry - Key trends and statistics 2016*, 2017, accessed 11 September 2017, https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf; Nicolaos Antonio Cutululis, telephone interview by Julia Sandén, 12 September 2017.

[27] “Acquisition of ABB´s HV cable business”. Offshore Wind Industry Magazine, no. 01 (2017): 12

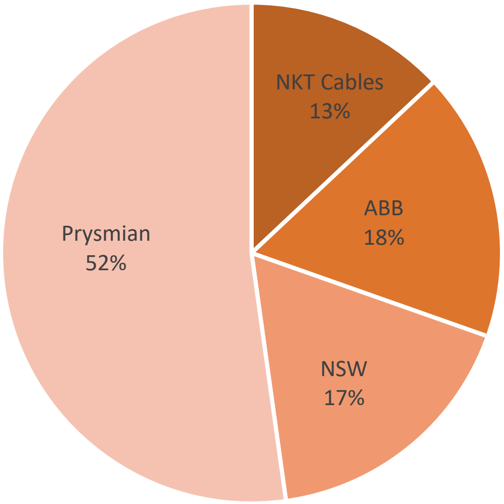

Figure 8. Market shares for high voltage subsea cables manufactured in 2016.[28]

To date, the European market has been covered primarily by European suppliers. However, with the projected growth in demand for HVAC subsea cables, new actors, mainly from Asia, are expected to enter the European market. Japanese and Korean cable manufactures have already expressed interest in entering the European market.[29] The logistics costs of entering the market are unlikely to deter these companies, because these costs are relatively small relative to the total value of the subsea cable.[30]

According to NKT, suppliers that are competitive in the subsea cable market are highly capital-intensive and offer state-of-the-art products, significant technological know-how, and the ability to deliver turnkey solutions. Differentiators include product design and capabilities (e.g. the ability to deliver long cable lengths without joints), innovation, and offshore service offerings.[31]

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[28] WindEurope. "The European offshore wind industry - Key trends and statistics 2016". Brussels. 2017 https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf (Accessed on 11 September 2017)

[29] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[30] Interview by Christoffer Bent, Julia Sandén, Christian Weiß and Steve Wendland. WindEnergy Hamburg, 27–30 September 2016

[31] NTK Holding. "2015 Annual Report". Brøndby. http://www.nkt.dk/media/84885/2015-NKT-Annual-Report.pdf (Accessed on 11 September 2016)

4.3.2 Manufacturing bottlenecks

Over the last decade, European cable manufacturers have steadily expanded their production capacity to meet the increasing demand for high-voltage subsea and underground cables. From 2008 to 2011, this capacity increase raised output by approximately 40 per cent.[32] Interviews with several manufacturers revealed that there are currently no major bottlenecks within the supply chain for HVAC subsea cables. However, one limiting factor is the ability of manufacturers to plan and design for the production of upcoming subsea-cable projects. Inconsistency in order flows, as well as high rates of cancellation and delays in planned offshore wind projects, makes it difficult for the manufacturers to utilise their production capacity efficiently.[33]

A stable increase in demand for onshore and offshore HVAC cables is foreseen. Based on the current production capacity, some experts anticipate a shortage of HVAC cables around 2020 to 2025. The additional demand will most likely be met by an increase in production capacity from established European cable suppliers and possibly cable suppliers outside Europe.[34] As demand increases, the availability of installation ships could become a concern.

4.3.3 Price trends

Although the overall demand for HVAC subsea cables has steadily increased, many European suppliers have struggled with temporary overcapacity due to a series of delays in the development of offshore wind projects in recent years. As a result, price competition has intensified and prices have decreased significantly over the past two years.[35] The price of HVAC subsea cables is expected to stabilise at the current (low) level.[36] Similarly, experts interviewed at the Offshore Wind Energy 2017 exhibition in London do not foresee any significant cost reduction for HVAC subsea cables within the next 10 to 15 years.[37] However, for HVAC transmission there is still potential for cost reductions from a system point of view. According to the International Renewable Energy Agency (IRENA), minimising the infrastructure required to support offshore wind transmission is the most promising strategy to lower costs. This is also applicable for HVAC subsea cables.[38]

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[32] Europacable. “Electricity transmission of tomorrow underground and subsea cables in Europe”. 2016. http://www.europacable.com/books/electricity_transmission_2016_06/assets/common/downloads/Electricity%20Transmission%20of%20Tomorrow.pdf (Accessed on 11 September 2017)

[33] Interview by Christoffer Bent, Julia Sandén, Christian Weiß and Steve Wendland. WindEnergy Hamburg, 27–30 September 2016

[34] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[35] Hungerschausen, Peter (Senior Sales Manager at Norddeutsche Seekabelwerke GmbH). Phone interview by Julia Sandén. 4 September 2017

[36] Ibid.

[37] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[38] International Renewable Energy Agency (IRENA). “Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016.

4.4 Technological trends

A key limitation of HVAC cables is their high electrical capacitance. Over long distances, (generally exceeding 80–100 km) the capacitive charging current is significant and reduces the cable's ability to transmit real power.[39] HVDC cables are therefore a more suitable option for long-distance transmission. However, compared to HVAC technology, an HVDC connection from OWFs to shore is riskier and more expensive. As a result, there are ongoing efforts to make HVAC subsea cables more suitable for longer offshore distances.[40]

Onshore, it is common to instal reactive power compensation to increase the viable distances for HVAC cables. The first reactive power compensation station installed offshore will be at Hornsea 1, the British OWF developed by the Denmark-based energy company Ørsted A/S. The wind farm will be connected to shore via three 120 km HVAC subsea cables (220 kV) in combination with a reactive power compensation station installed midway between the OWF and the shore. Ørsted A/S expects the construction of reactive power compensation to be more cost-efficient than are current HVDC systems.[41]

There is also a trend towards higher-voltage HVAC subsea cables, which have the benefit of reducing losses for a given power rating. The current voltage levels for HVAC subsea cables are generally 110 kV and 220 kV. Europacable expects voltage to increase to as much as 400 kV between the years 2025 and 2025, which will raise the power rating significantly.[42] This development will probably result from manufacturing advances in the cleanliness of pellet production and extrusion as well as from improvements in cable design and material selection.[43]

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http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 13 September 2017)

[39] European Network of Transmission System Operators for Electricity (entso). "Offshore Transmission Technology. Brussels". 2011. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf (Accessed on 11 September 2017)

[40] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 13 September 2017)

[41] Detlef Koenemann,"AC instead of DC", *Offshore Wind Industry Magazine*, no. 02 (2017): 34–35; "Project One", 4C Offshore, 2017, accessed 13 November 2017, http://www.4coffshore.com/windfarms/hornsea-project-one-united-kingdom-uk81.html.

[42] Europacable. "Europacable Stellungnahme BFO: Anbindungskonzepte Standardisierte Technikvorgaben". 2017. Access to the documents was provided by Bundesamt für Schifffahrt und Hydrographie (BSH).

[43] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 13 September 2017)

IRENA has also identified a trend towards lower-frequency AC transmission as another development that might have an impact in the longer-term future. The benefit of this technology is reduced capacitive effects for a given power rating. To date, low-frequency transmission has only been a topic for academia.[44]

4.5 Barriers to entry

As noted previously, any potential need for increased production capacity for HVAC subsea cables is expected to be met by established European cable suppliers and existing cable suppliers outside Europe. It is unlikely that entirely new companies will enter the market. This is primarily due to the large upfront investment required to set up a new manufacturing facility. For a new company entering the market, this large investment may be difficult to justify.[45]

It has also been suggested that a new cable manufacturing facility is unlikely to be established in the BSR. The market for offshore wind in the Baltic Sea is relatively small in comparison to offshore wind markets for the North Sea and other worldwide emerging offshore wind markets. However, regional SMEs may find business opportunities in the supply chain for HVAC subsea cables, particularly in the maintenance, service, and repair segments.[46]

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[44] Ibid.

[45] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[46] Ibid.

5. Overview and analysis of HVDC cables market

5.1 Component description

HVDC transmission technology is mainly applied when connecting two asynchronous networks and/or when the transport of high electrical power over long distances becomes uneconomical for HVAC transmission and greater control over power transmission is required. In subsea use, HVDC transmission is predominantly used to connect OWFs to land or transmit electricity over long distances through the sea where the use of overhead lines may not be technically or economically feasible. HVDC cables are also being used in land transmission projects to transmit a high volume of power. HVDC is a proven technology for transmission projects that interconnect asynchronous networks.47 HVDC underground cables are used to carry medium and high power (100 MW to 1,000 MW) over distances above 50 km. HVDC underground cables have been in commercial use since the 1950s. The primary types of HVDC cable technologies commercially available are mass-impregnated (MI) cables and XLPE cables. Self-contained fluid-filled cables are also becoming popular; however, they are used for very high voltage and short connections due to hydraulic limitations.[48]

5.1.1 Self-contained fluid-filled cables

Self-contained fluid-filled cables are paper-insulated oil-filled cables. These kinds of cables are more suitable for HVDC transmission over short distances of up to approximately 50 km. The insulation system in these cables must be under constant oil pressure. This oil pressure prevents the formation of cavities as the cable cools and the oil contracts. These kinds of cables can be used in both AC and DC operations. Examples of projects using low-pressure oil-filled cables are the interconnections between Saudi Arabia and Egypt (Aqaba Project) and the Spain-Morocco project.[49]

5.1.2 Mass-impregnated cables

Mass-impregnated subsea HVDC cables do not need oil-feeding and therefore have no limitation on length. Mass-impregnated cables are composed of a highly viscous impregnating material which does not cause any leakage in the event of cable damage/failure. Compared to oil-filled cables, the compact design of mass-impregnated subsea HVDC cables also allows for deep-water applications. An example using mass-

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[47] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems,* p. 11

[48] Ibid.

[49] Ibid.

impregnated subsea HVDC cables is the interconnection between Spain and Mallorca ("Cometa Project"). Although this type of cable is currently one of the most used, the use of extruded cables has risen in recent years. [50] Mass-impregnated cables have been in service for many years and are a mature technology that can be used for voltages up to ± 500 kV and 1600 A DC, which corresponds to a maximum pole-rating of 800 MW and bipole rating of 1600 MW. Conductor sizes are typically up to 2500 mm2 (with a transmission capacity of 2000 MW bipole). Further improvement in voltage and capacity can be expected in the future.[51]

5.1.3 Cross-linked polyethylene cables

Polymeric cables are only used in voltage-source-converter (VSC) applications that allow for a reversal of power flow with no polarity reversal. This technology has mainly been applied at voltages up to ± 200 kV (in service with a power capacity of 400 MW). However, recent projects such as European TEN-E France-Spain Interconnector (INELFE) has a voltage rating of ± 320 kV and power rating of 1000 MW per cable.[52]

5.2 Current demand

The European market for HVDC cables is growing due to an increased demand for long-distance transmission and interconnection between national networks.[53] Within the offshore wind industry, there is also a clear trend towards increased OWF capacity and locations farther from shore. These trends underlie the increased use of HVDC transmission for connecting OWF to shore.[54] Within the European offshore wind industry, 46 export cables were energised in 2016, including HVDC and HVAC subsea cables.[55] Figure 9 shows the demand forecast for HVDC subsea export cables in the Baltic Sea for the high and low scenarios developed in the Baltic InteGrid project. No HVDC export cable is expected to be installed in the Baltic Sea before 2025. Moreover, the cable demand in the low scenario is larger than that in the high scenario because the case studies on which the forecast is based assume that a large cluster of OWFs will not be commissioned until 2035, which is outside the timeframe for projections in Work Package 3.

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[50] Ibid., pp. 11–12

[51] Ibid., pp. 12–13

[52] Ibid., p. 13

[53] European Network of Transmission System Operators for Electricity (entso). "Offshore Transmission Technology". Brussels. 2011.
https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf (Accessed on 11 September 2017)

[54] WindEurope. "The European offshore wind industry - Key trends and statistics 2016". Brussels. 2017
https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf (Accessed on 11 September 2017)

[55] Ibid.

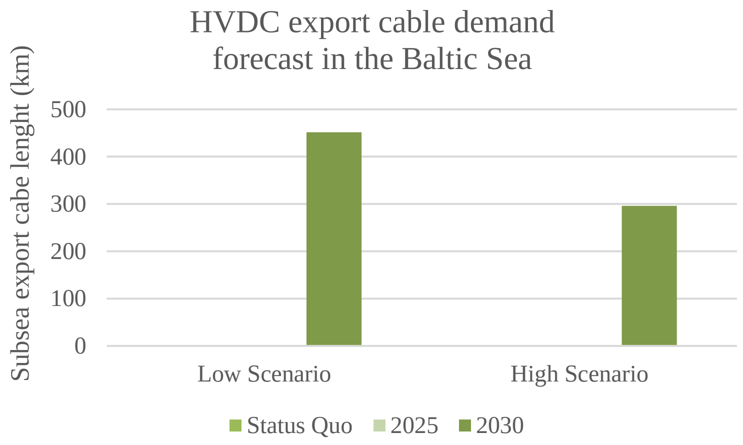

Figure 9. Cumulative demand forecast for HVDC export cables in the Baltic Sea.[56]

5.3 Market characteristics

The technology for HVDC subsea cables is rather mature; however, the use of DC systems for connecting OWFs to shore is still under development. HVDC subsea cables have been used for long-distance transmission and electricity exchange between asynchronous networks since the 1950s; as a result, the cable industry has gained experience with, and a comprehensive understanding of, the technology.[57]

In the field of offshore wind, however, only a few wind farms have been connected to shore with HVDC transmission systems (all located in German waters).[58] The limited experience and additional investment costs imply higher risks, making offshore developers hesitant to use HVDC technology. In addition, there are limited track records and experience. Indeed, apart from the Borwin 1, HVDC systems currently installed are only a few years old.[59]

5.3.1 Competitive landscape

Prysmian, NTK (formerly NTK Cables), and Nexans are the main HVDC subsea cable suppliers in Europe. For OWE converter stations currently operational in the German part

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[56] Own figure.

[57] European Network of Transmission System Operators for Electricity (entso). "Offshore Transmission Technology". Brussels. 2011. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf (Accessed on 11 September 2017)

[58] "Offshore converter database". 4C Offshore. 2017. http://www.4coffshore.com/windfarms/converters.aspx (Accessed on 9 October 2017)

[59] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

of the North Sea, all HVDC subsea cables were supplied by Prysmian and ABB (Table 1).[60, 61, 62]

HVDC Converter Stations	Export Cables	Main Suppliers	Commissioning Year
BorWin 1	HVDC ± 150 KV	ABB	2009
BorWin 2	HVDC ± 300 kV	Prysmian	2015
DolWin 1	HVDC ± 320 kV	ABB	2015
DolWin 2	HVDC ± 320 kV	ABB	2017
HelWin 1	HVDC ± 250 kV	Prysmian	2015
HelWin 2	HVDC ± 320 kV	Prysmian	2015
SylWin 1	HVDC ± 320 kV	Prysmian	2015

Table 1. Data on HVDC subsea cables connecting offshore wind farms in Europe.[63]

In 2017, NTK acquired the HV cable segment of ABB, including its manufacturing facilities and offshore-cable-laying vessels. The acquisition completed the exit of ABB from the cable market. NTK was already an established supplier of low-, medium-, and high-voltage AC cables (see section 3), and with the acquisition the company also entered the market for HVDC cables. In the coming years, NTK is expected to increase its revenue share within the offshore wind industry significantly and become one of the largest suppliers of HV subsea cables in Europe.[64,65] The acquisition of ABB further reduced the already small number of European HV subsea cable suppliers. Actors within the offshore wind industry raised concerns about market consolidation and the growing risk of reduced competition among the existing cable suppliers.[66,67]

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[60] "Offshore converter database". 4C Offshore. 2017. http://www.4coffshore.com/windfarms/converters.aspx (Accessed on 9 October 2017)

[61] "Offshore Wind farms, Impressive track record in offshore wind farms". Prysmian Group. 2017. https://www.prysmiangroup.com/en/products-and-solutions/power-grids/offshore-wind-farms (Accessed on 9 October 2017)

[62] "Offshore wind connections, references". ABB. 2017. http://new.abb.com/systems/offshore-wind-connections (Accessed on 11 October 2017)

[63] "Offshore converter database". 4C Offshore. 2017. http://www.4coffshore.com/windfarms/converters.aspx (Accessed on 9 October 2017)

[64] "Acquisition of ABB´s HV cable business". *Offshore Wind Industry Magazine*, no. 01 (2017): 12

[65] Interview by Bent Christoffer, Julia Sandén, Christian Weiß and Steve Wendland. WindEnergy Hamburg, 27–30 September 2016

[66] "ABB trennt sich vom Kabelgeschäft". Energate. 2016. http://www.energate-messenger.de/news/168041/abb-trennt-sich-vom-kabelgesch-ft (Accessed on 11 October 2017)

[67] Interview by Christoffer Bent, Julia Sandén, Christian Weiß and Steve Wendland. WindEnergy Hamburg, 27–30 September 2016

With a future increase in demand for HVDC subsea cables, suppliers from outside Europe may enter the European market (primarily companies from Asia).[68] The additional logistical costs facing these companies will most likely not be a problem because these costs are relatively small relative to the total value of the subsea cable.[69]

5.3.2 Manufacturing bottlenecks

Experts agree that, in the long run, the use of HVDC transmission for connecting OWFs to shore is bound to increase and become the standard. In the short term, however, the uncertainty and risk associated with the technology make it difficult to foresee how the demand will develop. The current supply of HVDC subsea cables in Europe is rather limited in capacity and scope, with only a few large suppliers and three main production centres.[70,71] Given the current production capacity, there is a risk that the increase in demand will cause a shortage of HVDC subsea cables in the offshore wind industry.[72]

Similar to trends observed in HVAC cables, the additional demand for HVDC cables will most likely be met by an increase in the production capacity of established European manufactures, possibly complemented by cable suppliers from outside of Europe.[73]

5.3.3 Price trends

The market for HVDC subsea cables is not as competitive as the market for HVAC subsea cables, resulting in lower price pressure and higher margins.[74] However, the price for HVDC systems is still expected to decrease, mainly due to technology development, improvements in system reliability, and increased installation experience. According to interviews conducted at the Offshore Wind Energy 2017 exhibition in London, it is likely that the largest potential cost reductions will be achieved before 2030.[75]

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[68] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[69] Interview by Christoffer Bent, Julia Sandén, Christian Weiß and Steve Wendland. WindEnergy Hamburg, 27–30 September 2016

[70] Institute for Sustainable Economics and Logistics (INWL) for Rostock Business. *Supply Chain Analysis: overview for the Baltic Sea Region*. Baltic InteGrid, 2017

[71] European Network of Transmission System Operators for Electricity (entso). ”Offshore Transmission Technology”. Brussels. 2011. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf (Accessed on 11 September 2017)

[72] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[73] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[74] Interview by Christoffer Bent, Julia Sandén, Christian Weiß and Steve Wendland. WindEnergy Hamburg, 27–30 September 2016

[75] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

5.4 Technological trends

For OWFs located more than 80–120 km from shore, HVDC transmission starts to become more cost-effective than HVAC transmission. HVDC cables do not have the same problems with electrical capacitance as HVAC cables, and transmission distances are theoretically unlimited. For longer distance, the higher revenue from reduced transmission losses outweighs the additional investment costs related to HVDC transmission (Figure 10).[76]

A typical trend for HVDC subsea cables is an increase in voltage levels. The benefits of increased voltage are higher power ratings, decreased transmission losses, and potential savings on conductor material. The current voltage levels for HVDC subsea cables connecting OWFs to shore are between 150 kV and 320 kV.[77, 78] Europacable anticipates voltage levels to increase to 525 kV by 2025 and 600 kV by 2030.[79] A technical restriction that could hamper this development is the limited capacity of the onshore grid connection points.[80]

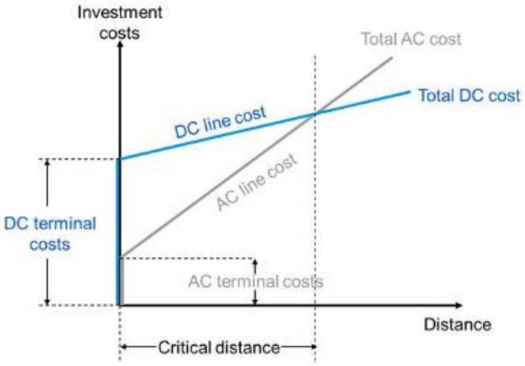

Figure 10. Cost relationship between AC and DC transmission.[81]

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[76] European Network of Transmission System Operators for Electricity (entso). “Offshore Transmission Technology”. Brussels. 2011. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf (Accessed on 11 September 2017)

[77] Ibid.

[78] European Network of Transmission System Operators for Electricity (entso). ”Offshore Transmission Technology”. Brussels. 2011. https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf (Accessed on 11 September 2017)

[79] Europacable. “Europacable Stellungnahme BFO: Anbindungskonzepte Standardisierte Technikvorgaben”. 2017. Access to the documents was provided by Bundesamt für Schifffahrt und Hydrographie (BSH).

[80] Ibid.

[81] International Renewable Energy Agency (IRENA). “Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 13 September 2017)

DC power take-off is an innovation in wind turbines that could have an impact on the implementation and cost structure for HVDC transmission. In the wind turbines, variable-frequency AC is converted to DC and then back to AC at the required grid frequency. The introduction of DC power take-off eliminates the second power conversion back to AC.[82] According to IRENA, this would result in cost savings as well as increased system reliability. Because DC power take-off enables the use of DC array cables, which in turn reduces the required number of cable cores from three to two, IRENA estimates a material decrease of approximately 20–30 per cent. The first commercialisation of DC power take-off is expected to be begin with wind farms commissioned around 2025.[83]

5.5 Barriers to entry

Any potential need for increased production capacity for HVDC subsea cables is expected be met by the established European and large international cable suppliers. It is unlikely that entirely new companies will enter the market. This is mainly due to the large upfront investment required to set up a new manufacturing facility. For a new company entering the market, this large investment may be difficult to justify.[84] However, regional SME may find business opportunities in the supply chain for HVDC subsea cables, particularly in the maintenance, service, and repair segments.[85]

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[82] KIC InnoEnergy, BVG Associates. “The future renewable energy costs: offshore wind.

How technology innovation is anticipated to reduce the cost of energy from European offshore wind farms”. 2014.

http://www.innoenergy.com/wp-content/uploads/2014/09/KIC_IE_OffshoreWind_anticipated_innovations_impact1.pdf

[83] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016.

http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 13 September 2017)

[84] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[85] Ibid.

6. Overview and analysis of AC-DC converter market

6.1 Component description

To transmit power from far-off OWFs through HVDC cables, AC power is converted to DC power, and vice versa, using AC-DC power converters. Power converters currently available on the market can be divided into two major categories: LCC and VSC. Both technologies can be used in a full HVDC scheme (e.g. AC/DC converter-HVDC line or cable-DC/AC converter) or in a back-to-back (B2B) HVDC scheme (e.g. AC/DC converter-DC circuit-DC/AC converter, with all components installed in a single station), as well as in the configuration of multiterminal HVDC (MTDC) applications. LCC and VSC have different characteristics and are operated in different manner because of the intrinsic differences between power electronic components. The characteristics of LCC and VSC are compared in Table 2.[86]

6.2 Line-commutated converters

LCC are the conventional, mature, and well-established power-converter technology that has been used since the early 1950s to convert electrical current from AC to DC and vice versa. Such converters require a robust AC voltage source at either end. Multiterminal LCC connections are possible and two schemes exist. However, larger systems with a more complex structure may not be practical configurations, mainly due to limitations on the controllability of LCC converters.[87]

6.2.1 Voltage-source converters

VSC are self-commutated converters using devices suitable for high-power and high-voltage applications. This technology can rapidly control both active and reactive power independently. It allows for greater flexibility and controllability, enabling converters to be placed at different locations in the AC network because no robust AC voltage source is required to be connected to the end. However, some technological challenges still exist and must be addressed for greater deployment in multiterminal applications (e.g. DC breakers, higher powers, losses reduction).[88]

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[86] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems* (Baltic InteGrid), p. 16

[87] Ibid.

[88] Ibid., p. 18

	LCC	**VSC**
Background	• Also known as current-source converter (CSC) • Since early 1950s • Typically used in thyristors • Connected by two power networks at either side of link	• Since 1999 • Unlike CSC, can also be used for connecting isolated networks to the grid, e.g. supply power from generation sources like offshore wind farms • Recent technology, compact VSC multilevel converters reduce losses
Key characteristics	• More powerful • Reduced losses • Requires robust networks in operation on both sides and therefore may be the preferred technology for interconnections of synchronous networks • Requires robust networks in operation on both sides and therefore can be preferred technology for interconnections of synchronous networks • Requires more stringent standards for cables; therefore cables designed for LCC can also be used with VSC, but not vice versa	• Younger technology • Able to provide a 'black start' (i.e. able to start without additional power at either end) • Currently limited in power (to approximately 3000 MW) and voltage (up to +/- 640 kV) • More flexible, smaller and lighter, and therefore preferable for offshore applications • Allows independent control of active and reactive power

Table 2. Comparison of LCC and VSC.[89]

6.3 Current demand

The onshore transmission system represents by far the largest market for converters in Europe. The European OWE converter-substation demand represents only a small fraction of the overall European converter market, and is mainly driven by HVDC-technology deployment in the industry.[90] The market for OWE converter substations in Europe is currently concentrated in the German part of the North Sea.[91] As more farms are built

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[89] Ibid., p. 17

[90] Interviews by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[91] "Offshore converter database". 4C Offshore. 2017. http://www.4coffshore.com/windfarms/converters.aspx (Accessed on 9 October 2017)

farther from shore, the OWE converters demand is anticipated to grow, given that production and installation costs of HVDC technologies will decrease to competitive levels.92 As shown in Figure 11, both high and low scenarios project only one converter station in the Baltic Sea in 2030. The offshore converter is expected to be installed in the German waters of the Baltic Sea and may also be connected with HVDC to the Swedish shore.

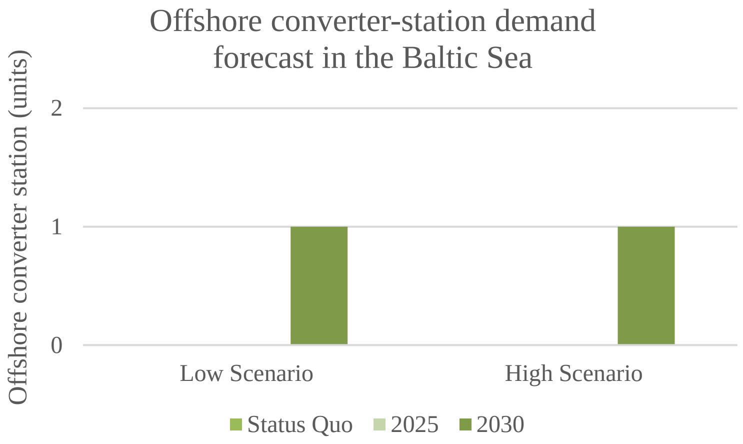

Figure 11. Cumulative demand forecast for offshore converter stations in the Baltic Sea.[93]

The market for VSC technologies is expected to grow at a higher rate since they require fewer filters and fewer components than do LCCs. In Europe, all currently installed OWE converter stations are of the VSC type (Table 3). At the same time, the expected growth in the VSC market will trigger an increase in the market for valves and circuit breakers, both integral components of converters.[94] Key factors that may challenge the demand growth include transmission congestion and instability, high initial costs, a lack of investment by power utilities in grid infrastructure, lengthy approval processes for transmission projects, and limitations at the technology level.[95]

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[92] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[93] Own figure.

[94] "IGBT Market worth $8,256.3 Million and Thyristor Market worth $3,632.0 Million by 2020." Markets and Markets. 2014 http://www.marketsandmarkets.com/PressReleases/igbt-thyristor.asp (Accessed on 11 October 2017)

[95] "HVDC Converter Station Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2016–2024." Transparency Market Research. http://www.transparencymarketresearch.com/hvdc-converter-station-market.html (Accessed on 10 October 2017)

6.4 Market characteristics

6.4.1 Competitiveness landscape

In Europe, there are only a limited number of OWE HVDC converter stations in operation, and the same major suppliers are involved in each project (Table 3). Siemens and ABB are the only European manufacturers to date that have sold multiple OWE HVDC converters (HVDC PLUS and HVDC Light). GE Grid Solutions, a joint venture between General Electric Digital Energy and Alstom Grid, is planning to commission an OWE HVDC converter project in the North Sea (VSC MaxSine) in 2018.[96] Due to the industry track-record requirement and rather small OWE converter market in Europe, it is unlikely that SMEs will be able to enter the supply chain to compete.

Offshore HVDC converter stations	Converter types	Main contractors	Commissioning year
BorWin 1	VSC (HVDC Light)	ABB	2009
BorWin 2	VSC (HVDC Plus)	Siemens	2015
BorWin 3	VSC (HVDC Plus)	Siemens	2019 (tentative)
DolWin 1	VSC (HVDC Light)	ABB	2015
DolWin 2	VSC (HVDC Light)	ABB	2017
DolWin 3	VSC (HVDC MaxSine)	GE Grid Solutions	2018 (tentative)
DolWin 6	VSC (HVDC Plus)	Siemens	2023 (tentative)
HelWin 1	VSC (HVDC Plus)	Siemens	2015
HelWin 2	VSC (HVDC Plus)	Siemens	2015
SylWin	VSC (HVDC Plus)	Siemens	2015

Table 3. European offshore converters.[97]

6.4.2 Manufacturing bottlenecks

No major bottlenecks in the OWE converter supply chain are foreseen at this point, and this is not expected to change given the status quo.[98]

6.4.3 Price trends

Technological progress has allowed for a reduction in the surface area and size of the VSC offshore converter stations. The compact design and need for less equipment has led to

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[96] “Offshore wind energy: TenneT awards ‘DolWin3’ project to Alstom, marking next step in Germany’s energy turnaround.” Alstom. 2013. http://www.alstom.com/press-centre/2013/2/offshore-wind-energy-tennet-awards-dolwin3project-to-alstom-marking-next-step-in-germanys-energy-turnaround/ (Accessed on 10 October 2017)

[97] “Offshore converter database”. 4C Offshore. 2017. http://www.4coffshore.com/windfarms/converters.aspx (Accessed on 9 October 2017)

[98] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

offshore substation platform size reductions, which ultimately aids in reducing installation and maintenance costs. Between 2011 and 2017, the size of offshore HVDC converter stations using ABB HVDC Light technology decreased by 40 per cent.[99] The OWE converter stations represent a significant share of the cost of the HVDC transmission system. LCC and VSC costs are largely similar.[100]

6.5 Technological trends

Four important aspects to consider when looking at the current and future technical state of HVDC converters are the transmission losses, transmission capacity, transmission distance, and security of supply. In terms of security of supply, factors that should be considered are reliability, availability, and maintenance (both the frequency at which scheduled repairs are required as well as the expected outage times that accompany maintenance periods).[101]

Efficiency losses for VSC converter stations have been reduced from approximately 3 per cent in 1999 to their present state of roughly 1 per cent. It is expected that in the coming decades transmission losses will decrease further due to advancements in semiconductor components and the use of improved technologies. Development from basic two-level and three-level converter-station schemes to the more common multilevel converter-station schemes will also allow for progress. Higher power ratings have gradually been achieved and continue to increase while absolute losses have remained the same or decreased. Ultimately an overall transmission loss percentage is expected to decrease.[102]

Because VSC technology is not subject to the commutation failures that accompany the reversal of power flow in LCC schemes, it is more suitable for the future development of meshed HVDC grids. The evolution of the HVDC grid is heavily reliant upon the further development, deployment, and interoperability of multiterminal VSC technologies on offshore converter stations.[103]

6.6 Barriers to entry

With regard to transformers, it is not easy for new companies to enter the supply chain for offshore converter stations. This is mainly due to the track-record requirement for

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[99] "High Voltage Direct Current Electricity: Technical Information." National Grid (UK). 2013. www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=13784 (Accessed on 11 October 2017)

[100] Ibid.

[101] "Annex to D3.1 - Technology Assessment Report - Transmission Technologies: HVDC LCC, HVDC VSC, DC breakers, tapping equipment, DC/DC converters." Modular Development Plan of the Pan-European Transmission System 2050. 2014. http://www.e-highway2050.eu/fileadmin/documents/Results/D3/report_HVDC.pdf (Accessed on 11 October 2017)

[102] Ibid.

[103] Ibid.

suppliers, the capital-intensiveness of the industry, the highly selective process, and the fact that existing manufacturers are already well established. Significant new market entries are unlikely in the near future. However, foreign supply is expected to increase in the next 10–20 years as the emerging OWE market deployment continues. For now, the main offshore converter suppliers are likely to remain those that have already become established in the market and gained a market reputation.[104]

7. Overview and analysis of transformer market

7.1 Common description

Although transformer technology was invented over a hundred years ago, the basic operating, physical, and design principles have remained relatively unchanged. Improvements have resulted mainly in increased efficiency, higher power rating, reduced weight, decreased dimensions, and reduced costs. As offshore wind power plants are built farther from shore, voltage must be increased substantially to transmit a large volume of power over long distances. The main purpose of transformers is thus to increase the output voltage to reduce losses, increase transmission capacity, and reduce copper or aluminium requirements.

Transformers are widely used in AC power systems, and their design depends on applications, operating voltage levels, and rated power. Transformers can be broadly categorised into two groups based on their application in power transmission and distribution: power transformers for transmitting power over long distances at high voltages, as well as distribution transformers for distributing power to consumers at medium and low voltage levels. Power transformers are the focus in this section because they fall within the Baltic InteGrid project scope. Depending on their application, power transformers can be further divided into categories, including generator step-up (GSU) transformers, step-down transformers, HVDC converter transformers, phase shifting transformers (PST), and system intertie transformers.[105]

GSU transformers are installed in generating substations and used to increase voltages to facilitate transmission of power over long distances. They generally operate at full load during in both day- and night-time. System intertie transformers are generally equipped with on-load tap-changers (OLTC) and used to reduce the incoming transmission from high to medium voltage. HVDC converter transformers connect AC grids and high-power converters, making the voltage suitable for the converter. They also act as isolators to protect the converter from grid faults. The designed transmission voltage for HVDC

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[104] Interview by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[105] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems,* p. 33–34

technology is constantly increasing. For example, ABB (a leading transformer manufacturer) developed an Ultra HVDC converter transformer with a voltage rating of 1100 kV, which can transmit power up to 10000 MW over distances as long as 3000 km.[106]

7.2 Current demand

The national grid, or rather the onshore transmission and distribution (T&D) system, is by far the largest market for power transformers in Europe. The offshore wind power transformer market is growing, with most deployment observed in the North Sea. The BSR share, however, is relatively low. Figure 12 shows the demand forecast for offshore transformer stations in the Baltic Sea until 2030 for both the high and low scenarios. The forecast shows a significant difference between the high and low scenarios in the number of installed transformers expected in 2025, but this difference is slight in 2030 projections.

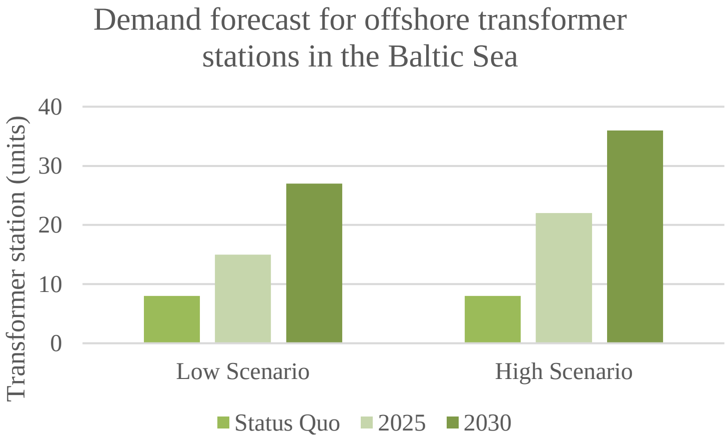

Figure 12. Cumulative demand forecast for offshore transformer stations in the Baltic Sea.[107]

7.3 Market characteristics

The basic physical principles of transformers are the same as they were 130 years ago. However, the efficiency, rating, weight, dimensions, and cost have improved significantly over time as they adapt to changing requirements.[108] The most important factor driving these improvements is the increase in OWF capacity and the associated need for increased transmission capacity. As the sector continues to grow, further moderate innovations are expected to reduce costs and allow expansion to new markets.[109, 110]

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[106] Ibid.

[107] Own figure.
[108] Ibid., XX

[109] "Offshore wind generation to fuel demand for T&D equipment market in Europe". Windpower Engineering and Development. February 14, 2017. http://www.windpowerengineering.com/featured/business-news-projects/offshore-wind-generation-fuel-demand-td-equipment-market/ (Accessed on 10 October 2017)

7.3.1 Competitiveness landscape

The competitive landscape for OWE power transformers is characterised by a few well-established suppliers and low diversity among products. Seniority and reputation appear to have a large influence on company performance. The main European power transformer suppliers (Siemens, ABB Group, CG Power System, and Schneider Electric) are important players in the OWE industry. Some OWE transformers have also been supplied by companies located outside of Europe (e.g. GE Industrial Solutions or the Hyosung Corporation), fuelling a trend for foreign companies to try to enter the European market. However, market entry is laborious for new manufacturers; there is a tendency to favour manufacturers that have a proven track record in the industry. Developers are seeking to acquire experience and build their reputation to minimise risk and gain maturity. Despite this, some foreign companies are able to supply a wide range of OWE components at a competitive price. Suppliers from China, Japan, and Korea are expected to become increasingly important in the European OWE power transformer market over the next 5–10 years.[111]

7.3.2 Manufacturing bottlenecks

The supply of tap changers for the OWE power transformers is dominated by the German company Maschinenfabrik Reinhausen GmbH. According to some experts, this monopoly might present a bottleneck in the future supply chain. A shortage in copper winding is also anticipated.[112]

7.3.3 Price trends

Prices of offshore power transformers are relatively stable. Further improvements in power density are expected, but in terms of CAPEX no significant cost reduction is foreseen. For foreign companies supplying transformers to the European OWE market, improvements in power density are essential to decrease logistics costs.[113] HVDC technologies are likely to have more room for cost reductions than HVAC technologies. By 2020, it is expected that the costs of DC substations will be reduced as design reliability and installation experience increase. The largest cost reduction is anticipated in 2030, when the technological maturity has increased. For AC substations, less significant cost reductions are foreseen. Technological maturity has already been reached and further cost reductions are expected to be associated with the optimisation of AC-cable installation.[114]

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[110] "Overview of the T&D equipment market in Europe." Technavio. https://www.technavio.com/report/europe-power-transmission-and-distribution-equipment-market-europe-2017-2021 (Accessed on 10 October 2017)

[111] Interviews by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[112] Ibid.

[113] Ibid.

[114] Ibid.

7.4 Technological trends

The main design factors considered when producing offshore power transformers are dimension and weight. Most power transformer manufacturers have difficulty striking a balance between an increased capacity and low size and weight. The emergence of new technologies and innovations is unlikely to be significant for the main OWE transmission components. Nevertheless, minor improvements are still expected (e.g. installation optimisation, better insulation techniques, and the use of natural oils).[115]

No official standard for offshore power transformers currently exists, and specifications often change in response to developer requirements. Significant cost reductions could be achieved through standardisation. Siemens, for example, is attempting to move towards standardisation with the development of its offshore transformer module (OTM). According to the company, the OTM will potentially reduce costs by up to 40 per cent, has a simple design, is lighter and smaller than conventional AC platforms, and is more environmentally friendly due to its use of obsolete mineral oil. Achieving size and weight reductions would also translate into savings in transportation, installation, and operation and management (O&M). The first OTM is planned to be tested in the 588 MW Scottish wind farm Beatrice, which is expected to be commissioned in 2019.[116, 117]

Malfunctioning of power transformers is rare but when it occurs it can generate considerable costs. The failure of the power transformer of the Danish wind farm Nysted in 2007 resulted in shutting down the OWF for more than four months while the component was replaced. As a result, some developers have started diversifying their power transformer systems by choosing to instal multiple smaller assets to reduce losses in case of failure. The 400 MW wind farm Global Tech 1, which has four transformers, is an example of this trend. In the event of a power transformer malfunction, the OWF would lose 25 per cent of power output rather than its full load.[118]

7.5 Barriers to entry

New market entries in the supply of offshore power transformers are unlikely in the near future. This is mainly due to the track-record requirement of the industry and the capital intensiveness associated with establishing a new manufacturing facility. However, an increasing presence of non-European suppliers (mainly from Asia) can be expected in the coming years.[119] Furthermore, power transformer suppliers typically provide a warranty on their products. Defects during the warranty period are rare, but when a failure occurs,

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[115] Ibid.

[116] Detlef Koenemann, *AC instead of DC* (Offshore Wind Industry Magazine 2017), 36

[117] "An offshore substation slims down". Siemens. 2017. https://www.siemens.com/customer-magazine/en/home/energy/power-transmission-and-distribution/an-offshore-substation-slims-down.html (Accessed on 10 October 2017)

[118] Detlef Koenemann, *AC instead of DC* (Offshore Wind Industry Magazine 2017), 36

[119] Interviews by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

servicing may be costly for manufacturers due to access constraints. This form of liability increases the risk to manufacturers and represents a barrier to entry for smaller and less experienced suppliers.[120]

8. Overview and analysis of offshore substation foundation market

8.1 Component description

Many types of OWE substation foundations exist, and choices are typically based on site conditions and platform properties. Relevant site conditions are water depth, wave heights, sensitivity to the soil, and water currents. Platform properties are mainly size and vertical and horizontal weights. Structural and cost-benefit analyses are important tools for foundation selection. Figure 13 shows five basic types: monopiles, gravity, tripods, jackets, and floating.[121]

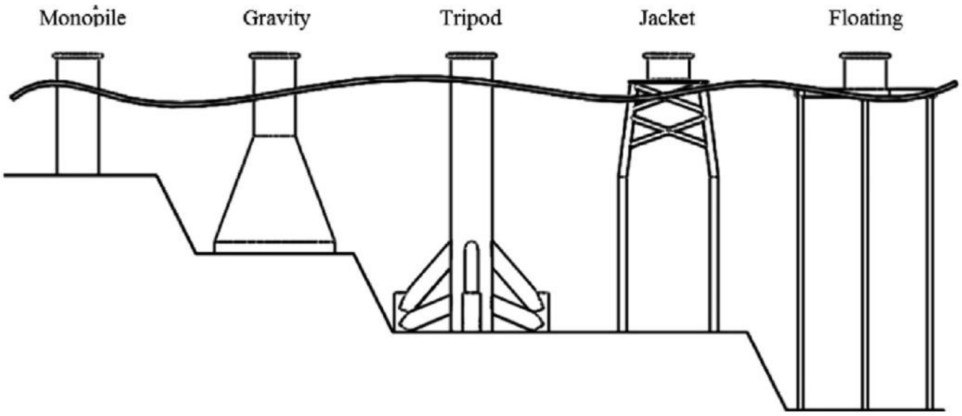

Figure 13. Offshore wind foundation types.[122]

8.1.1 Monopile foundations

Monopile foundations comprise most of all turbine foundations in the OWFs operating in Europe. This foundation type is drilled down into the seabed and is typically easy to instal in shallow to medium water depths (e.g. depth of 0–35 m). Advantages lie in its simplicity,

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[120] Ibid.

[121] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems,* 35

[122] Ibid.

light weight, and versatility. However, monopiles can be expensive for larger installations, such as converter substation platforms, and are sometimes difficult to demobilise. Recently, monopiles with larger diameters, called XXL monopiles, are considered viable alternatives to jacket foundations for installations in deeper water. For example, Veja Mate OWF has a monopile with a diameter of 7.8 m and weight of 1302.5 tonnes, the largest of its type. Ongoing research is also studying monopile use at depths of up to 50 m.[123]

8.1.2 Jacket foundations

Jacket foundations are made of truss frames, which consist of many tubular members welded together. To secure the structure from lateral forces, piling is driven through each leg of the jacket into the seabed — or through skirt piles at the bottom of the foundation. Jacket foundations have been applied to wind turbines (including Alpha Ventus OWF) and to converter platforms, like the 400 MW BorWin1 converter, which weighs 3200 tons.[124]

8.1.3 Gravity foundations

Gravity foundations are made of concrete — often filled with gravel, sand, iron ore, and/or stones to increase weight and stability — which can be constructed with or without small steel or concrete skirts. This type of structure uses its weight to resist wind and wave loading. They are suitable for virtually all soil conditions and have the advantage of allowing float-out installation. Steel gravity-based structures are preferable in deeper water than are concrete-based: they are lighter, which facilitates transportation and installation. However, this type of structure is often associated with high costs partially because of its large weight.[125]

8.1.4 Tripod foundations

Tripod foundations are standard, lightweight, three-legged structures made of cylindrical steel tubes. They consist of a central steel column supported by a steel frame. The central shaft transfers the forces from the tower into three vertical or inclined steel piles. These piles are driven 10 to 20 m into the seabed. To make it suitable for actual environmental and soil conditions, the base width and pile penetration depth can be adjusted. This type of structure is generally suitable for water depths of 20–50 m. Tripod foundations have good stability and overall stiffness, are suitable for most soil conditions, and are relatively rigid and versatile. However, this type of construction is relatively costly and difficult to decommission.[126]

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[123] Ibid., p. 37

[124] Ibid., p. 38

[125] Ibid., p. 38–39

[126] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems,* p. 37–38

8.1.5 Floating foundations

Because the cost of bottom-fixed foundations increases exponentially with water depth, floating foundations could become an attractive solution in deep waters. The break-even point of water depth is still unclear, however, largely due to limited experience with this type of foundation, which is at a relatively early stage of technological development. Floating foundations allow for some freedom of movement despite being held in place by an anchoring system, and this non-rigid property is susceptible to lower wave loads. Disadvantages are higher mooring and platform costs. When debating the use of this technology in electrical installations, one important consideration is the fact that floating electrical usually cannot be connected to MI power cables as they are not flexible enough to accommodate this movement.[127]

A pilot turbine called Hywind was first placed in waters off Norway in 2009. Since then, many other floating demonstration projects have been initiated, including the 2013 Fukushima Floating Offshore Wind Farm Demonstration (FORWARD), a project which included the world’s first 66 kV floating power substation (25 MVA). An advanced spar technology was used in this case as the substation foundation.[128] Moreover, the 30 MW Hywind Scotland Pilot Park OWF was commissioned in 2017 to test optimised floating foundation structures. The new design allows for a 17 per cent weight reduction and 25 per cent draught reduction (from 100 m to approximately 75 m); the latter is made possible by an increased diameter as compensation.[129]

8.2 Current demand

The OWE substation foundation market is growing, with most deployment observed in the North Sea.[130] The BSR share is relatively low, however. Future developments in the region are difficult to estimate because there is little certainty about which of the many planned projects will actually be completed.[131] Figure 14 shows the demand forecast for substation foundations in the Baltic Sea through 2030 (both high and low scenarios). As can be observed, there is a significant difference between the expected number of transformers installed in 2025 between the high and low scenarios, and no incremental difference in the 2030 projections.

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[127] Ibid., p. 38–39

[128] ”Fukushima Recovery, Experimental Offshore Floating Wind Farm Project”. HITACHI. 11 November 2013. http://www.hitachi.com/New/cnews/131111c.html (Accessed on 23 March 2017)

[129] “Hywind – Demo Offshore Wind Farm” and “Hywind Scotland Pilot Park Offshore Wind Farm”. 4C Offshore. 2017. http://www.4coffshore.com/windfarms/ (Accessed on 15 November 2017)

[130] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[131] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

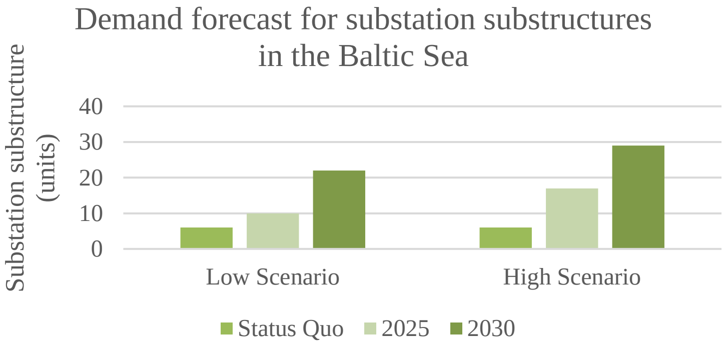

Figure 14. Cumulative demand forecast for substation foundations in the Baltic Sea.[132]

Monopile foundations represent the largest share of foundations for offshore wind turbines in Europe (see Figure 15) and in the BSR have also been used as substation foundations, along with jacket and gravity designs.[133] The European market for substation foundations is dominated by jacket foundations, which can handle large weights and have a good bearing capacity.[134] In the BSR, however, gravity-based designs thus far have been the most commonly used substations foundations. The technology can be found in four out of seven substations installed in the BSR, all located approximately 10 –15 km from shore.[135] Industry observers argue, however, that the future market for this type of foundation is limited because it is not cost-competitive in deeper waters.[136]

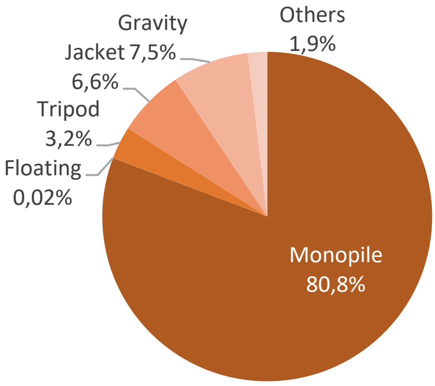

Figure 15. Share of foundation types for grid-connected turbines in 2016.[137]

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[132] Own figure.

[133] 4C Offshore. 2017. http://www.4coffshore.com/windfarms/ (Accessed on 15 November 2017)

[134] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

[135] “Offshore substations database”. 4C Offshore. 2017. http://www.4coffshore.com/windfarms/substations.aspx

[136] Eckert, Kai. “Heavy foundations fort the deep sea”, 33–35

[137] WindEurope. “The European offshore wind industry - Key trends and statistics 2016”. Brussels. 2017 https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf (Accessed on 11 September 2017)

As OWFs move farther from shore, other technologies, like floating foundations, are becoming increasingly attractive because they allow for installation in deeper waters.[138] Companies such as EDPR, Statoil ASA, and Ideol are working towards the development of floating foundations.[139] Technological progress could have a significant impact on the OWE European market; however, expert opinions diverge on the viability of the technology in the BSR.[140]

The submarine strata in the BSR is complex and characterised by non-cohesive soil layers of varying densities, which translate into relatively low bearing capacity relative to that in the North Sea.[141] This can represent a challenge for bottom-fixed foundation design and installation. According to some stakeholders, floating foundations may have an advantage in this respect.[142] Others consider floating solutions in the BSR unlikely due to the average water depth of the region.[143, 144] Despite this uncertainty about the BSR market, floating solutions could provide opportunities for the development of other markets, especially those in the North Sea and the Atlantic.

8.3 Market characteristics

8.3.1 Competitive landscape

Foundation structures must be tailored to site conditions and platform properties, which means that engineering and manufacturing are typically regionally based. To date, most offshore wind foundation manufacturers supplying the European market have been regionally based, with significant players located in the BSR, particularly in Poland and Germany.[145] Major offshore wind foundation manufacturers and their European market shares are presented in Figure 16. The market size of offshore wind substation foundations is relatively small, and the level of competition among suppliers is high.[146] The high capital intensity of the industry presents a major challenge to new companies entering the market.[147] Risk reduction can be achieved through the consolidation of pipe

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[138] Kaushik Das and Nicolaos Antonios Cutululis, *Technology catalogue: components of wind power plants, AC collection systems and HVDC systems,* p. 36

[139] Rocha, Ricardo (Offshore Wind Foundations Project Manager at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

[140] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[141] Cassidy, M. and Gourvenec, S. (2005). Frontiers in Offshore Geotechnics: Proceedings of the International Symposium on Frontiers in Offshore Geotechnics (IS-FOG 2005), 19–21 Sept 2005, Perth, WA, Australia, p. 384

[142] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[143] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

[144] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[145] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

[146] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[147] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

and jacket manufacturers, and this can be anticipated in the future. There is a trend towards fewer but larger-scale companies, which further challenges the capacity of new actors to enter the market.[148]

Manufacturing sites have typically been relatively close to OWFs. However, materials, logistics, and port activities are capital-intensive in Europe. Some industry experts foresee an increase in supply from non-European sources, provided that the products meet strict quality requirements.[149] One example of this trend is the East Anglia wind farm, whose wind turbine are partially manufactured in the Middle East. The substation foundations, however, were manufactured in Europe.[150] The rate of entry of new foreign suppliers into the European offshore wind industry can be influenced through policy design and thus depends on national strategies. [151]

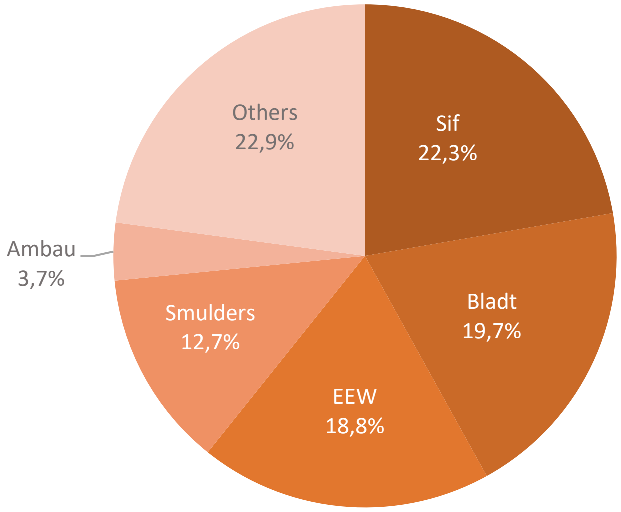

Figure 16. Offshore wind foundations: main manufacturers and market shares as of the end of 2016.[152]

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[148] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[149] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

[150] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[151] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[152] WindEurope. "The European offshore wind industry - Key trends and statistics 2016". Brussels. 2017 https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf (Accessed on 11 September 2017)

8.3.2 Manufacturing bottlenecks

At this time, no major bottlenecks are foreseen in the OWE substation foundation supply chain. This is not expected to change, given the status quo.[153]

8.3.3 Price trends

Economies of scale, greater experience in logistics, and installation optimisation have reduced costs. Further price reductions will likely result from technological improvements, manufacturing or commercial progress, and product stabilisation (e.g. through close collaboration or joint research and development (R&D) projects between pipe manufacturers and platform fabricants).[154] In some cases, monopiles are associated with lower costs and perceived as less risky than jackets foundations; this is largely due to the fact they have fewer joints and potential cracks, making them less vulnerable to corrosion.[155]

8.4 Technological trends

OWE substations have undergone considerable technological progress in recent years. R&D projects are being pursued in many countries, including England, Germany, Denmark, and the Netherlands.[156] Many resources are now being invested into technological development to achieve quality improvement, reach greater depths, and allow for standardisation. As a result, a variety of new solutions are emerging in response to growing design constraints. For example, a recent innovation occurred in the BSR as part of the Arkona project, where a new technology for corrosion protection was tested. An industrial infrastructure site named Thermalius was built in Rostock, Germany, to allow for the application of thermal-sprayed aluminium coatings on monopiles. Achieving metallisation of the complete foundation structures is an industry advancement.

Even though floating foundations have already been used for decades in the oil and gas sector, they are still considered to be at a relatively early stage of development in the OWE industry and are associated with relatively higher costs than other foundation types.[157] Many experts, however, expect this technology to be a ‘game changer’ by providing access to deeper waters and greater wind resources. Full maturity of floating technologies is forecast to enable wind farm installation at depths surpassing 100 m.[158, 159] Moreover, their production, installation, and decommissioning value chain differs from that of the other foundation types, and this may provide opportunities for new European companies to

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[153] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[154] Ibid.

[155] Eckert, Kai. “Heavy foundations fort the deep sea”, 33–34

[156] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

[157] Eckert, Kai. “Heavy foundations fort the deep sea”, 35

[158] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[159] Eckert, Kai. “Heavy foundations fort the deep sea”, 35

enter the OWE foundation supply chain, which thus far has been largely closed to entrants. Considerable progress is expected to result from the ongoing R&D for floating foundations, and significant cost reductions are expected by 2025.[160]

Continuous offshore foundation development offers great innovation potential for OWE deployment. Investment in the field must be sustained to further drive down costs and enable access to a wider range of locations and wind resources.

8.5 Barriers to entry

With regard to many other components within the OWE industry, the need for experience and a proven track record is a barrier for new companies seeking to enter the OWE foundation market. Other potential barriers include the considerably high financial risk and substantial capital expenditure required, the frequent delays due to financing and logistics, and the internal organisational risks (e.g. the need for high overhead to avoid affecting production capacity).[161] Many substation foundation contracts are awarded for engineering, procurement, and construction (EPC), and suppliers must be able to bear considerable risk.[162]

Furthermore, as the OWE industry becomes a scale industry, it is growing more difficult for smaller enterprises to enter the market and compete. In the supply chain for substation foundations, smaller companies such as secondary steel manufacturers often pair with larger entities to share responsibilities, reduce risks, and allow for financing.[163] Sectors like engineering, installation, logistics, and sub-components (e.g. small steelwork) are examples of potential openings for SMEs to compete in the supply chain.[164] Providing add-on products to the portfolios of existing companies could also create new business opportunities for SME (e.g. offering new metallisation services).[165]

The offshore wind substation foundation market is currently stable. However, because of the recent drop in oil prices, some projects in the oil and gas industry have been postponed or delayed. As a result, foundation manufacturers that formerly operated in the oil and gas sector have diversified their activities and entered the offshore wind foundation market. This has resulted in a higher level of competition in the offshore wind

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[160] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[161] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[162] Rocha, Ricardo (PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. July 25, 2017; Gose, Manfred (Senior Consultant at Lahmeyer International). Phone interview by Elizabeth Côté and Julia Sandén. 5 July 2017

[163] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[164] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[165] Rocha, Ricardo (OWE Foundations PM at E.ON). Phone interview by Elizabeth Côté and Julia Sandén. 25 July 2017

substation industry.[166]

To date, offshore wind foundation suppliers serving the European market have come from Europe. As noted before, however, foreign manufacturers have shown growing interest in the European market. According to some experts, another remaining barrier to entry for foreign companies is the quality defects observed in the industry on many occasions in the past; this has had the effect of closing the circle of recognised suppliers.[167] One example of this is the costly legal dispute between the Greater Gabbard OWF owners. When problems with some of the installed monopiles emerged in 2011, Greater Gabbard Offshore Winds Limited (GGOWL) — the joint venture between SSE Energy Supply Limited and RWE AG — asked the US constructor Fluor to proceed with repair. Fluor claimed €359 million, arguing that the requested rework was a design change. GGOWL counter-sued the contractor, suggesting that 52 of the 140 monopile transition pieces were flawed. The dispute was finally resolved in May 2013.[168] In interviews, some experts suggested that such incidents have reduced the level of trust towards foreign companies.[169]

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[166] Schorge, Christoph (Managing Director Erndtebrücker Eisenwerk at EEW), and Melissa Sassmannshausen (Head of Marketing at EEW). Phone interview by Elizabeth Côté and Julia Sandén. 2 August 2017

[167] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

[168] Wind power offshore. "*Be prepared for new technology defects*". https://www.windpoweroffshore.com/article/1217165/prepared-new-technology-defects (Accessed on 8 May 2018)

[169] Interviews by Elizabeth Côté and Julia Sandén. WindEurope Conference & Exhibition, Amsterdam, 28–30 November 2017

9. Overview and analysis of operation, maintenance, and service market

9.1 Activities description

Operation, maintenance, and service (OMS) activities have evolved greatly since 2001, with major improvements in condition monitoring and forecasting in particular. Technological innovations have allowed servicing to transition from a reactive to a more proactive approach. This strategic change has the potential to reduce OPEX and increase energy generation, as explained in the sections below.[170] OMS activities include what is achieved in between the completion of the installation work and the decommissioning of wind farms. As the scope of this work mainly focuses on transmission and distribution systems (excluding wind turbines), only balance-of-plant (BOP) activities are addressed. This includes the supporting components and auxiliary systems needed to produce energy. Important OMS activities include: contract management, operation management, onshore facilities, BOP planned maintenance and unplanned services, and offshore logistics.[171] A brief overview of these activities is provided in the following section. This overview includes examples of both underwater and above-water activities.

9.1.1 Contract management

Today wind farm owners employ three main approaches to managing contracts for OMS activity: hands-off, light-touch, and hands-on. Hands-off agreements are ‘full-package’ contracts with manufacturers that become responsible for BOP daily operations management and for planned maintenance and unplanned services. Light-touch contracts transfer the responsibility of BOP activities to other specialist contracts, including for electrical BOP, foundations, onshore operations, and vessel and helicopter support activities. In this type of agreement, the owner is responsible for the management of part or all of the necessary operating activities. With hands-on contracts, a team of OMS specialists is defined and works with specialised subcontractors (e.g. vessel operators and high-voltage electrical engineers) to ensure that all OMS activities are achieved. Hands-on contracts are the type of agreement in which the owner takes on the greatest risk; they also present the best opportunity to reduce OPEX and optimise energy generation. Among investors, however, the hands-off contracts are preferable because they minimise risks and transfer liability to key suppliers.[172]

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[170] International Renewable Energy Agency (IRENA). “Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[171] Ibid.

[172] Ibid.

9.1.2 Operations management

Operations management activities include daily workflow management and the use of systems that store and process Supervisory Control and Data Acquisition (SCADA) or other condition-monitoring and site information. These tasks are key to responding efficiently in case of system failure and in some cases may even prevent deficiencies. Adequate data collection and analysis allows for the mobilisation of required resources before failure occurs, thereby optimising energy production and the utilisation of capital, equipment, and personnel. Operations management activities are typically either subcontracted to specialists or implemented internally by the wind farm and grid owners.[173]

9.1.3 Onshore facilities

To provide for the OMS needs of offshore wind transmission, onshore bases are created at or near the dockside. This generally applies for sites less than 50 km from suitable ports. For wind farms with a capacity greater than 500 MW, the onshore facility is designed to support the activities of three or more personnel transfer vessels (PTV) as well as a team of approximately 45 offshore technicians and 15 onshore support employees, including management. This facility normally contains a control room, a store, and health and welfare amenities. For sites farther than 50 km from suitable ports, other support solutions are emerging. These are discussed in later parts of this document, particularly the sections on offshore logistics and future technological trends.[174]

9.1.4 Balance-of-plant OMS

Regular monitoring of electrical transmission components is an important activity to prevent corrosion, disturbance, and system failure. For example, the interface between monopiles and transition pieces or the welded joints of jacket foundations have called for remedial actions in some cases, and thus need regular monitoring. As for cables, disturbances may result from natural phenomena, such as tides or currents, but also from human activities (e.g. through the anchoring or jacking-up of vessel legs). Monitoring can be done through sensors that are installed by the offshore transmission owner or a contracting third party and used to conduct surveys and repairs. Surveyors formerly resorted to divers but are increasingly using sonar technologies that are piloted remotely by subsea vessels or aerial drones. It is common practice in the industry for the offshore transmission owner to reach an agreement with a specialist firm to survey, repair, and rebury the cables as needed.[175]

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[173] Ibid.

[174] Ibid.

[175] Ibid.

9.1.5 Offshore logistics

Offshores logistic activities mainly revolve around ensuring resource transport from the onshore base to the OWF. In the past, OMS activities for most projects were carried out from the closest port or base, using small personnel transfer vessels (PTVs). New designs for larger PTVs reduce transit time, allow for a greater range of maintenance activities, and support access through difficult sea conditions. PTVs are typically twin-hull customised vessels that can now be up to 27 m long to allow for the transport of as many as 24 passengers and 20 tonnes of spare parts or equipment and can reach speeds up to 30 nautical knots. Currently, most vessel hulls are made of aluminium, which provides great resilience. However, there is an increasing trend towards fiberglass to reduce the costs of construction and operation. Typically, these vessels are not directly owned or operated by wind farm or transmission owners, but rather supplied by specialised firms. Future improvements in personnel transfer and access to wind farms is also anticipated due to further progress in PTV design, which allows for the delivery of larger crews and greater payload capacities.[176]

As wind farms are built farther from shore, some wind farm owners are choosing to transport technicians by helicopter to save time when tasks do not require many parts or large amounts of equipment. Special features, such as dynamic positioning systems, enable technicians to access wind farms, even when waves are high.[177] Maintenance strategies that use helicopters for personnel transfer increase the efficiency of OMS activities and provide access to sites that PTVs are unable to reach due to weather conditions. However, if tasks require equipment or parts, a move towards larger service operation vessels (SOV) is needed. SOV are designed to be able to stay on-site for longer periods of time than are PTVs. They provide more sophisticated personnel access systems as well as a crane to further enable OMS activities. Siemens is the pioneer of SOV technologies.[178] Innovations in access solutions for far-offshore wind farms expand market opportunities. More information on SOV is provided in the section of the document on future technological trends.

9.2 Current demand

As the offshore wind industry is still at a relatively early stage of commercialisation and most of the existing wind farms have not been operating for more than two decades, OMS activities are still being adapted to changing parameters (e.g. increasing the capacity of OWFs or distance to shore). Planning and scheduling of maintenance and repairs remains

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[176] Ibid.

[177] Ibid.

[178] "Offshore wind: delivering more or less: an independent analysis commissioned by Statkraft UK." BVG Associates. July, 2015. https://www.statkraft.com/globalassets/4-statkraft-uk/offshore_wind_more_for_less_pages.pdf (Accessed on 10 October 2017)

a challenge, making cost estimates uncertain. As a rule of thumb, maintenance and repair costs for the entire wind farm are valued at a yearly blanket rate of 3 per cent of the investment cost. Experts estimate operating costs to represent roughly 18–25 per cent of the investment cost.[179] These figures are associated with the whole wind farm and are not specific to the transmission system.

9.3 Market characteristics

9.3.1 Competitive landscape

The offshore wind OMS sector is constantly evolving. As strategies and technological needs change, there is space for new companies to enter the market and compete, provided that they offer cost-saving solutions.[180] For example, the development of new sensor technologies provides an opportunity for SMEs to enter the offshore wind supply chain. Moreover, underwater drones used for tracing and monitoring cables are also a niche market for SMEs.[181] The provision of third-party servicing is expected to increase in the future, multiplying the number of players and thus increasing competition in the sector.[182] The HBC Group, which has a branch in Denmark, is one example of a company based in the BSR that offers OMS products. The company offers diving services, subsea inspection and maintenance products, remotely operated vehicle (ROV) work, and many other services.[183] In Germany, Baltic Taucherei- und Bergungsbetrieb Rostock GmbH, also known as Baltic Diver Germany, offers many offshore wind OMS products, including diving work, sea-cable laying and recovery, and ROV and sonar operations.[184] Additionally, large manufacturing companies (e.g. the Prysmian Group, ABB, Siemens, and GE Grid Solutions) provide additional OMS for offshore wind transmission system owners.

9.3.2 Price trends

In recent years, the offshore wind industry has experienced OMS improvements, which have led to cost reductions. The progress is mainly the result of an increase in operations experience and data accumulation.185 Between 2001 and 2015, OMS developments have

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[179] Iken, Jörn. “Costs falling faster than expected”. Offshore Wind Industry Magazine, no. 02 (2017): 44

[180] International Renewable Energy Agency (IRENA). “Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[181] Interviews by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[182] International Renewable Energy Agency (IRENA). “Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[183] Huth, Alexander (Sales and Project Management at HBC Group). “Deutsche Windtechnik Offshore & Consulting,” (HBC Group, 2017). Power Point presentation

[184] “Baltic Divers Germany Services”. Taucherei- und Bergungsbetrieb Rostock GmbH. 2015. http://baltic-taucher.com/home/ (Accessed on 11 January 2017)

[185] “Offshore wind: delivering more or less: an independent analysis commissioned by Statkraft UK.” BVG Associates. July,

driven the OPEX down by 3.2 per cent, reducing the levelised cost of electricity (LCOE) of OWE by 1 per cent.[186] Most of the savings from this period are related to improvements in PTVs and access systems.

Although this is a positive evolution, there is still room for improvement. Indeed, IRENA forecasts that with further OMS innovations, savings on OPEX may reach 6.3 per cent by 2030. This translates to a reduced LCOE of 2.5 per cent over the same time period.[187] Most of the savings projected for this period are associated with the implementation of condition-based maintenance, wind-farm wide control strategies, and further developments in personnel systems transfer (e.g. SOVs). The potential savings associated with OMS activities are relatively limited, though still significant. The greatest reductions in LCOE are expected to be associated with the arrival of a new generation of larger wind turbines rather than with further improvement in the OMS sector.[188]

9.4 Technological trends

Offshore wind energy OMS activities are at an early stage of development, and existing strategies and tools require improvements. Further technological progress and experience in the field is projected to reduce the operational cost of energy. Progress is expected to be driven by many fields, including weather forecasting and analysing, remote monitoring, inspections, repairs, condition-based monitoring, offshore logistics, and OMS strategies.

9.4.1 Weather forecasting and analysing

OMS activities are greatly affected by weather conditions. Improvements in weather forecasting and more accurate identification of favourable weather windows will enable a better use of resources and increase the efficiency of OMS activities. It is therefore necessary to improve the accuracy and granularity of forecasts. For an area of 100 km2, current forecast accuracy decreases significantly beyond five days in the future, which makes tasks requiring heavy equipment riskier. Great effort is currently being invested to improve accuracy to reasonable thresholds (e.g. accurate predictions up to 21 days). Further research, development, and demonstration (RD&D) are also conducted in the

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2015. https://www.statkraft.com/globalassets/4-statkraft-uk/offshore_wind_more_for_less_pages.pdf (Accessed on 10 October 2017)

[186] International Renewable Energy Agency (IRENA). “Innovation Outlook: Offshore Wind”. Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[187] Ibid.

[188] “Offshore wind: delivering more or less: an independent analysis commissioned by Statkraft UK.” BVG Associates. July 2015. https://www.statkraft.com/globalassets/4-statkraft-uk/offshore_wind_more_for_less_pages.pdf (Accessed on 10 October 2017)

industry to build more accurate models that help in interpreting weather forecasts.[189]

9.4.2 Remote monitoring, inspections, and repairs

When it comes to underwater monitoring activities, current practices have thus far relied mainly on regular diving operations. For example, when inspecting welded seams for cracks in offshore steel-based substation foundation structures, divers are required to travel to the location with their equipment, remove obstacles (e.g. crustacea, algae or debris), and create an electromagnetic field that, when combined with an iron filling, reveals potential structural damage. Depth and uncertain weather conditions make this work long and laborious. Nevertheless, structural health monitoring (SHM) is of great importance because OWE platforms are subject to strong loads (e.g. waves and wind) and corrosive conditions (e.g. salt water). As a result, maintenance activities are relatively expensive, time-consuming, and potentially dangerous. Minimising direct human intervention is essential to reduce OMS costs and safety risks. The industry has therefore shown a growing interest in automated or remotely operated systems. For instance, sensor rings monitored by ROVs could be used in place of divers and iron fillings. The ring is laid over the welded seam for the entire service life of the structure. Ultrasound waves are used to create an image of the welded seam and potential defects.[190]

The industry requires the sensor system design to offer long-term functionality and be reliable and robust in harsh environmental conditions. Those factors contribute to customer acceptance and to the cost efficiency of the new technologies.[191] The Fraunhofer Institute for Ceramic Technologies and Systems (IKTS), based in Dresden, Germany, has developed a technology for SHM systems that can be used at depths of 20–40 m and provide a service life of approximately 10 years. As of now, data reading must still be performed by divers at the sensor ring location. However, the IKTS continues to pursue research to automatise data-reading using ROVs. These box-shaped devices are not new. Similar systems are already in use in the oil and gas industry and in the OWE industry for visual inspection of underwater structures. For data-reading, ROVs would be used to connect reading devices and proceed to the inspection, which would provide results in only a few minutes.[192]

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[189] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[190] Eckert, Kai. "Technology for efficient underwater operation". Offshore Wind Industry Magazine, no. 02 (2017): 27

[191] Ibid.

[192] "Current research: reliable design of SHM electronics for application in harsh environmental conditions". Fraunhofer IKTS. 2017. https://www.ikts.fraunhofer.de/en/departments/electronics_microsystems/testing_electronics_optical_methods/reliability_microsystems/cr_reliable_design_of_shm_electronics.html (Accessed on 10 October 2017)

This technology was implemented in the Baltic 1 OWF project and has been functioning adequately. Although further improvements are still required, the IKTS hopes to have the system certified and commercialised by around 2021. This new monitoring approach would reduce stress on diving operations while allowing for better accuracy. The system also increases cost savings and time efficiency by providing information on the size and depth of defects; this information is useful in planning repairs.[193]

New remotely operated inspection and repair technologies are also being developed by HOME-Offshore, the Holistic Operation and Maintenance for Energy from Offshore Wind Farms project of a UK-based research consortium. The project investigates the possibility to incorporate robotics technologies into OMS activities. ROVs and remotely operated arms would not only minimise divers' exposure but also allow for longer work windows, as they are independent of diving exposure limitations (e.g. depth, temperature, and time). Further progress in remote inspection and repair technologies using robotics and autonomous systems can be expected in the future.[194]

9.4.3 Condition-monitoring

The OWE industry has thus far used a time-based schedule approach to plan maintenance activities. To minimise unnecessary maintenance, there is a growing tendency towards condition-based maintenance.[195] In this case, activities are planned on the basis of operating experience. Condition-monitoring depends on remote monitoring technologies, system integration, and the ability to coordinate between various disciplines to create a central diagnostic model.[196] Further progress in integrating automated prognostic and diagnostic tools would cut costs considerably.[197]

Modus Seabed Intervention is one company working to innovate system integration and has recently developed an unmanned underwater vehicle (UUV) that can be operate autonomously or as a cable-based ROV. The Modus system has an advantage over conventional autonomous underwater vehicles (AUV) because it features additional propulsions; these allow it to remain still, improving flexibility and making it easier to navigate. AUVs can accomplish different tasks and are suitable for surveillance and

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[193] Eckert, Kai. "Technology for efficient underwater operation". Offshore Wind Industry Magazine, no. 02 (2017): 27

[194] "UK Researchers Developing Human-Robotics O&M System." Offshore Wind. 7 February 2017. http://www.offshorewind.biz/2017/02/07/uk-researchers-developing-human-robotics-om-system/ (Accessed on 10 October 2017)

[195] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[196] Eckert, Kai. "Technology for efficient underwater operation". Offshore Wind Industry Magazine, no. 02 (2017): 27

[197] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

inspection operations.[198]

Although the strategy is not new (condition-monitoring technologies are already in use in onshore wind transmission systems), the offshore environment in which the work is performed is different. Technological development for this tool is progressing fast; however, the time required to change concrete behavioural patterns slows the transitional process down. Moreover, insurance companies must build trust in this new technology before a complete transition is possible.[199] Significant progress and benefits are anticipated for projects commissioned in the early 2020s.[200] Condition-based maintenance is expected to be used in AC technologies by the early 2020s and, for other system components, by the end of 2030.[201]

9.4.4 Improvements in offshore logistics for far-offshore farms

Today, only a few SOVs have been implemented to facilitate the servicing of wind farms located more than 50 km from shore. These vehicles are designed to provide accommodation, equipment, and workspace for up to 50 technicians, allowing them to support other daughter vessels. Increased SOV deployment is projected to service wind farms built farther from shore and sites that currently use onshore maintenance bases. Fred. Olson Windcarrier recently announced plans to construct a fixed offshore base (the 'Windbase'). The offshore OMS platform concept provides accommodation, a full-service base, and a helideck that eliminates the requirement of a quayside base for far-offshore wind farms. Fixed offshore bases may become a cost-effective option for some projects.[202]

Progress in OMS strategies for OWFs located far from shore improves economic viability by enabling access to sites that offer greater wind resources. It is anticipated that current innovations will benefit wind farms commissioned by 2020, with further OMS developments expected by 2030.[203]

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[198] Eckert, Kai. "Technology for efficient underwater operation". Offshore Wind Industry Magazine, no. 02 (2017): 27

[199] Interviews by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[200] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[201] Interviews by Elizabeth Côté and Julia Sandén. Offshore Wind Energy 2017, London, 6–7 June 2017

[202] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

[203] "Fred. Olsen Presents "Game-Changing" O&M Platform." Offshore Wind. 20 November 2015. http://www.offshorewind.biz/2015/11/20/fred-olsen-presents-game-changing-om-platform/ (Accessed on 10 October 2017)

9.5 OMS strategies

With the deployment of OWE, wind-farm density is expected to increase in certain areas, creating clusters. This provides an opportunity to better share OMS equipment and infrastructure, such as SOV or fixed platforms. Adopting a holistic view of OMS and using synergies to reduce interfaces are expected to increase efficiency and reduce annual operating costs. For example, companies such as Deutsche Windtechnik provide services to multiple wind farms and try to coordinate operating activities to save costs. For the company, taking a holistic approach translates to potential savings as high as 20–30 per cent.[204] Deutsche Windtechnik provides many products, including offshore substation inspection, maintenance, repair, and transmission of high- and medium-voltage power.

Another strategy to reduce OMS costs is awarding tenders across multiple wind farms. This strategy has been used by Ørsted A/S, for example, which invites tenders for multiple rather than single farms. Other companies, such as E.ON, have chosen to take matters into their own hands after reaching the end of the warranty period. By adopting a self-performed OMS strategy, E.ON took full responsibility for O&M activities to minimise the input of any other specialised company. The use of employees in multiple farms capitalises on synergies and builds in-house know-how.[205]

Regardless of the strategy adopted by operators, it is expected that the number of OME technicians per installed capacity unit of farms will decrease significantly with time. This change is driven mainly by the introduction of enhanced remote monitoring, prognostics, logistics, and online documentation technologies, as well as by faster interventions. It is anticipated that for wind farms commissioned in 2045, most OMS activities will be planned using condition-based maintenance technologies rather than as unplanned services. This will allow for a proactive rather than reactive approach and will optimise energy output.[206]

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[204] Garus, Katharina. "Utilize synergies, reduce interface". Offshore Wind Industry Magazine, no. 02 (2017): 30–33

[205] Ibid.

[206] International Renewable Energy Agency (IRENA). "Innovation Outlook: Offshore Wind". Abu Dhabi. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Offshore_Wind_2016.pdf (Accessed on 10 October 2017)

10. Conclusion

In 2017, the European offshore wind total installed capacity reached 15,780 MW, with 4,149 grid-connected wind turbines across 11 countries. WindEurope expects the capacity to grow to 25 GW by 2020.[207] Although most installed capacity is located in the North Sea, the BSR offers good conditions for offshore wind development. Based on the Baltic InteGrid, scenarios, the total installed offshore wind capacity in the BSR could reach 9.5 GW by 2030. The market analyses in this report were conducted for specific OWE transmission components (i.e. HVAC cables, HVDC cables, converters, transformers, and substation foundations) and OMS activities, with a focus on European and Baltic Sea markets. Analyses were completed based on a review of relevant literature, semi-structured interviews, and the technical catalogue developed in the context of the Baltic InteGrid project.

The offshore **HVAC subsea-cable** market is mature, with most of the supply provided by three main actors. European manufacturers are dominant, but new players are likely to enter the market as demand grows. New suppliers face significant barriers to entry, including high capital intensity, the need for high-level expertise, and the importance of delivering turnkey solutions. There are no major bottlenecks in the supply chain for HVAC subsea cables, although the potential scarcity of installation vessels could prove problematic as demand rises. Furthermore, it is unlikely that new cable manufacturing facilities will be established in the BSR due to its relatively small market size. SMEs may find business opportunities in the OMS segments. However, high electrical capacitance limits transmission capacity beyond 80–100 km, and work to make this technology more suitable for greater offshore distances has not yet been completed.

HVDC technology has emerged as a solution to the limitations of HVAC technology. The European market for HVDC cables is growing due to increased demand for long-distance transmission. The technology is rather mature, but its application to OWF is still relatively new. In the long run, the use of HVDC technology is likely to increase and become more common in the OWE industry. For now, however, uncertainty and risk associated with the technology make it difficult to forecast demand. Given the current production capacity, there is a risk of shortages when demand increases, a gap that is likely to be filled by established manufacturers. Because the market for HVDC cables is less competitive than that for HVAC, lower price pressure and higher margins are observed. Prices are expected to decrease significantly by 2030 with further technological advancement, increased system reliability, and greater installation experience.

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[207] WindEurope (2018): *Offshore Wind in Europe, Key trends and statistics 2017*

OWE converter demand in Europe is mainly driven by the deployment of HVDC technology. For now, the market is concentrated in the German portion of the North Sea. As farms are built farther from shore, demand is expected to grow, and design improvements are projected to reduce the costs of production and installation to competitive levels. Key factors that challenge market growth include transmission congestion and instability, high initial costs, lack of grid infrastructure investments, lengthy approval processes, and technological limitations. The same major converter suppliers are involved in each European OWE project, and due to the track record requirement and small market size, it is unlikely that SMEs will enter the OWE converter supply chain. No major bottlenecks are foreseen at this point. Recent technological progress has allowed for reductions in surface area and size, reducing installation and OMS costs.

OWE transformer efficiency, rating, weight, and dimensions have improved significantly, driven by increased OWF capacity and changing requirements. As the market continues to grow, further moderate innovations are expected. The competitive landscape for OWE power transformers is characterised by the dominance of a few well-established suppliers. Track record requirements are a barrier to market entry. Tap changer supply, dominated by Maschinenfabrik Reinhausen GmbH, may present a bottleneck in the future European supply chain for OWE transformers, along with copper windings. Prices of offshore power transformers are relatively stable. Further improvements in power density are expected, but no significant reduction in CAPEX is anticipated.

There is a high level of competition among **OWE substation foundation** manufacturers. Thus far, most suppliers on the European market have been locally based, with significant players in the BSR. The market is mature but remains largely closed due to the capital intensity and ‘know-how’ requirements that hinder market entry. At the same time, some industry experts predict an increase in non-European supply. Furthermore, segments like engineering, installation, logistics, and subcomponents are examples of potentially competitive areas for SMEs. No major bottlenecks are anticipated. The prices of OWE platforms are expected to decrease, driven by technological improvements and commercial progress. The European market for substation foundations is dominated by jacket foundations. In the BSR, gravity-based designs have been the most common thus far. An increase in demand for deeper water is contributing to a development push for floating foundations, which could enable the installation of OWF at depths surpassing 100 m.

The **OMS sector** is still relatively immature because OWFs have been operating for less than two decades and activities are still being adapted to changing parameters. Condition monitoring, forecast improvements, and technological innovations have allowed OMS to transition from a reactive to a more proactive approach, reducing costs and increasing energy generation. Most cost reductions have been driven by improvements in personnel transfer vessels and access systems. Future savings are expected from the use of a holistic approach to OMS strategies and improvements in weather forecasting; remote monitoring, inspections, and repairs; condition-based monitoring; and offshore logistics. Condition-based maintenance can be expected to apply to AC technologies in early 2020 and to other system components by 2030. Third-party service is also anticipated to grow. Large manufacturing companies have shown an increasing tendency to offer additional OMS products, such as turnkey solutions. There is space in the OMS market for new companies to compete, provided that they offer cost reduction solutions (e.g. underwater drones).

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Appendix A Maps of high and low development scenarios

A.1. High development scenario for offshore wind in the BSR until 2030

Figure 17 shows the expected offshore wind development in the BSR until 2030 based on the high scenario developed within the Baltic InteGrid project.

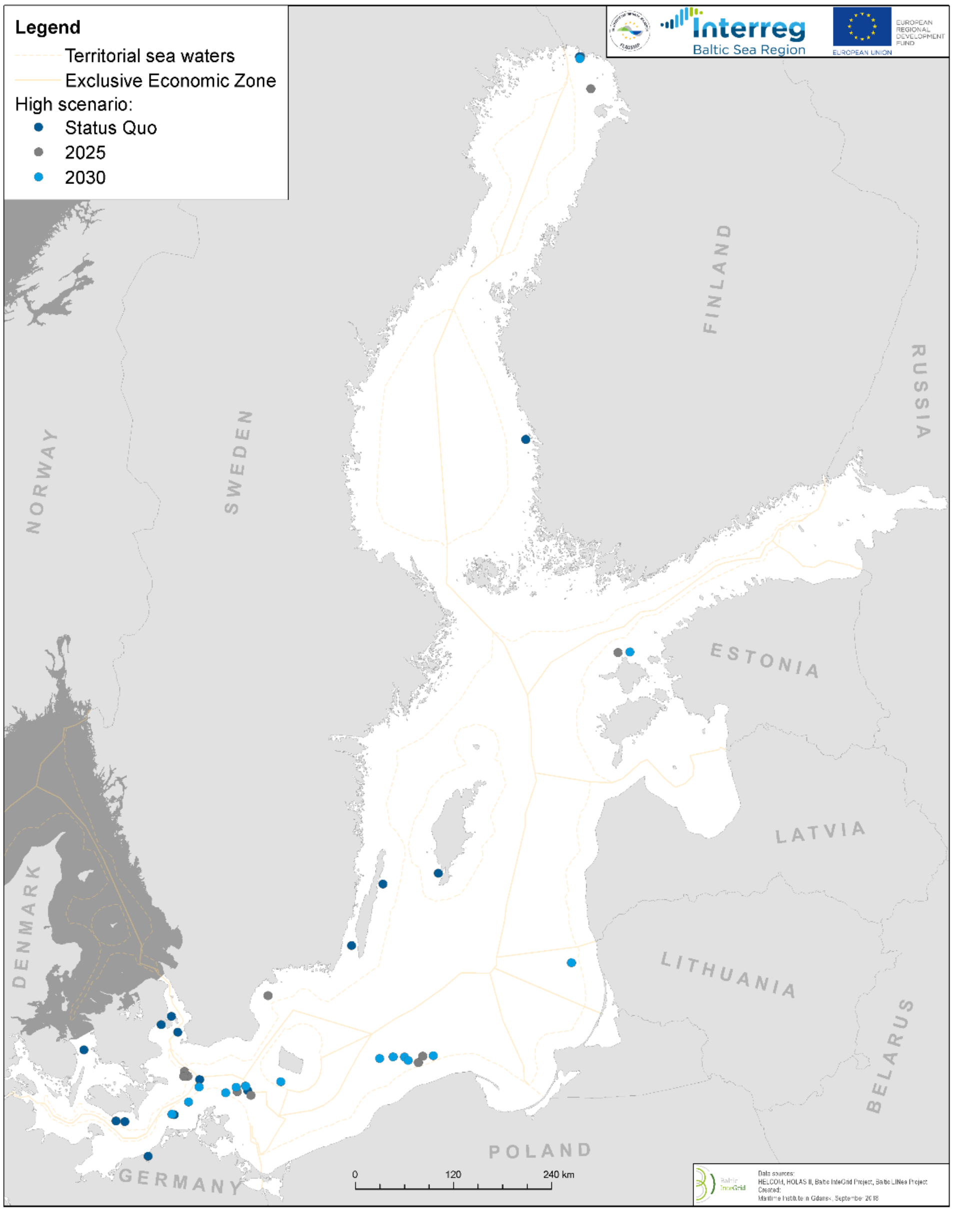

Figure 17. High development scenario for offshore wind development in the BSR until 2030.[208]

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[208] Maritime Institute of Gdansk. *Spatial planning: spatial maps and variants of Baltic Grid component locations*. Baltic InteGrid, WP3, GoA 3.5.

A.2. Low development scenario for offshore wind in the BSR until 2030

Figure 18 shows the expected offshore wind development in the BSR until 2030 based on the high scenario developed within the Baltic InteGrid project.

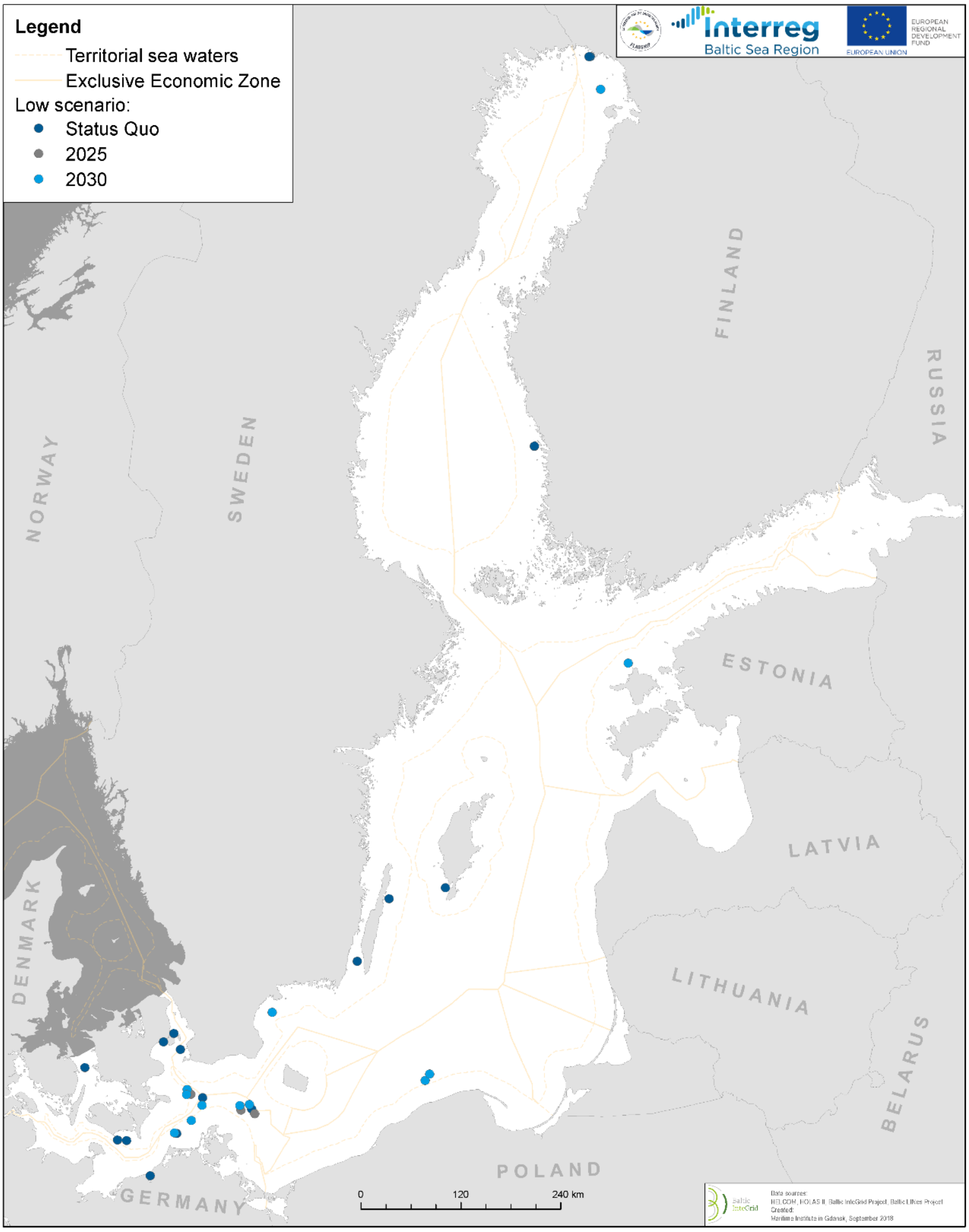

Figure 18. Low development scenario for offshore wind development in the BSR until 2030. [209]

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[209] Maritime Institute of Gdansk. *Spatial planning: spatial maps and variants of Baltic Grid component locations*. Baltic InteGrid, WP3, GoA 3.5.

Appendix B Detailed development scenarios for Member States in the BSR

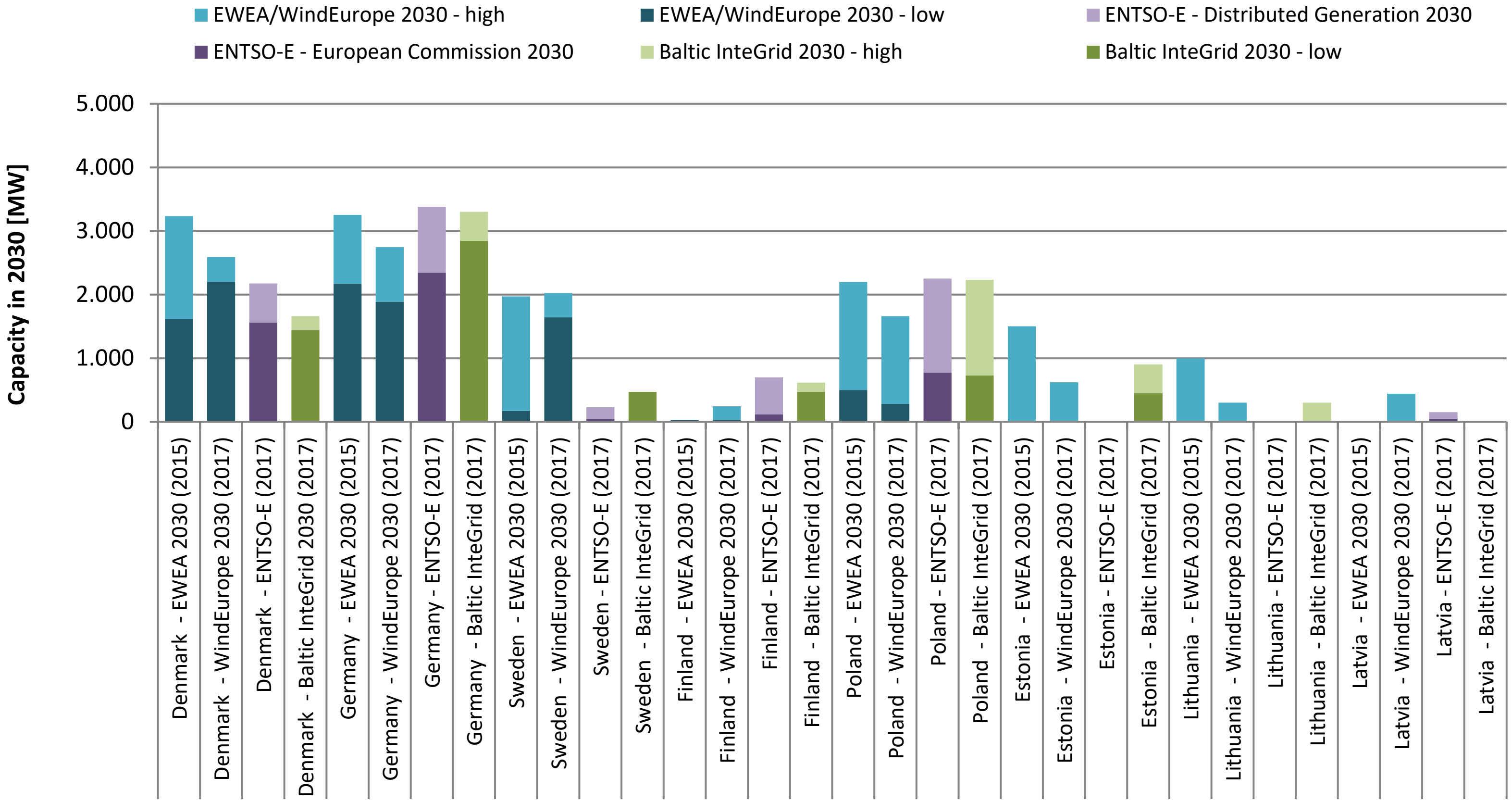

Figure 19. Detailed development scenarios for all BSR Member States.[210]

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[210] Own figure.

Appendix C Work Package 4: Case study 1 and 2, partial integration, high/low scenarios

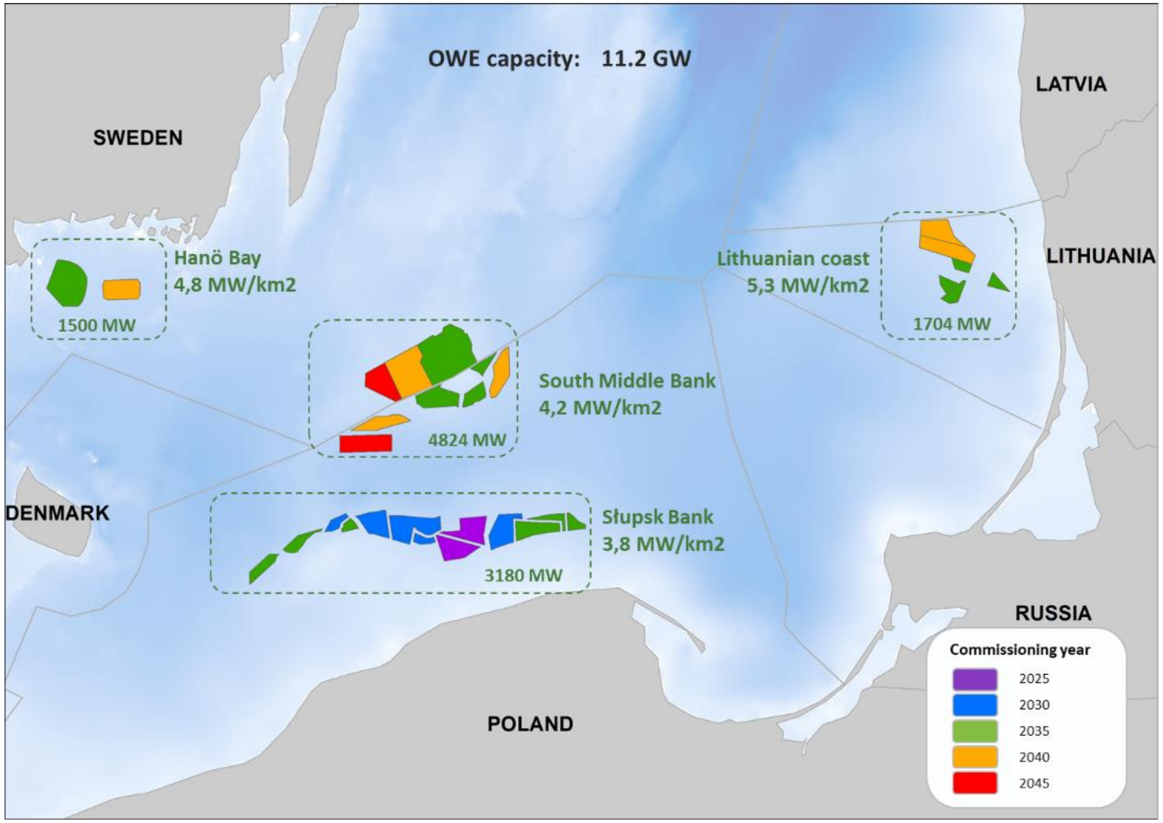

Figure 20. Case study 1, partial integration – high scenario.[211], [212]

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[211] The map estimates the connection points; it does not show the actual cable paths.

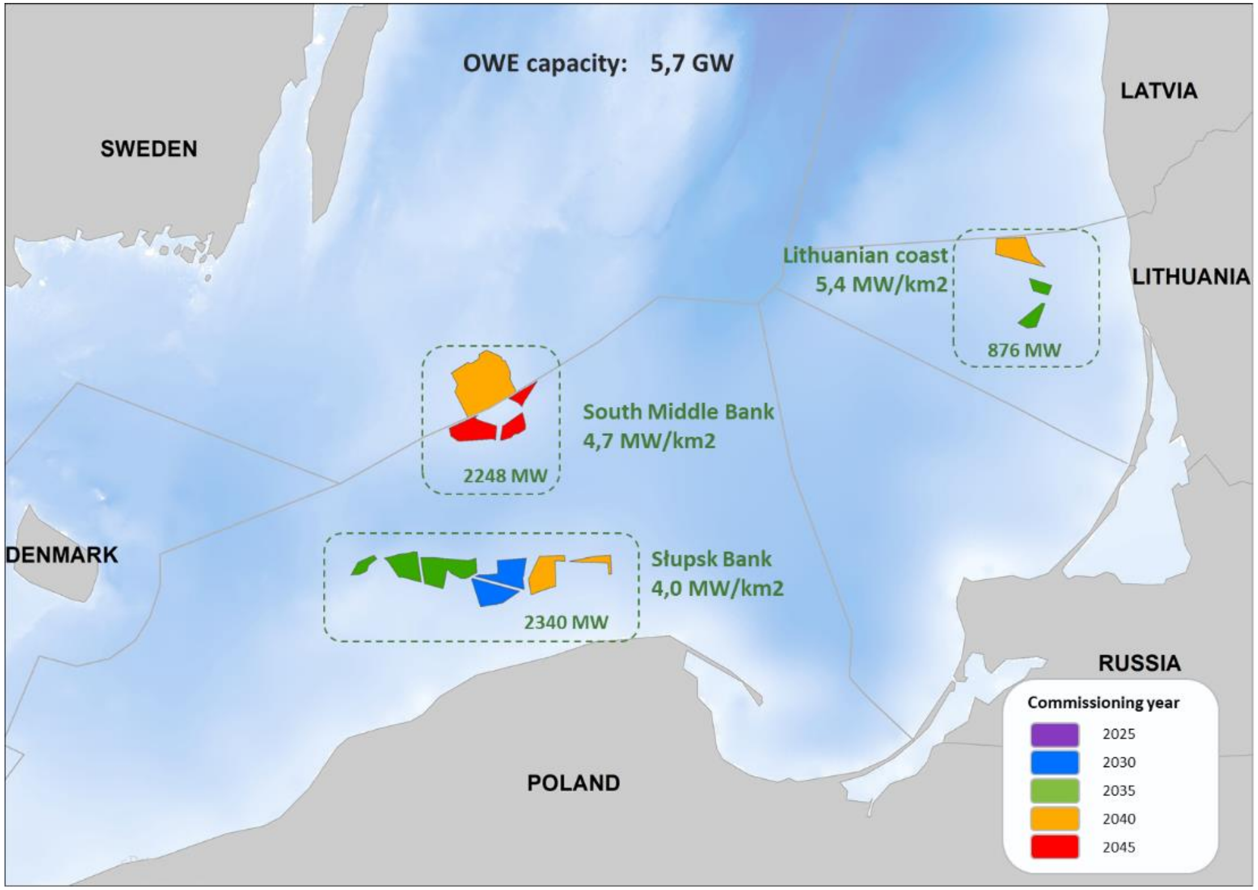

Figure 21. Case study 1, partial integration – low scenario.[213], [214]

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[212] Wójcik et al. *Towards a Baltic Offshore Grid: connecting electricity markets through offshore wind farms*. Baltic InteGrid. p. 39

[213] The map estimates the connection points; it does not show the actual cable paths.

[214] Wójcik et al. *Towards a Baltic Offshore Grid: connecting electricity markets through offshore wind farms*. Baltic InteGrid. p. 39

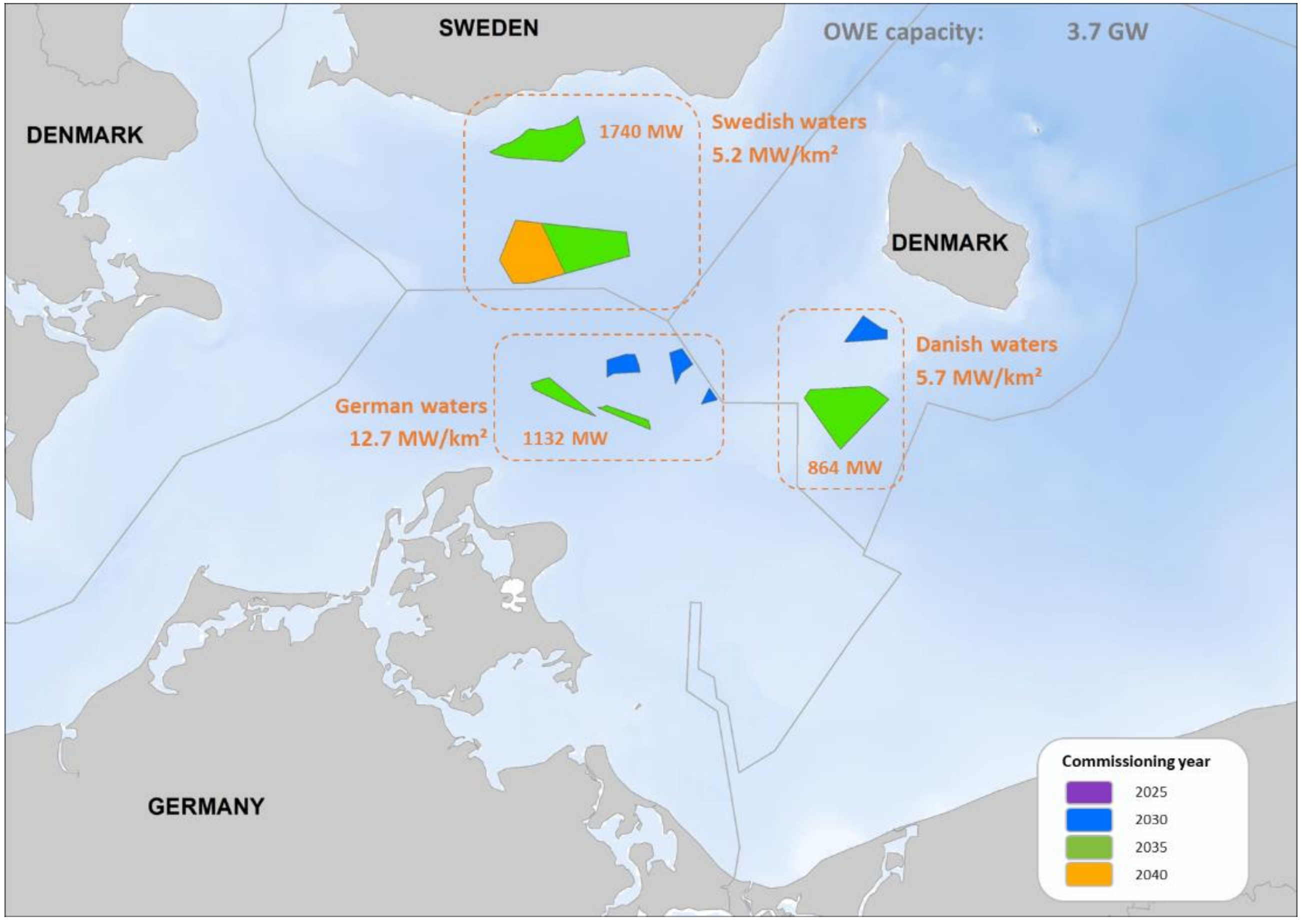

Figure 22. Case study 2, partial integration – high scenario.[215, 216]

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[215] The map estimates the connection points; it does not show the actual cable paths.

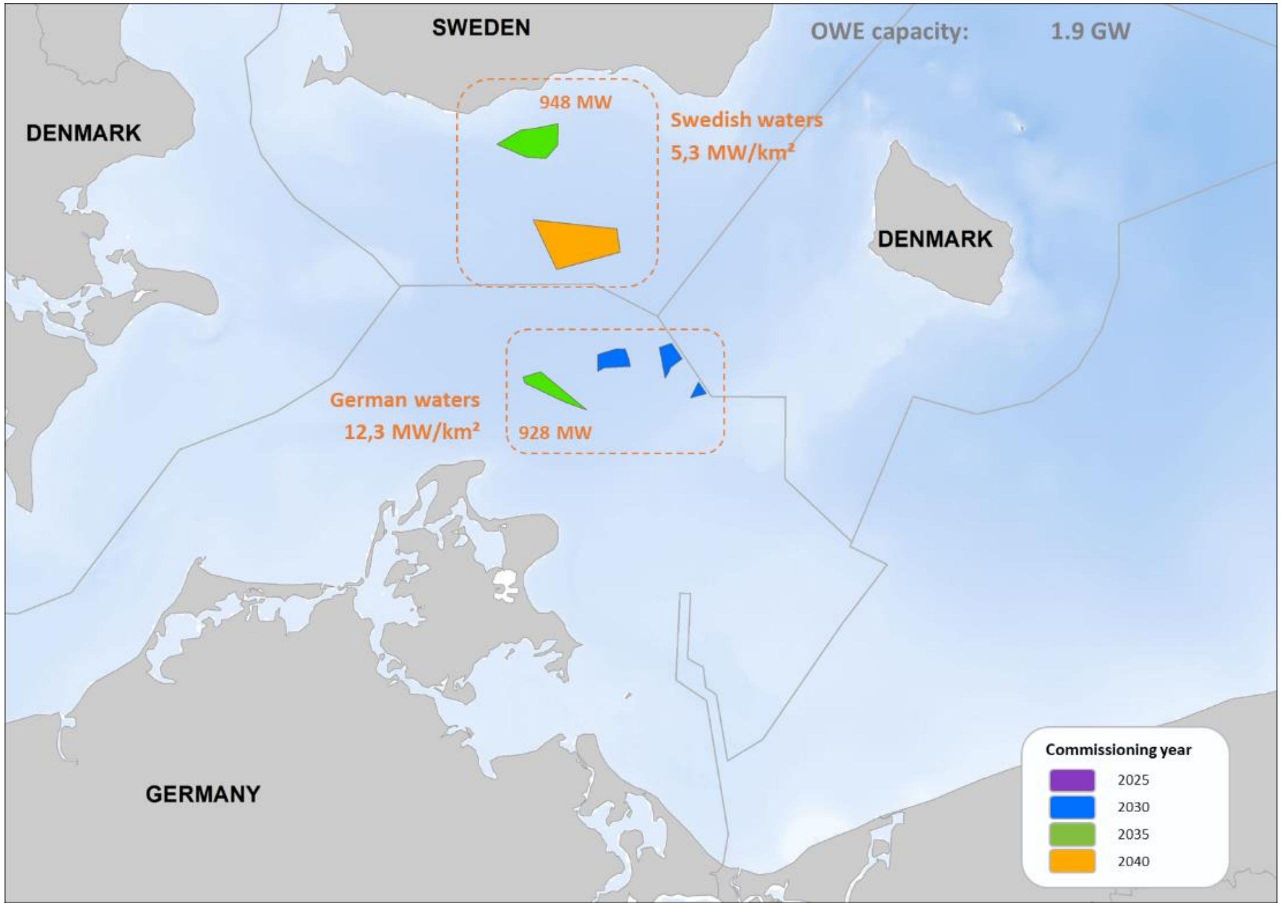

Figure 23. Case study 2, partial integration – low scenario.[217, 218]

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[216] Wójcik et al. *Towards a Baltic Offshore Grid: connecting electricity markets through offshore wind farms*. Baltic InteGrid. p. 65

[217] Please note that the map is not showing the actual cables paths, but gives an estimate of the connection points.

[218] Wójcik et al. *Towards a Baltic Offshore Grid: connecting electricity markets through offshore wind farms*. Baltic InteGrid. p. 65

Appendix D Index of semi-structured interviews

List of interviews conducted during various industry events with experts working for compagnies acting in different offshore wind sectors.

Table 4. Events Interviews Index.

Companies	Interview conducted by
Event: WindEnergy Hamburg, 27–30 September 2016	
NSW Norddeutsche Seekabelwerke GmbH	Bent Christoffer (Rostock Business)
Prysmian Group	Bent Christoffer (Rostock Business)
JDR Cable Systems	Julia Sandén (IKEM), Christian Weiß (Rostock Business)
nkt cables group	Julia Sandén (IKEM), Christian Weiß (Rostock Business)
ABB	Julia Sandén (IKEM), Steve Wendland (Rostock Business)
Nexans	Julia Sandén (IKEM), Steve Wendland (Rostock Business)
Event: Offshore Wind Energy 2017 in London, 6–8 June 2017	
EnBW Energie Baden-Württemberg AG	Julia Sandén (IKEM) Christian Weiß (Rostock Business)
Nexans Norway AS	Christian Weiß (Rostock Business)
Siemens Transmission & Distribution Limited	*Julia Sandén (IKEM),* *Elizabeth Côté (IKEM)*
CG Global Power Systems Belgium NV	Julia Sandén (IKEM), Elizabeth Côté (IKEM)
BVG Associates	*Julia Sandén (IKEM),* *Elizabeth Côté (IKEM)*
4C Offshore	Julia Sandén (IKEM), Elizabeth Côté (IKEM)
Hyosung Corporation UK	*Julia Sandén (IKEM),* *Elizabeth Côté (IKEM)*

Event: WindEurope Conference and Exhibition 2017 in Amsterdam, 28–30 November 2017	
BAUER Renewables	*Julia Sandén (IKEM), Elizabeth Côté (IKEM)*
WRS Rope Access	Julia Sandén (IKEM), Elizabeth Côté (IKEM)
Prysmian Group	*Julia Sandén (IKEM), Elizabeth Côté (IKEM)*
NTK	Julia Sandén (IKEM), Elizabeth Côté (IKEM)
ECN	*Julia Sandén (IKEM), Elizabeth Côté (IKEM)*

Table 5. Index of telephone interviews.

Name	**Position**	**Company**	**Date**	**Interviewer**
Manfred Gose,	Senior Consultant, Department Renewable Energies – Wind Energy	Lahmayer International GmbH	05/07/2017	Julia Sandén, Elizabeth Côté (IKEM)
Dirk Briese	CEO	Wind:research powered by trend:research GmbH	25/07/2017	Julia Sandén, Elizabeth Côté (IKEM)
Ricardo Rocha	Offshore Wind Foundations Project Manager – Arkona Offshore Wind	E. ON	25/07/2017	Julia Sandén, Elizabeth Côté (IKEM)
Christoph Schorge	Managing Director	Erndtebrücker Eisenwerk GmbH	02/08/2017	Julia Sandén, Elizabeth Côté (IKEM)
Peter Hungerschause	Senior sales manager	Norddeutsche Seekabelwerke GmbH	04/09/2017	Julia Sandén (IKEM),