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ENERGY HIGHLIGHTS

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Content

Offshore wind farms – challenges, risks and opportunities for building more resilient national energy systems

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EXECUTIVE SUMMARY

The energy transition is a pathway toward transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century. Renewable energy and energy efficiency measures can potentially achieve 90% of the required carbon reductions. In 2021, the European Commission adopted "Fit for 55", a set of policy proposals preparing the implementation of the European Green Deal. This package proposes to increase Renewable Energy Directive's (RED) renewables target to 40 percent by 2030. Wind and solar energy have become the lowest-cost renewable alternatives that are going to dominate the power supply matrix in many countries worldwide.

Wind energy offers many advantages, which explains why it is one of the fastest-growing energy sources in the world. Onshore wind developers are faced with multiple barriers ranging from land constraints, to public opposition to developments near residential areas. In contrast, offshore wind farms not only have the vast ocean for potential developments, but also face less resistance because they are located far from places where people live. The greatest advantage of locating turbines offshore however is that they are able to generate more energy over the ocean. It takes advantage of the force of the wind that is produced on the higher seas, where it reaches a higher and more constant speed than on land due to the absence of barriers. In order to cope with its climate change ambitious targets, the European Union will need to install 30 gigawatts of new wind farms every year between now and 2030 – a major acceleration in the expansion of wind energy.

The growth of the offshore wind industry has been fostered in European countries bordering the North Sea, where high quality wind resources and relatively shallow water have provided exceptionally good conditions in which to develop offshore wind technologies and bring them to market. Most of the capacity installed or operating for offshore wind to date is located off northern Europe. Over the last decade, offshore wind power has presented considerably increased capacity worldwide, reaching at the end of 2015 a quantity of 12.1 gigawatts developed in Europe. Further growth led to a total installed offshore wind capacity in Europe of about 18 gigawatts in 2018: United Kingdom made the largest contribution with 44% of all installations in megawatts, followed by Germany (34%), Denmark (7%), Belgium (6.4%) and the Netherlands (6%). By 2050, the installed capacity of European Union offshore wind projects is expected to increase by at least 20-fold to 12 gigawatts.

Offshore wind technology involves large turbines installed in the sea that harness the power of the wind to produce electricity. Turbine towers are becoming taller to capture more energy, since winds generally increase with altitude. Off-

shore turbines can also be located close to the load centers along the coasts, such as large cities, eliminating the need for long-distance transmission lines. However, there are several disadvantages of offshore installation, difficulty of access, and harsher conditions for the units. Locating wind turbines offshore exposes the units to high humidity, salt water and salt-water spray, which negatively affect service life, cause corrosion, and oxidation. In general, it makes every aspect of installation and operation more difficult, time-consuming, more dangerous and far more expensive than sites on land.

Developments in wind turbine technologies as well as in foundations and system integration have permitted moves into deeper water, further from shore, to reach larger sites with better wind resources. Floating foundations for deeper water are becoming a tested and proven technology. Currently, the offshore wind turbines, rooted to the seabed by monopile or jacket foundations, are restricted to waters less than 50 meters deep. By eliminating the depth constraint and easing turbine set-up, floating foundations could open the way for power generation from deeper waters. For these reasons, floating offshore wind could prove to be a game changing technology, allowing much wider exploitation of wind resources. Hybrid projects linking offshore wind to other uses – such as hydrogen production or battery storage – represent another important aspect for offshore wind to contribute more widely to the energy systems.

When wind turbines are grouped in large wind farms, they can have a significant effect on radars used for aviation, as they are typically designed to show only moving objects and filter out anything stationary. The interference between wind turbine and radar is now being considered as one of the major challenges towards seeking clearance for new wind energy projects. The tower of wind turbine generator along with the nacelle and the blades presents a large radar cross section to radars, thus creating static clutter. The interference varies according to turbine dimensions, type of radar and the aspect of the turbine relative to the radar. The masking can also occur when returns from the wind turbines are so large that returns from real aircraft are lost in the "clutter" (radar returns from targets considered irrelevant to the purpose of the radar). The extent of the impact caused by shadowing depends on the size and height of the turbine and the target of interest, i.e., different effects may be observed if looking at surface targets or air targets. While the number of wind farms is growing rapidly, the detrimental effect of wind farms on existing radar systems is raising serious concerns. Many radar designers have proposed mitigation techniques to overcome this issue; however, each technique has its own limitations.

The traffic volume and scale of ships are also predictably increasing at sea, which also means that the newly planned offshore wind farm site is particularly critical. The current limited maritime space makes offshore wind farm planning inevitably close to the main channels of surrounding ships and some customary routes. As the wind energy sector is developing, offshore wind farms will cover large areas, and will be located in deeper waters and near traffic lanes. Therefore, ship collision represents a major concern. During the lifetime of an offshore wind farm, collision events may occur with Offshore Supply Vessels (OSV) during the inspection and maintenance process, but also with commercial and passenger ships coming from the traffic lanes. The consequences of collision events may include structural damage of the offshore wind turbines or/and the striking ship, environmental damage and loss of human life.

While offshore wind energy has gathered the political support and investor confidence, several challenges remain. A key bottleneck is the availability and development of grid infrastructure, both offshore and onshore. This challenge, however, presents the opportunity to deploy new and innovative technologies. The future-proof grid will be smart, interconnected and based on a mix of different technologies for generation, transmission and distribution, delivery and control. High Voltage Direct Current (HVDC) can transmit power much more efficiently over long distances compared to wires carrying alternating current (AC), which today is the most common form of transmission for bulk power. The only constraint until now has been the transmission technology and its economic feasibility.

KEY FINDINGS AND RECOMMENDATIONS

The study examines different aspects of the offshore wind farms construction, but the key element for successful and timely deployment of offshore wind farms is co-operation between wind industry, government, the military and defence equipment sector.

- Military surveillance (including radar) systems and offshore wind farms can co-exist successfully. Although further innovation and co-operation is needed to find and deploy solutions which will allow to build out offshore wind farms in areas which are currently constrained due to their impact on air and maritime defence radar.
- Mitigation techniques available include a combination of operational mitigations and technical system modifications and upgrades. Many of the radar systems currently affected by wind turbine interference are likely to be upgraded significantly or replaced by next-generation radars over the next decades. Resilience to wind turbine interference should be a key design requirement for these next generation systems.

INTRODUCTION

The marine environment represents a virtually untapped source of energy, which could theoretically; meet the total global demand for power. Primary amongst these is wind power, which has rapidly increased capacity in recent years. Offshore wind energy is today the only commercial deployment of a marine renewable energy with wide-scale adoption. Ocean energy technologies are currently being developed and tested to exploit the vast source of clean, renewable energy that our seas and oceans have to offer. Although still at the research and development stage and not yet commercially available, promising ocean technologies, include wave energy, tidal energy, salient gradient energy and ocean thermal energy conversion. Wave and tidal energy are currently the more mature of these technologies (Blue Economy Report, 2020)[1].

Given the demand for renewable energy, it seems likely that for countries with large offshore wind and wave resources, an increasing proportion of their offshore coastal water will be turned over to marine renewable energy production. Technological improvements, competitive supply chains, and improving economies of scale will continue to reduce the costs of wind power, positioning it to lead the global electricity sector transition. The International Renewable Energy Agency (IRENA) forecasts that by 2050, onshore and offshore wind power will become the world's leading energy source, generating more than one-third of total electricity needs. The advancement of offshore renewables, such as offshore wind farms (OWFs) or wave and tidal energy devices, is response to increasing energy demands and a key pillar in the global transition to a carbon-free power sector (GWEC, 2019)[2].

The European Union's strategy on Offshore Renewable Energy[3], published in November 2020 is a crucial part of the European Green Deal, which aims at turning Europe into the first net-zero carbon continent by 2050. The Strategy proposes to increase Europe's offshore wind capacity from its current level of 12 gigawatts to at least 60 gigawatts by 2030 and respectively to 300 gigawatts by 2050 by tapping into the vast potential of all Europe's sea basins. The Strategy also acknowledges the high natural potential for offshore wind energy of the Baltic Sea. By 2050, 12% of world primary supply will come from energy, of which 20 percent will come from offshore wind (DNV GL Energy Transition Outlook 2020)[4]. In

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[1] European Commission. "The Blue Economy Report, 2020", European Union.

[2] Global Wind Energy Council (GWEC, 2019). "Global Wind report 2018". https://gwec.net/wp-content/uploads/2019/04/GWEC-Global-Wind-Report-2018.pdf. Retrieved: 28 March 2020

[3] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions" An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future". Brussels, 19.11.2020, COM (2020) 741 final.

[4] DNV GL "Energy Transition Outlook 2020: A Global and Regional Forecast to 2050", Oslo, Norway.

relative terms, offshore wind is growing 85-fold (2050 vs 2016). Europe is by far the world leader in offshore wind energy, with over 90% of the world's total installed capacity. Starting with only a small number of demonstration plants[5] in the early 2000s, the EU now has a total installed capacity of 22.1 gigawatts from 5047 grid-connected wind turbines across 12 countries[6]. Historically, offshore wind development mostly took place in the North Sea in Europe, although China has set ambitious targets for offshore wind. All the largest offshore wind farms are currently in northern Europe, especially in the United Kingdom and Germany, which together account for over two-thirds of the total offshore wind power installed worldwide. As of 2020, the 1.2 gigawatts Hornsea Project One in the United Kingdom is the largest offshore wind farm in the world[7]. Other projects are in the planning stage, including Dogger Bank in the United Kingdom at 4.8 gigawatts, and Greater Changhua in Taiwan at 2.4 gigawatts respectively[8].

Moving of wind installations from land to sea is due to several different factors: the land sites suitable for sustainable exploitation of wind from economic, environmental, and social resources are gradually decreasing. On one hand, the wind resources are abundant, stronger, and are more consistent in terms of their availability than land-based wind resources. In fact significantly higher energy production is achieved due to larger wind turbine ratings[9] and stronger wind profiles. Visual impact, as long as moving far enough from the coast, is reduced; it is possible to revitalize the offshore industrial sector and the ports, currently in decline in many European regions, and to create jobs in the frame of a "blue" and "green economy"[10]. One of the challenges related to offshore wind installation is the higher cost as compared to land-based counterparts, which, until a few years ago, was not completely compensated by the higher energy production.

Offshore wind has moved quickly from being a niche to a mainstream supplier of low carbon electricity, becoming a favored form of renewable energy generation. Large commercial-scale projects are currently operating in European waters for bottom-fixed wind turbines but other technologies are starting to catch up. Large commercial floating wind energy projects are being announced in some EU countries and ocean energy is reaching a level of maturity that makes them attractive to future applications. The main advantage of locating turbines offshore, however, is that they are able to generate more energy in the ocean. Since wind is both stronger and more consistent off the coast than on land, deployed to date offshore wind turbines can produce around 11 megawatts (MW), although the orders being taken for future deployment are about to produce between 14 to 15 megawatts of power. Onshore technical development is constant, which results that currently the largest onshore turbine can reach about 6 megawatts (MW). At its maximum potential, offshore wind production could reach more than 120,000 gigawatts (GW) or 11-fold the projected global electricity demand in 2040 (Lee& Tan, 2021)[11]. Even if the world only develops its most feasible, near-shore wind sites, those projects would still provide more electricity than it is consumed today. A study by Bosch et al. (2018)[12] has found the global offshore wind energy potential to be 329.6 terawatt-hours (TWh), with over 50% of this potential being in deep waters. These numbers underline the need to take advantage of the floating offshore wind energy source with a view to addressing the continous growth in global energy consumption.

[5] The first offshore wind farm (Vindeby) was installed in Denmark in 1991 and decommissioned in 2017.

[6] Wind Europe (2019). "Offshore Wind in Europe. Key trends and statistics 2018".

[7] Hornsea Project One is an offshore wind farm located off the Yorkshire coast within the Hornsea Zone in the southern North Sea.

[8] "Orsted clears Taiwan hurdle", ReNews – Renewable Energy News, 6 December 2017.

[9] The most important factors to obtain optimal kinetic energy from the wind are the diameter of the rotor blades and wind speeds. The greater the diameter of the blades, the greater the area of the space swept by the blades that has a direct correlation with the output of energy.

[10] Green economy strategies tend to focus on the sectors of energy, transport, sometimes agriculture and forestry, while the blue economy focuses on the fisheries sectors and marine and coastal resources.

[11] R.Lee, J.Tan. "The Rise of Wind Energy". Clyde& CO, 08 March 2021.

[12] J.Bosch, I.Staffel, and A.D. Hawkes. "Temporally explicit and spatially resolved global offshore wind energy potentials". In *Energy,* 2018, 163, pp. 766-781, https://www.doi.org/10.1016/j.energy.2018.153, 2018

The EU has the largest maritime space in the world and is in a unique position to develop offshore renewable energy due to the variety and complementarity of its sea basins. Regional co-operation has recently stepped up in some sea basins, with the North Seas Energy Co-operation (NSEC)[13] providing the most advanced example and reference point for other countries willing to tap the full potential of offshore renewable energy. Offshore renewable energy is now a European priority and co-operation at regional level is being extended to all sea basins. The work ongoing in the Baltic Energy Market Interconnection Plan (BEMIP) or the High Level Group for South-West Europe on interconnections and the Central and South Eastern Europe Energy Connectivity (CESEC) is very relevant in this context.

The North Sea has a high and widespread natural potential for offshore wind thanks to shallow waters and localized potential for wave and tidal energy. It is currently the world's leading region for deployed capacity and expertise in offshore wind. The Baltic Sea also has a high natural potential for offshore wind energy (European Commission, 2019)[14] and some localized potential for wave energy. Countries have started to co-operate more closely to tap this potential, including in the Baltic Energy Market Interconnection Plan (BEMIP) High-Level Group, the Vision and Strategies Around the Baltic Sea Initiative (VASAB), the Baltic Marine Environment Protection Commission (Helsinki Commission –HELCOM), and the EU strategy for the Baltic Sea Region[15].

As a renewable energy source, offshore wind has a much smaller impact on the environment than conventional power generation based on fossil fuels. The majority of offshore wind farms are located on the continental shelf, about 10 km off the coast in water depths of about 10 meters. Offshore wind production is much more complicated than onshore in terms of design of the wind turbines' system and construction of the wind farms. Turbines must be located above the crest level of the highest waves, and have strong support structures connected to the seabed by foundations. Existing installed offshore wind turbines with fixed foundations, such as gravity base, monopile, tripod and jacket foundations, are installed in water depths about 50 meters. For water depths greater than 50 meters, the wind resource is substantial but bottom-fixed offshore wind turbines are no longer an economic proposition for the wind resource exploitation. Consequently, floating offshore wind turbines[16] have attracted much interest in the past decade. As the costs of offshore wind power and energy storage have fallen in the few years in a row, there are plans to combine these two technologies together, to boost the flexibility and economic viability of offshore wind still further.

European maritime space is used for many offshore activities alongside wind power generation. Such offshore activities include oil and gas exploration, fisheries, submerged pipelines, transmission cables, ICT infrastructure, shipping lanes as well as recreational uses and defence. Some of these uses are mutually exclusive, but others can be combined. This all has created a need for marine conservation efforts, and during the last decade, the use of ecosystem-based spatial approaches[17] has considerably accelerated. Therefore, the rapid increase in renewable energy generation from wind has increased concerns about the impacts that wind arrays have on the marine environment and what these impacts mean for society. The seas in northern Europe are strongly affected by human activities and there is a great need for improved marine conservation efforts (Hammar et al, 2016)[18]. The same region is also the current hotspot for offshore wind power development. Today marine management often involves ecosystem-based marine spatial planning, a process that brings together multiple users of

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[13] Established in 2016.

[14] Ninety-three GW according to the study by the European Commission. "Study on Baltic Offshore wind energy cooperation under BEMIP". Final report, June 2019

[15] www.balticsea-region-strategy.eu

[16] A floating wind turbine is an offshore wind turbine mounted on a floating structure that allows the turbine to generate electricity in water depths where fixed-foundation turbines are not feasible.

[17] Ecosystem based marine spatial management is an approach that recognizes the full array of interactions within an ecosystem, including human uses, rather than considering single issues, species, or ecosystem services in isolation.

[18] Linus Hammar, Diana Perry, Martin Gullström. „Offshore Wind Power for Marine Conservation". In *Open Journal of Marine Science*, Volume 6 (1), January 2016.

the ocean/sea – including energy, industry, government, conservation and recreation – to make informed and coordinated decision about how to use marine resources sustainably.

In 2021, all coastal EU countries establish their maritime spatial plans and submit them to the European Commission, specifying the intended use of their national waters. As offshore wind turbines grow larger and are spaced further apart, co-location will increasingly need to be considered to balance all interests. One example of co-location is that offshore wind farms if developed as hybrid solutions, could serve both renewable energy resources and as a transmission link connecting two or more markets. Another example is that air and maritime defence radars might be upgraded, relocated or reconfigured to provide the needed coverage, thus allowing for a co-existence between defence needs and energy generation. However, the growing space requirements for offshore wind energy also raise a more general societal discussion of how to best utilize Europe's limited maritime space. Sites or areas with limited existing uses of the sea or seabed are becoming increasingly scares. Eventually, there will be too few areas to sustain the continued expansion of offshore wind generation needed to decarbonize Europe. Larger, more coherent areas are required and shared use of maritime space should be considered.

In order to identify barriers for offshore renewable energy developments in areas reserved for defence activities and to improve co-existence between energy and defence sectors, European Commission and the European Defence Agency (EDA) agreed to set up joint action (European Commission, 2020)[19]. European Defence Agency has also the Consultation Forum for Sustainable Energy in the Defence and Security Sector (CF SEDSS) in place, a European Commission funded initiative[20]. One of the working groups of CF SEDC – Renewable Energy Sources also includes works to support this action and contracted a study on Offshore Energy that is due to be released in the first quarter of 2022.

However, erecting a wind farm involves many considerations including consultations with various civil or military aviation interests. They may raise objections to a proposed wind farm for various reasons. One common objection is that wind turbine may be a threat to the safety of low-flying military aircrafts. Another objection is that wind turbine may appear as a strong radar echo. This echo may distract the radar from the target echoes, which are its main interest and can reduce the effectiveness of the radar by masking genuine target echoes (Wen-Qin Wang, 2013)[21]. The images produced by marine radars detect not only hard targets such as ships and coastlines, but also reflections from the sea surface, known as "sea clutter". Sea clutter echoes may make it impossible to detect some targets, while the presence of others may only be revealed by skillful adjustment of the controls or with the assistance of some form of signal processing. Therefore, offshore wind turbines may pose unique impacts to coastal radar systems given the differences in propagation of radar signals over the sea/ocean versus land, as well as the larger size of offshore wind turbines compared to land-based counterparts. The potential interference of wind turbine generation with the performance of ship-based radar systems raises concerns for safe marine navigation near or around offshore wind farms. As offshore wind deployment continues to grow, it is expected that there would be potential for interference with existing radar systems.

Exploiting the offshore wind energy potential introduces a number of challenges, one of which is the variable nature of the energy source. The intermittency results in a considerable variability on different time and spatial scales, leading to a highly fluctuating power production and even power-discontinuities of various durations (Sol-

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[19] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions" An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future". Brussels, 19.11.2020, COM (2020) 741 final.

[20] The Forum was established with the primary scope to create a defence-related community to share information, knowledge and best practices on improving energy management, increasing energy efficiency and buildings performance, utilizing renewable energy sources in the defence sector and enhancing resilience of defence related critical energy infrastructure.

[21] Wen-Quin Wang. "Detecting and mitigating Wind Turbine Clutter for Airspace Radar Systems". In *The Scientific World Journal*, Volume 2013, Hindawi Publishing Corporation.

brekke et al., 2020)[22]. Reserves are needed to balance the differences between power generation and load demand in power systems. Therefore, the integration of wind energy to power systems is confronted with many challenges, including reduction or elimination of power fluctuations, maintaining power quality and voltage profile when connecting to weak grids, prediction of wind power, and changes in the way conventional power plants are operated. This is turn may lead to adverse voltage variations and other effects. Energy storage can help address the intermittency of wind power, it can also respond rapidly to large fluctuations in demand, making the grid more responsive and reducing the need to build back-up power plants.

Energy storage has rapidly moved from nascent technology to a cornerstone of the energy transition. The effectiveness of an energy storage facility is determined by how quickly it can react to changes in demand, the rate of energy lost in the storage process, its overall storing capacity, and how quickly it can be recharged. The next stage of the energy transition is the ability to combine clean generation with its intermittent sources with grid scale storage solutions. It can be in the form of providing frequency response, reserve capacity, black-start capability and other grid services, to storing power in electric vehicles.

As the need for longer duration storage increases along with surging renewable deployment, there is an increased potential for near-commercial technologies to provide value. Power-to-X technologies have gained increased attention since they actually convert renewable electricity to chemicals and fuels that can be more easily stored and transported. Power-to-X is an umbrella term for a number of conversion, storage and re-conversion pathways that use surplus electricity power from renewable energy, typically solar and wind. “X” stands for the type of energy into which the electricity surplus is being converted. These are generally gases, liquids and heat.

Hydrogen (H_2) production through water electrolysis is a promising approach since it leads to the production of sustainable fuel that can be used directly in hydrogen fuel cells or to reduce carbon dioxide in chemicals and fuels compatible with the existing infrastructure for production and transportation (Vasconselos & Lavoie, 2019)[23]. The energy stored as chemical energy can be exploited in several final uses, which can be thermal, fuel for mobility applications, reconversion to electricity, or synthesis of liquid fuels or chemicals. This concept, which integrates several energy sectors by means of hydrogen as an intermediate energy vector, is known as *sector coupling*, and it is the driving force of the rising interest in hydrogen technologies because of its high decarbonizing potential.

Projects that are more multi-technology will be definitely seen in the future. The term “hybrid” offshore wind projects in Europe is also used to describe projects that double as interconnectors between two countries. Instead of building a cable, the interconnector passes through an offshore wind farm, potentially allowing power to be sold to two markets rather than one, thereby avoiding doubling up on transmission investments. A demo hybrid project of this kind, Kriegers Flak, between Denmark and Germany, is testing that concept, while Estonia and Latvia have agreed to collaborate on something similar. The world’s first energy islands will be constructed in Denmark, exploiting the immense wind resources in the North and Baltic Seas. The energy islands will serve as hubs that can create better connections between energy generated from offshore wind and the energy systems in the region around the two seas. The plan envisages the establishment of an artificial island in the North Sea that will serve as a hub for offshore wind farms supplying 3 GW of energy, with a long-term expansion potential of 10 GW. The value of offshore transmission connections to offshore wind farms can be substantially increased by connecting to more markets, eventually creating a meshed grid,

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[22] I.M. Solbrekke, N.G. Kvamsto, A.Sorteberg. “Offshore Wind power intermittency: The effect of connecting production sites along the Norwegian continental shelf”. In *Wind Energy Science Discussions*, European Academy of Wind Energy,13 May 2020, https://www.doi.org//10.5194/wes-2020-67

[23] Bruno Rego de Vasconselos and Jean-Michel Lavoie. “Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals”. In *Frontiers in Chemistry,* 5 June, 2019, https://doi.org/10.3389/fchem.2019.00392

based on clusters of wind farms. This will allow trade between markets, while improving dispatch and security of supply. This vision of an advanced offshore grid with interconnections doubling as export cables, eventually leads to dedicated energy hubs. New technologies, such as battery storage and automated demand-response, together with an optimized operation of the existing infrastructure, including the European gas grid might reduce or postpone the need for this transmission buildout.

At the same time, new infrastructure will be different as maturing technologies, such as HVDC (high voltage direct current)[24] and power-to-X (PtX) can share the load with onshore transmission lines and change the face of the future infrastructure expansion. Over the last several decades, High-Voltage Direct Current (HVDC) has emerged as a viable complement to alternating current (AC) power transmission, with the ability to connect asynchronous AC (Alternating Current) grids and allow power transmission across long distances with minimal losses. This is essential for applications such as offshore wind farms, which can operate at considerable distances from where the power they generate is needed. HVDC transmission systems are becoming more important in an energy landscape that is characterized by increasing digitalization, decarbonisation, and distributed generation. HVDC offers the most efficient means of transmitting large amounts of power over long distances, and help connect green power to the grid.

The study has six chapters. **Chapter 1** highlights the potential of offshore wind energy technology by giving an overview of its main trends and markets. **Chapter 2** focuses on the technological developments of offshore wind turbines, including different topologies of the foundations. **Chapter 3** explores the environmental impacts of offshore wind development such as marine mammals, birds, but also underlines the use of maritime spatial planning as a tool by alleviating some negative effects. **Chapter 4** studies offshore wind farms implications for aviation and navigational safety. **Chapter 5** examines integration of power from offshore wind turbines into onshore grids by providing an overview of the offshore grid transmission technologies. **Chapter 6** focuses on energy storage that is frequently identified as a key enabler for a large-scale expansion of renewable energy in the power grid. As future electricity system has to be smarter and more interconnected special focus is paid on smart grids.

CHAPTER 1 – OFFSHORE WIND POWER RESOURCES AND ITS POTENTIAL

Massive upscaling of wind turbines deployments offshore is critical to achieving global and national goals to decarbonize the electricity supply. With further technology improvements and better permitting procedures, wind energy will become the number one source of electricity soon after 2025. According to the analysis of European Technology Platform on Wind Energy (ETIP Wind) and Wind Europe (2021)[25], wind energy can help electrify 75% of Europe's energy demand and thereby deliver climate neutrality by 2050. In order to do so, the focus should be set on prioritizing the development of the necessary technologies: next generation onshore and offshore turbines, electrification solutions for transport and industry, as well as electrolysis for renewable hydrogen. Innovative new ventures such as green hydrogen and floating offshore wind will help to decarbonize hard-to-abate sectors (e.g. transport, buildings, industry and agriculture) and in this way allow expansion of new markets previously limited by geographical conditions. In particular, the adoption of floating foundation technologies has proved to be a promising technology for unlocking the wind potential on deeper waters (IEA, 2019)[26]. However, the remote or challenging locations, the intermittent character of the wind resources, and the necessity of long distances for energy transmission are considered the main drawbacks of wind energy.

Offshore wind power relates to the installation of wind turbines in large water bodies. Wind tur-

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[24] HVDC, pioneered by Hitachi ABB Power Grids in the 1920s, and commercially established in the 50s, differentiates itself from AC transmission systems through electrical current converter technology, converting AC to DC more efficiently.

[25] ETIP Wind & Wind Europe (2021). "Getting Fit for 55 and set for 2050 – Electrifying Europe with wind energy". June 2021, Brussels.

[26] IEA (2019). "Offshore Wind Outlook 2019". International Energy Agency, pp. 22-23.

bines extract kinetic energy from the atmosphere and convert part of it into electric power[27]. The remaining part of the energy is converted into turbulent kinetic energy; that generates wakes (downwind speed deficits). Wake losses occur when the wind speed is below the rated value and turbines are at least partially aligned to the angle of the incoming wind. The mean wind speeds at the majority of wind farms are well below the rated value. Wind directions in the turbulent atmospheric layer are inherently variable and they will vary with the time of the day, season, and other geophysical parameters. Wind farm layouts are designed to extract the maximum profit given historically observed wind direction and speed distributions, which typically results in larger streamwise turbine spacing in the most common wind directions. However, for other wind directions, wind turbines are closely spaced. Airborne observations show that turbulent kinetic energy is significantly increasing (factor of 10-20) above the wind farms (Siedersleben et al., 2020)[28]. These observations also indicate that wind farm wakes can extend up to 50-70 km under stable atmospheric conditions. At a given wind speed, colder and denser air masses provide more energy in comparison with warmer and lighter air masses. Moreover, atmospheric turbulence additionally reduces the energy output and increases the load on wind farm structures and equipment (IRENA, 2012)[29]. Observational evidence shows that wakes can increase the temperature by 0.5 degrees and humidity by 0.5 g per kilogram at hub height, even as far as 60 km downwind of wind farms.

Between the cut-in speed and the rated speed, where the maximum output is reached, the power output will increase cubically with wind speed. For example, if wind speed doubles, the power output will increase 8 times. This cubic relationship is what makes wind speed such an important factor for wind power. Due to this relationship between wind speed and energy output, sites with small differences in wind speed can have substantial differences in available wind energy (Belu, 2020)[30]. About 10 km off the coast, sea surface winds are generally 25% higher than onshore winds. These higher offshore wind resources can be utilized 2-3 times longer to generate electricity than onshore wind farms in the same period. Wind energy resources depend on the wind regime, varying in time and space due to large- and small-scale atmospheric circulations, surface energy fluxes, and geography. Wind regime is characterized by seasonal and regional variations in speed and in direction with average speed generally increasing northward. This causes chaotic wind/pressure regimes if the steering flow is weak.

Global wind energy resources are substantial, and in many areas, such as the USA and Northern Europe, could in theory supply all of the electricity demand. These resources are by their nature both huge in scale and highly dispersed, considering the ratio of the planet's surface area that is covered by oceans and seas compared to land mass. Europe's total installed OWF capacity reached 25 GW in 2020; of that capacity, 77% is installed in the North Sea (WindEurope, 2020)[31]. This implies that the North Sea forms one of the worldwide hotspots of OWF development. The strong and reliable wind resources in the North Sea at shallow water depths motivate these massive developments. The Baltic Sea holds an incredible potential for offshore wind in Europe, and could host as much as 93 gigawatts (GW) by 2050, up from 2.2 gigawatts today. In September 2020, eight Baltic countries – Poland, Germany, Denmark, Sweden, Finland, Estonia, Latvia, and Lithuania – signed a joint declaration with the European Commission to accelerate the build-out of new offshore wind farms in the region. Latvia and Estonia started discussions for a joint offshore wind project "ELWIND" in 2019. In 2020, the countries governments signed a Memorandum of Understanding to develop the 1 gigawatt offshore wind project in the Gulf of Riga. It is planned to create a hub where other projects in the region can join in[32].

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27 S.K. Siedersleben et al. "Turbulent kinetic energy over large offshore wind farms observed and simulated by the mesoscale model WRF (3.8.1)". In *Geoscience Model Development*, 13, 249-268, 2020.

29 IRENA. "Renewable Energy Technologies: Cost analysis series". In *Green Energy Technology 1*, 2012.

30 R.Belu (2020). "Assessment and Analysis of Offshore Wind Energy Potential". In *Entropy and Exergy in Renewable Energy.*

31 WindEurope (2020). "Offshore wind in Europe: Key trends and statistics 2020".

32 WindEurope press release. "Significant developments on offshore wind in the Baltic Sea", 7 January 2021.

Most of the offshore wind resource potential in China, Japan, Norway, and many other countries is available in water deeper than 30 meters. In contrast, most of the European offshore wind turbines installed to date are bottom-fixed and have been installed in water depth around 20 meters by diving monopiles into the seabed or by relying on conventional gravity bases. These technologies are not economically feasible in deeper waters. Instead, space frame structures, including tripods, quadpods, or lattice frames (jackets) will be required to maintain the strength and stiffness requirements at the lowest possible cost. The wind blows faster and more uniformly at sea than on land. A fast, steadier wind means less wear on the turbines components and more electricity generated per turbine.

The technical exploitable resource potential for offshore wind is a factor of the average wind speed and water depth, as it is only possible to generate electricity from offshore wind resources where turbines can be anchored. There are two types of foundations: bottom fixed and floating platforms. Economics limit these bottom fixed turbines to waters up to 60 meters deep. Turbines use a rotating motion to generate electricity. Stability of wind turbine is very important and is ensured by providing an appropriate foundation. The main task of foundation of wind turbine is that it transfers and spreads the loads to the soil at depth. The vertical and horizontal forces, which act on the turbine foundation, are due to self-weight and wind respectively. The height of wind turbine tower varies usually from 40 m to 130 meters. Higher wind turbine tower gives rise to greater wind speed; the wind force acting on the turbine generates a large moment at the foundation base.

Without additional innovation to reduce the cost of harvesting the abundant wind resources in deeper water, much of the offshore wind energy potential in the USA, Japan, South Korea and other promising markets could go untapped. The choice of one type or another will depend on sea or seabed conditions, the winds in the area, the size of the turbine, the depth of the harbors and many other factors. Floating offshore wind, based on floating rather than fixed structures, offers new opportunities and alternatives. It opens a door to sites further offshore by allowing the deployment of wind turbines in larger and in deeper offshore areas with higher wind potential. By using deeper waters, floating offshore wind farms also make projects feasible in remote locations that offer more powerful and reliable wind. However, this must be weighed against higher transmission costs.

Wind energy potential estimation is often based mainly on wind speed and the power curve of the turbine, and only marginally on the temporal and spatial variations in air density that is defined as atmospheric density that is the mass per unit volume of Earth's atmosphere. Air density like air pressure decrease with increasing altitude. It also changes with variation in atmospheric pressure, temperature and humidity. At 101.325 kPa and 15 degrees Celsius, air has a density of approximately 1.225 kg/m^3, about 1/1000 that of water according to ISA (International Standard Atmosphere). In the wind power production estimates, the air density is usually considered constant in time. Instead, a constant value around 1.225 kg/m^3 is assumed at sea level while at higher altitudes its yearly averages are used. Air densities lower than the standard sea-level value may require a complete redesign of the wind turbine blades, for example with regard to wind turbines located at high altitudes.

Many efforts have been made towards improving the performance of wind turbines through design optimization. As a key wind turbine component, the blade is a determining factor for energy harvesting efficiency and its aerodynamic shape optimization is very momentous. Rotor blades are the most important parts of a wind turbine in terms of performance and cost of the wind power system. The shape of the rotor blades has a direct impact on performance as this decides the conversion of kinetic energy related to the wind to mechanical energy (torque). The physical size of wind turbines, including towers and rotors (blades) has increased by over 50 % in the last decades. The blade radius of an average offshore wind turbine was 141 meters in 2018. As a matter of electrical output, larger blades gather more wind potential, spin more quickly, and can power higher-output wind turbines. Taller towers make it possible to cost-effectively tap the stronger wind resources that exist at higher altitudes, beyond the reach today's typical turbines and above interference from trees, buildings, and landscape or topographical features (Wind Energy Technologies Office, 2019)[33].

1.1 THE OFFSHORE WIND POWER POTENTIAL

As onshore and offshore wind power are one of the most considerable sources of renewable energy the question about its land use and power potential is crucial. Therefore, it is necessary to evaluate how this can be measured as many different factors are considered to affect the potential of offshore wind energy. Keivanpour et al. (2017) define three main groups of these factors: feasibility, sustainability and flexibility[34].

These three crucial aspects can be considered as integrated factors to assess all technical, environmental, economic, and social factors. Firstly, the feasibility for the operation of offshore wind energy depends on the suitable wind conditions in the area. Feasible wind resources in the offshore areas are the theoretical potential considering the natural and climate parameters. The wind resource is projected via satellite measurements and ocean bathymetry data (Govindji et al., 2014)[35]. Simulated winds by numerical weather prediction models are also common techniques for wind resource assessment.

According to the physics of the power of wind, the air density and wind speed are two essential parameters in estimating wind energy resources. Air density is a function of altitude, temperature, and other parameters. Hence, the wind speed at the hub level (usually at a height of 90 meters above the surface) is used for estimating wind resources. Furthermore, soil mechanics, extreme waves, wake effects, icing impacts, and lightning are also important technical parameters that affect the design of wind turbines in offshore areas. Marine subsurface conditions such as ocean depth temperature, marine growth, and seafloor scour could affect operation facility design. Bathymetry data are also essential factors in the estimation of the theoretical potential wind resources.

Offshore wind resources seem to be ample; however, geographical and spatial planning are factors that significantly reduce the theoretical potential. Shipping is a significant competitor for the offshore zones. Based on Arent et al. (2012)[36], shipping density is measured in kilometers of tracks per square kilometer and can be classified into three categories: 0-3, 5-15, and >15 km per km^2. Geospatial factors such as the distance to the coast, main shipping routes and areas which are crucial for maritime defense, have to be taken into consideration. In economic terms, the market potential is the total amount of renewable energy that can be implemented in the market taking into account the demand for energy, the competing technologies, the costs and subsidies of renewable energy sources, and the barriers. For example whether a wind farm is considered cost efficient heavily depends on expected electricity prices and the wind turbine construction costs.

The second group of factors summarizes the topics of sustainability. A main tool to measure this aspect is the life cycle assement which evaluates the impacts of a wind farm on economy, society and environment at each step of the life cycle. Especially social and environmental issues are of interest at this point. Thus, it is necessary to measure the change in social well-being considering visibility and health aspects as well as local development and energy security. Additionally, the effects on wildlife such as birds for example has to be taken into account and installation of wind turbines in corresponding areas has to be restricted.

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[33] Wind Energy Technologies Office (2019). "Offshore Wind Market Report". US Department of Energy.

[34] S.Keivanpour, A. Ramudhin, and D. A. Kadi, „The sustainable worldwide offshore wind energy potential: A systematic review". In *Journal of Renewable and Sustainable Energy* 9, 065902 (2017).

[35] A.I. Govindji, R.James, and A. Carvallo. "Detailed Appraisal of the offshore wind industry in Japan". Carbon Trust, 2014.

[36] D.Arent, P.Sullivan, D.Heimiller, A.Lopez, K. Eurek, J.Badger, H.E. Jørgensen, M. Kelly, L.Clarke, and P.Luckow. "Improved offshore wind resource assessment in global climate stabilization scenarios". Contract 303, 275-3000 (2012).

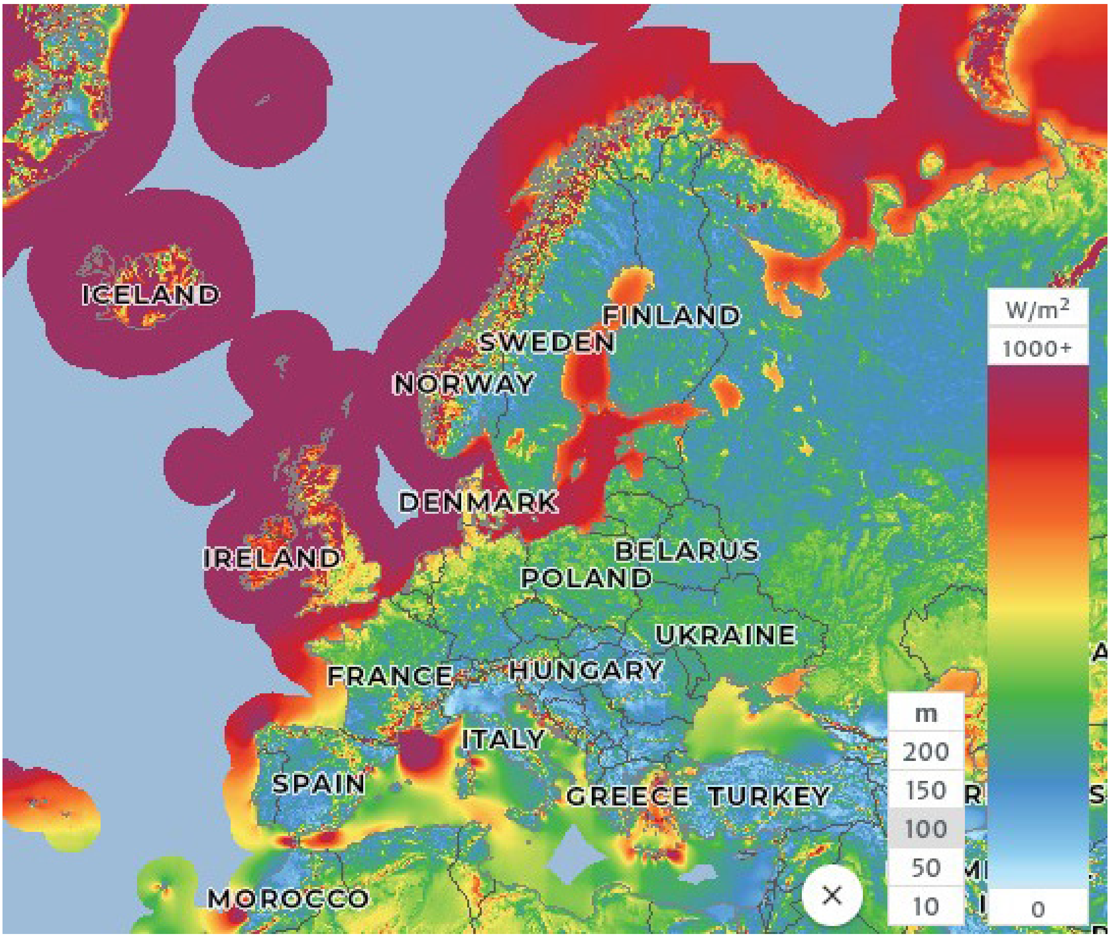

Figure 1: Wind power density in Europe in W/m² [38]

Thirdly, the factors of flexibility have to be taken into consideration. One of them are the market conditions, featuring the different types of costs as well as interests, taxes and inflation which may prohibit development and construction of potential wind farms. At this point also policy issues are rather important as taxes, subsidies or tariffs affect the profitability of offshore wind projects. However, even under rough conditions advances in technology will have a positive impact on the installation potential of offshore wind turbines. Additionally, they have impact on the potential location of wind farms as turbines may be built at further or rougher places which on the other hand, may reduce the construction costs making wind energy projects in question more profitable.

1.1.1 WIND POTENTIAL IN EUROPE

Europe is the most developed region in terms of offshore wind. Therefore, the potential is very well analysed in comparison to other world regions. The areas with the highest offshore wind potential are the North Sea, Baltic Sea, the western coasts of Spain, UK and Norway as well as some spaces located in the Mediterranean Sea (Figure 1). Currently the most offshore wind turbines are installed in the North Sea[37].

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[37] M. deCastro, S. Salvador, M. Gómez-Gesteira, X. Costoya, D. Carvalho, F.J. Sanz-Larruga, L. Gimeno, "Europe, China and the United States: Three different approaches to the development of offshore wind energy". In *Renewable and Sustainable Energy Reviews*", Volume 109, 2019, Pages 55-70. See also https://doi.org/10.1016/j.rser.2019.04.025.

[38] Global Wind Atlas 3.0, a free, web-based application deveoped, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://www.globalwindatlas.info

According to the the esimates of Wind Europe until 2050 up to 450 gigawatts are needed to achieve the European climate goals. Until 2025 at least 15 gigawatts of offshore wind power will be installed per year, with most of them being also located in the North Sea[39]. The main reason for this might be the that adjacent countries, like the United Kingdom, Denmark, Germany, Belgium and the Netherlands are most developed in terms of offshore wind power and will further increase their capacities. Further, the North Sea is presumed to be mostly unaffected by climate change while most of the other areas will probably face changes in wind power density and regimes. While most parts of the Mediterranean Sea and western part of Spain will decrease in wind power density, the western coast of the United Kingdom and Norway as well as the Baltic Sea are assumed to increase. However, not only power density is determining the position of wind farms. In Europe, „*The Marine Strategy Framework Directive*" MSFD (2008/56/E)[40] to ensure a good environmental status of maritime waters has to be respected. This directive complements „*The Water Framework Directive*"WFD (2000/60/EC), extending environmental protection into EU marine waters beyond the coastal waters. The same applies to the Natura 2000 areas which define spaces of community importance or special protection. Additionally, offshore wind farms can only be built where the environmental and positional conditions for construction are met or at least favourable enough to ensure profitability. Thus, many factors have to be taken into account for positioning and building wind farms. Concerning the technological development, in the GWEC „Global Wind Report" (2021) it is underlined that floating offshore wind farms will be one key aspect in the future development as well as the option for multi-use platforms which combine wind turbines with devices for other sectors to reduce overall costs[41]. Additionally, many other technology upcomings can be expected in the offshore wind sector for the next decades coupled with its more extensive use globally. This will increase the potential of further wind installations and overall effiency. Currently, further favourable conditions for more installations are reduced by licensing efforts in many European countries as well as guaranteed feed in tariffs which guarantee better economic planning opportunities[42].

1.1.2 FLOATING OFFSHORE WIND

Countries with relatively shallow water depths (less than 50 meters) and established maritime industries, often-leveraging oil and gas experience so far have dominated the offshore wind market. However, with the potential for bottom-fixed structures constrained over the long-term in many markets and mounting pressure to decarbonize and diversify energy portfolios, more countries are beginning to explore the potential for floating offshore wind. Particularly given that there are limited locations with shallow waters suitable for bottom-fixed foundations and that there is extensive wind resource in deep waters (50-200 meters), floating wind is potentially a highly scalable future energy source in number of markets. In particular, there is a significant potential and potential for growth in Japan, the United States and a number of European countries including the United Kingdom, Norway, France, and Portugal.

The potential for electricity generation from floating wind in Europe is vast. Over half of the North Sea is suitable for floating wind deployment, with water depths between 50 m and 200 m (Figure 2). On this basis, European Wind Energy Association (EWEA) estimate that the energy produced from turbines in deep waters in the North Sea alone could meet the EU's electricity consumption four times over (EWEA, 2013)[43].

There is also a significant wind resource in the Atlantic, particularly off the coast of Scotland and England, and in the west of France and off the coast of Portugal and Spain, where deep wa-

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[39] Wind Europe, "Our energy, our future", 2019, https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf

[40] The aim of the EU Marine Strategy Framework Directive 2008/56/EC, also known as MSFD, is to protect the marine environment across Europe. This directive sets a target of "Good Environmental Status" which must be achieved in EU marine waters by 2020.

[41] GWEC, "Global Wind Report 2021", 2021, https://gwec.net/wp-content/uploads/2021/03/GWEC-Global-Wind-Report-2021.pdf

[42] M. deCastro, X. Costoya, S. Salvador, D. Carvalho, M. Gómez-Gesteira, F.J. Sanz-Larruga, and L.Gimeno. (2019), "An overview of offshore wind energy resources in Europe under present and future climate". Ann. N.Y. Acad. Sci., 1436: 70-97.

Figure 2. Offshore wind resource and potential floating wind capacity in Europe, USA, and Japan (US NREL, 2012; EWEA, 2013; Marine International Consulting, 2013).

Country/Region	Share of offshore wind resource in deep water locations (less than 60 m depth)	Potential floating wind capacity
Europe	80%	4,000GW
USA	60%	2,450GW
Japan	80%	500 GW

ter precludes bottom-fixed offshore wind development. Floating offshore wind power is a new industry, and for example, Scotland looks set to be one of the first countries across the globe seeking to build it at scale. It has announced plans to lease parts of its seabed to offshore wind developers, to help carbonize its oil and gas industry. Deep water is also prevalent in the Mediterranean, where the wind resource is generally less extensive than the North Sea and Atlantic coastline, although there are pockets of strong and moderate wind, which could be well suited to floating turbines, particularly given that the less harsh marine conditions may allow for less conservative structural designs (Jeffrey & Sedgwick/ORECCA, 2011)[44].

EU targets for offshore wind of 60 gigawatts by 2030, with a view to reach 300 gigawatts by 2050[45] are expected to be achieved by predominantly using conventional bottom-fixed foundations in water depths below 50 meters. The 2030 target may also require a greater proportion from floating wind solutions. The precondition for this trend is that floating platforms prove to be cost competitive and the development of this wind energy technology is accelerated. While offshore wind deployment up to 2030 is to be dominated by the significant growth of bottom-fixed wind farms, from 2030 it is likely that adequate sites will become scarcer and more costly to develop with bottom-fixed structures, further from shore and in sites with challenging seabed and/or metocean conditions[46]. Thus, floating wind technology could be used to exploit deep-water locations closer to shore, and the added flexibility of floating structures means that it has the potential to be highly scalable.

Japan has been conducting research in floating technology for the past 20 years, establishing itself as a world leader in this area. However, it is only since Fukushima nuclear disaster in 2011 that concerted efforts have been focused on developing floating wind power. Surrounded by deep water, Japan is constrained by how much bottom-fixed offshore wind can be installed, but the proximity of deep-water locations makes it ideal location for floating wind turbines.

To capitalize on the ocean's full offshore wind potential, floating as well as fixed foundation solutions will be required. Some of the largest potential markets, such as Japan and the United States, possess few shallow-water sites suitable for offshore wind development. Floating foundations could be a game-changer in this regard. The development of the global floating offshore wind farms international market shows a large spread potential for floating wind power with over 92% of all the oceans being deeper than 200 meters, with better wind regimes further away from

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[43] EWEA (2013)."Deep Water: The next step for offshore wind energy", www.ewea.org/report/deep-water Accessed 28 July 2021.

[44] H.Jeffrey, J.Sedgwick. "ORECCA European Offshore Renewable Energy Roadmap". Produced by the University of Edinburgh on behalf of the ORECCA Project, September 2011.

[45] According to the CTP-MIX scenario from the Impact Assessment accompanying the 2030 climate target plan – COM (2020) 562 final.

[46] Metocean refers to the combined effect of the meteorology and oceanography.These factors include local surface wind, wind-generated local waves, long-period waves generated by distant storms et cetera.

shore. Floating offshore wind developments to date have been limited to demonstration projects in Europe and Japan. A floating foundation can surmount the engineering challenges of deep-water installations, and it offers a different approach to construction that also yields benefits. For example, instead of conducting most building work at sea using heavy-lift vessels, most of a turbine can be constructed quayside and pulled into position by less costly and readily available tugs. Even the largest of these projects, Hywind in Scotland and WindFloat Atlantic in Portugal, at 30 megawatts and 25 megawatts, respectively. Much bigger floating projects are coming. According to the USA Natural Renewable Energy Lab (NREL) estimates, we can expect floating technology at utility scale – 600 – 1,000 MW a project by 2024. Japan has been testing a number of floating offshore wind prototypes. France has launched ambitious plans for a string of pilot projects off its coast. Norway recently agreed to move forward with demonstration projects in its own waters. These countries see the potential to build their economies around renewable energy. Oil and gas developers, looking for ways to reduce their carbon footprint by diversifying their core business, mostly back this energy transition.

1.2 OFFSHORE WIND OUTLOOK

Although the expansion of offshore wind in Europe, particularly among the North Sea nations, is accelerating, the rise of offshore wind in Asia is remarkable. Taiwan leads in this respect, with the past year seeing some major projects reach financial decisions and others pursue construction. At the same time South Korea and Japan are advancing following a number of regulatory initiatives to improve the investment environment. Adding to this are developing in the USA where major permitting and financing hurdles have been cleared, and a number of large utility scale projects are moving quickly towards start of construction phase. The momentum behind floating offshore wind continues to build, with major developers announcing a number of projects in the past year, including in Asia where deeper sea waters make some bottom-fixed projets unviable and local industry is well placed to provide floating platforms. China's net zero by 2060 pledge, Joe Biden's presidential victory in the USA, and Europe's approach to green hydrogen are all key drivers that have resulted in a significant increase in offshore wind deployments. China, which recently pledged itself to net zero emissions by 2060 is now taking serious steps towards decarbonisation, including the power sector's pricing scheme in early 2021. In 2018, China reported that it had approved 40 gigawatts (GW) of offshore wind projects that would have to achieve grid connection by the end of 2021, ahead of the nation's feed in tariff. Following its 5.8 gigawatts (GW) installed capacity in 2021, the market will see a brief drop in additions. As costs continue to fall, and with the central government likely to add further support, installation rates will push to new records between 2026 and 2027.

Biden's administration has a goal of achieving net zero emissions in the USA power sector by 2035 and the broader economy by 2050. Wind and solar would have to become the largest sources of generation by 2035 alongside massive expansion in carbon capture and zero-carbon hydrogen. All major economies are trying to identify pathways to net zero emissions. The USA has a similar level of climate ambition to the European Union – a global leader in climate policy. Although the implications of net zero commitments are huge. Supply chains for raw materials, the geopolitics of energy, and global energy prices will all change radically in a net zero world.

However, after the United Kingdom leaving the European Union, it is not surprising that the largest offshore wind market in the world is China in 2030 – many analysts predicted already in 2020 that it could possibly surpassing the UK's total installed capacity by the end of 2021. China has overtaken the United Kingdom as the world's largest operator of installed offshore wind capacity, with oil and gas companies contributing to the offshore wind boom. Data released by China's National Statistics Administration shows that at the end of June 2021, China had increased utility-scale offshore wind electricity generation capacity to 11.13 gigawatts, rivalling the approximately 10.4 gigawatts of installed capacity of the

UK at the end of 2020. According to the statistics provided by the Global Wind Energy Council in 2020, China then ranked third behind the United Kingdom and Germany (8 GW). This growth outlook is solidified by 30 gigawatts of new capacity expected to be allocated in the coming years.

With more offshore wind capacity installed than any other country – almost 11 gigawatts – the United Kingdom is an example for the world aiming at a net-zero carbon footprint. Scotland remains an important regional market within the United Kingdom. Although, Scotland in comparison with England and Wales has started slowly in developing offshore wind projects, it can be predicted that over the coming decade Scottish projects are expected to make up approximately 40% of the market. The government's goal is to reach 40 gigawatts of offshore wind by 2030 and net-zero emissions by 2050. This is definitely the most ambitious offshore wind target in Europe. The development of offshore wind power plays a key role in the UK government's plan for a „*Green Energy Revolution*". The Hornsea One project, located of England's Yorkshire coast, is the world's largest operational wind farm. With 174 offshore wind turbines, the electricity produced is enough to power over a million homes with clean energy. A comparative newcomer to offshore wind generation, Germany's first offshore wind farm, Alpha Ventus, only started producing power in 2009. Since then, it has rapidly grown, becoming one of the world's largest producers of offshore wind energy with installed capacity of 6.4 gigawatts. Taking advantage of its location between the North and the Baltic Sea, Germany installed 136 new wind turbines in 2019. It is even installing a cable link to supply North Sea offshore power to Denmark to help that country achieve its zero-carbon ambitions. A steady buildout of turbines in the German North and Baltic Seas over the past decade has positioned offshore wind as a major contributor to the country's production of renewable energy. The German government has also faced repeated calls from the offshore wind industry to firmly establish a target of at least 20 gigawatts by 2030 and to build upon the 7.5 gigawatts of current installed capacity, especially as the country is lagging behind its European neighbors for new offshore wind investment in the early part of this decade (Clean Energy Pipeline, 2020)[47].

Denmark has one of the world's premier offshore wind markets that boasts Europe's third largest offshore fleet, with a cumulative capacity of 1.7 gigawatts. After Vattenfall commissioned the 407 MW Horns Rev 3 wind farm in August 2019, Denmark hit a major milestone as the country generated 47% of its electricity exclusively from wind energy in 2019[48]. As a result of the Energy Agreement that was established in 2018, Denmark plans to install three new offshore wind projects with a minimum capacity of 800 megawatts each, generating the equivalent power demand for 800,000 Danish households. With ambition to establish the world's first hydrogen economy, Europe's plans have opened up opportunities for countries like Denmark, Sweden and Ireland to push beyond their own means in terms of offshore wind. Without having to build HVDC (high-voltage direct current) transmission links, hydrogen offers an opportunity to export green energy to a continent-wide market, as it decarbonizes sectors like industrial heating and heavy transport.

While Europe and China will push beyond what is expected by most analysts, groups like Bloomberg and WoodMac have been conservative with regard to their home market of the USA. By the end of 2029 WoodMac expects there to be around 25 gigawatts offshore capacity in the USA, despite the constant delays to projects and the huge scarcity of installation vessels available in the USA waters. In March 2021, the Biden administration set a goal to build 30,000 megawatts of offshore wind capacity in the USA by 2030 and complete reviews of constructions and operation plans for a least 16 offshore wind projects by 2025[49]. About 42 megawatts of offshore wind capacity have been installed in the USA. By comparison, the world's leading markets, the United Kingdom and China, have each installed

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[47] Clean Energy Pipeline (2020). "Europe" Offshore Wind Outlook 2020". A division of Venture Business Research Limited, UK.

[48] Ibid, 2020.

[49] J. Gerdes. "Why floating turbines will unlock offshore wind energy's full potential?". In newsletter Energy Monitor (September 2021).

around 10,000 megawatts. The growth potential of the USA market is further supported with the findings of a recent American Bureau of Shipping (ABS) poll, where nearly 90% or respondents believe that offshore wind will play significant role in sustainable U.S energy strategy. While the USA market waits for its first Jones Act-compliant turbine installation vessel, it needs to keep a watch on the developments in Europe, where the supply chain may also face vessel constraints. It is critical time across the USA supply chain in which the developers will need to rely on European suppliers that are already in high demand to meet USA offshore wind plans.

Compared to the European offshore market, the USA market is different. Firstly there is the Merchant Marine (Jones) Act of 1920, which is a USA trade law that defines how maritime commerce is regulated. Specific restrictions limit the transfer of cargo between USA ports to vessels that are registered and built only in the USA. Ownership of these vessels must be by majority USA incorporated entities with USA citizen representation. Onboard vessel crews may use only US Coast Guard (USCG) credentialed mariners and a majority of USA citizens (Tremblay, 2021)[50]. In the wake of Presidentäs Biden decision to allow offshore wind development in the Pacific Ocean, California has emerged as a key player in advancing domestic clean energy goals. Building on the administrationsäs efforts to deploy 30 gigawatts (GW) of offshore wind by 2030. California's recently enacted Assembly Bill 525, which aims to construct up to 4.6 GW of offshore power in the state's waters by the end of the decade (NRDC, 2021)[51]. Beyond mandating the creation of a strategic development plan by June 2023, the law also includes far-ranging provisions to expand transmission lines, protect biodiversity, and upgrade port infrastructure. Meanwhile, the Bureau of Ocean Energy Management is stated to announce the first offshore lease sales in California waters this spring. These developments represent a major evolution in US offshore wind policy and entail significant growth of the industry.

At this point however, markets like California will be emerging in the floating sector mostly due to the Biden administration's legislation. California's annual technical offshore wind potential is 392 terawatt hours, or 157% of the state's 2019 electricity use. Installing 10,000 megawatts of offshore wind power capacity by 2040 would save 1 billion USD annual in electricity generation costs, finds a report published by the University of Southern California's Schwarzenegger Institute in 2021[52]. California's state government analysis published in March 2021 found that 10,000 megawatts of offshore wind, along with out-of-state onshore wind and long-duration energy storage, will be necessary to meet California's requirement of 100% carbon-free electricity by 2045. At the same time, California, after leading the USA – and often the world on energy efficiency and rooftop solar, electric vehicles and battery storage, fall so far behind in offshore wind. This is due to several reasons, unlike the sites hosting offshore wind in Europe, and those soon to be developed along the USA East Coast states like New York and New Jersey, California's most promising sites for offshore development are in waters too deep for turbines with foundations driven into the seabed. California will instead require floating turbines towed to the project site and anchored to the sea floor with mooring lines. Another hurdle is that some of the state's best sites for floating offshore wind, especially along the California's Central Coast, overlap with areas used by the US Navy for flight training. These challenges are not insurmountable as rapidly maturing floating offshore wind technology is exiting the pilot project stage. Much larger projects are scheduled to come online in Europe within a few years, and the conflicts with military use on the Central Coast have been resolved. In an agreement announced by the Biden administration and the State of California in May 2021, they identified coastal areas in the state that could support an initial 4,600 megawatts of offshore wind generation capacity. This also indicates that the USA will be catching up with the United Kingdom in terms of total installed capacity through the subsequent decade.

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[50] M. Trem blay (2021). "The complicated U.S. regulations for offshore wind vessels". In Windpower Engineering, August 2, 2021.

[51] S. Aylesworth & M. Chhabra. "California Enacts Plan for Smart Offshore Wind development". NRDC, 14 October 2021.

[52] Environment America Research & Policy Center and Frontier Group (2021). "Offshore Wind for America: The promise and potential of clean energy off our coasts".

Overall, offshore wind power will be one of the rising renewable energy sources in the future as the area of potential use is greater and far less limited than for onshore wind. Instead, the costs for offshore wind farms are the most important factor and far higher compared to the most onshore counterparts. With further technological development this gap may decrease which will lead to further contruction of offshore wind turbines. In Europe, there are many sites with high wind energy potential, while the North Sea will be the most important for the next years. However, also other areas will be developed in the future. Because of mostly favourable legal conditions and policies for more environmental friendly energy also an increasing amount of wind farms will be planned and constructed over the next years.

CHAPTER 2 – TECHNOLOGICAL DEVELOPMENTS OF OFFSHORE WIND TURBINES

The offshore wind industry is gaining momentum due to ambitious environmental targets, competitive costs, and huge market potential. This renewable source of energy provides an optimal load factor, minimizing the need for electricity storage or complementary dispatchable sources of energy. Among renewable and sustainable energies, offshore wind power shows a variety of advantages including high energy density, low turbulence and low wind shear[53]. According to the Norwegian think-tank DNV, the technology is predicted to grow worldwide, rising from the around 100 megawatts today to more than 10 gigawatts in 2030 and respectively 250 gigawatts in 2050[54]. Whilst helping governments achieve these targets for the purpose of decarbonisation of power sector, adoption of the technology can also provide potential synergies with "Power-to-X" technologies, for example using wind energy for the production of low-carbon hydrogen[55].

Offshore wind turbines originally evolved from onshore machines, adapted to the offshore environment, without the geometric and mass constraints imposed by road transport for onshore wind. Offshore wind turbines are similar to onshore counterparts and use substantially the same technology. The only significant difference as far as energy capture is concerned is that they are often larger. As with onshore machines, those used offshore are horizontal axis turbines with three-bladed rotors. Drive trains for offshore wind turbines are identical to those used on land too; some use gearboxes, relatively high-speed generators, while others are equipped with direct drive between the turbine rotor and the generator. Towers are of similar construction, but the foundations for offshore wind turbines are substantially different to those used onshore.

There are two trends for offshore wind power at present - the increase of turbine rated capacity and increasing distance from the shore to mitigate concern raised by civil complaints. Offshore wind turbines are increasing in size, with turbines in excess of 10 gigawatts (and blade diameters over 200 meters) being developed for deployment in the 2020s. At 140 meters from tip-to-tip, blade span now equals the wingspan on the average passenger airplane. It can also be foreseen that blade size along with turbine height, will only continue to grow in the coming years. The design is not only dependent on turbine loads and associated overturning moment[56], as well the wave and current loads need to be assessed as acting on the offshore wind turbine system as a whole. The offshore wind industry is currently dominated by three-bladed, horizontal-axis, upwind turbines mounted on tubular steel towers and foundations fixed to the seabed. The increase in turbine scale has been the primary drive behind the recent rapid reductions in the cost of offshore wind energy.

A great-untapped wind resource lies within the deep oceanographic environment far from shore. For these reasons, offshore wind development will need to extend to deeper waters and farther

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[53] Rapid change in wind velocity or direction. It is observed both, near the ground and in jet streams, where it may be associated with clear-air turbulence.

[54] DNV (2019). "Technology Outlook 2030: Wind energy – Going Offshore". Oslo, Norway.

[55] Power-to-Gas, Power-to-Liquids, or more generically, Power-to-X conversion concepts arise as a synergetic solution for both storing energy from intermittent renewable energy sources and producing carbon-neutral fuels from CO_2 emissions.

[56] The overturning moment of an object is the moment of energy capable of upsetting the object; that is, the point where it has been subjected to enough disturbance that it ceases to be stable, it overturns, capsizes, collapses, topples or otherwise incurs an unwanted change in the circumstances, possibly resulting in damage and certainly resulting in inconvenience.

from shore, spurring the need for substructures, which can accommodate such depths. According to the data provided by the Energy Technologies Institute in the United Kingdom, for European offshore wind farms in 2018, the mean distance from the shore was 33 km. However, the farther a wind farm is from the shore, the deeper the water depth of its candidate site. On the other hand, the long distance from the shore and deep-water depth hinder the economic feasibility of wind farms.

There are different types of foundations, according to the depth at which the wind turbine will be installed[57]. Most offshore wind turbines today are bottom-fixed that are located offshore and assembled on fixed foundations in shallow waters. This excludes sites with the strongest winds and, often, access to big markets. Some of the largest electricity markets Japan and the USA possess few shallow-water sites suitable for offshore wind development. Floating foundations could be game changers in this regard. The cost of foundation for offshore wind farms increases significantly as the depth of the sea increases from shallow to deep waters. Technologies for floating foundations for offshore wind turbines are evolving. Fixed offshore turbines are limited in water depth to approximately 30-50 meters. Despite the increase in complexity, a floating foundation offers distinct advantages such as flexibility in site location, and access to superior wind resources further offshore.

The offshore wind regime is generally more fierce than onshore with the potential for much higher average wind speeds and the conditions at sea are much more challenging due to the corrosive nature of salt water. To combat this, marine technologies used to prevent seawater damage to offshore oil and gas installations have been adapted for use by the wind turbine industry. In addition, the difficulty of carrying out maintenance works means that offshore wind turbines need to be extremely reliable. Most of them are now equipped with real-time condition monitoring systems that can highlight the development of potential faults.

From the energy producing point of view, larger wind turbines can capture more energy from the wind. Therefore, they must be able to withstand hard loading conditions due to the higher wind speeds and extreme wave conditions in areas afar from the shore. Different energy technologies have different load factors. No individual power plant is always available to supply electricity. All plants are unavailable at certain times, whether for routine maintenance or for unexpected reasons. The load factor of an energy technology is the ratio (expressed as a percentage) of the net amount of electricity generated by power plant to the net amount which it could have generated if it were operating at its net output capacity. As wind is variable, the probability that it will not be available at any particular time is higher. The load factor of offshore wind varies according to the site and the type of turbines, varying upwards from 30% to in excess of 50 %. For example, the year 2020 set a new record for the highest annual average capacity factor for a UK offshore windfarm: Hywind Scotland achieved 57.1% in the twelve months to March 2020 (Energy Numbers, 2021)[58].

Currently, researchers in the industry are working to develop better turbine technology, such as higher efficiency generators with more reliable blades to minimize energy and manufacturing costs. Wind energy industrial workers have recently developed differently shaped and configured blades to improve its robustness and rotational speed. Until 2007, there was a tendency to install offshore wind turbines in water depth below 20 meters and closer than 30 kilometers from shore. Today, in contrast, turbines are being installed routinely in water depths up to 40 m and as far as 80 km from shore. Most of the capacity installed or operating for offshore wind to date is located off northern Europe. Half of the capacity is in United Kingdom waters, one-third in German waters, and the rest almost entirely in

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[57] For the exploitation of the wind energy resource, the classification of waves according to water depth is the following: shallow waters from zero to 30 m, transitional waters from 30 to 50 m, and deep waters from 50 up to 200 meters.

[58] Energy Numbers. "UK offshore wind capacity factors". 01 March 2021.

other parts of the North Sea or in the Baltic Sea. In order to carry out maintenance, offshore wind turbines must have facilities to allow support vessels to moor and transfer staff. The turbines may also be able to receive maintenance staff by helicopter. Whether maintenance crews arrive by sea or air, this still means that the turbines must be serviced from a shore base. As offshore development advances, particularly where wind farms are located far from shore, it may become practical to build a "mother platform", similar to an oil and gas platform, alongside a wind farm to house the wind farm substation and to provide accommodation for operations and maintenance staff (Breeze, 2016)[59].

2.1 LOADS ACTING ON OFFSHORE WIND TURBINES

Wind turbines are exposed structures, which are subject to various external effects. Medium to high wind speeds are a functional requirement for operating wind turbines but along with other meteorological conditions, such as turbulence and wind shear also form a major source for the loading of wind turbines. For offshore wind turbines, oceanographic and other marine climate conditions are the second main category of external conditions, which substantially affect the loading of wind turbines (DNV GL, 2016)[60].

Apart from the usual difficulties met by land-based structure, offshore structures are placed in a hostile environment where high wave and wind loads become major considerations in their design (Haritos, 2007)[61]. The loads that affect an offshore structure can be divided in two categories: those due to the function of the structure (Functional loads) and those due to the environment (Environmental loads). The first category includes static or dynamic loads from the operation of the structure, the weight of the structure, the buoyancy etc. The second category includes loads that come from the direct or indirect interaction of the environment with the structure, such as wind-, wave-, earthquake- and current loads (Mavrakos, 1999)[62]. At sea, as winds are more stable and often of higher average speed, offshore wind farms have a load factor of 45%. Larger turbines are expected to produce higher load factors for several reasons, most importantly, larger turbines can access higher winds due to their increased height, and that a wind farm with fewer, larger turbines has increased efficiency.

Wind and wave effects mainly cause offshore wind turbine (OWT) system load characteristics. Field experiments have shown that the distributed wind velocity is variable in space, time and direction (Molenaar, cited in Van Der Tempel, 2011)[63]. Therefore, it is rather complicated to consider the effect of variation of wind velocity in more than one direction. Wind is a significant design factor. For this purpose, the wind conditions used in design should be determined from appropriate and detailed wind data statistics for specific site. In addition, this data should be consistent with other associated environmental parameters (Bai and Jin, 2016)[64].

The offshore wind turbine structures are slender and wave- and wind loads act on the lower and the upper part of the tower. Sea waves result from wind blowing across the surface of the water and they form one of the major components of environmental forces affecting OWTs. These often start as minute ripples and can grow considerably with time. As the waves crush against the OWT foundation, they cause considerable action whose magnitude depends on the wave height and wave period. The waves approach an OWT from more than one direction simultaneously. Due to this random nature, the sea state is usually described in terms of statistical wave parameters, such as significant wavelength, spectral peak period, spectral shape, and directionality. Near to the free surface zone, the wave forces may obtain their maximum values[65].

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[59] P.Breeze (2016). "Wind Power Generation".

[60] DNV GL (2016). "Standard DNV GL-ST-0437 "Loads and site conditions for wind turbines".

[61] N.Haritos (2007). "Introduction to the Analysis and Design of Offshore Structures – An Overview". In *EJSE Special Issue: Loading and Structures.*

[62] S.A. Mavrakos (1999). "Study and Design of floating structures". S.A. Mavrakos, NTUA Notes, NAME Department.

[63] J.Van der Tempel et al. (2011). "Offshore environmental loads and wind turbine design: impact of wind, wave, currents and ice". Woodhead Publishing Limited.

[64] Y.Bai and L.W. Jin (2016). "Loads and Dynamic Response for Offshore Structures"

[65] Ibid, 2016.

Most of the recent structures for wind turbines are monopiles, truss structures, tripods, gravity-based structures et cetera. The substructures exposed to the harsh sea environment, experience the extreme impact force, run-up, and scour. Breaking waves exert very high impact forces in very short duration on the substructures and the analysis is extremely intricate. Breaking process starts when the wave gains more energy, becomes unstable and dissipates the energy in the form of turbulence. During the wave breaking process, the energy of the wave system is focused close to the crest of the wave and a spatial spread of wave energy occurs. Due to the impact force on the substructures, the performance and fatique of the offshore wind turbine is affected. Wave run-up affects the design of boat landing and platform facilities of the offshore wind turbine structures. (Chella et al., 2012)[66].

2.2 OFFSHORE FOUNDATIONS

As the offshore oil and gas industry started over 60 years ago, it has evolved intensely. This evolution was forced by the need of exploiting oil and gas reserves in more challenging regions. Offshore wind development greatly relies on the adapted technology used in the oil and gas industry. It is due to similar construction requirements in terms of distance to shore, huge cost of geotechnical campaign, as well as dependency of these offshore installation tools, which are very restricted and expensive (Gjersøe et al., 2015)[67]. Therefore, engineering, construction, and installation companies already working in the oil and gas industry have played a key role in the development of offshore wind farms.

Nevertheless, it is key to point out the difference between oil and gas and the offshore windfarm industry in terms of the cost incurred by each one. At the same time, the offshore wind industry cannot completely afford all techniques already implemented in the oil and gas industry; therefore, this industry must seek their own technical solution based on the unitary cost reduction of the foundations (Pliego et al., 2016)[68]. At an earlier stage, offshore windfarms were developed close to shore with shallow waters and with favorable technical conditions. In this scenario, foundations were installed up to 20 meters water depth, characterized by sandy seabeds, which allowed their driving into or laying down of gravity base structures (Zhang et al., 2016)[69]. In recent years, due to the installation of offshore wind farms in deeper water, as well as the increase of wind turbine's power, other structures like jacket and tripods have been used, i.e, in Alpha Ventus offshore windfarm (Arany et al., 2016)[70].

Of those researched so far, it can be outlined that the cost of foundations increases significantly with depths, and therefore, the depth of the sea is the most crucial factor for the sustainability of offshore wind farms. Figure 3 summarizes the water depths and the expected use of different types of foundations of offshore wind farms. Fixed structures are considered suitable up to a maximum depth of 50 meters. Thus, it is assumed that there is a technical- economic barrier of about 40-50 m. Currently, above this depth, only floating structures are considered profitable.

2.3 MAIN TYPOLOGIES OF FOUNDATION TYPES

Located in such a dynamic and extremely powerful element as the sea, foundations become one of the main elements of these projects, receiving over one-third of the total cost (Oh et al., 2018)[72]. The foundations must support the wind turbines, absorbing all the forces and loads and providing a safe and stable base. This has become especially vital during the last years as wind farms are being located further from the coast, and every ele-

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[66] M.A.Chella, A.Torum and D.Myrhaug. "Technoport RERC Research 2012: An Overview of Wave Impact Forces on Offshore Wind Turbine Structures". Norwegian University of Science and Technology, Trondheim, Norway.

[67] N.F. Gjersøe, E.B.Pedersen, B.Kristiansen, N.O.Hansen, L.B.Ibsen. "Weight optimization of steel monopile foundations for offshore wind farms". In *Proceedings of International Offshore and Polar Engineering Conference*, Kona, HI, USA, 21-26 June 2015; pp. 245-252.

[68] M.Pliedo, F.P. García-Márquez, J.M.Pinar-Pérez. "Optimal Maintenance Management of Offshore Wind Farms" In Energies 2016, 9, 46.

[69] P.Zhang, Z.Zhang, Y.Liu, H.Ding. "Experimental study on installation of composite bucket foundations for offshore wind turbines in silty sand" In *Journal for Offshore Mechanics & Arctic Engineering*, 2016, 138, 061901

[70] L.Arany, S.Bhattacharya, J.H.G.Macdonald, S.J.Hogan. "Closed form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI". In *Soil Dynamic Earthquakes Engineering,* 2016, 83, 18-32

Figure 3. Summary of foundation types, depths, and use frequency

Band Designation	Frequency Range	Water depth (m)	Ground type	Expected depth (m)	Current Use
Monopile	Fixed	<15	Sand-clayey	50 (with guy wire	The most used
Gravity Base Structure (GBS)	Fixed	≤30	Requires the previous preparation of the terrain	30-50	Significant
Jacket	Fixed	>30 (25-50)	Different types of soils (non-rocky)	<50	Significant
Tripods	Fixed	~30	Different types of soils (non-rocky)	>40	Not common
Semisubmersible	Floating	>60	-	>60	Not common
Spar-buoy	Floating	>60	-	>120	Not common
Tension Leg Platform (TLP)	Floating	>60	-	>100	Not common

Source: Review on Wind Turbines Offshore Foundation and Connections to Grid (Manzano-Agugliaro et al., 2020).[71]

ment must be designed and optimized in detail, to avoid performance problems and reduce maintenance works. Recently, however, a number of entirely new concepts or ones that are adapted, from the oil and gas industry for example, have been introduced to better deal with these challenges.

Technological advancement has presented OWT with foundations of different shapes, sizes and materials. In selecting a cost-effective foundation, special considerations are given to the following factors as they greatly influence the economics of the project: soil conditions, loads, transportation, installation, and water depth. The depth of the water for instance, is a crucial cost-factor in determining the type of foundation to be used for a specific OWT project. Different water depths pose different engineering challenges for OWT foundations.

As Passon and Kühn (2005)[73] pointed out, OWT structures can be grouped into the first, second and third generation. The first generation includes fixed foundations such as monopile and gravity-base foundations. These are effective in shallow waters less than 30 meters deep. The second generation covers a more sophisticated range of foundations such as tetrapod caisson, asymmetric-tripod caisson, jacketed caisson, tripod caisson and tripod pile foundations. These are effective even in deeper waters, but still limited to 60 m (Bhattacharya, 2014)[74]. The third generation is the floating type. It is by all means the most cost effective solution in deep waters and has no limit to which water depth it can be installed.

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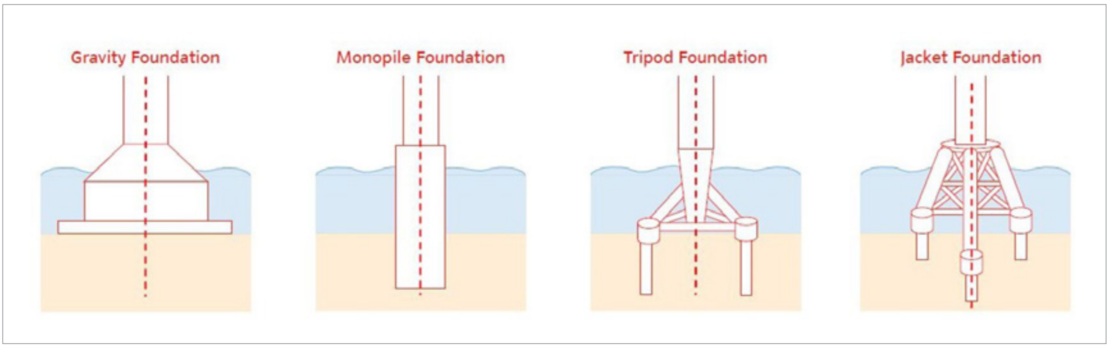
71 Manzano-Agugliaro, F., Sánchez-Calero, M, Alcayde, A., San-Antonio-Gómez, C., Perera-Moreno, A.J., Salmeron-Manzano. "Review: Wind Turbines Offshore Foundations and Connections to Grid". In *Interventions* 2020, 5, p. 2. MDPI.

72 K.Y. Oh., W.Nam. M.S.Ryu., J.K.Kim., B.I.Epureanu. "A Review of foundations of offshore wind energy converters: Current status and future perspectives". In *Renewable and Sustainable Energy* 2018, 88, pp.16-36.

73 P. Passon & M.Kühn (2005). "State-of-the-art and development needs of simulation codes for offshore wind turbines". Copenhagen Offshore Wind 2005 Conference

74 S.Bhattacharya. "Challenges in Design of Foundations for Offshore Wind Turbines". In *Engineering &Technology Reference*, 2014, pp. 1-9

Figure 4 Offshore wind turbines foundation types



Although the renewable energy market is seeing rapid development of floating offshore wind, bottom-fixed wind technology is still the primary choice for offshore wind farms. In bottom-fixed wind, approximately 80% of the foundations installed globally are monopiles. They offer several key advantages over other foundation types, such as simple design, serial fabrication and well-established transportation and installation procedures. However, in coming years, as wind farms expand into deeper waters (depth beyond 40 meters) with heavier turbines (10 MW and beyond), foundations will also have to increase in size to offset the resulting increases in overturning moment.

Main typologies of foundations used in the wind farms erected so far are monopiles, gravity base structures, jackets, and tripods. Key characteristics of these structures are described as seen in Figure 4. Below is a detailed description of these various types of foundations deployed in offshore wind farms.

2.3.1 MONOPILE FOUNDATIONS

In addition to their apparently conceptual simplicity, monopile foundations, seen in Figure 4B, are from the usual standards of onshore engineering. This is mainly due to their size and usage of transition piece between the pile and wind turbine tower.

Piles used so far can reach up to 5 m diameter with a weight above 600 tons and thickness around 100 meters where suitable. Its installation requires jack up vessels with enough carnage power to lift these piles as well as with a hammer, which can allow their driving into the seabed working from below sea level. The standard monopiles (those without lateral support) are mainly used in transitional water depth up to 25 meters, while monopiles with lateral support braces are suitable for depth from 25 m to 40 meters. Monopiles are suitable for semi-hard seabed, as hard seabed might lead to deformation of the steel piles during installations.

At present, it seems that the limit for the installation of monopiles is around 30 m depth, as indicated by Rüdiger (2013)[75]. In a theoretical sense, the development of new hammers with larger diameters could allow the installation of monopiles at greater depths. On the other hand, considering the substantial weight gain that this represents, it would not be a valid economic option. When evaluating the resistance of the soil against the pile load, factors such as pile dimension, strength and deformation properties of the soil and shear stress properties need especial considerations. Material properties such as stiffness and fatique limit the deployment of the mono-piles in deeper waters as steel materials are susceptible to fatique due to dynamic responses from waves and current loading. Besides, construction of this foundation requires minimal seabed preparation. Overall deflection (lateral movement along the monopile) and vibration, are limiting conditions for this type of foundation structures.

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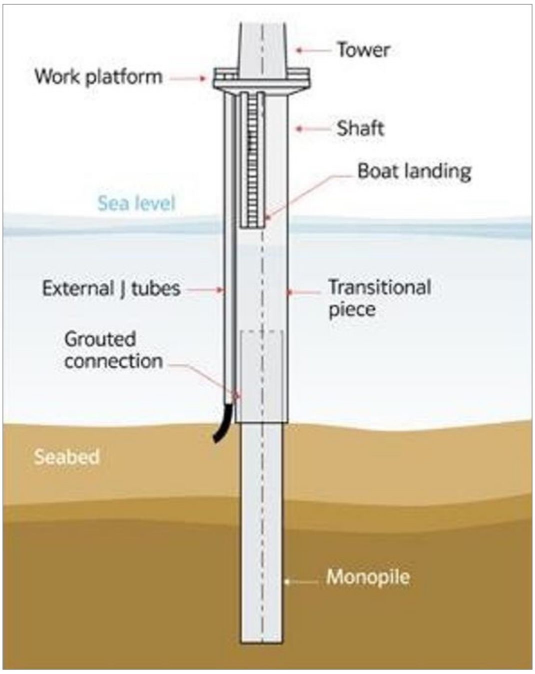
[75] S.Rüdiger (2013). "Steel Engineering and Construction", (accessed on 16 October 2021).

Figure 5. Monopile foundation



Source: Adapted from Omar Faruc Halici (2016)

2.3.2 GRAVITY BASE STRUCTURE

For those sites where ground conditions are good enough to support high pressures transferred from these structures, the gravity base foundation could be very competitive solution (Chiang et al., 2015)[76]. This structure comprises of slender steel or concrete pile like substructure fixed on heavy reinforced concrete foundations. As the name implies this foundation relies on the weight of the gravity base, which applies vertical pressure to the area below the stand on the seabed to support the structures and resist overturning. These are concrete-made structures, fabricated in a closer port to the final installation location where they are placed on rock-fill or loose stone and are protected against scour. Due to its size and weight, these structures require important ground preparation prior to their installation. To protect these structures from tidal and current effects, they are shaped with most of the weight concentrated on their base, leading to a smaller diameter at sea water level (He & Wang, 2016)[77]. Some details of the gravity-base structures are shown in Figure 6.

Figure 6. Gravity-base foundation

Source: Adapted from Windpower Engineering and Development (2021)

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[76] Y. Chiang, P. Lee, P. Chen, S.Lin, S.Hsiao. “A study on low-cost gravity base foundations for offshore wind turbine in Taiwan”. In *Proceedings of the International Offshore and Polar Engineering Conference*, Kona, HI, USA, 21-26 June 2015; pp. 289-296.

[77] R.He, L.Wang. “Elastic rocking vibration of an offshore gravity base foundation”. In *Applied Ocean Research*, 2016, 55, pp. 48-58.

Gravity-base foundations are well suited for homogeneous soils, with compact rocks and granites. External forces and bending moments transmitted by the turbines are transferred directly through the base of the foundation. The risk of shear failure under the base structure needs to be evaluated. Since concrete material is widely used to construct this type of structure, they are mostly used in shallow water depth between 0 to 25 meters. However, in Belgium over the Thornton Bank Offshore Wind Farm, six gravity-base foundations were constructed in water depth up to 28 meters (Peire et al., 2009)[78]. The size and weight makes it extremely difficult to transport and install, thereby limiting their deployment in deep water. Enormous port is also needed to construct these structures (Thomsen, 2011)[79]. This experience has proven that this kind of structures are very restricted by installations tools due to their huge weight, which leads to a higher cost than expected. Nevertheless, it seems clear that gravity base structures still have a wide room for improvement. This will mainly concern the installation activities, as they have to reduce their large dependency on installation vessels. To achieve that design for water depths higher than 20 m, the focus should be on weight reduction during transportation, taking advantage of their floating capacity (Whitehouse et al., 2011)[80]. On the other hand, these structures have the advantage of being simple concrete structures, which can be constructed by a number of construction companies. Based on that advantage, many studies have been carried out to find out the ways to optimize this kind of structures to be used for the offshore wind industry.

2.3.3 TRIPOD FOUNDATIONS

Figure 7. Tripod structure (Source: Maritek Ltd, 2021)

It is anchored into the seabed using a relatively small steel pile (0.9 m diameter) in each corner (Figure 7). The structure combines the structural function of a jacket foundation, as a triangular structure, with that of the monopile, keeping a core with great resistance to flexion (Chen et al., 2013)[81]. Tripods keep a central column under a wind turbine tower following the same structure as that of a monopile, but it is connected through a tubular structure to three lower legs where piles will be placed (Alti et al., 2011)[82].

The tripod however, has some specific advantages compared with the monopile and the jacket at water depths of 50 meters or greater as it is a sturdier construction than the monopile and easier to manufacture than a jacket. It will have its own specific niche and application in addition to those of the jacket and the monopile respectively.

Due to the piling requirement, the tripod foundation is not suited for locations with many large boulders. On the other hand, the tripod foundation could be a very competitive alternative in the following years for those locations where water depth is above 40 meters. These foundations have high resistance to dynamic responses

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[78] K.Peire, H.Nonneman and E.Bosschem (2009). "Gravity-Base Foundations for the Thornton Bank Offshore Wind Farm". In *Terra et Aqua*, 115, pp.19-29.

[79] K.Thomsen (2011). "Offshore Wind: A Comprehensive Guide to Successful Offshore Wind Farm Installation", Elsevier Science, UK, Chapter 1.

[80] R.J.S. Whitehouse, J.Sutherland, J.M.Harris. "Evaluating scour at marine gravity foundations". In *Proceedings of the Institution of Civil Engineers: Maritime Engineering,* 2011; Volume 164, pp. 143-157.

[81] D.Chen, K.Huang, V.Bretel, L.Hou (2013). "Comparison of structural properties between monopile and tripod offshore wind turbine support structures". In *Advanced Mechanical Engineering*, 2013, 5, 175684.

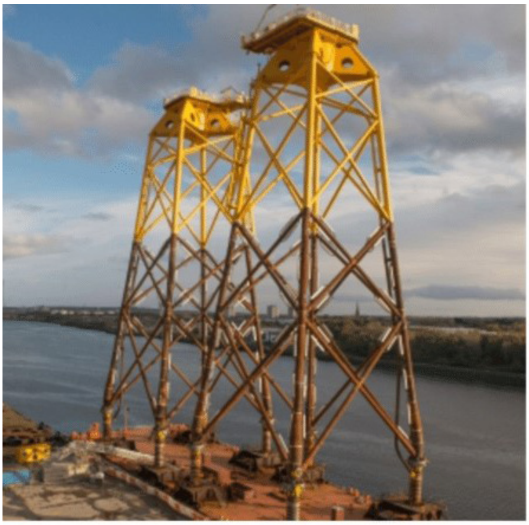
[82] N.Alti, F.Arena, G.Failla, V.Nava. "Fatique analysis of tripods and jackets for offshore wind turbines". In *Proceedings of the Sustainable Maritime Transportation and Exploitation of Sea Resources* – 14th International Congress of the International Maritime Association of the Mediterranean, Shanghai, China. In *Proceedings of the Sustainable Maritime Transportation and Exploitation of Sea resources* – 14th International Congress of the International Maritime Association of the Mediterranean, Genova, Italy, 13-16 September, 2011; Volume 2, pp. 1099-1106

like wave and current loading making them ideal for deeper waters. For offshore wind turbines of larger size, this type of foundation faces financial problems as they take more time to construct and install. Although scour protection may be needed around the tripod base in locations, where bottom currents are significant or where sediment is easily eroded.

2.3.3 JACKET FOUNDATIONS

Jacket foundations used in the offshore wind industry to date are based on a four-leg structure, where each of them is fixed to ground through a pile, which allows transfer of loads from the structure to the ground. This foundation has several advantages, for example low installation costs, since structural elements can be partially or fully assembled before floated for installation. On the other hand, extra corrosion protection measures have to be considered as they might lead to fatique in the structural components. Protective coating is used for the steel components in both the atmospheric zone and splash zone, while submerged component is cathodically protected.

Figure 8. Jacket foundation



Source: Adapted from the original photo by Usman Zafar (2018)

To date, only two offshore windfarm projects have been developed based on this kind of structures: "Beatrice" in Scotland, where two jacket foundation units were installed at around 45 m depth, and "Alpha Ventus" in Germany, where six jacket foundations were constructed for up to 30 meters in depth. In both cases, the wind turbine Repower 5MW was selected to be placed on top of these jacket foundations through respective towers, which is one of the heaviest wind turbines available on the market (Crampsie, 2014; Betke, 2014)[83][84]. There are other projects still under development based on water depths around 30 to 40 m. For these water depths, the weight of a jacket foundation is a bit lower compared to a monopile foundation, although the manufacturing process is significantly more complex and more expensive. Based on that, the jacket foundation could be seen as one of the more robust solutions for the development of offshore wind farms in the short term, and there are several installation companies working currently on the design of specific vessel to improve the handling of this kind of structures. This will allow for a better installation efficiency as well as for a reduction in the overall cost of the foundation.

2.4 FLOATING STRUCTURES

Recent trends in the wind industry point to the use of increasingly larger and more powerful machines with rated power ranging from five to ten megawatts exclusively designed for offshore use. Floating foundations offer greater flexibility in term of site selection for wind farms, and if properly designed, may result in comparable availability with equivalent offshore turbines on fixed foundations, while reducing the complexity and risks associated with offshore installation. Predictions indicate that floating offshore wind could be deployed at the utility scale by 2024 (NREL, 2020)[85]. Turbines can be located in areas with sea depths over 60 meters, harnessing the best wind resources and opening new sites to power generation. Floating turbines are moored to the seabed with multiple mooring lines and anchors, in much the same way as a floating oil

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[83] S.Crampsie. "Firm foundations". In *Energy Technologies, 2014*, 9, 64-67.

[84] K.Betke. "Underwater construction and operational noise at Alpha Ventus". In *Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, Results and perspectives",* Springer Spectrum, Wiesbaden, Germany, 2014; pp. 171-180.

[85] "Floating Wind Turbines on the Rise", NREL Offshore Wind Expert Discusses Future Powered by Floating Offshore Wind, April 2, 2020

platform. Turbines' motion controllers use sensors to regulate the turbine blades in adverse conditions, reducing strain on the moorings and maximizing electricity production.

Floating foundations offer the offshore wind industry two key opportunities: they allow access to deep-water sites with higher wind resources. Depending on depth and soil conditions, various concepts are used, but most common is the monopile. Floating foundations are already proven in harsh operating environments. Platform designs for offshore wind, however, require adaptation to accommodate different dynamic characteristics and a distinct loading pattern. The same process has already occurred largely for bottom-fixed foundation, including monopiles, jackets and gravity-base designs. Some experts are skeptical about the high costs of floating offshore wind turbines - currently the electricity they generate is often almost twice as expensive as near-shore wind turbines and three times that of land-based wind turbines will come down far enough to rival other clean energy technologies. Even though the floating wind farms may be cheaper in some cases than fixed offshore wind farms and deployable over a larger sea area, maritime engineering makes it expensive to build, deploy, and maintain. Lifespan of the foundations is short due to the corrosive nature of the marine environment. On the other hand, the costs of onshore and near-shore wind energy have been steadily falling as the efficiency of these technologies has been rising. The same trends are likely to lower the costs of floating offshore wind. The Hywind Scotland array – 75% owned by the Norwegian utility company Equinor has been in operation for nearly three years and remained afloat and generating power during Hurricane Ophelia in 2017 and throughout other harsh winter storms.

Floating wind power has enormous potential to be a core technology for reaching the climate goals in Europe and around the world. The ocean space beyond the reach of conventional offshore turbines makes up 80 percent of the world's maritime waters, opening the way for floating arrays. Globally, there are 13 announced floating offshore wind projects (nine in Europe – UK, Portugal and France, three in Asia – Japan and Korea and one in the USA). However, currently the only operational floating wind farm of scale is Hywind Scotland, developed by Equinor and commissioned in October 2017. Floatgen wind turbine demonstrator, which is installed 22 kilometers off Le Croisic (Loire-Atlantique) in France, also became operational in September 2018. To date, 73 megawatts of floating wind capacity has been installed globally; however, there has been a relatively low level of new capacity installed since 2018. The lack of installation activity is not representative of the significant project development activity that has been ongoing with key industry players for the next generation of projects. The recent installation of EDPR's 25 megawatts WindFloat Atlantic 2 floating pilot project will be followed by a series of pilot wind farms that are set to demonstrate the technical and commercial viability of floating wind technology (Carbon Trust, 2020)[86].

Other floating wind projects, some with turbines larger than Hywind, are now being built in Europe and Japan. In Portugal, the WindFloat Atlantic project, now under construction, is expected to produce enough power for 60,000 homes when it is completed later this year. France has integrated floating wind power into its clean energy plans, seeking to be a world leader in deploying the technology. It has dedicated sites and price supports for wind farms off Brittany and the Mediterranean coast. Scotland which aspires to cover all of its electricity needs with renewables this year, has new floating wind farms in the works including one just south of Hywind Scotland. Over 30 floating wind concepts are under development, each having their own respective strengths, which can differ by project site depending on the weather conditions, water depth, seabed conditions, local infrastructure, and available supply chain capabilities. The next generation of floating turbines capable of operating further from the shore could generate enough energy to meet the world's total electricity demand 11 times over in 2040, according to IEA estimates.

A major constraint on offshore wind has been the difficulty of building fixed constructions in depths greater than 60 meters. Hybrid projects

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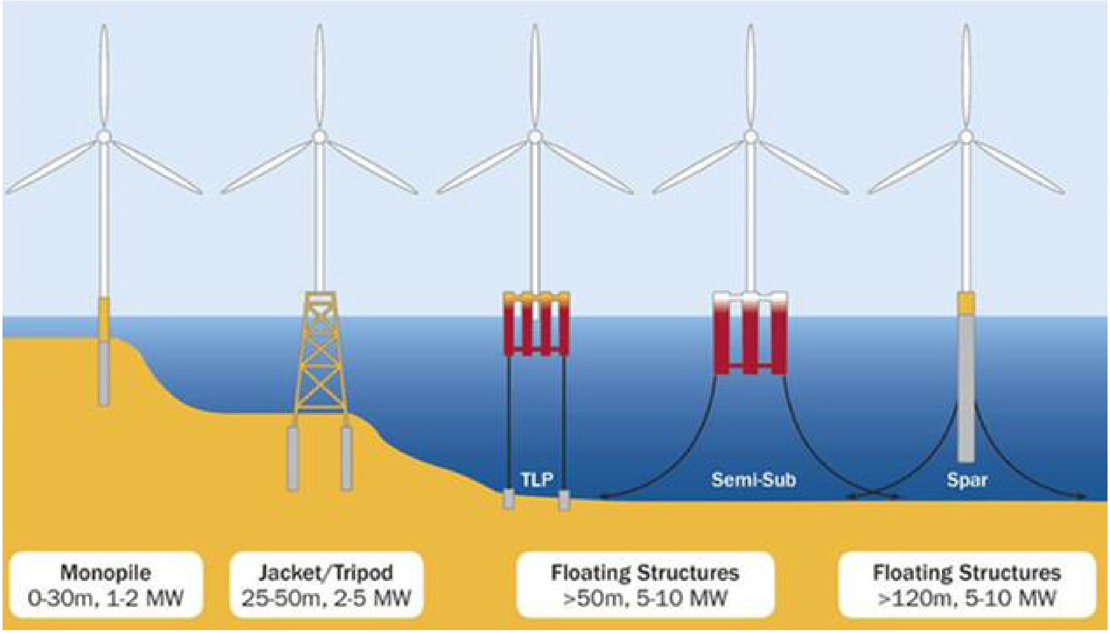
[86] Carbon Trust. "Phase II Summary Report". Floating Wind Joint Industry Project

Figure 9. Types of offshore wind turbine foundations (reproduced from reference 12, source Principal Power). Monopile and tripod/jacket foundations are currently proven technologies. Floating structures have been using three main types of foundations, which are adapted from the oil and gas industry: the Tension Leg Platform (TLP), semi-submersible (Semi-Sub), and Spar Buoy (Spar).



linking offshore wind to other uses – such as hydrogen production or battery storage – represent another important avenue for offshore wind to contribute more widely to our energy systems. In the past few years, this technology has made great strides, and Hywind shows that it can work as a whole park. Now the farms have to grow bigger to show governments and investors that they are feasible on a large scale.

From technical point of view, it is clear that floating structures still have some problems to be re-engineered on the dynamic behavior of their structures, catenary mooring lines, anchoring etc. Different floating support platform configurations are possible for use with offshore wind turbines such as tension leg platforms (TLP), spar-buoys and semi-submersibles as illustrated in Figure 9. Variants on these also exist, including the mounting of multiple turbines onto a single floating foundation.There is still no consensus about the buoyancy design (single-column, semi-submerged, tension leg platform), the material (steel or concrete), and a number of other features. The two most advanced systems are Hywind, a ballasted mono-column produced by Equinor, and WindFloat, the semi-submersible platform produced by Principle Power[87].

2.4.1 SEMISUBMERSIBLE PLATFORMS

Semi-submersible platforms typically consist of multiple columns and pontoons. The columns mainly provide the stability, while pontoons provide additional buoyancy. The center of the gravity is above the center of buoyancy, the stability is achieved by the restoring moment of the columns (Figure 9). The floating structure is kept in position by a mooring system, consisting of catenary or taut spread mooring lines and drag or suction anchors.

To optimize the foundation structure and achieve wind turbine stability, different floating wind prototype designers have created various innovative floating wind semi-sub-

[87] In October 2011, Principle Power deployed a full-scale two MW WindFloat prototype (WF1) 5 km off the coast of Agucadoura, Portugal.

mersibles. Common offshore wind submersible designs are WindFloat[88] and OC DeepCWind semisubmersible wind turbines (Roddler et al, 2011)[89]; in which braces that are slender structural elements connect the columns of the semisubmersible. For example, WindFloat developed by Principle Power has three large diameter columns with small diameter braces made of steel.

Although semi-submersibles have poorer fundamental stability than spar-buoy foundations and tension leg platforms, this concept is still the most popular so far in the industry for the following reasons. Firstly, the cost of anchoring system is lower than the tension leg platform, secondly its' transportation and installation is simpler than the other two concepts. The turbine can be installed on the semi-submersible in the dockside and towed out to site, avoiding the costly offshore installation.

2.4.2 SPAR-BUOY

It is a cylindrical ballast-stabilized structure, which gains its stability from having the center of gravity lower in the water than the center of buoyancy. Thus, while the lower parts of the structure are heavy, the upper parts are usually lighter, thereby raising the center of buoyancy. These are cylindric structures, which are also anchored to the seabed through a catenary mooring line. Their main difference from semisubmersible structures is that they come along with a lighter but longer structure, which come with a lower center of gravity. To date, the successful spar buoy in European water is manufactured in steel. As spar-buoy foundation weights approximately 8,000 tons, it is difficult to move it to nearby water. It is lifted with high capacity cranes on to a specially designed ship. At its destination, the ship is designed to take on water until the spar buoy floats free.

In terms of installation, it is important to note that due to issues with stability during wind turbines' assembly, these kind of structures are challenging and would require the use of heavy lifting cranes (with high daily rates as well as well as subject to weather downtime) rather than a more accessible concept than semisubmersible structure.

2.4.2 TENSION LEG PLATFORM (TLP)

One proposal for floating offshore wind turbines development is the concept of Tension Leg Platforms. TLP consists of a floating structure that uses a vertical tether system connected to the seafloor to achieve its required stability. There are wide ranges of TLP structure arrangements that have been developed for the different purposes they serve. These different types can be categorized into mono-column and conventional multi-column TLPs. Until the late 1990s, most of oil and gas production platforms consisted of square four-column configurations. Thus, TLPs are a promising option for intermediate water depths due to the limited motions of the platform, allowing for the reduction of turbine motions and loads (Bachynski-Polic & Moan, 2012)[90]. TLP may also prove more effective for the relatively light topside conditions.

CHAPTER 3 – ENVIRONMENTAL ASPECTS OF OFFSHORE WIND FARMS

Activities associated with offshore energy generation have implications for the surrounding marine environment as it is also home to diverse marine fauna and flora. Synergy between these economic and ecological functions is essential to ecologically sustainable development. Although our understanding of those implications has improved, particularly for marine megafauna (i.e large mammals, such as whales, dolphins, seals, and large fish such as sharks) much remains unknown about how offshore energy activities af-

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[88] In this project the wind turbine was installed off the coast of Portugal in 2011 and it is powered by a 2.3 MW wind turbine based on a three column semisubmerged structure moored to the seabed with three catenary lines.

[89] D.Roddler, A.Peiffer, A.Aubault and J.Weinstein. "A generic 5 MW WindFloat for numerical tool validation & comparison against a generic spar. In *30th International Conference on Ocean, Offshore and Arctic Engineering 2011*. OMAE2011-50278.\

[90] E.E.Bachynski-Polic; T.Moan. "Design considerations for tension leg platform wind turbines". In *Maritime Structures 2012*, 29, pp.89-114.

[91] G.W. Boehlert, A.B.Gill (2010). "Environmental and ecological effects of ocean renewable energy development – a current synthesis". In *Oceanography*, 23: 68-81.

fect marine ecosystems (e.g Boehlert & Gill, 2010)[91]. As with all energy supply options, wind energy can have adverse environmental impacts, including the potential to reduce, fragment, or degrade habitat for wildlife, fish, and plants. Here the importance of a well-performed Environmental Impact Assessment (EIA) comes into place helping in decision making whether the project is acceptable for the society from the environmental point of view.

Most evidence of how offshore energy activities affect the marine environment comes from studies of direct changes or responses (termed "effects") that can be quantified for a few species or habitats (known as environmental "receptors")[92]. Often the motivation to examine these hypothesized effects is required under an environmental impact. One important and generally unanswered question is whether the effects observed are biologically meaningful. Since marine environmental conditions vary between different locations as well over time, it is difficult to make universal assessments of the effects of offshore wind power. This increases the importance for conducting well-designed pilot studies and monitoring programs of the local environment. In addition, location-specific surveys minimize the risk that costly measures are used when they are not necessary.

Traditionally, environmental changes have been associated with physical effects (e.g. built structure or seabed related) or chemical (e.g fluid spill) effects. The focus has also been on direct and acute effects; however, many changes can occur indirectly and potentially over long periods (i.e, chronic effects, Gill 2005)[93]. These changes are linked to factors influencing ecological change, but can be more substantial than acute effects because they impart ecosystem changes (which can results in alteration of the benefits that human receive from the ecosystem such as fish for consumption) in the longer term of decades (Gill, 2005)[94].

The proximity of offshore wind farms (OWFs) to the coast can overlap with sensitive ecological areas that are protected under European legislation. In general, wind energy development do not represent a serious risk to wildlife, but poorly sited wind farms can pose a threat when they are located in or near areas of high ecological value, such as Natura 2000 sites. In Europe, marine protected areas fall under the European Commission initiative Natura 2000, which provides guidance regarding how to ensure that wind energy developments are compatible with conservation measures for key fish species and their habitats (European Commission, 2010)[95]. Marine conservation areas, often referred to as marine protected areas (MPAs), imply that human activities are restricted within designated areas in order to create safe havens for valuable populations or ecosystems.

The construction and operation of offshore wind turbines generates underwater sound that can potentially have an environmental impact on the marine life in the area. Noise is generated within the surrounding sea and seabed during installation and operation of the energy devices, and electromagnetic fields (EMFs) are emitted when electricity is transported through the cable network. The basic assumption that marine ecologists have adopted is that reduced noise and smaller EMF emissions are desirable because logically their impact within the marine environment is likely to be smaller (Inger et al., 2009)[96]. At the same time, the turbines can act as artificial reefs and no-take zones with positive effects on local biodiversity and possibly spillover effects (an undisturbed population can reproduce and spill over to other areas).

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92 Ibid, 2010.

93 A.B.Gill (2005). "Offshore renewable energy: ecological implications of generating electricity in the coastal zone". Review. In *Journal of Applied Ecology,* 42: 605-615.

94 Ibid, 2005.

95 Natura 2000 is the largest coordinated network of protected areas in the world and it stretches across 28 EU countries, both on land and sea. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive.

96 R. Inger, M.J.Attrill, S.Bearhop, A.C.Broderick, W.J. Grecian, D.J.Hodgon, C.Mills et al. (2009). "Marine renewable energy: potential benefits to biodiversity? An urgent call for research". In *Journal of Applied Ecology*, 46: 1145-1153.

Figure 10 gives an overview of the possible impacts of offshore wind farms on the environment. A distinction is made between the construction and operational phase, and different species and habitats.

Habitat/species	Construction phase	Operational phase
Marine mammals	Avoidance of areas with underwater noise due to piling	Possible attraction to wind farms due to high food abundance (see fish)
Seabirds	Disturbance by vessels (avoidance distance 2 km)	Collision risk, avoidance of windfarms, new habitat
Fish	Disturbance, change and loss of habitat negative impact on fish eggs and larvae	Decreased fishing and vessel activity leads locally to higher biomass and larger fish
Benthos	Disturbance, loss and change of habitat of soft substrate species	Higher biodiversity and a higher biomass of hard substrate species, stepping stone for invasive species
Sandbanks	Disturbance, loss and change of habitat	Loss and change of habitat

The present chapter provides an overview of the impacts on benthic species, fish, marine mammals and birds that have been discussed in relation to offshore wind farms.

3.1. POTENTIAL INFLUENCES OF OFFSHORE WIND ON MARINE ENVIRONMENT

Offshore wind farms can have positive and negative impacts on the underwater environment before installation, during construction of the foundations, laying electrical cables and during operation. Some negative impacts can be mitigated through careful site selection, foundation design, and operational planning. In the following sections, the negative and positive impacts of offshore wind farms are discussed in detail.

3.1.1 NEGATIVE IMPACTS

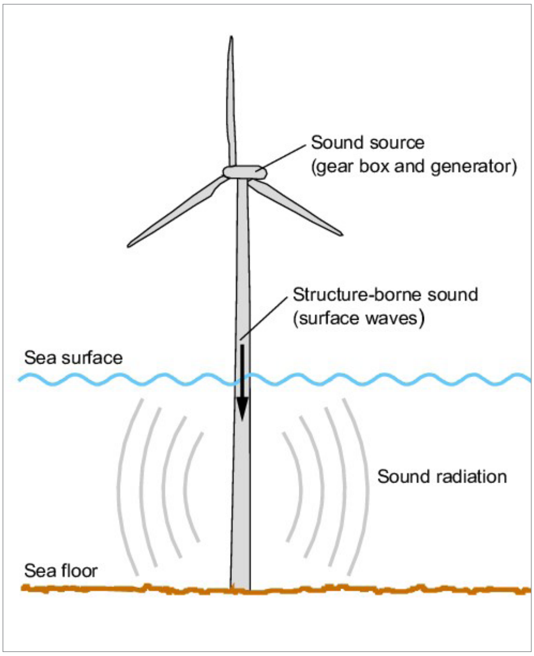
One of the first effects of OWFs have on their surroundings is physical damage caused by its construction. The main effects of this are seafloor habitat destruction and sediment suspension in the water column, caused by the disruption of sand and silt from the seafloor. Sediment suspension is likely to have a negative impact on fauna by increasing turbidity, mobilizing contaminants and smothering sessile suspension-feeding animals, such as corals, sponges and anemones. A reduction in visibility from sediment suspension can also affect photosynthesis in algae and disrupt key behaviors in visual animals.

Activities during all phases of wind farm lifetime produce underwater sound, a concern as high noise levels and/or persistent anthropogenic noise can affect marine life in many ways. For example, acoustic disturbance can affect the behaviors of marine animals as well as potentially cause serious injury. The ocean is an acoustically diverse environment. From a biological perspective, acoustics are vitally important in animal communication, reproduction, orientation, and prey and predator sensing. In terms of sounds produced by offshore wind farms, there is a number of potential sources as well as different temporal and spatial scales to consider. The noise comes from two fundamentally different contributions. The first is construction (and decommissioning) activities that can generate noise of considerable intensity but within a limited time. The second is operation of the wind farm where turbine machinery (and service activities) creates a low-intensity, yet almost continuous, underwater noise.

Offshore wind farm projects affect the environment in different ways during installation, operation and decommissioning stages. Currently, most studies on the potential effects of OWFs have focused on the installations and operation phases. Pile driving[97] during the construction of OWFs can generate noise up to 200 dB (Tougaard et al., 2008)[98] while the operation generates up to 120 dB. This noise is mainly generated above the water but it is transmitted through the tower and is then radiated into the surrounding water, adding to pre-existing noise from other sources. Underwater sound, like sound in the air, is disturbance from a source in a medium – here water is travelling in a three dimensional manner as the disturbance propagate with the speed of sound. Sound travels at different speed in different media, for example, its speed is determined by the density and compressibility of the medium. Density is the amount of material in a given volume, and compressibility is a measure of how much a substance could be compacted for a given pressure. The denser and more compressible, the slower the sound waves would travel. The speed of sound can also be affected by temperature. Sound waves tend to travel faster at higher temperatures (Ramboll, 2014)[99]. Therefore, acoustic disturbance can affect animal behavior, particularly those that are more sensitive to sound relying on their use of vocalization for communication and those that use echolocation for navigation such as cetaceans.

Noise mitigation systems such as bubble curtains (bubbles produced by hoses on the sea floor around the base of the turbine) have been shown to reduce the level of disturbance in harbor porpoises by 90%. However, the hindrance that OWFs construction poses to their communication could have a negative impact on their social interactions and migrations. This could also be the same for other cetaceans, but there is lack of research in other species. Other affected species include cod and herring, who can detect pile-driving noise from up to 80 km away.

Figure 11. Mechanism of underwater noise generation by an offshore wind turbine



Source: Reiner Matuschek 2020

Another potential issue with OWFs is electromagnetic fields (EMFs), which are generated by the transportation of the acquired energy through electric cables that are built into the seabed. Until the advent of marine renewable energy developments and offshore power transmission networks, electromagnetic fields were not considered as potential source of environmental disturbance. The electricity is traversed for long distances through a network of cables that transmits power from several devices to a large collector cable that is connected to shoreline substation, or an offshore substation that transforms the energy for the receiving electrical grid system. During transmission of the produced electricity, the cables will emit low-frequency electromagnetic fields (EMFs). At present, the industry standard for the design of the cables re-

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[97] Pile driving is associated with monopile wind and tidal turbines and other devices that require small piles for securing jacket foundations.
[98] J.Tougaard, M. Wahlberg. "Underwater noise from construction and operation of offshore wind farms". In Bioacoustics, April 2008.
[99] Ramboll (2014).Smalandsfarvandet Offshore Wind Farm Underwater Noise", Report.

quire shielding, which restricts the directly emitted electric fields but cannot shield the magnetic component of an EMF. The movement of water and organisms through the emitted magnetic fields will induce localized electric fields (Ohman et al., 2007; Degraer et al., 2020)[100]. If the alternating current (AC) cables are used, the magnetic field associated with the cable has a rotational component, which also induces electric fields in the surrounding environment.

A number of organisms that inhabit the coastal and offshore environment are able to sense either magnetic fields, electric fields, or both. Taxa that have been determined to be magneto-sensitive are generally those that undertake large-scale migrations or use Earth's natural geomagnetic fields for orientation (examples can be found among cetaceans, herptiles, teleosts, and crustaceans (Kirshvink, 1997)[101]. In a review of the state of knowledge, Gill et al. (2005)[102] found that little was known concerning electrically and magnetically sensitive marine animals; with regard to offshore wind farms, there were no studies of direct relevance. However, a small number of studies currently exist, some of which relate to just subsea cables (not necessarily from a renewable energy source) and others that have started to address the dearth of information available on the topic.

One of the more overlooked issues associated with OWFs is the introduction of non-indigenous and invasive species, which presents a threat to biodiversity. Artificial structures (including OWFs, oil rigs, breakwaters and ports), are known to promote the spread of non-indigenous species, which can disrupt trophic webs and cause shifts in the populations of native species, normally with a negative impact on the overall ecosystem. Since the start of international shipping, marine organisms have been distributed all over the world by ballast water or as fouling on boat hulls. Artificial hard substrates offer habitats for a large number of invasive species normally attached to rocky reefs. In general, artificial structures do not host exactly the same species as a natural hard substrate. The installation of offshore wind farms may not only introduce hard substrata in otherwise sandy-dominated bottoms, but can also provide new habitats for invasive species. Different hydrodynamics, such as more shelter due to new structures may lead to colonization of organisms very different to those on nearby hard substrates, thereby establish, and spread of non-indigenous species.

3.1.2 POSITIVE EFFECTS

OWF construction also introduces new habitats for indigenous species by introducing three-dimensional, hard substrate structures that act as artificial reefs in what would usually be a vast and flat seabed. Artificial reefs are manufactured structures (i.e., hard substrates) deliberately placed in the sea to mimic characteristics of natural reefs. The most common purpose for artificial reefs has been to improve biodiversity, particularly with respect to fishery species. Trawling may be prohibited from near the turbines and cables, but the wind farm area may be designed to benefit other fish stocks. The habitat protected from trawling may become a refuge for young and spawning fish and thus provide benefits to the fish populations beyond the immediate exclusion area. A second possible benefit is the sheltering effect. A safety buffer zone surrounding the wind turbines may become a *de-facto* marine reserve, as the exclusion of boats within this zone would reduce disturbance from shipping. Exclusion of some or all types of fishing could also result in local increases in prey abundance for top predators, whilst reducing the risk of bycatch in fishing gear. Further research is required to understand the ability of wind turbines to attract marine species and the effect of excluding fisheries.

It is now widely accepted that one of the most important effects of OWFs is the provision of new habitat that can be colonized by hard sub-

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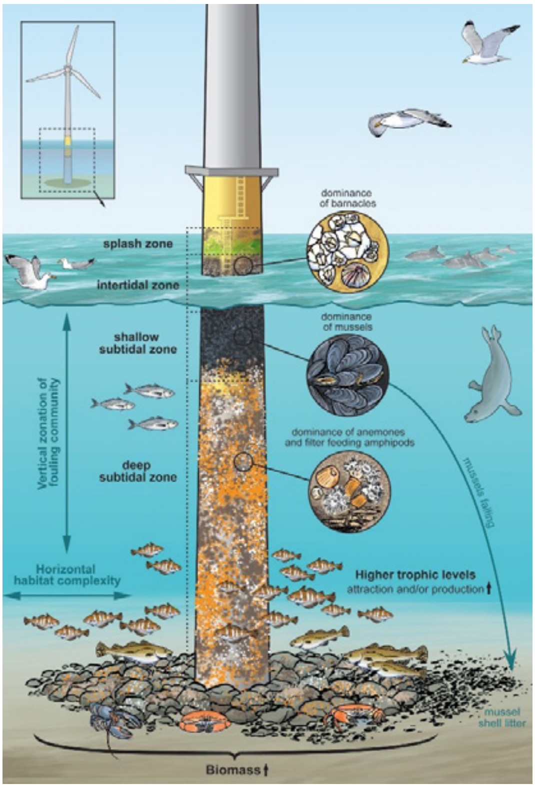
[100] S.Degraer, D.A.Carey, J.W.P. Coolen, Z.L.Hutchinson, F.Kerckhof, B.Rumes, and J.Vanaverbeke (2020). “Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis”. In *Oceanography 33(*40: 48-57.

[101] J.J. Kirshvink (1997). “Magnetoreception: Homing in on Vertebrates”. In *Nature 212*: 1232-1233.

[102] A.B. Gill (2005). “Offshore renewable energy: ecological implications of generating electricity in the coastal zone”. Review. In *Journal of Applied Ecology*, 42: 605-615.

strate species (Petersen & Malm, 2006)[103]. Setting aside the loss of soft sediment habitat due to the OWF footprint, these structures generally provide two distinct artificial habitat: hard vertical substrates and a complex range of horizontal habitats, depending on the type of foundation and the degree of scour protection[104] used (Langhamer, 2012)[105]. For example, the seabed of most of the North Sea consists of sandy soil. This sand is constantly moving due to waves and current. When a structure is placed offshore, it results in local increase of the current and wave motions. This fast flowing water stirs sand particles, picks them up and transports them away from the structure, creating a hole around the structure. This phenomenon is called scour. The effects of scour on the design of the offshore wind turbine can also be mitigated by protecting the soil around the pile against scour. The most cost effective method is the dumping of crushed rock. The basic idea behind the placing of a layer of rock is that the rock particles are selected in such a way that the increased current around the structure will not be able to wash them away. As more research is done in the area, future OWFs may even be designed to maximize their ability to create new habitats and provide an even bigger positive benefit. In addition, the novel surfaces occur throughout the full water column, from the splash zone to the seafloor, often in areas where comparable natural hard surfaces are absent (Figure 12). These attributes are largely unique to offshore energy infrastructure.

Figure 12. Offshore wind farm structures provide habitat for invertebrate organisms that foul the foundation along the depth gradient and attract predator fish, seabirds, and marine mammals. Illustration by Hendrik Gheerardyn.



Another potential benefit of OWFs is an increase in biodiversity, which is one of the main indicators of ecosystem health. This is believed to be the result of a reduction in sediment grain size and an increase in organic matter in the vicinity. For example, on the Nysted OWF in the Danish part of the Baltic Sea, more biological activity was recorded further up a turbine where blue mussels were most abundant. These species modify habitats by filtering organic matter from the surrounding water and act as a secondary hard substratum, which promotes biodiversity. The Egmond aan Zee offshore wind farm is the first large scale offshore wind farm built off the Dutch North Sea coast. It has also increased the diversity and abundance of benthic organisms and attracted higher abundances of certain fish, mammals (including harbor porpoises) and in some cases even birds. Biodiversity at the Horns Rev OWF in the Danish North Sea was found to be higher and also had a 7% increase in biomass resulting in 50 times more food available (Bio-Consult &Vattenfall, 2006)[106].

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[103] J.K. Petersen, T.Malm (2006). "Offshore wind farms: Threats to or possibilities for the marine environment". AMBIO: A Journal of the Human Environment, 35 (2): 75-80.

[104] Wind turbine foundations, substations and power cables need to be protected against seabed erosion, anchors and fishing nets. Therefore, rocks of all sizes at various depths are installed by fall pipe vessels, while pre-lay and/or post-lay rock berms are installed to protect cables.

[105] O.Langhamer (2012). "Artificial reef effect in relation to offshore renewable energy conversion: State of the art". In *The Scientific World Journal*, 386713, https://doi.org/10.1100/gcb.13915

[106] Vattenfall. "Benthic Communities at Horns rev before, during and After Construction of Horns Rev Offshore Wind Farm: Final Report". 31 May 2006.

It has been suggested that OWFs can also act as a safe place for many commercially targeted species due to the increased abundance of food available and protection from anglers, who tend to avoid OWFs for fear of entanglement. Research has shown that cod and pouting have benefitted from the construction of OWFs, as well as some species of crab. In the future, it may be even possible to combine OWFs and Marine Protected Areas (MPAs) as a way of further protecting commercial species whilst revitalizing threatened ecosystems. Finally, there may also be opportunities in the future to combine offshore wind farms with open ocean aquaculture. However, the understanding of the potential effects of offshore wind farms on marine ecosystems, as well as marine biodiversity, is steadily improving as empirical evidence from operational wind farms accumulates (Bergström et al., 2014)[107].

3.2 EFFECTS OF OFFSHORE WIND FARMS ON BIRDS, MARINE MAMMALS AND FISH SPECIES

The construction and operation of wind farms may have significant effects upon a range of fishes and invertebrates. As wind farms operate for many years, they have the potential for affecting animal stocks. As the number and size of offshore wind developments increases, there is a need to consider the consequences and cumulative impacts of these activities on marine species. It is essential to identify where whales, dolphins and other species occur to help avoid adverse impacts and to continue to monitor their response to the construction and operation of wind turbines. The main categories of marine animals relevant in the context of offshore wind farms are protected species of birds, seals, whales and dolphins both within and outside of protected areas.

3.2.1 BIRDS

Ornithologists are often concerned that OWFs may negatively affect the migration and breeding patterns of various avian species (Desholm and Kahlert, 2005)[108]. The construction of offshore wind turbines may affect birds as follows: (1) risk of collision, (2) short-term habitat loss during construction, (3) long-term habitat loss due to disturbance by turbines including from boating activities associated with maintenance works, (4) formation of barriers on migration routes, and (5) disconnection of ecological units, such as roosting and feeding sites.

Both the North and Baltic Seas support large concentrations of breeding, and wintering birds, and therefore are of international importance. Both seas are also part of a global flyway system and every year tens of millions of birds pass through on their way from breeding grounds to wintering areas and back. Hence, all European countries have obligations under national and international legislation (e.g. EU Bird Directive, EU Habitat Directive)[109] as well as under international conventions (e.g. Ramsar Convention, AEWA under Bonn Convention, Bern Convention) to protect and preserve habitats and bird populations. Wind turbines rotor blades sweep the air at altitude from tens of meters up to hundred meters. This fast moving obstacle can be difficult to avoid for birds under conditions of low visibility (Gill, 2005)[110]. According to the estimates, onshore wind power kills, on average, two birds per turbine a year while the numbers are less known at sea. However, available data indicate that losses at offshore locations are lower than on land (Rydell et al., 2011)[111].

Birds are particularly vulnerable for three reasons. Firstly, seabirds are negatively impacted through the loss and modification of resting and foraging grounds. Secondly and most importantly, they are killed because of collisions with turbine blades: for example, significant fatalities have been reported at marine wind farms

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[107] L. Bergström, L.Kautsky, T.Malm, R.Rosenburg, M.Walberg, N.A. Capetilli, and D. Willemson (2014). „Effects of Offshore Wind Farms on Marine Wildlife - A Generalized Impact Assessment". Environmental Research Letters, 9. www.doi.org://10.1088/1748-9326/9/3/034012

[108] M. Desholm, J. Kahlert (2005). "Avian collision risk at an offshore wind farm". In *Biology Letters*, 1: 296-298

[109] The EU Birds Directive (Directive 79/409/EEC) aims to protect all of the 500 wild bird species naturally occurring in the European Union. The Directive places great emphasis on the protection of habitats for endangered and migratory species.

[110] A.B. Gill. "Offshore renewable energy: ecological implications of generating electricity in the coastal zone". Review. In *Journal of Applied Ecology*, 2005, 42: 605-615.

[111] J.Rydell, H.Engström, A. Hedenström. J. Kyed Larsen, J. Pettersson et al. (2011). "Vindkraftens påverkan på fåglar och fladdermöss-syntesrapport". Naturvårdsverket, Bromma

situated close to breeding colonies (Everaert and Stienen, 2007)[112]. Thirdly, several studies have found that offshore wind farms act as barriers to travelling seabirds. Displacement from their favored routes is likely to increase travel distances, causing greater energy expenditure and potentially affecting the survival of nestlings by lowering provisioning rates. The main factors that contribute to collision fatalities are proximity to areas of high bird density or frequency of movements (migration routes, staging areas, and wintering areas), bird species (some are more prone to collision or displacement than others are), and landscape features that concentrate bird movement, and poor weather conditions. Studies have indicated that environmental impacts of wind farms include collision risks and diversion of bird migration routes and potentially bats (a problem for onshore wind farms, but little documentation exists for offshore sites). Moderate to high uncertainty is associated with acoustic impacts to wildlife during the offshore wind farms operational phase.

There are a number of potential negative impacts of offshore wind power development on birds. Impacts on migrating birds vary among species and locations. While single wind farms seem to have little effect on large-scale migration, cumulative effects may become important if wind power expands without consideration of migration routes. To avoid displacement, certain areas should not be developed. Even though some bird species have been shown to adapt to wind farms, many vulnerable species may be severely affected if wind farms are established in their traditional feeding or breeding areas. Concerning indirect effects it is hypothetically possible that diving birds that forage on offshore banks would benefit from offshore wind farm establishment due to reduced risk of bird bycatch in gillnets. However, this possibility of increased survival due to fishing reductions remains speculative.

3.2.2 MARINE MAMMALS

Offshore wind farms can potentially affect marine mammals in several ways. The physical presence of the turbines and the construction activities can cause animals to avoid the areas, partly or completely. The most important factor is likely to be underwater noise. Construction activities are generally noisy and especially pile driving operations generate very high sound pressures that may injure the animals at close range. The operation of wind turbines also generate noise, but at considerably lower levels which are only audible near the wind farm. Marine mammals use sound for foraging, orientation and communication and are therefore possible susceptible to negative effects of manufactured noise generated from construction and operating large offshore wind turbines.

Mammals are very dependent of their hearing systems that are used for several purposes: communication between other individuals of the same species, orientation, finding prey and echolocation[113]. The behavioral response by marine mammals to noise includes modification of normal behavior, displacement from the noisy area, masking of other noises, and the impossibility of acoustically interpreting the environment. The consequences from this disturbance could cause problems of viability of individuals, increased vulnerability to disease. It can also bring about increased potential for impacts due to cumulative effects from other impacts such as chemical pollution combined with stress induced by noise (Greenpeace, 2005)[114].

There has been a surge of human activity generating underwater noise during the last few decades. Studies have shown that construction noise related to offshore wind farms (especially pile driving) may cause behavioral changes in seals (*Phoca vitulina and Halichoerus grypus*)[115],

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[112] Everaert, J., Stienen, E.W.M (2007). "Impact of wind turbines on birds in Zeebrugge (Belgium). In *Biodiversity Conservation*, 16: 3345-3359

[113] Echolocation is a technique used by bats, dolphins and other animals to determine the location of objects using reflected sound. This allows the animals to move around in pitch darkness, so they can navigate, hunt, identify friends and enemies, and avoid obstacles.

[114] Greenpeace (2005). "Offshore wind: Implementing a new powerhouse for Europe, grid connection, environmental impact and political framework", Brussels, Belgium.

[115] Madsen et al. (2009). "Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs".

porpoises (*Phocoena phocoena*) and dolphins (*Tursiops truncates*). Disruption effects have been measured up to 20 kilometers from the pile-driving site. Most countries surrounding the North Sea have therefore introduced strict regulations about pile driving designed to protect any marine mammals that may be present. Underwater noise from percussive piling of foundations is likely to be the main source of potential impact from wind farm construction. It generates very high sound pressures, likely capable of inflicting permanent damage to the hearing of seals and porpoises and has been shown to cause behavioral disturbances at distances of tens of kilometers from the site.

Monitoring marine mammals living and moving is very difficult. Fortunately, the traditional visual surveys from ships and aircraft are being supplemented or replaced by other methods such as acoustic monitoring by stationary data-loggers, remotely controlled video monitoring and tagging of animals with satellite transmitters. Seals are rarely observed at sea and therefore seals were tagged with satellite transmitters to follow their movements. Horns Rev and Nysted[116] wind farms in Denmark have carried out comprehensive environmental monitoring programs between 1999 and 2006, covering baseline analysis, construction and operational phases. The highlight of the study shows different reactions between seals and porpoises. Seals were only affected during the construction phase, due to the high sound levels in pile driving operations. In the operation phase, it seems wind farms did not have any effect on seals. However, harbor porpoises' behavior was dissimilar at the two offshore wind farms. In Horn Rev, the population decreased slightly during construction, but recovered to the baseline situation during operation. In Nysted wind farm, porpoise densities decreased significantly during construction and only after two years of operation did the population recover. The reason for this slow recovery in unknown (DEA, 2006)[117].

These various species mentioned above require different spaces for foraging, breeding, spawning and migration, including the sea floor, the water column, the water surface and air space. Some are very specific in their requirements, others are more generalist; they also differ widely with respect to their distribution, population and conservation status. Apart from particular areas for feeding or breeding, the ability to move between areas is particularly important for species (e.g. for migratory species). Sound and echolocation are of key importance to some species. Some marine mammals are very sensitive to noise disturbance, with effects ranging from avoidance of areas to hearing impairment to physical injury.

Impacts can be mitigated by reducing the radiated noise from the pile driving by application of a bubble curtain, currently considered best available technology for reduction of noise radiation. The bubble curtain is expected to reduce the broadband source level of the piling. The reduction in radiated noise means that permanent hearing loss is not expected to occur either seals or porpoises. Reduction of radiated noise from piling is also predicted to reduce both impact ranges and duration of the disturbance of behavior (Tougaard et al., 2018)[118].

3.2.3 EFFECTS ON MARINE ECOSPHERE

Some aquatic animal populations are of national and international importance, including salmon, sea trout, cod and haddock, and crabs and lobsters, all of them being important from a socio-economic perspective, and they may be adversely affected by wind farms. Others species live in the midwater and will be affected by sounds. Survey and construction activities for wind farms may generate sounds that may affect the behavior of fishes and invertebrates directly or might mask the detection of important biological signals and orientation cues. Seismic and other surveys, pile driving or drilling, rock breaking, rock filling, dredging and trenching, the installation of foundations, and increased levels of shipping may all produce noise within the frequency bands to

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[116] A study was conducted to investigate whether the Harbor porpoise (Phocoena phocoena) occupying the area would remain or leave the area as noise levels increased considerably. According to the study, less echolocation activity during construction was recorded and concluded that the porpoises abandoned the area, with effects being recorded up to 15 kilometers away. More information can be found in the works of Carstensen et al. (2006). "Impacts of offshore wind farm construction on harbor porpoise: acoustic monitoring of echolocation activity using porpoise detectors".

[117] Danish Energy Authority (2006). "Offshore wind farms and the environment: Danish experiences from Horns Rev and Nysted".

[118] J.Tougaard; M.A. Mikaelsen. "Effects of larger turbines for the offshore wind farm at Krieger's Flak, Sweden: Assessment of impact on marine mammals", Scientific Report from DCE – Danish Center for Environment and Energy, No. 286, Arhus University, Department of Bioscience

which aquatic animals are sensitive. Electric cables from the wind farm may also affect fishes and invertebrates adversely, by causing habitat damage when they are installed, and by generating noise, chemical pollution, heat and electromagnetic field emissions during their operation (Taormina et al., 2018)[119]. It is important that migrating fishes, including salmon and sea trout reach their destinations immediately. Many migratory fishes, including salmon and sea trout, are moving along the coast to particular destinations. There should be no obstruction of their movements, which will cause problems in reaching these destinations, whether the fish are wishing to move upstream into rivers flowing into the sea, or have entered the sea from local rivers and are migrating to their feeding grounds. The eel is another fish that may swim past coastal wind farms on their marine spawning migrations.

Fishes need to have access to the various cues that they use to position and orientate themselves during their migrations. During passage through the sea, fishes use a variety of cues to orientate and navigate. It is evident that many species, including the salmon have s sense of direction. In some cases, this sense may be based on an ability to orientate with respect to the earth's magnetic field, or perhaps to celestial cues (Smith et al., 1981)[120]. Other cues might include sounds associated with the locations they are seeking and odor cues associated with particular locations or bodies of water, or the presence of particular patterns of water currents.

Many marine mammals, fishes, and aquatic invertebrates use sounds for obtaining information about the environment, and for communicating with one another. Sound propagates very quickly, and travels great distances in water, compared with air. Interference with the ability of aquatic animals to detect sounds adversely affect their fitness and survival and therefore, has adverse impacts, especially upon the sounds made by spawning animals, including cod and haddock.

It has been shown that salmon returning home through the sea do actively swim in a particular direction[121], indicating that they do use the earth's magnetic field for orientation and direction finding during their migrations. It is likely that other fish species also utilize the earth's magnetic field. The electromagnetic fields (EMFs) from subsea cables might interact with migrating fishes in the close vicinity of the cables, particularly if they are laid in shallow water. Floating wind turbines might also have electric cables within the water. It is common for returning adult salmon to follow the coast, swimming close to the shore, where they may be especially susceptible to EMF effects from cables. The magnetic fields generated by the export and inter-array cables can perhaps result in small- or large-scale disorientation and serve as a barrier to migration.

Comprehensive monitoring of both the effects and impacts of sound particle motion, substrate vibration, and electromagnetic fields on the migratory and spawning behavior of fishes are necessary before, during, and after the construction of wind farms. There is a need to assess the importance of such stimuli to a wide range of marine species. A current problem is that most of the research is based on effects upon marine mammals. There is currently much less effort in assessing effects and impacts upon fishes and aquatic invertebrates (Hawkins, 2020)[122].

3.3 MARITIME SPATIAL PLANNING FOR OFFSHORE WIND ENERGY DEVELOPMENT

The exploitation of seas and coastal areas for economic purposes is becoming increasingly important, but there are also growing concerns on environmental issues. Whilst spatial planning on land has been used as a tool for several decades, it is relatively new concept in the marine environment, with few concrete examples

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[119] B.Taormina, J. Bald, A.Want, G.Thouzeau, M.Lejart et al. (2018). "A review of potential impacts of submarine cables on the marine environment: Knowledge gaps, recommendations and future directions". In *Renewable and Sustainable Energy Reviews*, 96: 380-391.

[120] G.W.Smith, A.D.Hawkins, G.G.Urquhart, W.M. Shearer (1981). "Orientation and energetic efficiency in the offshore movements of returning Atlantic salmon Salmo salar". Scottish Fisheries Research Report, 21: 1-22.

[121] Ibid, 1981.

[122] A.D. Hawkins. "The Potential Impact of Offshore Wind Farms on Fishes and Invertebrates". Opinion in *Advances in Oceanography & Marine Biology*, 11 December 2020.

at present. The expanding offshore wind farms in Europe and a reduction in the available space at sea for other activities has led the European Commission to develop a plan to share the seas throughout the European Union[123]. To ensure that maritime activities can deliver growth and avoid sea-use conflicts, integrated planning of human activities both on land and sea is required. Most development and use, which takes place in the marine environment also has an onshore component or impact. The 2014 Maritime Spatial Planning Directive requires coastal states of the European Union to establish complete coverage of maritime plans by 2021 considering land-sea interactions in order to promote sustainable and integrated development and management of human activities at sea. The ultimate aim of maritime spatial planning is to draw up plans to identify the utilization of maritime space for different sea uses (European Commission, 2013)[124]. One of the minimum requirements of a plan is to "take into account environmental, economic and social aspects, as well as safety aspects" of relevant activities and uses in marine waters[125].

Today marine management often involves ecosystem-based marine spatial planning which serves to support sustainable, efficient and predictable use of marine resources. Allocation of space at sea helps to avoid conflicts between different uses (e.g. wind and wave energy, fishing, oil and gas exploitation, cables and pipelines, shipping, tourism, defence, environmental protection) which also often cross national boundaries. Maritime spatial planning is an instrument for reducing conflicts and strengthen the coordination between different sectors. A typical conflict, in particular in the Baltic and the North Sea, is between offshore wind facilities and fisheries, as both sectors have similar spatial interests, e.g. specific depth ranges and proximity to the coast (especially for small-scale fisheries). Key concerns are accidental damage (e.g. damage to cables, snagging fishing gear and ship strikes) and loss of access to traditional fishing grounds (as most countries restrict fishing around wind farms for safety reasons), while studies also refer to the ecological impact (e.g. habitat alteration and effects on flatfish spawning grounds).

As the marine space is limited for all potential activities, the idea to co-use an offshore wind farm site by installing aquaculture farms in between several wind turbines has seen considerable attention over the course of the last years. This has triggered interest in developing multi-use platforms at sea. More specifically, the concept of Multi-Use (MU) or the joint use of resources in close proximity by either single user or multiple users (Schupp et al., 2019)[126], has received a lot of attention over the past few years (Brennan and Kolios, 2014)[127] and is forecast to play integral role in future OWF development. Multi-purpose offshore platforms may combine offshore energy generation such as wind, wave, solar, marine currents and ocean thermal energy conversion, aquaculture, leisure and transport in different degrees and constellations. For example, harvest wind and wave power, using part of the energy onsite for multitrophic aquaculture[128] farm, and convert on-site the excess energy into hydrogen that can be stored and shipped to shore as a green energy carrier or sold to visiting ships as fuel, keeping them clean and emissions free. Some studies have proposed the combining of marine energies as a better alternative instead of using a single source of energy. They claim that many advantages could be achieved such as better liability systems, increased energy yields, smooth output power, and shared grid infrastructure. The costs of construction and maintenance could be significantly reduced via the use of shared resources

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[123] Directive 2014/89 EU, of the European Parliament & the Council of the European Union of 23 July 2014 Establishing a Framework for Maritime Spatial Planning, O.J. (L.257) 135.

[124] "Proposal for a directive of the European Parliament and of the Council establishing a framework for maritime spatial planning and integrated coastal management", COM (2013) 133 final, 12 March 2013, Brussels

[125] Directive 2014/89/EU, *supra* note 49.

[126] M.Schupp, M.Bocci, D.Depellegrin, A.Kafas, Z.Kyriazi, I.Lukic, A.Schultz-Zehden, G.Krause, V.Onyango, B.H.Buck. "Towards a common understanding of ocean multi-use. In *Frontier Maritime Science*, 6 (2019).

[127] F. Brennan, A.Kolios. "Structural integrity considerations for the H2Ocean multi modal wind-wave platform". EWEA, 2014, pp. 112-115.

[128] Integrated multitrophic aquaculture systems refer to the the co-culture of different species belonging to different trophic levels, and offer a sustainable approach. In these systems, organic and inorganic extractive species will feed on another species waste or to uneaten feed nutrients, acting as bioremediators.

such as foundations, logistics, operations, and maintenance. Combining marine resources of energy (wind, wave, tidal, floating solar farms, algae biomass, and ocean thermal energy conversion) with the different activities mentioned above could be fulfilled in very different ways and concepts. Various structures have been proposed under the funded projects of the EU. These projects are Innovative Multi-purpose offshore platforms: Planning, Design and Operation (MERMAID), Development of a wind-wave power open-sea platform equipped for hydrogen generation with support for multiple users of energy (H2Ocean) and TROPOS (Nassar et al., 2020)[129].

Multi-use is also linked to the concepts of co-existence and synergetic use of the sea, both representing key issues in maritime spatial planning. Co-existence is understood as the absence of conflict and the neutral sharing of marine space. Synergy refers to mutually beneficial use of the same sea space or marine resources, but equally to shared infrastructure, technology or human resources. A key driver for synergy between sectors is the expected efficiency gain and mutual benefit arising from the combination of uses is greater than the sum of their individual effects. One of the sectors where co-existence can be advantageous is definitely national defence as military and energy sectors are having different interests in the same geographical area. As defence interests override the interest of other economic sectors, national defence can be considered one of the main barriers to the development of offshore wind power in many countries. Co-existence is essentially important in NATO Recognized Air Picture (RAP) and Recognized Maritime Picture Areas (RMP). Recognized Air Picture is theoretically complete listing of all aircraft in flight within a particular airspace, with each aircraft being identified as friendly or hostile. The information may be drawn from a number of different sources, including military radar, civilian air traffic controllers, and allied nations or multinational organizations such as NATO. The term "recognized" means that the picture has been evaluated prior to its distribution. Therefore, it could be implied that defence and NATO in particular needs to find ways and means, technically, operationally to co-exist with such wind farms. Having offshore wind farms in their territorial waters and Exclusive Economic Zones (EEZ) could be advantageous for a number of training, tactical and operational matters (e.g. the Belgian Navy). Based on the Belgian example, the cooperation with the wind industry could prove very useful. For example, privately owned wind farms infrastructure could be shared with the Navy - antennas and radars can be mounted on the structures; offshore camera images can be shared to increase the maritime awareness and maritime picture in the coastal waters. In return, the Navy can ensure the security of these critical infrastructures that the wind farms are to Belgium. The matrix of wind structures can help create an underwater network to communicate with the drones, and even recharge their batteries. Coastal security is a team effort, involving the Navy, Federal Police and Customs working together from a single maritime information center.

The European Blue Growth strategy (European Commission, 2012)[130] aims to expand the new maritime sectors of aquaculture, energy, biotechnology, coastal tourism and mineral mining. Other established and traditional users, such as capture fisheries, often find themselves primarily concerned about exclusion from historically open fishing grounds and the resultant damage to their interests and livelihoods (Hooper et al., 2017)[131]. Another successful example of co-existence is between fisheries and wind farms that have been successfully co-located in Europe. For example, up to 90% of Danish annual gillnet fleet landings of place 2002-2012 were from areas overlapping with windfarms (Stelzenmüller et al., 2016)[132]. Belgium and the Netherlands

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[129] W.M.Nassar, O. Anaya-Lara, K.H. Ahmed, D. Campos-Gaona and M.Elgenedy. "Assessment of Multi-Use Offshore Platforms: Structure Classification and Design Challenges". In *Sustainability 2020,* 12, 1860

[130] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *"Blue Growth: Opportunities for marine and maritime sustainable growth"*, COM (2012) 494 final, Brussels, 13 September 2012

[131] T. Hooper, M. Austen. "The co-location of offshore wind farms and decapod fisheries in the UK: constraints and opportunities. In *Maritime Policy*, 2014, 43, pp. 295-300

[132] V. Stelzenmüller, R.Diekmann, F.Bastardie; T.Schulze; J.Berkenhagen; M.Kloppmann; G.Karuse, B.Pogoda; B.H.Buck, and G.Kraus (2016). „Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: A first socio-economic scoping". In *Journal of Environmental Management*, 183; pp. 794-805.

currently have their own laws in place concerning offshore access. The applicable regulations prohibit fishing within offshore energy facilities in Belgium and the Netherlands, primarily due to navigational safety concerns[133]. In Belgium, all non-maintenance vessels must remain at least 500 meters from wind farms at all times, which has angered anglers who are concerned about depleted stocks outside the wind farm area[134]. On the other hand, the United Kingdom does not restrict access to its offshore wind farms. To the contrary, anglers are only prevented from fishing in areas where turbines are under construction or closed for maintenance[135] . The UK approach is similar to that applied by the Coast Guard in the USA, which created a temporary safety zone during construction of the Block Island Wind Farm. The European approach indicates that navigation safety has been the primary reason provided for limits on access to wind farms, but that responses may vary from substantial prohibited areas around each turbine to more limited construction closures.

There are risks in allowing vessels to sail close to wind farms. The pylons could damage fishing gear and boats can collide with wind towers. If a fishing vessels get into trouble and needs rescuing, helicopters may have a difficult time safely flying amid the wind turbines. Meanwhile in Denmark most Danish wind farms have been built in areas that do not have much fishing activity. If fishing is disrupted or displaced because of a new offshore project, fisheries are eligible for compensation. The Netherlands is consulting in the fishing industry, wind energy companies, military and non-governmental organizations to develop a plan for its seas. The goal is to find a way for all the sectors to co-exist while still achieving sustainable energy targets and the 2021 marine spatial plan deadline.

CHAPTER 4 – POTENTIAL PROBLEMS FOR INSTALLING OFFSHORE WIND FARMS - AVIATION, NAVIGATION AND SAFETY AT SEA

The “open ocean” has become a highly contested space as maritime uses have increased and intensified over the last decades. While established uses, such as shipping, fishing or resource extraction expand and intensify, new uses such as offshore aquaculture or wind and wave energy generation are emerging and attempting to carve out space in an already crowded sea. Such shifts in resource use, management, and access can lead to conflicts over marine resources.

Among other interests in the blue economy, defence implications are a national priority in most countries; in the absence of other options (such as relocating military training areas), they override all other sectoral interests. The spatial needs and interests of national defence and security at sea are complex, as maritime activities could get in the way of military infrastructure. The rough undulating sea surface interacts with the electromagnetic waves emitted by radar to produce backscattered echoes with strong energy. Wind turbine arrays and the turbulent air generated by the blade rotation carries a signature appearing on traditional radar systems as a form of clutter (Brenner et al., 2008)[136]. Wind farms can also affect military operations, for example, turbines can interfere with low-level flight training routes, testing military equipment sensitive to electromagnetic noise, and with military radar systems. There may also be negative impacts on optical, radio and hydro-acoustic observation and the possibilities of veiling. Maritime activities can interfere with naval training areas, artillery ranges or airbases, in areas that need to be free of obstacles. Obstacles particularly include tall permanent installations such as offshore wind turbines.

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[133] Six hundred a fifty R.I. CODE R. Paragraphs 20-05-8.4.8. These restrictions are similar to those placed on offshore oilrigs in the same countries for navigational safety. Id. See also Raza Ali Mehdi, et al., *Improving Co-existence of Offshore Wind Farms and Shipping: An international Comparison of Navigational Risk Assessment Processes,* 17 WORLD MARITIME U.J. MARINE AFFAIRS 397, 416-17 (2018) (noting focus on navigational safety

[134] Id. The 500 meters turbine exclusion zone applies to the entire area of any wind farm with turbine spacing less than or equal to 1 km. Turbine spacing differs by farm, but Belgium prioritizes energy density in its offshore wind farms resulting in close spacing. RASMUS BORRMANN et al., DEUTSCHE WINDGARD GMBH, CAPACITY DENSITIES OF EUROPEAN OFFSHORE WIND FARMS 6, 16-17 (2018). As a result, the restriction appears to exclude fishing vessels from wind farm areas in several wind farms. Id. At 33-35 (collecting turbine spacing).

[135] Bolongaro, supra note 50.

[136] M.Brenner; S.Cazares; M.J.Cornwall, et al. “Wind Farms and Radar”. Mclean, Virginia: The MITRE Corporation, 2008, p.5.

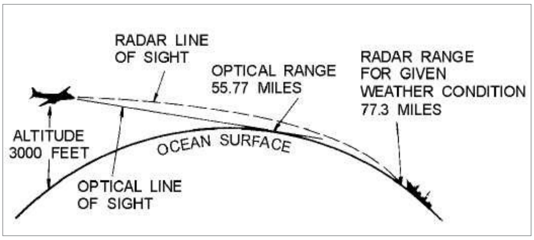
The military in each country, predominantly (but not exclusively) in the form of air forces, needs access to airspace for primarily two purposes: training and national defence. This includes the surveillance of the airspace above and surrounding territory, including over sea. Wind turbine developments can have a detrimental effect on military operations as military aviation operations are markedly different from civil operations, particularly with respect to operational low flying, and the sensitivity of military communications, navigation and air surveillance facilities (CAA, 2016)[137]. The military uses some airspace below 3000 meters for training operations and frequently flies at speeds of more than 463 kilometers per hour. High-speed operations include aircraft intercepts, air-to-air combat, close-air support for ground forces and photoreconnaissance. The mixture of fast military planes and slower civilian aircraft creates obvious low-altitude training safety concerns.

In addition, offshore wind farms have specific issues where they are in conflict with traditional activities such as navigation. There is consensus among stakeholders acknowledging that OWFs can pose risks to maritime operations in terms of reduced navigational safety. In some countries, navigation within the borders of an OWF is allowed; in that case crossing traffic can be expected to emerge from the wind farm.

4.1 INTERFERENCE EFFECTS OF A WIND FARM ON RADAR SYSTEMS

It is known that wind turbines present a source of interference with air-surveillance radars when they lie in the radar's line-of-sight. The radar horizon is a critical area of performance for aircraft detection systems that is defined by the distance at which the radar beam rises enough above the Earth's surface to make detection of a target at low level impossible. It is associated with the low elevation region of performance, and its geometry depends on terrain, radar height, and signal processing. This is associated with the notions of radar shadow, the clutter zone, and the clear zone. Airborne objects can exploit the radar zone and clutter zone to avoid radar detection by using a technique called nap-of-the-earth navigation. There are limits to the reach of radar signals. The antenna-rotation rate also affects maximum detection range. The slower an antenna rotates, the greater the detection range of a radar system. When the antenna is rotated at 10 revolutions per minute (rpm), the beam of energy strikes each target for just one-half time would hit if the rotation were 5 rpm. At the frequencies normally used for radar, radio waves usually travel in a straight line. The waves may be obstructed by weather or shadowing, and interference may come from other aircraft or from reflections from ground objects (Figure 13).

Figure 13. Radar Line-of-Sight (Source: RF Café, 2018).



The effects of this wind turbine interference are of concern to flight safety, internal security and national defence, and protection of life and property from weather events. To take advantage of steadier winds, offshore wind turbines are bigger as compared to the onshore counterparts, and they are continuing to grow. The result of these larger machines is the potential for a larger radar cross section and stronger return signal to radar systems, causing greater interference. Sometimes offshore wind farms are deployed near radar sites, and they may cause clutter degradation in shore-based vessel traffic service (VTS) radars and ship-borne radars, because the severe echoes they generate reduce the detection and measurement capabilities of the radar in the area around the wind farm. In some specific cases, the rotation of the blades may generate tracks initiation in VTS radars that use tracking algorithms, due to fluctuation of turbine returns.

The Radar Cross Section (RCS) is a fundamental quantity, which determines if a radar target

[137] Civil Aviation Authority (2016). "CAA Policy and Guidelines on Wind Turbines". CAP 764, Safety &Airspace Regulation Group.

can be reliably detected by a radar system. This quantity can be modified by altering the shape of the target. Increasing the target's RCS enhances its detectability to radars, which is a key aspect for civil applications like naval radar. In contrast, decreasing its RCS makes it possible to hide the target from radars, which is often required in military scenarios. Practically, the RCS of a target depends on: (a) the physical geometry and exterior features of the target; (b) the direction of the illuminating radar; (c) the radar transmitter's frequency; and (d) the electrical properties of the target's surface. RCS can also be defined as the amount of scattered power from a target towards the radar, when the target is illuminated by the radar signal (Knott et al., 1985)[138]. Some authors propose that the parameter RCS cannot be applied to wind turbines (and to any object on the ground) because the plane wave condition is not entirely fulfilled (Greving et al., 2011)[139]. The main authorities in the area of telecommunications and radar that have published guidelines for analyzing the impact of wind turbines use this parameter to account for the scattering of wind turbines and evaluate the potential impact a wind farm may cause (Civil Aviation Authority, 2010)[140].

Radars operating in an open environment will receive returns from many sources. Whenever a radar system transmits a signal for the detection of a target in the environment than the signal may experience reflection from the objects in the path. The existence of these objects in the signal path creates unwanted echoes, which are known as clutter. A radar system is required to process the returns from targets in the presence of this unwanted clutter. As the velocity of the blade tips can reach up to 75 m/s, the rotating wind turbine blade will impart a Doppler frequency shift any radar signal reflecting off the blade. In this case, the radar's moving target indication (MTI) depending on the designed thresholds in the processor may detect it as a non-static target. Moving target indication (MTI) is a mode of operation of a radar to discriminate a target against clutter. It describes a variety of techniques used to find moving objects, like an aircraft, and filter out unmoving ones, such as hills or trees. It contrasts with the modern stationary target indication (STI) technique, which uses details of the signal to directly determine the mechanical properties of the reflecting objects and thereby find targets regardless of their movement. In wind farms, variation in the wind direction at the turbine, the precise position of the blade in its rotation as the radar beam illuminates it, the pitch of the blade, and other factors may cause the amplitude and size of the radar echoes to fluctuate from one antenna rotation to another. At the sites with more than one turbine, the radar may illuminate two and more turbines during one antenna's sweeping time. This can result in the images on the radar screen moving about within the area of the wind farm over time. The extent to which this will happen depends on, amongst other factors, the minimum distance between objects that the radar can detect (Wang, 2013)[141].

Given a wind speed of more than approximately 3 m/s, the backscatter from the sea surface becomes visible in radar images. Ocean wave behavior can appear incredibly complex. All ocean waves are sinusoids of different wavelengths and amplitude that interact to form structures that are more complex. Many sources, such as currents, weather surface tension, and gravity contribute to the wide variety of wave structures in the ocean. At radio frequencies, backscatter from the open ocean is predominantly from surface waves caused by wind and the degree of roughness of this surface, known as the sea state. It is known that under various conditions, signatures of the sea surface are visible in the near range (less than three nautical miles) of nautical X-band radar images.

Such reflections of waves are mostly due to resonance between the radar waves and the features at the water surface (Bragg scatter)[142]. It occurs

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[138] E.F.Knott, J.F.Shaeffer, and M.T.Tuley. *"Radar Cross Section: Its Prediction, Measurement and Reduction"*. Artech House, Norwood, Mass, USA, 1985

[139] G.Greving, W.D. Biermann, and R.Mundt. "The radar cross section and wind turbines –definition and effect on the ground and finite distances". In *Proceedings of the International Radar Symposium* (IRS'11), pp. 803-808, Leipzig, Germany, September 2011.

[140] Civil Aviation Authority, *CAA Policy and Guidelines on Wind Turbines*, Civil Aviation Authority, London, UK, 2010.

[141] W.G.Wang. "Detecting and Mitigating Wind Turbine Clutter of Airspace Radar Systems". Hindawi Publishing Corporation, the Scientific World Journal, Volume 2013.

when the sea waves off which the radio waves scatter are spaced at half wavelength intervals, which causes constructive interference in the reflected signal from multiple waves. However, the base signal (the very short waves) is modulated by longer waves. Sea clutter is caused by the backscatter of the transmitted electromagnetic waves from the short sea surface ripples in the range of half the electromagnetic wavelength (i.e. approximately 1.5 cm). There are two types of waves at the ocean surface: wind sea and swell. Wind sea waves (also called young or growing waves) are waves under the influence of local winds. As waves propagate away from their generation area, or when their phase speed overcomes the local wind speed, they are called swell. Swell waves can propagate thousands of kilometers across entire ocean basins, with energy e-folding scales exceeding 20,000 km (Ardhuin, 2006)[143]. The longer waves like swell and wind seas become visible as they modulate the backscatter signal mainly via hydrodynamic modulation of the ripples by the interaction with the longer waves, and tilt modulation (Wetzel, 1990)[144]. The propagation of waves from a surface-based antenna is affected by atmospheric conditions, particularly those in the boundary layer. These effects frequently lead to anomalous propagation, when radar detection distances are significantly greater than usual. An extreme form of anomalous propagation occurs in the presence of a duct, which traps the waves in a shallow, quasi-horizontal layer (Turton et al., 1988)[145]. It can be assumed that based on larger turbines and the lack of terrain screening the impacts will be greater than those seen with the terrestrial wind farms did.

In 2016, the USA University of Texas conducted a study that focused on identifying the broader effects of electromagnetic interference to be caused by offshore wind farms (SANDIA, 2014)[146]. The findings for the electromagnetic systems studied showed that communications systems in the marine environment are unlikely to experience interference as the result of typical wind farm configurations, except under extreme proximity or operating conditions. Marine navigation radars and ocean monitoring high frequency (HF) sensors may experience interference under certain proximity and operating conditions as the result of typical wind farm configurations. Sensitive airborne radars may experience serious interference. However, the degree of interference may be system specific and dependent on whether wind farms are located within the operational area of the radar.

The underwater sound from a single wind turbine exhibits a relatively simple tonal structure, consisting of several frequencies between 100 and 1000 Hz, the amplitudes of which generally decrease with frequency. Local bathymetry and seabed composition determine the rate at which such sound is attenuated as it propagates away from a wind farm. The attenuation rate determines the range at which the sound pressure level is reduced to the ambient noise level. In the event that hydrophones or seismic sensors are within the range where sound from the wind farm is above the ambient level, it is anticipated that conventional signal processing such as filtering and beam forming can mitigate the potential interference.

Thus, due to the virtual absence of noise exceeding background levels radiated underwater by wind turbines at frequencies above 1 kHz, interference with underwater acoustical systems is deemed unlikely at such frequencies. At frequencies below 1 kHz, the tones radiated by wind turbines may cause interference with certain acoustical systems when placed in close proximity to a wind farm. The definition of "close proximity" depends on many factors, both environmental and specific to the wind farm itself.

Finally, another potential challenge with off-

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[142] William Lawrence Bragg and his father William Henry Bragg first proposed Bragg diffraction (also referred to as the Bragg formulation of X-ray diffraction) in 1913. The periodic structures of reflective surfaces or volumes can be investigated with the much larger wavelength used in radar devices.

[143] Ardhuin, J.H., Jenkins, A. "On the interaction of surface waves and upper ocean turbulence". In *Journal of Physical Oceanography* 2006, 33, pp. 1301-1323.

[144] L.B.Wetzel (1990)."Electromagnetic scattering from the sea at low grazing angles". In *Surface Waves and Fluxes, volume II Remote Sensing,* G.Geernaert and W.J.Plant (Editors), Kluwer Academic Publishers, Doordrecht, the Netherlands, pp. 109-171.

[145] J.Turton; D.A. Bennetts & S.F.G Farmer. "An introduction to radio ducting". In *Meteorological Magazine* 1988, 117: 245-254.

[146] SANDIA National Laboratory. "Wind-Turbine/Radar Interference: Offshore Test Options". SAND2014-17870.

shore wind turbines is the interference from electromagnetic fields created by the electric cables running from the turbines underwater to the shore that could affect orientation and navigation of ships (SANDIA, 2014)[147]. It is well established that alternating current (AC) and direct current (DC) submarine power cables produce a magnetic field, the intensity of which is directly related to the applied voltage. An electromagnetic field (EMF) is a combination of an electrical field (created by voltage or electrical charge) and a magnetic field (created by electrical current). When electricity is transmitted in a cable an electromagnetic field forms around the cable. From a large amount of research carried out, it appears that there is no influence in navigation of surface ships (with one configuration being an exception), nor any issues other than perhaps a minor effect on certain species of fish and sea creatures that has yet to be determined.

The characteristics and strength of the magnetic field depend upon whether AC (alternating current) or DC (direct current) is being transmitted and the configuration of the cables used (for example, AC or single, bi-polar and coaxial cables for DC). In all cases, the EMF strength is proportional to the current and surrounds the core concentrically: leading to the note that the EMF of power transmitted at a voltage of 17kV is less than one-quarter of that transmitted at a voltage of 36 kV.

Briefly, the implications of radar interference are manifold. It makes it difficult for air traffic control authorities to detect a plane in the air column above or in the shadow of an OWF. Alternatively, it may produce a false aircraft track. For marine radar users, it may reduce the ability of shipping to detect the presence of vessels in the detected area. For a weather radar, it may generate false readings of meteorological disturbances, negatively affecting forecasting accuracy (Varga et al., 2013)[148]. Wind turbine radar interference is an urgent and complex problem facing the wind industry, compounded by the drive to improve renewable energy contributions within Europe and beyond.

The global importance of the issue has resulted in leading associations for wind energy across the world identifying it as a key area, resulting in the creation of several dedicated task forces formed specifically to find viable mitigation strategies. For example, in September 2021 United Kingdom launched "*Air Defence and Offshore Wind: Working Together Towards Net Zero*", a strategy and implementation plan that sets the direction for collaboration between Government Departments and the wind industry to identify, assess and deploy solutions that will enable co-existence of air defence and offshore wind. Mitigation of the adverse impacts of wind farms on current air defence systems will be a stepping-stone towards a longer-term solution that will enable co-existence. This document[149] offers a roadmap through which future co-existence of these competing concerns are addressed, to assure that a satisfactory radar picture can be achieved in the presence of wind farms.

4.2 OFFSHORE WIND FARMS IMPACTS ON AVIATION

Wind turbines have a substantial impact on aviation and airspace. Airspace is classified and regulated, depending upon the way that the airspace is used. Flight rules for pilots differ significantly for different airspace types. Airspace around major airports and on the national and international airways structure is "controlled" or regulated. Other airspace may be "uncontrolled" and is open and accessible for all. 'Danger Area" airspace used by the military is often "restricted", meaning civilian aircraft may not be necessarily permitted to fly through it.

As developments move further offshore, the use of aviation is expected to increase, driven by safety and efficiency grounds. Helicopters cover distance quickly and allow the transfer of personnel and equipment to and from offshore structures.

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[147] SANDIA National Laboratory. "Wind-Turbine/Radar Interference: Offshore Test Options". SAND2014-17870

[148] D.Varga; J. Matthews; L.Norins et al., "Mitigation Techniques to Reduce the Impact of Wind Turbines on Radar Services". In *Energies* 2013, 6, pp. 2859-2875

[149] Department for Business, Energy & Industrial Strategy, Ministry of Defence, the Crown Estate. "Air Defence and Offshore Wind Strategy & Implementation Plan". Government UK, 29 September 2021.

At the low heights at which helicopters operate "offshore", the airspace is generally "uncontrolled". Therefore, it does not require an air traffic control (ATC) clearance or service. Generally, the airspace above and around an offshore wind farm will be uncontrolled and potentially used by a variety of civilian and military aircraft, and by Unmanned Aircraft (UAS). As the airspace is uncontrolled, it does not follow that there is no radar coverage. As a general principle, with the exception of the North Sea, the further offshore, the less likely there will be extensive radar coverage to turbine level (RenewableUK, 2019)[150].

Turbines are significant physical structures that can penetrate volumes of airspace designed to be clear of obstacles ("Obstacles Limitation Surfaces"). In order to ensure that aircraft departing during marginal weather conditions do not fly into terrain or obstacles, the aviation authorities publish instrument departure procedures that provide obstacle clearance to pilots as they transition between the terminal and en-route environments. These procedures contain specific routing and minimum climb gradients to ensure clearance from terrain and obstacles. Pilots operating during periods of reduced visibility and low cloud ceilings rely on terrestrial and satellite based navigational aids (NAVAIDS) in order to navigate from one point to another and to locate runaways. Although civilian aviation authorities do not consider impact on military airspace or training routes, they will notify the military of proposed structure located within these segments of airspace. Impact on these segments of airspace can result in military objection to the proposed development.

It is therefore essential that the safety of aerodromes, aircraft and airspace is guaranteed and as wind turbines increase in size and in number, their potential impact on aviation operation increases correspondingly. Combining the current drive for renewable energy and the increasing number of wind farms indicates that wind turbines and aviation are being required to operate closer together. Interactions between wind turbines and aviation activity are potentially complex. The impacts of offshore wind farms are assessed in the same way as its onshore counterparts. Clearly, by their nature, wind farms at sea are less likely to be near airfields than those on land, and thus avoid many of the impacts on aviation that onshore developments may cause.

Another issue is how to mark and illuminate wind farms. This is particularly relevant for large-scale developments, especially those offshore. Night lighting is a very sensitive issue that has prompted many debates among aviation communities and public. Each country is establishing its own standards for day marking and nighttime illumination of turbines. The International Civil Aviation Organization (ICAO) has issued some guidance for the marking and illuminating of wind turbines, as distinguished from any other obstacle (ICAO, Annex 14, volume 1)[151]. However, states are able to and are applying their own standard obstacle marking and illuminating standards, but often enhancing them to reflect the unique nature of wind turbines. If inappropriately lit or marked, wind turbines can pose a hazard to low-level aircraft, particularly at night.

4.2.1 RADAR AND OTHER COMMUNICATION, NAVIGATION AND SURVEILLANCE SYSTEMS

There are a number of ways in which wind farm can have an impact on the operation or safety of the air traffic services provided by civil aviation authorities, and others such as the Ministry of Defence (MoD) and airports. The development of sites for wind turbines has the potential to cause a variety of negative effects on aviation. These include (but are not limited) to physical obstructions; the generation of unwanted returns to Primary Surveillance Radar (PSR); adverse effects on the overall performance of communication, navigation and surveillance equipment; and turbulence. This also includes the degradation of voice communication facilities and en-route navigation

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[150] RenewableUK. "Offshore Renewables Aviation Guidance (ORAG): Good Practice Guidelines for Offshore Renewable Energy Developments". Issue 2, January 2019.

[151] Annex 14 to the Convention on International Civil Aviation. Aerodromes, Volume 1: "Aerodrome Design and Operations". Chapter 6. Visual Aids for Denoting Obstacles, section 6.2.4 Wind turbines, 7th Edition, July 2016, International Civil Aviation Organization.

aids. The role of en-route radars (a type of PSR) is to provide long-range awareness of air traffic travelling between airfields. En-route radars typically have a larger maximum operating range than ATC radars.

In basic terms, a PSR transmits a pulse of energy that is reflected back to the radar receiver by an object that is within its Line of Sight (LOS). The amount of reflected energy picked up by the receiver will depend upon a number of factors such as the size, shape and orientation of the object, as well as receiver sensitivity and the weather. In general, the larger a wind turbine is, the more energy will be reflected and there is an increased chance of it creating false returns to radar (i.e. Returns that are not aircraft). These unwanted returns are known as clutter. Issues may be compounded by increasing numbers of wind turbines, which could potentially cause greater densities of clutter.

Providing that it remain within radar line of sight (LOS), generally closer a wind turbine is to a radar station, the greater the likelihood its reflected energy will be picked up by the radar receiver. It also follows that the taller a turbine is, the greater the distance from the radar that it will remain within radar LOS (unless the turbine is hidden by terrain). A characteristic that makes wind turbines more unpredictable is the fact that as the turbines rotate to follow the wind, the cross-sectional area presented to the radar at any given time, and therefore the RCS of the turbine, will vary depending upon wind direction. This presents challenges to generating a "standard" turbine RCS for radar modelling purposes. Given that aviation safety issues are involved, a conservative approach should generally be adopted. In general, secondary surveillance radar (SSR) differ from PSRs as rather than measuring the range and bearing of targets through detecting reflected radar signals, a SSR transmits an interrogation requesting a dedicated response. Upon receiving an interrogation, the aircraft then transmits a coded reply, which the SSR can use to ascertain the aircraft's position as well as decode other information contained within the response. Wind turbine effects on SSR are traditionally less than those on PSRs are but can be caused due to the physical blanking and diffracting effects of the turbine towers, depending on the size of the turbines and the wind farm. These effects are typically only a consideration when the turbines are located very close to the SSR i.e. less than 10 km. Secondary surveillance radar (SSR) energy may be reflected off the structures during both the interrogation and reply phases. In effect, the signals are bounced off the wind turbines and can therefore arrive at the intended target from a false direction. This can result in aircraft, which are in a different direction to the way the radar is looking, replying through the reflector and tricking the radar into outputting a false target in the direction where the radar is pointing, or at the obstruction.

The height of offshore renewable energy facilities can act as a physical barrier to low flying aircraft. Obstructions can infringe approach and departure routes from offshore oil and gas installations. Wind energy developments (including anemometer masts) located near an offshore helicopter installation could potentially introduce obstructions that would have an impact on the ability to conduct essential instrument flight procedures to such facilities in low visibility conditions. Such restrictions have the potential to affect not only normal helicopter operations but also threaten the integrity of offshore installation safety cases where emergency procedures foresee the use of helicopters to evacuate the installation.

With the expansion of offshore wind energy, more people, from ship crews to turbine technicians will be working at sea and on top the massive structures. Ensuring their safety becomes critical. The term "*offshore operations*" is used to describe situations where not only a part of flight takes place over large bodies of water but when most of the flight, are to be completed away from dry land. Driven by industry demand, the use of helicopters in offshore operations has increased greatly in the recent years.

Flag states and coastal states have a duty to render assistance to persons found at sea in danger of being lost and people in distress[152]. No matter

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[152] This is required based on Article 98 of the UNCLOS, but this core obligation comes from both treaty laws (SOLAS Convention, adopted in 1974 and the SAR Convention adopted in 1979).

where an accident occurs, the rescue of persons in distress at sea will be coordinated by a Search and Rescue (SAR) organization and assist ships in distress, not only because of international treaties such as the international Convention for the Safety of Life at Sea (SOLAS) and the SAR Convention of 1979, but also out of moral obligation. This core obligation under both treaty law and customary law applies in any maritime zone. While implementing this duty, states can either perform directly the search or rescue operations, namely through their own SAR services or ask a vessel, which is located in the proximity of the endangered person. Offshore wind turbines pose a serious threat to helicopters (and to surface rescue craft) due to their large moving rotor blades. This can create a flight safety hazard to SAR helicopters. For example, in UK, the Maritime Coastguard Agency requires SAR helicopters and surface rescue craft to operate around and within offshore wind farm, by recommending that developers plan for at least two lines of orientation unless it can clearly demonstrate that fewer are acceptable.

Emergency services such as Coastguard and Air Force helicopters require the ability to rapidly detect and react to maritime casualties. All of the foregoing require consistent and effective radio communications systems. In restricted visibility, and in the absence of voice communications where casualties might report positions within the marked turbines configuration, radar would be the major means of casualty detection. Failure of any radar, navigation or communication system could give rise to increased risks to safety or lead to marine casualties and reduce the effectiveness of emergency service operations.

4.3 OFFSHORE WIND FARMS IMPACTS ON NAVIGATION

The location, size and irregular shape of offshore wind farms present new challenges to the safe navigation and communication of shipping and emergency rescue. Shipping has an impact on where OWFs can be located, as well as on the marine environment. The issue of maritime safety is of high priority within the Baltic Sea region since it is relatively small sea, with many rocky shallows and narrow straits as well as harsh winter ice conditions.

One of the primary navigational hazards associated with OWFs is the increased risk of ship-to-ship collisions due to greater congestion in marine areas outside the wind farm's boundaries[153]. An OWF may encroach on an existing sea-lane, forcing maritime traffic into an increasingly confined area and raising the likelihood of collision between ships. Wind turbines might interfere with, for example, ships' maneuvering space, as ships need adequate sea room to avoid collision. This risk will apply to special purpose vessels not under their own power. It concerns vessels encountering mechanical difficulties and all vessels facing adverse weather or sea state conditions. In particular, when an OWF is located at the starboard side of a shipping line, the Collision Regulations (COLREGs)[154] state that vessels in the shipping line must give way to vessels emerging from the OWF. A second hazard relates to the risk of allision between ships, either powered or drifting near offshore wind turbines. Allision[155] and collision hazards encompass those encountered by recreational yachts, fishing, military and other vessels.

This increased vessel density may also cause the mixing of small, large, faster and slower vessels and speeds while also changing the geometry of interactions as vessels come within close range of each other. At the same time, vessels interactions will become more complex, such as vessels approaching the structures from different sides forcing crossing situations or other entering and exiting schemes. The increased traffic density and reduced sea space might lead to the creation of choke points. If a wind farm is located adjacent to another navigational constraint, or adjacent to

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[153] For the purposes of this study, hazard will be defined according to the Canadian Center for Occupational Health and Safety. It is any source of potential damage, harm or adverse health effects on something or someone under certain conditions at work", available online http://www.ccohs.ca/oshanswers/hsprograms/hazard_risk.html; RenewableUK, "Offshore Wind and Marine Energy Health and Safety Guidelines", prepared by SgurrEnergy Ltd. For RenewableUK (2014: issue 2), pp.212-216.

[154] The Collision Regulations apply to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels.

[155] These terms are sometimes used interchangeably, but technically, a collision occurs when two vessels strike each other. An allision occurs when a vessel strikes a stationary object, such as a bridge or dock.

another wind farm, then vessels transiting in between have reduced room in which to manoeuvre to avoid collision (MCA, 2008)[156]. Maritime chokepoints are congestive pathways in some of the world's famous shipping routes (e.g. Strait of Malacca).

Similarly, land-based and offshore wind turbines may alter or restrict flight paths for aircrafts flying at low heights. For navigational safety, lightning is currently required on all wind energy turbines, but artificial lightning comes with its own environmental consequencies.

4.3.1 MARITIME REGULATORY FRAMEWORK

The established maritime regulatory framework derives from international conventions implemented into national law by maritime administrations as flag, coastal or port states. Flag states[157] have the authority and responsibility for enforcement of appropriate international memoranda, conventions, and protocols that the state has ratified, adopted or acceded to through national regulation. The flag state may also agree dispensations from either certain requirements of regulations through the demonstration of equivalency or issuance of an exemption. In addition, to flag state responsibilities, port states around the North Sea are responsible for enforcement under the requirements of the Directive for Port State Control (Paris MoU) and/or other national regulations.

The International Maritime Organization (IMO) is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. IMO's International Convention for the Safety of Life at Sea (SOLAS) requires contracting states to maintain Vessel Traffic Services (VTS), based on the amount of ship traffic and its related risks[158]. VTS is an internationally recognized measure to ensure the proper level of navigation safety in coastal and heavy traffic areas. In the VTS centers located along the coastline, the sea traffic situation is followed in real-time based on information transmitted by Automatic Identification System (AIS), radars, cameras and very high-frequency (VHF) radios. The SOLAS convention also requires the AIS to be fitted aboard international voyaging ships with 300 or more gross tonnage, and all passenger ships regardless of size. Since fishing vessels and pleasure crafts are not always equipped with AIS[159], navigational conflicts can be difficult to avoid. AIS information also supplements marine radar, which continues to be the primary method of collision avoidance for water transport. Although technically and operationally distinct, the Automatic Dependent Surveillance – Broadcast (ADS-B) system is analogous to AIS and performs a similar function for aircraft.

According to EU law, offshore wind farm development must satisfy two assessments processes: Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA). According to the European "EIA Directive (85/337/EEC)[160] on the assessment of the effects of certain public and private projects on the environment" an EIA is not mandatory in case of projects that are not listed in Annex II of this directive, which includes among other things installations for the harnessing of wind power for energy production (wind farms). The EIA process ensures that environmental consequences of projects such as offshore wind farms are identified and assessed before authorization is given. In 1996, European Commission started consideration of introduction of the obligatory environmental assessment (the so-called Strategic Environmental Assessment – SEA) plans and programs. SEA is the process of appraisal through which environmental protection and sustainable development

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[156] Maritime and Coastguard Agency (2008). "Offshore Renewable Energy Installations (OREIs) – Guidance to Mariners Operating in the Vicinity of UK OREIs". MGN 372 (M+F).

[157] The flag state of a merchant vessel is the jurisdiction under whose laws the vessel is registered or licensed, and is deemed the nationality of the vessel. A merchant vessel must be registered and can only be in one jurisdiction, but may change the register in which it is registered.

[158] The main tasks of modern vessel traffic services are: (a) ensuring a high level of safety in the waters covered by monitoring, (b) increasing the efficiency of vessel traffic, (c) protection of the marine environment.

[159] The Automatic Identification system (AIS) is an automatic tracking system that uses transceivers on ships and its information can be used in Vessel Traffic Services (VTS). It is a marine traffic monitoring system established by harbor or port authorities, similar to air traffic control for aircraft.

[160] The EIA Directive (85/337/EEC) is in force since 1985 and applies to a wide range of defined public and private projects, which are defined in Annexes II and II.

may be considered, and factored into national and local decisions regarding Government (and other) plans and programs. This can encompass oil and gas licensing rounds and other offshore energy developments, including renewables and gas and carbon dioxide storage. It provides means for looking at cumulative effects and appropriately address them at the earliest stage of decision making alongside economic and social considerations. In essence, an EIA assesses the impacts of infrastructure like OWFs on other systems such as the marine environment, shipping, fishing, tourism and leisure craft activities, or even other existing offshore renewable energy installations in the area. In most coastal states[161], there are stringent processes requiring OWF owners/developers to demonstrate that they have thoroughly assessed the maritime risks and implemented adequate risk management measures.

These above-mentioned processes are generally referred to as navigational risk assessments (NRAs) that are often part of the EIA studies. Although NRAs are generally commissioned by developers (only in the Netherlands that the state itself conducts the NRA) and checked by approval authorities as a part of the licensing process, there are also examples of NRAs being used as part of the marine spatial planning process in countries like Belgium and the Netherlands (Mehdi et al., 2018)[162]. The core premise of the NRA process is to assess the risk of maritime accidents near OWFs. Thus, a NRA process essentially enables stakeholders to assess the probability, consequence and overall risk that an OWF poses to ship safety, with various tools and even stakeholders feedback.

4.3.2 NAVAL RADAR SYSTEMS

Marine radar has played a pivotal role in the field of remote sensing applications, especially for maritime navigation, marine rescue, maritime surveillance, and national defence. Marine radars are electronic navigation instruments that use a rotating antenna to seek a narrow beam of microwaves around the water surface surrounding the ship to the horizon. These radars are X band (9.2 to 9.5 GHz frequency with a short wave length of 3 cm) or S band (3 GHz frequency with longer wavelength of 10 cm) radars on ships, used to detect other ships and land obstacles, to provide bearing and distance for collision avoidance and navigation at sea. X band radar is mainly used for accurate navigation and to detect targets around the ship. S band is used for long distance detection and navigation system, but it is less sensitive to sea and rain clutter. X band radar is also used by vessel traffic service (VTS) and S band radar by weather services.

Maritime radars detect targets by microwaves reflected from them, generating a picture of the ship's surroundings on a display screen. Radar is a vital navigation component for safety at sea and near the shore. At the same time, marine radars face the problems of sea clutter when detecting the surface ships, low-flying aircraft, icebergs, and other small surface objects. Sea clutter is highly dependent on the ocean state, radar grazing angle, wind velocity, and direction. Furthermore, sea echoes generally appear to have sea spikes, which will decrease the target detection performance, especially for the targets of low speed and low RCS. What is worse, when the grazing angle of marine radar is lower than 3 degrees and the lengths of targets to be detected are smaller than 30 meters, such as growlers, buoys, and small boats. This means that the height of these targets are also low, the detection problem will be very difficult. The target detection in sea clutter at the condition mentioned above is very important, because the primary purpose of marine radar is early warning targets, then to track or recognize those (Wu et al., 2011)[163].

Radars are rarely used alone in a marine setting. A modern trend is the integration of radar with other navigation displays on a single screen, as

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[161] A Coastal State is a small or medium-sized state situated by the ocean that has full sovereignty within its territorial waters. It also enjoys certain sovereign rights on the continental shelf and in the exclusive economic zones off its coast.

[162] R.A.Mehdi; J.U. Schröder-Hinrichs; J. Van Overloop; H.Nilsson; J.Pallson. "Improving the co-existence of offshore wind farms and shipping: an international comparison of navigational risk assessment process". In *Journal of Maritime Affairs 2018,* 17: 397-434.

[163] P.Wu; J. Wang; and W.Wang. "A Novel Method of Small Target Detection in Sea Clutter". In *International Scholarly Research Network*, ISRN Signal Processing, Volume 2011.

it becomes quite distracting to look at several different screens. Therefore, displays can often overlay an electronic Global Positioning System (GPS) navigation chart of ship position, and a sonar display, on the radar display. This provides a combined view of surroundings, to maneuver the ship. In commercial ships, radars are integrated into a full suite of marine instruments including chart plotters, sonar, two-way marine radio, satellite navigation (GNSS), Electronic Chart Display and Information System (ECDIS), and emergency locators (SART). A satellite navigation system uses satellites to provide autonomous geospatial positioning. It allows small electronic receivers to determine their location to high precision using time signals transmitted along a line of sight by radio from satellites. Global navigation satellite system (GNSS) is a general term describing any satellite constellation that provides positioning, navigation, and timing (PNT) services on a global or regional basis. While GPS is the most prevalent GNSS, other nations have fielded their own systems to provide complementary, independent PNT capability. By definition, GNSS provides global coverage. Examples of GNSS include Europe's Galileo, the USA's NAVSTAR Global Positioning System (GPS), Russia's GLONASS and China's BeiDou Navigation Satellite System. Galileo is a global GNSS owned and operated by the European Union, GLONASS by the Russian Federation, and BeiDou (BDS) respectively by the Republic of China.

The other satellite navigation system such as an Electronic Chart Display and Information System (ECDIS) is a geographic information system used for nautical navigation that complies with IMO regulations as an alternative to paper nautical charts. The system generates audible and/or visual alarms when the vessel is in proximity to navigational hazards. ECDIS is a navigational information system, interfaced with other navigational equipment such as the GPS, Gyro[164], RADAR, and ARPA[165], Echo Sounder[166] et cetera. ECDIS also incorporates and displays information contained in other nautical publications such as Tide Tables and Sailing Directions and incorporates additional maritime information such as radar information, weather, ice conditions and automatic vessel identification.

Contrary to marking systems, VTC has the ability to interfere with the vessel's movement through commands issued by maritime traffic controllers who supervise all vessels 24 h a day. At present, information about position is obtained from GNSS, which are the basic source of navigational information on vessels. Bearings and distances can be obtained by using the marine radar. When determining the radar bearing, good sea practice indicates that, the observations are made at the center of the radar echo, which has a significant impact on the quality of the final determination. In the case of small vessels, the obtained distances are not affected by large errors, which significantly affect the final determination of the co-ordinates of the vessel's positions at sea. However, when observing radar echoes from large and very large vessels, it can often be seen that the measured distances refer to the nearest side of the vessel and not to the location of, for example, the position of the radar antenna, which should be considered as the vessel's position. The location of the measurement is significantly different from the radar echo center, which has a significant impact on the final determination of the coordinates of the vessel's position at sea (Bole et al., 2005)[167].

4.3.2 ROUTING DECISIONS AROUND WIND FARMS

As wind farms are developed, vessel traffic will be displaced and may be funneled into smaller areas, increasing vessel density with a concurrent increase in risk collision, loss of property, loss of life, environmental damage. Vessels navi-

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[164] The ships main gyrocompass gives the heading of the vessel with respect to true north. A gyrocompass is a form of gyroscope, used widely on ships employing an electrically powered, fast spinning gyroscope wheel and frictional forces among other factors utilizing the basic physical laws, influences of gravity and the earth's rotation to find the true north.

[165] A marine radar with automatic radar plotting aid (ARPA) capability can create tracks using radar contacts. The system can calculate the tracked object's course, speed and closest point of approach, thereby knowing if there is a danger of collision with the other ship or landmass.

[166] Echo sounder is a type of sonar used to determine the depth of water by transmitting acoustic waves into water. The time interval between emission and return of a pulse is recorded, which is used to determine the depth of water along with the speed of sound in water at that time.

[167] A.Bole; B.Dineley; A.Wall. "Radar and ARPA Manual, 2nd eds; Elsevier Butterworth-Heinemann Linacre House: Oxford, UK.

gate clear of a wind farm for the simple reason of avoiding collisions with turbines. Many factors affect the routes vessels take, but generally they take the most direct and safe route. Smaller and slower moving vessels tend to transit closer to shore, whereas larger and faster moving ones tend to transit in deeper water further offshore.

For vessels navigating around wind farms, there are three factors, which dictate how they plan their passage. Firstly, the distance should be a comfortable buffer so that if an incident was to occur on board, or another vessel was encountered, there would be sufficient sea room to make an evasive manoeuvre. Secondly, concerns have been raised over the visibility of a wind farm. Visually a wind farm may obscure smaller craft, such as recreational, fishing and maintenance vessels. If a sufficient clearance is given from the edge of the wind farm then there is more time to respond to a collision situation involving such craft. Furthermore, concern has been raised regarding the impacts of wind turbines on marine radar. Reports of reflections, false echoes and other spurious effects have been seen when navigating near to a wind farm. It is not the wind turbines themselves, which create these effects; it is often more inadequate radar setup and configuration (Marico Marine, 2007)[168]. A vessel may therefore choose to navigate further from a wind farm to reduce these effects and improve their situational domain awareness.

Operational safety zones are typically defined to safeguard the safety of the OWFs and of passing maritime traffic. The safety zone is an area around the OWFs corresponding to the minimum clearance distance of the wind farm boundaries from shipping routes. OWF safety zones have been suggested in the literature and by several guidelines and regulations. For example, under the United Kingdom legislation, the OWF reserved area has been defined as 500 meters during construction. The UK Maritime and Coastguard Agency (MCA, 2016)[169] suggests that a distance between the OWF boundary and shipping routes less than 0.5 nautical mile is intolerable. Some studies have provided some recommendations on safety zone selection based on expert judgements or experience. Rawson and Rogers (2015)[170] suggest that the passing distance of ships should not be less than 1,000 m to reduce the risk of collisions. Ultimately, safety zones are assessed on a case-by-case basis using a risk-based approach, taking into account maritime traffic and site-specific conditions so that the collision and contact risks are as low as reasonably practicable.

Finally, the safety distance a vessel chooses to navigate around a wind farm is weighed against commercial pressures associated with additional distance, fuel and passage time requirements. Re-routing (displacing) traffic may also increase the weather related casualty risk to smaller vessels engaged in coast-wide shipping by forcing them further offshore, where they will be subjected to larger sea states, and where their transits will be commingled with deep draft vessels moving at higher speeds. In general, and where no other constraints are present, commercial shipping typically follows straight routes between waypoints to reduce transit time and fuel costs. Additional deviations from this route to pass obstacles increases costs and may make some routes uneconomical (Toke, 2010)[171].

Much of the analysis and guidance provided for safe passing from offshore wind farms has been industry led. The UK Maritime and Coastguard Agency (MCA) established one of the most significant efforts to categorize the safe passing distance of shipping from a wind farm in 2004 in response to new developments in the Greater Wash area of England (MCA, 2008)[172]. The distances are based upon domain theory, a safety

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[168] Marico Marine (2007). “Investigation of Technical and Operational Effects on marine Radar Close to Kentish Flats Offshore Wind Farm”. British Wind Energy Association.

[169] Maritime and Coastguard Agency (2016). “Navigation: Watchkeeping Safety – Use of VHF Radio and AIS”. Marine Guidance Note, MGN 324 (M+F) Amendment 1.

[170] A.Rawson & E.Rogers (2015). “Assessing the impacts to vessel traffic from offshore wind farms in the Thames Estuary”. In *Scientific Journals of the Maritime University of Szczezin,* 2015, 43 (115), pp. 99-107.

[171] Toke (2010). “The UK offshore wind power programme: A sea change in UK energy policy? In *Energy Policy* 39 (2), pp. 526-534.

[172] Maritime Coastguard Agency (2008). “Offshore Renewable Energy Installations (OREIs) - Guidance on the UK Navigational Practice, Safety and Emergency Response Issues”. Marine Guidance Note, MGN 371 (M+F).

buffer around a navigating vessel, and impacts of turbines on radar. Distances from turbines are given the following "risk classification":

- 0 to 0.45 nautical mile (nm) is intolerable – significant impacts upon radar and navigational risks;
- 0.45 to 2 nm is tolerable – medium/high risk – based on collision regulations and ship domains. 1 nautical mile is the minimum acceptable distance to the boundary of a Traffic Separation Scheme (TSS)[173];
- 2 nm to 3.5 nm is tolerable – low risk;
- >3.5 nm – very low risk

This guidance was adapted as part of the Atlantic Coast Port Access Route Study (ACPARS) conducted by the US Coast Guard (USCG, 2012)[174]. One of the objectives of the ACPARS study was to determine whether the Coast Guard should initiate actions to modify or create safety fairways, Traffic Separation Schemes or other routing measures. In addition, an effort focused on determining the appropriate width of navigation route was undertaken for alongshore towing operations. These efforts enabled to identify navigation safety corridors along the Atlantic Coast (Maine to Florida) that combine the width necessary for navigation and additional buffer areas based on the planning guidelines. To ensure safety of navigation, the Coast Guard needs to characterize the impacts of rerouting traffic, funneling traffic, and placement of structures that may obstruct navigation.

4.4 OFFSHORE WIND FARMS RADAR INTERFERENCE MITIGATION

A number of mitigation techniques are being considered to reduce the impact of wind turbines on radars. By using several discrimination techniques in pre-detection, detection and post-detection stages can help to mitigate the wind turbine interference. These techniques include using two channels for elevation discrimination (pre-detection), an enhanced constant false alarm rate (CFAR) detector and enhanced moving target detector (MTD) algorithm (detection), and improved tracking and classification algorithms (post-detection). In the CFAR detector, the threshold is computed after substituting the returns in the cells showing extremely large power with the returns in the cells showing extremely large power with the average noise power. The use of an enhanced CFAR algorithm eliminates the effect of "detection shadowing" where the aircraft detection is masked by the stronger wind turbine return and is not detected within several nautical miles of the wind farm.

Post-processing techniques have the potential to render victim' radars less susceptible to returns from turbines, and "gap-fillers" reduce the area around farms in which targets cannot be detected. Sensitivity reduction in the direction of the farm for fixed radar installations is also being considered by antenna modification, antenna tilting, and physical obscuration techniques such as radar absorbent material (RAM) fences and modification of the layout of turbines within farms to better fit into clutter map cells of some radar types. Although, in case of older generation and legacy radars, signature reduction of the wind turbines themselves has the potential to benefit all radar systems, marine and aviation, and is likely to form an important part of the overall solution to the radar-wind interaction problem. The next generation radars rely on artificial intelligence, deep learning algorithms that can produce better than human results in image recognition, generating a close to zero fault rate. Deep learning is a machine learning method based on artificial neural networks. It uses multiple layers, which progressively help to extract higher-level features from the raw input. For example, in radar data processing, lower layers may identify reflecting points, while higher layers may derive aircraft types based on cross sections. Similar to cognitive radio networking and communication, artificial intelligence can play the role of cognitive decision-maker, for example in cognitive radar antenna selection. It enables deploying a full array and then selecting an optimal sub-array to transmit and receive the signals in the target en-

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[173] Traffic Separation Scheme (TSS) is a routing measure aimed at the separation of opposing streams of traffic by appropriate means and by the establishment of traffic lane: an area within defined limits in which one-way traffic is established.

[174] USA Coastguard (2012). "Atlantic Coast Port Access Route Study". Final Report.

vironment. Another example is the segmentation of radar point clouds through deep learning algorithms. The UK Offshore Wind Industry Council Aviation Workstream has commissioned a study by the UK's Offshore Renewables Energy Catapult to examine the impacts of the layout and the use of windfarm SCADA data to assist radar performance.

The majority of aviation and marine radars can be considered as operating over 2 frequency bands, 2.7-3.1 and 9.1-9.41 GHz. The former encompasses the bulk of modern air defence (AD) radars, military and civil air traffic control (ATC) terminal approach and primary surveillance radars (PSR), including a proportion of marine vessel traffic services (VTS) and long range marine navigation radars associated with larger vessels. X-band radars within the latter frequency range are predominantly associated with the marine environment, these frequencies typically encompassing marine navigation radars on smaller craft and further VTS operated by port authorities (Pinto et al., 2009)[175].

Modern technologies can also help finding the best mitigation techniques, Funded through the UK Department for Business, Energy and Industrial Strategy Net Zero Innovation Portfolio and delivered by the Defence and Security Accelerator, Defence Science and Technology Laboratory have organized several competitions which aim to develop technologies that reduce the impact of offshore wind farms on AD surveillance. One of the awarded projects was about an advanced nano-scale Radar Absorbing Material (nRAM) at the manufacturing stage of offshore windfarms ensuring radar frequency absorption is integrated into the base materials of offshore wind farms.

4.4.1 MITIGATION TECHNIQUES (GENERIC CLASSIFICATION)

As apparent from the discussion above, the focus on mitigating non-moving clutter implies that there are shortfalls in currently deployed radar systems when the clutter has moving components such as the blades of wind turbines. Therefore, mitigation of offshore wind turbines interference must rely on new systems, enhancements to old systems, alternate data sources, or potentially limiting the utility of fielded systems in affected locations. For the purposes of this study, mitigation methodologies can be divided into the following categories:

- **Operational:** Operational methods involve using the non-modified system with operational constraints. For example, re-siting a radar, by using a secondary data source (i.e., Automatic Dependent Surveillance Broadcast (ADS-B). A Global Positioning System (GPS) based broadcast from an aircraft can provide its position – rather than a skin track of an aircraft), limiting altitudes of flight over the wind farm. Another option is using existing modes available on a radar, or shutting down wind farm operations during certain events are some examples of operational mitigation.

- **Modification:** Radar modifications could encompass hardware changes, software and signal processing changes, or potentially both. Such as adding an additional signal processing and display system – typically known as a "sidecar". Real-time testbed is used to implement and evaluate the mitigation approaches on radars. Except in the case of the addition of a sidecar, it is expected that the original equipment manufacturer (OEM) would be required to make the modification to the radar.

- **Addition:** Adding other secondary sensors- those to be designed to be less affected by wind turbines – with the purpose to provide data in affected regions. These proposed systems – commonly called *"in-fill" radars* – would be expected to be relatively inexpensive and short range, and probably need to be deployed near or within the wind farm itself and potentially on a turbine mast, or masts. Although, the primary affected radar would need some modification to accept and integrate the data from the infill systems.

- **Replacement:** Although typically not a feasible alternative for near-term mitigation except through normal life-cycle replacement. The

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[175] J.Pinto, J.C.G. Matthews, G.C.Sarno. "Stealth technology for wind turbines". In *IET Radar Sonar Navigation*, 2010, Volume 4, Issue 1, pp. 126-133.

next generation of radars are designed with mitigation features, which make them more wind farms friendly.

4.4.2 COMMON CLUTTER MITIGATION DESIGNS

Surface-based radars have been designed over decades to reject clutter, although the term "clutter" is a relative term. For example, the radars designed to detect airborne returns/targets have transmitted waveforms and signal processing to reduce the reflected returns from the ground and the surface. The waveforms and clutter rejection methodologies have historically been based upon the assumption that the surface-based clutter returns are non-moving, or very slowly moving. Although this is not an exhaustive list, the following are common clutter rejection methods.

- **Siting Optimization:** Siting may be optimized for clutter reasons, and clutter fences (including berms and terrain features to mask a specific direction) – frequently used in radar test sites. This can also be placed around the radar site to reduce the illumination of clutter at certain aspects. Tower mounting, which provides longer-range capability – also makes site modification more difficult or merely infeasible.
- **Three-Dimensional (3D) radar:** It provides for radar ranging and direction in three dimensions. In addition to range, the more common two-dimensional radar provides only azimuth for direction, whereas the 3D radar also provides elevation. By employing a "pencil beam" of relatively high-resolution capability, a 3D radar can point its beam above the clutter for a cleaner measurement. Still, if measurement close to the surface is required, there is the possibility that clutter sources will be illuminated. Even if the surface is illuminated, measuring data in multiple beams – even if sequentially and not simultaneously – can provide insight into the clutter environment and allow for more rejection methods.
- **Moving target indicator (MTI):** In some radar applications, "moving targets" signals are embedded in strong stationary clutter. Moving targets will produce a Doppler frequency shift, while the stationary clutter has very small spectral spreading around zero frequency. The moving target indicator (MTI) radar is a pulsed radar that uses the Doppler frequency shift as a means for discriminating moving targets from stationary clutter. It is a relatively simple and common method to mitigate clutter. The radar will transmit a series of pulses (three or four consecutive pulses, for example) by using a series of summing circuits to delay and add the pulses together with amplitude multipliers and phase shifts applied to each pulse. If the returns are from a moving target, the phase of the signal changes from pulse to pulse, while a non-moving target has a consistent phase that – through the summing circuit – will cancel itself out and allow the moving target to pass.
- **Moving target detection (MTD).** The task of moving target detection is to identify the physical movement of the target in a specific area. MTD radars are a class of Pulsed Doppler (PD) systems that typically employ a smaller number of coherent pulses than typical PD systems. The smaller number of processed pulses reduces the Doppler/velocity resolution capability of the system but still can provide significant attenuation of non-moving returns.
- **Clutter Map.** A clutter map is produced in a radar when returns are saved and processed as follows: (1) A set of returns are identified as clutter in specific "bins" (e.g. range, angle, Doppler) by comparing returns from multiple scans and looking for consistent returns in specific bins, or in some designs looking for specific Doppler returns. (2) Those bins are either blanked (ignored) or the "consistent' signal (generated by averaging multiple scans) is subtracted from the current measured signal in that bin. Blanking a bin in a system without required resolution can result in dropouts, which may bring about a loss of measurement of a desired target; therefore, subtraction is preferred. For example, blanking a range-angle bin in a 2D radar would result in targets flying about the clutter source being essentially invisible to the radar. Likewise, if it is a 3D radar, the map can also be beam-dependent and further reduce the chance of missing an intended target.

- **Simultaneous-beam processing.** Using multiple beams simultaneously allows for higher resolution in angle, and can offer the ability to attenuate signals in angle if the radar architecture allows it. Either depending upon the number of beams in the vertical (elevation) or horizontal (azimuth) planes or both – a radar can further separate potential interference sources in angle in addition to range and Doppler.

  An active electronically scanned array (AESA), known as active phased array radar (APAR) is a type of phased array whose transmitter and receiver functions are composed of numerous small solid-state transmit/receive modules. AESA radars aim their beam by emitting separate radio waves from each module that interfere constructively at certain angles in front of the antenna. Advanced AESA radars can improve on the older passive electronically scanned array (PESA) radars by spreading their signal emissions out across of band of frequencies, which makes it very difficult to detect over background noise, allowing ships and aircraft to broadcast powerful radar signals while remaining stealthy. AESAs add many capabilities of their own to those of the PESAs. Among these are the ability to form multiple beams, to use each transmit/receive modules for different roles concurrently. Like radar detection, and more importantly, their multiple simultaneous beams and scanning frequencies create difficulties for traditional correlation-type radar detectors.

CHAPTER 5 – INTEGRATION OF POWER FROM OFFSHORE WIND TURBINES INTO ONSHORE GRIDS

Wind farm collection systems gather the power generated from wind turbines including submarine power cables and transfer the electricity generated from offshore to onshore grids as shown in Figure 14. Strong growth of offshore wind energy requires an expansion of the offshore and onshore electricity grid. The larger size of the wind farms and their greater distance from the onshore grid pose technical and economic challenges.

Subsea power cables are critical infrastructure for the transmission of renewable energy globally. Array cables run between the turbines of an offshore wind farm by connecting them to the offshore substation, export cables in turn, take the power from the offshore substations and connect to the main power grid onshore. The voltage levels of export cables that are vital for transmission of the generated power to the grid, range from 33 kV for nearshore wind farms without offshore substations and up to 132 kV, 150 kV and 220 kV for further offshore sites with 1 or 2 substations. Since 2013, over 80% of projects in Europe have

Figure 14. Wind farm integration in power grid

Source: Adapted from Nordsee GmbH, 2020

deployed export cables with a voltage greater than 150 kV.

The offshore substation acts as a transformer to convert the voltage level of electricity to allow it to be brought to shore via an export cable. The onshore station then transforms that electricity to the required voltage to be connected to the grid. For example, in the German section on the North Sea, converter stations have been built to convert alternating current (AC) from several farms to direct current (DC) and export to shore over long distances. For smaller offshore wind farms built inshore, cables can be bundled and run directly to the shore without the need for an offshore station. Electricity interconnectors are the physical links, which allow the transfer of electricity across national borders. This exchange of power helps to ensure safe, secure and affordable energy supplies. Interconnectors also facilitate cross-border energy exchange from areas with surplus production to areas with supply shortfalls.

AC technology is mature and proven for land-based applications and relatively short offshore tiebacks. Subsea AC cables are limited in their capability to transmit power beyond a certain distance, depending on cable characteristics, installation conditions, and system operating mode. Therefore, one of the greatest challenges of the offshore wind farms installation is the transmission of large amounts of energy over long distances. For interconnecting the wind farms, there are two alternatives: high-voltage alternating current (HVAC) and high-voltage direct current (HVDC). Today, HVAC is chosen in most of the projects located at a relatively short distance to the shore. HVAC cables have a high capacitance[176] per length, so in addition to the delivery electrical current, there is capacitive current as well. The latter is fluctuating every half cycle, and is utilizing part of the total current delivery capability. The use of AC collection grids or its DC counterparts in windfarms is motivated by the availability of control and protection devices. Presently, efficient and cost-effective control and protection devices for the DC collection grids may not be a problem anymore (Deng et al., 2013)[177]. The use of DC is rapidly increasing following the evolution of power electronics and typologies of AC-DC converters. Different cable system solutions are available for DC applications. The power converters are significantly compact and smaller as compared with the power transformers of similar power rating. This reduces the size and weight of wind turbine generators, and hence the offshore wind farm. For an offshore wind farm with DC collection grid and HVDC transmission system, two platforms (rectifier and inverter stations) are needed; this also reduces the cost of platform installation. Technically, the power converters perform power rectification, power conditioning, power filtering, and power compensation.

For large-volume introduction of wind power generation, it is becoming essential to improve power quality. A power conditioner alleviates changes for generation and contributes to higher power quality. Many of these power disturbances, particularly the transient surges, can be harmful to sensitive electronic equipment with low-voltage DC power supplies. Power disturbances can cause altered data and sometimes equipment damage, which in turn, may result in loss of production. The power conditioning provides the control of frequency, voltage, power factor, and speed of rotating machines. Active power filters are power electronic devices dedicated to improving the quality of the electrical energy and the efficiency of its use. The main objective of electricity distribution grids is to transport electric energy to end users with required standards of efficiency, quality and reliability, which requires minimizing energy losses, and improving transport processes. Reactive power compensation is one of the well-recognized methods for its contribution to the reduction of energy losses, along with other benefits.

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[176] Capacitance is an electrical property that refers to the capability to store an electrical charge. A capacitor is constructed of two conductive materials separated by an insulator, or dielectric. Capacitance is a concern in cabling, because all cables are, in a way, long capacitors. This can affect the signal that is being transmitted down the cable, so manufacturers seek to control capacitance in a variety of engineering techniques.

[177] F.Deng; Z.Chen. "Operation and control of a DC-grid offshore wind farm under DC transmission system faults". In *IEEE Transaction on Power Delivery*, 2013, 28 (3), pp. 1356-1363.

With more offshore energy generation, there is a need for a transmission grid to transport the electricity as well as to supply offshore production facilities with power in an efficient way. At present, offshore wind, farms have connected to the electricity grid by way of constructing individual routes of connection from offshore to onshore infrastructure (“point-to-point connection"). While such transmission arrangements were suitable in the past – at one point, expectations were that offshore wind would provide only a small contribution. The prospect of significant increase in capacity and its supporting infrastructure, including grid connection, has brought to the fore the need to coordinate the grid connection system to ensure both (i) the costs of construction are economical; and (ii) the associated infrastructure’s impact on the landscape (both onshore and offshore) is less invasive. One option to overcome these challenges are going beyond the current point-to-point connections to establish a meshed offshore transmission grid (DNV GL, 2020)[178].

A meshed offshore grid connecting offshore energy generation and offshore installations to land could provide significant financial, technical and environmental benefits compared to the current point-to-point connections. The largest number of units that will be connected to the offshore grid will be wind turbines, while other generation types (wave power plants, gas turbines on platforms) will play a minor role. The main share of the produced electric power will not be consumed offshore but transferred to shore via high voltage direct current (HVDC). Current offshore HVDC systems are point-to-point systems, connecting offshore installations (power production or power users) or directly to shore. To reduce cost, a meshed offshore transmission grid would be preferable, connecting several installations with both power producers and consumers directly without going through the onshore grid. Compared to point-to-point cable, a meshed grid would have a higher utilization and reliability.

An onshore meshed HVDC grid is being built currently in China. In the EU, the PROMOTioN project is developing and demonstrating cost-efficient offshore HVDC equipment as well as developing recommendations for a regulatory framework for HVDC offshore grids and financing mechanisms. Given the long planning/permission/construction cycle for typical offshore project (at least five years), a full-fledged meshed offshore grid will probably not be implemented there within the next 10 years. An earlier shape or part of meshed HVDC grid (with no less meshing, fewer offshore HVDC converters) would likely be up and running by 2030[179].

Eliminating the need to construct individual points of connection for each wind farm, as well as the relevant grid reinforcements, is undoubtedly an area in which significant savings could be made once the relevant technologies are sufficiently developed. It is estimated that multi-purpose interconnectors (MPI), one of the proposed alternatives to point-to-point connection could save consumers 6 billion GBP by 2050 due to the reduction in grid infrastructure needed. MPIs would utilize the existing technology of interconnectors, which provide a point-to-point connection to transmit electricity between two countries and allow surplus renewable electricity to be exploited when needed. By connecting clusters of offshore wind farms to an interconnector, the need to have necessary infrastructure to connect wind farms to the transmission grid would be greatly reduced (James, 2021)[180]. Coordinated, multipurpose, interconnected HVDC transmission infrastructure is the optimal way to integrate offshore wind farms into transmission infrastructure. On the other hand, the construction of multi-purpose interconnectors leads to more involved technical arrangements on interconnector use and brings about regulatory complications that need to be solved.

Since electrification can be both energy efficient and low carbon, many sectors will continue to electrify, leading to sector integration, sector coupling and integrated and complex system dynamics. Cross-border and cross energy system

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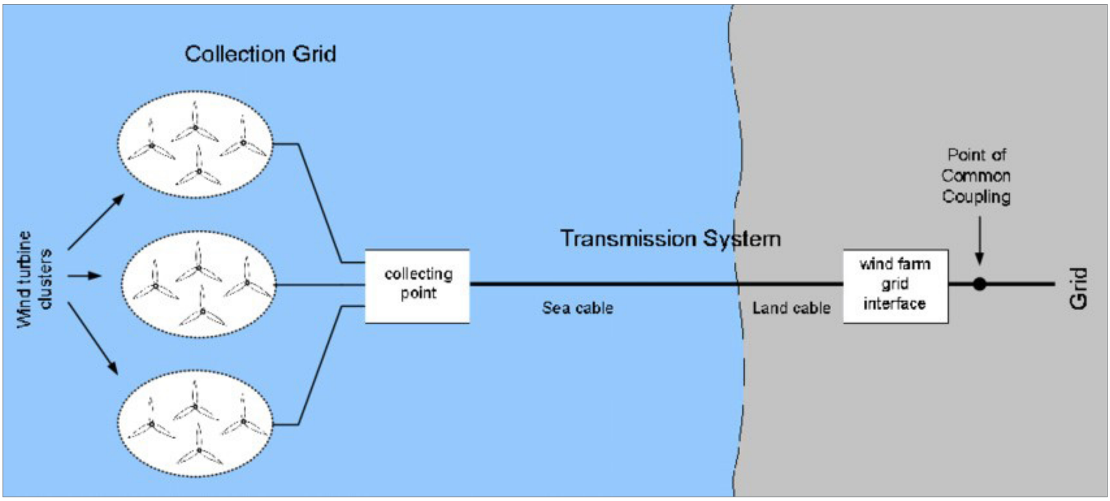
[178] DNV GL (2020). “Technology Outlook 2030: The offshore grid of the future”.

[179] Ibid, 2020.

[180] L.James “Offshore transmission – will point to point connections become pointless in an integrated future? Burges& Salmon

Figure 15. General layout of the offshore wind farm and connection to transmission grid on land (Source: adapted from Georgios Stamatiou).



coupling refers to the idea of interconnecting (integrating) the energy consuming sectors – buildings (heating and cooling), transport, and industry – with the power-producing sector. Nowadays, energy systems are planned, designed and operated in silos with a strong national focus. However, large-scale offshore wind production needs to be transported to deep inland locations across country borders. The traditional solution of continuously reinforcing and extending the electricity grid is not sustainable from a cost and societal perspective. Successful integration of offshore wind and transmission to inland demand centers therefore requires cross energy coupling to other sectors (hydrogen, heat, et cetera) to provide the required flexibility, as depicted in Figure 15.

5.1 OFFSHORE WIND TURBINE TECHNOLOGY

Wind turbines are usually classified into two categories: (1) fixed speed and (2) variable speed ones. Fixed speed wind turbines work at the same rotational speed regardless of the wind speed, whereas variable speed turbines can operate around their optimum power point for each wind speed, using a partial or full additional power converter. Variable-speed wind turbines enable one to maximize the conversion efficiency under any wind speed conditions, since they provide the ability to control the rotor speed of rotation. Simultaneously, the mechanical stresses during wind gusts are reduced. In addition, the quality and controllability of the power fed into the electric grid can be improved through appropriate design and control of the power electronic converter that is employed for interfacing the wind turbine output power to the grid. As a result, variable-speed wind turbines are much efficient as compared to the fixed speed counterparts (Koutroulis, 2018)[181].

Many factors can influence the choice of wind energy conversion systems for offshore wind farms with DC collection systems. These include ability of speed control, type of power converter including control and protection methods. However, the most important requirement is that the wind turbines must be robust and maintenance free, since it may be very expensive and difficult under some weather conditions to do offshore maintenance or repairs. The generators that are used to convert the mechanical power obtained from the wind turbine into electric power are generally either doubly fed induction generators (DFIG), or squirrel cage induction generators (SCIG), or permanent magnet synchronous generators (PMSG).

Type 1 represents a conventional SCIG based

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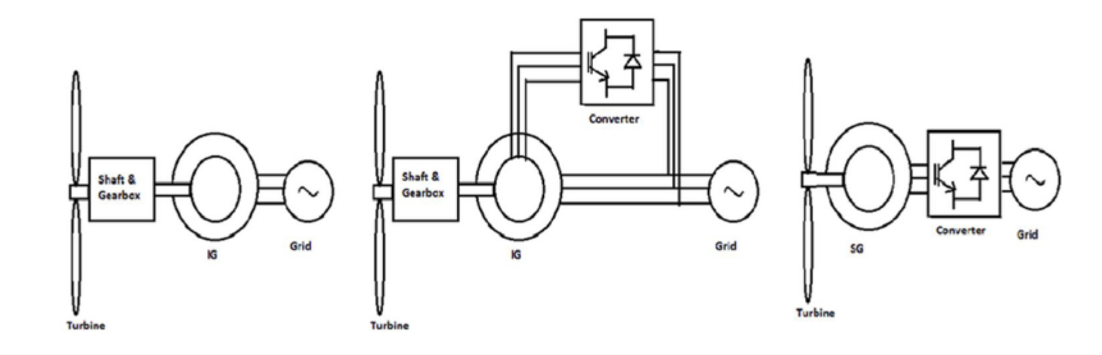
[181] E.Koutroulis. "Power Converters and Generators for Wind Energy Conversion Systems". In Comprehensive Energy Systems, 2018.

Figure 16. Wind turbine generator technologies. WT with multiple-stage geared and SCIG, (b) variable speed-based WT concept with DFIG system, c) direct-drive based WT with PMSG system



Source: Adapted from Shrikant Mali, 2017.

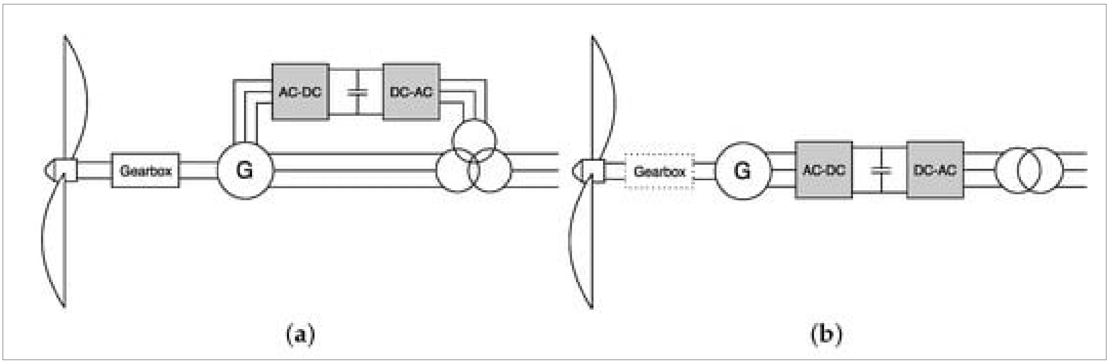
structures with fixed ratio gearbox connected to grid through a step up transformer. The soft starter here limits the inrush current, while reactive power compensation is provided by capacitor banks as depicted in Figure 16. In SCIG-based systems, the generator is coupled to the grid by back-to-back three-phase (AC-DC-AC) power converters. The AC/DC converter controls the generator; the DC/AC converter or the grid side converter controls the DC bus voltage and the active and reactive powers injected into the grid. The controllers are designed so that maximum power is extracted from the wind at all wind speeds; thus, maximum system efficiency is achieved; the generated active power is transmitted through the DC-bus to the grid while ensuring the unity power factor.

The type 2 is another structure that generally consists of a wound rotor induction generator (WRIG), having variable resistors in rotor circuit. This type of wind turbine generators utilize two bi-directional back-to-back static power electronic converters of the voltage source type. One converter is connected to the AC network at either the generator stator terminals or the tertiary winding of a three-winding generator step-up transformer. Through this variable resistance, rapid rotor current control can be achieved, which helps maintain constant power during adverse wind conditions.

Type 3 turbines make use of doubly fed induction generators (DFIGs) as presented in Figure 17. The DFIG stator is connected directly to the electric grid through an interconnection transformer, while its rotor windings are power supplied by a power electronic conversion unit, consisting of AC/DC and DC/AC converters, with a power rating of the order of 30% of that of the wind turbine. The DC/AC power converter is used to control the frequency and current of the rotor windings for the maximization of the generator's power production. The possibility of having a consistent-frequency AC from a DFIG when operated by a variable speed rotor enhances energy efficiency of the system.

Type 4 or permanent magnetic synchronous generator (PMSG) based turbines are directly driven systems with full-scale AC-DC-AC converters. A PMSG generator is interconnected with the electric grid through a power electronic interface comprising an AC/DC and a DC/AC converter. The grid-side converter adjusts the voltage of the DC bus, as well as the amount of reactive power injected into the electric grid, while the rotor-side converter regulates the generator speed. The possibility to be directly connected to a wind turbine without using the gearbox is crucial in harsh weather conditions. PMSG based turbines are suitable for offshore installations due to advantages they offer such as high density, simple control schemes, no rotor winding, bi-directional power flow and self-excitation structure. The voltage and frequency from the grid side can be controlled with small influence from the wind speed.

Figure 17. Variable speed wind turbines. DFIG wind turbine generator; (b) fully converter wind turbine generator.



Source: Fernandez-Guillamon et al., 2019[182]

Nowadays, variable speed wind turbines as seen in Figure 17 are the most commonly installed wind turbine generators (Edrah et al., 2015)[183]. For variable-speed operations, all three above-mentioned systems need power electronic converters. The PMSG- and SCIG-based systems need full-scale power electronic converters, whereas the DFIG-based systems need partial-scale power converters. Compared to DFIG-based systems, the PMSG and the SCIG-based systems could be more attractive due to the dropping cost of power electronics over time and due to the absence of brushes. Hence, the main advantages of SCIG-based systems are their reliability, their ruggedness in design and their low operation and maintenance costs (Zribi et al., 2017)[184].

5.2 OFFSHORE GRID TRANSMISSION TECHNOLOGIES

Offshore wind technology gets better every year with more innovative turbine and blade designs. Despite the design of a wind turbine, the difficulties of exporting electricity back to shore will remain. Operators of offshore wind farms are increasingly designing their systems for higher voltages because of the continuous rise in power demands, also because it makes the process of transmitting the energy generated by the wind farm more efficient. Offshore wind farms currently operate at 66kV and are preparing for an upgrade to associated cabling and connection equipment.

Offshore turbines are being engineered for even greater capacities, which presents new challenges for energy transmission in the turbines themselves and in the offshore wind farms. As well as technical challenges, health and safety considerations are another important factor. Installations out at sea also need to be as easy as possible to maintain and offer maximum resistance to salt water and the harsh marine climate. Moreover, health and safety aspects must be taken into account as a priority alongside the technical requirements. From a technical standpoint, offshore wind farms are governed by the standards set by the International Electrotechnical Commission (IEC).

The offshore wind farm cables are installed from land at a power source to sea at the turbines. Installing the portion of cable from land to sea can also be known as near shore cable installation. Inter-ray, inter-platform and export cables are key components, which require careful analysis and design in view of their mechanical properties, electrical voltages and installation methodologies. Cables are the most pivotal and weakest

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[182] A.Fernandez-Guillamon, K.Das and N.A. Cutululis and A. Molina-Garcia (2019). "Offshore Wind Power Integration into Future Power Systems: Overview and Trends".

[183] M.Edrah, K. L. Lo, and O. Anaya-Lara. "Impacts of high penetration of DFIG wind turbines on rotor angle stability of power systems". In *IEEE Transactions of Sustainable Energy* 2015, 6, pp. 759-766.

[184] M.Zribi; M.Alrifai and M. Rayan. "Sliding Mode Control of a Variable-Speed Wind Energy Conversion System Using a Squirrel Cage induction Generator". In *Energies 2017*, 10, 604.

link in transferring offshore wind power to the grid. If the cable fails, power production drops and this affects the economic value of offshore wind. Most cable failures are due to one of the following five major causes such as (1) fatique due to erosion of the support sand, (2) failure of cable structure damage from incorrect installation; (3) manufacturing problems; (4) and damage from ship anchors. Cable faults affect both the inter-ray cables connecting the turbines and the export cable from the wind farm to the grid connection point onshore. There is a need for a new generation of high tensile light cables for floating offshore units. There is also a need to develop lead-free HVDC and HVAC cables using new sealant technologies.

High-voltage DC (HVDC) power transmission plays a key role in the global power grid today and will continue to play a key role in the future, particularly for high-voltage, large-capacity, long-distance power transmission. The HVDC transmission can be divided into two methods, i.e., a line-commutated converter (LCC) using thyristors and a voltage source converter (VSC) using insulated-gate bipolar transistors. Most HVDC systems in operation today are based on the line-commutated converter (LCC)[185], where the converter process relies on the line voltage of the AC system to which the converter is connected. In the converter, the DC current cannot change direction. As a result, reversal of power flow direction can be achieved only by reversing the polarity of DC voltage. This technology is mainly applied to transmit power over long distances with a power rating up to 12,000 MW through overhead lines or subsea cables. HVDC power transmission is becoming more and more competitive compared to HVAC power transmission, especially for bulk power transmission over long distances. This is due to many technical and commercial advantages shared by both HVDC transmission systems using current source converters (CSC)[186] and HVDC transmission systems using the more recently developed voltage source converters (VSC).

With the development of the manufacturing level of self-commutating power electronic devices and the arise of new DC cables with new insulation materials, the HVDC systems are applied more often into direct current transmissions and offshore wind farm systems. The power transformer station is installed offshore on a platform, which steps up the voltage to 161kV across the AC collector or AC bus. A short AC cable transfers power to the HVDC-rectifier platform, on which power converter is installed for HVAC to HVDC conversion. Once onshore, an HVDC-inverter platform is used for HVDC to HVAC conversion. Three platforms are required for an offshore wind farm integrating an AC collection grid with HVDC transmission line. The advantage of using HVDC transmission system is that low quantity of DC cables is needed, no changing current, and skin effect exists in the DC cables, power factor is always close to unity and there is less radio interference.

For the design of a DC collection grid, the power converters or rectifiers replace the 50 or 60 Hz power transformers installed in the wind turbines. The power converters are significantly compact and smaller compared with the power transformers of similar power rating. For an offshore wind farm with DC collection grid and HVDC transmission system, two platforms (rectifier and inverter stations) are needed; this also reduces the cost of platform installation. Technically, the power converters in wind turbines perform power rectification, power conditioning, power filtering, and power compensation. The power rectification enables the conversion of signals (voltage and current) from AC to DC. The power conditioning provides the control of frequency, voltage, power factor, and speed of rotating machines. The power filtering injects (or absorbs) specific signal components for power quality. Moreover, the power compensation enhances the voltage/angle stability.

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[185] Another HVDC technology is the voltage-source converter (VSCs) based on semiconductor devices such as insulated gate bipolar transistors, which allow fully independent control of both active and reactive power flow and voltage, including power export and import.

[186] In a current source converter (CSC), the DC current is kept constant with a small ripple using a large inductor. In practice, the most applications a LCC equals a CSC. The direction of power flow through a CSC is determined by the polarity of the DC voltage, whereas the direction of current flow remains the same.

Currently, there are no operational offshore wind farms with DC collection grids, although only theoretical and small-scale prototypes are being investigated worldwide. Therefore, a suitable configuration for the wind farm with DC collection grid, which has been practically verified, is not available yet. This chapter examines the key technologies associated with the wind farm with HVDC transmission system, typical configuration of the DC collection grids including control and protection methods are reviewed.

5.2.1 HIGH VOLTAGE DIRECT CURRENT (HVDC)

HVDC (high-voltage direct current) is a key enabler for a carbon-neutral energy system. It is highly efficient for transmitting large amounts of electricity over long distances, integration of renewables and interconnecting grids, opening up for new sustainable solutions. Although, this positive trend carries new challenges for grid stability and highlights importance of new interconnection, often through HVDC technology, between the different synchronous grid areas. As wind farms are growing in terms of rated power, offshore wind power plants are also being located farther from the coasts and grid entry points. These factors present significant technical challenges.

HVDC transmission system consists of three basic parts: (1) converter station to convert AC to DC; (2) transmission line, (3) second converter to convert back to AC. High-Voltage Direct Current (HVDC) transmission systems can be configured in many ways based on cost, flexibility, and operational requirements. The simplest configuration is the back-to-back interconnection that has two converters on the same site without any transmission lines. This type of connection is used as an intern tie between two different AC transmission systems. The mono-polar link connects two converter stations by a single conductor line and earth or sea is used as a returned path. The multi-terminal HVDC transmission systems have more than two converter stations, which could be connected in series or parallel.

A high-voltage cable for high-voltage direct current HVDC transmission has the same construction as the AC cables. Many HVDC cables are used in DC submarine connections, because at distances longer than 100 km, AC can no longer be used. The longest submarine cable today is the NorNed cable between Norway and the Netherlands, which is almost 600 km long and transports 700 megawatts, a capacity equal to a large power station. When choosing between AC or DC for connecting offshore wind farms to the grid, the main parameters to be considered are rated power, distance to shore and the distance on shore to the nearest strong grid connection point, which can be up to 100 km away. A major advantage of AC is the low station cost. However, in AC transmission, losses rise with the voltage, the capacitance and the cable length. Beyond the so-called critical length (100 to 150 km depending on cable type) there will be no capacity left for active power transmission. The classical way to increase the transmission capacity is to increase the voltage level, but as reactive power increases with the square of the voltage, the voltage increase reduces the critical length.

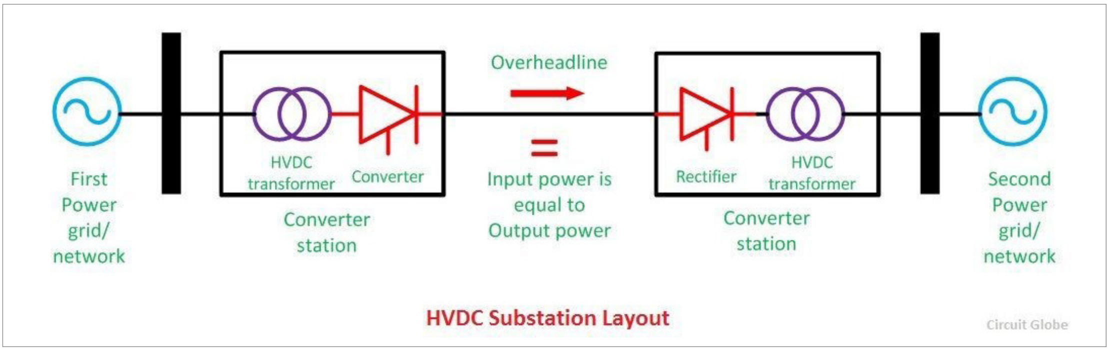
Two classes of HVDC systems exist, depending on the types of power-electronic devices used: 1) line-commutated converter HVDC (LCC-HVDC) using thyristors and 2) voltage-source converter HVDC (VSC-HVDC) using self-commutated devices, for example, insulated-gate bipolar transistors (IGTBTs). LCC-HVDC systems are capable of handling power up to 1 GW with high reliability. LCC consume reactive power from the AC grid and introduce low-order harmonics, which inevitably results in the requirement for auxiliary equipment, such as capacitator banks, AC filters, and static synchronous compensators. On the other hand, VSC-HVDC systems are independently able to regulate active and reactive power exchanged with the onshore grid and the offshore AC collection grid. The reduced efficiency and cost of converters can be identified as drawbacks of VSC-HVDC systems. Power levels (typically about 300-400 MW) and reliability are lower than those of LCC-HVDC are. HVDC is applied for distances greater than 100 km for offshore wind power transmission. Besides HVAC and HVDC, high-voltage low-frequency AC (LFAC) transmission has been recently proposed. In LFAC systems, an intermediate frequency level is used, which is created using a cyclo converter that lowers the grid frequency to a smaller value, typically to one-third its value. In general, the main advantage of the LFAC technology is the increase of power capacity and transmission distance for a given submarine cable compared to 50-Hz or 60-Hz HVAC. This leads to substantial cost savings due to the reduction in cabling requirements (i.e., less lines in parallel for a desired power level) and the use of normal AC breakers for protection (Jagannadh et al., 2018)[187].

Currently, 40 of the over 90 offshore wind farms in Europe have a nameplate capacity (intended full-load sustained output) higher than 200 megawatts (MW) and roughly one-third of these are connected to the grid by HVDC transmission, individually or in groups. So far, there are seven HVDC offshore wind connection systems in operation, and another three under construction. They are all located in the area of the North Sea known as German Bight and are operated by the transmission system operator TenneT Offshore (ABB, 2018)[188].

HVDC technology offers several advantages over the traditional AC technology, making it a promising and cheaper solution for future expansions of the grid or new interconnections. Some of the advantages of HVDC systems are lower power losses and costs in long distance power links (Shang &Liang, 2014)[189]; lesser number of electrical conductors with smaller diameters and lower weight are needed to transmit the same amount of power (Johannesson et al., 2009)[190]. This also includes capability of transmitting power over long distances with underground or undersea cables and capability of interconnecting asynchronous grids (Dambone Sessa et al., 2019)[191]. In addition, power flow controllability and flexibility of HVDC systems improves system stability during AC transients and allows efficient transmission of power from fluctuating and renewable power sources. Hence, HVDC transmissions will have a significant part in the power grid transition to a more sustainable and renewable source based generation (Keshri and Tiwari, 2018)[192]. Grid connection of remote offshore wind power plants, bulk power transmissions and interconnections between nations are some examples of its application, which will contribute to the power grid of the future.

However, HVDC grids, similar to high voltage alternating current (HVAC) grids, are not failure proof. Fault between conductors and ground can

Figure 18. HVDC Substation layout (Source: Circuit Globe, 2020)



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[187] P. Jagannadh, J.Vijaychandra, A. Kumar. “Transmission of AC Power from Offshore to Onshore by Using Low Frequency AC Transmission”. In *International Research Journal of Engineering and Technology (IRJET)*, Volume: 05 Issue 04, April 2018.

[188] ABB. “HVDC technology for offshore wind is maturing”. 24 October 2018.

[189] L.Shang, W.Liang (2014). “The review of high voltage DC transmission lines fault location”. In *International Journal for Computer, Consumer and Control (IJ3C)*, 3. pp. 21-28.

[190] K.Johannesson, A.Gustafsson, J.Karlstrand, and M.Jeroense (2009). “HVDC light cables for long distance grid connection”. In *European Offshore Wind Conference* (Stockholm).

[191] S. Dambone Sessa, A.Chiarelli, and R.Benato (2019). “Availability analysis of HVDC-VSC systems: a review”. In *Energies* 12: 2703,

[192] J.P.Keshri, H.Tiwari (2018). “Fault location methods in HVDC transmission system – a review”. In *Intelligent Computing Techniques for Smart Energy Systems* (Rajasthan; Springer Singapore).

happen. During fault conditions in an HVDC grid, two critical situations take place: the voltage drops sharply and the current increases rapidly to very high values, which is critical in grids with voltage source converters (VSC), the modern HVDC technology. Its power electron devices can withstand only twice its rated current (Baran and Mahajan, 2007)[193] and not the high fault-induced currents. If the fault is not cleared very fast, the VSC converter disconnects for self-protection. If this is the case, the entire HVDC grid can be lost with corresponding large blackout. Hence, very fast and reliable protection systems are needed in order to avoid damages in the components (Azazi et al., 2014)[194]. This way, a fault must be detected, located and declared in a very short range of time, which can be defined in the order of 10 ms according to the literature (Descloux et al., 2012)[195]. Hence, fast protection algorithms and HVDC circuit breakers (CBs) have to be developed and an appropriate fault-clearing strategy has to be adopted in order to minimize the impact of fault condition in both the DC and the AC systems.

At present, HVDC transmission systems are gaining relevance in long distance and renewable energy integration projects over the conventional AC transmission systems. It is mostly due to several advantages as improved flexibility and independent active and reactive power controllability. HVDC systems have many advantages over HVAC systems; therefore, this technology has received a lot of attention recently. For example, in comparison with HVAC, there is no radiation, induction, and dielectric losses. In addition, the lines of the HVDC systems produce low-intensity noise interference compared to HVAC transmission lines (Alassi et al., 2019)[196]. The HVDC systems allow a friendly integration of renewable energies, ensuring their stability and optimal operation. Therefore, they need advanced control and optimization methods to perform their optimal and proper operation. The control of the HVDC systems is carried out by managing the power electronic converter devices related to each energy resource, while the optimal operation of the HVDC systems is performed to obtain the best operation point. In general, to ensure a satisfactory operation of an electrical network, even with AC or DC technologies, it is mandatory to use different levels of control. They are to be entrusted with the stabilization of the grid and the possibility recovering the secure operation after large disturbance events. This is also relevant with regard to the possibility to maintain the grid in an optimal operation point under steady-state conditions.

5.2.2 HIGH VOLTAGE ALTERNATING CURRENT (HVAC)

Many transmission configurations and design topologies have been proposed for power transfer. HVAC transmission is one of the good solutions for transmission of offshore power at 50 or 60 Hz, if the distance is less than 50 km to shore. The traditional wind farms near to shore are built with HVAC transmission as considering the cost. The HVAC system consists of offshore wind farm, substation, AC submarine cable and onshore substation.

Although AC transmission is a well-known and trusted technology for control and protection, ease of connection, voltage transformation and circuit interruption, it is limited by the amount of reactive power required to energize the circuit – which is larger for underground (or undersea) cables than for overhead lines – making it expensive for high power and long distance. HVAC is more economical than the other topologies for small distances. However, the cables have considerable higher capacitance. As a result, the charging current is more in case of HVAC cables, which will cause heavy power loss. As the distance of transmission increases, the active power will be-

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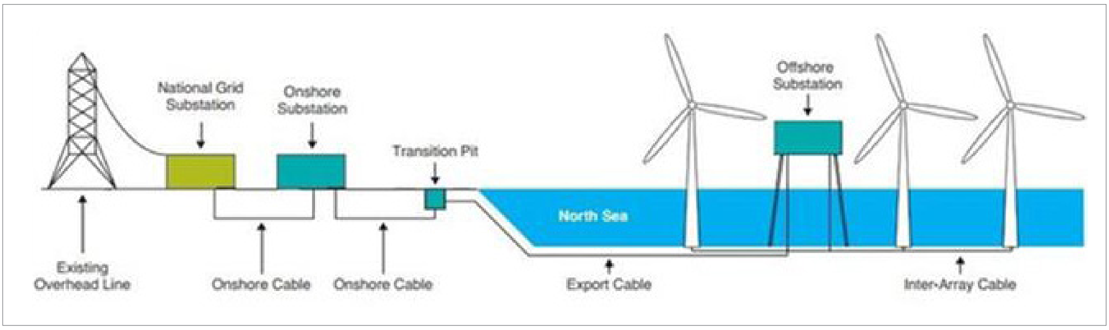
[193] M.E.Baran, N.R. Mahajan (2007) “Overcurrent protection on voltage-source-converter-based multiterminal DC distribution systems”. In *IEEE Transactions on Power Delivery*, 22, pp. 406-412.

[194] S.Azazi, M.Sanaye-Pasand, M.Abedini, and A.Hasani (2014). “A travelling-wave-based methodology for wide area fault location in multiterminal DC systems”. In *IEEE Transactions on Power Delivery*.

[195] J.Descloux, P.Rault, S.Nguefeu, J.Curis, X.Guillaud, F.Colas, and B. Raison (2012). “HVDC meshed grid: control and protection of a multi-terminal HVDC system”. In CIGRE Session, Paris.

[196] A.Alassi, S.Bañales, O.Ellaban, C.Adam, C.MacIver. “HVDC transmission: technology review market trends and future outlook”. In *Renewable and Sustainable Energy Review*, 2019, 112, pp. 530-554.

Figure 19. HVAC transmission system (Source: Windfair, 2015)



come zero. Beyond the 50 km distance, reactive power compensation is essential. Therefore, additional compensation equipment is required.

The trend of offshore installation is going deeper into a sea because of higher wind potential. For this HVAC is not a feasible option. For long distances and when the power levels are high, the HVDC transmission is a feasible option for integrating an offshore wind farm to grid.

5.2.3 DIODE RECTIFIER UNIT BASED HIGH VOLTAGE DIRECT CURRENT

High Voltage Direct Current (HVDC) is a beneficial technology for the transmission of large offshore wind power over long cables to the shore. However, the main drawback is the high converter cost. To reduce the cost related to offshore wind power integration, diode rectifier unit (DRU)-based HVDC systems have recently received notable interest. By replacing the VSC of an offshore station with a diode rectifier, in addition to the significant reduction of volume and weight, transmission losses and cost can be potentially reduced by up to 20% and 30%, respectively, and the transmission capacity can be increased by 33% (Seman et al., 2015)[197]. DRU-HVDC systems also have the advantages of high reliability, modular design, full encapsulation, and reduced operation and maintenance costs[198]. Siemens has proposed a so-called DRU to connect offshore wind farms to shore in a more cost-effective way (Siemens, 2015)[199]. The DRU solution could reduce the space, weight, operating expenditure as well as capital expenditure compared to current VSC-HVDC converter solutions. According to Siemens, the total expenditure will be decreased by 30% and transmission losses will be decreased by 20% when the DRU is used. The reason for lower losses are lower switching and conducting losses of diodes compared to insulated-gate bipolar transistor (IGBTs) due to a lower on state voltage and switching frequency. According to Siemens, the DRU is able to transmit 1.2 GW of power from OWF that are located more than 160 km away from shore. The set up would look as follows: diode rectifiers would do the offshore conversion from AC to DC and the onshore conversion to DC would be performed by VSCs. For connecting and operating an existing wind farm with an HVDC link, that uses DRUs.

Since the DRU is effectively a passive device with no controllability, the OWF AC system must be regulated and controlled by the wind turbines (WTs). Voltage and frequency control of an offshore network by WTs connected to a DRU-HVDC system was proposed by Blasco-Gimenez et al. in 2010.[200] It proves that such a solution is technically feasible in steady states and during various transcients. The developed control scheme was further tested and validated during three-phase faults at the onshore HVDC converter AC terminals. However, the proposed control

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[197] S.Seman, R.Zurowski, and C.Taratoris. “Interconnection of advanced Type 4 WTGs with Diode rectifier based HVDC solution and weak AC grids”. In *Proceedings of the 14th Wind Integration Workshop*, Brussels, Belgium, 20th-22 October 2015.

[198] Ibid, 2015.

[199] Siemens AG. “Siemens revolutioniert Netzanschluss von Offshore-Windkraftwerken”. In *Neunte Maritime Konferenz* 2015.

[200] R.Blasco-Gimenez, S.A. Villalba, J.Rodriguez-D'Derlée, F.Morant, and S.Bernal-Perez (2010). “Distributed Voltage and Frequency Control of Offshore Wind Farms Connected With a Diode-Based HVDC link”. In *IEEE Transactions on Power Electronics*, vol. 25, pp. 3095-3105.

requires measurements at the point of common connection (PCC) for each wind turbine, necessitating the need for high-speed communication. The DRU-HVDC system is robust against various faults, and it can automatically restore power transmission after fault isolation. Simulation results confirm the system performance under various fault conditions.

5.3 TRANSMISSION CABLE TECHNOLOGIES

So far, lapped cables (high-density paper tapes, impregnated with a high-viscosity compound) have proven suitable for voltages of up to 700 kV DC (in their paper-polypropylene laminated (PPL) taped version) without requiring fluid pressure feedings, thus allowing these cables to be installed in HVDC links in very long lengths, up to several hundreds of kilometers. However, where system requirements permit, the use of an extruded insulation offers several remarkable advantages, such as lighter, easier-to-handle cables, which can operate at high temperatures and at high electrical stresses. Due to recent technology improvement, extruded cables are presently adopted for voltages up to 600 kV DC (Prysmian Group, 2021)[201].

5.3.1 XLPE INSULATION TECHNOLOGY

The basis of this technology is polyethylene that requires a cross-linking process, which is essential for stabilizing the insulation material. Cross-linked polyethylene (PEX or XLPE) has been around for quite some time. The first cross-linking methods emerged in the 1930s and practices have continued to evolve since, with other processes being developed throughout the years. Cross-linking is a very intricate process. XLPE raw material powder is formed and processed into sturdy, durable products, usually formed into cylindrical shapes that can be used for long tubing. The tubing can act as a strong, long-lasting insulator to various wires and cables, protecting it from all sorts of external elements. During the process, a number of by-products are created (such as methane, cumyl alcohol, acetophenone, etc.). These by-products should be removed after the cross-linking with a specific thermal treatment process, known as "degrassing". This operation decreases the amount of residual by-products present in the cable. Electrical and thermomechanical working performance should be selected accordingly to guarantee reliable system operations at the increasing voltage levels.

Recently developed XLPE material present higher cleanliness and lower electrical conductivity, allowing for an increase of the maximum allowable electrical stresses in the insulation (if compared to the previous XLPE materials). As a result, it is possible to reach cable voltage levels up to 600 kV, while reducing thicknesses at standard voltages with lighter and less expensive cables.

When high DC voltage is applied to an insulating layer, a leakage current will flow through it, producing heat and rising the insulation temperature. This increases the insulation electrical conductivity, allowing for more current to flow and thus generating more heat, leading to thermal runaway and ultimately to electrical breakdown. It is therefeore necessary to mitigate the risk of thermal runaway due to heat generation inside the insulation. The next-generation XLPE material for HVDC cable insulation systems requires an optimized composition with low DC conductivity, limitation of space charges effects and high electrical breakdown strength.

XLPE cleanliness is of utmost importance in achieving good DC conductivity. One key aspect was the reduction of peroxide content to decrease the quantity of residual by-products. Peroxide is normally added to the insulation base material at high temperature and pressure right after the extrusion. The new XLPE material also produces an electrical conductivity that is less dependent on temperature and electric stress, meaning that the conductivity is more stable between cold and hot conditions. The electrical field in the insulation also varies less between different cable operating conditions.

5.3.2 P-LASER CABLE TECHNOLOGY

This technology is based on High-Performance Thermoplastic Elastomer (HTPE) insulation,

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[201] Prysmian Group (2021). "Extruded Cables for HVDC Power Transmission". Milan, Italy.

which, compared to Cross-Linked Polyethylene (XLPE)-based, neither have cross-linking process nor require the time-consuming degassing process. A further advantage is that the material itself is fully recyclable, which will become mostly relevant for the decommissioning stage of old HVDC links.

Moreover, it is important to highlight that the P-Laser technology is fully compatible with existing cable accessories and can be integrated in networks using different insulation technologies. In comparison with the traditional XLPE-based insulation counterparts, P-Laser technology ensures improved electrical characteristics in HVDC cable systems, more efficient cable manufacturing and lower environmental impact.

Electrical performance of HVDC cables depends on electrical resistivity of the insulation, which is a function of temperature, electrical field intensity and space charges distribution. The presence of space charges can significantly affect the electrical properties of the cable insulation system, limiting the possibility of having stable and therefore reliable performance of the insulation at the highest voltage levels (which are increasingly required in the market).

HPTE technology does not require chemical reactions to achieve the properties needed for long-term electrical integrity of HVDC insulation systems. It is also suitable for very fine filtration during the insulation phase, just upstream of the extrusion crosshead. This feature helps avoid by-products, making this the most simple and effective solution against the well-known problem of space charge traps created by the by-products themselves, as provided by P-Laser performance under high electrical gradient at high temperature.

Due to the thermoplasticity of HPTE material, the ambers generated by scorch are also completely absent, with advantages for cable reliability and for practical aspects. It is in fact, possible to carry out a very long production campaign and with a very high level of filtration, without the risk of affecting cable quality.

5.4 CHALLENGES IN OFFSHORE WIND POWER PLANTS

The aspect of power quality cannot be undermined, as a single wind turbine can contribute up to 10 megawatt of power into the grid and it is used as a standalone distributed generation. In offshore wind power plants, due to intermittent nature of wind, various power quality fluctuations in voltage and frequency, and circulation of harmonics that ultimately effect the system stability can take place. This section addresses these challenges, which need to be taken into consideration for continuous supply of stable energy to the customer.

5.4.1 POWER QUALITY ISSUES

During the last decade, there has been an increasing focus on power quality (PQ). The interest and demand for quality assurance of electrical power has several fundamental causes. Firstly, large amounts can be saved by permanently keeping track of the quality of power from the electrical grid or network. Based on the analysis from the measurements, a cost effective maintenance or upgrading of transmission and distribution assets is possible. A second reason for the increased focus on power quality is the deregulation of the electrical power market.

Power quality disturbances at offshore wind power plant are regularly monitored to check whether, output complies with the permitted grid regulations. It is worth mentioning that power quality issues include flickers, voltage sags/swell, harmonics, transcients as well as voltage and frequency fluctuations. Table below shows some power quality issues with respect to severity to the grid (Hossain et al., 2018)[202].

Flickers can be defined as fast variation in supplied voltage that may last for a certain period so that variation in electric light can be recognized visually. The voltage drop is generated over the source impedance of the grid by the changing load current of an equipment or facility. The International Electrotechnical Commission's (IEC) standard 61400-21 establishes codes for defining

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[202] E. Hossain, M.R.Tur, S. Padmanaban, S. Ay, and I. Khan "Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices". In *IEEE Access*, vol 6, pp. 16816-16833, March 2018.

Figure 20. Power Quality Issues in Power System (Source: Hossain et al., 2018)

PQ Issue	Construction phase	Outcome	Affect
Flicker	Supply Voltage variation	Equipment damage or malfunction	Moderate
Harmonic	Nonlinear loads, cable, Transformer	Power loss, overheating of load	Moderate
Voltage Sag	Sudden switching, inrush current, poor wiring	Overloading issue, Grabbed signal	Moderate
Voltage Swell	Heavy loads on/off, fault at supply side	Equipment damage, data loss, overheating	Mild
Transient	Lightning, snubber circuits	Efficiency loss, disturbance in equipment	Severe
Frequency Instability	High loading	Motors and sensitive load malfunction	Mild

PQ requirements of wind generation. A portion of the mentioned standard makes use of the time domain readings of current and voltage taken at terminals of the wind turbine to measure flickers due to the switching action. A wind turbine produces more flickers in weak grids because of inverse relationship of flickers emission and short-circuit capacity. Another important factor to affect flickers level is grid impedance angle. Flickers emission reduction can be achieved by maintaining 90 degrees angle difference between grid impedance angle and turbine power factor. Variable speed turbines have the ability to manage reactive power; flickers can be alleviated by regulating this reactive power (Ahmed & Zobaa, 2016)[203].

In an offshore wind power plant penetrated grid system, the voltage source inverter stimulates some harmonics, while the others harmonics are from grid background, which are reflected back to the turbine farm terminals, and therefore at the point of common coupling (PCC). In an electric power system, a harmonic of a voltage or current waveform is a sinusoidal wave whose frequency is an integer multiple of the fundamental frequency. Harmonic frequencies are produced by the action of non-linear loads such as rectifiers, discharge lighting, or saturated electric machines. Harmonics problem have been a significant issue in three-phase power systems and it is increasing due to the growth of the modern technology, which converts the old bulky power system loads into small size power electronic loads. In addition, the large capacitance in the form of subsea cables and compensating capacitor banks resonant frequencies influences the frequencies of the system. These resonances result in the amplification of the harmonic emission in two ways. Firstly from individual turbines into the power grid i.e. primary emissions and secondly, flow of harmonic currents from the grid into the wind park termed as secondary emission.

In addition to harmonics, offshore wind power plant could also cause supraharmonics (SP), i.e. distortion in the frequency range above 2 kHz. The magnitude of SP at the point of common coupling (PCC) is usually lower than regular harmonics (3rd, 5th, 7th). However, lack of standard limits to quantify the effects of these high frequency emissions in offshore wind power plant is the area that needs to be investigated.

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[203] I.A.Ahmed and A.F.Zobaa. "Comparative Power Quality Study of Variable Speed Wind Turbines". In *International Journal of Power and Energy Conversion (IJPEC)*, vol 4, no 4, p. 97, July 2016.

Voltage sags and interruptions are related power quality problems. They are the result of faults in the power system and switching actions to isolate the faulted sections. A voltage sag can be caused by a short circuit, overload, or starting of electric motors. The magnitude and duration of voltage sags are frequently used to define them. A voltage sag happens when the root mean square voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle to one minute.

5.3.2 STABILITY ISSUES

The fast-growing penetration of offshore wind farms poses a challenge to the voltage stability of the power systems. Voltage stability refers to the ability to maintain steady voltages at all buses in a power system after being subjected to a disturbance. When the penetration of offshore wind farms significantly increases, large voltage drops may occur suddenly, which has a significant impact on the balance of real and reactive powers in power system. Large oscillation of real and reactive powers may force the voltage to vary beyond the boundary of stability. Thus, maintaining voltage stability in case of large-scale offshore wind farm is challenging. The operation of offshore wind farms is required to have the capability of voltage support at the point of common coupling.

Stability issue in offshore wind farm power plants is mostly caused, either by any uncertainty occurring at wind turbine side, or a fault/disturbance at the grid side. With an increasing number of wind farms connected, controlling dynamic characteristics of overall power systems is becoming some challenges. A related phenomenon of sub-synchronous resonance (SSR) has gained attention in recent years. It has been reported to cause oscillations below system's rates frequency in grid connected wind farm system in vicinity of series compensated transmission line (Buchhagen et al., 2016)[204]. To investigate this issue, an independence-based stability analysis is usually adopted which makes use of ratios of analytically derived impedances of offshore wind power plant and line converters looking from the Point of Common Coupling (PCC)[205] side.

Stability of the power system is the system's ability to stay in a state of operating equilibrium under the normal operating condition and recover an acceptable state of equilibrium subject to disturbance. The ability of the power system to maintain synchronism under small disturbance is small signal stability (SSS), a class of power system stability. The small signal stability refers to how a system behaves whenever a minor change occurs in its state variables. This stability issue generally happens due to lack of damping torque, which leads to increase the amplitude of rotor oscillations. Any variation in the operating conditions of the power system can be analyzed through eigenvalues of the system state matrix (Kundur, 1994)[206].

The ability of a synchronous power system to return to stable condition and maintain its synchronism following a relatively large disturbance arising from very general situations like switching on and off of circuit elements, or clearing of faults, is referred to as transient stability in power system. Severe disturbances may contain component outages, reduced inertia, load variations or faults that cause large excursions of generator's rotor angle. The response of the system is affected by the nonlinear power-angle relationship. The interval of interest while observing transient stability is generally 3 to 5 seconds following the disturbance. This time period can extend up to 10-20 seconds in case of large system with prevailing inter-area fluctuations. A study presented in Hui et al (2019)[207] applies efficient feedback control scheme by utilizing mechanical power as well as DC channel power of the system as control objective to enhance the transient stability of the interconnected wind farm system.

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[204] C.Buchhagen, C.Rauscher, A.Menze, and J.Jung (2016). "BorWin1 – First Experiences with harmonic interactions in converter dominated grids".

[205] PCC is a common interconnection point for different customers connected to the same utility power supply. If current harmonic injections by customer loads are not limited, the power quality at the PCC will be affected.

[206] P.Kundur (1994). "Power System Stability and control – Prabha Kundur – McGraw Hill Education".

[207] Q.Hui, J.Yang, X.Yang, Z.Chen, Y.li, and Y.Teng. "A robust control strategy to improve transient stability for AC-DC interconnected power system with wind farms". In CSEE Journal of Power and Energy Systems, June 2019.

5.3.3 VOLTAGE AND FREQUENCY ISSUES

In an electrical power system, the reactive power flow is related to the voltage variation, while the frequency change corresponds to a change in the active power in the system. In an offshore wind power plant, electromechanical devices that are usually used to generate the electricity are the induction generators, which require reactive power for excitation. Therefore, DFIG based wind farm are of lesser help for supporting the grid with reactive power when compared to synchronous machines (Howlader et al., 2016)[208].

With increasing level of offshore wind energy penetrations into the grid, voltage stability is becoming a challenge. PMSG based wind turbines are able to manage reactive power in case of voltage deviation at the PCC. Nevertheless, for induction based wind generators it is not the case as they accelerate during disturbances/faults, which require reactive power consumption. Voltage control of a wind farm need to be designed in such a way that demand of reactive power output to be met is in accordance with the dispatch instructions from grid side to support the voltage of PCC. In this regard, voltage and reactive power control must meet the requirements below:

- Voltage at Point of Common Coupling should be maintained ranging from 97% to 105% of the nominal voltage at grid side;
- Its speed of regulation and control accuracy should meet the demand of voltage control of grid operation.

A frequency higher than the rated frequency usually improves the power factor but decreases locked-rotor torque and increases the speed and friction and windage loss. At a frequency lower than the rated frequency, the speed is decreased, locked-rotor torque is increased, and power factor is decreased. Offshore wind energy penetration in the grid proportionally increases the unpredictability and frequency variation of the power output. The operating conditions change due to these deviations in frequency, because it alters the frequency related parameters like reactance and the slip of the wind turbines. The intermediate DC voltage in this AC-DC-AC interface creates electrical decoupling between offshore wind farm and the grid. Consequently, the system inertia reduces, as the generator rotor does not see the changes in frequency. Additionally, the interconnected conventional power units are overburdened to regulate the frequency variations. This phenomenon deteriorates frequency and inertia regulation, especially in islanded systems with no grid support.

In European power grids, frequency regulation is maintained within limits using three-way control strategy. In case of any deviation, primary control keeps the balance between power generation and consumption. Secondary control triggers automatically when there is active power deficit on the line. This stage lasts for about 15 minutes, and if the frequency deviation persists, tertiary control comes online. It mitigates the persistent frequency deviations after the production outages or long-lasting load variations. Time control makes sure that discrepancy between synchronous time and universal coordinated time of the system must be avoided, which happens due to frequency deviation (Wu et al., 2018)[209].

CHAPTER 6 - ENERGY STORAGE AND SMART GRIDS AS ENABLERS OF ENERGY TRANSITION

Energy storage has long been used for a variety of purposes, including supporting the overall reliability of the electricity grid, to help defer or avoid investments in other infrastructure, and to provide backup energy during power outages. Storage technologies can capture energy during periods when demand or costs are low, or when electricity supply exceeds demand, and can surrender stored energy when demand or energy costs are high. Energy storage technology is a vital part of smart grid, and it can be utilized for grid-connection of renewable energy. Therefore, it is a dominant factor in the integration of renewable sources, playing a significant role in

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[208] A.M.Howlader and T.Senjyu. "A comprehensive review of low voltage ride through capability strategies for the wind energy conversion systems". In *Renewable and Sustainable Energy Reviews*, vol 56, pp. 643-658, April 1, 2016.

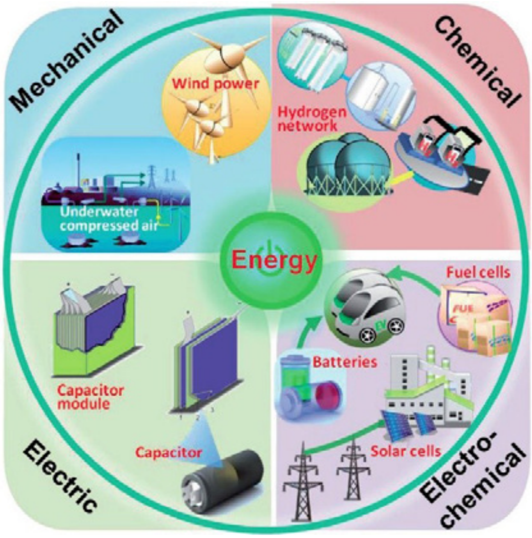
[209] Z.Wu et al. "State of the art review on frequency response of wind power plants in power systems". In *Journal of Modern Power Systems & Clean Energy*, vol 6, no 1, January 2018.

maintaining a reliable electricity system. Many studies suggest that deep penetration of renewables is not viable without energy storage systems, due to challenges such as intermittency of renewable sources, required flexibility in electricity supply, and power quality issues (Ueckerdt et al., 2015)[210]. The need for storage is particularly acute in densely populated northern Europe, where many countries are building offshore turbines to harness the winds blowing across the North Sea. The capacity factor of current offshore wind turbines without energy storage is very low, typically less than 50 % (Assis et al., 2015)[211].

Many types of electricity storage exist, all of which have common characteristic feature that they convert electricity into stored energy in some medium through a conversion device, and then, either through the same device or another, convert that stored energy back into electricity, while losing some in the round trip due to dissipative processes (Figure 21). Depending on its characteristics, there are various uses and applications for energy storage technologies. The applications for energy storage vary based on time scale. Shorter duration devices, like flywheels and supercapacitors are better suited to provide black start services, power quality, and operating reserves to the grid. Longer duration technologies, like hydrogen fuel cells and pumped hydro storage are more suited to power fleet optimization and intermittent balancing. Pumped storage is by far the largest-capacity form of grid energy storage available. As of 2020, the USA Department of Energy Global Energy Storage Database reports that pumped-storage hydroelectricity accounts for around 95% of all active tracked storage installations worldwide, with a total installed capacity of over 181 gigawatts. The main disadvantage of this storage technology is the specialized nature of the site required, needing both geographical height and water availability.

Fuels of different sorts such as hydrogen, ammonia, and bio-ethanol deliver very attractive options for long-duration storage where energy may be stored for years and discharge over periods of months. Hydrogen can fulfill the role of energy storage and even act as an energy carrier, since it has a much higher energetic density than batteries and can be easily stored. Considering that the offshore wind sector is facing significant growth and technical advances, hydrogen has the potential to be combined with offshore wind energy to help in overcoming disadvantages such as high installation cost of electrical transmission systems and transmission losses.

Figure 21. Classification of different types of energy storage technologies



Source: Adapted from review article "Flexible Graphene-, Graphene-Oxide-, and Carbon-Nanotube-Based Supercapacitors and Batteries" by R.Zhang, A.Palumbo, J.C. Kim, and E.H. Yang (2019).

Many technologies can be applied for the production of fuels and chemicals from carbon dioxide (CO_2) and hydrogen (H_2), such as synthetic natural gas, Fischer Tropsch (FT) products[212], methanol, or even polymers and specialty chemicals. The process of converting the power generated from solar and wind sources to different types of energy carriers for use across multiple sectors, or

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[210] F.Ueckerdt, R.Brecha, and G. Luderer. 'Analyzing major challenges of wind and solar variability in power systems". In *Renewable Energy*, volume 81, pp. 1-10, 2015.

[211] Assis, A., Jaison, P.P, Joseph, A.E (2015). "Energy storage system for floating wind turbines".

[212] Fischer-Tropsch (FT) is a well-known technology for production of gas, liquid, and solid hydrocarbons from synthesis gas, also named syngas. It contains a mixture of H_2 and CO, and usually some CO_2.

to be reconverted back into power, has the potential to increase the flexibility of the power grid. It builds an optional place to put the temporary surplus of power from renewable sources and reduces carbon by displacing fossil fuel energy sources in other sectors. Power-to-X is based on converting power (electricity) to diverse substances, for example power-to-heat, power-to-liquid or power-to-gas to enlist some of them. Several authors have already analyzed these technologies combined with the wind resource. For example, the main applications of power-to-gas has been proved in Denmark to be successful tool to complement wind power plants (Hou et al., 2017)[213]. However, both investment costs of facilities and energy losses (due to the low efficiency in the conversion process) are high. Hence, the hydrogen produced from wind power also has a high cost. Consequently, future works should be focused on reducing investment and maintenance costs for such power conversion solutions.

Piloting power-to-X technologies is gaining ground and even reaching an industrial scale, the Audi methanisation plant[214], the Carbon Recycling International methanol synthesis plant (alkaline electrolysis, geothermal steam emission CO_2, and methanol synthesis)[215], and the Sunfire Power-to-Liquids plant (solid oxide electrolysis, Direct Air Capture of Carbon Dioxide, and Fischer-Tropsch synthesis planned) being examples of this trend[216]. Direct air capture of carbon dioxide (DAC) is a technology for collecting CO_2 from ambient air, where the concentration of CO_2 is orders of magnitude lower than that of point sources such as flue gas and other industrial emissions. DAC uses a medium (solid or liquid) that has an affinity to CO_2. The medium is a base, which forms covalent bond with the partially acidic C atom of CO_2 (Murphy et al., 2015)[217].

The main issues of the Power-to-Gas (PtG) concept are related with high investment costs, low technology readiness, and significant transport and storage problems of the hydrogen itself. In practice, the low energy density of gaseous hydrogen requires high pressure to keep a reasonable tank size, or alternative storage solutions (e.g. liquefaction, hydrides). Among these, a transition strategy proposed to overcome the technical difficulties of hydrogen storage and the absence of a dedicated delivery network is the admixing of hydrogen in the natural gas infrastructure (up to 20% volume). The natural gas enriched with hydrogen can then be used by engines, or separated for uses in pure form in the chemical sector and in the electrochemical devices, contributing to the abovementioned sector coupling and fostering decarbonisation. Despite these critical aspects, hydrogen solutions remain relevant because of the possibility of decoupling power and energy capacity in the storage phase, the scalability, and the full decarbonisation achieved with this energy vector. Consequently, a strong development is foreseen in the next years, in particular in sectors in which electrification is not an efficient or feasible solution. Numerous demonstration and laboratory PtG projects have been developed in the last years. As of 2019, 56 PtG hydrogen projects were in operation for a total capacity of 24.1 megawatts, out of which 21 were injection of the product into a natural gas grid. Most of the projects are located in Central Europe; in particular, Germany, Denmark, and the Netherlands, but there are also projects in Italy, Spain, United Kingdom, and the United States of America (Crespi et al., 2021)[218].

There are four major chemical storage technologies in the form of ammonia, hydrogen, synthetic natural gas, and methanol. Currently, the most

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[213] P.Hou, P.Enevoldsen, J.Eichman, W.Hu, M.Z.Jacobson, Z.Chen. "Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark". In Power Sources, 2017, 359, 186-197.

[214] The process involves synthetic natural gas production using alkaline water electrolysis and methanisation of raw biogas. See also Audi Media Center, (accessed 23 April 2021), https://www.audi-mediacenter.com/de/brennstoffzelle-audi-b-tron-242

[215] CRI, World's Largest CO_2 Methanol Plant for the Production of Blue Crude Planned in Norway, (2017), (accessed 23 April 2021), http://carbonrecycling/is/george-olah/

[216] Sunfire, First Commercial Plant for the Production of Blue Crude Planned in Norway, (2017) (accessed 23.04.2021), https://www.sunfire.de/en/company/press/detail/first-commercial-plant-for-theproduction-of-blue-crude-planned-in-norway

[217] Murphy, L.J.; Robertson, K.N; Kemp, R.A; Tuononen, H.M.; Clyburne, J.A.C. "Structurally simple complexes of CO_2". In *Chemical Communities*, 51, (2015), 3942-3956

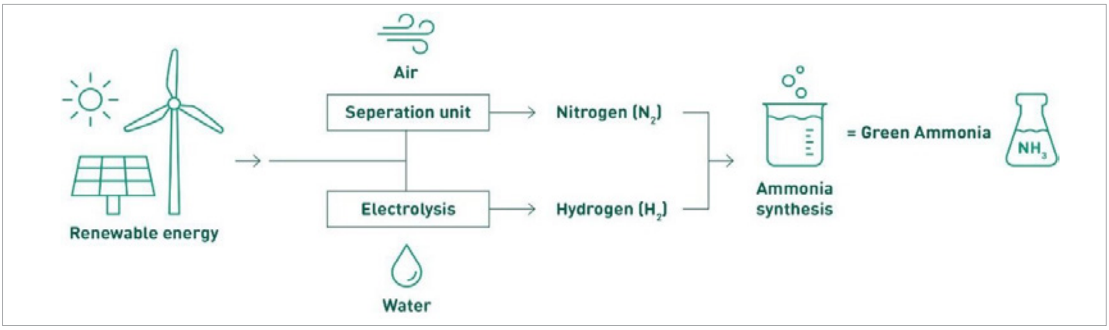
[218] E.Crespi, L.Mammoliti, P. Colbertaldo, P. Silva, and G.Guandalini. "Sizing and operation of energy storage by Power-to-Gas and Underwater Compressed Air systems applied to offshore wind power generation". E3S Web of Conferences 312, 01007 (2021), 76th Italian National Congress ATI.

promising solution for large-scale energy storage is chemical storage, which is possible by generating hydrogen (H_2), ammonia (NH_3) or carbon-based synthetic fuels (though other options also exist). Synthetic or carbon-neutral fuels capture CO_2 in the manufacturing process. In this way, this greenhouse gas becomes a raw material, from which gasoline, diesel, and substitute natural gas can be produced with the help of electricity from renewable sources. The electricity demand for the production of these fuels increases from H_2 and NH_3 to carbon-based gases and liquid fuels. An additional advantage of such synthetic fuels is the relative ease of adapting existing and proven technologies for their transport, storage and use. Nevertheless, all alternative fuels are currently significantly more expensive than fossil energy. This remains the major economical obstacle for implementing non-fossil carbon neutral and carbon free technologies (Lauf & Zimmermann, 2021)[219].

The use of ammonia and hydrogen as fuel or energy storage has been attracting a lot of attention in recent years. Hydrogen has great potential, however, issues associated with hydrogen storage and distribution are currently impeding factors for its implementation. On the contrary, the infrastructure and distribution systems currently in place are far more compatible with ammonia. Additionally, from the point of view of physical properties, ammonia can be easily liquefied at room temperature at about 10 bar or at -33 degrees of Celsius under ambient pressure, which is similar in properties to LNG thus offering easy transportation or storage in the liquid phase. Overall, ammonia seems a very promising energy storage medium and carrier, but most of the ammonia produced globally is used for fertilizers.

The production of ammonia (NH_3) via the Haber-Bosch process requires H_2 and N_2. Industrial ammonia production plants may use compressed ambient air (78% N_2 content) or for generating high purity N_2 via air separation technology. For H_2 as source material several options are available: (1) typically produced by steam reforming of fossil fuels at Haber-Bosch plants, releasing huge amounts of CO_2. However, only when the NH_3 is further processed into urea, the CO_2 is used in the production process. (2) H_2 production from the electrolysis of water is currently used in countries with large amounts of cheap electricity. However, both production pathways mentioned above are very cost intensive. (3) The usage of waste H_2 from industrial chemical production seems to be very promising option as well. In the Netherlands, waste from H_2 from a "Dow Benelux" has no usage for the waste H_2. Dow Benelux outlined its plants to reduce current CO_2 emissions from its Terneuzen, the Netherlands, on its path to achieve net-zero emissions by 2050. The hydrogen would be used as a clean fuel in the production process. The CO_2 would be captured and stored until alternative technologies develop (Moares, 2021)[220] .

Figure 22. Ammonia-based energy storage system



Source: Adapted from Refining & Petrochemicals, 2021

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[219] Dr J. Lauf, Dr R.Zimmermann. "Connecting production facilities and transport infrastructure for creating robust and carbon-neutral sector-integrated energy systems". NATO Energy Security Center of Excellence, December 2021.

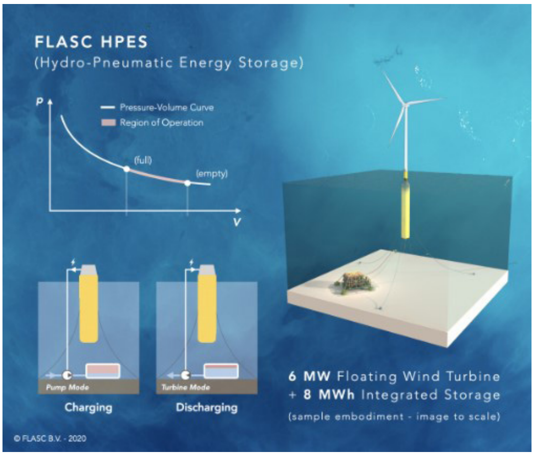
[220] R.Moares. "Dow Benelux to Build Green Hydrogen Plant in the Netherlands". In *Industry Europe*, 01 July 2021.

The ammonia produced by utilizing renewables via the Haber-Bosch process could help reduce above vast emissions in the ammonia industry. Green ammonia has very good energy storage properties to solve the problem of electricity storage for renewable energy plants, like wind farms and photovoltaic solar systems. Ammonia can be produced at these sites to mitigate this issue by utilizing excess renewable energy.

Most of the efforts in advancing the research on the use of green ammonia for energy storage is concentrated in Europe, with notable projects in countries like Australia, the USA, and Japan. In 2020, Siemens launched its green ammonia energy storage demonstrator in the UK. The demonstrator uses renewable power to make ammonia, a compound traditionally used to boost crop fields, by combining hydrogen, extracted from water and nitrogen from air. The ammonia is stored in a tank and converted back into electricity when either needed, through traditional combustion methods or by “cracking” it into nitrogen and hydrogen. In the latter method, the hydrogen can then be used in hydrogen fuel cells to power devices such as electric vehicles (Power Technology, 2020)[221].

In the offshore segment, batteries are not very suitable for this task due to safety and reliability issues. There are other offshore energy storage systems under development, but these typically rely on the external hydrostatic pressure. Consequently, these storage systems tend to be more viable in deep waters below 500 meters. The start-up FLASC has developed Hydro-Pneumatic Energy Storage (HPES) technology that can be co-located with fixed-bottom and upcoming floating wind farms (Figure 23). The patented technology comprises a closed dual-chamber system containing a pre-charged gas, which can be compressed air or nitrogen. It can be integrated with a variety of embodiments: from completely subsea designs, to integration in a monopile, or even within a wind turbine floater.

Figure 23. Adapted from FLASC Hydro-Pneumatic Energy Storage, 2020



The massive integration of variable renewable energy in modern power systems is imposing several challenges; one of them is the increased need for balancing services. Coping with the high variability of the future generation mix with the incredible high share of renewable energy, the power system requires developing and enabling sources of flexibility. To a certain extent, the grid can manage the variability of renewable energy itself. In order to make renewable energy more competitive and integrate even more renewables to the grid, it is necessary to find new, smart solutions for energy storage to provide firm power. For example, the Danish company Ørsted has been exploring the possibility of combining offshore wind farms and battery storage. It added storage to its Burbo Bank scheme in the United Kingdom to stabilize the wind farm’s delivery frequency to the grid in what was believed to be the first use of storage and offshore wind (Ørsted, 2019)[222]. For these reasons, storage solutions are becoming an important cornerstone in the energy system with rapid progress in new technological solutions, (for example batteries and hydrogen) and an increasing share of variable renewable power.

Flexibility in terms of generation and storage is going to be crucial in years to come and so far, in terms of storage, batteries have dominated the market. Recently, energy companies have start-

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[221] “Could Ammonia be the next key player in energy storage?” In *Power Technology*, February 6, 2020.

[222] “Ørsted’s first stand-alone battery storage project now complete”. Press release, 02 January 2019.

ed to look closely at the role of hydrogen electrolysis units can play by converting the surplus generation or indeed the day-to-day generation into green hydrogen, which can either be used for transport, heat or gas and industrial fuel or can later be converted back into electricity when required. There are several ways to commercialize renewable hydrogen generation into the energy system. For example, the surplus of electricity produced by offshore wind farms can be stored as hydrogen, and later to generate power in fuel cells or as fuel in hydrogen vehicles.

6.1 THE CONTEXT FOR OFFSHORE WIND TO HYDROGEN IN EUROPE

Producing hydrogen from offshore wind at an energy island[223], platform or even inside the turbine itself, and then sending it by ship or a pipeline to onshore industrial clusters used for clean fuels and chemicals, could be a market game-changer for offshore wind in the future. The ability to produce green hydrogen offshore independently of the power system and export gas rather than electricity, removes the need for building electrical infrastructure that can add complexity and increase cost of wind energy projects. Offshore wind and green hydrogen are uniquely suited technologies that could combine to play a massive role in the global energy transition, but must move quickly to achieve scale, technical reliability and price-competitiveness to achieve their joint potential. There is still a way to reach cost levels, which can compete with grey hydrogen including emission costs (i.e carbon pricing).

Offshore wind energy is seen as a natural transition for many oil and gas companies that have long experience in offshore engineering. To replace the existing 70 million tons of grey hydrogen produced each year – mainly used for oil refining, ammonia fertilizer production and as a chemicals feedstock – with green H_2 would require almost 900 gigawatts of dedicated offshore wind projects. The expertise in gaseous fuels and large-scale offshore deployment of the world's oil and gas big companies has a key addition to the project experience built up by power utility majors. Some of the European major energy firms, such as Equinor and Shell, have followed this pathway for several years. However, other European major oil companies have recently adopted radical shifts in strategic direction that will transform them over the coming decades. It is all about change from big oil to big energy company and expansion in renewable power. For example, British Petroleum (BP) plans to take its first steps into the growing market for green hydrogen alongside the offshore wind company Ørsted by developing a hydrogen project at one of its refineries in Germany. The refinery will host an industrial-scale electrolyzer with an initial capacity of 50 megawatts, which is capable of producing enough of the green gas to replace a fifth of the refinery's existing hydrogen demand, which relies on fossil fuels (BP, 2020)[224].

In 2020, BP, TotalEnergies, Shell, and Eni acquired 5.4 gigawatts of offshore wind capacity; and in 2021, correspondingly 4.5 gigawatts out of 7.98 GW of capacity auctioned during the UK Crown Estate Round 4 leasing auction. Consortiums that included either BP or TotalEnergies won it (The Crown Estate, 2021)[225]. The interests of these large and influential energy majors are a key driver behind the European interest in hydrogen and, in particular, the interest in the combination of offshore wind and hydrogen.

Hydrogen can be produced from a variety of processes associated with a wide range of emissions depending on the technology and energy source used (European Commission, 2020)[226]. Renewable hydrogen (or green hydrogen) is produced through electrolysis using renewable energy sources and it is a near-zero carbon production

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[223] The world's first energy islands will be constructed in Denmark. The plan envisages the establishment of an artificial island in the North Sea that will serve as a hub for offshore wind farms supplying 3 GW of energy, with long-term expansion potential of 10 GW. The energy island in the Baltic Sea will be Bornholm, where electrotechnical facilities on the island will serve as hub for offshore wind farms off coast supplying 2 GW of energy.

[224] "BP and Ørsted to create renewable hydrogen partnership in Germany". BP press release, 10 November 2020.

[225] "Offshore Wind Leasing Round 4 signals major vote of confidence in the UK's green economy". The Crown Estate, February 8, 2021, https://www.thecrownestate.co.uk/en-gb/media-and-insights/news/2021-offshore-wind-leasing-round-4-signals-major-vote-of-confidence-in-the-uk-s-green-economy, (accessed August 23, 2021).

[226] European Commission. Questions and answers: A Hydrogen Strategy for a climate neutral Europe. Press Corner 2020, https://ec.europa.eu/commission/presscorner/detail/en/QANDA_20_1257

route (IRENA, 2020)[227] with its cost 5.09 EUR per kilogram in 2020 (Hydrogen Council, 2020)[228]. The hydrogen production is currently largely dominated by the reforming of methane, which converts methane in hydrogen by the so-called Steam Methane Reforming (SMR)[229]. This technology produces low-cost hydrogen, although with considerable emissions (approximately 10 kg CO_2/kg H_2). Fossil-based hydrogen with carbon capture and storage (CCS) will be an additional option when the technology scales and reaches market maturity (also called as blue hydrogen). However, such hydrogen is not necessarily carbon emissions free. CO_2 capture efficiencies are expected to reach 85-95% at best, which means that the other 5-15% is leaked (IRENA, 2020)[230]. Fossil-based hydrogen is produced from conventional steam methane reforming (SMR) or coal gasification representing currently the primary sources of global hydrogen production. Long seen as a key element in global decarbonisation, green hydrogen has emerged the limelight as an accelerant for the energy transition, with the potential onshore only superseded by what might be achieved offshore, where hydrogen could be produced, stored and shipped to landfall for industrial use and in the future become a fuel for zero-emission shipping.

An increasing number of countries are beginning to recognize the need for and potential of hydrogen. This is emphasized in recent reports by authoritative international organizations such as the International Energy Agency (IEA)[231] and the International Renewable Energy Agency (IRENA)[232]. In Japan and elsewhere in Asia, hydrogen is seen as a key way to diversify the energy mix and to become less dependent on the oil and natural gas imports, in addition to contributing to climate policy. In China, the beneficial impact on air quality is seen as a key reason to encourage the use of hydrogen in mobility. Countries such as Japan and South Korea are anticipating large-scale imports of hydrogen. By contrast, Australia and New Zealand's hydrogen strategies focus on the potential for exports. Potential is greater in regions where cheap renewable electricity can be generated on a large scale, such as in the Middle East, North Africa, and more recently in Spain and Portugal. In Norway, hydrogen will be used for maritime applications and work is underway related to the production of "blue" hydrogen by using carbon capture and storage (CCS).

High costs represent hydrogen's biggest challenge. It is expensive to produce, store and transport. Europe is engaged in studying and implementing safety and technical standards for the production, storage, and transport of hydrogen. The solutions and standardization will have impact on costs. The cost of production depends not only on the cost of renewable electricity, but also on the capital and on operating costs of electrolyzers. The number of available electrolyzers limits global hydrogen production capacity. Europe has the greatest planned electrolyzer and associated renewable capacity globally, mostly produced from offshore wind and solar PV. One of the drivers is the European Union's green hydrogen targets and associated funding to scale up production to decarbonize hard-to-abate sectors in line with the bloc's long-term Net Zero by 2050 target. With excellent wind and solar resource availability, Australia holds the second position following Europe, the country aiming to export green hydrogen and ammonia (IEA, 2021)[233]. Europe's electrolyzer capacity should reach 40 gigawatts by 2030 based on country targets and industry plans, and another 40 gigawatts of capacity targeted from imports[234]. Japan and Spain,

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227 IRENA. "Hydrogen: A renewable energy perspective". Abu Dhabi, UAE, 2020.

228 Hydrogen Council. „Path to hydrogen competitiveness. A cost perspective". Oslo, Norway; 2020.

229 Steam methane reforming (SMR) reacts the methane in natural gas with high-temperature steam in the presence of a catalyst. This produces hydrogen, and ultimately carbon dioxide. The standard SMR process has the considerable disadvantage of releasing large quantities of CO_2 into the atmosphere.

230 Ibid, 2020.

231 "The future of hydrogen, seizing today's opportunities". IEA, 2019.

232 "Hydrogen from renewable power: technology outlook for the energy transition". IRENA, 2018.

233 IEA (2021). "Renewables 2021: Analysis and forecasts to 2026". Fuel report, December 2021, Paris, France.

234 40 GW are expected to be deployed in Europe and on additional 40 GW will be exported to the EU from neighboring countries. See: "A hydrogen strategy for a climate-neutral Europe." Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, August 7, 2020.

for example have targets in place to make hydrogen more cost competitive by supporting electrolyzer production. Europe has a strong electrolyzer market, but capital costs are predicted to remain high until industrial scale-up brings costs down (Hydrogen Europe, 2019)[235]. The cost of renewable electricity is expected to decrease as more offshore wind comes online across Europe, this in turn should lower the cost of green hydrogen production. The International Energy Agency (IEA) estimates that the global price of green hydrogen will decrease to 1.10-2.40 EUR/kg by 2030 and according to Bloomberg NEF (BNEF) by 2050 green hydrogen costs will have fallen by 85 percent to 0.85 EUR/kg[236]. To verify green hydrogen's renewable origin, a certificate or guarantee of origin system for green hydrogen will need to be developed across Europe to allow the production of renewable hydrogen to be tracked and to appropriate price signals.

Floating wind, which was once considered the most expensive form of wind power, may become the most economical way to produce the green hydrogen. Electrolyzers need as many load hours as possible, which far-offshore wind farms could provide due to the stronger, steadier winds in open sea. Still, as the chemical, refining and ammonia sectors move to green hydrogen between today and towards 2050 to meet national emissions reduction targets. To do so, they will need huge quantities, and one of the main pathways to produce low-carbon hydrogen at large scale for their use will be offshore and floating wind. Floating wind is currently more expensive than bottom-fixed offshore and onshore wind, which affects negatively on its potential for green hydrogen production. After all, the price of electricity used to split water molecules into hydrogen and oxygen accounts for about two thirds of the price of the resulting hydrogen (H_2). Green hydrogen is currently two to six times more expensive than grey H_2 derived from unabated natural gas, which emits 9 to 12 tons of CO_2 for every ton of hydrogen produced. Floating wind-to-hydrogen's economics improve too due to the fact that the more hours per year that an electrolyzer is working, the cheaper the hydrogen production costs are. Therefore, renewables projects with high capacity factors that channel all their output to electrolyzers are the best option for cost-effective green hydrogen. Floating wind has an average capacity factor of 65% compared to 50% for bottom-fixed offshore wind.

With many offshore wind farms already installed and even more being planned, offshore wind is likely to play an important role in the production of hydrogen in Europe. The next phase of offshore wind projects will include extra-large 12-megawatt turbines and have more capacity than ever before. Many of the next generation offshore wind projects will face long distances to shore, limited interconnection points, and projected grid constraints. Therefore, they may be well suited for dedicated hydrogen production or for converting excess capacity to hydrogen. In addition, offshore wind has a higher capacity factor than other renewables, meaning an electrolyzer can operate for a greater proportion of time and produce more hydrogen. Many of the potential end uses of hydrogen, such as refineries, the metal industry, marine transport, and export/import facilities are located on the coast, near to offshore windfarm locations.

6.2 ELECTROLYZER TECHNOLOGIES

Electrolysis technologies will play a central role in future energy systems, acting as a vital link between the electric, gas, and thermal grids and providing fuel for the transportation sector. Studies show that greater than 40 to 50% penetration of wind power and photovoltaics in the electricity system requires further sector integration in combination with efficient energy conversion and storage technologies such as electrolysis. On a European scale, analyses show that 1600-gigawatt electrolysis and 7500 terawatt-hours of chemical storage may be needed to decarbonize

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[235] "Hydrogen Europe Vision on the Role of Hydrogen and Gas Infrastructure on the Road toward a Climate Neutral Economy". Hydrogen Europe Secretariat, April 2019.

[236] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions "A hydrogen strategy for a climate-neutral Europe." COM (2020) 341. See also "Hydrogen Economy Outlook", Bloomberg BNEF, and March 30, 2020. This estimate for green hydrogen is from a range of renewables, including less expensive solar.

heavy-duty transport such as trucks, ships, and planes (Hauch et al., 2020)[237].

Electrolysis is the core technology of power-to-X (PtX) solutions, where X can be hydrogen, syngas, or synthetic fuels. When electrolysis is combined with renewable electricity, the production of fuels and chemicals can be decoupled from fossil resources, paving the way for an energy system based on 100% renewable energy. Hydrogen production via electrolysis may offer opportunities for synergy with dynamic and intermittent power generation, which is characteristic of some renewable energy technologies. Electrolysis is the process of using electricity to split water into its component parts of hydrogen and oxygen. This reaction takes place in a unit called electrolyzer. During an electrolysis process, water undergoes disassociation into hydrogen and oxygen when an electric current is applied. Electrolyzers can range in size from small, appliance-sized equipment that is well suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse gas emitting forms of electricity production. Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Different electrolyzers function in different ways, mainly due to the different type of electrolyte material involved in an ionic species it conducts.

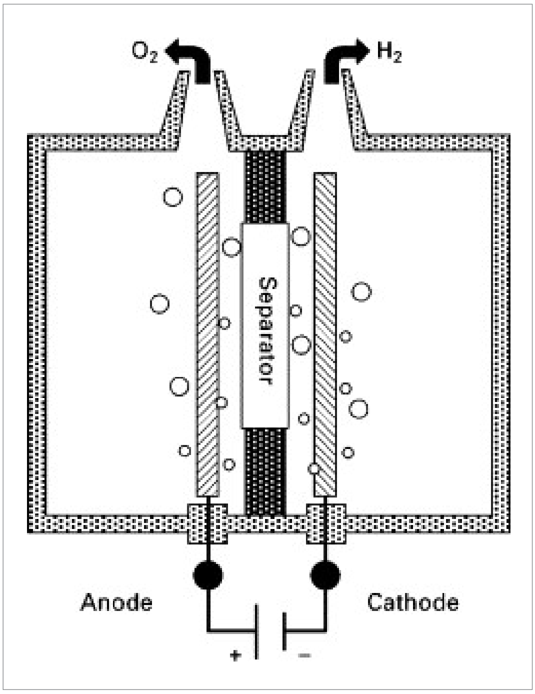
Electrolyzers are also classified based upon production technology. There are mainly three types of water electrolysis technologies: (a) alkaline water electrolysis, (2) polymer electrolyte membrane (PEM) water electrolysis, and (3) solid oxide electrolysis (SOEC).

Alkaline water electrolysis is the most mature technology that has been installed at a commercial level due to its high-energy conversion efficiency and reliable performance. Polymer electrolyte membrane water electrolysis can be implemented in a compact system and operate at higher current density with quick response to renewable electricity. Solid oxide electrolysis cell (SOEC) technology has an important role to play in the sustainable energy economy of the future. This technology has achieved a set of economics that make commercial viability possible today (Crolius, 2020)[238]. The ultimate goal of water electrolysis technologies is to produce green hydrogen reliably at a cheap price from intermittent and fluctuating renewable energy sources.

6.2.1 ALKALINE ELECTROLYZERS

As a well-established technology alkaline water electrolysis is the dominating technology due to the lower cost of production. This type of electrolyzer has been used in the chemical industry approximately for 100 years, thus while further progress is expected, both PEM and SOEC development will definitely be faster. Several megawatt industrial electrolyzers are used in the industry for the large-scale production of hydrogen in view of different end-uses. The first commercialized water electrolysis system was based on the principles of alkaline water electrolysis, and alkaline-based systems remain the most utilized water electrolysis systems.

Figure 24. Alkaline water electrolyzer



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[237] A.Hauch et al. "Recent advances in solid oxide cell technology for electrolysis". Science, 09 October 2020, volume 370, Issue 6513.

[238] S.H.Crolius."The Future Is Here for Solid Oxide Electrolysis Cell Technology". Ammonia Energy Association, October 22, 2020.

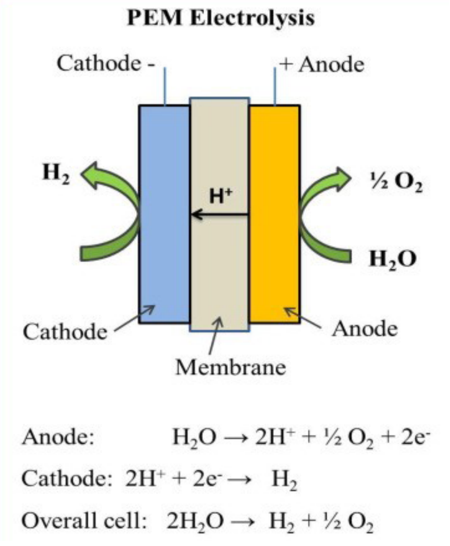
A schematic of an alkaline water electrolyzer is given in Figure 24. Alkaline electrolyzers are typically composed of electrodes, a microporous separator and an aqueous alkaline electrolyte of approximately 30 weight percent potassum hydroxide (KOH) or sodium hydroxide (NaOH). In alkaline electrolyzers, the most common cathode material is nickel (Ni), with a catalytic coating such as platinum (Pt). For the anode nickel (Ni) or copper (Cu), coated with metal oxides such as manganese (Mn), wolfram (W) or ruthenium (Ru) are used. The industry has developed electrolyzers that can deliver up to approximately 60 kg/h (≈670 Nm^3/h).

There are also a number of technological disadvantages associated with the alkaline electrolysis system: low current density, limited ability to operate at low loads, and the inability to operate at high pressure. The latter two limitations are due to the crossover of gases possible through the separator. This will increase both with increasing pressure of hydrogen at the cathode and will also increase with reduced load where the oxygen production rate decreases and the hydrogen concentration in the oxygen stream can increase to dangerous levels (H_2 lower explosion limit >4%).

6.2.2 PROTON EXCHANGE MEMBRANE ELECTROLYZER

The key of proton excahange membrane (PEM) electrolysis technology lies in proton exchange membrane, which is an organic film with strong chemical stability, proton conductivity and good gas separation. The membrane electrode assembly is formed by the diaphragm and porous electrode composed of catalysts on both sides of the distribution. In PEM water electrolysis, water is electrochemically split into hydrogen and oxygen at their respective electrodes such as hydrogen at the cathode and oxygen at the anode. PEM water electrolysis is accrued by pumping of water to the anode where it is split into oxygene (O_2), protons (H^+) and electrons (e^-). These protons are traveled via proton conducting membrane to the cathode side. The electrons exit from the anode through the external power circuit, which provides the driving force (cell voltage) for their reaction. At the cathode side the protons and electrons re-combine to produce hydrogen, the following mechanism as shown in Figure 25.

Figure 25. Schematic diagram of PEM water electrolysis



Source: Adapted from the article „Hydrogen production by PEM water electrolysis – A review" (Shiva et al., 2018).

PEM electrolysis has the advantages of safety, cleanliness and high efficiency. Compared with alkaline electrolysis, it has low ohmic loss, high current density and hydrogen purity. The disadvantages are high cost and short life, so it is currently only suitable for small-scale hydrogen production. One of the reasons is that most of the proton exchange membranes currently used are fully sulfonic acid type membranes, which are highly acidic when infiltrated by water. Moreover, due to the higher theoretical oxygen evolution potential, most metals will corrode at this potential, so palladium (Pt) noble metals are mostly used as catalysts for the anode and cathode. In addition, the cost of proton exchange membrane is also relatively high, and such exchange membrane is prone to degradation during use, so the membrane life is short. At present, the main problem is to find more durable proton exchange membrane materials in thermodynamics and chemistry, and reduce the diffusion coefficient of membrane solid phase. For noble metal catalysts, the cost can be reduced by decreasing catalyst load and developing alloy catalyst (Li et al., 2020)[239].

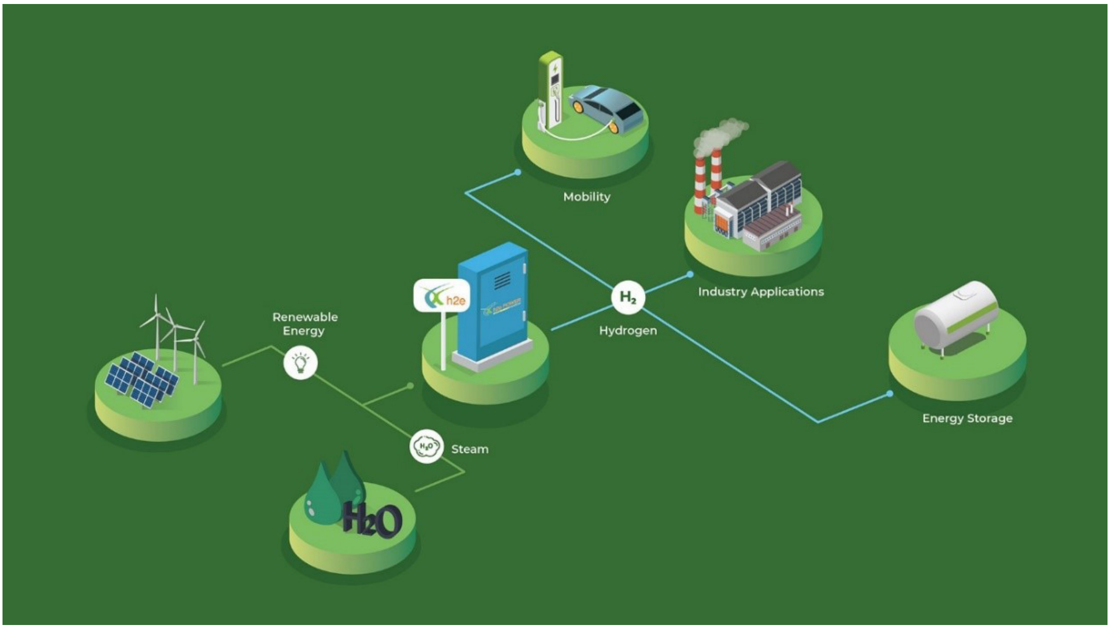
6.2.3 SOLID OXIDE ELECTROLYZER

The solid oxide electrolysis (SOEC) was first introduced by Donitz and Erdle in the 1980s. It is the leading technology for production of green hydrogen by high temperature electrolysis. With solid-oxide electrolyzer, excess renewable electricity can be efficiently converted to energy carriers such as hydrogen via electolysis of steam or synthesis gas (syngas, H_2 + CO) via co-electrolysis of steam and carbon dioxide. The produced hydrogen or syngas could be further processed to easy-to-store and –distribute synthetic methane (METH) or liquid fuels, particularly, methanol (MeOH), dimethyl ether (DME) and gasoline (GASO). These fuels can be either used in the transportation sector or converted back into electricity to address peak demand. Unlike conventional alkaline or proton exchange membrane based low-temperature electolysis, SOEC offers high electrical efficiency, and uniquely enables co-electrolysis of steam and CO_2, and opportunity of thermal integration with industrial processes, e.g., fuel-synthesis processes.

The SOEC technology for producing hydrogen, carbon monoxide, or syngas has developed rapidly in recent years, from material-, cell-, and stack levels to system levels of design (Zheng et al., 2014)[240]. Solid oxide electrolyzer cells have gained much attention to generate hydrogen from electricity as they operate at high temperatures (approximately 500-950 degrees Celsius) which increases the reaction kinetics and reduces electrical energy requirements. SOECs use a solid-ceramic material as the electrolyte that selectively transfers negatively charged oxygen ions to the anode. Unlike PEM and alkaline electrolyzers, water is dissociated into hydrogen and oxygen ions at the cathode.

This technology can drastically reduce the power needed to split water into hydrogen, and there-

Figure 26. Solid oxide electrolysis (Source: adapted from the original scheme by h2e Power, 2021)



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[239] J.Li, W.Liu, and W.Qi. "Hydrogen production technology by electrolysis of water and its application in renewable energy consumption". E3S Web of Conferences 236, 02001 (2021). School of Mechanical Engineering, Tiajin University of Commerce, China.

[240] Li, Q., Zheng, Y., Guan, W., Jin, L., Xu, C., Wang, W.G. "Achieving high-efficiency hydrogen production using planar solid-oxide electrolysis stacks". *In International Journal of Hydrogen Energy* 2014, 39 (21), pp. 10833-10842.

fore significantly increase power-to-hydrogen efficiency (up to >95% HHV H_2) when external heat (150-180 degrees Celsisus) is provided to the system to generate steam (Nechache & Hody, 2019)[241]. This improvement in efficiency can lead to a strong reduction in hydrogen cost, as power consumption is the main contributor to the cost of hydrogen in electrolysis. SOEC has attracted an abundant deal of attention due to the electrical energy converts into the chemical energy along with producing the ultra-pure hydrogen with greater efficiency. Solid oxide electrolysis operates at high pressure at high temperatures 500-850 degrees Celsius and utilizes the water in the form of steam. Electrolysis process conventionally uses the O^{2-}conductors which are mostly from nickel/yttria stabilized zirconia, operating principle of SOE has shown in Figure 26.

Nowadays, some of the ceramic proton conducting materials have been developed and studied in solid oxide fuel cells. Ceramic proton conducting materials for SOEC electrolysis process demonstrate high efficiency and superior ionic conductivity than O^{2-}conductors at an operating temperature of 500-700 degrees Celsius. The main characteristics of solid oxide electrolysis technology is higher operating temperature which is an advantage as compared to low temperature electrolysis. Although, the SOEC having some issues related to lack of stability and degradation, which have to be solved before going to commercialization on a large scale.

6.3 SYSTEM CONFIGURATIONS

There are two possible options for the system configuration related to the location of the electrolyzer: it can be placed offshore, near the wind farm, or onshore, near the existing grid coupling point.

6.3.1 OFFSHORE ELECTROLYZER SCENARIO

One of the significant costs in an offshore wind farm is the equipment to bring the electricity to shore, mainly the cables, transformers, and power electronics. Considering a high-Voltage Alternative Current (HVAC) transmission system, losses are around 1% to 5% for wind farms with nominal power from 500 to 1000 MW and located 50-100 km from shore (Negra et al., 2006)[242]. For a HVDC system, losses range from 2% to 4%, depending on nominal power and distance (ibid). However, hydrogen travelling through a pipeline has considerable lower losses under 0.1%, along with reduced initial costs for an underwater pipeline compared to underwater electrical cables and the power electronics needed.

Since the output pressure of a PEM is around 30 bar, additional compression is required to export the hydrogen to shore. The hydrogen compressor and export pipeline must be sized according to the distance to shore, operating pressure of the electrolyzer, flow of hydrogen, and pressure drop along the pipeline. A study done by North Sea Energy (2019)[243] estimated the required pipeline diameter and pressure, assuming an output pressure of 68 bar and 20 m/s maximum travel speed. The results show that for a 1 to 2 GW wind farm located 50 to 200 km from shore, the minimum diameter of the pipeline ranges from 0.25 to 0.41 m, while the minimum input pressure ranges from 83 to 100 bar.

To size the PEM, the nominal power does not need to be equal to the wind farm's nominal power, since the wind farm might not spend large periods of time at nominal power. From an economic point of view, the most interesting approach might be to slightly undersize the electrolyzer, since the revenue lost when the wind farm is at nominal power could be lower than the additional cost of a more more powerful electrolyzer (Offshore Renewable Energy (ORE) Catapult, 2020)[244]. Furthermore, the energy used in purifying the water and compressing the hydrogen for transmission, along with the wake and array losses, lowers the actual available power for the electrolyzer.

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[241] A.Nechachse, S.Hody. "Test and evaluation of a hybrid storage solution for buildings, based on a reversible high-temperature electrolyzer". In Electrochemical Society's Transactions", 2019, volume 91, Number 1.

[242] N.B.Negra, J.Todorovic, T.Ackermann. "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms". In *Electric Power Systems Research*, 2006, 76, pp. 916-927.

[243] North Sea Energy (2019). "A Vision on Hydrogen Potential from the North Sea".

[244] Offshore Renewable Energy (ORE) Catapult (2020). "Offshore Wind and Hydrogen: Solving the Integration Challenge".

Two electrolyzer configuarations are possible: a unique centralized electrolyzer fed by the whole wind farm or individual electrolyzers, one per wind turbine. The main components for the centralized electrolyzer system are the same as for the individual electrolyzer system, since the operating principle is similar.

6.3.2 CENTRALIZED ELECTROLYZER

In a centralized electrolyzer system, the individual installation of the wind turbines is the same as a typical offshore wind farm, with turbines in strategic places to minimize losses by the wake effect. The power produced by each individual turbine is transmitted to a central platform through regular underwater cables, while voltages can differ, newer and higher power turbines, such as the Haliade-X 13 MW, operate at 66 kV (General Electric, 2020)[245].

Once the electrical power reaches the central platform, most of it can be rectified to DC; the other part is used to power the seawater pumps and hydrogen compressor in AC. The DC power is used mainly to produce hydrogen but also to power the backup power source and the supporting systems. The produced hydrogen exits the electrolyzer at high purity and with a pressure of 30 bar, so the next step is compressing it to the desired pipeline input pressure. After being compressed, the hydrogen is fed into the export pipeline, where it is transmitted to the shore.

6.3.3 INDIVIDUAL ELECTROLYZERS

When sufficient wind is present, most of the electricity is fed into the rectifiers to power the electrolyzers and possibly refill the backup power source. The remaining power is used to power the seawater pumps, which need AC electricity. In case, no offshore compression is available, the produced hydrogen exits the electrolyzer and is exported by a small dimension pipeline to a subsea collection manifold, which receives the hydrogen produced by each turbine-electrolyzer system and exports it to shore using a bigger diameter pipeline. However, if offshore compression is needed, the hydrogen exits the electrolyzer and is exported by a small dimension pipeline to a collection manifold in a platform, compressed to a desired pressure, and exported to shore by a pipeline. This approach becomes more viable as the nominal power of a turbine keeps increasing, since more powerful electrolyzers can be installed individually, and economies of scale can play their part.

Since bottom fixed and some floating options, such as spar buoy, require significant modifications to be able to support the extra infrastructure, the semi-submersible platform like the one used in WindFloat Atlantic is the best choice for the individual electrolyzer approach (ERM, 2019)[246]. To make the platform suitable for all the equipment, modifications need to take place, such as creating a floor on which to put the equipment that is shielded from waves and potential water splashing, as well as modifying the buoys and ballast to accommodate the additional weight.

6.3.4 ONSHORE ELECTROLYZER SCENARIO

This approach is also known as a hybrid system, where the energy produced is transmitted to shore as electricity in conventional cables; once onshore, the energy can be sold directly to the grid or used to produce hydrogen. The main advantage of this system is flexibility: when the market price for electricity is high, the investor can sell electricity directly to the grid; when market price for electricity is low or the grid level curtailment must occur, the energy can be redirected to an electrolyzer to produce hydrogen. Curtailment occurs when the production of electricity is greater than the consumption, which leads to a need to reduce the production.

Since the electroyzer in this case will be onshore, it is possible to place the electrolyzer and all other sensitive equipment inside a building, where they can be sheltered from the elements, this also provides a better work environment for the personnel responsible for the operation and maintenance. Furthermore, since access to the

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[245] "GE's Haliade-X offshore wind turbine prototype operating at 13 MW". General Electric, press release, 22 October 2020.
[246] ERM. "Dolphin Hydrogen Phase 1 – Final Report". October 2019.

electrolyzer is much simpler than if it was offshore, the increased maintenance requirements and decreased power density of an AEL do not present as big an obstacle, so the reduced capital expenditure investment of this technology means both AEL and PEM, are viable when the electrolyzer is installed on land.

HVDC is a more expensive technology that only becomes interesting when wind farms are located far from shore and/or have high nominal powers. In the case of HVAC, longer lines imply more powerful line-reactive compensators to account for the capacitive losses, which in turn increases the cost. Since HVDC transmission does not show capacitive losses, the transmission losses are lower in the case of HVDC. To summarize, transmission losses and costs are lower in the case of HVDC, and even though the initial investment for HVDC transmission (stations and equipment) is higher than HVAC, the difference in cost diminishes when the transmission distance increases.

Regarding the source of water, the two possible options are connecting the electrolyzer to the freshwater grid, an option that might not be viable due to environmental concerns in areas with recurring droughts, like southern Europe, or installation of a desalination unit next to the electrolyzer. Even though the water produced by desalination unit is clean, and the water is freshwater grids has been previously treated, further treatment such as deionizing the water is still required for both options before being used in electrolyzis (IRENA, 2020)[247].

6.4 OFFSHORE WIND AND SMART POWER GRIDS

With increasing share of offshore wind energy the demand of monitoring options and forecasting solutions is rising as well. The use of technologies to ensure stable and reliable power supply is the key feature of modern power supply networks so called smart power grids. This covers monitoring of power plants as well as data analysis. In this subchapter both aspects are addressed and the specifics for offshore wind power will be highlighted.

The concept of a smart grid is derived from a traditonal power grid, which is a network that delivers electrical power from power plants where it is generated and distributed to users. A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience and stability. An electrical grid includes wires, substations, transformers, relays switches and other mechanical and intelligent electrical devices. The term „smart grid“ reflects a broad concept of load management. However, there is no precise definition that covers exactly what that concept includes, and in particular who decides what load should be dispatched.

Smart grid can also be defined as a two-way communications between a complex set of intelligent electronic devices used to monitor and control physical processes that result in generation, distribution and storage of electricity in a safe, reliable and efficient way. The technologies used which include an energy management system, allow for combining existing power generation sources (diesel, gas turbine, coal, hydro, nuclear) with solar and wind power generation, energy storage, and waste heat recovery technologies, all connected to an intelligently (automated) managed microgrid, ensuring uninterrupted supply of electricity (Butrimas, 2021)[248].

In short, the smart grid is the integration of existing electrical power systems with the communication and automation systems that monitor and control it, with the aim of improving the safety, efficiency, reliability resilience and economy of operation of the electricity supply. Smart grid

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[247] IRENA (2020). "Green Hydrogen Cost Reduction: scaling up Electrolyzers to meet the 1.5 degrees Celsius Climate Goal".

[248] V.Butrimas (2021). "Assessment study of cybersecurity of smart-grid technologies employed in operational camps". NATO Energy Security Center of Excellence.

encompasses such control devices and the data stream that flows through them. Sensors for example play a key role in smart grids. Sensor data sent to the controller needs to be trusted since the system will use the telemetry to adjust the flow of power accordingly. The concern here is the compromise of the sensor or a malfunctioning sensor that sends bad data to the controller. Data of course is important but also the equipment that produces data. For example, sun sensors are used in the operation of movable solar panels and wind direction sensors help in pointing the windmill toward the wind. If the sensor data is compromised, it will affect the function of the equipment. The compromise can happen both unintentionally (maintenance/manufacturer issue) or intentionally (cybersecurity issue).

Smart grid has enhanced capabilities for monitoring and utilizing two-way communication among devices that belong to a system of power generation, distribution and storage. This smart capability allows for more efficient transmission of power beween where the power is produced and where it is used. This is done in a variety of ways by automatically reacting to changes in demand by controlling and redirecting the generation and usage of power in the system. The smart grids control systems ability to autonomously react and correct a problem in the grid improves the system's safety, availability and resilience. For example, if a critical piece of bulk power equipment was overloaded or overheating, a message would go out to the smart grid control system. The management system would automatically isolate the device and re-balance the grid until the equipment is checked, repaired or replaced. The power needed to fill gap may come from a smart grid connected centralized power plant, wind farm, photovoltaic (PV) array, energy storage system or power utility.

In comparison to their onshore counterparts offshore wind farms are in most cases larger in terms of height and blade length and further face tougher weather conditions which leads to challenges in building but also in monitoring. In general, nearly all parts of a wind turbine show vulnerabilities over time which makes adequate monitoring systems a necessity if major losses because of failed maintenance should be prevented. Moeini et al. point out that especially the electrical subsystems are affected the most by failures[249]. However, also a cracking of the rotor bars is considered a frequent issue. Further, they highligt that vulnerabilities depend highly on the type of the wind turbine. Squirrel cage generators are less vulnerable than doubly fed induction generators or permanent magnet synchronous generators, but also less efficient to generate power under changing wind conditions.

To monitor the different kinds of potential weaknesses various systems and strategies are used featuring mostly either supervisory control and data acquisition (SCADA) systems or condition monitoring systems (CMSs)[250]. For example, a common monitoring technique for electrical drive train components is the generator current signature analysis, which helps to identify electrical as well as mechanical faults by checking for changes in the magnetic field of a turbine. This method is especially useful as it is non-inversive and thus can be easily used for any wind turbine. A further technique is the thermal monitoring by sensors between rotor and stator windings to analyse the temperature and prevent damage by crucial temperature changes. The tracking of temperature is also important when it comes to the monitoring of power electronic converters as unexpected high temperatures are a clear indicator for an upcomming failure[251].

For the mechanical components of a wind turbine vibration monitoring can be carried out. Via high sensitivity sensors malfunction of the gearbox, bearings or other components can be detected and prevented. Time synchronous averaging is one of these vibration based monitoring methods and useful to identify non synchronous system

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[249] Moeini R, Entezami M, Ratkovac M, et al. Perspectives on condition monitoring techniques of wind turbines. In *Wind Engineering*. 2019;43(5):539-555.

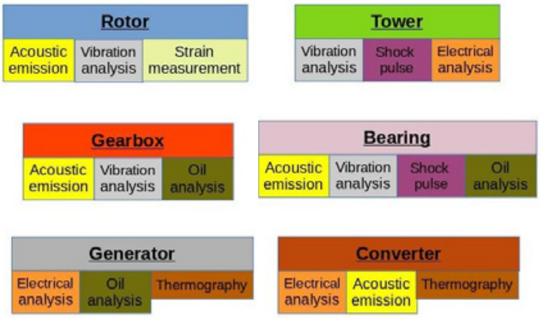
[250] Lian J, Cai O, Dong X, Jiang Q, Zhao Y. Health Monitoring and Safety Evaluation of the Offshore Wind Turbine Structure: A Review and Discussion of Future Development. Sustainability. 2019; 11(2):494.

[251] Teay S H, Batunlu C, Albarbar A, Smart sensing system for enhancing the reliability of power electronic devices used in wind turbines. In *International Journal on Smart Sensing and Intelligent Systems, 2017*, 10(2): 407-423.

parts which then can be inspected and repaired or replaced accordingly[252]. A further technique is to monitor the acoustic emission of the turbines to determine misbehaviour of some mechanical parts[253].

Moreover, the monitoring of the structure of a wind turbine, so called structural health monitoring, is an upcomming issue. With increases in height wind turbines face tougher environmental impacts. To keep track of potential failures, different techniques and sensors can be used. These can be for example various temperature sensors as well as acceleration sensors, vibration sensors and displacement transducers.

Figure 27. Condition Monitoring options for specific parts of a wind turbine (similar to Moeini et al.[1])



However, to detect the signs of upcomming maintenance problems it mostly is not enough to install the sensors or obtain data via one of the described methods. Instead, in many cases different forms of artificial intelligence or machine learning algorithms are used to evaluate the sensor data and determine whether a specific observation is problematic or not. An example is the work of Bangalore et al. who apply different versions of artifical neural nets (ANN) to the monitoring of the gearbox[254].

Stetco et al. (2019) differentiate between two main types of machine learning, the supervised and unsupervised learning and further between regression and classification methods[255]. The more frequently used algorithms for wind turbine monitoring are supervised or semi-supervised algorithms. This can for example be a regression for the wind power curve or the lifetime prediction of different turbine components. Therefore, either parametric or non-parametric modelling techniques can be used, while parametric approaches are interpretable but non-parametric ones often are more accurate in prediction. Common methods are polynomial curve, logistic or probabilistic models (parametric) as well as cubic splines, neural nets and fuzzy approaches (non-parametric).

Regression models can also be used to determine the state of a wind turbine or one of its parts, however at this point classification models are more usual. According to Stetco et al.,[256] this is especially the case when images or sounds have to be evaluated. By using methods like decision trees, neural nets or support vector machines an available time series or just a specific point of time can be analysed and the state of the turbine evaluated. Classification techniques often achieve a high accuracy may require a lot of data to be efficient.

Finally, the results of monitoring will be reported to a human who evaluates them and makes decisions about maintenance, rechecking or replacement. Therefore, it is helpful to get insights about the process how the results are obtained to decide how meaningful a specific method or result is. This is an issue most machine learning algorithms lack currently and which should be more addressed in the future.

For offshore wind turbines monitoring it is even more needed but also more difficult as already pointed out above. Carroll et al. found that the

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252 Tcherniak D, Mølgaard LL. Active vibration-based structural health monitoring system for wind turbine blade: Demonstration on an operating Vestas V27 wind turbine. *Structural Health Monitoring*. 2017;16(5):536-550.

253 Salameh J.P, Cauet S, Etien E, Sakout A, Rambault L. Gearbox condition monitoring in wind turbines: A review. In *Mechanical Systems and Signal Processing*, 2018;111:251-264.

254 Bangalore P, Letzgus S, Karlsson D, Patriksson M. An artificial neural network-based conditionmonitoring method for wind turbines, with applicationto the monitoring of the gearbox. Wind Energy. 2017;20:1421-1438. doi:10.1002/we.2102

255 Stetco A, Dinmohammadi F, Zhao X, Robu V, Flynn D, Barnes M, Keane J, Nenadic G. Machine learning methods for wind turbine condition monitoring: A review. Renewable Energy. 2019;133: 620-635. doi:10.1016/j.renene.2018.10.047.

256 Ibid, 2018.

failure rates for offshore wind turbines are significantly higher than onshore[257]. Especially the generator is up to five times more often affected in the case of an offshore wind turbine. Therefore, different techniques have to be applied. Genereally, these techniques do not differ from the universal methods described above. However, some of them are not applicable for offshore wind turbines. These are especially visual monitoring techniques as there is no place for sensors to be installed in front of the turbine. Further, sensors which are placed on the outer side of the turbine have to be adjusted to the tougher weather conditions.

It is highlighted that more reasearch in monitoring and mainetance of offshore wind turbines have to be made (Lian et al., 2019)[258]. Technologies for better data transmission of the offshore wind turbines have to be developed, for example. Especially for deep sea wind turbines wireless and more efficient solutions have to be found. Further steps have to be made in terms of real time measures and maintenance systems without direct human interaction. Together with large area monitoring and combination of different evaluation systems and algorithms offshore wind energy can be a valid alternative and substitute to conventional power sources.

CONCLUSIONS

Future power scenarios include offshore wind energy as an important generation source that according to the IEA is one of the big three sources of clean energy alongside solar and onshore wind. Many countries are considering floating wind technology, as it opens up new areas with high-wind resources that are not suitable for bottom-fixed installations. Technically, the long-term survivability of floating structures has already been successfully demonstrated by the marine and offshore oil industries over many decades. The costs of offshore wind energy have fallen significantly in recent years, making it the cheapest large-scale source of renewable energy.

This study discusses and reviews some aspects of offshore wind power plants for a massive integration into power systems. Due to technological progress in the last decade, we can see several characteristics such as offshore wind turbines are becoming bigger and more powerful; as well, water depth and distance to shore have significantly increased. In the same way, electrical transmission has also evolved from HVAC to HVDC solutions. Moreover, HVDC technology currently offers three different possibilities: LCCs (based on thyristors), VSCs (based on insulated-gate bipolar transistor) and DRU (diode rectifier unit). The advantages and drawbacks of each technology have been discussed in the study. Different future advancements currently under development are also described such as PtX (Power-to-X) conversion, as well as hydrogen energy storage.

So far, the growth of offshore wind has been focused on countries bordering the North Sea, where high quality wind resources and relatively shallow water have provided exceptionally good conditions in which to develop offshore wind. Germany and the United Kingdom take up the large part of offshore wind capacity, although a group of smaller countries including Denmark, the Netherlands and Belgium are other front-runners. For 2030, installed capacity is expected to multiply by four from 2018 levels of approximately 20 GW. With the ongoing development of the technologically more challenging floating wind turbines, other countries with deeper coastal waters (such as Spain) are likely to be added to the list of countries making use of offshore wind. Based on the estimates of WindEurope, the Baltic Sea holds an incredible potential for offshore wind, and could host as much as 93 GW by 2050, up from 2.2 GW today.

Despite its many advantages, however offshore wind energy generation is also accompanied with many challenges. In addition to the technical and cost-related challenges, further barriers to the continued growth of the offshore wind industry stem from the environmental impact of OWFs.

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[257] Carroll J, McDonald A, McMillan D. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy. 2016;19:1107-1119. doi:10.1002/we.1887

[258] Lian J, Cai O, Dong X, Jiang Q, Zhao Y. Health Monitoring and Safety Evaluation of the Offshore Wind Turbine Structure: A Review and Discussion of Future Development. Sustainability. 2019; 11(2):494.

Marine biologists, for example carefully study the impact of OWFs on marine life. Similarly, ornithologists are often concerned that OWFs may negatively affect the migration and breeding patterns of various avian species. Although, there is still much that is unknown about the effects of the environment.

Among other challenges, the focus is also on the defence implications (wind farms interference with air defence radars). Large-scale deployment of offshore wind that, if unmanaged, could have adverse impacts on the air defence radars used to deliver security of the country and its airspace. Wind farm developers face objection from radar operators because large wind turbines can interact with radar signals, causing interference. Challenges for the navigational safety are also discussed especially in the context of intense traffic at sea. The space around the ship and the nearby OWF should provide a safe buffer to allow in appropriate maneuver to be performed in an emergency, to avoid the hazard.

The world is undergoing a substantial energy transition with an increasing share of intermittent sources of energy on the grid such as wind and solar. These variable renewable energy sources require an energy storage solution to allow a smooth integration of these sources. Offshore wind has an important role to play in the future energy supply. This call for a systematic approach, paying attention to the balance between energy supply and demand and the connection between the offshore and onshore energy infrastructures. Attention must be paid to the transmission, storage and distribution of various energy carriers, such as electricity and gas. Hydrogen has an important role to decarbonize certain sectors, particularly industry and some transport and heating. Extensive storage and flexibility is required, with electric, thermochemical and gaseous storage all being deployed alongside interconnectors.

Therefore, offshore wind should be incorporated into planning for the national hydrogen strategies, as it could be an important source of power located adjacent to many ports and industrial facilities to meet increased demand. Interest in using offshore wind for green hydrogen production across Europe is driven by large offshore wind capacity targets, declining offshore wind costs, favorable policies, and a focus on economy-wide decarbonisation.

A WAY FORWARD

Wind turbines affect legacy radar as their echo characteristics often match those of an actual aircraft, which radar seeks to track. For these reasons, they cause two main types of interference with radar: direct interference and Doppler interference. Direct interference is caused by the high refelectivity of the turbine components: towers, nacelles, and blades, reduing the sensitivity of the radar via increased background noise, creating false readings and shadowing areas of radar coverage. Doppler interference is caused by the moving blades of a turbine that can generate false targets, false Moving Target Indication/Detection (MTI/MTD), and impacts both airborne and fixed radar.

Where non-technical mitigation such as terrain shielding are not possible, there are three main solutions to limit the impacts of wind turbines on radar: (1) improving radar design to distinguish between wind turbines and actual targets, e.g. radar upgrades, gap fill radar. (2) Reduce the reflectivity of the turbine, e.g via stealth technology to reduce the turbine's RCS or (3) remove the clutter from the radar's vision, e.g. blanking or suppressing of radar cells where turbines are known to be.

As a follow-up study based upon 2 previous studies on onshore and offshore wind power, the NATO Energy Security Center of Excellence will conduct a study in 2022, the scope of which is on the wind turbines impact for defence. The focus of the study „*Coherence of onshore and offshore wind farms with military requirements*" will be on the reduction of negative impact of the planned wind farms on the use of radar efficiency of the Lithuanian Armed Forces. The study will also build up on best practices in the development of onshore and offshore wind farms in countries with a similar geographical, geopolitical and security situation (e.g. Estona, Denmark and Finland).

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