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FLOATING OFFSHORE WIND OUTLOOK

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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation; a centre of excellence; a repository of policy, technology, resource, and financial knowledge; and a driver of action on the ground to advance the transformation of the global energy system. A global intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy and geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security, and low-carbon economic growth and prosperity. www.irena.org

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Disclaimer

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ABBREVIATIONS

ABS	American Bureau of Shipping
AEM	anion exchange membrane
BOEM	US Bureau of Ocean Energy Management
CAPEX	capital expenditure
CfD	contract for difference
CO_2	carbon dioxide
DOE	US Department of Energy
EEZ	exclusive economic zone
EMF	electromagnetic field
EUR	euro
GBP	British pound
GW	gigawatt
GWh	gigawatt hour
HBL	Hydrogen Backbone Link
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IEC	International Electrotechnical Commission
IPF	international patent family
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre of the European Commission
JWPA	Japan Wind Power Association
kV	kilovolt
kW	kilowatt
kWh	kilowatt hour
LCOE	levelised cost of electricity
LCOH	levelised cost of hydrogen
METI	Ministry of Economy, Trade, and Industry
MSP	marine spatial planning
MW	megawatt
MWh	megawatt hour
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OPEX	operational expenditure
PEM	proton exchange membrane
PV	photovoltaic
QI	quality infrastructure
R&D	research and development
TLP	tension-leg platform
TRL	technology readiness level
TWh	terawatt hour
USD	United States dollar
VSC	voltage source converter

EXECUTIVE SUMMARY

The international community aims to achieve a scenario in which global average temperature rise is limited to 1.5 degrees Celsius (°C) of pre-industrial levels this century by rapidly decarbonising hard-to-abate sectors. At the 2023 United Nations Climate Change Conference (COP 28) in Dubai, United Arab Emirates, a historic pledge was made to **triple renewable energy capacity and double energy efficiency by 2030**. Renewables constituted 87% of new power capacity additions and 43% of global installed generation in 2023, setting annual records. Offshore wind power, with its high-capacity factors and growing competitiveness, is a focal point in energy transition plans. Despite progress in offshore wind – with a total of 63 gigawatts (GW) of installed capacity in 2022 – meeting the 1.5°C goal requires capacities of 494 GW by 2030 and 2 465 GW by 2050.

A subset within the offshore wind sector that is gaining particular interest among stakeholders is floating offshore wind. This interest relates to the tremendous wind energy potential available in open waters and to the higher level of social acceptance of floating offshore wind, given that most of these turbines are located far from the coast, which energy players consider to be high-demand "real estate". The global floating wind industry is still nascent, with around 270 megawatts of operational capacity as of 2023. However, the global pipeline for new floating projects is 244 GW, evidencing the great interest in this technology.

From a market and geopolitical perspective, the G7 countries are increasingly scaling up national efforts to enhance their floating offshore wind capacities – with the United Kingdom, France, the United States and Japan among the most active countries in this sector. Key challenges associated with this technology are its limited operational scale and its high requirements for capital and operational expenditures (CAPEX/OPEX) compared to fixed-bottom offshore wind. Nevertheless, the projected economies of scale are expected to make floating offshore wind competitive and commercially viable by 2035.

Politically, international co-operation around this industry must be accelerated, and technological familiarity needs to be promoted among decision makers to raise the profile of floating offshore wind. From a regulatory perspective, there is a strong necessity to develop enabling frameworks to create a conducive ecosystem for floating offshore wind developments.

Technologically, floating offshore wind is a very innovative space, with several component concepts being explored and with varying technology readiness levels – an observation that corresponds with the insights gleaned from trends in offshore wind patent data. The foundations (spar, barge, semi-submersible, tension leg platform), mooring systems and grid infrastructure (use of high-voltage direct current [HVDC] cables) are elements that are evolving continuously, and many offshore wind developers are active in this space. As the industry continues to grow, increases in investments will be required to achieve greater project scales. Furthermore, to allow for technological consolidation to facilitate stable industry growth, there is an implicit requirement for increased standardisation and certification.

Ancillary considerations such as ramping up investments for port infrastructure development – in tandem with appropriate offshore-onshore grid planning – will be essential if floating offshore wind is to solidify its position in the energy transition.

High generation capacities for floating offshore wind can be coupled to other sectoral activities, such as hydrogen production. Different institutions/consortia are trialling several projects, which are especially relevant if sited close to hydrogen demand centres. Research areas that need further investigation include the optimal parameters to safely produce hydrogen offshore and transport it onshore.

As efforts to accelerate the energy transition continue, it will be important to ensure its sustainability. Floating offshore wind projects, by their nature, are sited at much farther distances from shore and in deeper waters. This means that the environmental and biodiversity impacts from this technology are much lower compared to fixed-bottom offshore wind. However, the floating offshore wind industry is still nascent, and there will be a continuous need to conduct detailed data collection and assessment on environmental impacts to verify this observation.

The ocean provides value to many maritime stakeholders whose business prospects and economic livelihoods are closely intertwined with, and depend on, the marine environment. In the context of floating offshore wind, the needs of the fishery sector in particular must be factored in during project development. Fishing activities tend to occur in similar locations as floating offshore wind projects. Key risks to the co-existence of these two sectors are fish species getting entangled in mooring lines and rogue fishing gear impeding the functions of components of floating wind sub-structures. To promote symbiotic relationships, it is important that fishing industry stakeholders be consulted for their views in the very early stages of project development. It is equally important to leverage tools such as marine spatial planning to identify zones where overlaps do not lead to unintended conflict situations.

The table below provides key observations across priority thematic areas that countries can consider to support the sustainable development of their floating offshore wind industries.

Area of intervention: Political

Observation	Recommended actions
Accelerate international co-operation	• G7 to engage with IRENA Collaborative Framework on Offshore Renewables to share best practices. • Continue to participate in joint research projects and leverage strengths of each entity.
Promote technological familiarity among decision makers	• Organise floating offshore wind capacity building activities. • Engage with global industry leaders and associations.

Area of intervention: Policy and regulation

Observation	Recommended actions
Adopt best practices in policy frameworks that consider floating offshore wind	• Set long-term deployment and cost reduction targets for floating offshore wind. • Develop public revenue support mechanism for floating offshore wind such as feed in tariffs; contract for difference etc.
Develop enabling frameworks for floating offshore wind	• Streamline offshore wind permitting processes. • Actively develop regulations that encourage the use of marine spatial planning.

Area of intervention: Hydrogen production

Observation	Recommended actions
Support the coupling of floating offshore wind to hydrogen production	• Site offshore hydrogen production as close to hydrogen demand centres. • Prioritise floating hydrogen production and transport close to shore • Develop and implement quality infrastructure requirements for hydrogen value chain.

Area of intervention: Technology and infrastructure

Observation	Recommended actions
Enhance the maturity of floating wind technology and reach commercialisation	• Increase investments in floating offshore wind industry. • Leverage best practices from offshore oil and gas sector.
Expand and re-imagine the grid Infrastructure for floating offshore wind	• Provide guidance on expansion of grid infrastructure with minimal impact on maritime activities. • Develop inter-operable grid components and expand HVDC networks. • Prioritise development of dynamic semi-submersible cables and floating sub-stations.
Prioritise developments and investments in port infrastructure	• Identify viable port sites that can support floating offshore wind deployment. • Set up dedicated committees that can be responsible for designing port development strategies. • Ensure that industry and port operators place an emphasis on developing a competent workforce. • Maintain active dialogue with vessel manufacturers and shipyards.
Promote standardisation of key floating offshore wind components	• Implement standards and certification schemes developed by international organisations. • Support national standard bodies to participate in international standard technical committees.

Area of intervention: Sustainability

Observation	Recommended actions
Address potential environmental impacts	• Undertake detailed environmental impact assessments. • Engage in continuous & transparent environmental data collection.
Prioritise co-existence with the fisheries sector	• Involve representatives from the fisheries sector as early as possible in the project planning process. • Designate "fishing areas and corridors" at offshore wind farms. • Make all surface and sub-surface data accessible. • Facilitate active communication between wind farm operators and fishing vessels.

1. INTRODUCTION

The global energy transition is off track, according to the International Renewable Energy Agency's (IRENA) *World Energy Transitions Outlook 2023*. This is due in part to the aftermath of the COVID-19 pandemic and to the ripple effects of ongoing geopolitical events, which have been further compounded by diverse financial and social challenges. These factors are hindering progress towards a successful energy transition (IRENA, 2023a).

According to IRENA and its 1.5°C Scenario,[1] the current pledges and plans made by countries to mitigate the impacts of climate change are insufficient to meet the goals of the Paris Agreement on climate change, as well as the goals adopted at the most recent United Nations Climate Change Conference (COP 28) in Dubai, United Arab Emirates. IRENA has found that by implementing Nationally Determined Contributions (NDCs), long-term low greenhouse gas emission development strategies (LT-LEDs), and net-zero targets, countries have the potential to reduce global carbon dioxide (CO_2) emissions 6% by 2030 and 56% by 2050, compared to 2022 levels. However, most climate pledges are yet to be translated into detailed national strategies and integrated into policy and financial frameworks.

IRENA's Planned Energy Scenario shows that at the current pace of development, and considering the existing plans and announced policies and targets, global CO_2 emissions are projected to reach 35 gigatonnes (Gt) by 2050. This signals an urgent call for action to accelerate the energy transition. Most of the technological avenues and emission mitigation measures to resolve this situation exist today and are ready for massive deployment (IRENA, 2023a).

Another key challenge hampering the energy transition, especially for developing countries, is access to finance. Although global investment across all energy transition technologies reached a record high of USD 1.3 trillion in 2022, from now until 2030 the annual investment must quadruple by more than USD 5 trillion per year to remain on the 1.5°C pathway. Under IRENA's Planned Energy Scenario, cumulative investments of USD 103 trillion are planned until 2050 for the global energy sector, and to comply with a 1.5°C target an additional USD 47 trillion will be required until 2050. Around USD 1 trillion of annual investments in fossil fuel-based technologies need to be diverted towards energy transition technologies and infrastructure (IRENA, 2023a). The envisioned operationalisation of the "Loss and Damage Fund" announced at COP 28 is a positive development in the context of access to finance.

In the power sector, renewables represented 87% of capacity additions and reached 43% of installed power generation globally in 2023. With regard to capacity, 2023 was a record year for renewables with a total of 473 gigawatts (GW) added, representing the largest increase ever recorded (IRENA, 2024a). In a 1.5˚C Scenario, an annual investment of USD 2.2 trillion will be required from now until 2050 to transform the power sector; this includes USD 1.4 trillion for renewable power generation capacity deployment and USD 0.8 trillion for power grids and flexible solutions. Most of these investments, around 75%, are expected to be directed towards G20 nations (IRENA, 2023a).

From an economic perspective, renewable electricity costs are consistently decreasing worldwide, making renewables the most cost-effective power source for different end-use applications. According to IRENA's

[1] *The 1.5°C Scenario describes an energy transition pathway aligned with the 1.5°C climate goal to limit global average temperature increase by the end of the present century to 1.5°C, relative to pre-industrial levels. It prioritises readily available technology solutions, which can be scaled up to meet the 1.5°C goal.*

latest analysis, in 2022 the levelised cost of electricity (LCOE) for newly installed utility-scale solar photovoltaic (PV) projects fell 29% when compared to the cheapest fossil fuel-fired solution. A similar trend is being observed for the LCOEs of onshore and offshore wind, which fell 52% and 59% respectively when compared to the cheapest fossil fuel alternative (IRENA, 2023b).

The increasing competitiveness of renewable energy, along with enabling regulatory frameworks, are bolstering the business case for renewables to dominate the future power generation and end-use mix. However, a majority of the deployments are concentrated in China, the European Union (EU) and the United States, accounting for 75% of total capacity additions. Significant efforts are required to ensure that the positive developments in well-known energy systems can be replicated and tailored to developing nations that lack access to electricity, helping to realise Sustainable Development Goal 7 on ensuring access to affordable, reliable, sustainable and modern energy for all (IRENA, 2023a).

The shift towards sustainable energy calls for a rapid expansion of renewable-based electricity generation. In IRENA's 1.5°C Scenario, a significant increase in electrification is envisaged across various sectors by 2050, with global electricity demand reaching 87 000 terawatt hours (TWh) per year. The renewable energy share in the power generation mix would rise from 28% in 2020 to over 90% in 2050 (in absolute terms, from 7 468 TWh to 82 148 TWh). In terms of generation capacity, with 2020 as a baseline, renewables are expected to increase four-fold (11 174 GW) by 2030 and 12-fold (33 216 GW) by 2050. To be compliant with IRENA's 1.5°C Scenario, in the decade to 2030 the average annual additions in new renewable energy capacity will need to be 975 GW, or three times the total capacity added in 2022 (295 GW) (IRENA, 2023a).

Offshore wind is increasingly becoming an attractive solution that several countries are exploring to accelerate their energy transition efforts. The following sections provide an overview of recent developments in this technology.

1.1 OFFSHORE WIND IN THE ENERGY TRANSITION

The attractiveness of offshore wind as a tangible solution to contribute to the energy transition is attributed largely to the availability of offshore locations, its high energy output and its gigawatt scalability. Offshore wind can provide cost-effective energy services to densely populated coastal areas and is becoming an attractive solution due to positive developments in turbine, foundation and system integration technologies. There is also a push to move offshore wind project sites farther from shore and in deeper waters due to their tremendous energy potential compared to fixed-bottom configurations. Offshore wind is a mature technology and dominates the offshore renewables sphere (IRENA, 2021a).

Denmark deployed the first operational offshore wind farm in 1991 with a capacity of 5 megawatts (MW) (Ørsted, 2023). In the past two decades, the global installed capacity of offshore wind has grown rapidly to reach an estimated 63 GW by the end of 2022. This represents a nearly 20-fold increase from 2010, with Asia and Europe each contributing around half of today's overall installed capacity (IRENA, 2023a, 2024b).

As of 2023, the world's largest offshore wind farm is the United Kingdom's Hornsea 2 project, which has a capacity of 1 386 GW and a total of 165 turbines, each with a size of 8 MW (Ørsted, 2022). The largest offshore wind farm currently under construction is the Dogger Bank project off the east coast of the United Kingdom, where the first set of General Electric (GE) Vernova's Haliade-X 13 MW turbines has been installed. Each of the 107 metre (m) blades on the first operational turbine at Dogger Bank can produce enough clean energy to power an average home for two days with just one rotation (SSE Renewables, 2023). IRENA's findings on the competitiveness of offshore wind are shown in Box 1.

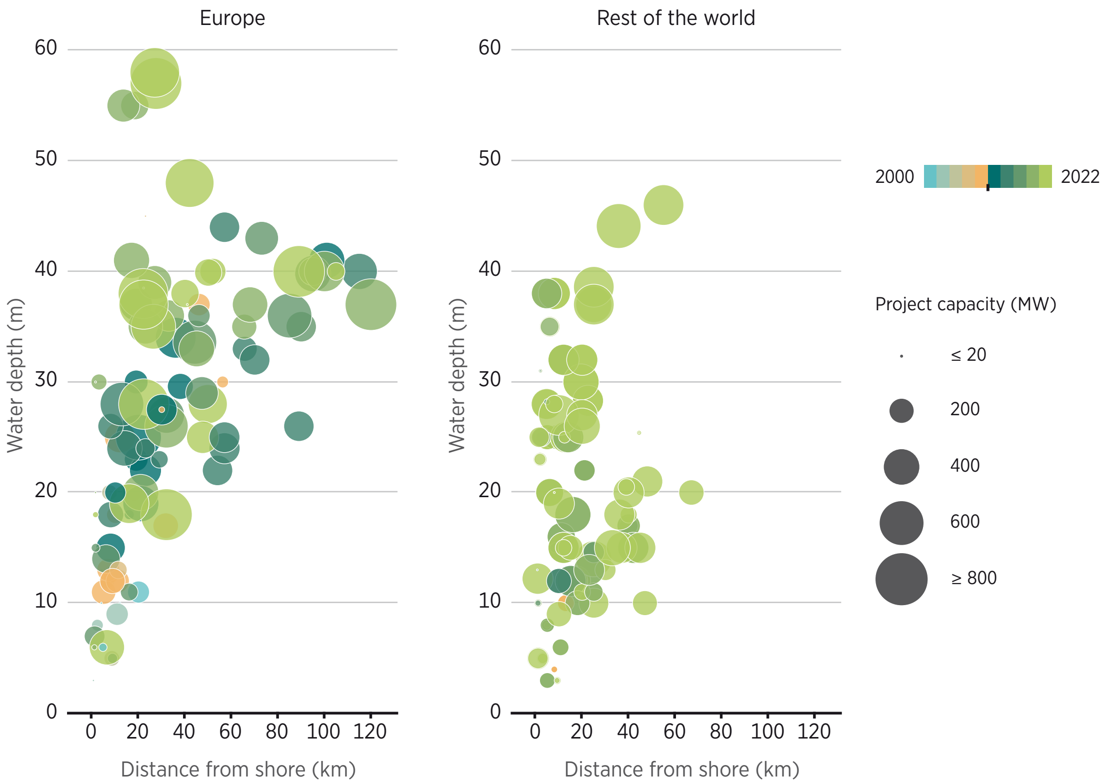
Box 1 **IRENA perspective on the competitiveness of offshore wind**

Because of its offshore location, its high energy output per square metre, and its ability to be built up quickly at gigawatt-scale, offshore wind is a valuable option to provide electricity to densely populated coastal areas in a cost-effective manner (IRENA, 2021a). Given its potential, offshore wind is expected to play a key role in the energy transition towards 2050.

During the period from 2010 to 2022, a massive deployment of offshore wind resulted in a twenty-fold increase in installed capacity. During this same period, the global weighted-average total installed cost fell 34%, from USD 5 217 per kilowatt (kW) to USD 3 461/kW. At its peak in 2011, the global weighted-average total installed cost was USD 5 975/kW, or 1.7 times higher than its 2022 value (IRENA, 2023b). In addition, technology improvements (such as larger turbines with longer blades, higher hub heights and innovations in foundations) as well as new locations (farther from shorelines, where the wind resource increases) are resulting in higher estimated lifetime capacity factors. The estimated lifetime capacity factor for newly commissioned projects increased from 38% in 2010 to 45% in 2017 and then dropped to 42% in 2022.

These trends underscore the potential for significant advancements through the process of learning via research and development (R&D), leading to technological enhancements. Initially, offshore wind farms were situated closer to shore and at shallow depths (see Figure 1) (IRENA, 2022a, 2023b). However, thanks to stronger and more consistent wind resources, research, development, and demonstration (RD&D) initiatives have prompted a shift of wind farms to greater distances from the coast and into deeper waters.

Figure 1 Offshore wind turbine development trends, 2000-2022



Source: (IRENA, 2023b).

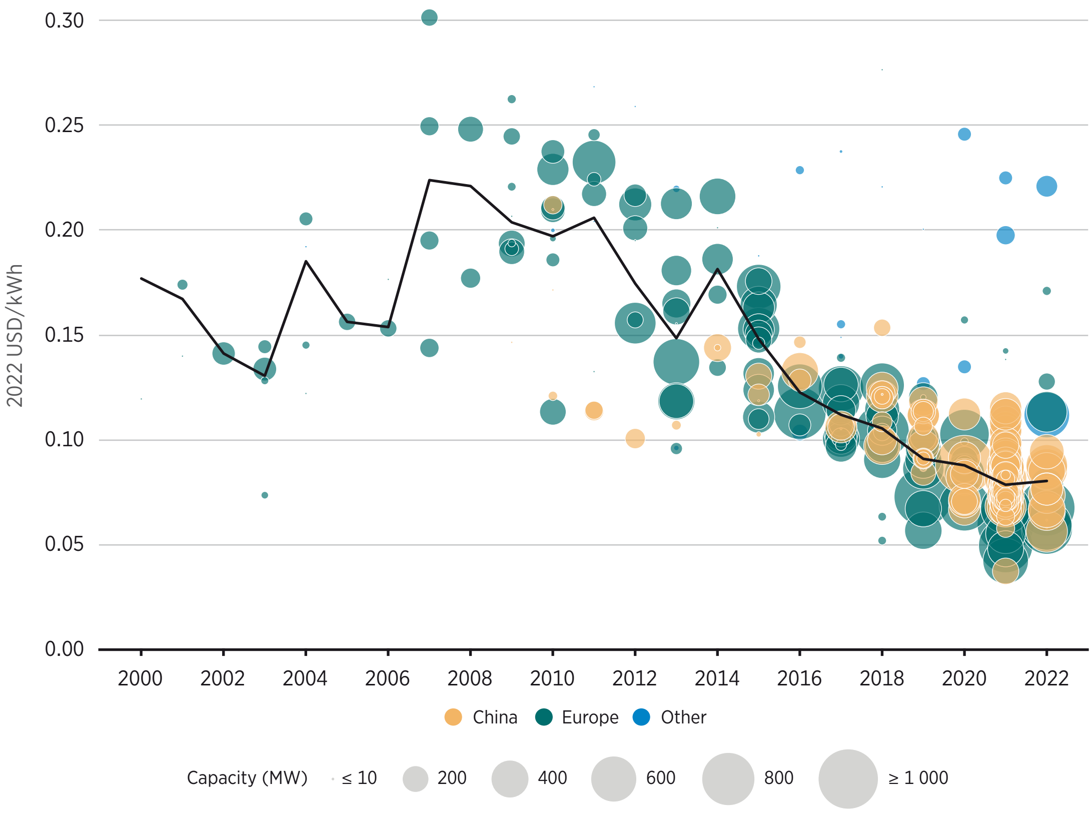
Notes: km = kilometres; m = metre; MW = megawatts.

Box 1 Continued

The technical potential that can be realised in waters deeper than 50 m, mainly through the use of floating offshore platforms, represents an opportunity for countries and regions that have substantial seabed drops (such as Japan, China, the United States and Europe) to position wind farms much farther from the coastline. However, the geographical distribution of offshore wind projects has remained consistent, led by Europe (including the United Kingdom, Denmark and Germany) and Asia (dominated by China and Japan).

The technology improvements discussed above, and the growing maturity of the industry have resulted in a 59% decline in the weighted-average levelised cost of offshore wind for the period 2010-2022, from USD 0.197 per kilowatt hour (kWh) to USD 0.081/kWh (see Figure 2). In 2021 alone, this cost fell 13% year-on-year, although in 2022 a 2% increase was observed (IRENA, 2023b).

Figure 2 Weighted-average levelised cost of offshore wind, 2000-2022



Source: (IRENA, 2023b).

Notes: kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

According to IRENA's latest data and analysis, in 2022 global offshore wind capacity grew to 63.2 GW, which is a positive development considering the impact that the COVID-19 pandemic had on sectoral activity (GWEC, 2023; IRENA, 2023a). However, to comply with a 1.5°C Scenario, the global offshore wind capacity would need to increase to 494 GW by 2030 and 2 465 GW by 2050. According to IRENA's Planned Energy Scenario (*i.e.* business as usual),[2] global cumulative offshore wind capacity is expected to reach 275 GW by 2030 and 1197 GW by 2050

[2] *The Planned Energy Scenario is the primary reference case for IRENA, providing a perspective on energy system developments based on governments' energy plans and other planned targets and policies in place at the time of analysis, with a focus on G20 countries.*

– indicating that targets will not be met at the current pace of sectoral development (IRENA, 2023a). To achieve the 1.5°C Scenario, annual offshore wind capacity additions would need to rise six-fold, with 54 GW added in each year of this decade, compared to the 8.9 GW that was added in 2022 (IRENA, 2023a).

Although the demand for offshore wind energy is expected to grow in the coming years, there are concerns that supply chain activities in the industry face significant strains. A recent study by the Global Wind Energy Council and BCG found that there is increasing volatility in supply chains due to auctions not attracting sufficient bids and/or defects in key components of wind turbines, such as foundations and blades (GWEC and BCG, 2023). The study notes that the after-effects of the COVID-19 pandemic have impacted the capital and operating expenditures (CAPEX and OPEX) for wind projects, in addition to the higher interest rates that financial institutions are applying to new project loans. The study highlights that the variety of policy signals from different governments, as well as increased localisation of manufacturing capacities, are complicating offshore wind supply chain logistics and activities. The development of conducive regional supply chains and the standardisation of key technological concepts are potential solutions to reduce the economic pressures that offshore wind project developers are experiencing.

Over the past two decades, Belgium, China, Denmark, Germany and the United Kingdom have been the leading countries in offshore wind energy deployment in the global market (IRENA, 2021a). However, other countries have outlined plans to become active players in this market. In April 2023, energy ministers from the nine members of the North Seas Energy Cooperation (NSEC) agreed to achieve offshore wind capacities of at least 120 GW by 2030 and 300 GW by 2050 (Wind Europe, 2023a). Sub-national jurisdictions in some countries have set firm targets for offshore wind, for example Victoria in Australia (9 GW by 2040) and Nova Scotia in Canada (5 GW by 2030), (GWEC, 2023).

The following section provides an overview of some of the major offshore wind developments in select countries that have made a tangible impact in the global energy transition discourse.

1.2 OFFSHORE WIND DEVELOPMENTS IN SELECT MARKETS

Europe

Given the geopolitical developments in the region, there has been increased urgency for EU Member States to accelerate their renewable energy transition. At the end of 2022, Europe had a total offshore wind capacity of 30 GW, with the leading countries being the United Kingdom, Denmark, Germany and Italy. The REPowerEU programme seeks to wean the region off fossil fuels while removing obstacles to green energy deployment, such as complex permitting protocols for commissioning offshore wind projects (IRENA, 2023c). In early 2023, the European Commission presented its Green Deal Industrial Plan, which comprises, among others, the Net Zero Industry Act (aiming to strengthen the EU's industrial base for clean technologies), Critical Raw Materials Act (to increase Europe's capacity to source and refine critical raw materials) and more flexible state aid rules (GWEC, 2023).

United Kingdom

The United Kingdom is a leader in the European offshore wind space. In 2022, the country **added an estimated 3 GW of wind power capacity, with 90% of this being offshore wind** (GlobalData, 2023). The compound annual growth rate in this UK sector is projected to be 14% between 2022 and 2030, with cumulative capacity reaching 40 GW (GlobalData, 2023).

In October 2023, the world's largest offshore wind farm under construction, Dogger Bank, started producing energy 130 kilometres (km) off the coast of Yorkshire. The wind farm will comprise 277 offshore turbines with a cumulative installed capacity of 3.6 GW and is being installed in three phases: A, B and C. Power from the first offshore turbine at Dogger A is being transmitted to the UK national grid via a high-voltage direct current (HVDC) transmission system for the first time ever. The blades on the offshore turbines are GE's Haliade-X 13 MW turbines (with a length of 107 m and on monopile foundations) and are among the most innovative in the industry. The project is being managed by SSE Renewables in a joint venture with Norway's Equinor and Vårgrønn (Equinor, 2023a; SSE Renewables, 2023).

France

France has set a **target of achieving an offshore wind installed capacity of 18 GW by 2035 and 45 GW by 2050** (Wind Europe, 2024). As of 2023, the country had awarded 4.6 GW of offshore wind projects (of which 2 GW were operational / under construction), and there were ongoing tenders for 3.4 GW. Annual tender volumes are expected to increase to 2 GW from 2025 onwards as part of the Sector Deal passed in March 2022. France hopes to allocate 15.5 GW of new offshore wind projects within the next 10 years (Vatnøy, 2023a).

In 2024, France's second fully operational offshore wind farm with a capacity of 500 MW was inaugurated. There are 15 offshore wind projects in the pipeline, with 3 of them under the process of construction: Yeu/Noirmoutier (500 MW), Courseulles-sur-Mer (450 MW), Diepe/Le Tréport (500 MW) along with a partly commissioned project (500 MW Saint Brieuc) (Wind Europe, 2024).

The country plans to hold two offshore wind auction rounds in Q3/Q4 2024 with capacities of 1.2 GW and 1.5 GW. In the long term, the government is consulting with stakeholders to identify new sites for offshore wind development until 2050 – an activity which can unlock a further 8-10 GW of capacity within the next couple of years (Wind Europe, 2024).

Germany

At the end of 2022, the **total offshore wind installed capacity in Germany was 8 GW** (European Commission JRC, 2023). The country has set a target for 30 GW of offshore renewables connected to the grid by 2030 (Reuters, 2023a).

In 2023, Germany's Federal Maritime and Hydrographic Agency (BSH) launched a new development plan to expand offshore wind. The plan provides a detailed overview of the potential locations for new offshore wind farms in the North and Baltic Seas, as well as ancillary considerations such as the tendering schedule and commissioning procedures. Notably, the BSH aims to accelerate grid connections by defining connection systems, specifying cable routes for offshore platforms and ensuring adequate connection capacities. The plan also envisions potential interconnections with other European countries, paving the way for a robust European offshore power grid that seamlessly links individual wind farms (BSH, 2023; Buljan, 2023a).

According to a 2023 report by the Joint Research Centre (JRC) of the European Commission, Germany will place a priority on fixed-bottom offshore wind (European Commission JRC, 2023). However, because of the country's crucial role in the regional offshore wind value chain, Germany can contribute to floating offshore wind developments in Europe. Since 2010, EU Member States have spent EUR 1.42 billion (USD 1.53 billion) on public research and innovation in wind energy, of which Germany accounts for 42% (European Commission JRC, 2023). Among EU Member States, private funding for R&D is concentrated in Germany (and Denmark) due to the presence of large original equipment manufacturers (OEMs) for many offshore wind energy components. Germany ranks second in the total number of innovators in wind energy, according to the JRC's study (European Commission JRC, 2023).

The Americas

United States

The passage and implementation of the Inflation Reduction Act (IRA) in the United States has led to an increased interest in offshore wind. A crucial component of the IRA is the provision of a production tax credit and an investment tax credit for wind and solar energy projects through 2024 – which will eventually become a technology-neutral tax credit that will be available through 2032. The IRA legislation also includes a production tax credit for new manufacturing of clean energy components, which provides equipment manufacturers with a component-specific tax credit for each unit produced domestically (GWEC, 2023). The IRA has tax incentive provisions to support the production of clean hydrogen; however, with regard to coupling offshore wind with hydrogen production, clear plans are yet to be defined related to turbine and electrolyser configurations (IRENA, 2023a; NREL, 2023a).

Canada

Canada has an **offshore wind technical potential of 9 321 GW; of this, 7 282 GW can be made accessible through floating wind technology**, and 2 039 GW could be tapped into by using fixed-bottom foundations (Buljan, 2022).

Starting in 2025, the province of Nova Scotia has decided to offer leases to allow for 5 GW of offshore wind energy by 2030, as well as to couple the energy generated to hydrogen production. To further this coupling, Canada and Germany have established the Canada-Germany Hydrogen Alliance, an agreement to enable Canada to export its green hydrogen to Germany by 2025. The leases for offshore wind development in Nova Scotia will be granted through a competitive bid process jointly managed by the provincial and federal governments, with the first call for bids scheduled for issue in 2025 (Buljan, 2022).

In July 2023, EverWind Fuels announced a USD 1 billion investment to purchase three wind farm development projects (530 MW total capacity) to support Phase 1 of Nova Scotia's green hydrogen and ammonia project. The wind farms will be located and developed at Windy Ridge, Bear Lake, and Kmtnuk, and the energy will be transmitted through Nova Scotia's power grid to the Point Tupper facility, where it will power PEM (proton exchange membrane) electrolysers. The green hydrogen and ammonia plant is being built in partnership with the engineering and construction firm Black & Veatch (Brook-Jones, 2023).

Brazil

Brazil's current government, elected in 2023, has placed a premium on national offshore wind development. The country has **around 8 000 kilometres of coastline, with an impressive potential of more than 1 200 GW of offshore wind**. The recent passage of federal decree 10946/2022 has set clear guidelines on the appropriation of the country's maritime space. Additionally, legislation (PL 576/2021) is being developed to establish a one-stop shop for offshore wind permitting and licencing. Brazil's Wind Energy Association (ABEEólica) is the main institution leading the country's offshore wind development (GWEC, 2023).

Asia

China

China remains the global leader in offshore wind development and **added 16.9 GW of offshore capacity in 2021**. Key areas of the country where offshore wind projects are gaining traction are Fujian, Guangdong, Guangxi and Jiangsu. In its 14th Five-Year Plan (2021-2025), China has committed to further expanding the role of renewable energy in its energy mix, aiming for renewables to contribute more than 50% of total new primary energy consumption. The current model for supporting renewable energy deployment is based on the grid parity model, whereby electricity generated from renewables receives the same tariff as electricity from coal-fired power plants (GWEC, 2023). Offshore wind will continue to play a large role in this endeavour, as evidenced by China's dominant presence in the global wind supply chain (GWEC *et al.*, 2023).

Japan

Japan aims to increase its offshore wind power installed capacity to **10 GW by 2030 and 30-45 GW by 2040** (GlobalData, 2023). In pursuit of these targets, in December 2022 the country resumed public auctions for offshore wind projects, with revised rules such as higher scores for projects with early start dates and a capacity limit of 1 GW that a single consortium can win in the case that multiple ocean areas are auctioned. Japan has already undertaken two auctions, with offshore capacities of 1.5 GW and 1.8 GW, and a third was initiated in January 2024 aimed at allocating 1.1 GW of capacity (MLIT, 2020). The Noshiro Port Offshore Wind Farm, with a capacity of 84 MW, is the country's first commercial full-scale offshore wind farm and became operational at the end of December 2022 (GlobalData, 2023).

Republic of Korea

To reduce its overall greenhouse gas emissions 40% by 2030, and to reach net-zero emissions by 2050, the Republic of Korea is aiming to increasingly harness the potential offered by offshore wind. The country has set a **target of 14.3 GW of offshore wind by 2030, up from the current capacity of 140 MW**. The government has discussed developing a one-stop shop to replace the existing fragmented permitting ecosystem, while simultaneously enabling appropriate site identification and improved stakeholder co-ordination through a single channel (Frias, 2023). In November 2023, the Republic of Korea organised its second auction with a target volume of 1.5 GW for offshore wind projects. The acceleration of offshore development in the country revolves around improving port infrastructure, increasing manufacturing capacity and enhancing workforce skill development (Frias, 2023).

India

In 2023, India's Ministry of New and Renewable Energy released a strategy paper that outlined a tender trajectory for reaching **37 GW of offshore wind by 2030**, as well as identifying 15 pilot offshore wind projects. India aims to leverage its strong supply chain capacity to tap into its offshore wind potential, with the country being the second largest market for gearbox, blade and generator manufacturing in the Asia-Pacific region (GWEC, 2023; Jagdale, 2023). During 2024-2025, the Ministry announced auctions to offer 7.2 GW of offshore wind capacity in the state of Tamil Nadu, and the National Institute of Wind Energy was appointed as the lead institution for the forthcoming bidding process (MNRE, 2024).

1.3 FLOATING OFFSHORE WIND AND REPORT OBJECTIVE

Most of the discussion in this report so far has focused on developments in fixed-bottom offshore wind installations, which are the dominant configuration in the offshore wind sector. However, a second configuration, **floating offshore wind**, is gaining traction among the offshore wind industry and community.

The attractiveness of floating offshore wind stems from the fact that this technological avenue allows for greater access to plentiful wind resources at greater water depths (at least quadruple the ocean surface area when compared to fixed-bottom wind). Floating wind promotes greater flexibility with regard to high wind speed site selection, while also ensuring low social and environmental impact (DNV, 2022).

Japan, under its 2023 G7 Presidency, requested IRENA to undertake a study to provide an overall stocktake of global floating offshore wind developments. The core objective of the present report is to provide the following information on floating offshore wind, which is elaborated further in the subsequent chapters:

1. Technological underpinnings.
2. Market developments.
3. Ancillary considerations with regard to port infrastructure, operation and maintenance, and storage options.
4. Coupling energy generation with hydrogen production.
5. Sustainability aspects with regard to broad environmental impacts and stakeholder considerations.

2. FLOATING OFFSHORE WIND

2.1 TECHNOLOGICAL UNDERPINNINGS

This section provides a technological overview of some of the key components that constitute a floating offshore wind turbine.

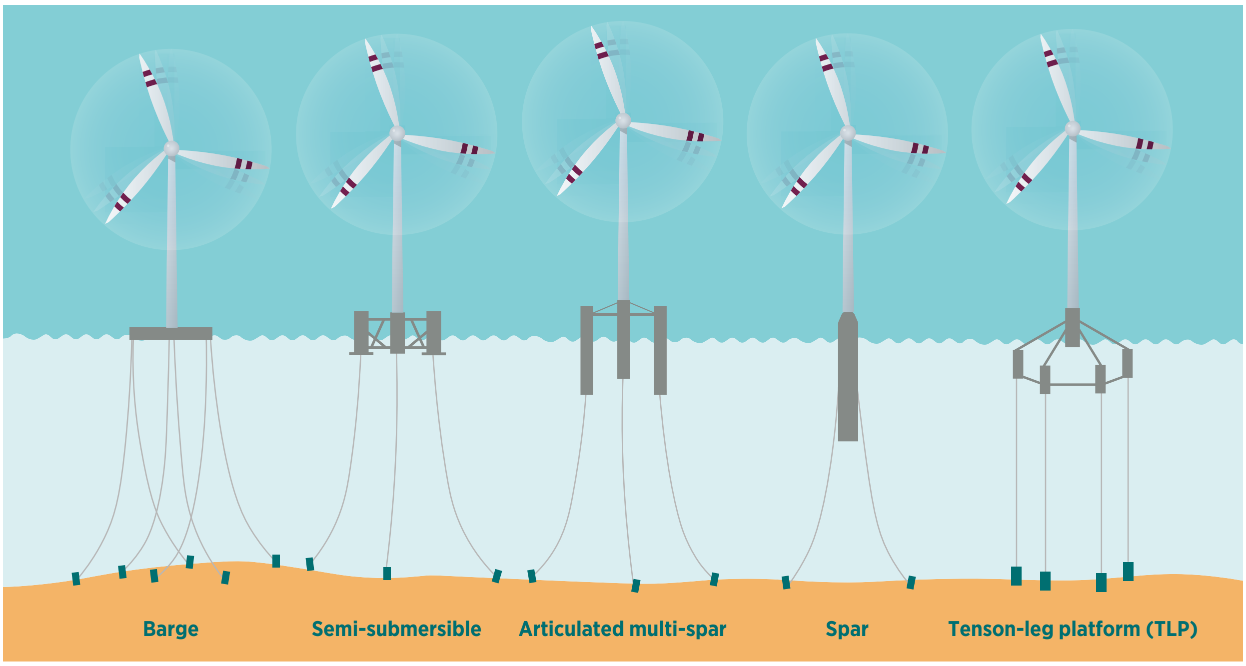
Foundations

The floating foundation – or, more accurately, the floating sub-structure or floating platform – is the dynamic construct on which a floating offshore wind turbine is installed. The turbines themselves are the same as those used for fixed-bottom configurations.

At distances far off the coast, and in deeper waters, it is necessary that floating foundations are strong enough to counteract the thrust and inertial forces of the wind turbine. The foundations must also minimise pitch motions, which will maximise the operational efficiency of the turbines. This stabilisation is achieved through one of three methods: 1) *gravity-stabilised* (by increasing the distance between the centre of gravity and the centre of buoyancy); 2) *waterplane-stabilised* (by increasing the up-and-down movement of different angles of air across water, *i.e.* pitch moment); and/or 3) *moor-stabilised* (with mooring lines) (Edwards *et al.*, 2023).

Considering these stabilisation avenues, there are four major categories of floating foundations: **spar (including articulated multi-spar), barge, semi-submersible ("semi-sub")** and **tension-leg platform (TLP)** (see Figure 3), (Edwards *et al.*, 2023; IRENA, 2021a). The industry does not have a clear consensus on preferences, and state of art suggests that a case-by-case selection is being done depending on factors such as depth and the type of seabed.

Figure 3 Main categories of floating offshore wind turbine foundations



Source: IRENA (2021a).

The main raw materials used to construct floating foundations are steel and concrete. Semi-sub foundations use steel, whereas barge and spar foundations utilise concrete – but these materials can be used interchangeably if required. Steel has been the dominant material in the offshore wind industry; however, there is a push towards concrete, which can reduce the material cost by 50% and lead to 40-50% lower greenhouse gas emissions when compared to steel (Efthimiou and Mehta, 2022a).

Table 1 provides descriptions as well as comparisons of the broad advantages and disadvantages of each floating sub-structure category.

Table 1 Comparison of major categories of floating foundations

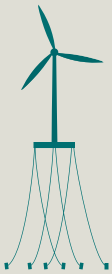
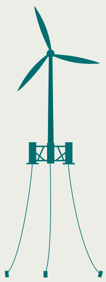
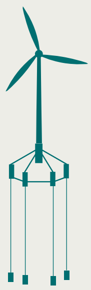
SUB-STRUCTURE	DESCRIPTION	CHARACTERISTICS	EXAMPLES – PLATFORM NAME (TECHNOLOGY DEVELOPER)
BARGE 	The most common structure is a shallow and wide floating platform that sits along the water surface. Water stabilisation is used.	• No need for deep dock or special tow/ installation equipment • Proven technology (70 MW in operation) • Less material required to manufacture than spar • Not dependent on water depth • Lower pitch-and-roll motions (relative to spar) • More deck space for maintenance • Can be constructed onshore or in a dry dock • Fully equipped platforms (including turbines) can float with drafts below 10 m during transport • Barge foundations can offer improved stability by increasing the water plane area as far from the centre of gravity • Lowering the centre of gravity of semi-subs can contribute to their stability, which is achieved by using a ballast (a weight attached to the base of the structure) **Challenges:** • More difficult to manufacture than spar • Large seabed footprint • Larger heave motion	• Damping Pool (BW Ideol) • SATH • Floatgen (BW Ideol) • Deep Wind (Deep Wind Consortium)
SEMI-SUB 	The typical foundation comprises 3-5 vertical cylinders that are connected in a triangular shape and linked by connecting bracings / submerged pontoons. The wind turbine is attached to one of the columns and is stabilised through water and gravity stabilisation. The columns provide the hydrostatic stability, and pontoons provide additional buoyancy. The foundation is kept in position by catenary or taut spread mooring lines and drag anchors.		• WindFloat (Principle Power) • Fuyao (CSSC Haizhuang Wind Power) • Fukushima Shinpu (Mitsubishi Heavy Companies) • Eolink (Eolink) • China Three Gorges (China Three Gorges) • W2Power (Enerocean) • Nezzy2 (EnBW) • VolturnUS (New England Aqua Ventus) • Fukushima Mirai (Mitsuit Engineering) • FPP (Floating Power Plant) • Hakata Bay Scale Pilot Wind Lens (Kyushu University)
SPAR 	The structure comprises a single vertical cylinder with low water plane area, ballasted to keep the centre of gravity below the centre of buoyancy (stabilised through gravity) with a ballast at the bottom. The wind turbine is directly connected to the ballast. The foundation is kept in position by catenary or taut spread mooring lines with drag or suction anchors	• Manufacturing simplicity • Proven technology (118 MW in operation) • Small heave motion • Requires deep operational water (>100 m) for larger turbines **Challenges:** • Difficult to tow, as it requires a deep dock or sheltered area, as well as a large offshore crane to install the turbine • Heavy and large structure that has a high fatigue load on the base • Larger pitch-and-roll motion • Low deck space for maintenance	• Hywind (Equinor) • Tetraspar (Stiesdal) • SpinWind (Gwind) • SeaTwirl S1 (SeaTwirl) • Fukushima Hamakaze (Japan Marine United Corporation) • Deep Wind (Deep Wind Consortium) • Hybrid Spar (Toda Corporation)

Table 1 continued

SUB-STRUCTURE	DESCRIPTION	CHARACTERISTICS	EXAMPLES – PLATFORM NAME (TECHNOLOGY DEVELOPER)
TENSION-LEG PLATFORM (TLP) 	The submerged foundation is connected to mooring lines. A central column is the interface between the foundation and the wind turbine above the surface. The foundation is stabilised through moors and is highly buoyant, with the central column and arms connected to tensioned tendons that secure the foundation to the suction / piled anchors.	• Small heave-and-pitch motion • Low seabed footprint • Can be sited at variable water depths • Light and small structure, which implies lower material costs • Tendency for lower critical wave-induced motions • Can be assembled onshore or in a dry dock • Taut mooring lines contribute to good stability **Challenges:** • Requires a special purpose-built installation vessel • Expensive mooring lines and anchors with high vertical load • A single mooring line failure can result in catastrophic event. • Has a low technology readiness level compared to other categories • No space for maintenance • Not suitable for project sites with large tidal range	• Blue H (Blue H Engineering) • Float4Wind (SBM Offshore) • SWAY (Hybrid spar-TLP by Inocean) • Pelastar (Pelastar)

Based on: (Edwards *et al.*, 2023; Efthimiou *et al.*, 2022a; IRENA, 2019).

Turbine and tower

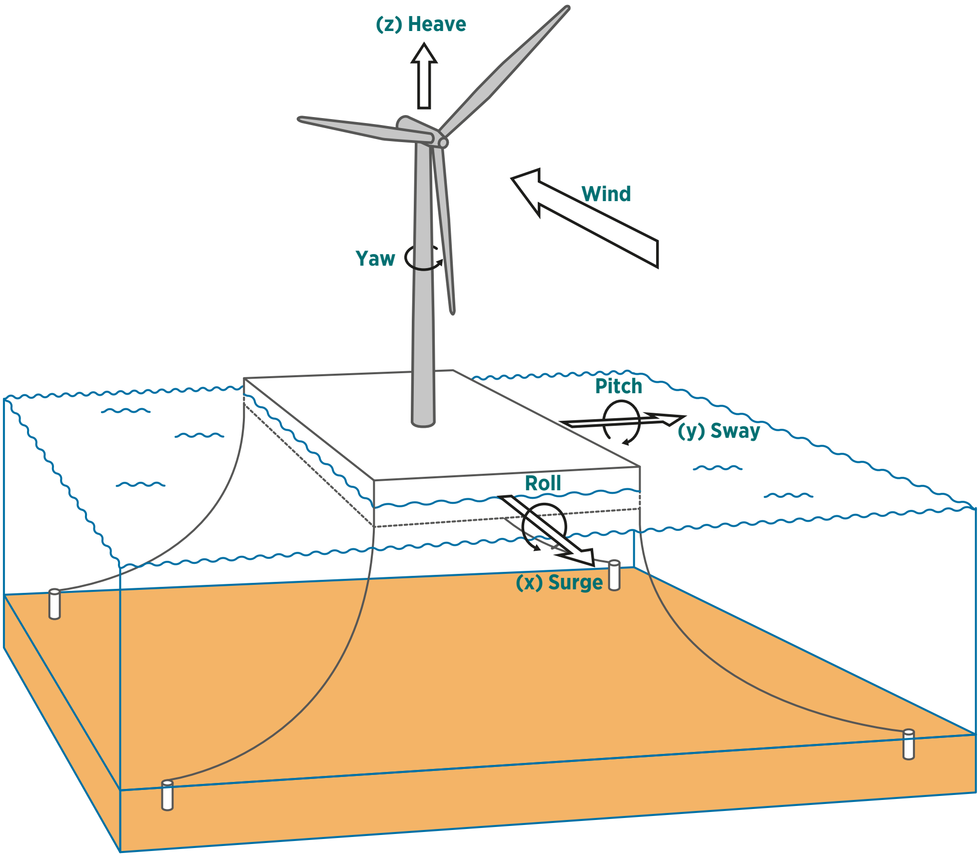
The turbines and towers used in fixed-bottom offshore wind projects are widely adopted for floating applications, with minor modifications. Innovations being explored to optimise the performance of floating systems include co-designing control systems with the tower and platform, as well as making turbines typhoon-resistant (Efthimiou *et al.*, 2022a).

Mooring system

To maintain and control the position of the foundation, a mooring system is required. A key objective of this system is to ensure that the structure remains in a fixed position relative to another fixed point within the site where the foundation is located. The key components of the mooring system are the mooring lines (or tendons) and the anchor, as these elements are responsible for transferring generated forces from the foundation to the seabed. Keeping the foundation stable at great water depths is crucial, as unwanted motions can damage power cables (Efthimiou and Mehta, 2023; WFO, 2022).

The configuration of the mooring system is dependent on several factors, such as the site conditions, choice of foundation, power cables, *etc.*, which all influence the "six degrees of freedom" or motion associated with a turbine (see Figure 4). The system can be characterised as being "compliant" or "restrained". When a foundation has a soft compliance, it means that it is susceptible to motions, whereas a harder compliance implies more stability but, in turn, results in higher mooring loads; hence achieving the correct balance is imperative (Efthimiou *et al.*, 2023; WFO, 2022).

Figure 4 Six degrees of motion for a wind turbine



Surge (x)
Displacement along longitudinal axis

Sway (y)
Displacement along lateral axis

Heave (z)
Displacement along vertical axis

Roll
Rotation about longitudinal axis

Pitch
Rotation about lateral axis

Yaw
Rotation about vertical axis

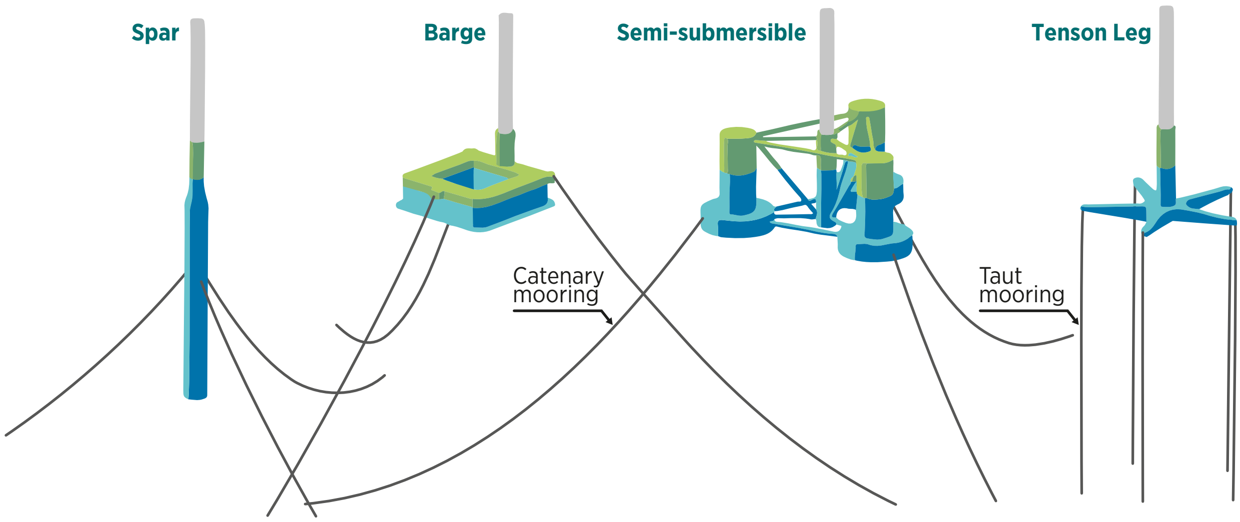
Source: (Efthimiou *et al.*, 2023).

Another important variable with regard to mooring systems is redundancy, or the ability of a component or system to maintain or restore its function after a failure incident has occurred (DNV, 2021). The incorporation of multiple mooring lines at individual anchor points can potentially increase the redundancy of the system, but this simultaneously increases costs – thus, a balance needs to be sought (DNV, 2021).

Mooring lines

The two broad categories of mooring lines are: a) taut lines (made from rope) that originate from the platform to a high-load vertical anchor – used commonly in TLP foundations; and b) catenary lines (made from freely hanging chains), which extend horizontally on the seafloor and have drag anchors at the ends – used in spar, barge and semi-sub foundations (Edwards *et al.*, 2023; Efthimiou *et al.*, 2023; WFO, 2022). Figure 5 provides simplistic illustrations of mooring lines. Connecting mooring lines on the platform above the water surface can allow for easier installation and maintenance (Edwards *et al.*, 2023).

Figure 5 Floating foundation mooring lines



Source: (Edwards *et al.*, 2023).

The categories for mooring lines can be further divided into the following (WFO, 2022):

- **Plain catenary** – chain that is between the anchor point and the floating foundation; typically used at shallow depths.
- **Multi-catenary** – chains that are a hybrid of chain and synthetic ropes (see paragraph below), which achieves stationary motion by taking advantage of the weight and stiffness characteristic of this hybrid composition.
- **Buoyant semi-taut** – a hybrid mooring line with a greater proportion of synthetic rope, with buoyancy modules to prevent damage from contact with the seabed.
- **Taut** – ropes that are under high tension and are connected to the anchor point; this is the main concept behind TLPs.

An innovation in mooring lines that is gaining traction in the floating wind space is the use of synthetic rope fibres (made from polyester or carbon fibre) instead of steel chains. The main advantages of this are the avoidance of corrosion, high fatigue load capacities and low failure rates. The ropes also are conducive to mass production and can be transported to the site easily. Challenges include marine growth on the upper parts of the rope; the ingress of seabed material within the rope (leading to increased wear); and mechanical damage arising from external cuts to the rope (Efthimiou *et al.*, 2023; WFO, 2022).

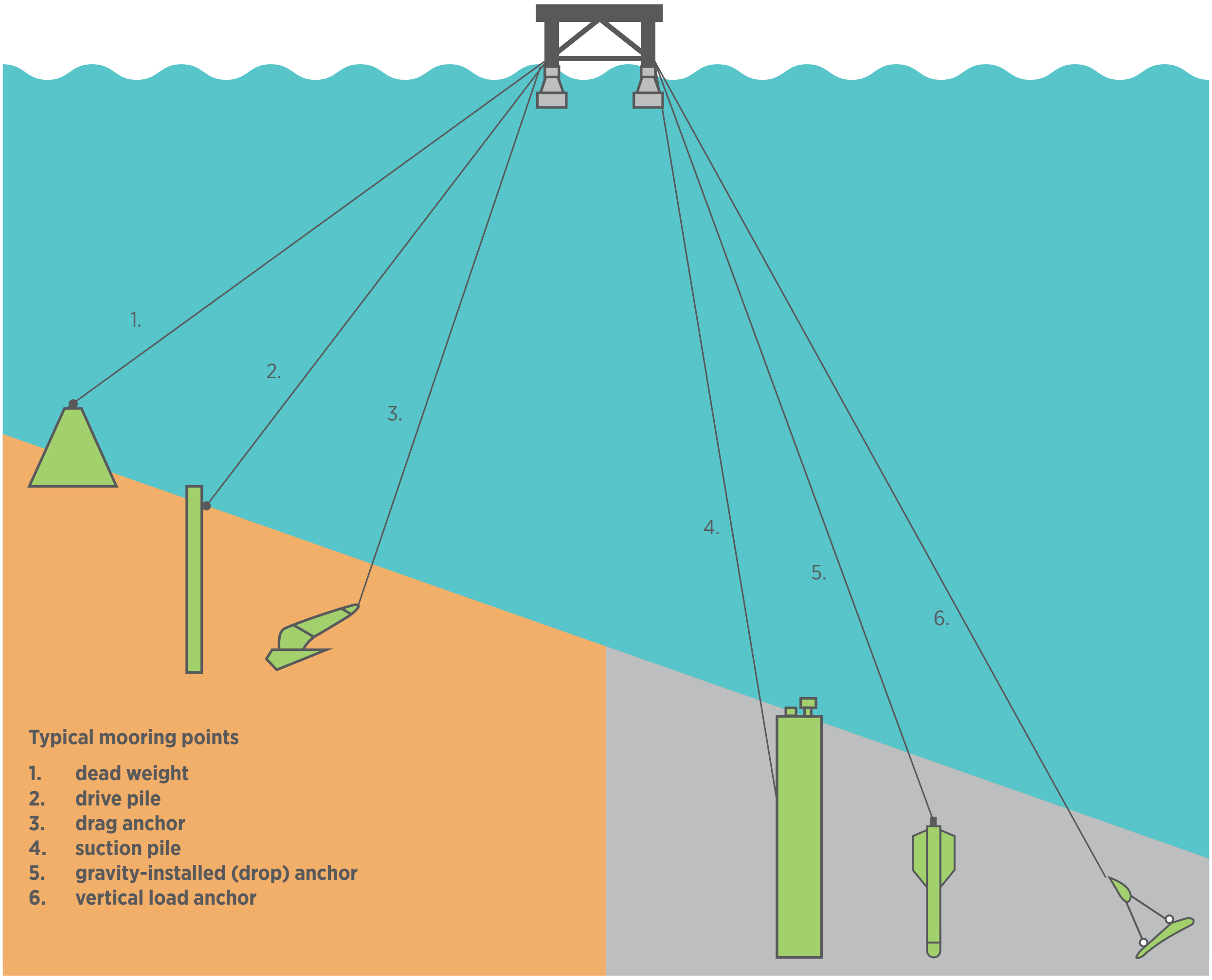
Load reduction devices are another solution that is being fitted to the upper parts of mooring lines to provide additional stability and reduce peak loads (by 50%) as well as fatigue stresses (by 30%). This solution can potentially reduce the length of rope required and serve as a cost-effective solution (providing 5-8% CAPEX savings). Tensioners, featured in the lower part of mooring lines, are also being used to make quick adjustments to the tension of the lines (Efthimiou *et al.*, 2023; WFO, 2022).

TLP foundations sometimes use a single-point mooring system – a taut or catenary system that is attached to a single point on the foundation. Due to this configuration, the platform has degrees of freedom around this point and can align the wind turbine with the direction of the wind – a phenomenon known as "weathervaning". This system can also be used for semi-subs and barges, with its application being common for multi-turbine platforms (Edwards *et al.*, 2023)

Anchors

The anchor is the main interface that secures the floating foundation to the seabed. Different anchor types that can be used include deadweight, driven pile, drag, suction pile, gravity drop and vertical load (see Figure 6). The seabed characteristics largely dictates the choice of anchor, and this will influence the mooring line choice (Efthimiou *et al.*, 2023).

Figure 6 Types of anchors for floating foundations



Source: (Efthimiou *et al.*, 2023).

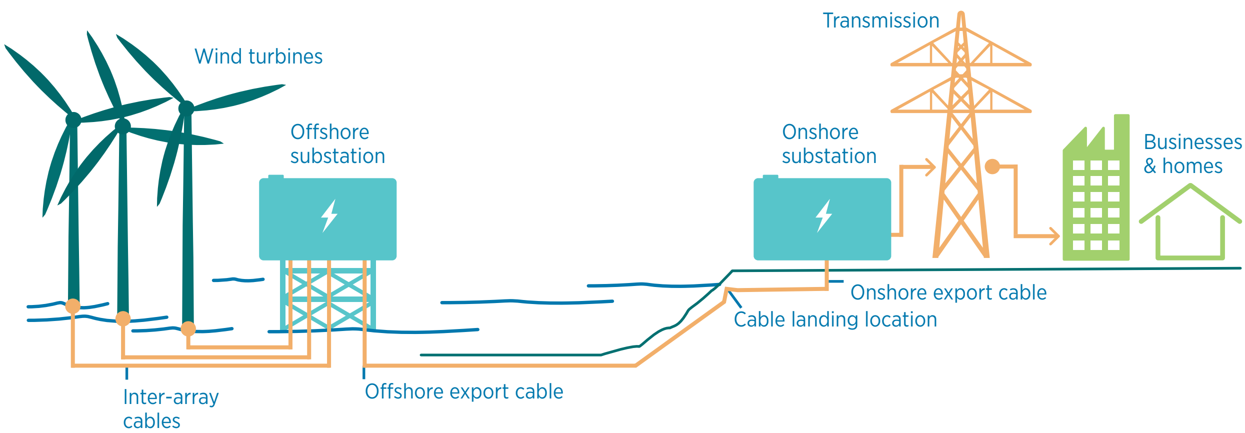
Drag anchors are the most common anchor design choice as they have a high seabed penetration and have resistance to significant loads horizontally. However, drag anchors are not particularly resistant to vertical loads. Other options used by the industry include driven piles, which can be affixed to the seabed with a hammer, and suction caissons, which use pressure to set themselves in the seabed (they can also be recovered following installation), (Efthimiou *et al.*, 2023; WFO, 2022).

Anchors are a very established component. However, an innovation that is being explored is the development of shared anchor systems (in deep water depths) that allow multiple foundations to be connected to a single anchor. For example, Equinor's Hywind Tampen project off the coast of Norway uses 19 anchors for 11 turbines; this is less than the Hywind Scotland project, which has 15 anchors for 5 turbines (BVG Associates, 2023; Efthimiou *et al.*, 2023; WFO, 2022).

Power transmission

To transport the electrical energy from offshore to the onshore site, it is necessary to have a robust offshore power transmission system that can handle these significant power flows. Figure 7 provides a simplistic overview of the key components of an offshore power transmission system.

Figure 7 Offshore wind transmission components – AC export cable



Source: (DOE *et al.*, 2023).

Before cabling for the floating offshore wind farm is even started, the project developer undertakes a detailed survey of the seabed to ensure that no impediments are present; this is followed by the clearing of any debris via a grapnel run. The cable installation involves cable laying, which is then followed by testing and inspection via remote video recordings (BVG Associates, 2023).

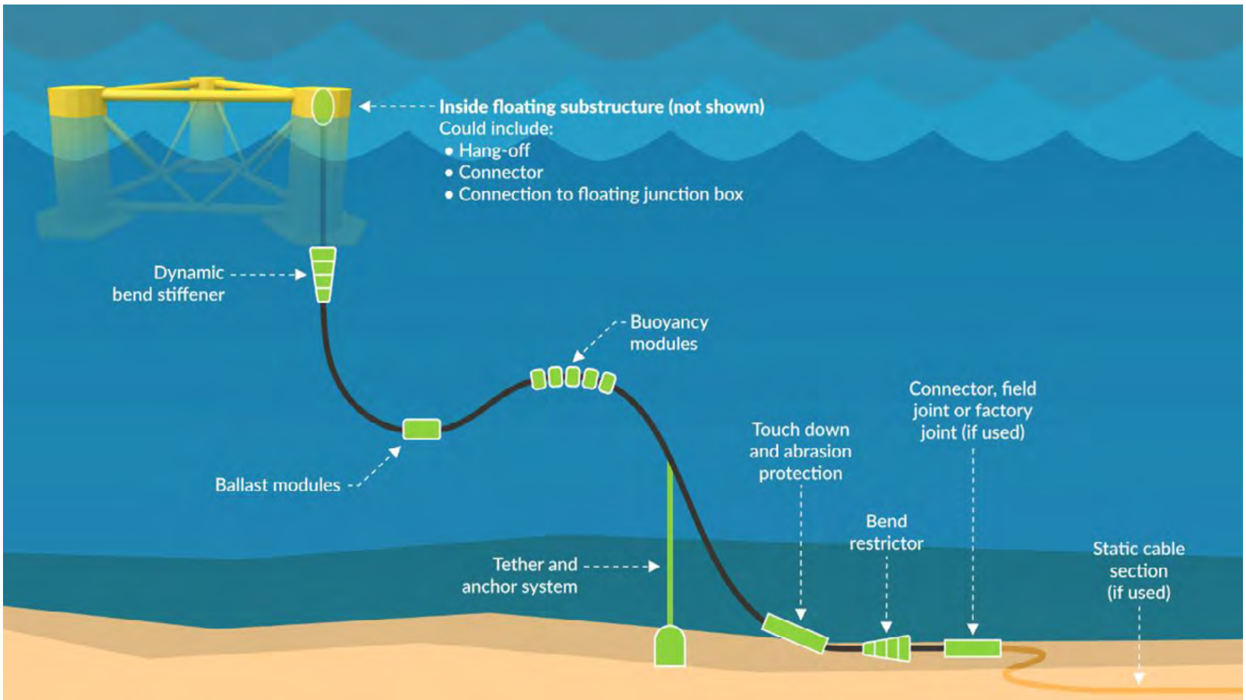
Cables

The cable network sequence for offshore-to-onshore power transmission is as follows: 1) *array cables* are used to transfer the power generated from the wind turbine to an offshore sub-station; and 2) *export cables* are used to then transfer the power from the offshore sub-station to an onshore sub-station.

A standard offshore wind subsea cable features a combination of sealing, insulation and protective layers. Having an insulated power core design is very important, and there are three main insulated power core design types: 1) dry (with a lead sheath); 2) semi-wet (with a polyethylene sheath); and 3) wet (no sheath but has an impervious metallic screen). The wet design is most advantageous due to its light weight and flexibility.

A key element for floating offshore wind cabling is the fact the cables are **dynamic,** meaning that they are designed to follow and withstand the motion of the floating sub-structure caused by wind, waves and current. They are developed specifically to be exposed to saltwater, to have high fatigue loads and to have tolerance to the motions of foundations and oceans. Dynamic cables usually have a non-lead insulator sheath and an additional armouring layer when compared to static cables (BVG Associates, 2023). An overview of the dynamic cabling system can be seen in Figure 8.

Figure 8 Floating offshore wind dynamic cabling system



Source: (BVG Associates, 2023; WFO, 2024).

Array cables

The array cables are usually designed to ensure that they can connect multiple turbines to the offshore sub-station. These cables are dynamically designed between the floating sub-structure and the seabed. The set-up for the cabling can be a single length of dynamic cable between the turbines, or dynamic cables that connect to each turbine with a static cable at the end (BVG Associates, 2023; WFO, 2024).

The array cables can be attached to the floating foundation either before or after its installation. The best practice is to connect these cables to the foundation before its installation, and the same protocol of export cable laying can be used. If the cable is laid after the foundation has been installed, then the cable must be pulled into the offshore sub-station (if it is the first connection in the array or loop). This is then followed by attaching the bend stiffeners and buoyancy modules to cables, and the cable-laying vessel proceeds to lay the cable towards the next turbine at the wind farm array. A remotely operated vehicle is used to hook up the cable to the turbines and offshore sub-station (BVG Associates, 2023; WFO, 2024).

Export cables

The export cable is the key cabling interface that allows for the power generated offshore to be transmitted onshore by linking the respective sub-stations. The offshore export cables are mostly static, as they run across to the shore with a dynamic segment that is connect to the offshore sub-station (BVG Associates, 2023).

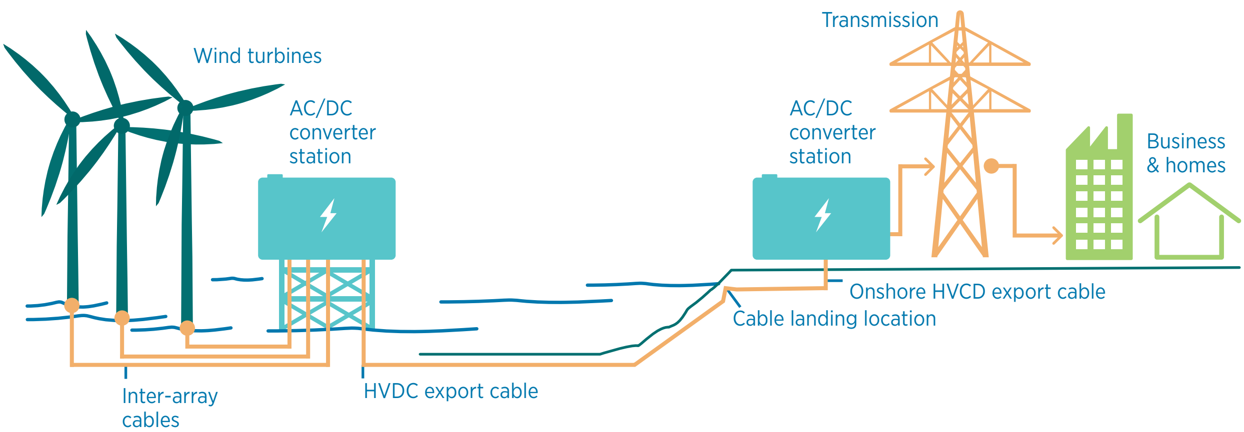
The export cables are laid from the floating wind turbine to the offshore sub-station using a cable-laying vessel. They are sometimes buried 1-4 m under the seabed using a cable plough installed on the vehicle itself. An alternative would be to lay the cable first, followed by a remote operation vehicle to guide the cable and eventually undertake the trenching (BVG Associates, 2023; WFO, 2024).

The subsea section of this cable terminates at a transition joint pit, which is where the offshore export cable connects. After the onshore section of this export cable is laid, comprehensive tests are undertaken to ensure the cable is operating as close as possible to the intended voltage. Following the laying, a test is undertaken to ensure that the cables operate at close to the intended voltage. The export cable is connected to the onshore sub-station (BVG Associates, 2023; WFO, 2024).

An innovation in export cables is the increasing shift towards high-voltage direct current (HVDC) cables, which cater to large projects with at least 1 GW of capacity and are used in locations beyond 80 km offshore. The main advantage of this technology is the reduction of energy losses and the avoidance of additional equipment (such as expensive shunt reactors) to compensate for the excessive reactive power generation of the high-voltage alternating current (HVAC) subsea cable – effects that are directly related to distance and depth.

The main disadvantage of HVDC converter stations is that they are expensive, so they become more cost-effective when project sites are more than 80 km from shore; the stations can provide additional capabilities related to voltage regulation, grid forming and black-start readiness (BVG Associates, 2023). Figure 9 shows an illustration of the power transmission value chain when HVDC is used.

Figure 9 Offshore wind transmission components – HVDC export cable



Source: (DOE *et al.*, 2023).
Notes: HVDC = high-voltage alternating current; AC = alternating current; DC = direct current.

Box 2 provides a few more innovation insights into HVDC, as identified by WindEurope and Hitachi Energy.

Box 2

Recent innovations in HVDC systems

An HVDC system comprises: a converter station that transforms alternating current (AC) into direct current (DC), a transmission line, and another converter station at the end of the chain that converts DC back to AC, which allows for integration of the power into onshore grids for end-use applications (see Figure 9). The two main categories of HVDC technologies are two-line commutated converter (LCC) and voltage source converter (VSC) – the latter of which has witnessed significant innovations over the past 25 years.

VSC converters use insulated gate bipolar transistors, which now have a tremendous voltage level and power range, enabling developers to implement cost-effective deployment of multi-terminal meshed DC grids. Due to continuous innovations, VSC converters have empowered network operators with features such as fast active power control, dynamic AC voltage control, and black-start capability, which all reinforce the transmission system with high availability and resilience. The transistors in VSC converters allow for the precise control and conversion of electric power by working in tandem with advanced control centres.

From a power system security perspective, the HVDC breaker can allow grids to be divided into protection zones and any protective measures can be implemented with high selectivity, as seen in AC grid systems. Hence, if there are faulty lines or short circuits in the HVDC grid network, the breaker will allow for the incident area to be isolated without halting the operations of the overall network. HVDC breakers have a technology readiness level (TRL) of 8 – indicating their high readiness to be implemented in large-scale offshore wind projects.

Source: (WindEurope and Hitachi Energy, 2023).

Cable accessories

Cable interfaces are key accessories to ensure that the cables attach to the foundations as well as to the offshore sub-station. Hang-off clamps are interfaces that allow cables to connect to the offshore sub-station, and pull-in heads allow cables to connect to the floating foundation. Bend stiffeners and bend restrictors are crucial elements to reduce the bending forces applied on cables. Dynamic cables also have their own tether and anchor system to protect the cable from ocean current loads. Abrasion protection sleeves protect exposed cables at the entry/exit from the seabed. Buoyancy and ballast modules are used to keep the cable in a particular shape (*e.g.* lazy wave) to reduce fatigue loads (BVG Associates, 2023).

Offshore sub-station

The main objective of the offshore sub-station is to serve as the interface that connects the array cables (originating from the wind turbines/farms) to the export cables. The configuration of this sub-station comprises an electrical power system (the key element being the transformer), auxiliary systems, a housing structure to hold the components and a fixed foundation (typically a jacket foundation). The sub-station can either be HVAC or HVDC. For the HVAC sub-station, there is typically one sub-station that caters to a single wind farm and has capacities of hundreds of MW. For the HVDC sub-station, several wind farms can be connected in AC (66-132 kV) – often with intermediate transformer stations to increase the voltage – to an offshore HVDC converter station (BVG Associates, 2023).

The offshore sub-station is usually fabricated offshore and installed directly on a jacket/monopile foundation (which has been installed previously). This is a very heavy operation and requires vessels that can handle 2 000 (t) tonnes of weight minimum. If vessels are not available, a barge is used to transport the sub-station to the installation site, and cranes are used to attach it to the foundation (BVG Associates, 2023).

There are ongoing efforts to advance the development of floating offshore sub-stations, which are essential to siting floating offshore wind parks at depths of 100 metres or more. DNV is leading a joint industry project in this regard (DNV, 2023a).

Onshore sub-station

The onshore sub-station has a similar electrical configuration as the offshore sub-station – it includes shunt reactors in the case of HVAC sub-stations, and a comparable converter station in the case of HVDC sub-stations. The main difference between the offshore and onshore sub-station is that the latter is located on land, is close to the export cable and adapts the voltage received from the offshore sub-station to the voltage used by transmission grids – usually 400 kV and above (BVG Associates, 2023).

The same considerations as for fixed-bottom offshore wind installations apply: the onshore node and the surrounding grid should be capable of handling the injection from the floating offshore wind park, avoiding curtailments and guaranteeing power system robustness.

Offshore-onshore network topology options

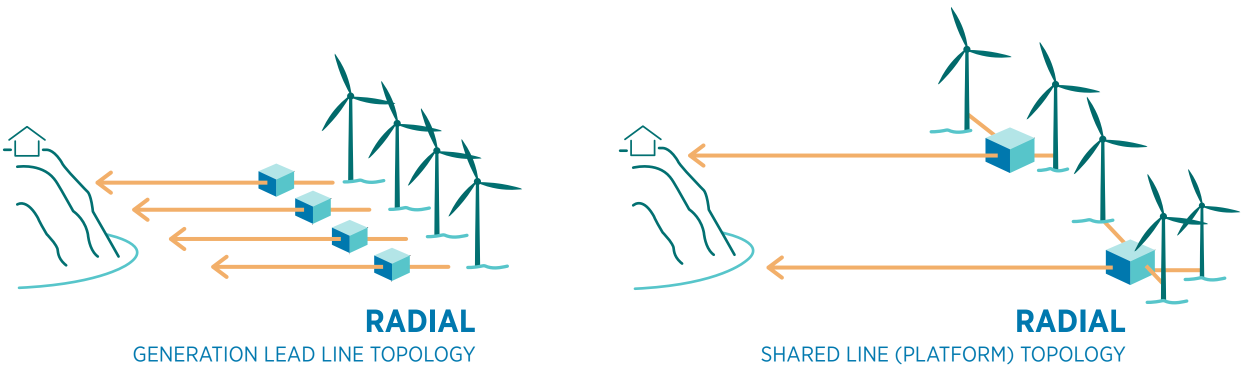
The configurations for offshore-to-onshore power transmission follow two broad categories: radial and network.

In a radial configuration, the power has a single path from the generation to the onshore load, which has the following topologies:

- Generational lead lines connect single wind plants to a single interconnection point onshore. This is the quickest and most common approach used due to the least risk involved (DOE *et al.*, 2023)
- Shared lines allow for two or more wind plants to be connected via a shared export cable; the main advantage is the reduction of cables required, which results in socio-environmental benefits. The main aspect to consider is the requirement of additional co-ordination to achieve this set-up (DOE *et al.*, 2023).

Figure 10 provides a simplistic illustration of the radial offshore network topologies.

Figure 10 Radial offshore network configuration



Source: (DOE *et al.*, 2023).

A network configuration is based on the radial configuration, but it includes offshore interlinks between offshore nodes, or combining one or more offshore nodes with two or more onshore nodes. This design allows for the introduction of multi-directional power flows, which can enable different power rerouting options and also reduce transmission congestion (DOE *et al.*, 2023). These topologies are envisioned for fixed-bottom offshore wind parks, but they are especially challenging for floating parks due to the depths where multiple cables should be placed. Additionally, such developments add complexity to the project, implying a later commissioning horizon, which counters the need for rapid deployment of floating wind offshore to meet the 2030 target.

2.2 FLOATING OFFSHORE WIND MARKET INSIGHTS

Although floating offshore wind projects are not as mature as fixed-bottom offshore projects, they have a potential capacity of more than 13 TW in deep waters worldwide (IRENA, 2021b). Currently, the leading regions in the development of floating offshore wind are Europe, the United States, South-East Asia and China (DNV, 2022, 2023b). The world's first floating wind project, consisting of a single 2.3 MW turbine, was installed in 2009 in Norway. As of 2022, around 200 MW of floating wind projects had been installed, accounting for 0.1% of global wind installations (onshore and offshore) (Enerdata, 2022).

RenewablesUK estimates that the current global installed capacity for floating offshore wind is 277 MW; however, the global pipeline for new floating projects was around 244 GW as of 2023 (pipeline projects grew 32% between 2022 and 2023), (en:former, 2023). Of this pipeline of projects, 175 GW are at early stages of development, 68 GW are in planning and/or with lease agreements, 576 MW are consented or in pre-construction phase, and 46 MW are under construction (en:former, 2023).

Levelised cost of electricity

From a cost-competitiveness perspective, the levelised cost of electricity (LCOE) for floating wind farms has been more than USD 0.2/kWh, according to IRENA's Renewable Energy Cost Database. This is ascribed to the small sizes of farms and pioneering developments (see Figure 11). Technology improvements and the growing maturity of the offshore wind industry are expected to accelerate a cost reduction in floating offshore wind, comparable with the 59% cost decline that occurred for fixed-bottom foundations from 2010 to 2022 (see Box 1) (DNV, 2022).

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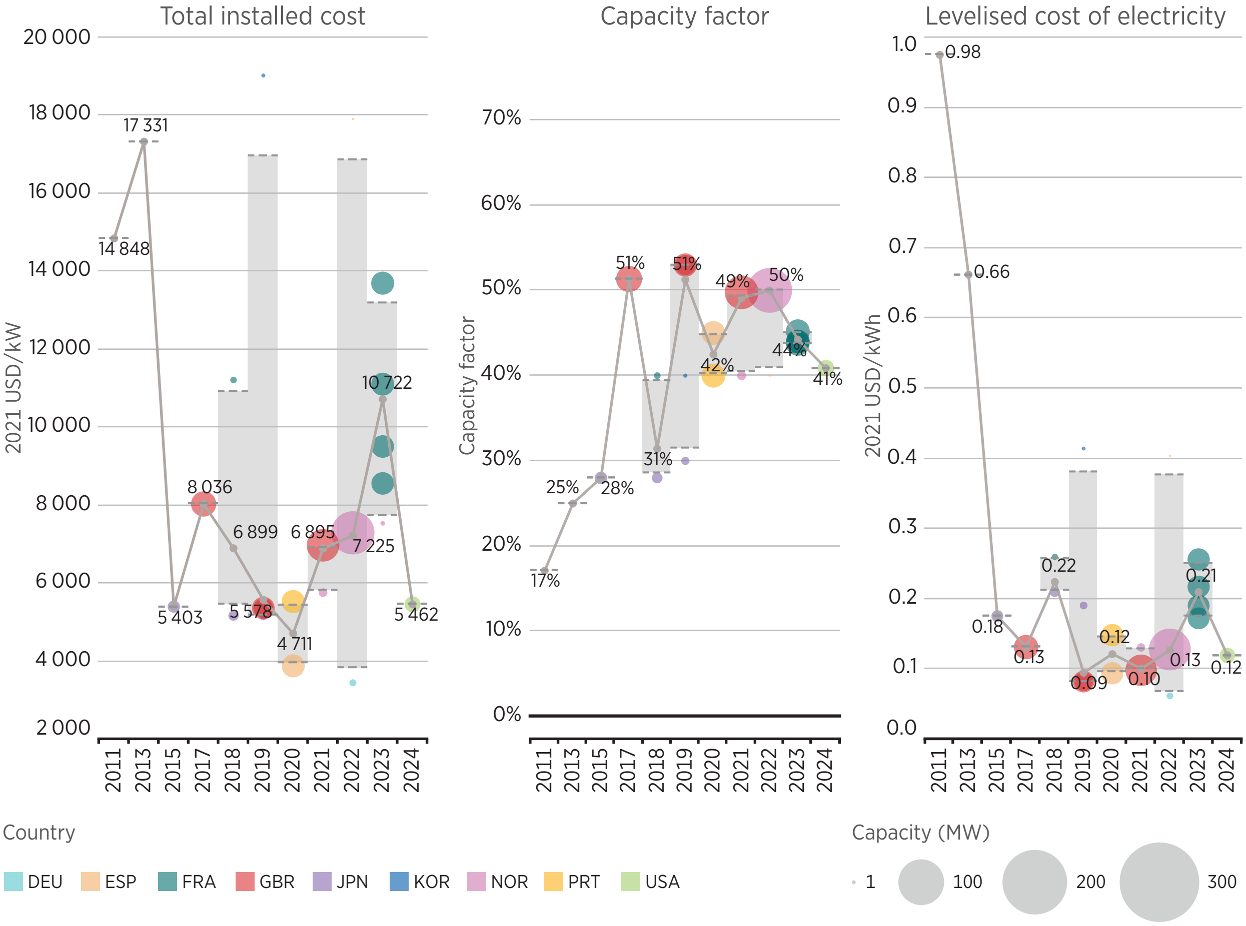
Figure 11 Projections on the competitiveness of floating offshore wind power, 2011-2024



Source: (IRENA, 2023b).

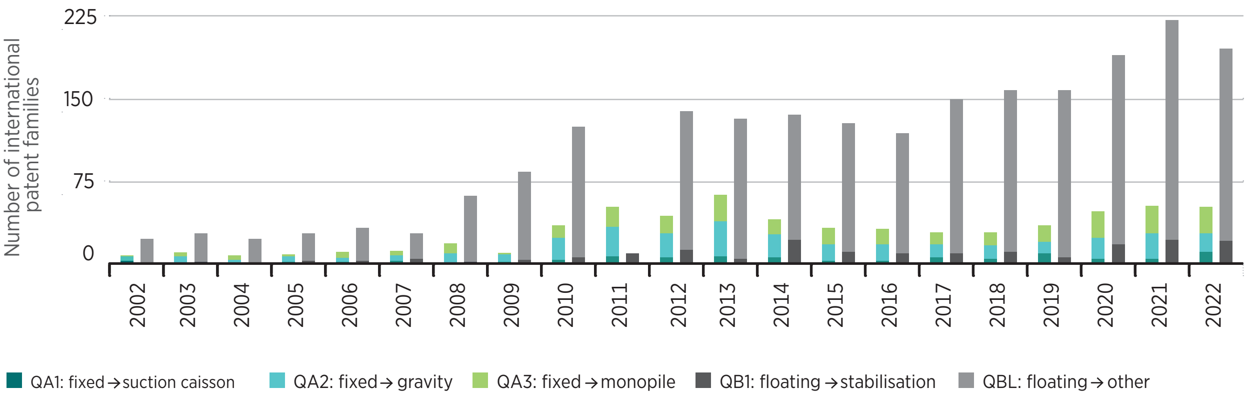
Key opportunities for reducing the LCOE lie in the requirements of raw materials to produce floating sub-structures, the complexity of design and fabrication, and the maintenance requirements due to the motion on the floating sub-structure, turbine and mooring system. Scaling up projects and streamlining operational expenses are driving factors for achieving cost-effective floating foundations. Innovations are specifically targeting these, with the aim of lower maintenance needs and standardised installation protocols (DNV, 2022).

Trends from offshore patent data insights

By examining patent data, innovation trends across technologies can be identified. During the period 2002-2022, the trend of international patent families[3] (IPFs) in both fixed and floating foundation technologies showed an initial increase until 2011-2013, then a subsequent decline, followed by a continuous and ongoing surge from 2017 onwards. On an annual average, a majority of the IPFs (78%) are focused on floating solutions, demonstrating the priority placed by industry on this technology to accelerate the maturation of the offshore wind sector at large (EPO and IRENA, 2023), (see Figure 12).

[3] *IPFs are patents that have more than one country in the list of publications, assignees, inventors or first-priority countries. Using this concept allows for the identification (and exclusion) of single national filings that have no family members in other patent jurisdictions. Patents filed at the European Patent Office, the World Intellectual Property Organization and other regional patent organisations are by default IPFs.*

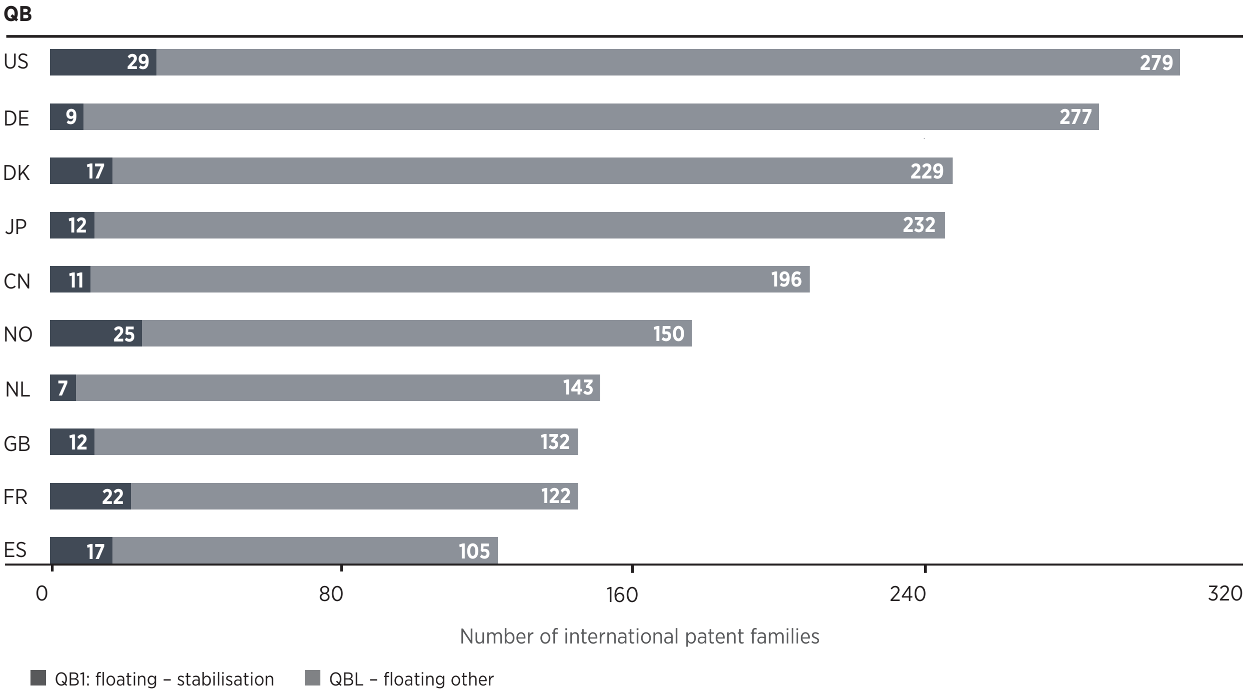
Figure 12 Offshore wind foundation patent trends, 2002-2022



Source: (EPO *et al.*, 2023).

The top five patenting countries for floating offshore wind are the United States, Germany, Denmark, Japan and China (see Figure 13) (EPO *et al.*, 2023).

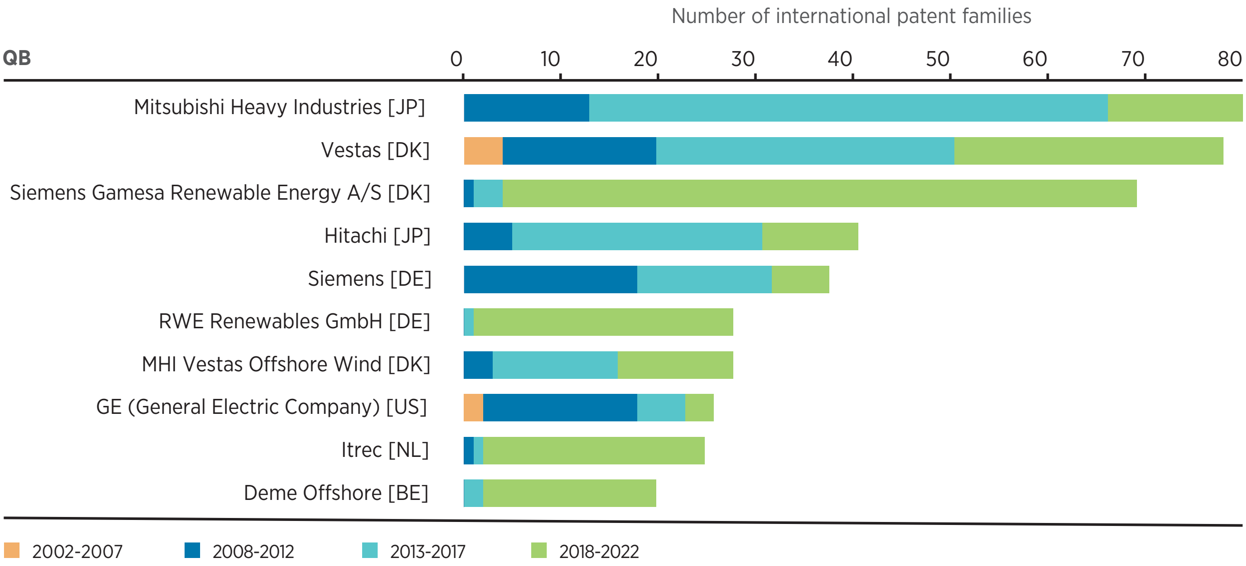
Figure 13 Top 10 patenting countries for floating offshore wind foundations, 2002-2022



Source: (EPO *et al.*, 2023).

Leading companies with regard to floating technologies are Mitsubishi Heavy Industries (Japan), Vestas (Denmark), Siemens Gamesa Renewable Energy A/S (Denmark) and Hitachi (Japan). During 2013-2017, Mitsubishi and Hitachi directed 67% and 63% of their respective IPFs to floating solutions, whereas Siemens Gamesa Renewable Energy A/S dedicated 94% of its IPFs to floating solutions between 2018 and 2022; this provides insights into Europe's increasing pace to scale up floating offshore wind (see Figure 14) (EPO *et al.*, 2023).

Figure 14 Top 10 patenting companies for floating offshore wind foundations, 2002-2022



Source: (EPO *et al.*, 2023).
Notes: BE = Belgium; DE = Germany; DK = Denmark; JP = Japan; NL = Netherlands; US = United States.

Prospects for floating offshore wind development

Floating wind will continue to gain interest among the offshore wind industry. Key outlooks for this technological avenue within the next five years, based on DNV's consultations with industry experts, are as follows:

- Over time, it is envisaged that the number of floating wind turbines in operation will increase. This will provide the industry with more insights on the day-to-day operational requirements, enable it to evaluate the performance of wind turbines effectively and allow for better replacements for components. DNV estimates that more than 40 floating wind concepts are under development, many of which could be announced by end of this decade. Common threads across concepts include the need for mooring lines and installation vessels, and these will continue to evolve as well (DNV, 2022).
- The current cost-competitiveness of floating wind farms is very low, with their LCOEs exceeding USD 200 per megawatt hour (MWh) (compared to USD 50 per MWh for fixed-bottom turbines). This is largely ascribed to the small sizes of existing floating wind farms and to the nascent nature of the technology and supply chain network. The LCOE of floating wind farms is expect to drop to USD 100 per MWh by the middle of this decade, and to USD 67 per MWh by 2050 (DNV, 2023b). The main drivers for this increased competitiveness are the expected development of larger floating wind farms (with 15-50 turbines, up from 3-5 turbines); lower foundation costs due to technology optimisation and standardisation; and efficient OPEX costs (DNV, 2022, 2023b).
- Investments in floating offshore wind projects are expected to gain momentum as the technology continues to mature. To facilitate these investments, governments and industry stakeholders will need to support the creation of stable regulatory environments, foster partnerships and continue to catalyse technological innovation. Markets are also expected to mature with certainty of demand, reductions of risks and the development of new business models to attract investors (especially at early stages) (DNV, 2022).
- Offshore wind is projected to account for 40% of total wind energy production in 2050; floating offshore wind is anticipated to account for 15% of total offshore wind energy, contributing 264 GW by 2050 (DNV, 2022). Many industry stakeholders have expressed confidence that the floating offshore wind industry will reach full commercialisation without any subsidies by 2035; thus, it is imperative that as many floating wind farms as possible are deployed by 2030 (DNV, 2023b).

The following sections highlight recent market and project developments for floating offshore wind in various regions and countries across the world.

2.3 RECENT FLOATING OFFSHORE WIND DEVELOPMENTS

Europe

Floating offshore wind projects are gaining strong momentum in Europe. Norway and the United Kingdom are the leading countries, with France, Spain, Italy and Portugal also ramping up their efforts to develop new projects (en:former, 2023). Floating offshore wind is being explored in EU countries and regions with deep waters (between 50 and 1000 metres), with the perspective that new markets will open within the Atlantic Ocean, the Mediterranean Sea and potentially the Black Sea (European Commission JRC, 2023)

Among foundation concepts, semi-submersible and spar-buoy technologies are the most mature with a technology readiness level (TRL) of 8-9. As of the end of 2022, 27 MW of floating offshore wind was installed in EU sea basins (European Commission JRC, 2023). Between 2009 and 2022, the EU committed EUR 132 million (USD 142) towards floating offshore wind research and innovation under its FP7, H2020 and Horizon Europe initiatives. The EU is funding both the NEXTFLOAT project (a lightweight integrated floating platform system) and MarineWind (a co-ordination project to address bottlenecks in floating wind) (European Commission, 2022; European Commission JRC, 2023; MarineWind, 2024). A total of 18 GW of floating wind is expected to be installed in Europe by 2035 (European Commission JRC, 2023).

Looking to the future, in October 2023 the EU launched its Wind Action Plan with 15 key recommendations to ensure that the region reaches its target of 500 GW of offshore wind capacity before the end of this decade. The actions largely revolve around accelerating deployment, speeding up permitting, and reimagining auction designs. Key tenets that have been welcomed by the wind industry are the inclusion of EUR 90 million (USD 97 million) from the project development pot of the EU's Innovation Fund for wind farm projects over the next three years, and making wind project auctions more attractive by assessing the impact of negative bidding and ceiling prices, as well as including price indexation that factors in inflation vectors (European Commission JRC, 2023; Vatnøy, 2023b; Wood Mackenzie, 2023).

Norway

Norway has taken a leading role in promoting the development of floating offshore wind, with 94 MW of capacity installed (en:former, 2023). The country has a combined offshore wind capacity of 340 GW, and in March 2023 it offered 1.5 GW tenders for up to three 500 MW floating projects in the deepwater Utsira Nord area (Snieckus, 2023). In Utsira Nord, LiDAR technology has been used to undertake wind, wave, current, and environmental measurements, with the objective of improving decision-making processes for the forthcoming three floating wind project areas to be awarded (Norwegian Offshore Wind, 2023).

The largest floating wind farm in the world, Hywind Tampen, became operational in August 2023 with a power generation capacity of 88 MW. This wind farm is located 140 kilometres from shore at water depths between 260 m and 300 m. The project was led by Norway's Equinor and had financial support (around NKK 2.86 billion or USD 267 million) from Enova and the Norwegian Business Sector's NoX fund (Equinor, 2023b).

Norway is also in the preliminary stages of the GoliatVind project, led by Odfjell Oceanwind, Source Galileo Norge and Vår Energi. This will be a 75 MW floating wind array installed at a depth of 400 m in the Barents Sea near the Arctic Circle. The aim is to have the project operational by 2026, with annual electricity production of 300 gigawatt hours (GWh). The wind turbines, with capacities of 15 MW each, will be fitted to the Deepsea Star semi-submersible hub and connected onshore via an existing power line maintained by Odfjell (Snieckus, 2023).

While the Norwegian industry faces many positives, it is not immune to challenges. A recent example of this was the indefinite halt of Equinor's 1 GW Trollvind project due to lack of availability of appropriate technology, supply chain inefficiencies and a strained project timetable (Lee, 2023a).

United Kingdom

The UK government recently raised its ambition by setting a floating wind target of 5 GW by 2030, as part of its broader aim to reach 50 GW of offshore wind by the end of the decade. The UK Crown Estate is looking to allocate 4 GW of floating wind leases in the Celtic Sea by swiftly stepping up to large-scale floating wind arrays. In 2022, Scotland awarded 15 GW of leases to floating wind projects (Ford, 2022).

One of the very first floating offshore wind farms, which became operational in 2017, was the Hywind Pilot Park, built and connected to the grid off the coast of Aberdeenshire in Scotland. The farm is located 29 kilometres offshore and sited in waters ranging from 95 to 120 metres deep. The farm has five spar-type platforms that each host a 6 MW Siemens turbine, with a total capacity of 30 MW. The mooring system consists of catenary lines made from steel wires and chains as well as clump weights (Edwards *et al.*, 2023).

In 2021, Principle Power was able to successfully commission the Kincardine Offshore Wind Farm. This project uses the WindFloat foundation, a semi-sub type that has three cylindrical columns, each with a separate heave plate. The foundation hosts a single turbine connected to a single column, and the mooring system has four catenary lines. The wind farm is located 15 kilometres off the coast of Aberdeenshire in water depths of 60-80 m. The five foundations each support a 9.5 MW Vestas turbine (Edwards *et al.*, 2023).

In September 2023, Buchan Offshore Wind submitted an Offshore Scoping Report to the Scottish Government's Marine Directorate to develop a 1 GW floating offshore wind farm that will be located 75 km northeast of Fraserburgh on the Aberdeenshire coast. If operationalised, the project will support putting Scotland at the forefront of floating wind, offering benefits to the country's offshore wind supply chain as well as skills and employment opportunities (Buchan Offshore Wind, 2023; BW Ideol, 2023; Renews, 2023).

In Scotland, Quantum Energy has committed GBP 300 million (USD 381 million) in equity investment to upgrade the Ardersier Port. This would enable the port to cater to the needs of offshore wind projects in Scotland, the United Kingdom and Europe, as well as aid in the decommissioning of aged oil and gas assets. BW Ideol has acquired an exclusivity agreement to develop a concrete floater production line at the port facility (BW Ideol, 2023).

In November 2023, the UK government increased the maximum price that offshore wind projects can receive in the next Contract for Difference (CfD) auction[4], in response to the challenges facing the global offshore wind supply chain. The maximum strike price was increased by 66% for offshore wind projects, from GBP 44 to GBP 73 (USD 56 to USD 93) per MWh, and by 52% for floating offshore wind projects, from GBP 116 to GBP 176 (USD 147 to USD 224) per MWh, ahead of Allocation Round 6, planned for later in 2024 (UK Government, 2023).

[4] *The CfD scheme ensures that renewable energy projects receive a guaranteed price from the government for the electricity they generate.*

Project Erebus is the first pilot and planned floating offshore wind farm venture that will be located in the Celtic Sea. The project developer is Blue Gem Wind, a joint venture between Total and Simply Blue Energy. The project aims to take advantage of the 50 GW of attainable capacity in the Celtic Sea and is expected to have a total capacity of 100 MW. The foundation choice is WindFloat, and the turbine is yet to be determined. The wind farm is expected to become operational in 2026 (Blue Gem Wind, 2023; Edwards *et al.*, 2023).

France

France has announced that by 2050, half of its total offshore wind projects will be floating; this represents a total capacity of 20 GW in absolute terms (Memija, 2023). To support this goal, the European Commission has approved (under EU state aid rules) EUR 2.08 billion (USD 2.25 billion) to support the construction and operation of a floating offshore wind farm off the coast of South Brittany in France. The aid for the 230-270 MW project will be provided over a period of 20 years through a CfD scheme, and the project is expected to be operational in 2028 (Memija, 2023). In May 2024, BayWa r.e. and Elicio have secured a contract this 270 MW floating offshore wind farm in Brittany (Power Technology, 2024).

The technology provider BW Ideol is leading the operation of the Floatgen project in France, which produced 1.74 GWh of energy during the first quarter of 2023 and has produced a cumulative 25.9 GWh of energy since 2019 (BW Ideol, 2023, 2024). The project has also received two new connection cables, which will serve to support hydrogen production in the future. Floatgen is anchored at a depth of 33 metres and is built on BW Ideol's "Damping Pool" float constructed from pre-stressed reinforced concrete. The floater is held in place by six semi-rendered nylon anchor lines (BW Ideol, 2023; Lara, 2023). The Floatgen pilot project recently upgraded its concrete barge technology to a technology readiness level (TRL) of 7-8, and its inspection for re-certification was carried out by drones (BW Ideol, 2023; European Commission JRC, 2023). France is also testing the tension-leg platform protype (TRL 6) through its X1 Wind project launched off the coast of the Canary islands (European Commission JRC, 2023).

In 2023, EDF successfully installed three floaters of the Provence Grand Large project, which have a combined capacity of 25 MW (8.4 MW per turbine) and are located 40 kilometres west of Marseille in water depths of around 100 m. This is the first project using a tension-leg floater developed by SBM Offshore in co-operation with IFP Energies Nouvelles (Vatnøy, 2023a). During the storm Ciaran that passed through Europe in October-November 2023, EDF reported that 65 GWh of electricity was produced from 30 October to 5 November, which corresponds to average power of 384 MW or 80% of its load factor (Lara, 2023).

France is also working on four smaller projects, each estimated to produce around 30 MW, which should be operational within the next two years (European Commission JRC, 2023). One such project is EoL Med (led by BW Ideol), whose steel blocks will be assembled at Port La Nouvelle, and the construction period is expected to last 18 months, requiring 250 000 person-hours (BW Ideol, 2023).

Italy

As of 2022, Italy had a total installed capacity for offshore wind of 30 MW (TEHA *et al.*, 2023). To be compliant with its long-term strategy of being carbon neutral by 2050, the country's offshore wind capacity will need to reach 20 GW, which will require significant acceleration efforts in this space. Fixed-bottom offshore solutions are not ideal in Italy due to the morphological characteristics of the ocean, which comprises marine areas with deep waters (TEHA *et al.*, 2023).

The oceanographic landscape for Italy is conducive for floating offshore wind developments, with a technical potential of 207.3 GW – making it the third largest potential market, according to the Global Wind Energy Council (Global Wind Energy Council and Ocean Renewable Energy Action Coalition, 2021; TEHA *et al.*, 2023). Sicily (25 GW), Sardinia (20 GW) and Apulia (29 GW) are the regions with the highest floating offshore wind potential and where projects will be sited (Serri *et al.*, 2020; TEHA *et al.*, 2023).

In addition to its maritime characteristics, other key advantages that Italy can tap into to accelerate its floating offshore wind development include its strong steel manufacturing capabilities (ranked second in the EU-27) and its experience in building ships and vessels (ranked first within Europe) (TEHA *et al.*, 2023).

Industry players have shown growing interest in supporting Italy to develop its floating offshore sector. GreenIT – a consortium between Eni, CDP Equity and Copenhagen Infrastructure Partners – has made commitments to develop three floating offshore wind projects in Latium and Sardinia, which are expected to become operational between 2028 and 2031, with a cumulative capacity of 2 GW (Eni, 2023). BayWa r.e. is leading the development of 14 floating offshore wind plants in Lazio, Apulia, Sardinia and Sicily – with 3-5 projects also expected to become operational in 2030 with cumulative capacities of 2 GW (BayWa r.e., 2024). Renantis and BlueFloat Energy have invested EUR 18 billion (USD 19.5 billion) to develop six floating offshore wind farms in Italy with a cumulative installed capacity of 5 500 MW (BlueFloat Energy, n.d.).

Looking forward, there is a need for Italy to revisit the development of its permitting protocols to ensure that processes are accelerated, as well as to take action to develop a Marine Spatial Planning Framework, which will guide the development of locations that have a high floating wind potential (IRENA, 2023c; TEHA *et al.*, 2023). Additional action areas that Italy will need to consider as it taps into its tremendous floating wind potential are increased investments in the expansion of grid infrastructure and the development of port infrastructure (see later discussion).

Portugal

Portugal has recently taken a strong interest in leveraging floating offshore wind in pursuit of its sustainable energy transition. In 2020, the EU's first floating wind farm – the 25 MW WindFloat Atlantic project with a semi-submersible foundation – was installed in Portugal off the coast of Viana do Castelo (European Commission JRC, 2023). In April 2023, Greenvolt and BlueFloat Energy entered a partnership to support Portugal in achieving its target of 10 GW of offshore wind by 2030. Within this partnership, Greenvolt aims to support Portugal in speeding up its permitting processes, and BlueFloat Energy would lead on the technological expertise related to floating offshore wind (BlueFloat Energy, 2023).

In September 2023, Portuguese association Forum Oceano and Norwegian Offshore Wind signed a Memorandum of Understanding with the objective of strengthening collaboration between their respective offshore wind supplies (Vatnøy, 2023c). During October-December 2023, Portugal announced its first auction for floating offshore wind, with strong interest from stakeholders in Norway. Within the auction, three areas are suggested with a total capacity of 8 GW – Viana do Castelo (2 GW), Leixios (2 GW) and Figueira da Foz (4 GW) – with the first auction aiming to offer seven sites with a total capacity of 3.5 GW. The auction could either follow a centralised model (where grid connection, site exclusivity and 20-year CfD are offered to bidders), or a decentralised model (where only site exclusivity, price and non-price criteria are offered to bidders) (Vatnøy, 2023d).

Spain

Spain is also positioning itself to integrate floating offshore wind into its energy mix. The country aims to install up to 3 GW of floating offshore wind by 2030; to achieve this goal, the government has committed to investing EUR 200 million (USD 216 million) in research and innovation and to prepare a dedicated offshore renewables regulatory framework (Wind Europe, 2023b).

In September 2023, Spain's DemoSATH Floating Wind Project – developed by Saitec Offshore Technologies, RWE and Japan's Kansai Electric Power Co., Ltd – became operational and started providing power to the national grid. The project is a concrete twin-hull barge structure comprising modular and pre-fabricated components. It has single-point hybrid mooring lines (made of chain and fibres) that allows for better alignment with ocean currents. The turbine capacity is 2 MW, and the project is located 3.2 km off the coast of Bilbao at water depths of 85 m (RWE, 2023a).

Spain's first offshore wind auction, that will take place during 2024, is allocating exclusively floating capacity, mainly in the Canary Islands, where companies such as Equinor, Naturgy and Greenalia have plans for hundreds of MW of floating offshore wind (Wind Europe, 2023b).

Asia

Japan

Japan's geographical characteristic as an archipelago has endowed it with the world's seventh largest coastline and sixth largest exclusive economic zone (EEZ), thereby making offshore wind a serious enabler for the country's energy transition efforts (Coca, 2023a). Japan's offshore wind technical capacity comprises around 420 GW of floating wind and 130 GW of fixed-bottom wind, according to the Japan Wind Power Association (JWPA) (JWPA, 2020). The country has set an introductory target for 10 GW of offshore wind capacity by 2030 – awarding 1 GW annually in pursuit of this goal – and aims to have 30-45 GW of capacity by 2040 (METI, 2020).

Japan's Ministry of Economy, Tourism and Industry (METI) has organised auctions for designated offshore wind sites in the Akita, Aomori, Chiba, Nagasaki, Niigata and Yamagata prefectures. The first and second rounds of the auction awarded 1.7 GW and 1.8 GW, respectively, of offshore wind projects, and the third round was initiated in 2024 with the rights to develop 1.1 GW of projects to keep in line with Japan's 2030 target.

JWPA projects that 60 GW of floating wind turbines could be installed in Japan by 2050 to meet the country's carbon neutrality goals (Reuters, 2023b). In 2021, Shell, Equinor, and Ocean Winds, together with Japanese companies, formed a group with the aim to achieve a floating wind target of 2-3 GW in Japan by 2030; this is in recognition of the fact that Japan has very large seabed drops off the coast and floating wind generation potential of 8 000 TWh, which is eight times higher than the country's annual electricity demand (Buljan, 2021; Coca, 2023a).

Between 2020 and 2021, several European companies – including Aker Offshore Wind and Mainstream Renewable Power, BW Ideol, RWE and SSE Renewables – expressed interest and signed agreements with Japanese partners to develop floating offshore wind projects (Buljan, 2021). In 2023, RWE together with Mitsui & Co., Ltd and Osaka Gas Co., Ltd. were among the winning bids during an METI auction to develop a 684 MW commercial offshore wind project off the coasts of Murakami and Tainai in Niigata prefecture (RWE, 2023b).

In November 2023, the Japan Renewable Energy Institute (JREI) launched a study on the country's offshore wind power potential in its territorial seas and EEZ. The analysis found that the technical capacity of floating offshore wind in Japan is 542 GW[5] when excluding the country's territorial seas and contiguous zones, but this potential rises to 733 GW when these areas are considered, under the same assumptions. The top three regions for floating offshore wind in the country are Hokkaido (173.5 GW), Kyusyu (173.0 GW) and Tohoku (61.4 GW). In terms of foundation choice, JREI notes that the semi-submersible floating type is the preferred option at water depths of up to 50-90 m, while various types of floating type technologies can be used especially at depths beyond 100 m (Tetsuo, 2023).

To support reaching carbon neutrality by 2050, the Japanese government is ready to commit USD 153.8 billion to activities related to hydrogen production, the integration of renewable energy and enhancing energy efficiency measures. Japan will be expanding its grid development plan, ensuring a level of investment that will be eight times higher than investments in the last decade. A key infrastructure project is the establishment of an HVDC undersea cable from Hokkaido to Honshu. For floating offshore wind, the government has allocated JPY 34.5 billion (USD 220 million) for investing in local manufacturing capacities to produce wind turbines, floating foundations and sub-stations (METI, 2023a).

The government is considering enacting legislation to allow offshore wind farms to be built in Japan's EEZ. The current model permits offshore wind farms to be built in the country's territorial waters within 12 nautical miles (around 22 km) from the coast. To accelerate floating offshore wind developments, stakeholders are requesting that project development zones be expanded, given rising fears that suitable project zones could become less available in the future (METI, 2023a). In March 2024, the Japanese government amended the Renewable Energy Maritime Utilization Act to allow for the siting of offshore wind farms within the EEZ for a maximum duration of 30 years (Nikkei, 2024). This would expand the location of offshore wind power generation from the current territorial waters to the EEZ.

JWPA and Norwegian Offshore Wind signed a Memorandum of Understanding in March 2023 with the objective of fostering the exchange of best practices as well as ensuring better supply chain integration between both countries to facilitate the development of floating offshore wind in Japan (JWPA and NOW, 2023; Vatnøy, 2023e). In October 2023, Japan also signed a Memorandum of Co-operation and Letter of Intent with Denmark to promote bilateral co-operation in the field of renewable energy, including floating offshore wind power generation (METI, 2023b).

Japan's first major floating wind farm, the Goto project, was commissioned in 2018, and construction is ongoing. This project has a capacity of 16.8 MW and was expected to be commissioned in January 2024; however, this was delayed to January 2026 due to design issues with the spar platform (Argus, 2023; Toda Cooperation, 2023). The wind farm will feature eight 2.1 MW Hitachi turbines installed on hybrid spar-type, three-point mooring floating foundations offshore of Goto City in Nagasaki Prefecture (Durakovic, 2022a).

China

China's floating offshore technology is gradually advancing and offering new opportunities in untapped markets. The first floating wind platform, CNOOC Guanlan, became operational in 2023 and is positioned 136 km offshore of Wenchang (Hainan Province) in waters deeper than 120 m (Lewis, 2023). The platform has

[5] *JERI has taken the following parameters as assumptions: annual wind speed of 8 metres per second (m/s) or higher, territorial seas plus the contiguous zone in the EEZ, and water depth of 50 m or higher but less than 200 m, considering the fact that as distances and water depths for floating projects increase, the operational CAPEX costs increase substantially.*

an installed capacity of 7.25 MW and can produce up to 22 GWh of electricity (Buljan, 2023b). In May 2023, China National Offshore Oil Corporation (CNOOC) announced the installation of a five-kilometre subsea cable, which has established a transmission link between the offshore oil and gas platforms of the Wenchang oilfield to the floating wind platform (Liu, 2023).

China also successfully installed the first offshore wind turbine for its Qingzhou Four Project, located 67 km off the South China Sea at water depths of 45-47 m. When completed, the project will have an installed capacity of 500 MW. It will have 40 Mingyang offshore wind turbines (MySE11-230 and MySE12-242), which also includes three floating wind turbines with respective capacities of 11 MW, 12 MW and 16.6 MW (Norwegian Energy and Environment Consortium, 2023; Power Technology, 2023).

China is expanding its floating wind ambitions by planning to establish a floating offshore wind farm with a capacity of 1 GW off the coast of Wanning in Hainan Province by 2027, for which a successful feasibility study was completed in 2022 (Aegir, 2022).

The China Renewable Energy Engineering Institute (CREEI) will lead efforts in this area and has recognised the need to leverage its strong equipment manufacturing capabilities as well as its robust raw material processing ecosystem to accelerate floating offshore wind development. Strengthening co-operation with Europe by tapping into the region's excellent environmental survey, engineering design, testing, construction, and operation and maintenance capabilities is also necessary for China to realise its floating offshore wind ambitions (CREEI, 2023).

Republic of Korea

The Republic of Korea has established several partnerships to promote floating offshore wind projects. The Korea Floating Wind Project – a partnership between Ocean Winds and Mainstream Renewable Power, together with Kumyang Electric Co. – aims to establish a 1.3 GW floating wind farm located 80 km from Ulsan City. The project is envisioned to include 60-100 wind turbines at water depths of around 250 m and is anticipated to generate power starting in 2028 (Principle Power, 2023).

In 2022, Shell and CoensHexicon signed a Memorandum of Understanding with Korea Southern Power Co. Ltd to support the 1.3 GW MunmuBaram floating wind project (with 84 Vestas turbines), planned 60-85 km off the coast of Ulsan. However, in 2023 Shell was looking to divest its majority interest in the project due to a lengthy permitting process and cost inflation in the industry (Bassoe, 2023; Durakovic, 2022b; Radowitz, 2021).

The venture firm SK E&S and Copenhagen Offshore Partners recently reached financial close for the Jeonnam 1 project, a 99 MW offshore wind farm off the coast of Shinan County. The project is expected to power 60 000 households in the Republic of Korea, and in tandem with two future project phases (Jeonnam 2 and 3), with 800 MW total capacity, it will support the country's ambitious target of 14.3 GW of offshore wind power by 2030 (Copenhagen Offshore Partners, 2023).

The Firefly Floating Wind Farm Project is another planned project that will replicate and leverage the experience from the Hywind Pilot and Tampen projects (Edwards *et al.*, 2023).

In February 2024, the Republic of Korea awarded a front-end engineering and design contract to Aker Solutions and Principle Power to develop floating foundations for the planned 500 MW Haewoori Offshore Wind 2 and three further 500 MW projects off the coast of Ulsan. Principle Power will lead the design elements of these foundations based on its WindFloat technology, and Aker Solutions will lead in the installation of the inter-array cables, wind turbine integration and co-ordinating port logistics (Aker Solutions, 2024; Principle Power, 2024; Renews, 2024).

The Americas

United States

Two-thirds of the offshore wind potential of the United States is in deep waters, and the country is directing significant efforts and resources towards advancing floating offshore wind technology and projects. According to a 2022 offshore wind study by the National Renewable Energy Laboratory (NREL), the technical potential of floating wind is 2 773 GW, with an annual energy generation potential of 8 972 TWh (NREL, 2022). The country has 6 198 MW of floating projects in its pipeline, with a majority of these initiatives under site control (NREL, 2023a).

In 2022, the Biden-Harris administration launched the Floating Offshore Wind Energy Shot, which seeks to reduce the cost of floating offshore wind energy more than 70%, to USD 45/MWh, by 2035. The United States has set a target to reach 15 GW of floating wind by 2035, which builds on the country's existing goal of deploying 30 GW of offshore wind by 2030 (White House, 2022).

The December 2022 wind energy auction by the US Bureau of Ocean Energy Management (BOEM) drew competitive high bids from five companies, totalling USD 757.1 million for five leases off the shore of California. The leased areas have the potential to produce more than 4.6 GW of floating offshore wind energy. The Gulf of Maine has also been identified as a suitable location for offshore wind projects. The BOEM recently published draft wind energy areas in the Gulf of Maine and the Gulf of Mexico, parts of which may be made available for a lease sale in 2024 that may eventually site floating offshore wind projects.

The Redwood Coast Offshore Wind Project, located in an area of Humboldt County (California) that has tremendous offshore wind potential, is a pilot floating offshore farm that is expected to be operational in 2026, with a capacity of 100-150 MW. The venture will rely on the WindFloat foundation technology (Edwards *et al.*, 2023; RCEA, 2024).

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The US Department of Energy (DOE) is leading on efforts to harness the potential of floating wind in the United States. Among the key activities being undertaken, from a collective budget of USD 50 million, are:

- The DOE is facilitating the ATLANTIS initiative, which is a design programme to determine the best floating turbine configuration by maximising the rotor area-to-weight ratio as well as increasing the efficiency of power generation. Turbine designs are validated by collecting data from a range of experiments across different scales (ARPA, n.d.).
- In 2022, the DOE launched the Floating Offshore Wind ReadINess (FLOWIN) Prize, for which USD 6.85 million has been invested.[6] The objective of the competition is to find solutions that allow for cost-effective domestic manufacturing of commercial floating technologies in US waters. The competition has three phases. In the first phase, applicants must have a commercial design that can be mass-scaled, along with identified requirements to achieve this goal. The second phase focuses on refinement of the design, and the final phase is the development of a roadmap to mass produce the solution (DOE, 2022a). In 2023, eight winners were identified to take part in the second phase of the competition (DOE, 2023a).
- The DOE is managing the National Offshore Wind Research and Development Consortium, which supports R&D projects that directly respond to critical, near-term offshore wind development priorities. California recently joined this consortium, and it is envisioned that the state's membership will allow for the identification of new avenues to make floating wind more competitive in the country (DOE, 2023b).
  - The consortium received funding of USD 3.5 million from the DOE to support five projects on ocean co-use and transmission. The two ocean energy projects will be designed to focus on monitoring protected marine mammals and designing floating arrays for fishing compatibility. Three transmission projects aim at increasing the durability of subsea power cables, evaluating the impacts of grid stability due to new offshore wind connections, and improving grid planning by enhancing offshore wind forecast generation (DOE, 2022b).
- NREL is undertaking a Floating Wind Array Project (2022-2025) that has received USD 3 million in support from the DOE. The project aims to develop an integrated design tool set that will enable a systemic approach for establishing a floating offshore wind farm array, by considering crucial parameters such as the individual floating offshore wind turbines, array layout, mooring lines and anchors, subsea power cables and environmental conditions of the project site. Three tasks from the project are: 1) to develop a model that will determine the strength of anchors and power cable requirements as a function of seabed soil characteristics; 2) building an array model (based on FAST.Farm) that will allow for assessing the environmental impacts of projects; and 3) creating an optimisation framework that will allow the development of a reference floating array design that can be used as a baseline for future project developments (NREL, n.d.).
- The DOE's Pacific Northwest National Laboratory and the BOEM have deployed a floating scientific research buoy located around 24 km east of Oahu, Hawaii to collect and map offshore wind resource, meteorological and oceanographic data (DOE, 2023b).

[6] *The total prize pool is USD 5.75 million, plus up to USD 1.1 million in vouchers for technical support from DOE national laboratories.*

3. FLOATING OFFSHORE ANCILLARY CONSIDERATIONS

3.1 PORT CAPACITY

Unlike fixed-bottom offshore wind turbines, which are constructed mostly offshore, most of the components for floating offshore wind turbines are constructed onshore near waters. Hence, there is a great emphasis on improving the capacities of ports to ensure that they are suitable for the assembly of components as well as the activities undertaken by specialised vessels for mooring and anchors. Some of the variables that are considered when determining a port's suitability for floating offshore wind assembly include the size and draft of the planned foundation, the height of the wind turbines (which will determine the onshore crane requirements for blade fitting), the distance to the offshore project location, and the required vessels to tow components to the offshore site (ABP, 2021; Efthimiou and Mehta, 2022b; NREL, 2023b).

A critical parameter when choosing a port is to ensure that it is as close to the project site location as possible. If a port has a dry dock but has waters with a sufficient draft or barge, this greatly facilitates the load-out of the assembled components. If ports do not have a strong water draft, then an additional step of moving the fabricated elements from the quay into the water must also be factored in. Further considerations include the availability of specialised welding machines, cranes and scaffolding (Efthimiou *et al.*, 2022b). A summary of the key port parameters for floating offshore wind is provided in Table 2.

Table 2 Port requirements to cater to floating offshore wind assembly

PARAMETER	RATIONALE
Shipyard and fabrication facilities	By having equipment and facilities that can support the manufacturing of floating wind turbine components, there is value added to the port by attracting new investors and original equipment manufacturers (OEMs).
Storage space	Because ports usually host multiple floating foundations and components, having suitable quayside (dry storage) and/or harbour basin (wet storage) is preferred.
Water depth	The water depths at the port influence the type of foundations that can be assembled there as well as the shipping vessels that can access the port to transport components offshore.
Cranage	Very few cranes are capable of lifting 10 MW-plus offshore wind turbines onto floating foundations. Sometimes heavy-lift vessels are substituted for cranes to fulfil this objective.
Weight-carrying capacity	The storage and assembly areas of the ports must have high weight capacity factors to ensure that they can adequately sustain the heavy weights of the floating foundations and turbine components.
Interface between fabrication facility and water load-out	If the floating assembly is done in a dry dock, then the water loading for transport comprises either flooding or sinking the area (depending on conditions) with sufficient water drafts. If the floating wind turbine is assembled on the quay, then heavy equipment will be required to load it onto a launching bar for transport to the project site – an expensive process.
Distance to project site	This parameter will determine the weather conditions for transport of floating structures.
Port availability	Because ports are busy hubs, including the floating wind sector is an activity requiring approval from the port manager and other stakeholders.

Based on: (Efthimiou *et al.*, 2022b; NREL, 2023b).

An overview of how ports play an important role in the construction of floating offshore wind turbines is provided in Table 3.

Table 3 Overview of the role of ports in the assembly of floating offshore winds

COMPONENT	PRE-FABRICATION	ASSEMBLY AND LOAD-OUT	TURBINE FITTING	INSTALLATION
Floating offshore wind turbine	• Pre-fabrication of steel/ concrete components. • Turbine blades and tower are manufactured at a dedicated facility.	• Pre-fabricated components are assembled and loaded into port water.	• Turbine tower and blades are installed sequentially or as one whole unit.	• Assembled floating offshore wind turbine is towed out to the project site location and connected to the mooring system as well as dynamic cabling.
COMPONENT	**FABRICATION**	**FITTING**	**INSTALLATION**	
Mooring and anchors	• Mooring lines are manufactured at a dedicated facility. • Anchors can be constructed at port with the right facilities.	• Mooring lines and anchors (*i.e.* mooring system) are assembled at port and kept at the quay until required.	• Mooring lines and anchors are installed at the project site before the arrival of the floating turbine.	
COMPONENT	**FABRICATION**	**INSTALLATION**		
Power cables	• Cables are manufactured at a dedicated facility.	• Cables are taken directly to the project site.		

Based on: (ABP, 2021; Efthimiou *et al.*, 2022b; NREL, 2023b).

Examples of how ports have been used to assemble floating offshore turbines are as follows:

- The five spar foundations for Hywind Scotland were fabricated and fully assembled in Spain. Following their fabrication, the full foundation and other components were assembled in Norway's fjords, which had suitable water depths to undertake this activity. The assembled structure was towed from Norway to the project site in Scotland (Hywind Scotland, 2017; ORE Catapult, 2021a).
- For EFGL's 30 MW floating offshore wind project in the Mediterranean Sea off the coast of France, the columns for the semi-sub foundations were pre-assembled in Türkiye and Greece and fully assembled at the Fos-Sur-Mer shipyard in France. The columns are to be transported to the main harbour at Port-la-Nouvelle, where the other components such as the turbine and mooring system will be installed and then transported to the project site, 16-18 km from the port (Efthimiou *et al.*, 2022b).
- France's Provence Grand Project (25 MW) will be the country's first project to use TLPs, whose foundation was constructed at the metal fabrication site in the port of Marseille-Fos. The steel for the foundation weighs more than 300 t, and the turbine blades are 45 m high and 80 m wide. To be assembled, these components were lifted to water locations with depths of more than 40 m, such as Gloria quay at Port-Saint-Louis-du-Rhône, which is located away from the port's main maritime traffic. The assembled components were towed to the project site in the third quarter of 2023 (Efthimiou *et al.*, 2022b; Provence Grand Large, n.d.).
- BW Ideol's demonstrator Floatgen foundation (barge type) was constructed at the Saint-Nazaire port in France (near Nantes), with the concrete foundation being assembled directly on the construction barges quayed at the port. Other components such as the turbines and cables were brought to the port and stored for between 1.5 and 2 years before the actual assembly of the floating wind turbine was scheduled to occur (BW Ideol, n.d.; Efthimiou *et al.*, 2022b).

Ports are a crucial part of the offshore wind supply chain. As this industry continues to mature, it remains imperative that countries develop their local and regional supply chains to ensure that the floating wind capacities projected for 2030 and 2050 become a reality. It is important that investments are made in ports in order to transform and equip them with the facilities to cater to the floating offshore wind industry (Efthimiou *et al.*, 2022b). For example, ORE Catapult estimates that if sufficient funds are invested to upgrade ports in the Celtic Sea (up to GBP 1.24 billion or USD 1.57 billion), then 3 200 jobs can be created, and these ports would be able to actively lead the manufacturing of foundation, mooring and cabling components; however, government regulatory bodies will be crucial to attract this level of funding (ABP, 2021).

Box 3 provides high-level insights from a recent NREL study on the envisioned port capacity development trends along the west coast of the United States.

Box 3 **Insights on port developments along the US west coast**

In the United States, the main port categories being considered for offshore wind development are manufacturing and fabrication sites (which deal with the production of crucial offshore components); staging and integration sites (which focus on assembling turbine components); and operation and maintenance (O&M) sites. Several ports along the US west coast can support floating offshore wind operations, for example the ports of Humboldt and San Francisco in California, Portland in Oregon and Vancouver in Washington. The average port development site cost with an area of 32 hectares along the west coast is USD 25 million for an O&M type site; USD 458-525 million for a manufacturing and fabrication type site; and USD 700 million to USD 2 billion for a staging and integration type site. The current limitations for port construction and/or upgrading are the long permitting and authorisation times (ranging from 8-25 years from planning to construction), as well as securing stable investment streams.

However, if more resources and funds are directed towards upgrading port networks, there is a tremendous opportunity to benefit states and communities with new employment opportunities (*e.g.* 4 000-6 000 direct manufacturing jobs), and to enable a competitive price for clean energy. There is a need to ensure that communities are consulted in the port development process. For example, many of the planned ports along the US west coast (the Washington coast, Columbia River Basin and southern California) have high community and workforce impacts that prevent them from accessing the local potential benefits from offshore wind ports, due to factors such as linguistic isolation, long periods of unemployment and lower educational attainment.

From a cost-competitive perspective, modelling suggests that the LCOE for floating offshore wind project can increase between 5% and 15% (between USD 70 and USD 85/MWh) as the distance from the port increases from 50 km to 400 km. The largest contributor is costs associated with vessels. The modelling results show that capital costs are not dependent on port proximity or component installation times, as the assembly duration for floating offshore wind components is much longer compared to the transport of these components to the site by vessels.

Supply chain modelling assesses that the United States currently does not have a robust floating offshore wind supply chain network. The west coast will likely rely on supply chains found in other markets to procure raw materials, undertake component production and meet growing workforce demands. Models suggests that a supply chain for floating offshore wind on the US west coast can be cost-competitive by procuring components from regions such as South-East Asia, due to the efficient transport costs that can offset the lower labour and material costs from international suppliers. Incentives within the Inflation Reduction Act (IRA) for offshore wind* can improve the competitiveness further; however, a reliance on imported steel will tilt the geopolitical advantage to international supply chains. The modelling notes that the United States will need to increase its manufacturing capabilities for floating offshore wind energy components as well as start producing raw material (such as steel) domestically to allow for benefits to be gained from the IRA provisions.

Finally, deployment scenarios indicate that investments in the range of USD 15-30 billion will be required to have purpose-built port sites to achieve 25-50 GW of floating offshore wind energy along the US west coast by 2045. California, which has set a significant target for 25 GW of offshore wind capacity by 2045, will require a minimum of two ports that have four staging and

Box 3 **Continued**

integration sites. A supply chain for floating offshore wind on the US west coast could reduce life-cycle CO_2 emissions from vessels by 40% relative to a scenario where components are imported internationally.

*The IRA includes a 10% bonus investment tax credit for offshore wind energy projects that source a prescribed threshold of manufactured products from the United States (known as "domestic content"). The threshold is set at 20% for projects that begin construction before 2025 and scales to 55% after 2027.

Source: (NREL, 2023b).

3.2 OPERATION AND MAINTENANCE REQUIREMENTS

The increasing demand for offshore wind solutions presents opportunities for innovations in operation and maintenance (O&M). However, these requirements need to be balanced with the need to keep the LCOE as low as possible. The increasing distance of floating wind turbines from the shore presents novel O&M considerations that must be factored in (WFO, 2023).

O&M comprises the combined activities during the complete lifetime of the wind turbine to ensure that it functions smoothly and that any associated risks are addressed as soon as possible. The O&M phase becomes operational as soon as the construction work is complete, and the primary purpose is to ensure that financial returns are given to the investors by seeking an optimal balance between operational expenditures and energy yields from the turbines (BVG Associates, 2023).

Operation

Operation typically focuses on the management of assets such as wind turbines, the undertaking of site/remote monitoring as necessary, and marine operation supervision as required. An operations control centre with qualified staff (with knowledge in areas such as logistic co-ordination and equipment management, among others) is responsible for ensuring that the offshore assets are working optimally. Most control centres use a Supervisory Control and Data Acquisition (SCADA), in tandem with others, to gain access to real-time historical data on the wind turbines, sub-stations, offshore crew and vessels. This allows for preventive maintenance to take place if required. Operationally, it is also imperative to have technicians who are certified and trained in areas such as electrical safety, wind turbine rescue, offshore survival, and first aid, among others, to respond to different risks (BVG Associates, 2023).

Maintenance

Maintenance focuses on ensuring the operational integrity of all the components that drive the activities of an offshore wind asset, as well as ensure that operating expenditures (OPEX) are kept as minimal as possible. There are two broad categories of maintenance: preventive (planned) and corrective (unplanned).

- **Turbine maintenance** is a key activity that is undertaken frequently. However, for floating offshore wind, maintenance can be challenging due to the presence of motion (no matter how many control variables are in place). Typical turbine maintenance includes inspection, ensuring the security of bolted joints and replacing any worn parts. Blade inspection, specifically looking for leading-edge erosion, is critical. These activities are undertaken either by drones (using high-resolution digital or thermographic cameras) or rope access technicians. If the damage is too severe, the blades must be towed to back to port/shore, where repair actions are undertaken. Turbine warranties are usually five years, and the supplier provides the technicians within this period (BVG Associates, 2023).
- **Balance of plant maintenance** involves monitoring the integrity of all other components aside from the turbine. For the sub-structure of the floating foundation, it is imperative that any corrosion be identified as early as possible, and this activity is usually undertaken by remote-operated vehicles. These vehicles are also used to check the integrity of the mooring system (usually every 6-12 months) by ensuring that anchors remain embedded in the seabed and that fatigue and wear are kept minimal (achieved through photogrammetry). Visual inspections of buoyancy, load-reduction devices and tensioners are also undertaken. Visual maintenance of cables, connectors, and joints is done remotely, and the electrical integrity is checked using techniques such as distributed acoustic and temperature sensing as well as partial discharge monitoring. The offshore sub-stations are designed to minimise on-site maintenance, although the reliability against fatigue (caused by the dynamics of the floating platform), in components such as the transformer or the gas-isolated switchgear, must still be proven in the long term (BVG Associates, 2023).

- **Statutory inspections** focus on ensuring that all the health and safety requirements relevant for an offshore wind farm are available and kept "up to date". Examples of such obligations include access to advanced communication systems, different medical/survival kits, fire extinguishers, and landing points, among others. These safety-critical items are subject to a statutory inspection regime, and compliance checks are undertaken frequently (BVG Associates, 2023).

Not undertaking proper maintenance measures can result in financial implications for offshore wind project developers and manufacturers. In August 2023, Siemens Gamesa noted that its financial performance for the third quarter of 2023 was not positive because components used in the company's wind farms had experienced increased failure rates (four times for the bearing and five times for the blades). Supply chain issues such as high product costs have also limited the company's progress in expanding offshore activities. To address the quality aspects of its components, Siemens Gamesa has rapidly implemented a stricter process for supplier qualification, re-investigated its factory production lines to ensure that quality standards are met, and focused on a concentrated rather than a broad product portfolio (Eickholt, 2023).

On-site repairs

When heavy repairs are required for floating offshore wind turbines, the most common practice is "tow-to-port", where the turbine is brought onshore for repairs. However, this is not the best avenue as the logistics are complex, weather conditions need to be stable, and there is a shortage of appropriate vessels to undertake this task. Furthermore, established solutions such as jack-up vessels cannot be adapted to the O&M of floating turbines due to crane height limitations, water depths, and high reliance on seabed conditions, among other factors. Some innovations that are being explored to cater to on-site repair of floating offshore wind turbines are **tower add-on cranes** and **platform-based cranes** (WFO, 2021, 2023).

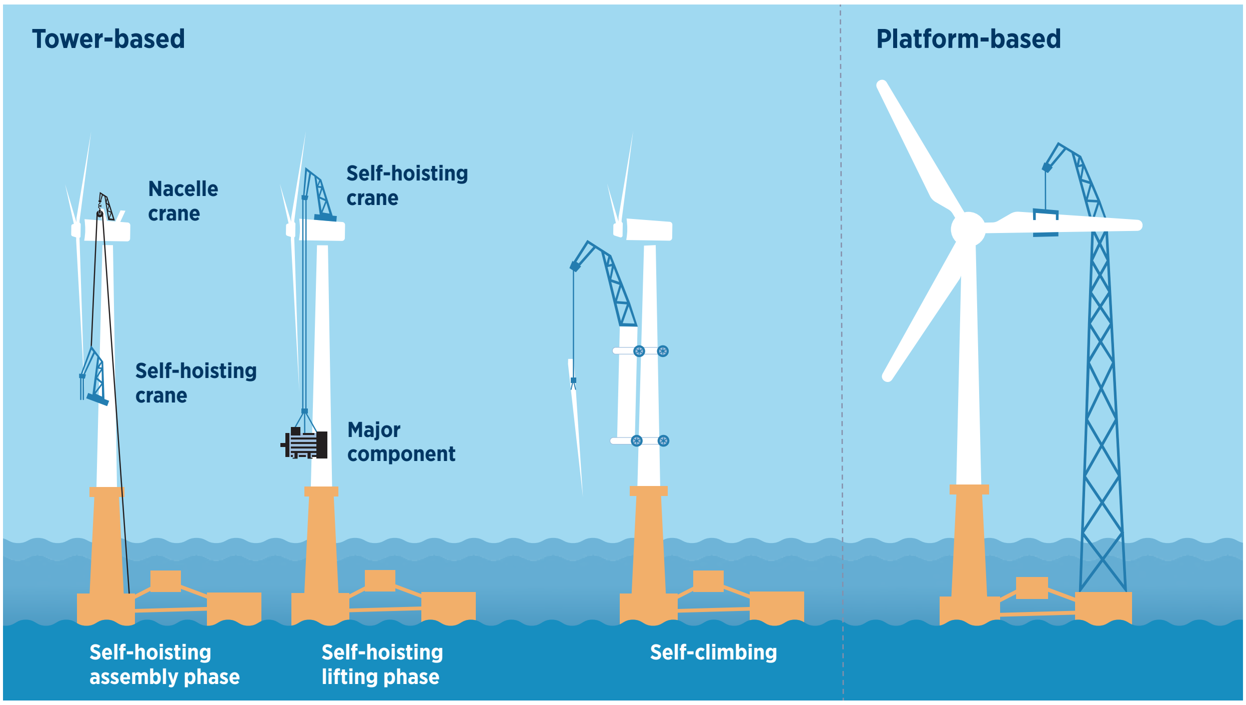
Two main concepts for tower add-on cranes are being tested: 1) **self-hoisting cranes**, which are installed on the turbine using wires attached to the nacelle, enabling lifting operations for components to be undertaken; and 2) **self-climbing cranes**, which use braces/pins installed on the tower to traverse the turbine and contribute to lifting operations for either maintenance or assembly purposes (WFO, 2021, 2023).

Platform-based cranes can be attached to the foundation to undertake maintenance activities. For this solution, additional ballasting needs to be employed to provide counterweight and to ensure the stability of the foundation. Advantages of this configuration include the ability to use existing heavy-lift vessels to install the crane, and freeing up "real estate" space at ports. However, the adaptability of these cranes to different foundations is a challenge, among others (WFO, 2021, 2023).

Both of these crane innovations need to factor in sufficient hook-up/hang-off points, nacelle and baseplate compatibility, access to tower, ballasting and motion compensation as part of the overall on-site technical set-up (WFO, 2021, 2023).

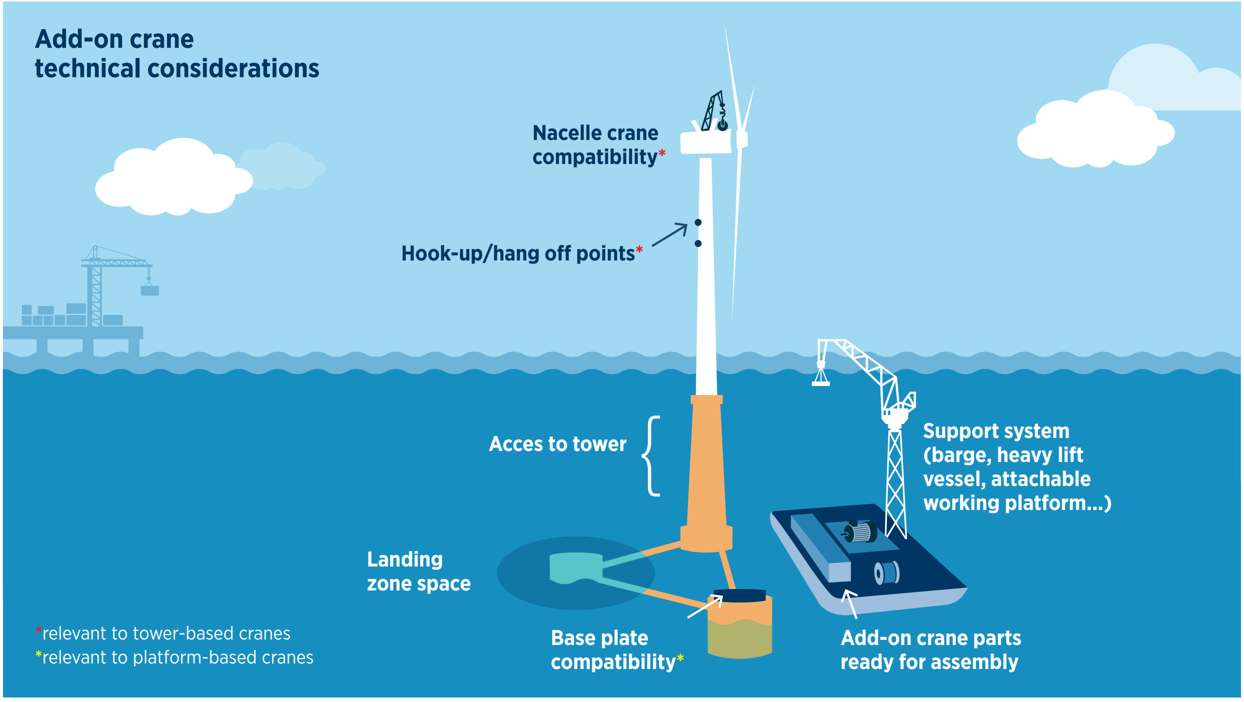
Figures 15 and 16 provide schematic overviews of these two offshore solutions for cranes as well as technical requirements for maintenance activities.

Figure 15 Tower and platform-based cranes for on-site repairs



Source: (WFO, 2023).

Figure 16 Technical design considerations for on-site cranes



Source: (WFO, 2023).

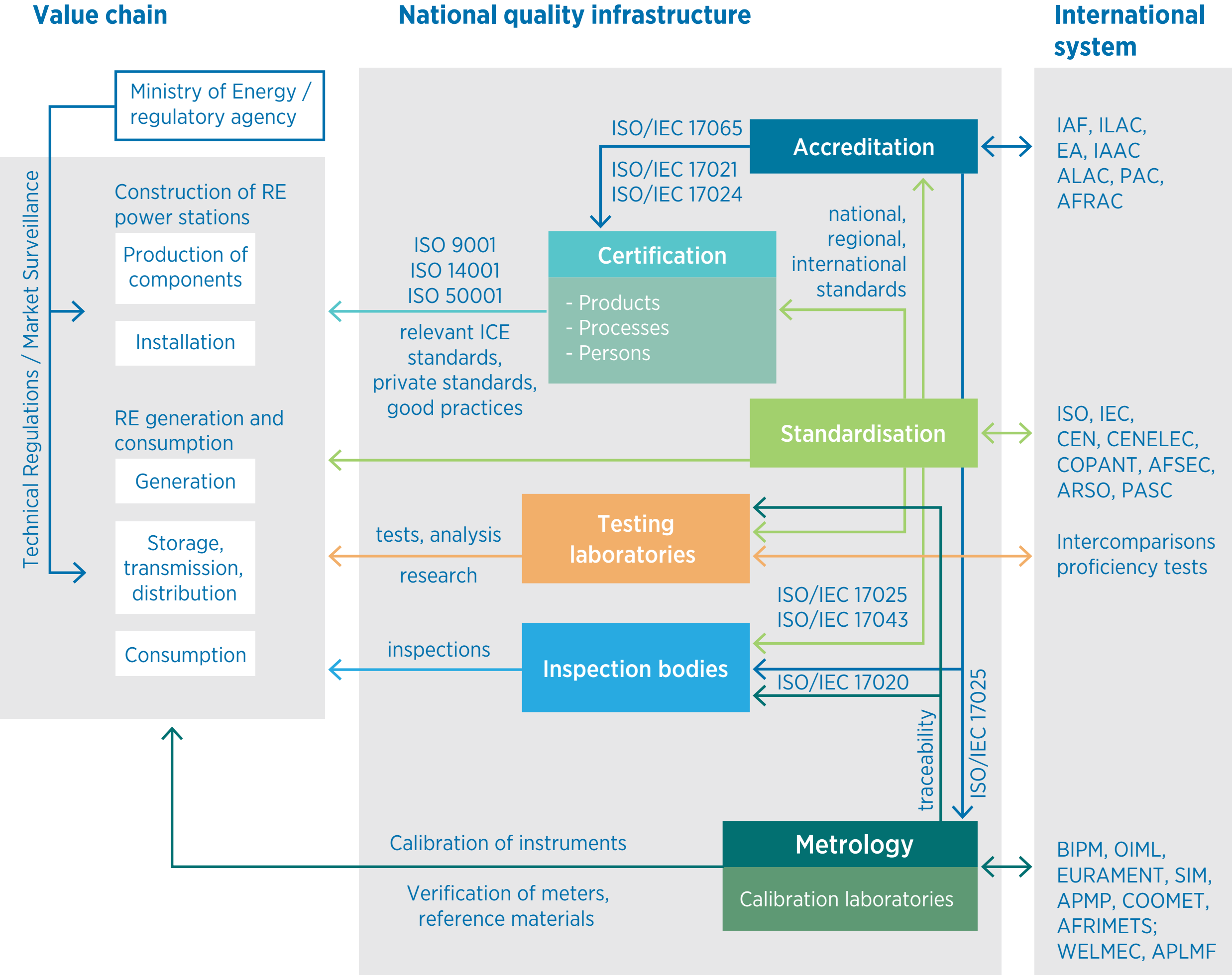
Vessel cranes, which have an established track record in the oil and gas industry as well as in the fixed-bottom offshore wind sector, are also being explored for providing repair services to floating offshore wind turbines. Semi-submersible, mono-hull heavy-lift and new-generation jack-up vessels are some candidates that are being considered; however, this is still a very nascent idea (WFO, 2023). A recent innovation has been the Offshore Heavy Maintenance enabler system (a giant telescopic tower) that is being developed by Dolfines, which can lift standard cranes or tools to compliant heights for many models of offshore wind turbines, to perform blade installation and/or major component replacements. The unique attribute of this system is the ability to be installed quay side at ports or at the jack-up vessel, allowing for flexibility. This system is patented and recently received an "approval in principle" from Bureau Veritas and Marine & Offshore (Boutrot, 2024).

Looking to the future, there is a growing need for investment to make the vessels that are suitable for floating wind operations more accessible. Industry players are observing that the current global fleet of available vessels is facing shortage, largely due to supply chain constraints impacting the predictability of meeting supply and demand requirements (Chetwynd, 2023).

3.3 STANDARDISATION

As the floating offshore wind industry is expected to grow rapidly in the coming years (with potential commercialisation by 2035), it is imperative that a robust quality infrastructure ecosystem for this sector also be established. Quality infrastructure (QI) is the national system of organisations, policies, legal framework and practices required to assure the quality, safety and sustainability of products and services. It comprises the key components of metrology, standardisation, accreditation and conformity assessment – which entails testing, certification and inspection (IRENA, 2015; Kellermann, 2019). Figure 17 provides an overview of how a QI ecosystem is generally structured.

Figure 17 Elements of a quality infrastructure system



Source: (IRENA, 2015).

Notes: AFRAC = African Accreditation Cooperation; AFRIMETS = Intra-Africa Metrology System; AFSEC = African Electrotechnical Standardization Commission; APAC = Asia Pacific Accreditation Cooperation; APLMF = Asia-Pacific Legal Metrology Forum; APMP = Asia Pacific Metrology Programme; ARSO = African Organisation for Standardisation; BIPM = International Bureau of Weights and Measures; CEN = European Committee for Standardization; CENLEC = European Committee for Electrotechnical Standardization; COOMET = Euro-Asian Metrology Cooperation; COPANT = Comisión Panamericana de Normas Técnicas; EA = European Accreditation; EURAMET = European Association of National Metrology Institutes; IAAC = Inter American Accreditation Cooperation; IAF = International Accreditation Forum; IEC = International Electrotechnical Commission; ILAC = International Laboratory Accreditation Cooperation; ISO = International Organisation for Standardization; OIML = International Organization of Legal Metrology; PAC = Pennsylvania Accreditation Centre; PASC = Pacific Area Standards Congress; RE = renewable energy; SIM = Inter-American Metrology System; WELMEC = European Cooperation in Legal Metrology.

Some of the key benefits offered by QI, as identified by IRENA and reinforced by the International Organization for Standardization (ISO, 2023), include but are not limited to the following activities:

- Support the identification of inferior products, thereby protecting fragile components and allowing for greater technological impacts.
- Facilitate market access by providing investment security, which can attract capital from new businesses and contribute to the creation of new employment opportunities.
- Accelerate market expansion where QI can facilitate cost reductions for international trade through the principle of reciprocity based on mutually accepted QI.
- Contribute to the improvement of product/component designs, which can be achieved by stringent testing and certification that facilitate design refinements as well as product robustness.

- Ensure that manufacturers' products conform to the highest market standards, which allows for manufacturers to scale up the volumes produced without compromising on quality.
- Support high confidence in products among end users, due to the assurances that a strong QI system offers and promotes better evaluation of performance metrics.

As stated earlier, the current offshore wind industry is experiencing supply chain barriers that are hampering its growth as well as its sustainability. The major concerns impacting the development plans and financial close for planned projects are high raw material costs and high labour costs. Innovators are exploring many floating offshore wind foundation concepts; however, in tandem there is a strong call from industry players for increased efforts to standardise these concepts to reduce potential strains on supply chains and to promote resource efficiencies (DNV, 2023b; Efthimiou *et al.*, 2022a, 2022b).

Standards

In the context of offshore wind, some of the need for standards is to promote the safety of systems and personnel, ensure system integrity, facilitate uniformity across the value chain, and formalise technical aspects such as procurement and project contracts. Standards for floating offshore wind are available across the value chain, from site selection all the way to decommissioning. ORE Catapult has compiled a list of the important design and certification standards relevant for floating offshore wind (from the International Electrotechnical Commission [IEC], the American Bureau of Shipping [ABS], DNV and Bureau Veritas; see Annex A). Key gaps in their analysis that need to be addressed include the lack of alignment on standards focusing on geotechnical anchor design, no applicable wind standards that apply to very novel design concepts, and no concrete guidance for dynamic sections of cables and synthetic mooring lines (ORE Catapult, 2021b).

Box 4 summarises a recent development for sustainability standards in China.

Box 4 **New sustainability standards proposed for China's wind industry**

China is a global leader in offshore wind power and has recently launched a set of sustainability standards for recycling retired wind turbines. The emphasis is on re-using and recycling turbine blades with the intention of preventing landfilling and burning practices. For blade recycling, the standard encourages manufacturers to use approaches such as heat, chemicals and physical pressure to break the blades. For the blade hubs, towers, and nacelles, the proposed standards encourage recycling through physical blasting and then using magnets to extract any recoverable metals. According to China's Tsinghua Suzhou Research Institute for Environmental Innovation, by 2030 around 35 million t of waste will need to be recycled from decommissioned equipment, with a potential to recover between 100 t and 240 t of steel, copper, aluminium and glass fibre per megawatt of capacity. The proposed standards will be open for consultation before being revised and adopted formally.

Source: (Ng, 2024).

Gaps being addressed: The case of floating sub-stations

One of the major gaps identified in the quality infrastructure for floating offshore wind is related to standards for floating sub-stations. These critical installations are the central node of the offshore wind park, from which the export cables are connected to shore; however, the state-of-the-art for floating sub-stations is not as mature as for floating turbines. One reason is that, for certain cases in relatively shallow waters, a fixed-bottom sub-station can be a compromise solution, where oil and gas offshore expertise can be leveraged.

However, lacking both know-how and early developments of floating offshore sub-stations can quickly become a bottleneck for accelerating the deployment of floating offshore wind, as this is forecasted to make extensive use of deepwater locations.

Acknowledging the key relevance of this gap, DNV has launched a joint industry project (JIP) to promote technology development for floating offshore wind sub-stations, with particular attention to how export cables and topside equipment tolerate movements of a floating sub-structure. In addition to identifying technological and standardisation needs, the JIP is focused on establishing a joint understanding and alignment of best practices for the design, construction, and operation of offshore floating sub-stations. Based on the ongoing work, DNV will update the standard DNV-SE-0145 to specifically address floating sub-stations, together with DNV-ST-0359 on power cables for floating applications (DNV, 2023a).

Certification

Project certification is a well-established practice. It largely focuses on undertaking third-party conformity assessments for completed installations to ensure that these are compliant with relevant technical standards. However, these certification requirements are not mandatory in all offshore markets. For example, the United Kingdom does not formally require this certification but undertakes it as best practice, whereas in Germany and Denmark certification is mandated by law. Most project certification schemes have a modular structure to consider individual requests during this process. Certification schemes usually differ in the mandatory and optional modules, assets within the system boundary and terminology used. Some of the most-used project certification schemes for floating offshore wind projects are IECRE OD-502, DNVGL-SE-0190, DNVGL-SE-0422 and DNVGL-RU-OU-0512 (ORE Catapult, 2021b).

3.4 ENERGY STORAGE

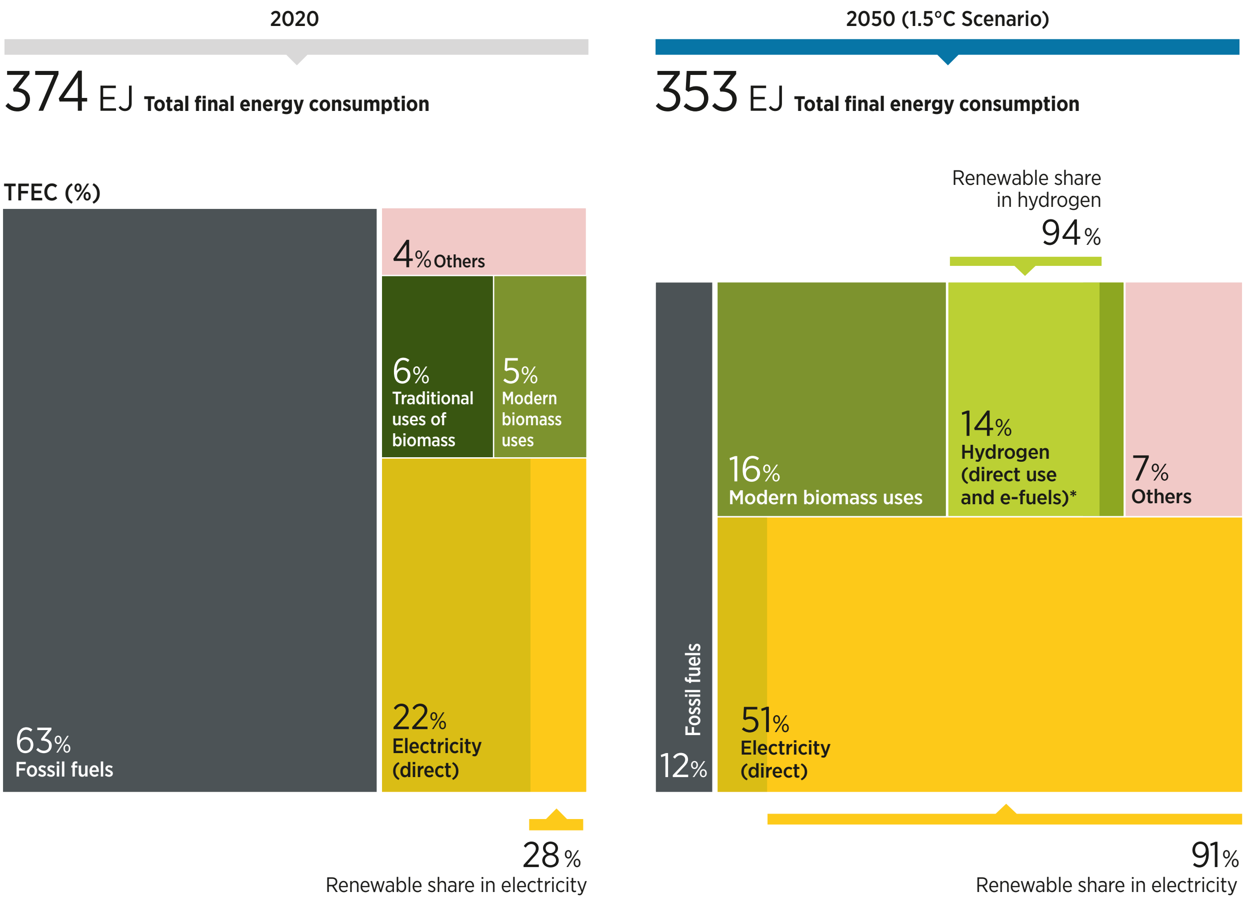
In moments when the energy generated by offshore wind is in surplus (*i.e.* leading to curtailments) or when conditions are not optimal to generate sufficient energy (*e.g.* very low or extreme wind speeds, maintenance, *etc.*), it is advisable that storage options are available so that energy supply and demand from offshore wind can be maintained. While this is still a very nascent area, offshore wind industry players are exploring potential avenues to address this directly at the offshore site. This also implies benefits for powering the ancillary services of the wind park in these situations. Storage options include:

- **Submarine pump storage:** This application takes advantage of the hydrostatic effect of water in the deep sea. A potential configuration for this option is the installation of a hollow concrete sphere on the wind turbine at sufficient water depth. When energy needs to be stored, the electrical energy from the turbine drives a pumping motor, which releases out of this concrete sphere. Meanwhile, when additional energy needs to be generated, water can be let into the sphere, which would allow for the turbine to rotate due to the action of deep-sea hydrostatic pressures (Puchta *et al.*, 2017).
- **Battery energy storage system:** The inclusion of a battery system, at either the turbine or park level, allows (on top of the gross storage and delivery of energy) for overall improvement of the dynamic characteristics of the wind production, by damping oscillations and contributing to voltage stability.
- **Hydrogen:** Leveraging the energy generated by offshore wind to produce hydrogen is an avenue through which energy surpluses can be put to useful work for the provision of ancillary services. Additionally, in some cases where the depths or end uses of energy make it relevant, offshore hydrogen production at a floating wind farm can substitute the electricity transmission to the shore. The potential of coupling floating offshore wind with hydrogen is detailed in the next section.

4. HYDROGEN PRODUCTION COUPLING

To achieve an energy ecosystem that is compliant with a 1.5°C Scenario by 2030 and 2050, IRENA stresses the imperative of augmenting the installed capacity of renewable energy (through an annual tripling in magnitude); improving energy efficiency practices (through an annual doubling in magnitude); and transitioning to the renewable electrification of energy services that are currently supplied by fossil fuels (IRENA, 2023a; IRENA and WTO, 2023). Figure 18 provides a visual representation of the envisioned 2050 energy mix as part of IRENA's 1.5°C Scenario – wherein electrification will play a major role.

Figure 18 Envisioned evolution of total final energy consumption between 2020 and 2050



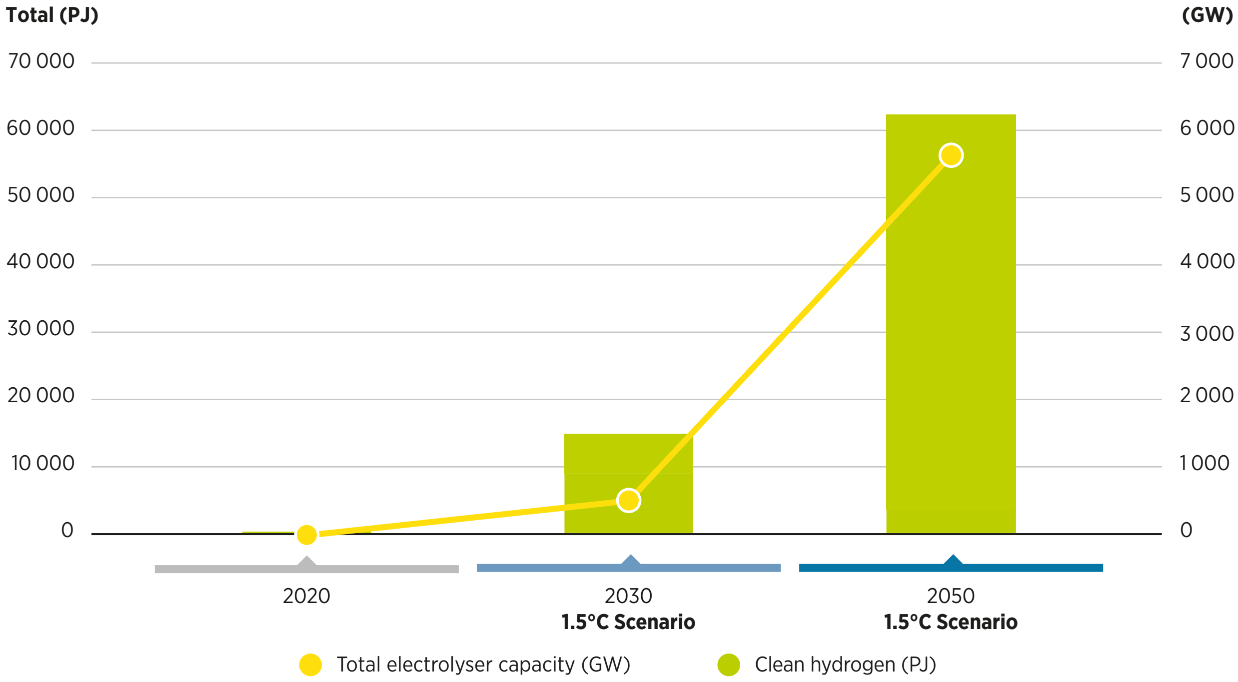
Source: (IRENA, 2023a).

However, not every energy service can be electrified; hence, a renewable molecule is required as either a feedstock or chemical agent as part of the process. Renewable hydrogen, also referred to as green hydrogen, is increasingly being viewed as a promising conduit to interconnect renewable electricity generation with the decarbonisation of hard-to-abate sectors. Hydrogen has diverse applications and, along with its derivatives (such as ammonia and methanol), will contribute to an estimated 14% of the final energy demand in 2050, with 94% of this hydrogen being green (IRENA, 2023a; IRENA *et al.*, 2023).

According to the Breakthrough Agenda 2023, the global consumption of hydrogen reached 95 Mt in 2022. However, so far, the primary source from which this hydrogen is derived is fossil fuels (without carbon capture or storage). The main uses for this "grey" hydrogen are in fertiliser production and downstream chemical processes.

Due to the current composition of the hydrogen production pathway, global emissions from this activity are equivalent to 1100-1300 Mt of CO_2 – highlighting hydrogen's position as a contributor to climate change rather than a mitigator of its impacts (IEA *et al.*, 2023; IRENA *et al.*, 2023). To "clean up" the current hydrogen production pathways, green hydrogen will need to be scaled up rapidly, with the preferred route being through electrolysis. At present, the global installed electrolyser capacity is negligible and will need to increase to more than 5 700 GW by 2050 to accelerate the global deployment of green hydrogen (IRENA, 2023a; IRENA *et al.*, 2023) (see Figure 19).

Figure 19 Green hydrogen supply requirements in 2030 and 2050



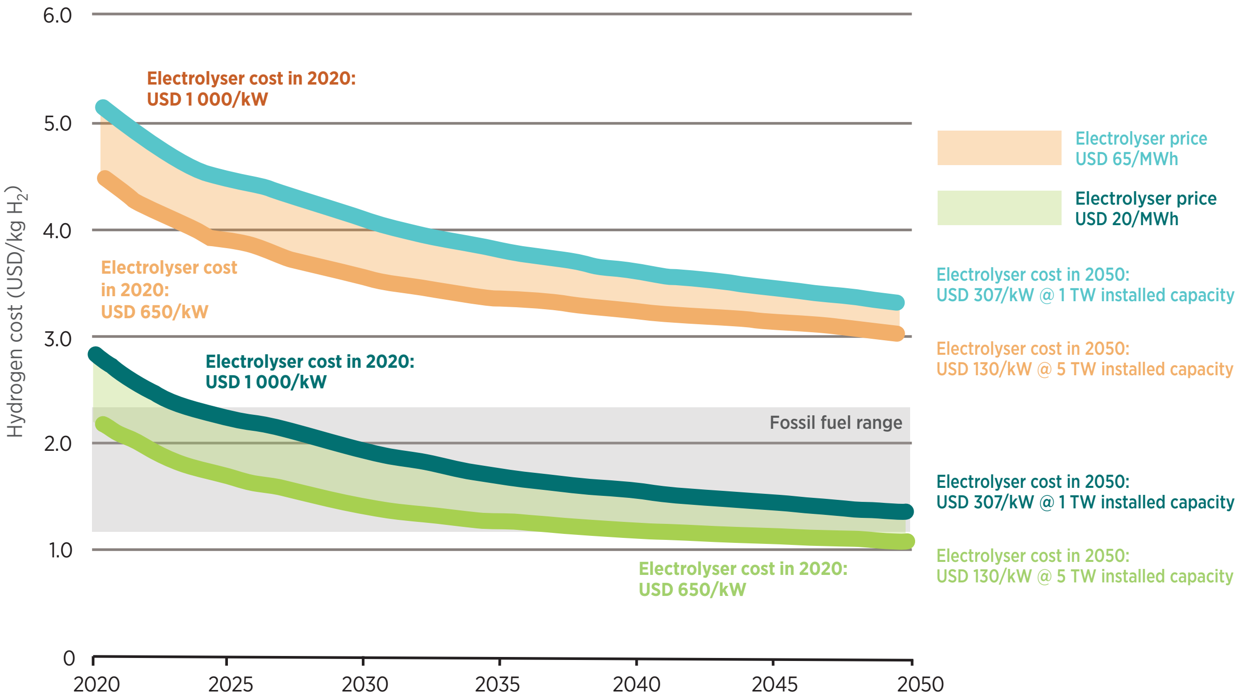
Source: (IRENA, 2023a).
Notes: 1.5-S = 1.5°C Scenario; GW = gigawatt; PJ = petajoule.

4.1 COST OF GREEN HYDROGEN

A key barrier that has prevented the deployment of green hydrogen is its higher cost of production when compared to the current paradigm. However, the costs are dependent on two primary variables: the cost of the inputted renewable energy, and the capital cost of the electrolysers (alkaline, PEM, AEM [anion exchange membrane] and solid oxide).

The costs of electrolysers remain high (USD 1000/kW), but economies of scale and technological improvements are expected to bring them down. Electrolyser cost reductions combined with downward trajectories in electricity prices are expected to make green hydrogen production cheaper (at less than USD 1 per kilogram [kg] of hydrogen) than any other low-carbon alternative for hard-to-abate sectors as we approach 2050 (see Figure 20) (IRENA, 2020).

Figure 20 Cost of green hydrogen production as a function of electrolyser deployment, 2020-2050



Source: (IRENA, 2020).

The levelised cost of hydrogen (LCOH) is another indicator for measuring the cost-competitiveness of this energy carrier. The LCOH is the ratio between the **total CAPEX+OPEX and total hydrogen production**. It is reliant on the annual production and cost of the hydrogen system – which itself are functions of the individual components within the system. For green hydrogen, the potential configurations of these systems are either to connect a single renewable energy technology with the electrolyser, or a hybrid system where one or more renewable energy technologies feed power to the electrolyser (IRENA, 2022b).

In a 2020 reference scenario used by IRENA modelling, the LCOH is found to range between USD 85/MWh and USD 190/MWh; this is much higher than for natural gas, which has a levelised cost of USD 30/MWh during the period 2020-2021. Energy modelling by IRENA shows that the global average LCOH in 2050 for a stand-alone green hydrogen production system would reach USD 1.5/kg hydrogen in many countries, and an LCOH below USD 2/kg hydrogen will allow forecasted hydrogen demand to be met in 2050 (IRENA, 2022b).

IRENA will publish a parallel report on "Shaping sustainable international hydrogen value chains", which will provide further perspectives on recent developments pertinent to the production, competitiveness and sustainability of clean hydrogen.

Considering the geographical constraints of producing green hydrogen onshore due to high water stress and extensive land use, among others, initiatives for production offshore have been planned in recent years. Additional benefits include higher capacity factors in the electrolysers when connected to offshore wind sources (IRENA and Bluerisk, 2023). Consequently, the application of this approach to floating offshore wind counterparts is being envisioned enthusiastically due to its huge potential.

4.2 TRANSPORTING HYDROGEN

In IRENA's 1.5°C Scenario for 2050, most of the international trade in hydrogen occurs via pipelines (55%) and shipping (45%), the latter of which would transport the hydrogen directly as ammonia, to be used as input for the fertiliser industry and as synthetic fuel (IRENA, 2022c). Nevertheless, minimising transport requirements leads to maximising energy efficiency, implying that renewable energy generation in the proximity of the hydrogen consumption points must always be explored.

In line with this rationale, transport of hydrogen in the floating wind offshore context should start with assessing hydrogen needs in the coastal regions near to the offshore location. Once this need is identified, alternatives for short-distance transport of hydrogen will be defined by the configuration of the hydrogen production (*e.g.* pipelines or transport by ship from offshore electrolysers).

4.3 FLOATING OFFSHORE WIND AND HYDROGEN PRODUCTION

Offshore wind is increasingly being viewed as an innovative avenue for producing hydrogen. This is ascribed to the large capacity factors available offshore as well as the growing financial incentives to support this technological coupling, due to the economies of scale associated with both offshore wind energy and hydrogen production. Wind farms are increasingly going offshore, and many hydrogen end users are located in coastal areas, which are other incentives to develop the synergies between these two sectors (Arthur D. Little, 2023; IRENA, 2021a). At offshore sites, there is potential to use the hydrogen produced to supply power to aquaculture and desalination systems (Kumar *et al.*, 2023).

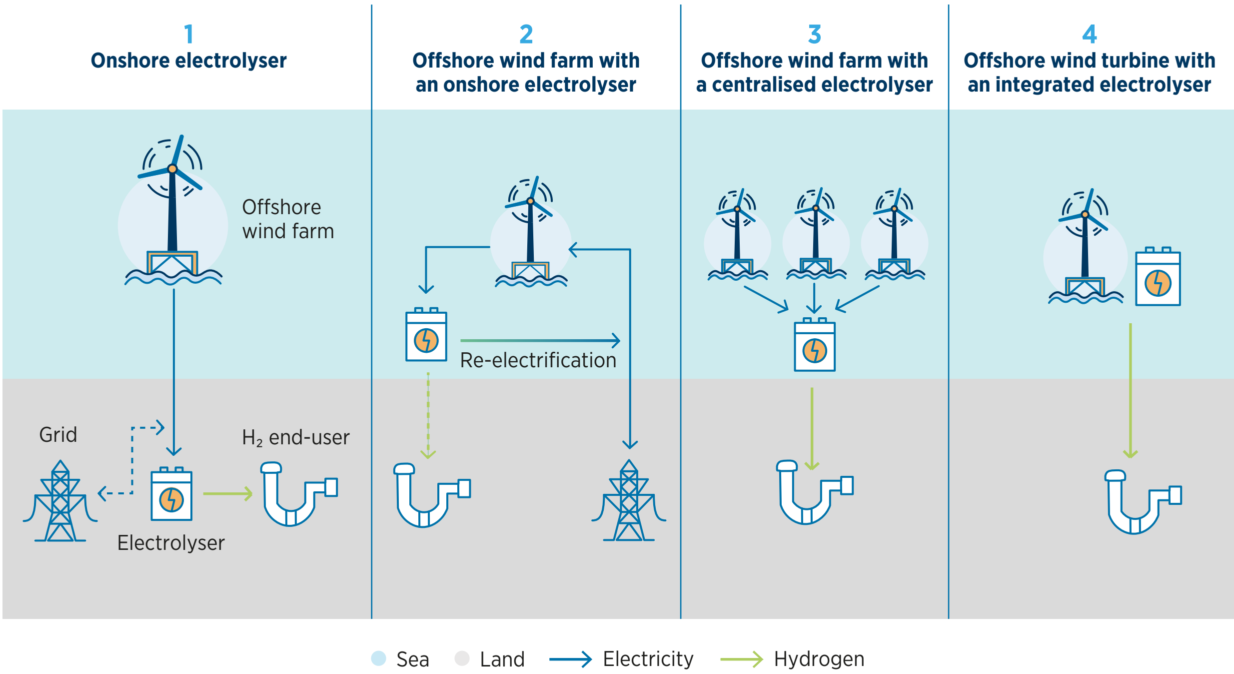
Hydrogen production configurations

The coupling of offshore wind with hydrogen is primarily being explored by connecting offshore wind turbines with electrolysers. These electrolysers can contribute to energy storage activities by adapting voltage fluctuations, which can adjust imbalances and maintain energy demand requirements. Hydrogen itself can serve as a storage conduit for energy generated by offshore wind in the form of gas, liquid or liquid organic carriers such as ammonia and methanol (Kumar *et al.*, 2023). The configurations being explored for this coupling are as follows (Arthur D. Little, 2023; IRENA, 2021a):

- **An offshore wind farm with an onshore electrolyser:** In this configuration, offshore wind energy is transmitted to an onshore sub-station (see section 2 for the power transmission value chain). The onshore sub-station is connected to an electrolyser that can either transmit electricity to the grid or produce hydrogen (the decision lies with the project developer).
- **An offshore wind farm with a centralised electrolyser:** In this configuration, the offshore wind energy is transmitted to a central offshore platform housing an electrolyser (instead of the offshore sub-station). The hydrogen produced is then transported onshore via hydrogen pipelines or ships.
- **Offshore wind turbine with an integrated electrolyser:** In this set-up, the small electrolysers are sited directly on the turbine, which allows for hydrogen production on-site and can be transported potentially via ships. This configuration is particularly relevant for floating offshore wind due to the potential of providing sufficient and direct power for the electrolysis. This is a very nascent idea but can potentially be used on semi-sub foundations, as no modification to the electrolysis unit is envisaged and/or there is not a need to build a separate housing structure for the electrolyser.

Figure 21 provides an overview of the three offshore hydrogen coupling concepts, and its onshore counterpart.

Figure 21 Options for offshore wind and hydrogen configurations



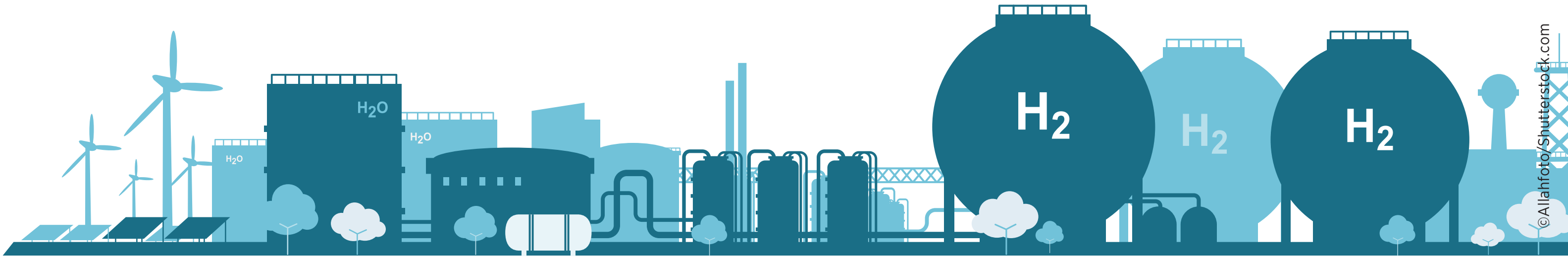
Source: (IRENA, 2021a).

Qualitative observations on the three offshore wind–hydrogen configurations are presented in Table 4 (Arthur D. Little, 2023; IRENA, 2021a).

Table 4 Qualitative comparison of offshore wind–hydrogen configurations

CONFIGURATION	OBSERVATIONS
Onshore electrolyser	• Promotes flexibility by allowing offshore energy to be used for either electricity or hydrogen production. This allows for the set-up to operate for grid stabilising or to support hydrogen markets. • The cost per kilometre for export cables onshore is higher than for hydrogen pipelines, which is compounded by the energy transmission losses associated with AC and DC cables. • Having centralised hydrogen production onshore can facilitate the scale-up of electrolysers; however, the farther the offshore wind farms are located from these sites, the higher the increase in CAPEX/OPEX cost. • Allows the co-location of electrolysers closer to demand centres, facilitating offtake.
Centralised offshore electrolyser	• Limited flexibility, as the economic viability to install both export cables and hydrogen pipelines is low. All of the electricity produced must be focused on hydrogen production. • Cost effectiveness is achieved through the introduction of hydrogen pipelines, which are cheaper than export cables. • The introduction of hydrogen pipelines can facilitate the connection of offshore wind farms that are located far from the shore or at large water depths.
Electrolyser sited on turbine	• Shares similar advantages as centralised offshore hydrogen electrolysers, but in addition allows for simpler turbine electronics as electricity conversion steps can be omitted. • Scalability can be a challenge, as each turbine will require its own electrolyser; however, this can be a coupling option for floating offshore wind farms. • Makes use of the available space inside the structure, even for compressed hydrogen storage. It is a possible solution where depths are not suitable for cables or pipelines.

Source: (Arthur D. Little, 2023; IRENA, 2021a).



The maturation of these alternatives will define the case-optimised solution, leading to a tipping point in terms of distance and depth, from which, in addition to the ancillary observations listed, offshore hydrogen production becomes competitive.

Hydrogen production challenges

While this innovative coupling is trending in the industry, there are key challenges in the foreseeable future that need to be addressed for this innovative avenue to be mainstreamed:

- Currently the cost of electricity from floating offshore wind is higher when compared to other clean energy sources such as solar PV. When coupled with hydrogen, costs rise due to the requirement of niche storage and transport for hydrogen in addition to the offshore equipment. These higher costs can result in the LCOH reaching USD 1.5/kg hydrogen, without including the cost for the electrolyser. The trade-off for countries that are considering this coupling is the higher cost of supply versus higher energy dependence; hence a higher production cost could be favoured by countries with high offshore energy potentials (IRENA, 2022b). Current prices for green hydrogen range between USD 2.5/kg and USD 6/kg hydrogen, which is around two to three times higher than its closest alternative, blue hydrogen (Kumar *et al.*, 2023). However, very high capacity factors from floating offshore wind would lead to a lower LCOE and thus a lower LCOH.
- Key technical constraints that are hampering this coupling include the limited availability of electrolysers (especially considering the additional need of marinisation); the provision of hydrogen infrastructure near onshore locations; the high requirement of desalination facilities to purify seawater to be used in the electrolysis process; and identification of the best transport route to bring offshore-produced hydrogen onshore (Arthur D. Little, 2023; IRENA, 2021a). Specific infrastructure constraints that have been identified are as follows (IRENA, 2021c; Kumar *et al.*, 2023):
  - The storage of hydrogen is a key technical constraint that needs to be addressed due to the requirement of large storage facilities to account for the low energy density per volume. While this is a cross-cutting challenge for hydrogen development, this constraint could be particularly apparent in the offshore environment, with space at a premium. Innovative storage solutions may be required.
  - The liquefication and/or compression of hydrogen is an energy-intensive process and requires materials that can handle these pressure loads – thereby contributing to system complexity.

  - Transmission of hydrogen offshore via repurposed natural gas pipelines is a topic that is being investigated by the industry. However, this avenue is very uncertain, due to potential technical and regulatory challenges. In repurposed pipelines, it may not be possible to transport hydrogen at the pressures required to make this feasible. As transmission distances increase, pressure drops become more frequent, thereby necessitating the increased use of compressors to maintain sufficient delivery pressure; this, however, leads to cost increases. Floating offshore wind locations are expected to be within the EEZs, which extend up to 370 km from shore, and this becomes an additional consideration for submarine radial pipelines.
  - Due to hydrogen's high energy density, this energy carrier is extremely volatile and requires very little energy to ignite. Hydrogen can also interact with welded joints in pipelines, resulting in corrosion that eventually leads to accidents and/or complete failure of the system. Hence, there is a strong requirement for experienced personnel to operate these production facilities, which is not readily available at this moment.
  - The technologies involved for offshore green hydrogen products, as well as their offloading onshore, are still very novel and do have safety concerns, which need to be investigated further.
- Regulatory frameworks are not yet well developed for offshore hydrogen production. In many cases it is not clear which regime(s) producers would need to navigate and conform to. Further clarity in regulatory framework treatment of offshore hydrogen production could help reduce risks in preliminary investments.

4.4 SITING CONSIDERATIONS

Considering the challenges noted, key factors for the siting of offshore wind–hydrogen production that have been identified in the research are as follows:

- Project locations need to have access to low-cost renewable energy electricity, as this is a key component for the overall LCOH. Other parameters such as the distance from shore, water depth and capacity factors also influence the LCOH, as well as determining the types of offshore technologies that can be used, the installation cost and O&M expenditures (Kumar *et al.*, 2023).
- The choices of electrolyser (PEM, alkaline, solid oxide), desalination systems, and compressors, along with their operational performance efficiency, all impact the quantity and quality of hydrogen production. The electrolyser is an especially crucial component, as its CAPEX influence on the LCOH reduces as the running hours increase, resulting in growing dependency on electricity prices. To produce low-cost hydrogen, it is essential to have low power costs that permit electrolysers to operate a high full-load of hours (IRENA, 2022b; Kumar *et al.*, 2023).
- Project sites need to be situated close to hydrogen demand centres, as economies of scale can be achieved by facilitating supply chain optimisation and leveraging infrastructural synergies with these centres. A blue economy can be fostered by siting offshore hydrogen production centres near offshore aquaculture, ports, and oil and gas complexes, as they can be the nearest markets for the hydrogen produced (IRENA, 2021a; Kumar *et al.*, 2023).

- Social acceptance for these coupling projects is imperative, which can be achieved by effectively communicating the social benefits (including energy and water security) and job creation opportunities offered by offshore wind projects and decarbonised industries. The provision of green investments/grants, development of green zones, and dedicated green energy budgets by governments are key enablers for this coupling to be realised (Kumar *et al.*, 2023).

A practical insight into offshore wind-hydrogen production is presented in Box 5, which provides an overview of the key assessment findings from Phase 1 of the Hydrogen Backbone Link project in Scotland.

Box 5 **Scotland's Hydrogen Backbone Link project**

Within Europe, Scotland has some of the highest offshore wind capacity factors (reaching 60%) and power densities (at 1 000 to 2 000 watts per cubic metre). The country has taken advantage of this resource advantage by accelerating its fixed and floating offshore developments. Scotland is home to the world's first commercial floating wind farm (Hywind Scotland), and in 2023 through its ScotWind and INTOG leasing rounds the country allocated 30 GW of new offshore wind capacity, with more than half being floating wind. Scotland's energy transition plan includes becoming a net exporter of green hydrogen, with a target of 94 TWh annually to be exported to Europe by 2045.

To link Scotland's offshore wind capacity with its stated green hydrogen ambitions, the Hydrogen Backbone Link (HBL) project will catalyse the development of pan-European hydrogen export infrastructure, wherein Scotland (and the rest of the United Kingdom) will be able to lead the development of an extensive hydrogen transport and distribution system. The project aims to cater to 10% of north-western Europe's hydrogen import requirements by 2030. The HBL project falls under the ambit of the Net Zero Technology Centre, which was awarded GBP 16.7 million (USD 21.2 million) in public funding from the Scottish Government's Energy Transition Fund. The first phase of the HBL will last until March 2025, and 10% (GBP 1.6 million or USD 2 million) of the energy transition fund was allocated to the project, with the remainder (GBP 3.2 million or USD 4 million) coming from industry players.

The HBL is adopting the pipeline avenue for transporting the hydrogen that is produced offshore and is leveraging the connectivity possibilities that already exist in the United Kingdom and Europe. The project developers have chosen this transport avenue because the distance between these regions is less than 3 000 km, and research indicates that pipelines are a competitive option within this distance parameter.

The most preferred pipeline option that has been identified is the development of a new pipeline from Scotland to Germany. The bore backbone pipeline will run from Flotta (Scotland) to Emden (Germany) and have pipeline spurs originating from Sullom Voe, Cromarty Firth and St. Fergus. The route of the pipeline backbone will follow the leasing areas as identified by ScotWind and will be sited near German offshore wind farms (BorWin, DolWin, HelWin and SylWin) that will enable connection to offshore wind power hydrogen electrolysers in the future. In Scotland, there will be a strong requirement to develop large-scale offshore wind developments as well as associated infrastructure in the identified hydrogen supply hubs – Flotta, Sullom Voe, Cromarty Firth and St Fergus. The projected capital investment cost for this pipeline is GBP 2.97 billion (USD 3.77 billion), with sustained CAPEX costs reaching GBP 90 million (USD 114 million) and OPEX costs reaching GBP 843 million (USD 1 billion).

Box 5 **Continued**

Some of the key technical assessments made by the Net Zero Technology Centre with regard to the delivery of an offshore hydrogen pipeline system within the HBL project are as follows:

- Given that no offshore hydrogen pipelines exist currently, it will potentially be required to repurpose sections of existing natural gas pipelines (which will be connected to the backbone) for delivery of hydrogen. The repurposed pipelines would need to follow the ASME B31.12 standard, which is the leading guidance document on design approaches for hydrogen pipelines. The SIRGE and CATS pipelines have been identified as lines that can be repurposed; however, more research on fatigue, bending stress, and lateral stability, among other parameters, needs to be undertaken to confirm the pipelines' readiness for hydrogen transport.
- Valves are an important pipeline component to ensure the safety of hydrogen transport through this medium. The assessment from this project indicates that current valves used for natural gas pipelines can be used for hydrogen as well. However, if any existing valves are leaking, this leads to a high safety risk if hydrogen is transported, due to the high leakage rate of hydrogen compared to natural gas. More work with industry and standards organisations is needed to fill in gaps in standards, testing methodology and requirements for valves in hydrogen gas transport service.
- Compression systems will be needed to transport hydrogen through pipelines, due to its low volumetric density. A piston compressor (or reciprocating compressor) is the recommend option for hydrogen transport; however, this is limited by the fact that these compressors are costly, have poor reliability and use lubricants that can contaminate the hydrogen. Further research and innovation into emerging technologies, such as turbo, electrochemical, and compact centrifugal designs, will be required for the HBL project.
- Storage of hydrogen is a challenge for the industry at large, and appropriate solutions will be needed for the HBL project. The most popular choice is cryogenic liquid storage tanks, but no large-scale options exist on the market today. Storage innovations such as salt caverns, repurposed pipelines and subsea storage tanks are still very nascent. There is also a need for more investigation on purification technologies post-storage, which remains a gap.
- Hydrogen is an extremely volatile carrier, hence the installation of appropriate safety systems is a stringent requirement. In the context of pipelines, key challenges to be addressed include identification of appropriate inline inspection regimes and gas velocity measurements. Existing leak detection systems can be used to detect hydrogen leaks, and magnetic flux tools used for natural gas pipelines can be used to detect corrosion within inner/outer pipeline walls. Another challenge to mitigate/manage is hydrogen embrittlement, which can be achieved by using high-grade steel pipelines with high stress and toughness for large transmission volumes.

In summary, the Net Zero Technology Centre notes that technically hydrogen can be transported via pipelines; however, significant resources and investments are required in developing a robust quality infrastructure to get a more detailed analysis of whether natural gas pipelines can be repurposed for hydrogen transport. Innovations in the development of the next generation of compressors as well as storage capacities are also necessary for the success of the HBL project.

Source: (NZTC, 2023).

4.5 PERSPECTIVE ON THE COUPLING OF FLOATING OFFSHORE WIND AND HYDROGEN

From a market and industrial perspective, the coupling between offshore wind and hydrogen production has focused more on fixed-bottom rather than floating offshore wind. IRENA consultations with industry players operating in the floating wind sector have largely found that hydrogen coupling is not a priority at this stage in the sector's development. This is because the current focus is on making floating wind technologies more commercial and competitive, as well as preparing supply chain activities to cater to the expected demand for these solutions in the future.

Floating wind projects are located farther offshore than their fixed counterparts, and this distance and depth present it as a cost-effective alternative. However, the previously mentioned challenges associated with hydrogen production result in this coupling needing to comply with higher technical and safety requirements, for which the floating wind industry has yet to develop. This does not imply that this coupling will not be explored in the future, and ongoing initiatives are being pursued to better understand this avenue. Annex B provides an overview of some of the fixed and floating offshore hydrogen production initiatives being considered. The ambitious capacities and approaches illustrate the potential benefits that coupling offshore wind and hydrogen production may bring.

5. SUSTAINABILITY OF FLOATING OFFSHORE WIND POWER

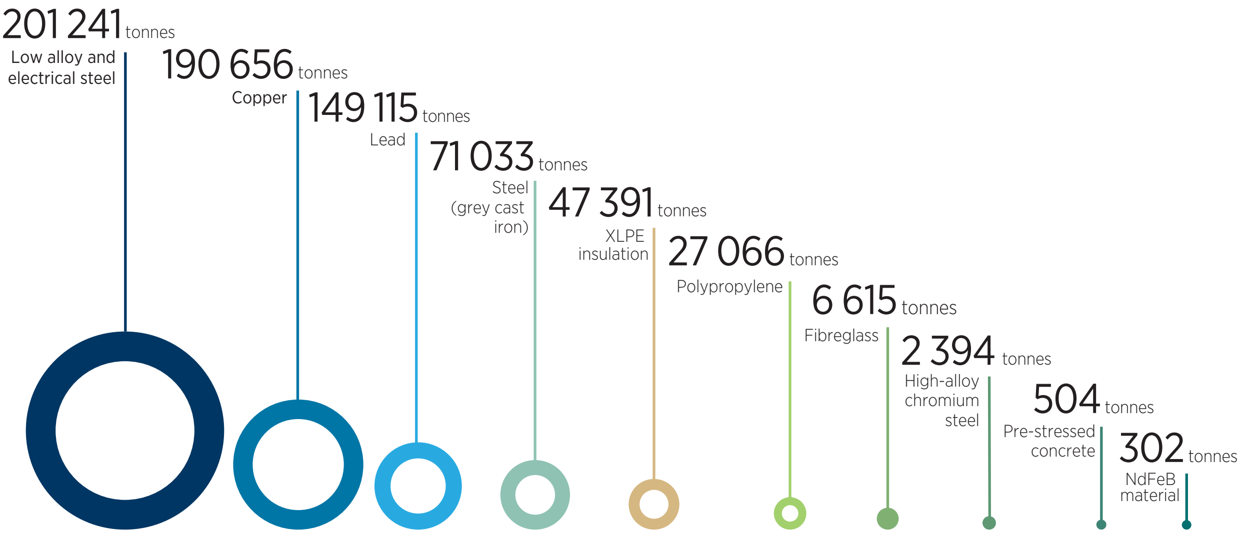
The success of floating offshore wind is heavily reliant on the effective manufacturing production of every component of this technology. The development of robust local supply chains and promoting skills development among the workforce can result in positive socio-economic gains (IRENA, 2019). However, an important facet of floating offshore wind project development is ensuring that the technological production and operational impact is sustainable. This section touches on some of the sustainability factors that need to be considered when pursuing floating offshore wind solutions.

5.1 MANUFACTURING CONSIDERATIONS AND SUSTAINABLE INNOVATIONS

While the potential for floating offshore wind is tremendous, it is equally important that increased efforts be made to reduce, re-use, and recycle the raw materials and residues that arise from these projects.

- Turbine blades are the component with the highest sustainability factor, as they are made from composite materials that allow them to have high performance-to-weight ratios. According to (IRENA, 2019), around 2.5 million t of composite materials are used in the wind industry, and large amounts of turbines are expected to enter the decommissioning phase soon. To promote sustainability in this phase, it is important to explore a wide range of recycling options. Composite materials can be recycled through either mechanical processes (such as cutting the turbine blades into small pieces) or thermal processes (combustion or pyrolysis) (IRENA, 2019). An overview of the material requirements for a 500 MW offshore wind plant is presented in Figure 22.

Figure 22 Material requirements for a 500 MW offshore wind plant



Source: (IRENA, 2019).

Note: XLPE = cross-linked polyethylene; NdFeB = neodymium iron boron.

Another important consideration is the fact that rare earths materials (such as neodymium and dysprosium) are integral materials that are used in the permanent magnets found in generators that employ a direct-drive configuration (IRENA, 2023d). One megawatt of direct-drive wind turbine capacity requires around 500 kg of permanent magnets (Gielen and Lyons, 2022). IRENA's analysis has found that the mining and processing of these critical materials is geographically concentrated in select countries: China, Australia, the Democratic Republic of the Congo and Chile. All economies participating in the renewable energy transition will rely on a steady demand of these materials to allow for technological developments to continue; however, supply chains remain concentrated in select countries. There are attempts to restructure these value chains to allow for new mining and processing facilities to be established in other regions; however, this is proving difficult due to the long lead times to commence operations (IRENA, 2023d). With regard to the wind industry, innovation and research are being undertaken to potentially develop rare earth-free permanent magnets or to replace neodymium with other rare earth elements, including praseodymium, dysprosium and terbium (Gielen and Lyons, 2022).

Through several recent developments, manufacturers of wind turbines have been able to develop new processes to ensure that this essential component can be recycled and re-used. Examples are presented below:

- **Carbon Rivers:** Carbon Rivers commercialises a process to recover clean, mechanically intact glass fibre from decommissioned wind turbine blades. These blades are typically 50% glass or carbon fibre composite by weight. The company's innovative approach upcycles all blade components, including steel, preventing significant waste from reaching landfills. It has already upcycled thousands of tonnes and is developing a facility to process 50 000 t annually. The company's pyrolysis-based method breaks down organic components, converting them into raw hydrocarbon products for energy production, resulting in a net positive energy output (DOE, 2022c).
- **Vestas:** In February 2023, Vestas introduced a turbine recycling methodology that entails introducing an element of circularity within the company's epoxy-based turbine blades without altering the production processes. Epoxy-based turbines have been notorious to break down due to their chemical resiliency, leading many technology developers to believe that it would be impossible to recycle these blades, which are commonly used in turbines. Vestas has developed a chemical process that can break down epoxy blades into their most essential raw material. This process was co-developed with Aarhus University, Danish Technological Institute and Olin. Given the success of the trial phase, the focus now is on making this solution a commercial one (Vestas, 2023a).
- **Siemens Gamesa:** Siemens Gamesa has developed RecycleBlades, which allows the company to reclaim the blade components (resin, fibreglass, wood) by using a mild acid solution treatment. These blades are currently being used in RWE's Kaskasi offshore wind farm in the German North Sea. The wind farm has a cumulative generation capacity of 342 MW, which can power 400 000 households (Siemens Gamesa, 2022).

In June 2023, Vestas and Ørsted announced a sustainability partnership wherein Ørsted would procure at least 25% low-carbon steel wind turbine towers and blades that would be made from recycled materials from Vestas, in all of the companies' forthcoming joint offshore wind projects. The previously mentioned Vestas blade recovery material innovation is being scaled up with its partners Olin and Stena Recycling (Vestas, 2023b).

5.2 FLOATING FOUNDATION ENVIRONMENTAL CONSIDERATIONS

Because floating offshore wind farms are sited in deep waters, it is important to ensure that environmental impacts on the marine ecosystem are not detrimental to the ecosystem's overall sustainability. Table 5 provides a summary of some of the general and broad environmental impacts that can occur due to the presence of offshore wind projects at greater water depths.

Table 5 General environmental impact considerations from offshore wind projects

ENVIRONMENTAL CONSIDERATION	DESCRIPTION
Changes in seabed substrate	The introduction of offshore foundations into the seabed results in the creation of a hard-bottom habitat, which in the absence of the foundation is mostly composed of soft-bottom substrates. The creation of this new habitat can result in displacement of sediments, which can impact sessile species that do not have the capacity to find alternative soft-bottom habitats. For floating foundations, the main contact point with the seabed is via the mooring system, particularly the anchor. The extent to which these anchors and chains are designed to absorb wave action drag along the seafloor is limited, resulting in a disturbance of the habitat surrounding the anchor system. Undertaking surveys such as benthic baselines and habitat mapping can allow for appropriate wind farm siting to ensure that biodiversity patterns are not altered greatly.
Invasive species	Invasive species can be defined as organisms that are not native to a specific area. Invasive species can have significant environmental impacts and negative spillover effects. The impacts of this risk differ depending on whether the components are constructed onshore in port and then towed to site, or if they occur during operation and maintenance activities. For floating foundations that are constructed in port, such as semi-subs, invasive species can colonise components and be transported to offshore wind farm sites. During the operation and maintenance phase, the vessels that cater to these requirements can be conduits for the transport of invasive species via their hulls or ballasts. Due to their porous nature, concrete anchors bring a higher probability of invasive species colonisation when compared to their steel counterparts.
Wake effects	The presence of floating sub-structures and components in the below-the-ocean level can create impediments to water flows, which can result in turbulences as the water accelerates around these "external objects" – known as the wake effect. The magnitude of the wake effect is directly proportional to the size of the foundation and sub-structure in the ocean. For floating foundations, wake effects have been observed as far as around 200 metres down-current. Anchors that embed themselves into the seabed (such as pile, drag and suction caisson) have a small profile and hence low wake effect when compared to their deadweight counterpart. Because floating foundations are sited in deep waters, the currents are weaker near the seabed, which also contributes to smaller magnitudes from the anchoring system.
Sediment – suspended/ deposition	During the installation of offshore wind foundations, the preparation of the seabed (through activities such as dredging, excavation and ploughing) as well as activities from support vessels can cause sediments from the seabed to become suspended. This can impact the nature of organic matter that relies on sediment size and benthic activities. Floating mooring systems that have deadweight anchors or suction caissons do not impact the seabed significantly and will not result in increased sediment suspension. Embedded anchors, on the other hand, contribute to sediment deposition. The influence of anchor rod drag on sediment deposition is still not known.
Release of contaminants	Sediments at the seabed can contain harmful chemicals/substances such as arsenic, heavy metals and pesticides originating from human activity. The disturbance to the seabed can result in the discharge of these contaminants. Floating foundations that use embedded anchors, suction caissons and deadweight anchors can cause lower re-suspension of these substances than their fixed-bottom counterparts.
Electromagnetic field impacts	Floating offshore wind projects require a significant amount of cabling to ensure that the power generated can be transmitted onshore. By its very nature, these "grid" components will generate electromagnetic fields (EMFs), which potentially have environmental impacts. EMFs have a decreasing magnitude in the following order due to the lower amount of power transmitted: HVDC cables, export cables and inter-array cables. The distances of the cables as well as the cable material also influence EMF strength. Crustaceans, bony fish and turtles have high sensitivities to EMFs and can show physiological impacts; however, data on these trends are very limited or site-specific. The overall impact of EMFs on marine species appears to be negligible, but more research on their interaction with subsea grid infrastructure is required.

Based on: (Farr *et al.*, 2021; Horwath *et al.*, 2020).

Based on the commentary presented in Table 5, it can be inferred that the environmental impacts resulting from floating offshore wind activities are lower compared to their fixed-bottom counterparts due to the "reduced interface" with the ocean seabed.

5.3 BIODIVERSITY IMPLICATIONS

Biodiversity refers to the biological diversity of life on earth in all its forms, from the very smallest organisms to the largest ones. The global ecosystem is diminishing rapidly due to the impacts of climate change; however, if preserved it can contribute greatly to efforts to combat this crisis (Ørsted, 2023). Ocean health is a key aspect of biodiversity, as the oceans are a source of oxygen for many life species as well as a carbon sink. However, the absorption of carbon has resulted in ocean heating and acidification, which in tandem with over-exploitation of ocean energy resources is causing sea levels to rise as well as impacting marine and coastal diversity (IRENA, 2021a, 2023e; Ørsted, 2023). It is therefore imperative that offshore wind projects include biodiversity considerations in their planning and implementation.

A neutral or positive biodiversity impact arising from offshore wind foundations is the potential to serve as artificial reefs that can foster the creation of new biodiversity habitats. For floating offshore sub-structures, the mooring anchors and subsea cables (if exposed) can also serve as artificial reefs (at mid-water depths) for invertebrates and reef-associated fishes. If fishing activity is restricted in these areas, these artificial reefs can serve as "protected areas" (Farr *et al.*, 2021; Horwath *et al.*, 2020).

The noise pollution arising from floating offshore wind farms is much less compared to fixed-bottom offshore wind farms due to the absence of high-acoustic sound generation processes such as piling, which can disturb the pre-existing habitat at project sites (Farr *et al.*, 2021; Horwath *et al.*, 2020).

Collision with avian species is another key biodiversity challenge associated with wind development, and this risk is particularly low for offshore wind projects when compared to their onshore counterparts. Avian species that rely on gliding rather than flapping are at greater risk for collision with offshore wind turbines, as they usually fly at heights that are in the same range as the blade sweep zone, especially in high wind conditions that may reduce manoeuvrability options (Farr *et al.*, 2021; Horwath *et al.*, 2020).

According to research by (Farr *et al.*, 2021), the greenhouse gas emissions across the entire life cycle of floating offshore wind are around 15.35 kg of CO_2-equivalent per MWh, with the manufacturing phase being the largest contributor. Even considering uncertainties, this emission factor is still less than one-tenth of the minimum emission estimates for natural gas, and less than one-twentieth of the estimates for coal. The absence of pile driving (which has high noise emissions and greatly displaces marine mammals) as well as the ability to transport onshore-built components for floating offshore wind projects all contribute to minimising the biodiversity impact.

Looking at the biodiversity considerations along with the potential environmental impacts presented earlier, the overall environmental footprint for floating offshore wind projects in deeper waters is lower compared to fixed-bottom projects. However, most floating offshore wind projects are still at the demonstration phase, and these impacts can scale up linearly or non-linearly as project capacities increase in the future. More detailed research and analysis will be required to fully ascertain the environmental and biodiversity footprint for floating offshore wind farms (Farr *et al.*, 2021).

5.4 STAKEHOLDER CONSULTATIONS

When developing offshore wind projects, it is imperative to engage with other maritime communities to ensure the acceptance of projects sited in areas where there are common interests. The best window to undertake these consultations is during the planning stage of the project development phase, to allow for efficient space to share and discuss ideas, which can help to speed up permitting times and mitigate future conflicts (Efthimiou, 2022). For example, after undertaking consultations with community stakeholders in the design process, the demonstration Pentland Floating Offshore Wind Farm in the United Kingdom reduced its initial planned project area by 50% and the number of turbines from 10 to 7 (Pentland Floating Offshore Wind Farm, 2022).

Some key objectives to fulfil when undertaking stakeholder consultations are as follows (Efthimiou, 2022):

- **Mitigation** of potential impacts to all stakeholders due to siting of an offshore project. By taking these considerations into account, the project developer can amend plans to be as inclusive as possible. Best practices include using quieter foundations; arranging turbines with sufficient spacing, in line and at consistent depth; and reducing vessel speed.
- **Co-existence** to identify opportunities for offshore wind to work symbiotically with other marine industries and result in opportunities for communities. Examples of co-existence include collecting and sharing ocean data with fisheries, sharing energy generated with maritime users at a subsidised rate and using profits generated to invest in other industries such as fisheries and tourism. For example, the developers of the Fukushima Forward Project used remote vehicles to collect data on how their floating project would impact fisheries operating in the project site. Based on this exchange of information, new and adapted fishing methods were investigated (Fukushima Forward, n.d.).
- **Compensation** should be provided if negative impacts to stakeholders from offshore wind projects become unavoidable. This could entail direct financial compensation to the impacted stakeholder group. For example, Ørsted agreed to pay USD 28.9 million over 25 years to the East Hampton Town community as part a "Host Community Agreement" to facilitate the installation of an onshore four-mile, 138 kV electricity transmission line for the company's South Fork Wind Farm Project (Durakovic, 2020).

Fisheries

A major concern that is very applicable to floating offshore wind farms is the increased chance for collisions between marine mammals / fish species and floating sub-structures, or the entanglement of these structures in materials such as fishing nets and lines. Because floating foundations rely on mooring lines to maintain their stationary position in deep waters, the type of mooring system as well as the turbine array will determine the magnitude of this challenge. This potential does create tension between developers of floating offshore wind and the fishing industry.

Among mooring line choices, taut systems present the lowest risk of marine entanglement due to their lower sweep-volume ratios, low curvature and high stiffness (Farr *et al.*, 2021). Catenary systems present the highest risk because they have contrary properties to taut systems. Mooring systems have been found to be unlikely to entangle marine mammals due to their high modulus, with diameters ranging between 100 and 240 millimetres (Farr *et al.*, 2021). On the contrary, fishing gear, which has a lower modulus with diameters ranging between 1 and 7 millimetres, can entangle species such as baleen whales.

Another key challenge with regard to the co-existence of fishing and floating offshore operations is the increased likelihood of fish species getting entangled in "rogue" fishing gear that has accumulated in floating wind facilities, which can lead to injuries or death to species that find themselves in this situation (Farr *et al.*, 2021; Horwath *et al.*, 2020).

Potential solutions for the co-existence of floating offshore wind and fisheries

From an operational perspective, the use of high colour-contrast fishing ropes or acoustic signals can deter marine species entanglement. However, the most efficient solution is to site floating offshore wind projects to reduce overlap with areas such as feeding grounds and migration corridors (Farr *et al.*, 2021; Horwath *et al.*, 2020).

A key tool that can support the effective use of marine space is marine spatial planning (MSP). MSP is a comprehensive approach to regulating the space allocation of the marine environment by factoring in different uses by various stakeholders. By undertaking such planning early in the development process for offshore wind projects, there is a lower risk of conflicts arising among stakeholders, given that their needs and concerns have been factored in when implementing plans (European MSP Platform, n.d.; IRENA, 2023c).

To provide some perspective on how MSP can be beneficial for the co-existence of offshore wind and fishery activities, Box 6 provides some insights that the European Commission has identified based on the use of MSP in Poland and Scotland. Other EU Member States have their own MSP plans and legislation (European MSP Platform, n.d.). In a recent example of new MSP legislation, Spain passed a Royal Decree 150/2023 on 28 February 2023 approving the Marine Spatial Management Plans (POEM). The decree establishes a framework for the protection of marine space, which delimits the areas for current and future offshore wind and marine energy installations, and contains an inventory of the distribution of existing and possible future human uses and activities in the marine environment.[7]

[7] *Further details of MSP in Spain are available at: www.miteco.gob.es/es/costas/temas/proteccion-medio-marino/ordenacion-del-espacio-maritimo.html and www.infomar.miteco.es/visor.html.*

Box 6 **Best practices for the co-existence of offshore wind and fisheries**

- **Use high-level policy tools to ensure that impacts are considered in project development:** The Marine Scotland Act and the UK Marine Policy Statement, enacted in 2010 and 2011 respectively, require marine planning authorities to factor in the socio-economic impacts of offshore wind development and to ensure symbiotic existence with other ocean users. Poland has leveraged MSP to ensure that concrete offshore targets are set, and these are being included in its National Programme for the Development of Offshore Wind Energy.
- **Acknowledge the special status of fishers in the planning and tendering process:** Poland has ensured the involvement of fisheries in all steps of the offshore wind development cycle process. In the country's MSP planning process, as a first step, the government organised several in-person interviews with the fishing community. The outcomes from this meeting resulted in two follow-up meetings to further discuss their concerns and to identify co-existence solutions. These exchanges resulted in providing planners with perspectives on implementing "fishery-friendly" solutions for offshore wind development.
- **Draw on fishers' knowledge to identify suitable project sites:** In 2011, Marine Scotland piloted a fishery mapping project known as ScotMap. The main objective was to collect information on the activity patterns of fishing vessels that do not have vessel monitoring systems. The data for this project were collected via physical interviews with around 1 000 fishers, and the insights collected allowed for mapping of high fishing activity between 2007 and 2011. Offshore wind developers have leveraged these socio-economic data to support co-existence avenues. Poland's National Marine Fisheries Research Institute has implemented a similar initiative, which was used to develop a fishing activity map that was fed into the country's MSP planning processes.
- **Develop fishery corridors:** Poland has established blue corridors to ensure that offshore wind developments do not impact the migration patterns of marine species. These zones prohibit the establishment of offshore wind projects and are only accessible by fishing vessels. This is a potential avenue to mitigate conflicts between fisheries and offshore energy.

Source: (European Commission, 2021).

To provide practical insights on fisheries and floating wind projects, Box 7 highlights key points from an Equinor study that commissioned the Marine Directorate of the Scottish Government to investigate the use of static commercial fishing gear at the Hywind floating project site.

Box 7 **Key insights from an Equinor study on the use of static fishing gear at the Hywind project site**

The most recent ScotWind leasing round has allocated 20 potential zones for offshore wind development projects, of which 14 are expected to be floating. In Scotland, legislation allows fishing to be undertaken at offshore wind sites, unlike in other EU nations such as Germany. The primary concern for the Scottish fishing industry with regard to floating offshore wind is safety and liability issues that arise due to damage to wind farm assets. There has been limited research on how fishing can be effectively conducted near a floating offshore wind farm. The rationale behind the Equinor research study was to understand the kind of fishing gear being

Box 7 **Continued**

used and to identify fishing trial areas within the Hywind project site (characterised by a spar buoy foundation, a three-point mooring system and suction anchors).

The project site has water depths between 97 m and 117 m, and its seabed comprises mainly sand and gravel along with a low content of organic matter (between 0.75% and 2.1%). Near the turbine structure, spawning and nursery sites were found for herring, sprat and mackerel, alongside the presence of species such as veined squid, cod, haddock and European hake, among a variety of other organisms. Mackerel and herring were species that had been commercially exploited in the project area.

To address the research questions, Equinor designated three fishing areas within the wind farm, as well as a control area located outside the project site. During the study, a different area was visited to simulate commercial fishing, and four fishing methods (triple-parlour fish traps, crab creels, prawn creels and electronic jiggers) were tested independently. During the investigation period, haddock was the most popular species caught using the fish traps.

Key findings from this study were as follows:

1. Vessels that were used to deploy fishing gear adhered to fishing boundaries, therefore eliminating the risk of collisions with wind farm assets when not within this boundary.
2. There was successful retrieval of all fishing gear, which mitigated the risk of loss of equipment that can result in entanglement of species.
3. Safe deployment of gear following correct protocol prevented any potential snagging occurrences. No damage to gear was observed due to any to environmental externalities.
4. Conflict with other maritime users was avoided through the provision of timely "Notice to Mariners" (NtM) communications and reflective markers on the gear.

This short practical investigation by Equinor at its Hywind project site found that in optimal sea and weather conditions, safe fishing activities can be undertaken – under the assumption that standard maritime safety and navigation rules of the sea, in tandem with offshore wind safety parameters, are adhered to. For this test study, Equinor's assigned "fishing areas" were at a minimum distance of 200 m from a turbine and 50 m from the dynamic sections of the export/inter-array cables.

Equinor notes that its study was the first of its kind and lasted a very short duration (four days). The company recommends replicating similar studies and expanding the choice of fishing methods used to get a better understanding of co-existence facets between the offshore wind industry and fisheries.

Source: (Wright *et al.*, 2023).

6. WAY FORWARD AND CONCLUSIONS

This report aimed to provide a holistic overview of the floating offshore wind industry by collating and sharing information on market and technological developments, ancillary considerations (port and grid infrastructure requirements and energy storage options), sustainability and coupling with hydrogen production. While the floating offshore wind industry is still at an early stage, stakeholders are seizing the current momentum to ensure that this technology matures quickly, harnesses the tremendous technical capacity at deeper depth and allows for greater contribution to global energy transition efforts.

Based on the analysis conducted as well as on feedback provided by Members of IRENA's Collaborative Framework on Ocean Energy and Offshore Renewables, key recommendations that can promote floating offshore wind along the themes presented in the report are as follows.

6.1 POLITICAL CONSIDERATIONS

Observation 1: Accelerate international co-operation

As the technology continues to mature, floating offshore wind is poised to get increasing attention from governments and the offshore wind industry. Floating offshore wind is currently concentrated in certain markets, but this is expected to expand in the coming years. While the floating wind industry is nascent, it is imperative that, from the start, international co-operation in this field continues to scale up and prevent the development of silos.

Recommended actions:

- **G7 members to co-operate with IRENA's Collaborative Framework to collect and disseminate key trends and learnings from floating offshore wind.** The Collaborative Frameworks are platforms that aim to drive peer-to-peer collaboration and knowledge exchange on different facets of the energy transition. These frameworks are designed to bring together public, private, inter-governmental and non-governmental actors to promote co-operation and co-ordinated actions within the scope of the initiative. IRENA has a dedicated Collaborative Framework on Ocean Energy and Offshore Renewables (CFOR) whose purpose is to facilitate discussions on the developments pertinent to offshore renewables. The G7 and other countries should continue to leverage the CFOR as a means for driving international co-operation by sharing insights and knowledge with IRENA's broad membership on the developments occurring in the floating wind space.
- **Continue to participate in joint research projects within the G7 as well as other countries, leveraging the strengths of each entity in such endeavours.** To drive international co-operation, there is a need to continue developing joint R&D programmes and projects on floating offshore wind. This is already happening in this space, for example with Japan entering partnerships with Denmark and Norway to leverage these countries' strong track record on offshore wind to replicate similar successes within the Japanese national context.

Observation 2: Promote technological familiarity among decision makers

Floating offshore wind remains a novelty under the umbrella of offshore wind technologies. Hence, it is very likely that policy makers, civil servants and regulators are not sufficiently familiar with the technological underpinnings to support driving the industry forward.

Recommended actions:

- **Organise capacity building among countries that have floating offshore wind expertise.** It will be important for decision makers who are interested in gaining more perspective on this technology to approach the leading countries (such as Norway, the United Kingdom and Denmark) to organise knowledge-sharing workshops and project site visits. Undertaking these activities on a consistent basis will allow for interested parties to gain the necessary practical insights on floating wind to determine the key actions that will need to be taken to develop the industry given their own regional/national context.
- **Engage with industry leaders/associations to gain perspectives on their technological capabilities and offerings.** Companies such as Equinor, BW Ideol, RWE, and SSE Renewables, among others, are the key technology providers for floating offshore wind. Active dialogue by political stakeholders with these players will be crucial to understand which solutions are best suited based on the oceanographic characteristics of countries' deep waters.

6.2 POLICY AND REGULATIONS

Observation 3: Adopt best practices in policy frameworks that consider floating offshore wind

Given the infancy of the floating offshore wind industry (when compared to its fixed-bottom counterpart), there will be a growing need to ensure that policy frameworks (such as energy roadmaps and Nationally Determined Contributions) include specific provisions on floating wind. This will promote increased technological visibility as well as increase confidence among investors to support new/planned projects – thereby increasing confidence in the industry.

Recommended actions:

- **Set long-term deployment and cost-reduction targets for floating offshore wind, in line with the 2030 Agenda and beyond.** Most of the G7 countries and markets included in this report have included floating wind capacity targets to be reached between 2030 and 2050 (see section 2.3). For example, the United States is aiming to reduce the LCOE of floating offshore wind to USD 45/MWh by 2035 through its Floating Wind Shot Initiative (White House, 2022).
- **Develop public revenue support for floating offshore wind via feed-in tariffs, feed-in premiums, technology-specific auctions, power purchase agreements, Contracts for Difference, quotas, certificates, fiscal measures, *etc.*** For example, in November 2023 the United Kingdom increased the maximum price for offshore wind projects in its forthcoming CfD auction, with the maximum strike price for floating offshore wind for the planned Allocation Round 6 increasing by 52% to GBP 176/MWh (USD 223/MWh) (up from GBP 116/MWh or USD 147/MWh) (UK Government, 2023).

Observation 4: Develop enabling frameworks for floating offshore wind

For floating offshore wind to become successful, there will be a need to ensure that regulatory frameworks covering permitting processes, revenue support and infrastructure requirements are readily available. It will be important to determine if existing offshore wind frameworks can be applied in a "floating context" or if dedicated regulatory requirements will need to be developed.

Recommended actions:

- **Streamline offshore wind permitting processes.** Accelerating permitting protocols is a key tenet to facilitate relevant authorisation for new floating offshore wind projects and associated infrastructure – one-stop shops represent an attractive solution, among others, in this endeavour (IRENA, 2023c). For tenders, it is also important not to pit fixed and floating solutions against each other. The inclusion of non-price elements in auctions will increase the attractiveness of bids from potential developers.
- **Actively develop regulations that encourage the use of marine spatial planning.** The ocean is used by many maritime users, and leveraging effective solutions such as MSP can foster sustainable management of the space and resources available.

6.3 TECHNOLOGY AND INFRASTRUCTURE

Observation 5: Enhance the maturity of floating wind technology and reach commercialisation

There are several concepts for floating wind technological components (particularly foundations and turbine blades) that are at different stages of R&D as well as commercial readiness. As interest in this sector continues to grow, it will be important to ensure that these technological innovations are reliable and fulfil their intended purpose.

Recommended actions:

- **In consultation with industry, direct more resources and investment towards existing floating offshore wind solutions to promote economies of scale.** By making available new investment mechanisms (from public and private avenues), there will be a strong justification to developers to continue to improve and expand the scales of floating offshore wind projects. By doing so, there will be a positive spillover effect on the expansion of project pipelines, which can bring new stakeholders to contribute to the development of the industry. Section 2.3 provides an overview of the different stakeholders making investments to ensure that the potential of floating offshore wind is fully tapped.
- **Exploit the transferrable knowledge from the oil and gas sector and apply relevant insights to floating offshore wind development.** The offshore oil and gas industry has a wealth of experience and knowledge that can be used to inform the development of key technological components, such as foundations and mooring systems. Taking best practices from this established industry can also help to ensure that floating solutions have increased resistance towards harsh conditions that exist at greater depths and farther distances from the coast (Edwards *et al.*, 2023; IRENA, 2021a).

Observation 6: Expand and re-imagine the grid infrastructure for floating offshore wind

Given that floating offshore wind projects are sited much farther from shore than their fixed-bottom counterparts, the grid infrastructure requirements (cables, sub-stations, *etc.*) need to be carefully planned and implemented. Floating offshore wind will also require dedicated grid infrastructure considerations that are unique to this technology. Section 2.1 provides perspectives on this topic.

Recommended actions:

- **Provide clear guidance on how the enlargement of the grid infrastructure is to be developed sustainably while also ensuring smooth integration with other maritime activities.** As offshore wind projects continue to gain momentum, this will be an increasing requirement from both government and grid stakeholders.
- **Develop inter-operable grid components as well as standards for floating offshore wind, along with the promulgation of HVDC, to support the scale-up of offshore grid infrastructure.** Given that cross-border grid infrastructure developments are necessary, there will be a need for distribution and transmission operators to have grid elements that are compatible with each other. HVDC technologies have the advantages of greater power transmission capacity and low transmission losses and should become mainstreamed to permit greater offshore wind capacity to come online.
- **Prioritise industrial-scale deployment and institutional facilitation of dynamic semi-submersible cables and floating sub-stations.** These are key enablers of floating offshore wind in deep waters, which will unlock the enormous potential of offshore wind in countries that have been limited by a narrow continental shelf next to their coastlines.

Observation 7: Prioritise developments and investments in port infrastructure

Ports are an essential node within the floating offshore wind value chain, given their key activities in assembling and storing components of this technology; serving as starting point for these solutions to be brought to their project site; and influencing the OPEX cost – as elaborated in section 3.1. There is a consensus among industry that most ports globally are not fully prepared to take on the responsibilities of floating offshore wind (DNV, 2023b). Hence, regulatory frameworks and investments need to be made to expand the capabilities of ports globally to ensure their continued relevance in this growing industry.

Recommended actions:

- **Support collaboration between governments and industry stakeholders in identifying viable port sites that can cater to floating offshore wind demand**, and undertake detailed assessments on the required investments to make ports "floating offshore wind compatible". These stakeholders can explore financial investment mechanisms – such as grants, private investment, tax credits and funds allocated from the national budget – to develop these ports.
- **Set up dedicated committees that can be responsible for designing port development strategies.** This body should comprise major port stakeholders and other relevant players (such as representatives from maritime and coastal communities) to develop a "living strategy" that encompasses the identification of suitable port locations, development of time frames, investment mechanism options and co-existence with communities – all in support of expanding floating wind energy infrastructure.
- **Ensure that industry and port operators place an emphasis on developing a competent workforce** that can contribute to activities related to floating offshore wind. This can be achieved by creating new training programmes in tandem with the expansion of existing avenues that can result in the creation of new employment opportunities while also meeting demands of port development. Benefits of port development should also be communicated to communities that can aid in workforce development.
- **Maintain active dialogue with vessel manufacturers and shipyards.** This will provide perspectives on how these players can actively contribute to floating offshore wind development given increased demand for this technology. Efforts will also be needed to explore if existing vessels can be modified/ retrofitted with relevant technologies, or if fresh investments in the development of new vessels are required to cater to floating offshore wind requirements.

Observation 8: Promote standardisation of key floating offshore wind components

Different entities are developing a variety of floating offshore wind solutions and concepts. To facilitate stable industry development as well as contribute to the sustainability of supply chains, efforts should be made to standardise and drive convergence as much as possible. This can lead to better resource efficiencies and optimisation, as well as offer "common blueprints" for supply chain actors. The promotion of standardisation will contribute greatly to reducing the LCOE of floating wind, making it an attractive technological solution moving forward.

Recommended actions:

- **Consider implementing and following the standards and certification schemes that have been developed by international standard-setting organisations and industry players.** Annex A provides an overview on some of the key standards across different floating wind components that should be mainstreamed across the industry.
- **Support national standardisation bodies to become members of technical committees within international standard-setting organisations.** Examples of committees that are developing standards for the wind industry at large include ISO/TC 60 (gears), ISO/TC 67 (oil and gas industries including lower carbon energy) and IEC/TC 88 (wind energy generation systems).

6.4 HYDROGEN PRODUCTION

Observation 9: Support the coupling of floating offshore wind to hydrogen production

The coupling of floating offshore wind and hydrogen is not a priority for the industry at this moment in time; however, pilot initiatives are demonstrating the potential coupling opportunities. Continued innovation and investment in this space should be encouraged so that when the challenges associated with offshore hydrogen production are lesser in magnitude, the industry can capitalise on best practices and scale up this coupling rapidly. Annex B provides a non-exhaustive overview of some floating offshore wind and hydrogen coupling initiatives.

Recommended actions:

- **Site offshore wind and hydrogen production (if coupled) as close as possible to other maritime sectoral activities and/or hydrogen demand centres.** The purpose of this is to leverage existing infrastructure to increase the economic viability of this coupling.
- **Give priority to floating hydrogen production and transport to shore, which can be techno-economically preferable to offshore grid development.** In addition to the bathymetric constraints, factors at the nearest onshore area, such as industrial hydrogen needs or a weak grid leading to potential curtailments, can notably favour the exploitation of the offshore renewable resource.
- **Develop quality infrastructure requirements (such as standards, testing methodologies and inspection regimes) for key hydrogen value chain components such as electrolysers, pipelines, and compressors, to ensure safety of production.** Hydrogen is a very volatile energy carrier and therefore has inherent safety risks that are amplified especially when production is located offshore, given that maintenance activities are not easily accessible when compared to its onshore analogue.

6.5 SUSTAINABILITY

Observation 10: Address potential environmental impacts

Because floating offshore wind projects are situated far from the coast and in deeper waters, the environmental impacts on the surroundings are lesser in magnitude than for fixed-bottom offshore wind projects. This is because the "floating" nature of the technology results in a lower interface imprint between the sub-structure and the seabed – with mooring lines and anchors being the only contact point. However, given the infancy of the industry and the lack of scale, more research into these environmental (as well as biodiversity) facets is needed. Sections 5.2 and 5.3 provide perspectives on these topics based on a recent literature review.

Recommended actions:

- **Undertake detailed environmental impact assessments.** This is a key pre-project development step that provides a comprehensive landscape on the potential environmental and biodiversity disruptions that can result due to the project. It is important that these practices be strongly regulated as well as foster knowledge exchange in this area. Establishing dedicated programmes on this topic can foster co-operation among different stakeholders.
- **Engage in continuous environmental data collection and make the results accessible.** Several players (industry, academia, governments) are undertaking various activities and workstreams to collect different environmental data points. Efforts should be made at a national, regional, and international level to share these data collection practices as well as results – to allow for a repository that can be tapped by the global floating offshore industry.

Observation 11: Prioritise co-existence with the fisheries sector

Fisheries are an important stakeholder whose needs must be factored in when developing and operating floating wind farms. This is because fisheries operate in similar maritime areas as where floating wind project are frequently located. Remaining ignorant of the needs of fisheries can lead to situations of conflict and can stall project development plans. See section 5.4 for more information.

Recommended actions:

- **Involve representatives from the fisheries sector as early as possible in the project planning process.** By undertaking such a practice, there is ample opportunity to consider their views and concerns as project plans are developed. The use of marine spatial planning can contribute greatly to the avoidance of conflicts between offshore wind project developers and maritime stakeholders.
- **Designate "fishing areas/corridors" for wind farm operations that can allow the fishing community to safely undertake their activities.** For fisheries that use static gear, this practice can reduce the likelihood of snagging, vessel safety concerns and damage to infrastructure.
- **Make accessible all available data on the surface and sub-surface positions of floating wind farm infrastructure.** This includes providing data on the locations of mooring chains, dynamic cables and anchors on the plotters (*e.g.* FishSAFE) used by fishers to plan their fishing routes.
- **Enhance active communication between wind farm control centres and fishing vessels entering the area of operation.** This promotes a healthy dialogue between offshore wind developers and the fishing community by lowering risks for miscommunication and potential rescue operations in the event of emergencies.

6.6 FINAL INSIGHTS

Floating offshore wind has a tremendous potential to bring offshore wind power to the forefront of the energy transition. The industry is still at a very nascent stage, which provides a unique opportunity for the international community to work together symbiotically on a relatively "blank canvas" to make this technology commercially viable as soon as possible. The observations and recommendations provided in this report are vectors that can greatly accelerate the development of this promising technology. The G7 members, with their vast capabilities, are in a pole position to cross this new frontier whose potential awaits to be unleashed.

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ANNEXES

ANNEX A LIST OF IMPORTANT FLOATING OFFSHORE WIND STANDARDS

A. IEC Floating Wind Design Technical Standards as recommended by ORE Catapult

IEC TS 61400-3-2					
General	IEC 61400-1 IEC 61400-3-1			**Corrosion Protection and Control System**	IEC 61400-1 (CS) IEC 61400-3-1 (CS) ISO 19904-1 (CP) ISO 12944-9 (CP)
Environmental and Soil Conditions	IEC 61400-1 IEC 61400-3-1 ISO 19900 ISO 19901-1	ISO 19901-4 ISO 19904-1 ISO 19906 API RP 2FPS		**Stability**	IMO res. MSC.267(85)
Materials and Construction	ISO 19901-7 ISO 19905-1			**Fatigue Limit State**	IEC 61400-1 IEC 61400-3-1 ISO 19904-1
Safety Levels and Safety Concepts	IEC 61400-3-1 ISO 19904-1			**Ultimate Limit State**	IEC 61400-3-1 ISO 19904-1
Design Methods and Loads	IEC 61400-1 IEC 61400-3-1 ISO 2394 ISO 19900	ISO 19901-2 ISO 19901-4 ISO 19901-7 ISO 19904-1	ISO 19906 API RP 2FPS API RP 2T ITTC Guid. 7.5-02-07-3.8	**Transport and Installation**	IEC 61400-3-1 ISO 19904-6
Stationkeeping System and Anchor	ISO 1901-4 ISO 19901-7 ISO 19904-1 APR RP 2T			**Commissioning, Surveys and O&M**	IEC 61400-3-1 ISO 19901-6 ISO 19904-1
Mechanical and Electrical Equipment	IEC 61400-1 IEC 61400-3-1			**Serviceability and Accidental Limit State**	ISO 19904-1
Wind Turbine	IEC 61400-1				

Source: (ORE Catapult, 2021b).

B. ABS Floating Wind Design Technical Standards as recommended by ORE Catapult

ABS 195						
General	ABS Class Rules ABS FPI Rules ABS MOU Rules ABS RA Notes				**Corrosion Protection and Control System**	API PR 2SK (CP) API PR 2T (CP) NACE SP0176 NACE SP0108
Environmental and Soil Conditions	ABS FPI Rules ABS OWT Guide IEC 61400-1	IEC 61400-3-1 ISO 2533 API RP 2MET			**Stability**	ABS FPI Rules ABS MOU Rules
Materials and Construction	ABS FPI Rules ABS MOU Rules ABS OI Rules ABS Mat Rules ABS OWT Guide	ABS Chain Guide ABS FA Guide ABS Fibre Notes ACI 213R ACI 301	ACI 318 ACI 357 ACI 395 ASTM C31 ASTM C39	ASTM C94 ASTM C172 ASTM C330 AISC St. Const. Manual	**Fatigue Limit State**	ABS FA Guide ABS PMS Guide ABS Fiber Notes API RP 2T
Design Methods and Loads	ABS FPI Rules ABS MOU Rules ABS Mat Rules ABS MV Rules ABS LRFD Guide ABS PMS Guide	ABS Semi Notes ABS Fiber Notes ABS Anchor Notes ABS Pile Notes ABS FOWT Notes IEC 61400-1	IEC 61400-3-1 IEC 61400-3-2 ISO 19904-1 ISO 19906 ACI 318 ACI 357	AISC St. Const. Manual API RP 2A API RP 2MET API RP 2N API RP 2T API Spec. 9A	**Ultimate Limit State**	ABS USA Guide ABS Fibre Notes
Stationkeeping System and Anchor	ABS FPI Rules ABS OI Rules ABS Mat Rules ABS OWT Guide	ABS Chain Guide ABS Fiber Notes ABS Anchor Notes ABS Pile Notes	API RP 2A API RP 2SK API RP 2T API RP 9B	API Spec. 9A	**Transport and Installation**	ABS FPI Rules ABS Anchor Notes ABS Pile Notes
Commissioning, Surveys and O&M	ABS Class Rules ABS FPI Rules ABS MOU Rules	ABS Mat Rules ABS CSurv Rules ABS Chain Guide	ABS NDI Guide ABS RBI Guide ABS MRMT Guide	ABS Fiber Notes ISO 19903	**Mechanical and Electrical Equipment**	ABS MOU Rules IEC 61400-3-1
Other	ABS MOU Rules[1] IEC 61400-24[2]	1. Helicopter deck, guards and rails, piping, bilge system, ventilation, firefighting 2. Lightning protection			**Wind Turbine**	IECRE OD-501
					Safety Levels and Safety Concepts	ISO 19904-1

Source: (ORE Catapult, 2021b).

C. Bureau Veritas Floating Wind Design Technical Standards as recommended by ORE Catapult

BV NI572					
General	BV NR445 BV NR571 BV NR578	ISO 19902 API RP 2A API RP 2T		Safety Levels and Safety Concepts	BV NR493
Environmental and Soil Conditions	BV NR493 BV NI 605 IEC 61400-3 ISO 19901-1 ISO 29400	EN 1997 IMO MODU Code IMO MSC/Circ.884 IMO A765(18)		Wind Turbine	BV NI 525 IEC 61400-1 ISO 76 ISO 281 ISO 6336 series
Materials and Construction	BV NR216 BV NR426 BV NR445 BV NR467 BV NR576 BV NI 594	API RP 2T ISO/IEC 17021 ISO 9001 ISO 19903 EN 106 EN 1992	AISC Steel Construction Manual AWS D1.1	Mechanical and Electrical Equipment	IEC 60092 series IEC 61892 series IEC 61400 series IEC 60092-401 IEC 61400-24 IEC 61892-6
Corrosion Protection and Control System	BV NI 423 BV NR445 BV NR493 BV NI 605 ISO 9226	ISO 11306 ISO 12944 NORWOK M-501 ASTM G1		Stationkeeping System and Anchor	BV NR493 BV NR578 BV NI 604 BV NI 605 API RP 2T
Design Methods and Loads	BV NR426 BV BR445 BV NR467 BV NR493 BV NR571	BV NR578 BV NI 611 IEC 61400-3 API RP 2T ISO 19901-2	ISO 29400 EN 1993-1	Transport and Installation	BV NR526 ISO 29400 API RP 2A IMO MSC/Circ.884 IMO A765(18)
Fatugue Limit State	BV NR493 BV NR578 BV NI 604	BV NI 611 API RP 2T		Commissioning, Surveys and O&M	BV NR445
Stability	BV NR445 BV NR578 ISO 29400	IMO MSC/Circ.884 IMO A765(18) IMO Res MSC.267(85)		Ultimate Limit State	BV NI 615 API RP 2A
Other	BV NR445[1] BV NR467[2]	1. Mooring support, hull attachments, heli deck, bilge system 2. Lifting appliance foundations, bulwarks, guard rails		Serviceability and Accidental Limit State	BV NR445

Source: (ORE Catapult, 2021b).

D. DNVGL Floating Wind Design Technical Standards as recommended by ORE Catapult

DNVGL-ST-0119						
General	DNVGL-ST-0126 DNVGL-ST-0376 DNVGL-RP-A203 IEC 61400-1	Circ.1023–MEPC/Circ.392 Guidelines for Formal Safety Assessment		**Corrosion Protection and Control System**	DNVGL-ST-0076 DNVGL-ST-0126 DNVGL-ST-0438 DNVGL-OS-A101 DNVGL-OS-D202	DNVGL-OS-E301 DNVGL-RP-0416 DNVGL-RU-OU-0102 NORSOK M-001
Environmental and Soil Conditions	DNVGL-ST-0126 DNVGL-ST-0437 DNVGL-RP-C205 DNVGL-PR-C207	DNVGL-RP-C212 IEC 61400-1 ISO 19901-2		**Stability**	DNVGL-OS-C301 DNVGL-RP-C205	
Materials and Construction	DNVGL-ST-0126 DNVGL-ST-C501 DNVGL-ST-C502 DNVGL-OS-B101 DNVGL-OS-C103 DNVGL-OS-C105	DNVGL-OS-C106 DNVGL-OS-E301 DNVGL-OS-E302 DNVGL-OS-E303 DNVGL-OS-E304 DNVGL-RP-E304	DNVGL-RP-E305 ISO 13628-5 ISO 898-1 EN 1992-1-1 EN 1992-2 EEMUA pub #194	**Fatigue Limit State**	DNVGL-ST-0126 DNVGL-OS-C401 DNVGL-OS-E301 DNVGL-OS-E303 DNVGL-RP-E305	DNVGL-RP-F401 DNVGL-CG-0129 DNVGL-RP-C203 BS 7910
Safety Levels and Safety Concepts	DNVGL-ST-0126			**Ultimate Limit State**	DNVGL-ST-0126 DNVGL-RP-C202 EN 1993-1-1	EN 1993-1-8 Eurocode NORSOK N-004
Design Methods and Loads	DNVGL-ST-0126 DNVGL-ST-0437 DNVGL-ST-C501 DNVGL-ST-N001 DNVGL-OS-C101 DNVGL-OS-C103 DNVGL-OS-C105 DNVGL-OS-C106	DNVGL-OS-C401 DNVGL-OS-D101 DNVGL-OS-E301 DNVGL-OS-E303 DNVGL-OS-F201 DNVGL-OTG-13 DNVGL-OTG-14 DNVGL-RP-C103	DNVGL-RP-C104 DNVGL-RP-C201 DNVGL-RP-C205 DNVGL-RP-C208 DNVGL-RP-F205 IEC 61400-3	**Transport and Installation**	DNVGL-ST-0437 DNVGL-ST-N001 DNVGL-RP-N101 DNVGL-RP-N103	
Power Cable	DNVGL-ST-0359 DNVGL-ST-N001 DNVGL-OS-F201 DNVGL-RP-0360 DNVGL-RP-C203	DNVGL-RP-C205 DNVGL-RP-F105 DNVGL-RP-F107 DNVGL-RP-F109 DNVGL-RP-203	DNVGL-RP-F204 DNVGL-RP-205 DNVGL-RP-F401 ISO 13628-5 API Spec. 17J	**Commissioning, Surveys and O&M**	DNVGL-ST-0126 DNVGL-OS-E301 DNVGL-OS-E303	
Stationkeeping System and Anchor	DNVGL-ST-0126 DNVGL-ST-C501 DNVGL-OS-C105 DNVGL-OS-E301 DNVGL-OS-E302 DNVGL-OS-E303 DNVGL-OS-E304	DNVGL-RP-C207 DNVGL-RP-C212 DNVGL-RP-E301 DNVGL-RP-E302 DNVGL-RP-E303 DNVGL-RP-E305 DNVGL-RU-OU-0102	EN 1573 EN 1997-1 NORSOK M-001 NORSOK N-006 PTI DC 35.1	**Mechanical and Electrical Equipment**	DNVGL-ST-0076 DNVGL-ST-0359 DNVGL-ST-0378 DNVGL-OS-A101 DNVGL-OS-D101 DNVGL-OS-D201	DNVGL-OS-E301 IEC 61892-6 ISO 13628-5 EEMUA pub #194

Source: (ORE Catapult, 2021b).

ANNEX B NON-EXHAUSTIVE OVERVIEW OF OFFSHORE WIND AND HYDROGEN COUPLING PROJECTS

PROJECT	TYPE	REGION	DESCRIPTION	CAPACITY	YEAR	REFERENCE
AquaVentus	Fixed	Germany – North Sea	The initiative plans to generate 10 GW of electricity from offshore wind farms to power electrolysis units in the North Sea. The objective is to produce 1 million t of green hydrogen and transport it onshore via pipeline.	10 GW (offshore wind)	2035	(AquaVentus, 2023)
AquaDuctus (SEN-1)	Fixed	Germany	AquaDuctus falls under the AquaVentus initiative and aims to establish GW-scale offshore hydrogen pipelines (400 km) in Germany's North Sea. Within Germany's recent offshore wind development plan to ramp up capacity to 30 GW by 2030, a zone has been created (SEN-1) to establish a hydrogen pipeline that will enable 1 GW of electrolysis capacity. Germany's Gascade and Belgium's Fluxys have made approval and funding applications to connect AquaDuctus with this dedicated zone. Their application aims to commence hydrogen production and flow through this pipeline by 2030.	1 GW (electrolysis)	2030	(AquaDuctus, n.d.; Collins, 2023)
NorthH2	Fixed	Netherlands	A consortium comprising Eneco, RWE, Equinor, Shell, GasUnie and Groningen Seaports is exploring avenues to produce hydrogen offshore in the Netherlands. The objective of this project is to provide 2-4 GW of hydrogen by 2030 and to reach a capacity of 10 GW (equivalent to 750 000 t) annually by 2040. A feasibility study was recently completed, and project development plans are under way.	4 GW (hydrogen by 2030) 10 GW (hydrogen by 2040)	2030	(NorthH2, n.d.)
Hollandse Kust and North Waddenfall Demonstration Projects	Fixed	Netherlands	The Dutch government foresees two lots (tender structure to be finalised) for offshore hydrogen demonstration projects: **Demo 1: 100 MW (Hollandse Kust region) to be operational by 2027** This first project will focus on demonstrating the ability to produce hydrogen at sea, with the project being added to the wind farm, thus not requiring any new wind production. The government is looking to co-operate with Gasunie to bring the hydrogen ashore once operational, with further options being explored with TenneT to connect the electrolyser to a converter station. **Demo 2: 500 MW (north of the Wadden Islands region) to be operational by 2031** The project location was decided based on the current allocation for wind projects in the Netherlands, with the area being designated as a future wind farm zone, which will be well connected to the future offshore hydrogen network. An existing natural gas pipeline running near the Demo 2 zone (NGT) is being investigated for its feasibility to be re-used for hydrogen transport, as previously investigated by DNV and "certified" by BV.	100 MW and 500 MW	2027 and 2031	Input provided from engagement with DNV experts and (Lee, 2023b)

PROJECT	TYPE	REGION	DESCRIPTION	CAPACITY	YEAR	REFERENCE
PosHYdon	Fixed	Netherlands	The project aims to install a hydrogen production plant on an existing offshore oil and gas platform (Q13a-A) managed by Neptune Energy. This platform is located 13 km off the shore of Scheveningen in the Hague. The project is being managed by a consortium comprising Nel Hydrogen, InVesta, Hatenboer, Iv-Offshore & Energy, Emerson, Nexstep, TNO, Neptune Energy, Gasunie, Noordgastransport, NOGAT, DEME, TAQA, Eneco and EBN. The objective is to gain technical and practical insights on hydrogen production using offshore wind-driven electrolysis. The current capacity of the electrolyser being tested is 1 MW, which is expected to produce 400 kg H_2/day. The green hydrogen will be transported via existing gas pipelines onshore, and the proposed blending specification by the Ministry of Economic Affairs and Climate Policy is 0.5% PosHYdon is expected to become operational during the third and fourth quarters of 2024.	1 MW (electrolysis)	2024	(PosHYdon, 2023, n.d.)
Oyster	Floating	Grimsby (UK)	A consortium comprising ITM Power, Ørsted, Siemens Gamesa Renewable Energy and Element Energy is investigating the feasibility and potential of connecting electrolysers with offshore wind turbines. The first phase of the project (2021-2024) is aimed at developing a MW-scale integrated electrolyser that can operate offshore; demonstrating its cost-competitiveness compared to existing electrolysers on the market; and developing a test programme that can validate the performance of the system. This project has received a grant of EUR 5 million (USD 5.4 million) from the EU's Clean Hydrogen Partnership.		2024 (completion of phase 1)	(Oyster, n.d.)
BEHYOND	Floating	Portugal	The project is being undertaken by a consortium comprising TechnipFMC, EDP, CEiiA, WavEC and the Norwegian University USN. With funding from the European Environment Agency and Norwegian grants, the project aims to develop a conceptual solution as well as techno-economic analysis on a modular approach to couple hydrogen production with offshore wind. There is a particular focus on exploring how hydrogen electrolysers can be integrated in floating offshore wind turbines. An assessment study completed in 2021 found that offshore hydrogen production is feasible; however, it will only become economically viable when both the offshore and hydrogen industries reach a sufficient level of maturity.		2021 (techno economic feasibility study completed)	(BEHYOND, n.d.)

PROJECT	TYPE	REGION	DESCRIPTION	CAPACITY	YEAR	REFERENCE
H2Mare	Floating	Germany	A variety of German institutions such as Fraunhofer, DECHEMA, and BAM, among partners, are undertaking various research activities to produce offshore hydrogen by integrating the electrolyser directly into the wind turbine. There is also an emphasis on exploring how this hydrogen can be used in power-to-X activities such as methanol and ammonia production. Updates on the project as of 2023 included the commencement of testing seawater desalination for offshore electrolysis as well as looking into wastewater management for power-to-X activities. Fraunhofer has also demonstrated the technical and economic feasibility of producing hydrogen offshore using PEM electrolysis (Fraunhofer ISE, n.d.; Hydrogen Tech World, 2023).			(BMBF, n.d.; Mueller and Dittmeyer, 2023; Siemens Energy and Fraunhofer Institute for Wind Energy Systems, 2023)
Dolphyn	Floating	Scotland, North Sea, and Celtic Sea	This project, led by ERM, aims to integrate the necessary hydrogen production components (electrolyser and desalination unit) into a semi-sub floating offshore design structure. Efforts are being made to establish a commercial demonstrator 10 MW concept for this technology before 2030, with trials having commenced in 2023 at Milford Havens (Wales). Once this demonstrator is classified as a proven technology concept, the aim of the project is to deploy a series of these units in the North and Celtic seas with a cumulative network capacity of 100-300 MW towards the late 2020s.	10 MW (offshore capacity)	2030	(Dolphyn Hydrogen, n.d.)
SeaWORTHY	Floating	Spain	The SeaWORTHY technology (Sustainable dispatchable Energy enabled by wAve-Wind OffshoRe plaTforms with onboard HYdrogen) has been developed by Floating Power Plant. Their technological concept focuses on integrating offshore wind and wave power to support hydrogen production and contribute to the development of the offshore power-to-X market. A key technological underpinning of SeaWORTHY is its P-Demo platform. This is a semi-submersible platform housing technology that synergises a 4.3 MW wind turbine generator, a 0.8 MW wave energy converter and a comprehensive hydrogen system – comprising a 1 MW electrolyser, 48 MWh of energy storage and a 1.2 MW fuel cell. The annual generation capacity of this concept is 11.05 GWh. Floating Power Plant has secured a EUR 26 million (USD 28 million) grant from the EU to improve the technology readiness level of their concept from level 6 to level 8. The testing of this concept will take place off the coast of Las Palmas in the Canary Islands at the PLOCAN test site and will be the world's inaugural wind-wave-hydrogen unit.	4.3 MW (Offshore turbine) 1 MW (electrolyser)		Contact with representatives from Floating Power Plant

PROJECT	TYPE	REGION	DESCRIPTION	CAPACITY	YEAR	REFERENCE
Lhyfe	Floating	Le Croisic (France)	Lhyfe has developed a demonstrator offshore hydrogen electrolysis system (1 MW), which has proven to generate hydrogen in dynamic offshore conditions through an experiment the company conducted during 2022-2023. The installation of this system at port started in September 2022, and it was towed to the offshore wind project site (SEM-REV) off the coast of Le Croisic (near Nantes) in May 2023. The system started production of hydrogen in June 2023 and was towed back to port in November 2023. During this entire period, the Lhyfe team was undertaking data collection/analysis and monitoring the performance of the electrolyser unit. The results of the experiments and data demonstrated that the electrolyser was able to adapt to difference in wind variability and had similar performance when compared to its performance onshore. The experiment also confirmed the system's ability to manage wind power variability under specific offshore conditions. The electrolysis system operated as part of the planned research tests, even at maximum production capacity. The performance achieved was as high as on land, confirming the reliability of the installation. The onboard maintenance systems were also able optimise efficiency and ensure safety of crucial components – even in harsh conditions such as when storm Ciaran passed through in October 2023. The successes and results from this first phase experiment are now being fed into the second phase (project name HOPE), which has received EUR 33 million (USD 35.7 million) from the European Commission and the Belgian government. The aim of this new phase is to scale the Lhyfe demonstrator system to 10 MW to produce around 4 t/day of green hydrogen, to be transported onshore via pipelines. Lhyfe endeavours to reach green hydrogen production capacity of 22 t/day by 2024 and up to 80 t/day in 2026.	1 MW (electrolyser) 10 MW (electrolyser second phase 2024)	2024	(Interempresas, 2024; Lhyfe, n.d.)

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