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The Future of Offshore Renewables

Energy Research Paper

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Offshore renewable resources can be captured through various technologies such as offshore fixed or floating wind turbines, floating solar photovoltaic panels, wave and tidal conversion systems, and other ocean energy technologies such as ocean thermal energy conversion and salinity gradient. What is driving the outlook for these technologies? What is driving their costs? What are the synergies among these technologies and with offshore oil & gas projects? What will offshore renewable energy hubs of the future look like?

ENERGY RESEARCH PAPER

This research paper is part of a 12-month series published by the Al-Attiyah Foundation every year. Each in-depth research paper focuses on a current energy topic that is of interest to the Foundation's members and partners. The 12 technical papers are distributed to members, partners, and universities, as well as made available on the Foundation's website.

03 EXECUTIVE SUMMARY

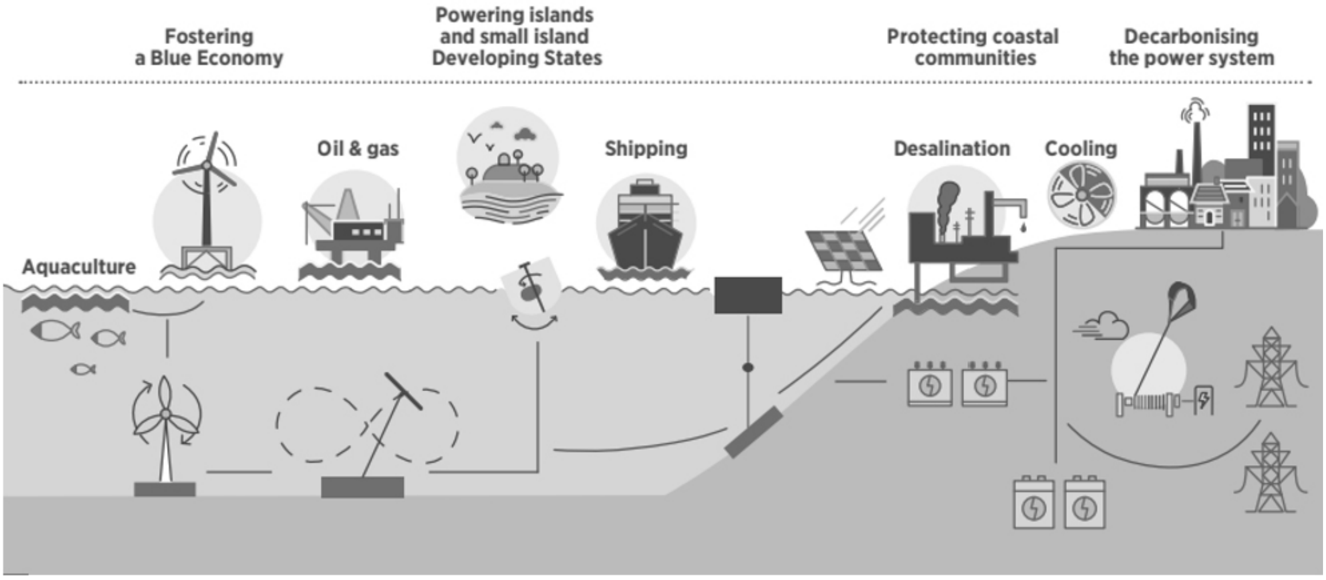
Introduction

- Offshore renewables are estimated to mitigate ~5.4 gigatons / day of carbon dioxide emissions by 2050, which accounts for 10% of global efforts to keep the temperature increase below 1.5°C under the Paris Climate Accords.
- Offshore wind is rapidly maturing and is poised to play an important role in the future global energy mix. Global offshore wind capacity additions are projected to increase by 50% to 30 GW / year in 2027, underpinned by policy support across the United States, Europe, and China.
- Growth in ocean energy generation has been slower than expected over the last decade. Presently, global cumulative capacities stand at 534 MW, with an annual electricity generation of 1.6 TWh[i]. Technological trends are moving from tidal barrage generation to tidal stream and wave generation.
- Offshore floating wind has the potential to bridge capacity gaps in offshore wind generation by accessing deeper waters. Levelized Cost of Electricity (LCOE) for bottom-fixed and floating wind may converge by 2035.
- The global floating solar PV market is expected to reach 6 GW by 2031 as solar PV developers battle limited land availability and increasing land costs for ground-mounted solar PV projects.

Cost of Offshore Renewable Generation

- Europe has been the front-runner in the global decline in LCOE for bottom-fixed offshore wind. In 2021, the average LCOE for newly commissioned projects in Europe declined by 29% y-o-y to US$ 0.065 / kWh, mainly driven by technological improvements in wind turbines and projects being developed further from shore in deepwater, leading to average capacity factors increasing from 42% to 48%.
- Offshore floating wind generation costs are projected to decline by 23% between 2021 – 2025 to US$ 0.13 / kWh. Like bottom-fixed offshore wind, the decline in LCOE will be led by improvements in turbine sizes and project location and, specifically, innovative and optimised use of mooring systems, anchoring systems, and dynamic cables in floating structures.
- Floating solar PV generation costs currently average US$ 0.354 / kWh. Some countries could achieve cost parity with small-scale ground-mounted PV and rooftop solar PV and potentially reach competitive prices of US$ 0.05 / kWh and US$ 0.04 / kWh by 2050.
- Ocean energy harnesses waves, tides, currents, and thermal and salinity gradients. The cost for ocean energy generation is uncertain and too high to compete with offshore wind due to its early-stage technological readiness. However, tidal generation shows the greatest potential to become cost-competitive, with initial assessments for a 12 MW unit estimating generation at US$ 0.20 - US$ 0.45 / kWh, compared to US$ 0.30 – US$ 0.55 / kWh for wave generation.

Figure 1: Interaction between Offshore Renewables and the Blue Economy



Synergies between Offshore Oil & Gas and Renewables

- Synergies between the offshore energy industries exist in three main areas: 1) cross-utilisation of expertise in developing offshore conventional and renewable infrastructure; 2) electrification and decarbonisation of offshore oil & gas platforms with renewable (or low-carbon) electricity; 3) combination of complementary resources, such as offshore hydrogen generation, and combining the different temporal patterns of renewable types; and 4) shared infrastructure, such as the possibility of converting decommissioned offshore oil & gas platforms for offshore renewable generation, and / or other low-carbon projects such as power-to-X or gas-to-electricity (gas-to-wire), or carbon capture, use and storage (CCUS) projects.

Offshore Renewable Energy Hubs (OREHs) of the Future

- Offshore Renewable Energy Hubs of the future will utilise synergies between offshore wind, floating wind and solar PV, and ocean energy through combined systems and connect offshore renewable resources to power-to-X technologies for hydrogen / electricity generation.

The world's oceans contain an abundant renewable resource, from wind, waves, tides, the sun, thermal, and salinity differences that can be efficiently extracted by modern technologies and devices, either by converting them into electricity (for offshore consumption and / or onshore consumption through grid connections) or an energy storage medium (such as batteries or hydrogen).

Offshore renewable resources can be captured through various technologies such as offshore fixed or floating wind turbines, floating solar photovoltaic panels, wave and tidal conversion systems, and other ocean energy technologies such as ocean thermal energy conversion and salinity gradient.

These resources can help decarbonise offshore oil & gas operations, produce low-carbon electricity and hydrogen, and contribute to the expansion and decarbonisation of the global blue economy, consisting of maritime shipping, offshore aquaculture and farming, water desalination, and cooling.

Offshore renewables are estimated to mitigate ~5.4 gigatons (Gt) / day of carbon dioxide emissions by 2050, which accounts for 10% of global efforts to keep the temperature increase below 1.5°C under the Paris Climate Accords[ii]. The global climate value (i.e., the value of financial return adjusted to climate risks and opportunities) for offshore wind generation alone is estimated to be US$ 100 billion if there is no climate policy, compared to US$ 120 billion if there are carbon caps (i.e. a limit on permissible emissions), and US$ 450 billion if there is an effective implementation of a global carbon tax[iii].

Offshore Renewables

Offshore renewables include fixed and floating wind in the seas, ocean energy (wave, tidal, current, thermal, and salinity gradient), and floating solar PV.

Floating wind uses the same general turbines as conventional onshore wind farms, or "bottom-fixed" offshore turbines that are deployed on top of floating structures secured to the seabed with mooring lines and anchors.

Ocean energy technologies are based on the source used for electricity generation. For example, tidal stream and tidal barrage technologies are used to extract tidal energy that is generated from the rise and fall of water levels (or tides) in the ocean due to gravitational pulls of the moon and the sun. Wave technologies convert the motion of waves into energy. Current energy taps larger-scale one-way motions of ocean waters. Ocean thermal energy conversion (OETC) generates electricity from the temperature differentials between the ocean's depths and its surface. Salinity gradient uses the difference in saltiness between the sea and fresh-water, or between concentrated brine and the sea.

Floating solar PV (also known as floating photovoltaic) are solar arrays consisting of PV panels affixed on buoyant structures that float on top of a water body. These floating solar panels are mostly placed on generally calmer oceans.

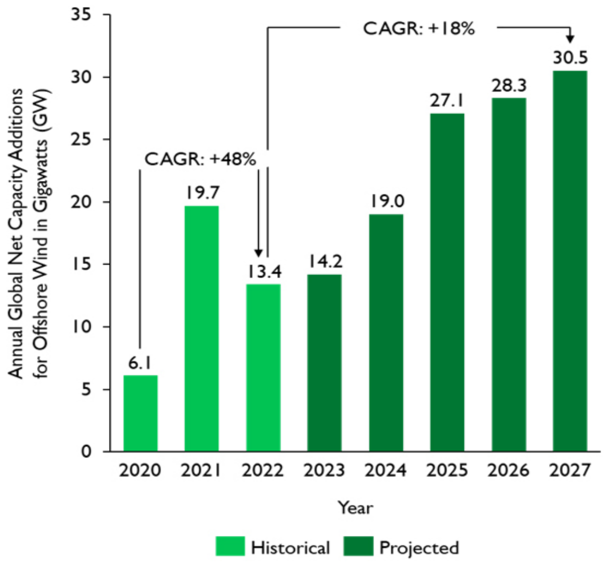
However, offshore infrastructure is also vulnerable to climate change itself. Increases in global temperature will impact meteorological and oceanographic parameters through changes in wind speeds, wave heights and periods, ocean current speeds, and sea levels and depths, subsequently affecting the design of offshore energy infrastructures, coastal structures and operations, and their ability to withstand environmental loads.

Although these topics are a subject of research, it is expected that Atlantic hurricanes will become more intense (though not necessarily more frequent), and some other areas of the world that have rarely experienced hurricanes will see more, such as the Mediterranean. On the other hand, a lower pole-to-equator temperature gradient will cause weaker winds generally, reducing output. Dust and haze from onshore desertification could affect the output of floating solar panels, while ocean currents may also shift in response to temperature changes and the injection of meltwater into the seas.

A recent IPCC report on climate change has stated that rising sea levels are one of the reasons causing higher coastal inundation levels for tropical cyclones[iv]. Tropical cyclone rainfall rates are projected to increase in the future due to an increase in anthropogenic warming and the subsequent increase in atmospheric moisture content[v].

Offshore wind is rapidly maturing and is poised to play an important role in the future global energy mix. Global offshore wind capacity additions are projected to increase by 50% to 30 GW / year in 2027, underpinned by policy support across the United States, Europe, and China[vi].

Figure 2: Annual Global Net Capacity Additions for Offshore Wind



The United States has set a target of 30 GW of offshore wind capacity by 2030, which will power 10 million homes, support 77,000 jobs, and stimulate investment across the supply chain[vii]. The current administration of President Joe Biden has issued two executive orders that outline offshore wind generation as a critical element of the United States' climate change policy goals, and supports the Jones Act as part of its broader policy that seeks to maximise the use of domestic supply chains and materials[viii].

In 2020, the European Commission published a dedicated strategy on offshore renewable energy to help realise the European Union's ambitious energy and climate targets for 2030 and 2050. The strategy outlines a target of 60 GW of offshore wind and 1 GW of ocean energy by 2030, and 300 GW and 40 GW, respectively, by 2050[ix].

In 2020, China announced subsidies of RMB 0.85 / kWh (US$ 0.12 / kWh) to offshore wind projects that were connected to the electricity grid by the end of 2021[x].

These subsidies have been phased out.[xi] Currently, Chinese support for offshore wind projects involves provincial governments providing financial subsidies to projects that are not qualified for national subsidies[xii].

Growth in ocean energy generation has been slower than expected over the last decade. Presently, global cumulative capacity stands at 534 MW, with an annual electricity generation of 1.6 TWh, i.e., an average capacity factor of 34%[xiii]. The technological trend is moving from tidal barrage generation to tidal stream and wave generation.

A key characteristic of ocean energy is its higher predictability and dispatchability compared to other renewables such as solar PV and wind. Tidal resources are determined by the moon's location and gravitational movement, which can be accurately forecasted through various space technologies. Wave and current movements are more continuous than wind, and water contains much more unit energy than wind because of its greater density.

Remote islands often lack land, need a stable energy supply, and have good pre-conditions for ocean energy generation. They also have a higher demand for energy, to power other offshore industries such as aquaculture, desalination, and cooling. Their grids are often carbon intensive and their energy costs are high. Hence, ocean energy can be a viable alternative solution to fossil fuel generation across remote islands, which will not only offset their emissions from conventional fossil fuel generation, but also replace costly electricity generation from diesel, and help reduce land use for onshore electricity generation.

The International Energy Agency (IEA) estimates ocean energy generation could increase to 27 TWh in a 2050 Net-Zero emissions scenario[xiv]. This is still not very material given that wind generation from all sites globally was 2105 TWh in 2022. Contrastingly, the International Renewable Energy Agency (IRENA) has estimated that ocean energy generation could account for 4% (881 GW) of the energy mix by 2050, which at a 34% capacity factor implies 2640 TWh of generation[xv]. However, ocean energy capacities must increase by 33% between 2020 – 2030 for these scenarios to materialise[xvi].

Figure 3: Global Ocean Energy Capacities

The deployment of ocean energy varies by geography; for instance, tidal generation, specifically tidal barrage projects, are mostly common across France, South Korea, Canada, and the United Kingdom. Currently, three large-scale tidal barrage projects, the 254 MW Sihwa Lake Tidal Power Project in South Korea, the 240 MW La Rance Tidal Power Project in France, and the 20 MW Annapolis Tidal Project in Canada, account for 98% of the global installed ocean energy capacity[xvii].

Until now, tidal barrage has been the most mature ocean energy technology. But in the long-term, it is likely to be overtaken by tidal stream, which has a higher theoretical electricity generation potential, requires lower capital investment, and has a small environmental impact[xviii].

Presently, eighty planned tidal stream projects with a total capacity of 1.9 GW, are expected to become operational over the next five years[xix]. The United Kingdom intends to develop the most, with six projects expected to be operational by 2026[xx].

Despite wave energy's larger resource potential of ~29,000 TWh / year, its deployment is likely to be limited compared to tidal energy technologies due to its early-stage technological readiness[xxi]. Currently, there are nine operational wave energy projects with a total capacity of 2.3 MW – most of them are demonstration projects across Europe with an installed capacity of less than 1 MW.

The largest wave energy project in the world is the 1.25 MW Ocean Energy Buoy Project in Hawaii, United States[xxiii].

Other early-stage technologies such as OTEC, salinity gradient, and ocean current could pick up, depending on their technological improvements and commercialisation. However, these technologies are far less mature than their counterparts and are still in the conceptual and / or research and development phase.

Offshore floating wind has the potential to bridge capacity gaps in offshore wind generation. Current forecasts project that the levelised cost of electricity (LCOE) for bottom-fixed and floating wind may converge by 2035[xxiv].

Experiences from bottom-fixed wind show an ability to rapidly bring down costs, which could open up floating wind opportunities for more countries, in addition to the greater floating wind resources. (see section "cost of offshore renewables generation").

Equinor has been at the forefront of developing and commercialising utility-scale floating wind projects across Europe. The 88 MW Hywind Tampen Floating Wind Project in Norway, located around 140 kilometres off the coast of Norway (in the Norwegian North Sea), is the world's largest floating wind project, developed by Equinor, alongside Vår Energi, INPEX, Idemitsu, Petoro, Wintershall Dea, and OMV. (see section "synergies between offshore oil & gas and renewables").

Equinor has also partnered with Masdar in developing the 30 MW Hywind Scotland Floating Wind Project[xxv]. Since its commissioning in 2017, the project has had the highest average capacity factor out of all offshore wind projects in the United Kingdom, proving the potential of floating offshore wind projects[xxvi].

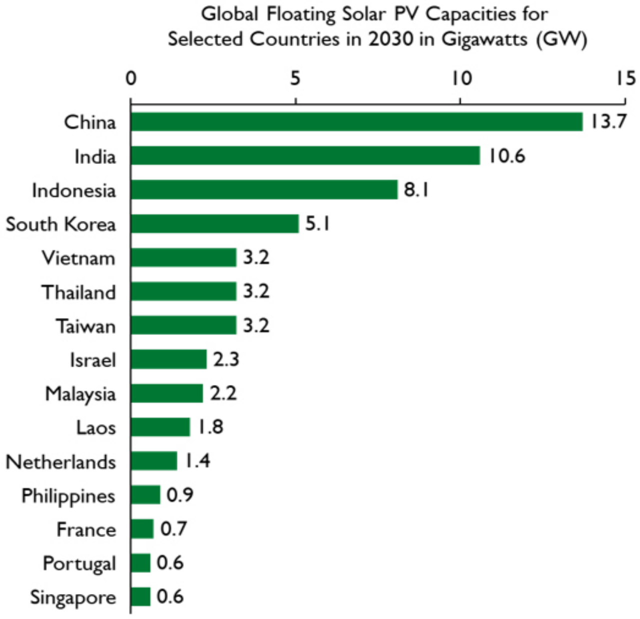
Today, Europe (specifically Norway and the United Kingdom) dominates the global offshore floating market with 113 MW of operational floating wind capacity[xxvii]. But this will likely change by the end of this decade, with South Korea, Japan, and Taiwan emerging as new markets.

South Korea, through its Renewable Energy 2030 Implementation Plan, will develop 12 GW of offshore wind capacity by 2030 of which 6 GW will be floating wind[xxviii]. Japan's floating offshore wind potential of 424 GW is three times its offshore fixed-bottom wind potential[xxix]. Construction is underway on the 17 MW GOTO Offshore Floating Wind Project along the coast of Goto City. The project will generate electricity to the grid at US$ 0.29 / kWh[xxx]. Taiwan is currently developing a 1.3 GW floating wind project[xxxi].

The global floating solar photovoltaic (PV) market is expected to reach 6 GW by 2031 as solar PV developers battle limited land availability and increasing land costs for ground-mount solar PV projects[xxxii].

Asia-Pacific dominates the global floating solar PV market, accounting for 90% (3 GW) of the global capacity additions in 2022. In the medium-term, China will continue to lead in global floating solar installations, with cumulative capacities expected to increase by 12% / year to 14 GW by 2030[xxxiii]. This includes installations on lakes and rivers as well as marine.

Figure 4: Global Floating Solar PV Capacities for Selected Countries in 2030



Outside Asia-Pacific, the Netherlands has Europe's largest floating solar PV capacity, with 48 MW, accounting for 32% of Europe's total capacity in 2022. Although Europe is a small market for floating solar PV, the trend is positive, and large capacity projects are expected by 2025. However, given the grid constraints and higher LCOE for floating solar PV generation, it will remain more expensive than rooftop PV.

The future outlook for offshore renewables is dependent on its technological maturity and cost-competitiveness with fossil fuel generation. Record reductions in LCOE have been registered for offshore wind, floating wind and solar PV, and ocean energy generation.

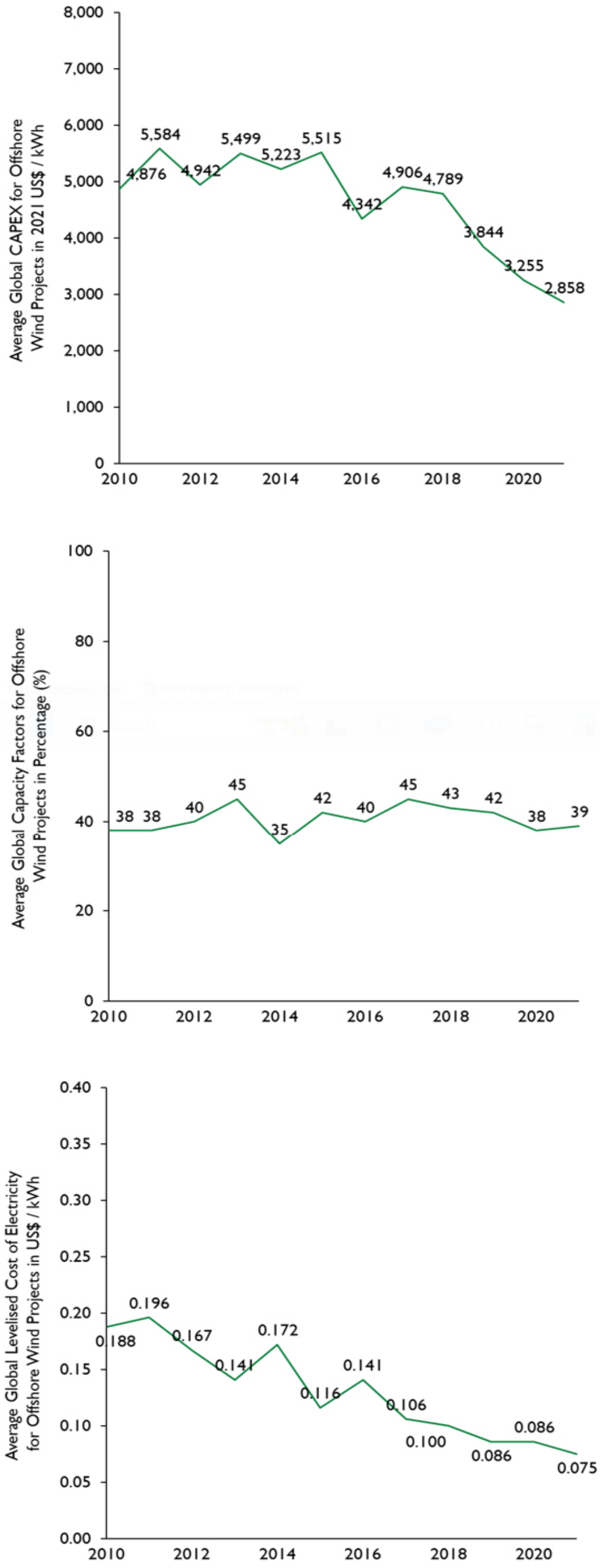
Europe has been the front-runner in the global LCOE decline for bottom-fixed offshore wind. In 2021, the average LCOE for newly commissioned projects in Europe declined by 29% y-o-y to US$ 0.065 / kWh, mainly driven by technological improvements in wind turbines and projects being developed further from shore in deep waters, leading to average capacity factors increasing from 42% to 48%[xxxv].

Offshore wind development has significantly benefitted from the experience gained from onshore wind projects, mainly from the standardisation of higher-capacity turbines, longer blades with higher hub heights, and a three-bladed horizontal axis turbine system, which can change the angle of the blade as per the wind direction and operate at different rotation speeds. These improvements have led to higher average capacity factors for wind generation, with larger turbines unlocking economies of scale benefits.

Moving from land to offshore shallow water areas (with water depth < 20 metres), then into intermediate water depths of 20 metres – 60 metres, and finally towards deepwater areas with depth > 60 metres has required the development of different foundations to support the wind turbines, and ultimately contributed to the declining LCOE for offshore wind generation.

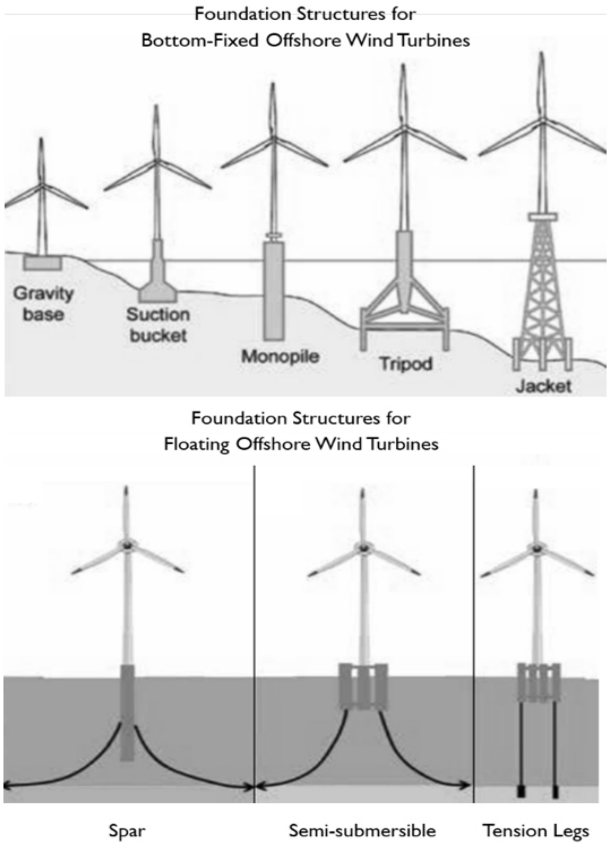
The choice of foundation for an offshore wind project depends on the water depth, seabed type, and possible environmental impact. Foundations designs for shallow or intermediate waters are typically bottom-fixed, including monopiles, tripods, jackets, foundations with suction buckets and gravity-based structures.

Figure 5: Global Average Capital Expenditure (CAPEX), Capacity Factors, and Levelised Cost of Electricity for Offshore Wind Generation



These designs are mature and have been widely developed, especially monopile foundations, the most commonly used foundations in European offshore wind projects, given their simple design and installation process.

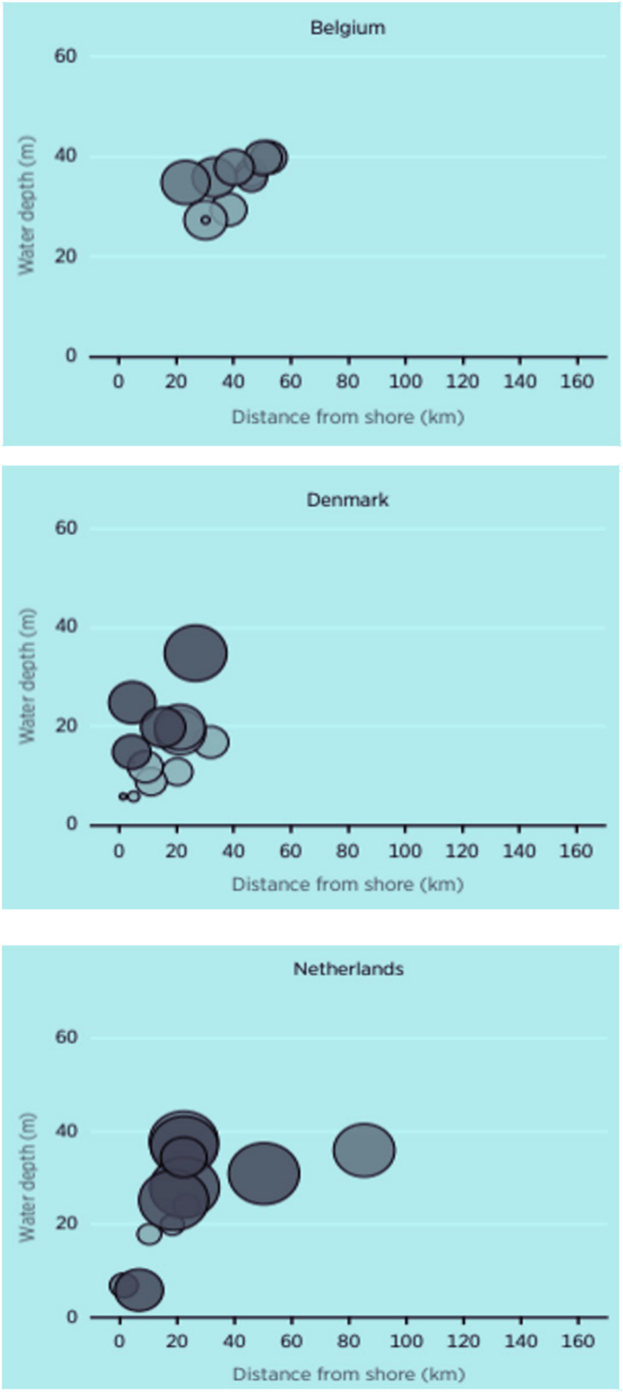
Figure 6: Foundations for Offshore Wind Projects

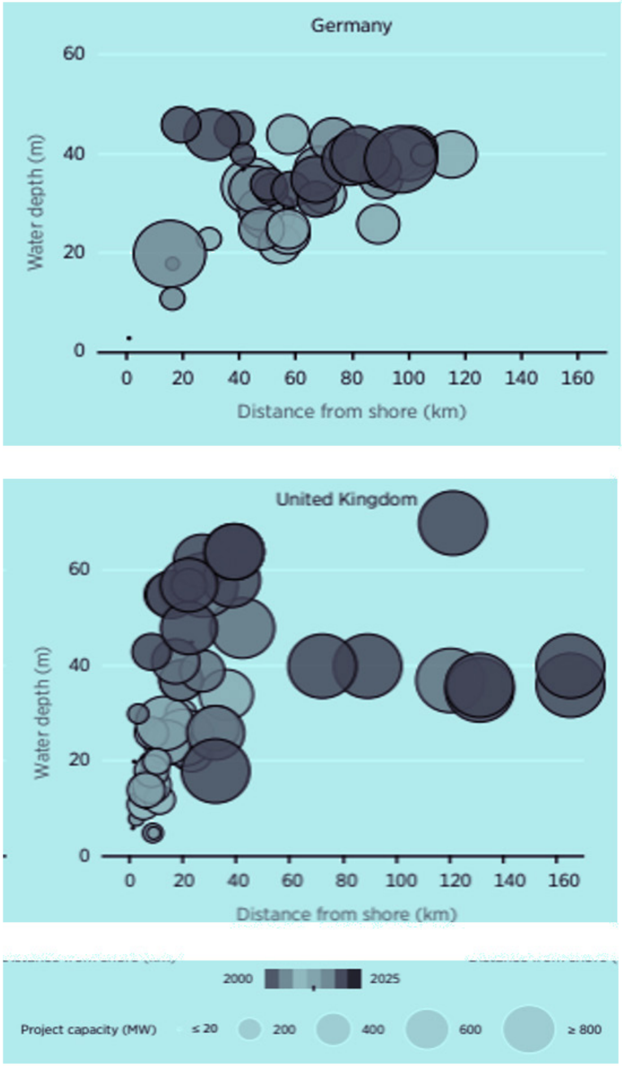


The European trend of developing further-from-shore projects in deepwater is primarily common in Germany and the United Kingdom, with the latter having the largest total capacity located ≥50 kilometres from the coast.

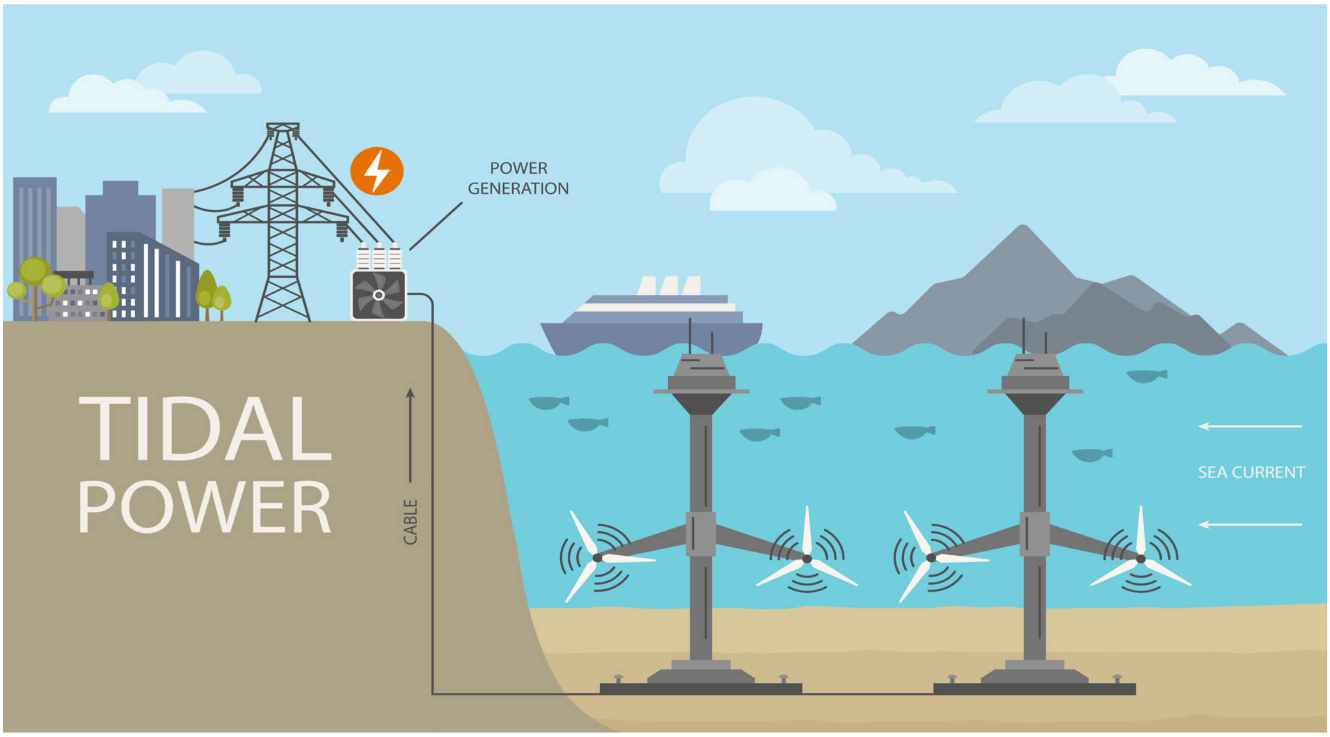
In 2000, European offshore wind projects had an average capacity of 25 MW and were positioned in water depths averaging 7 metres, with locations averaging 5 kilometres from the shore[xxxvi]. In 2022, these figures increased significantly, with project capacities averaging 590 MW, water depths averaging 39 metres, and distance from the shore averaging 23 kilometres[xxxvii]. An example of this trend is Norway's 88 MW Hywind Tampen Wind Project, commissioned last year, located 140 kilometres from shore in water depths of 260 metres – 300 metres[xxxviii].

Figure 7: Distance from Shore and Water Depths for Offshore Wind Projects by Country





Although it is easier to install large turbines in offshore wind developments since they are easier to transport by ship, the operation and maintenance (O&M) costs for offshore wind projects are much higher than onshore generation, accounting for 23% of total capital expenditure (CAPEX) over the project lifecycle, in comparison to 5% for onshore wind generation[xxxix].



Offshore floating wind generation costs are projected to decline by 23% between 2021 – 2025 to US$ 0.13 / kWh[xl]. Like bottom-fixed offshore wind, the decline in LCOE will be led by improvements in turbine sizes and project location and, specifically, innovative, and optimised use of mooring systems, anchoring systems, and dynamic cables in floating structures.

In 2022, Corewinds (a European Union-funded project) conducted virtual simulations across two floating offshore wind sites, the Canary Islands and the United States, and concluded 60% and 55% cost reductions, respectively, could be achieved in installing mooring systems for offshore floating wind projects[xli].

In deepwater offshore areas, floating wind turbines are more economically feasible since bottom-fixed foundations are too large and expensive. Floating turbines are attached to the seabed through mooring lines and have spar, semi-submersible, or tension leg platform designs. Hywind Scotland uses semi-submersible floating wind turbines. However, spar and tension leg platform design developments are increasingly tested in pilot projects.

Both bottom-fixed and floating structures have been extensively used at commercial scale by the offshore oil & gas industry, leading to the availability of relevant experience and expertise (see section "Synergies between Offshore Oil & Gas and Renewables"). However, foundations and support structure designs for offshore wind have different requirements for oil & gas platforms, and therefore new skills need to be developed.

Floating solar PV generation costs currently average US$ 0.354 / kWh. Some countries could achieve cost parity with small-scale ground-mounted PV and rooftop solar PV and potentially reach competitive prices of US$ 0.05 / kWh and US$ 0.04 / kWh by 2050[xlii].

Floating solar PV is one of the less technologically mature offshore renewable energy technologies, and for it to be commercially viable, a very large ocean surface area needs to be covered with solar panels to produce sufficient power, which presents many design and spatial planning challenges. In addition to this, cables, modules, and electrical components must be fitted with special insulation.

Until now, floating solar PV has been mostly deployed on lakes and reservoirs with limited or absent silent currents. In these locations, plastic floating structures are connected to steel frames supporting solar PV panels. However, in seas with relatively high currents, these systems struggle with capacity factors due to their flexibility and the large forces exerted by waves. More solid floating platforms made of steel or concrete are needed to support the PV panel deck, such as the concept developed by Equinor and Moss Maritime[xliii].

Given these technical requirements, current investment costs exceed those of onshore solar PV generation. Still, a 13 MW floating solar PV project in Malaysia achieved an LCOE of US$ 0.051 / kWh through a 21-year power purchase agreement (PPA), providing optimism for future cost reduction potential[xliv].

The cost of ocean energy generation is uncertain and too high to compete with offshore wind due to its early-stage technological readiness. However, tidal generation shows the greatest cost potential with initial assessments for a 12 MW unit estimating generation at US$ 0.20 - US$ 0.45 / kWh, compared to US$ 0.30 – US$ 0.55 / kWh for wave generation[xlv].

Although these costs are uncompetitive with fossil fuel generation and offshore wind, recent project experiences suggest that additional cost reductions could be unlocked through a better assessment of resource and dispatchability.

In 2016, a European Commission study proposed cost targets for ocean energy generation. Tidal generation targets were set at US$ 0.165 / kWh by 2025, US$ 0.11 / kWh by 2030, and targets for wave generation were set at US$ 0.22 / kWh by 2025 and US$ 0.165 / kWh by 2030[xlvi]. The study concluded that the decline in LCOE over the coming years will be attributed to an increase in operational capacity allowing developers to unlock economies of scale benefits, increase in project experience, and improved commercial terms offered by electricity offtakers.

In 2018, a similar study was conducted by United Kingdom-based Offshore Renewable Energy Catapult, which derived LCOE for tidal stream generation at US$ 0.40 / kWh, which could decline to US$ 0.20 / kWh at 100 MW of capacity, US$ 0.12 / kWh at 1 GW capacity, and eventually to US$ 0.11 / kWh at 2 GW[xlvii].

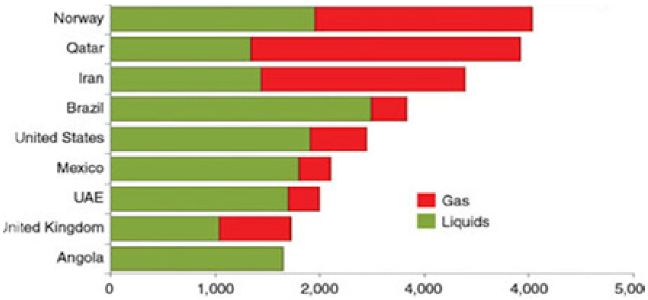
Like the European Commission study, it highlighted that further reductions could be achieved through economies of scale, larger turbines, and accelerated industry learning of new technologies, supply chains, O&M, weather data, and site familiarity.

Tidal energy could reach US$ 0.11 / kWh by 2030, whilst wave energy costs could decline to US$ 0.22 / kWh by 2025 and US$ 0.165 / kWh by 2030[xlviii].

The synergies between the offshore energy industry exist in three main areas: cross-utilisation of expertise in developing offshore conventional and renewable infrastructure; electrification and decarbonisation of offshore oil & gas platforms with renewable (or low-carbon) electricity; and the possibility of converting decommissioned offshore oil & gas platforms for offshore renewable generation, and / or other low-carbon projects such as Power-to-X (PTX) or gas-to-electricity (gas-to-wire), or carbon capture, utilisation, storage (CCUS) projects.

The leading offshore oil and gas producers are shown in Figure 8. They include the main Gulf producers, the North Sea (Norway and UK) and the Atlantic (US, Mexico, Brazil, Angola). These, along with south-east Asia, are likely to be the leading areas for exploiting synergies between hydrocarbon extraction and offshore renewables.

Figure 8: Leading offshore hydrocarbon producers (million barrels of oil equivalent per day)[xlix]



Approximately, a third of the components used in an offshore wind project have potential synergies with the offshore oil & gas industry. There is a significant upside for offshore wind developers in terms of access to expertise and supply chain efficiencies.

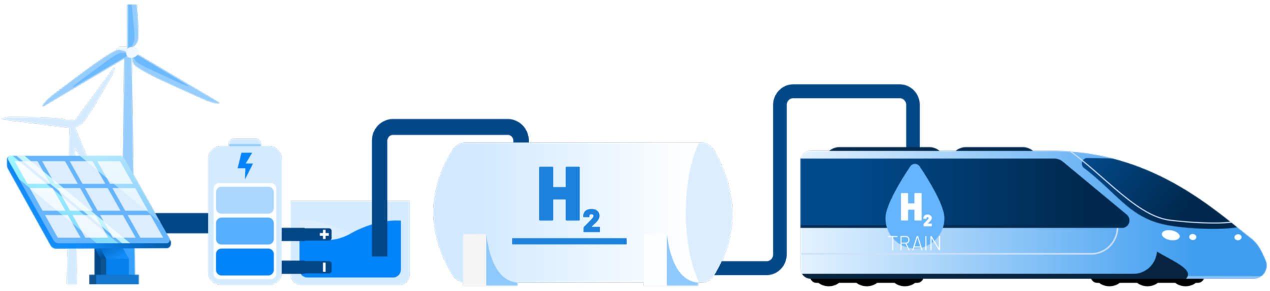
The offshore oil & gas industry's expertise in developing energy infrastructure is the most beneficial to wind developers, including in foundations / structures, project management, vessel operations, cables connected to the onshore electricity grid, seabed survey / investigation, and Balance of System (BOS), EPC, and O&M.

The offshore oilfield services industry also has transferable assets and competencies, such as the provision of tugs, mooring systems, heavy lifting vessels, cabling, and the implementation of safety standards. These synergies are likely to be realised in floating wind infrastructure since it involves capabilities that most offshore wind developers lack.

Furthermore, electrification of offshore oil & gas platforms will create demand for renewable electricity generated through offshore renewable projects (mainly offshore wind) that are in close proximity and can also displace gas and / or diesel generation. This will reduce emissions and free-up fuel that would have been burnt on platforms, subsequently extending fields' lives.

Around 5% of offshore wellhead production globally (~1.7 MMBL / day) is used as fuel to power offshore oil & gas platforms[l]. This is not only inefficient but also reduces their sales volumes, which is often enough to justify their investment cost / calculations. However, there are technical challenges that need to be overcome.

Firstly, offshore wind electricity is variable and requires backup in the form of batteries, hydrogen fuel cells, continuing use of some gas fuel, and / or connection to the onshore electricity grid.



Norway's 88 MW Hywind Tampen Wind Project only provides 35% of the annual electricity demand of the five platforms (the Snorre A and B, and Gullfaks A, B and C platforms), demonstrating some constraints of variable electricity supply[li].

Secondly, a balance needs to be maintained between the economic feasibility of platform electrification and the cost of achieving it. For offshore oil & gas platforms close to land, grid-connected electricity could be a more feasible alternative to offshore wind supplies, whereas other platforms that are late in their project life may not justify the investment.

Offshore oil & gas platforms nearing end-of-life can be repurposed for renewable generation and / or other low-carbon projects such as PTX, gas-to-electricity (or gas-to-wire), and CCUS.

Through PTX pathways, surplus offshore renewable electricity can be converted to green hydrogen (i.e. hydrogen produced from renewables) or its derivatives (such as ammonia) for energy storage and subsequently address imbalances between resource availability and demand, especially for intermittent offshore renewables such as offshore wind (see section "offshore renewable energy hubs (OREHs) of the future").

PTX projects offer direct ways to provide an energy source or an input feedstock for various industrial processes. The stored energy (in the form of green hydrogen) can be transported through an existing gas pipeline connected to the shore.

Onshore, the hydrogen can be converted to methane or ammonia production (through Power-to-Gas) for use in refineries and / or fertiliser production, transformed to methanol (Power-to-Liquids) for use in fuel cells, or changed to electricity (Power-to-Power).

However, the economic viability of this option depends on the state of the available infrastructure, its remaining asset life, if it can be repurposed, and the cost of transporting the hydrogen / electricity produced from shore.

Another option is gas-to-electricity (or gas-to-wire), which involves generating electricity from offshore gas and connecting to shore through an electricity connection. This is mostly common for fields that lack gas pipeline connections.

Depleted offshore oil & gas fields could also be used to store carbon dioxide (CO_2), which could be brought to the offshore platforms using an existing pipeline infrastructure. If the platforms are already electrified, they could also be used for CO_2 compression. There are also cross-synergies between gas-to-electricity and CCUS. For example, surplus electricity produced from offshore gas could be converted to hydrogen with CCUS capabilities, with the possibility of storing the carbon directly back in the reservoirs.

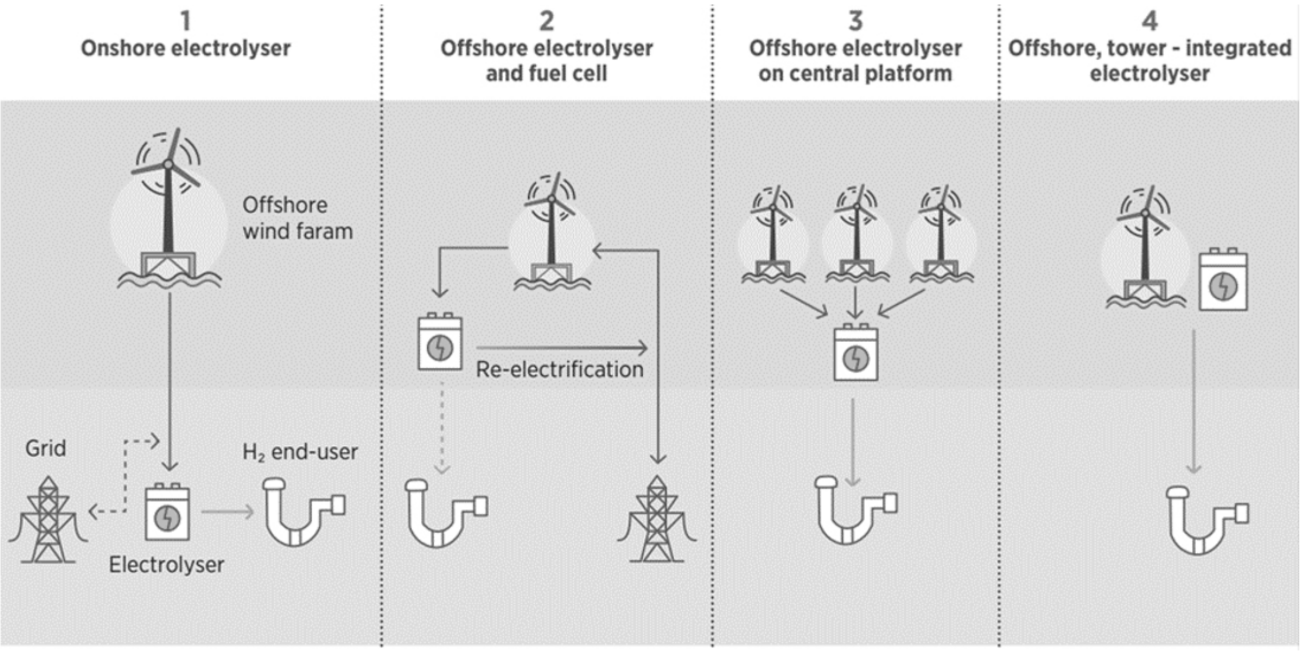
Offshore Renewable Energy Hubs (OREHs) of the future will utilise synergies between offshore wind, floating wind and solar PV, and ocean energy through combined systems and connect offshore renewable resources to PTX technologies for hydrogen / electricity generation.

Combined systems of offshore energy projects can be co-located or hybrid projects. Co-located projects deploy independent systems at the same site, whereas hybrid projects combine different offshore renewable technologies on the same platform. Different combinations of ORE technologies have been proposed and designed, such as wind-wave, wind-solar, wind-tidal, wave-solar, as well as wind-solar-tidal-wave.

The Aegean and Alboran Seas, the Gulf of Lion, the Gulf of Gabès, the Gulf of Sidra in the Mediterranean, and the Gulf of Suez and Gulf of Aqaba in the Red Sea have been identified as areas of high potential and low variability for hybrid cultivation of offshore wind and solar PV.

The EU-SCORES Project, led by the Dutch Marine Energy Centre, is developing a 3 MW grid-connected Offshore Wind – Solar PV Hybrid Pilot Project, 2 kilometres from the Belgian coast[liii]. The project will assess the complementary profile of wind and solar PV generation, their integration with the electricity grid, and the survivability of large floating structures. The EU-SCORES Project is also developing a 1.2 MW grid-connected Wave Energy Array along the Portuguese coast[lii].

Figure 9: Offshore Wind-to-Hydrogen Configuration



The project's energy generation will be compared to the Wind Float Atlantic project. Both projects will be fully scaled up by 2025.

Recent developments have also focused on developing renewable technologies fitted with electrolysers for hydrogen production, which may be more efficient in transporting hydrogen back to land than electricity. Siemens Energy and Siemens Gamesa are developing a 5 MW integrated system that fully integrates an electrolyser into an offshore wind turbine as a single synchronised system to produce green hydrogen directly[liv].

They are targeting a total investment of ~EUR 120 million over the next five years in developing this innovative solution, with a full-scale demonstration in the North Sea expected by 2025 – 2026[lv].

The increasing interest in coupling offshore wind with hydrogen is attributed to three main factors. Firstly, offshore wind has one of the highest capacity factors at an average of 39% (compared to 17% for solar PV in southern European conditions), leading to higher electrolyser utilisation and increased hydrogen production. Secondly, the economic feasibility of wind-to-hydrogen is supported by industrial offtakers of hydrogen near coastal areas. Thirdly, offshore wind-to-hydrogen projects require less land than onshore gigawatt-scale projects.

However, the LCOE for offshore-to-hydrogen will need to improve to produce cost-competitive hydrogen. Current LCOE of US$ 75 / MWh for offshore wind generation translates to an average levelised cost of hydrogen (LCOH) of US$ 5.9 – US$ 14.7 / kilogram, compared to US$ 1.9 – US$ 8.4 for grid-connected electricity[lvi]. In perspective, the LCOH for grey hydrogen (produced from oil & gas without carbon capture and storage) currently ranges between US$ 0.5 – US$ 1.7 / kilogram (depending on the gas price [lvii]).

However, recent developments and innovative business models have led to the emergence of different methods for coupling offshore wind and hydrogen production.

An example of a hybrid project that utilises offshore wind to produce hydrogen is the Surf 'n' Turf Project in the United Kingdom, where excess wind and tidal current power generated on the island of Orkney is used to produce hydrogen, which is transported by ship to a fuel cell in Kirkwall where it makes electricity on demand[lviii].

A consortium of RWE, Equinor, Eneco, Gasunie, Groningen Seaports, and Shell is developing a 4 GW H2North Wind-to-Hydrogen Project (in the Ten Noorden van de Waddeneilanden area, north of the Wadden Islands) that will be expanded to 10 GW by 2040[lix] [lx].

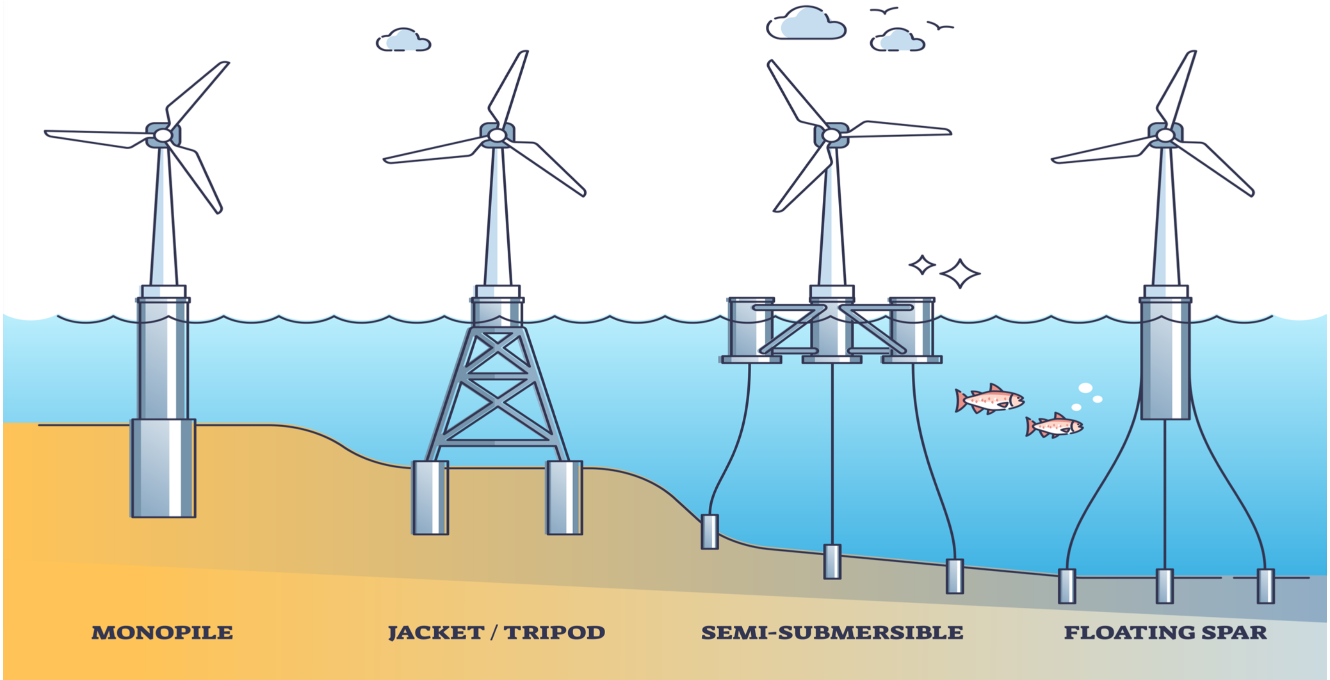
Separately, Shell is developing a 200 MW electrolyser in the Port of Rotterdam, which will be powered by the Hollandse Kust Offshore Wind Project[lxi]. The project will produce 60 tonnes / day of hydrogen, supply the Shell Energy and Chemicals Park in Rotterdam through the HyTransPort Pipeline, and replace some of the grey hydrogen used in the refineries[lii].

Tractebel Overdick is developing a floating wind foundation system for 15 MW wind turbines and an offshore hydrogen production platform in the German North Sea that can utilise 800 MW of electricity from offshore wind[lxiii].

A joint venture of SolarDuck and Voyex is developing a 65 kW F-PV array connected to a 10 kW electrolyser to produce hydrogen bonded with a liquid organic hydrogen carrier (LOHC)[lxiv].

The system is being developed on SolarDuck's proprietary floating technology that resembles an offshore oil platform[lxv]. The hydrogen output will refuel ships from various offshore floating solar PV units across the Mediterranean, Caribbean, Southeast Asia, and other offshore markets with high solar radiation.

Denmark is constructing two OREHs on artificial islands in the North Sea and the Baltic Sea, with 3 GW of wind capacity each, with a potential long-term expansion of 10 GW on the Baltic Sea island[lxvi]. The wind energy will be used to power residential consumers, while green hydrogen will be used for end-use sectors such as aviation, heavy-duty transport, industry, and shipping.



Offshore renewables are a key energy source in the race to net zero by 2050. They can help cut carbon emissions significantly and meet a substantial portion of the Paris Climate Accords target. Offshore wind is the most advanced and promising technology to achieve this, with rapid annual growth expected in the medium-term, supported by policies across the United States, Europe, and China.

Offshore wind is the most advanced and promising renewable resource among these sources. It will continue to be supported by policy-driven deployment across the United States, Europe, and China. The increase in offshore wind capacities combined with technological improvements and innovative project designs will increase its capacity factors and drive down generation costs.

This will also support offshore floating wind generation, which could achieve cost parity with bottom-fixed wind in the medium-term, in contrast to floating solar PV, which may take longer.

Although other offshore renewable technologies such as ocean energy are still in their infancy and their high cost of generation makes them currently uncompetitive with offshore wind, their geographic diversity and potential complementarity could make them a component of an integrated offshore energy system.

Offshore renewables can be used to electrify and decarbonise offshore oil & gas operations in the short-to-medium term. In the long-term, decommissioned offshore oil & gas platforms could be converted into offshore renewable energy hubs, connecting offshore renewable resources with hydrogen production. They can also be repurposed for CO_2 storage, again powered by renewables. This would enable the offshore petroleum industry to transition into a lower-carbon model which still retains its skills and some converted assets.

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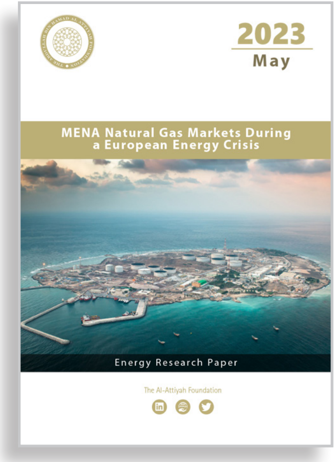

May – 2023

MENA Natural Gas Markets During a European Energy Crisis

The Middle East and North Africa (MENA) region has always been a strategic cornerstone of the European energy mix, but now it has gained newfound value for the continent as it adapts rapidly to a "Russia-less" energy world. In the shortterm, these MENA countries are set to be instrumental to European energy security.

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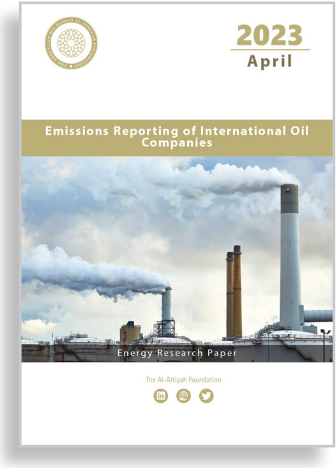

April – 2023

Energy-Report-2023-04- Emissions Reporting of International Oil Companies

The oil and gas industry, a major contributor to global greenhouse gas (GHG) emissions, faces increasing pressure from environmental, social, and governance (ESG) factors influencing investment decisions. Despite the uncertainty of its future in the energy transition context, demand for oil and gas is not expected to diminish in the nearterm.

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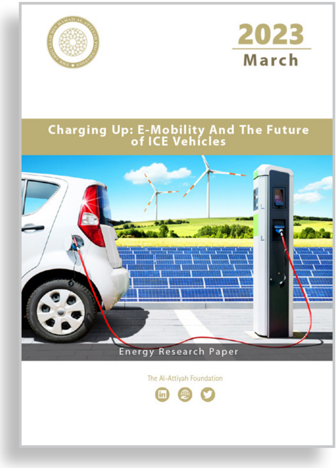

March – 2023

Charging Up: E-Mobility And The Future of ICE Vehicles

Electric vehicles have gained significant market share in the past year and numerous automakers have committed to predominantly EV futures. EVs have gained range, costs have fallen, and numerous governments have rolled out supportive packages for their manufacturing, purchase and charging.

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