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ARTICLE

GREENER IS CHEAPER: AN EXAMPLE FROM OFFSHORE WIND FARMS

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Abstract
Offshore wind farms (OWF) are now in operation and increasingly under construction as scalable, sustainable energy sources. In fact OWFs are currently the cheapest form of new energy projects in Europe. The levelized cost of energy (LCOE) for OWF has fallen drastically due to decades of innovation facilitated by both taxpayer and private sector funding. This emerging industry is experiencing massive worldwide growth with the potential to accelerate the decarbonization of regional and the global economy as well as bring a reliable source of green hydrogen into commercial use, all with minimal disruption to ecosystems and impacts on biodiversity. This paper provides a historical perspective of wind energy harnessing and shows that wind turbines are the oldest, largest and one of the smartest machines. We also highlight the potential of offshore wind energy to provide new solutions to (a) meet clean energy demand for a growing world population, (b) improve energy security of nations through other downstream technologies such as production and storage of dispatchable fuel (such as green hydrogen battery storage) and (c) through supply complementarity improve resilience of nuclear power plants in high-seismic-activity areas. Offshore wind industry can also become a gold standard for future industries, and the paper provides insights into the new green economics and jobs and factories for the future. We show that environment-friendly regulation is driving innovations even further to enhance sustainability of OWF. Examples include material recycling, landfill ban on blade disposal and ecofriendly low-noise offshore construction to protect biodiversity.

Keywords: offshore wind power; LCOE; sustainability; green hydrogen; energy transition; net zero

JEL codes: O14; O33; O44

1. Introduction: Climate change, energy transition and energy from wind

The United Nations recently declared that we are facing a climate emergency with manifestations such as continuous ocean and atmospheric warming, heat waves, drier soils and rising sea levels. The effect of climate change can be catastrophic to our planet, leading to vast amount of land being uninhabitable leading to climate refugees. Island and coastal nations are already and will continue to be disproportionately affected by climate extremes. The UK Committee on Climate Change has set the needed target to reduce greenhouse emission to net zero by 2050. The European Union aims to be a carbon-neutral market by 2050 with an economy with net zero greenhouse emissions. The United States under the Biden administration has also set an ambitious target of carbon pollution-free power by 2035 and net zero emissions economy by no later than 2050 through measures such as IRA (Inflation Reduction Act) (WH, 2023).

1.1. Energy transition and pathways to achieve net zero

Energy transition must involve decarbonization of the economy, and the backbone of a modern economy is energy. A practical way to achieve the net zero target is to run the country mostly on electricity where possible, producing energy from renewable sources without burning much fossil fuel. Ideally, one should have an entirely clean energy-based system through a mix of renewable, sustainable and low-carbon sources, and this is technologically feasible.

1.2. Wind power

Wind power is of course a well-established renewable energy technology and has the potential to tackle many current technological and societal challenges such as sustainable energy sources and air pollution reduction. Wind power has been used for centuries for sailing ships, sawing wood, grinding grains, and moreover it is one of the oldest sources of 'machine' power. The invention of wind-powered sawmills by Dutchman Cornelis Corneliszoon van Uitgeest in the late 16th century helped Holland increase ship production through automated wood-cutting, outcompeting their European rivals who were relying on slow manual processes. Figure 1a shows a windmill from Holland used for sawing wood. Modern-day wind power is harvested through wind farms, either onshore or offshore. Offshore wind farm has plenty of advantages due to scalability, higher energy generation, faster construction and reduced time to get planning permission.

Offshore wind farms provide new, carbon-free, generation assets that are now rapidly scaling in the EU, East Asia, and while more slowly, the United States is joining this push with a 2030 target of 30 GW (Figure 1b). These turbines convert the kinetic energy of wind into electrical energy, which can be used to power homes and businesses. Offshore wind farms can also be larger than onshore ones, as the wind is often stronger and more consistent over the ocean. Additionally, they do not take up land space and can have less visual impact on the surrounding area. By using renewable energy sources like wind power, the offshore wind farm can help reduce greenhouse gas emissions and decrease dependence on fossil fuels.

A typical offshore wind farm can generate 1 GW of power, approximately equivalent to two standard nuclear power plants (NPP). A typical wind turbine can produce 10–18 MW of power, and therefore 1 GW of offshore wind farm power involves installing 60–100 offshore turbines. Figure 1 compares 16th-century windmills with modern-day wind power.

Figure 2 shows a schematic of offshore farm with the main components: energy generation assets (wind turbines) and transmission assets (substations and the electric cables) that feed the national grid. A typical wind turbine comprises three rotor blades, a nacelle, a rotor hub, a tower and foundation. The main raw materials for manufacturing the turbines are steel (typically 66–79%), glass fibre/carbon fibre and plastic (11–16%), iron/cast iron (5–12%), copper (1%), aluminium (1–2%). Table 1 summarizes the materials inventory used for wind power generation. Currently, 85–90% of the materials used in wind power generation can be recycled. Recycling of blades is currently a challenge due to the composite nature and they are often repurposed to construct roofs, bike sheds, foot bridges and so forth There are

(a) Dutch wind mill (b) Present day offshore wind farm

Figure 1. Wind energy generation (16th century) and modern day (21st century).

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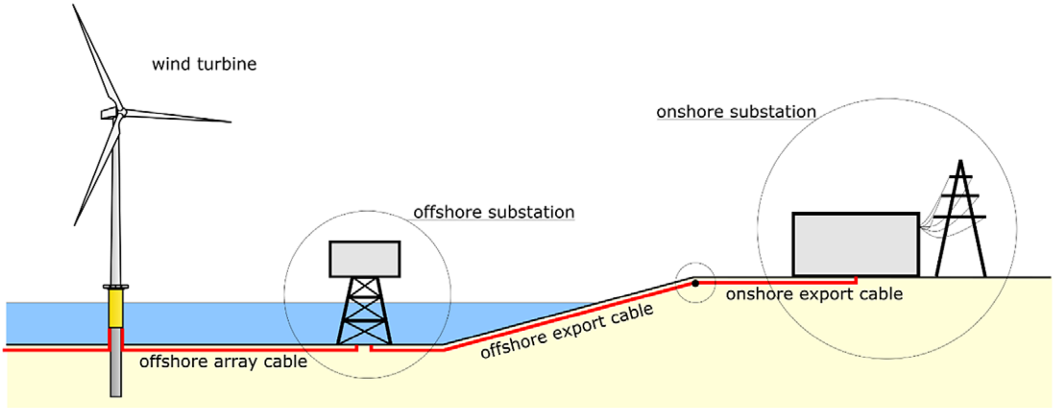

Figure 2. Schematic of a wind farm.

Table 1. Materials used for the construction of wind farm

Components	Materials
Rotor blade	Glass fibre, carbon fibre, epoxy resin, PVC, wood
Nacelle	Cast iron, steel, HDPE, epoxy resin, glass fibre
Tower	Steel
Foundation	Steel, aluminium, concrete
Submarine cable	Lead, copper, steel, HDPE
Offshore substation	Steel, concrete, cast iron, aluminium

other ideas for blade recycling through energy recovery where blades are shredded and can be used as fuel in cement kilns or power plants to generate heat or electricity.

Figure 3 shows a wind resource map showing the wind speed along the coast based on the study conducted by the World Bank. Average wind speeds (WS) over 7 m/s are considered to constitute a financially viable project. Figure 4 shows power curve for six turbines, which shows the energy production corresponding to wind speeds. It is clear that wind turbine produces the maximum power at wind speed of about 12 m/s.

International Energy Agency (IEA, 2019) in their special report showed that offshore wind can generate 11 times more electricity than the world needs. There are a few more similar studies such as Possner and Caldeira (2017) where it is shown that offshore wind farm of the size of India in North Atlantic can produce enough electricity to power the world. Essentially, the untapped potential of offshore wind is vast. Based on IEA assessments, offshore wind could potentially generate a whopping 420,000 terawatt-hours of electricity globally per year while the entire world consumed 23,000 terawatt-hours of electricity in 2018.

1.3. Innovation in wind turbines

Figure 5 shows the evolution of wind turbines over the past 20 years, and this is clearly due to innovation. The turbine rated power increased by 10 times in a span of circa 20 years. In other words, one machine can produce 10 times more electricity (i.e. 2–20 MW) and can also operate in different extreme conditions. These machines are smart in the sense that the turbine can turn horizontally towards or away (known as yaw control) from the wind in order to maximize energy production. The blades are also

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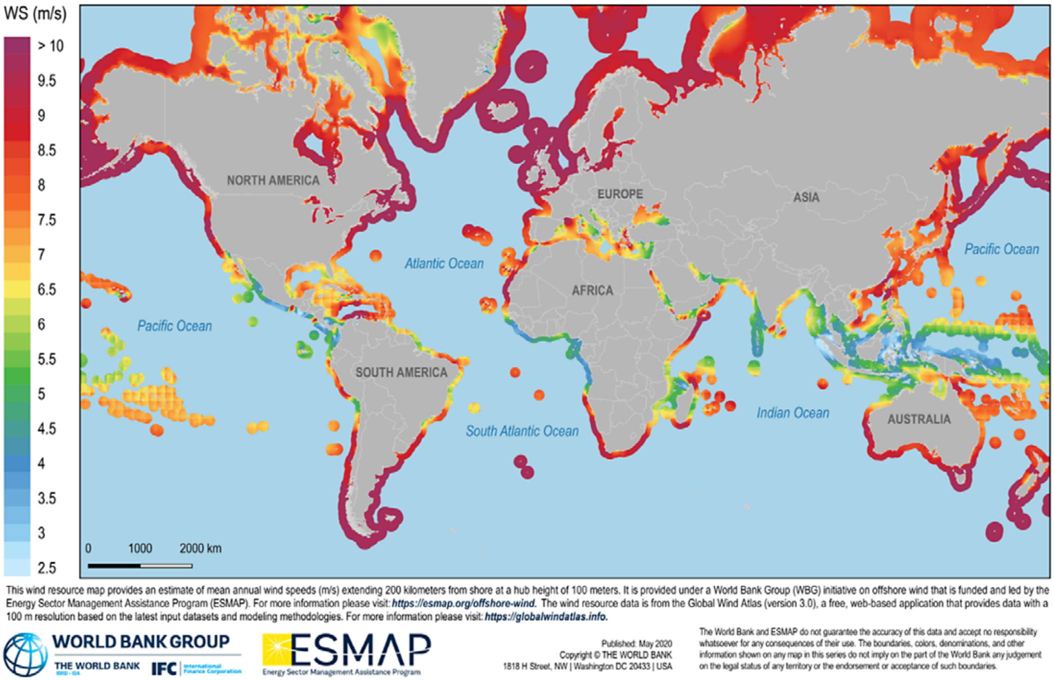

Figure 3. Global offshore wind speeds (World Bank Initiative, 2020).

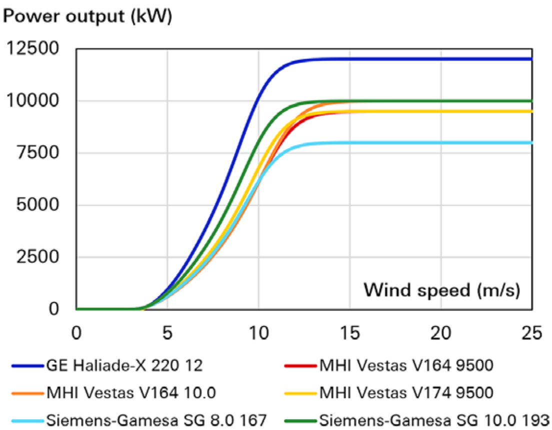

Figure 4. Power curve.

designed to twist (pitch control) during the operation for better performance/energy generation as well as during extreme wind condition (i.e. hurricane/typhoon) to avoid damages.

1.4. Aside: Oldest, largest and a smart machine

Wind power has an established track record for centuries and is the oldest source of 'machine' power which fits the definition of a machine (namely a piece of equipment with several moving parts that uses wind power to carry out a particular type of work such as sawing wood). It can also be said that offshore wind turbine machines are also the largest moving machines. A typical 10 MW turbine will have three

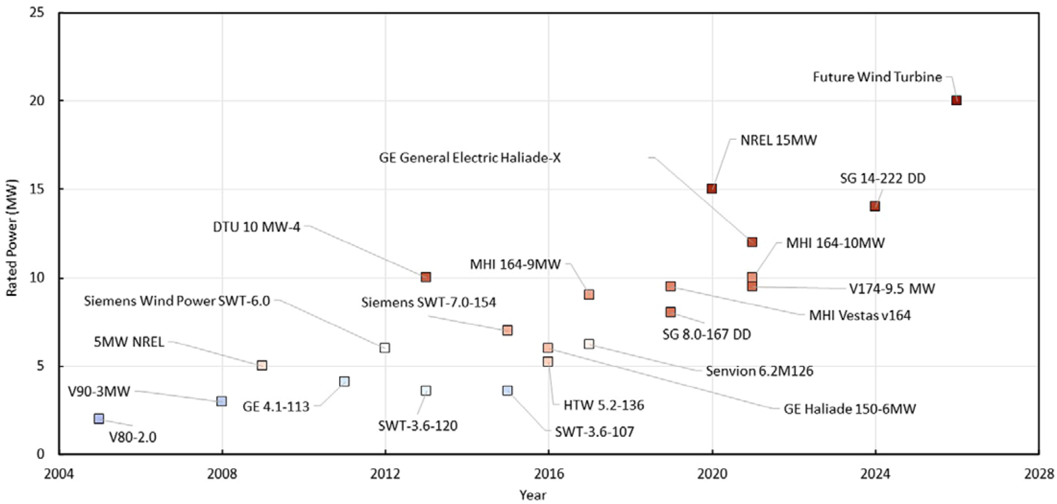

Figure 5. Nameplate capacity innovation in wind turbines.

80-m-long blades and each weighing circa 35 tonnes turning at average of 8–10 RPM. As mentioned in the previous section, the machine carries out control operation through yaw action or pitch to maximize power production.

2. Sustainability of wind farm and tackling intermittency of wind power

There are different definitions of sustainability. The United Nations Brundtland Commission (WCED, UN, 1987) defined sustainability as 'meeting the needs of the present without compromising the ability of future generations to meet their own needs'. This section shows some of the sustainable aspects of offshore wind power: origin of wind resources, wind power generation, storing of wind power and complete decommissioning of offshore wind power systems. The recyclability of materials from a wind turbine is discussed in the previous section.

2.1. Origin of wind resources

Simply put, wind will blow as long as the sun is shining. The ultimate source of energy responsible for the creation of wind is the sun. Sun bombards the surface of the earth with radiation energy leading to a continuous warming. Out of this energy, the largest amount is sent back to space and only a small amount is transformed into heat energy. Due to the shape of the earth and having different materials (water and land), its surface is not heated evenly resulting in the equator getting more energy than the poles. As a result, there is a continuous heat transfer from the equator to the poles.

The atmospheric air consists of nitrogen and oxygen and they expand when heated and contract when cooled. Solar radiation causes the air to get warmer and lighter and less dense than cold air. This also results in the rise of warm air to higher altitudes and the creation of areas with lower atmospheric pressure, where the air is warmer. Due to the variance in pressure, the air will move from a high-pressure to a lower-pressure area, in an attempt to reach equilibrium, thus causing wind.

Wind is essentially atmospheric air in motion and is very complex; see Figure 6. At 30° and 60° latitude, there is a major change in atmospheric pressure creating zones of high and low pressure, respectively. The air circulation within these zones is known as cells and the major winds thus created as trade winds. Due to the diurnal motion of the earth, the wind deflects to the right in the northern

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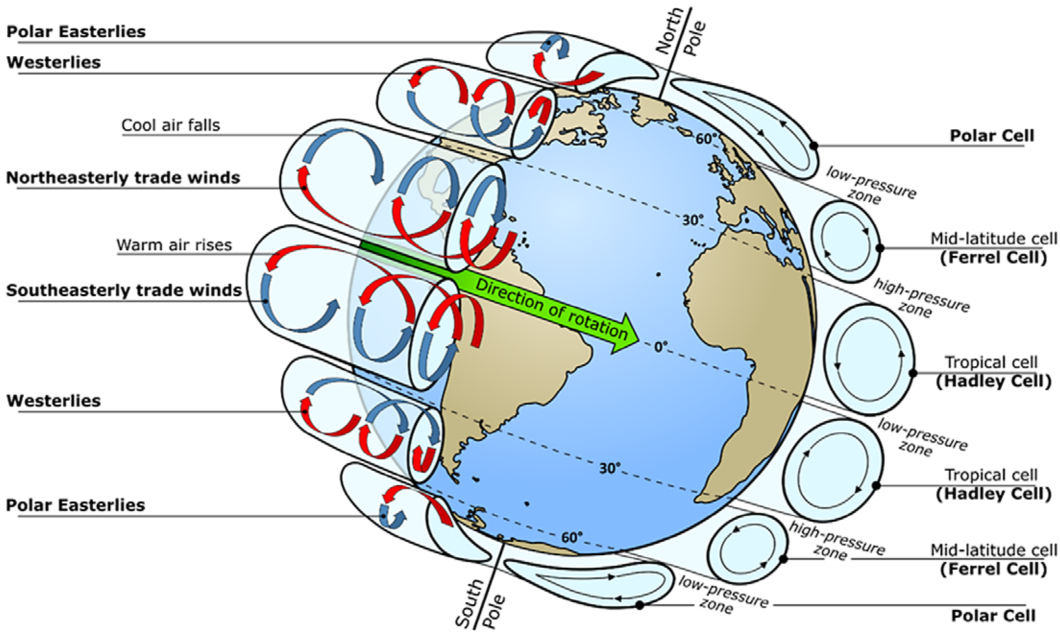

Figure 6. Global circulation of wind.

hemisphere and to the left in the southern one, leading to a spiral movement of the air mass; this phenomenon is known as the Coriolis Effect. Figure 6 describes the mechanism of the above global wind system. In addition to this global wind system, there are localized influences as well and are mostly related to the terrain of an area and its proximity to water bodies. For further details, see Letcher (2023).

2.1.1. Storage of wind power: Battery

The power curves in Figure 4 show that a turbine can generate power from a wind speed starting from as low as 4 m/s and reach the rated power at about 12 m/s. It is often argued that wind does not blow all the time, and when you need power, there may not be the desired wind. Also, when the wind is blowing at optimum speed, there may not be the need for the power. To combat these problems, technologists have developed systems that can store the excess electrical power generated by wind in batteries, optimizing it with the grid.

The combination of offshore wind and storage technologies, such as batteries, will become important to secure grid stability. Figure 7 shows a schematic of battery storage. For example, the Japanese wind farm Ishikari Offshore Wind project located around 3 km off the coast of Hokkaido will comprise 112 MW of wind power generation from 14 Siemens Gamesa 8 MW wind turbines and will be paired with the 100 MW/180 MWh BESS (battery energy storage system). However, such technologies often need rare earth metals for battery production, which needs unsustainable extensive mining and effects of commodity trading (similar to oil and gas trading). The next section shows another technology (dispatchable fuel) that may address some of the above challenges.

2.2. Hydrogen production using offshore wind: The Japanese ‘Jidai’ concept

The 2011 Fukushima Daiichi NPP disaster was a watershed moment in the history of mankind; see Bhattacharya and Goda (2016). Following the disaster, many countries such as Germany and Japan

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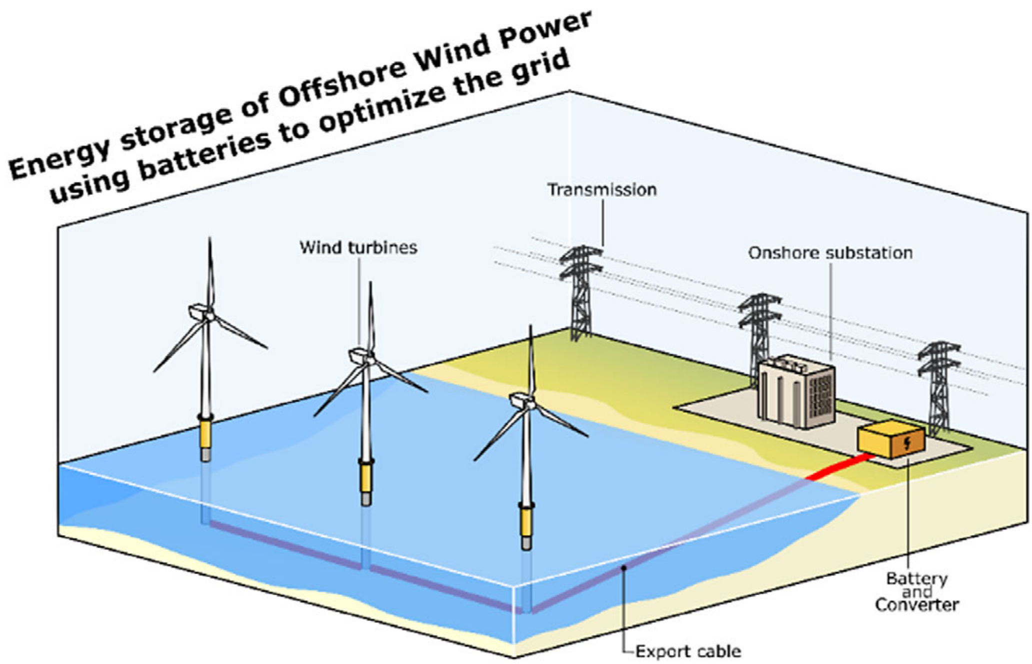

Figure 7. Combining offshore wind with battery storage.

reduced their reliance on nuclear power and compensated with fossil fuels and renewables. Within the framework of global warming, and among others such as energy security, Japan aims to become a carbon-free country through a 'hydrogen society'. The main idea is to generate hydrogen from water through renewable energy sources such as wind, solar and hydroelectricity. Japan named it the Jidai concept. Similar attempts are also ongoing in major European economies. These attempts have been boosted by other technology developments such as the invention of hydrogen-powered cars, trains, ships and even aircrafts.

The Jidai concept shown in Figure 8 is a four-step process: (a) seawater is desalinated; (b) electrolysis is used to produce hydrogen and oxygen from water; (c) hydrogen gas is compressed to 700 bar to reduce storage volume; and finally (d) high-pressure hydrogen gas is stored in a module-based tank system that can be used in fuel cells or via direct combustion.

Ongoing studies demonstrate that a 100% hydrogen gas network is equally as safe as the currently popular natural gas. It is worth noting that burning natural gas to heat homes and businesses accounts for approximately a third of the UK's carbon emissions. Hydrogen-powered commuter trains are available, and it has been reported in *New Civil Engineer* that 30% of the UK rail fleet could be suitable for running hydrogen-powered trains (Ibbetson, 2019; Bhattacharya *et al.*, 2021). In summary, wind power has the potential to carry the transition to low carbon energy, transforming the fossil fuel energy landscape to a more sustainable energy future.

2.2.1. Hydrogen or battery, or both?

The potential of hydrogen is huge: through the existing offshore infrastructure of pipe networks, hydrogen can be transported for distribution. With the advent of hydrogen cars and trains, the economy can be transformed and the energy transition can happen smoothly. Battery production needs expensive metals such as lithium, cobalt and nickel to be mined. These metals, unlike hydrogen,

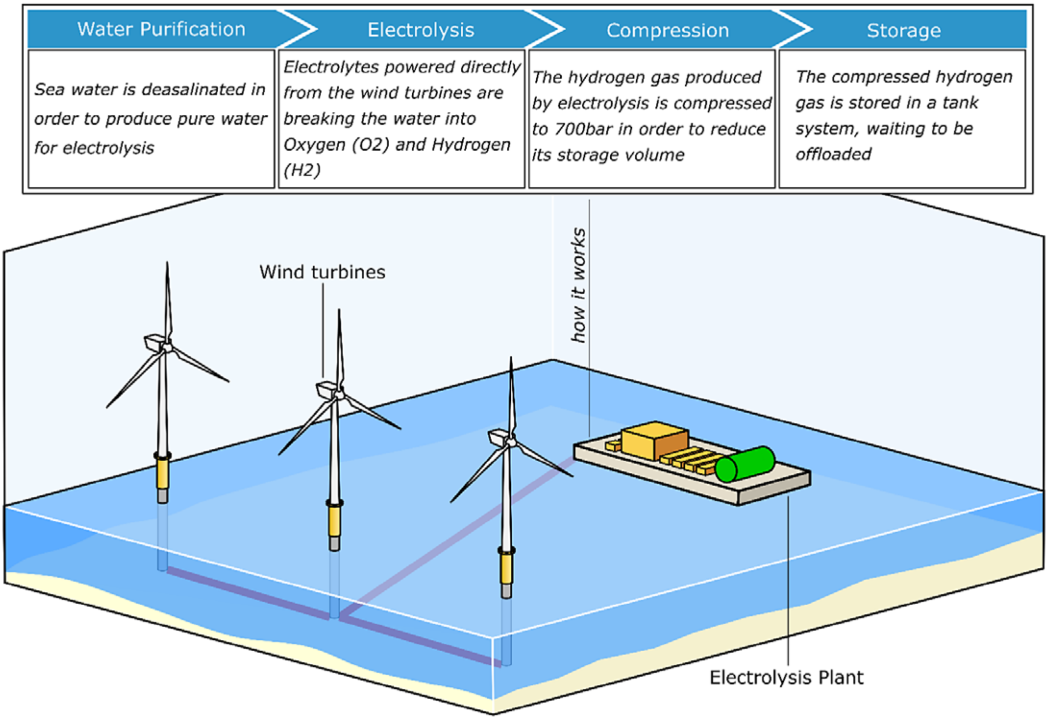

Figure 8. Green hydrogen: An application of offshore wind.

can be seen as a trading commodity like oil and gas. One evolving hybrid scheme is to couple offshore wind to both conventional batteries for short-term storage and to H_2 systems for longer-term energy storage.

3. Increasing resilience of NPP through the use of offshore wind turbines

Following the 2011 Fukushima NPP disaster, one of the main technological challenges is the seismic resilience of existing NPPs so that similar incidents may not happen. Table 2 shows the summary of the three major nuclear accidents, and it appears that cooling power for the reactor is vital for safety. It may be inferred that seismic resilience of NPP is directly linked to resilience of the cooling power.

In the context of offshore wind, it is of interest to describe the performance of near-shore offshore wind turbines in Japan during the 2011 Tohoku earthquake.

Table 2. Case studies of major global NPP disasters

Name of NPP	Cause of failure
Three–mile Island (USA)	Damage to reactor core due to cooling loss
Chernobyl (Russia)	Overheating, steam explosion and meltdown
Fukushima (Japan)	Failure of emergency cooling caused an explosion after the shutdown of reactor during the cascading events of Tohoku earthquake

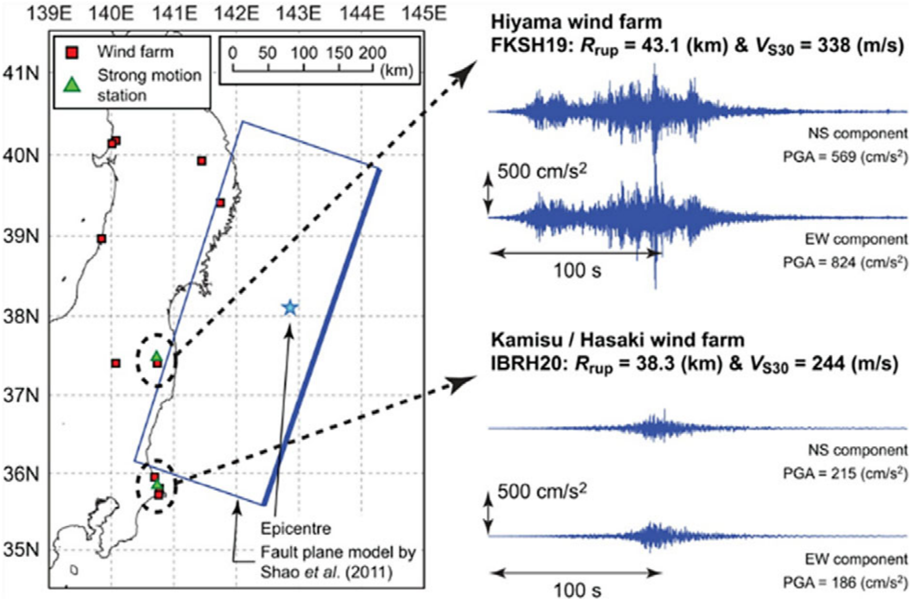

Figure 9. Details of the 2011 Tohoku earthquake and locations of the wind farms.

3.1. Case study: Performance of near-shore wind farm during 2011 Tohoku earthquake

A devastating earthquake of moment magnitude 9.0 struck the Tohoku and Kanto regions of Japan on 11 March 2011 at 2:46 PM, which also triggered a tsunami; see Figure 9 for the location of the earthquake and the operating wind farms. The earthquake and the tsunami caused effects such as liquefaction, economic loss, loss of life, damage to national infrastructures but very little damage to the wind farms. Extensive damage was also caused by the massive tsunami in many cities and towns along the coast. Figure 10 shows photographs of a wind farm at Kamisu (Hasaki) after the earthquake, and Figure 11 shows the collapse of a pile-supported building at Onagawa where for the first time the world saw complete uprooting of piled foundations. At many locations (e.g. Natori, Oofunato and Onagawa), tsunami heights exceeded 10 m, and sea walls and other coastal defence systems failed to prevent the disaster.

The earthquake and its associated effects (i.e. tsunami) also initiated the crisis of the Fukushima Daiichi NPP. The tsunami, which arrived around 50 minutes following the initial earthquake, was 14 m high which overwhelmed the 10-m-high sea walls, flooding the emergency generator rooms and causing a power failure to the active cooling system.

Limited emergency battery power ran out and subsequently led to the reactor heating up and the subsequent meltdown leading to the release of harmful radioactive material to the surrounding environment. Power failure also meant that many of the safety control systems were not operational. The release of radioactive materials caused a large-scale evacuation of over 300,000 people and the clean-up costs are expected to be of the order of tens of billions of dollars. On the other hand, following/during the earthquake the wind turbines were automatically shut down (like all escalators or lifts), and following an inspection, they were restarted.

3.1.1. Why did the wind farm stand up?

Seismic effects on offshore wind turbines have been studied extensively by analysing recorded ground acceleration time-series data in two directions at Kamisu and Hiyama wind farms; see, for example, Bhattacharya and Goda (2016), Bhattacharya (2019) and Amani *et al.* (2022). The wind turbine

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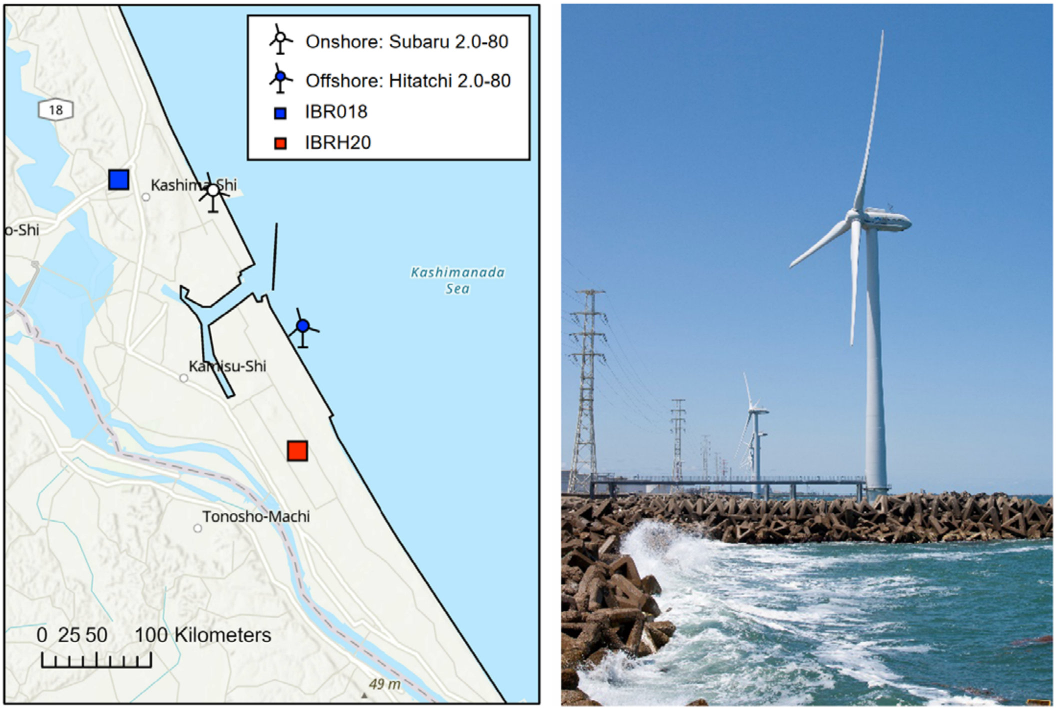

Figure 10. Photograph of the Kamisu (Hasaki) wind farm following the 2011 Tohoku earthquake.

Figure 11. Collapse of the pile-supported building following the same 2011 Tohoku earthquake.

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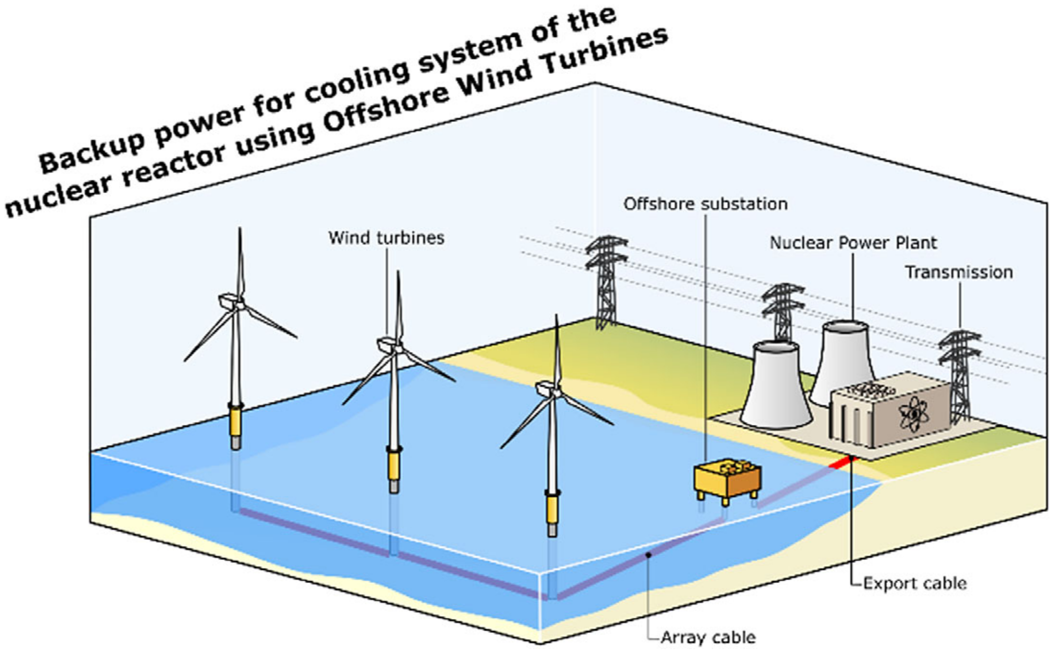

Figure 12. Proposition of additional backup power for resilience of NPP.

structures are very flexible and slow to react to the violent seismic motion making them resilient. In other words, due to non-overlapping of vibration periods, these structures will not get tuned in and as a result they are relatively insensitive to earthquake shaking. However, earthquake-induced effects such as liquefaction may cause some damages.

3.1.2. Forward outlook

If there had been more offshore wind turbines operating, the disaster may have been averted or the scale of damages could have certainly been reduced. The wind turbines could have run the emergency cooling system and prevented the reactor meltdown. Figure 12 shows schematically the proposed additional backup system to enhance resilience of offshore wind farm system. A study has been conducted by Kolli *et al.* (2023) to show the application of such a system for an NPP in India.

4. Economics of offshore wind energy and LCOE statistics

Offshore wind farm development is technically complex, lengthy, risky and capital-intensive, primarily because of the more demanding operations over the sea. In order to assess the economics of an offshore wind farm, it is essential to consider three phases: investment, operation and decommissioning. The investment phase includes the development, design and fabrication of all the components and their installation and is the most capital-intensive.

The investment phase can last up to nine years, with most of this time spent in planning and obtaining consent – activities that can take up to five years on their own. After the investment, the wind farms are expected to produce electricity to the grid for at least 20–30 years. During this operation phase, regular maintenance is required to keep the downtime minimum and prolong the lifespan of the whole project. When the operation phase is over, there is the decommissioning phase where there are two options: the entire project is dismantled and disposed, which marks the end of the farm's lifecycle; or the farm is

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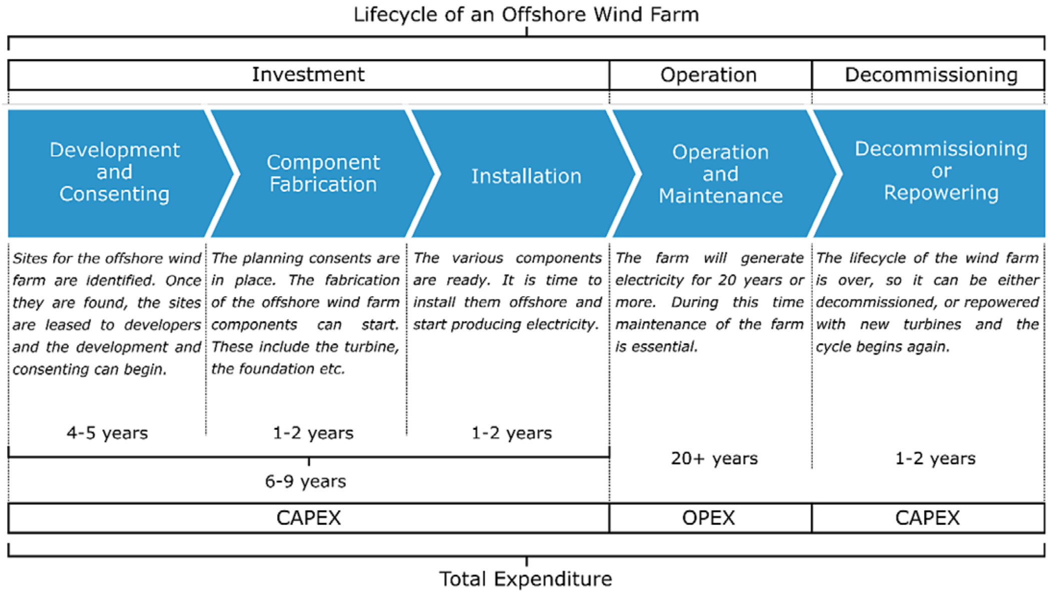

Figure 13. Lifecycle of an offshore wind farm in the early years of development.

repowered with new turbines and a new lifecycle begins. The lifecycle of an offshore wind farm (along with all the different phases) is illustrated in Figure 13 (Nikitas, 2020).

The total cost of the offshore wind farm can be divided into two fundamental cost categories: the capital expenditure (CAPEX) and the operational expenditure (OPEX). In general, CAPEX is defined as the initial one-time expenditure required to build an income-generating asset and achieve its commercial operation. On the other hand, OPEX can be defined as the ongoing cost, either once or recurring, associated with the operation of the asset. Both can be further divided into more detailed costs. For example, CAPEX can be divided into three main categories. These are turbine costs (including all the wind turbine components), construction costs (including foundation, electrical infrastructure, assembly and installation costs) and development costs (including the planning, insurance, construction and contingency financing and decommissioning costs). Similarly, OPEX includes two main categories of costs, which are the operation and maintenance costs. In a typical project, the contribution of these two costs towards the total cost is approximately 75% for CAPEX and 25% for OPEX.

4.1. LCOE

LCOE is a metric used to assess the cost of generating electricity from a particular energy source over its entire lifespan. It is a standardized way to compare the cost of different energy technologies. The LCOE takes into account all the costs associated with a specific energy project, including the initial investment, operational and maintenance costs, fuel costs (if applicable and is zero for wind) and the expected energy output over the project's lifetime. These costs are then spread out over the expected energy production to calculate the levelized cost. LCOE allows for a fair comparison of different energy sources, such as solar, wind, coal, natural gas and nuclear power. By considering the lifetime costs and energy output, it provides a more comprehensive understanding of the economic viability and competitiveness of different energy options. Figure 14 shows the global trend in LCOE of offshore wind, following Machiridza and Bhattacharya (2023), and this clearly shows a descending trend. For the UK, the reduction of cost is remarkable: LCOE for offshore wind reduced from £160/MWh to £44.00/MWh from the latest round of auction. In contrast, the negotiated strike price for nuclear energy from Hinkley

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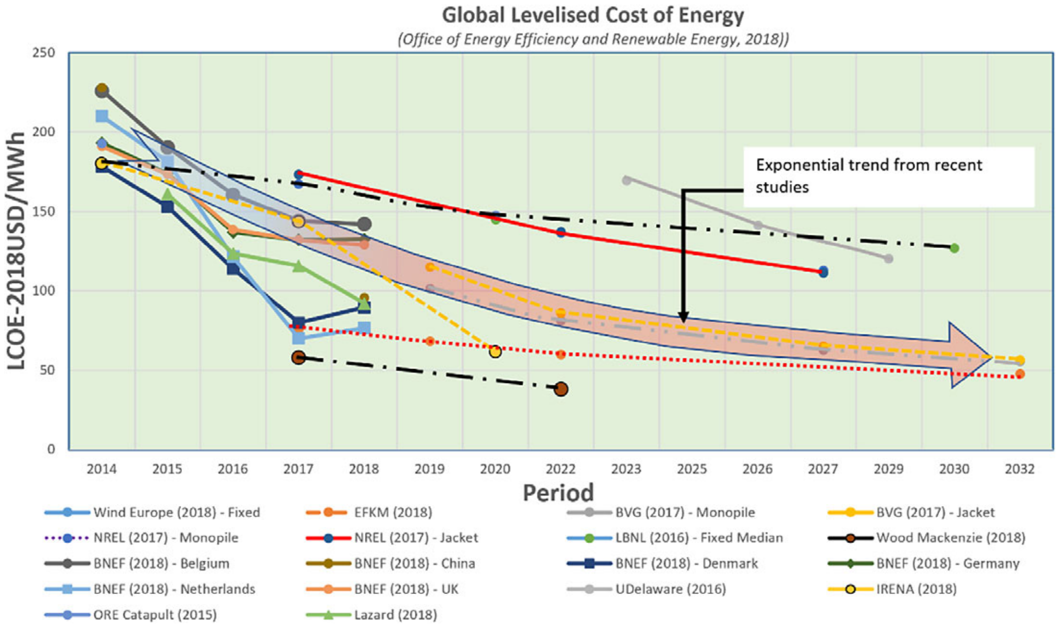

Figure 14. LCOE of offshore wind.

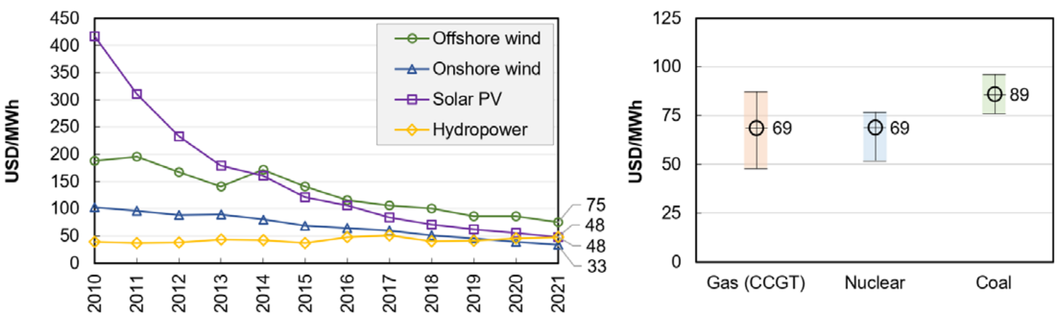

Figure 15. Comparison of LCOE for various forms of energy.

Point C in the UK is £92.50; see UK Government (2016). Figure 15 shows the LCOE for various forms of energy.

The massive cost reduction is achieved by utilizing efficiently the inherent advantages of offshore wind and, at the same time, minimizing the cost disadvantages. Wind farm sites are selected further offshore and often in deeper waters to get best wind resource (faster and consistent) and avoid fishing and shipping channels. Good wind resources enhance electricity generation and thereby revenue. Further cost reduction is achieved through the optimization of key components by broadening the global supply chain as well as installation and maintenance activities. The construction process of offshore wind farm can be expedited with minimum disruption to the lives and livelihood of an economy using the sea routes and taking advantage of global supply chain. Figure 16 shows a wind farm construction using marine vessels. By contrast, an onshore wind farm construction suffers from disruption as can be noted from Figure 17 where one blade for 2.75 MW turbine is being transported. For example, for a UK wind farm, it is possible to have the steel tower and foundations fabricated in Singapore or South Korea and the turbines assembled in Germany.

Figure 16. Construction of offshore wind farm.

5. Discussion and conclusions

Offshore wind farm is one of the cheapest forms of energy, and one of its main advantages is that the fuel is free and is a sustainable source. Wind turbines alone make for approximately 30–35% of the capital cost of the whole project. Therefore, their optimization is a key driver to cost reduction of offshore wind power (see Figure 5). The reliability of wind turbine technology is constantly updated through improved generators with direct-drive, gearless nacelles and high-power output. There are also significant improvements that can reduce manufacturing and assembly costs, based on the optimization of supply chain and the standardization of components.

There are other advantages, and some are listed below:

(a) In many countries such as the United States and China, large population centres (e.g. New York, Boston, San Francisco, Shanghai) are closer to offshore and therefore electricity generation is close to the consumption. See Figure 18 for two large economies investing in offshore wind.
(b) There will be efficient use of marine space, including harvesting other forms of renewable energy such as solar, geothermal, wave, hydrogen and tidal; see Figure 19. In the future, wind farms will also see fish farms/aquaculture.

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Figure 17. Transportation of blades (58.7 m long for GE 2.75–120 wind turbines) to Muirhall Onshore Wind Farm, South Lanarkshire (Photo credit: https://www.collett.co.uk/muirhall-wind-farm/).

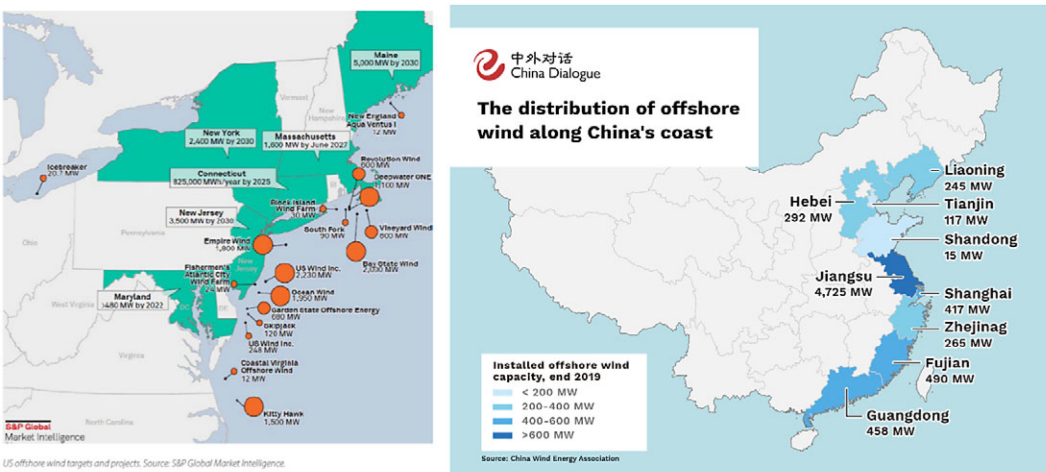

Figure 18. Offshore wind farm construction (either planned or operational) in two large economies.

(c) Most of the materials used in offshore wind farm construction are recyclable. Therefore, the industry will reduce the use of primary raw materials and less mining for energy production. This new industry is an example of circular economy with the aim to maximize resource efficiency and minimize waste generation.

(d) Modular design and manufacturing can be adopted based on local content and locally sourced materials, thus reducing the carbon footprint. Future wind farms will see the use of low-carbon green concrete for foundations, which will lead to longer operational life and lower the carbon footprint.

(e) Offshore wind farms can also generate noise that can impact marine life, especially during the construction and installation of the turbines. Certain countries such as Germany imposed

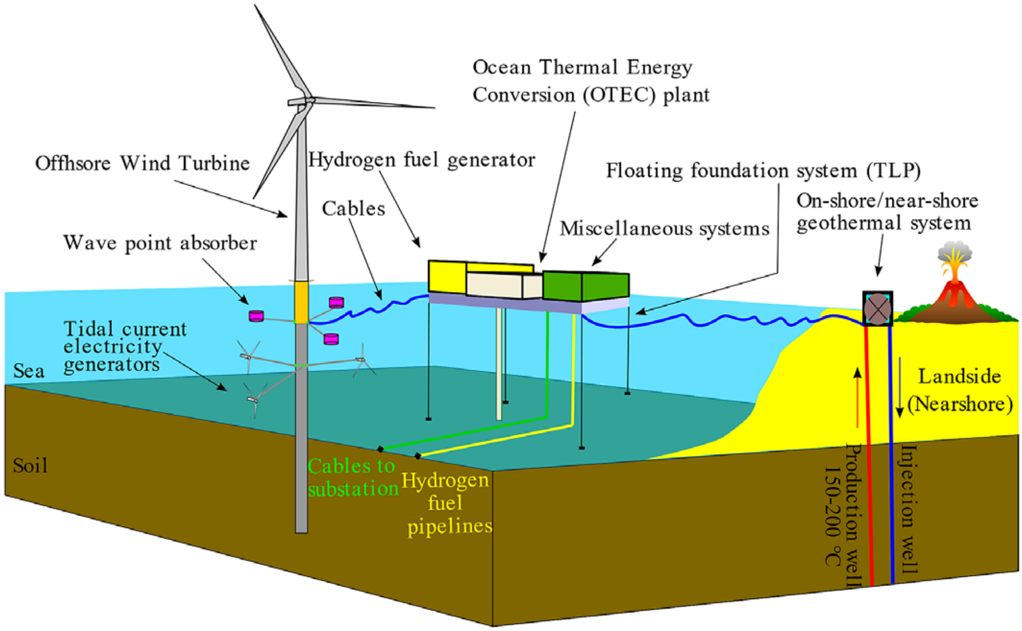

Figure 19. Efficient use of space for energy generation.

regulations on noise to reduce the impact on marine life and conserve biodiversity. These regulations led to innovations on eco-friendly foundation installation.

(f) Compared to nuclear power, offshore wind requires less materials; see Figure 21. Offshore wind farms can be fully decommissioned in few weeks at a fraction of a cost compared to NPP.

In summary, wind power has the potential to carry the transition to low-carbon energy, transforming the fossil fuel energy landscape to a more sustainable energy future. Furthermore, offshore wind farm is scalable and relatively easy to construct due to the sea routes and vessels available to transport parts from manufacturing sites to turbine locations.

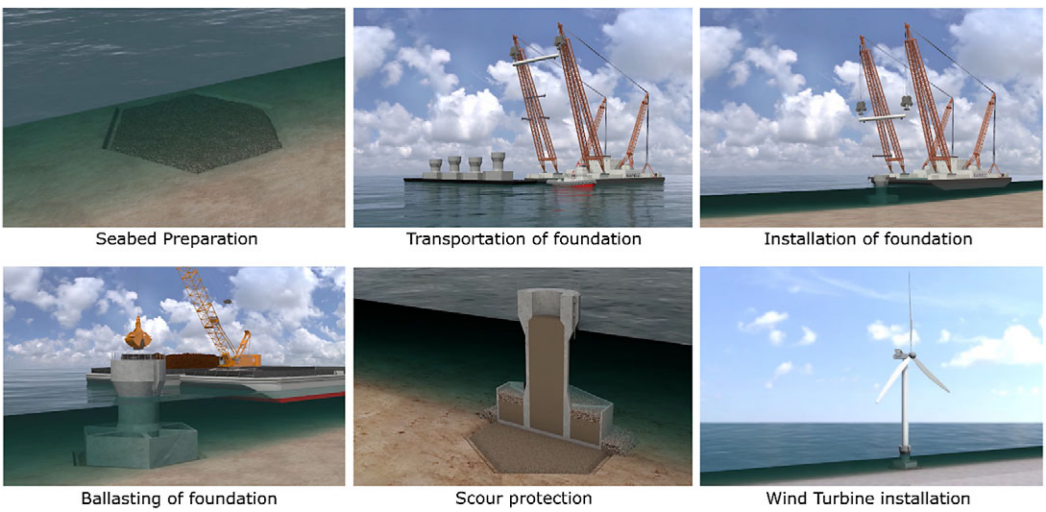

Figure 20. Concrete foundation used for supporting wind turbine in Sweden.

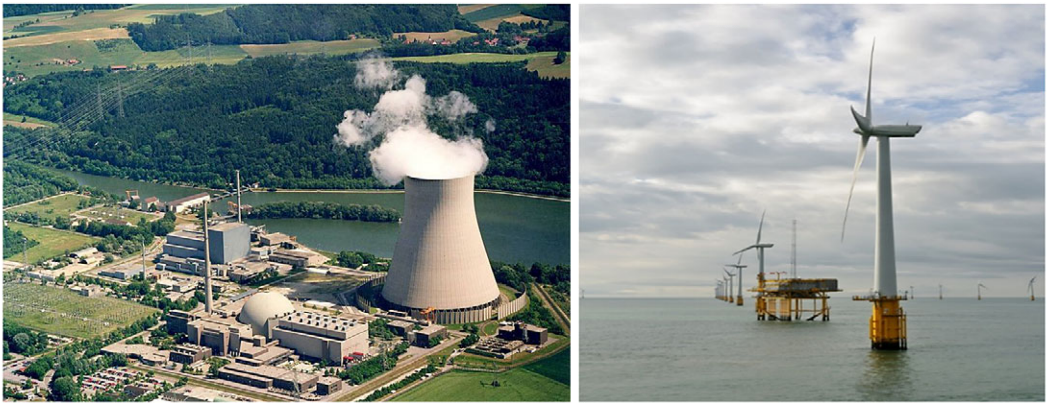

Figure 21. Relative construction material for NPP and OWT.

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