OFFSHORE WIND FARMS SITING

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INTRODUCTION

The first USA offshore wind farm is located 3 miles southeast of Block Island, Rhode Island. The 5-turbines 30-MW of rated capacity, $290-million project is developed by Deepwater Wind to supply power to 17,200 Rhode Island homes by generating 125,000 MW.hrs of energy per year. It is built to withstand a 100-year storm. The Rhode Island Coastal Resources Management Council selected the location after organizing a thorough ocean mapping initiative. Block Island is expected to receive about 90 percent of its energy needs from the wind farm, with supplementation from the mainland grid. Diesel power was the main source of the island's energy. Deepwater Wind is planning a larger utility-scale project with over 200 turbines that would serve a larger territory, including multiple markets in New England as well as Long Island, New York [1].

Europe utilizes substantial offshore wind energy. More than 3,000 turbines are in operation as part of 82 wind farms located in the European waters. Europe had a head start over other locations due to an early commitment to climate change mitigation. Denmark installed the first offshore wind farm in 1991. It was until 2001 when the USA considered its first offshore project. The challenges in the USA include a complex regulatory regime and competing natural gas prices.

In September 2015, the Department of Energy (DOE) released a report that detailed strong progress for the USA offshore wind market. Including the Block Island Wind Farm, there are 21 projects totaling 15,650 MWs in the planning and development stages. The USA coastal states are a source for 80 percent of the USA's energy demand.

Figure 1. Block Island, Rhode Island offshore wind turbines foundation jackets, July 27, 2015. Source: Deepwater Wind.

Dong Energy, a Denmark-based company, proposes to build a wind farm 15 miles south of Martha's Vineyard. Seattle-based Trident Winds is seeking to build the first offshore wind farm in California by the city of Morro Bay, located on the central coast. Planned offshore wind farms in Oregon, Virginia and New Jersey have been selected to receive USA federal funding.

The 468-MW Cape Wind farm offshore of Cape Cod was originally on track to become the first major project in the USA but has been beset by financial issues with the utility companies. Following a decade of studies, the USA Department of the Interior (DOI) approved the $1 billion Cape Wind offshore project on April 21, 2010. Cape Wind is a 130 turbines wind project at Nantucket Sound, off the coast of the State of Massachusetts. Its rated maximum electric power output is 468 MW, with an average anticipated output of 182 MW. Opponents of the project suggested it would disturb culturally significant sites on the seabed floor and would visually interfere with their cultural activities. Proponents countered that Nantucket Sound is far from pristine with already existing undersea power lines, communication towers along its coasts and the visual impacts associated with fishing, shipping, aviation, and recreational boating. Those visual impacts exceed those from wind turbines located at least 5.2 miles offshore from the coast. Other offshore wind power proposals exist in other northeastern states seeking to tap into a wind production potential of 1 million MW.

Earlier, on June 23, 2009 the DOI had approved five exploratory leases for wind power projects off the coasts of New Jersey and Delaware that would be capable of generating electricity for more than 1 million homes. The leases were the first of their kind.

Offshore wind farms have been completed, or are planned, in Denmark, Sweden, Germany, the United Kingdom, Ireland, Belgium and elsewhere. Offshore wind is attractive in locations such as Denmark and the Netherlands where pressure on land locations is significant and hill-top sites are no more available. In these areas, offshore winds may be 0.5 to 1 m/s higher in speed than onshore, depending on the distance. The higher wind speeds do not usually compensate for the higher construction costs but the chief attractions of offshore are a large resource and a low environmental impact.

There has been opposition to offshore wind farms in the UK close to the shoreline. President Donald Trump from the USA; before his presidential bid, joined the opposition but lost a court case against the construction of 11 wind turbines in an offshore wind farm by Viking Energy a few miles offshore the Aberdeen, Scotland’s coast and within sight of his Menie Estate golf course resort.

Figure 2. Offshore wind farms, Germany.

The first offshore wind farm was built in 1991 at Vindeby, Denmark. Other prominent projects are the Middelgrunden farm outside Coppenhagen and the world's largest wind farm at Nysted in the Baltic Sea.

Table 1. Planned and existing offshore wind turbines in Europe, 2009.

Country	Planned turbines	Operational turbines
Germany	1,584	15
UK	1,095	316
Belgium	163	6
Denmark	90	273
France	21	-
Netherlands	-	96
Sweden	-	70
Ireland	-	7
Norway	-	1

EVOLUTION OF WIND ENERGY DEVELOPMENT

The way in which wind power systems evolved has been influenced by the nature of the support mechanisms. Early developments in California in the USA and subsequently in the UK were mainly in the form of wind farms, with tens of machines, and in some instances hundreds or more.

In Germany and Denmark the government incentives favored investments by individuals or small cooperatives and so there were numerous single machines and clusters of two or three.

The more favorable wind conditions at sea have favored the introduction of offshore wind farms in Europe.

WIND CONDITIONS AT SEA

INTRODUCTION

The water surface on lakes and the seas is smooth and has a very low roughness at constant wind speeds. With increasing wind speeds, some of the energy content of the wind is transferred into wave energy, leading to an increase in roughness. Once the waves have been generated, the roughness decreases back. We thus have a surface with varying roughness.

Nevertheless, the roughness of the water surface is still very low compared with the land surface. The obstacles such as islands and lighthouses are few but must be taken into account in wind turbines siting.

WIND SHEAR AT SEA

With a low value of the roughness over water surfaces, the wind shear is low. Consequently the wind speed does not change much with the change in the hub height of wind turbines.

The result is that the structural towers can have a height equal to ¾ of the rotor diameter, compared with towers on land that have typically a height equal to, or higher than the rotor diameter. This translates into a capital cost advantage in the shorter structural towers.

TURBULENCE INTENSITY OVER WATER

The wind over water is generally less turbulent than on land. Thus offshore wind turbines are subjected to less fatigue loading resulting in longer design lifetimes than land-based turbines.

The low turbulence is caused by the observation that the temperature variations between different altitudes at sea are lower than on land. The sun's radiation penetrates to several meters below the sea's surface, whereas on land it is absorbed in the upper layer of soil which heats up to a higher level than the water surface. The temperature difference between the water surface and the air is lower at sea than on land, leading to the observed lower turbulence.

WIND SHADE AT SEA

The wind shade effects from land at sea location is important, extending its effect to as far as 20 kilometers. However, it appears that the wind resource at sea may be 5-10 percent higher than on land.

ECONOMIES OF SCALE OF OFFSHORE WIND FARMS

Economies of scale can be realized by building wind farms, particularly in the civil engineering and grid connection costs and possibly by securing quantity discounts from the turbine manufacturers.

Economies of scale deliver more significant savings in the case of offshore wind farms and many of the developments involve large numbers of machines.

Table 2 compares the typical parameters for offshore and onshore wind farms. It may be noted that the offshore projects use machines with three times the power rating of the onshore projects.

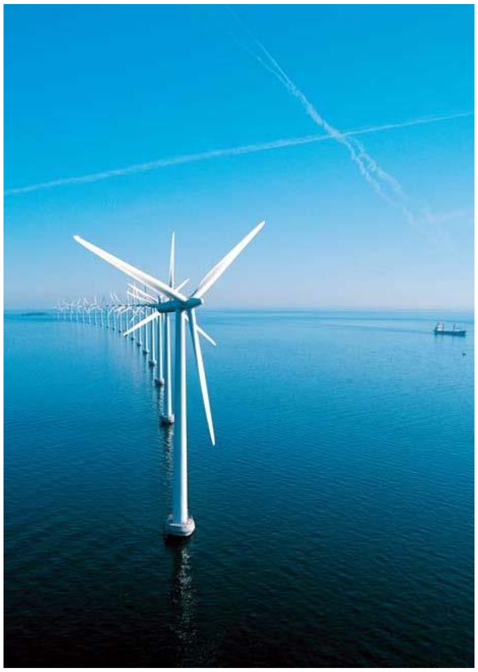

Figure 3. Offshore 40 MW wind farm using 2 MW wind turbines, Denmark. Source: Bonus energy.

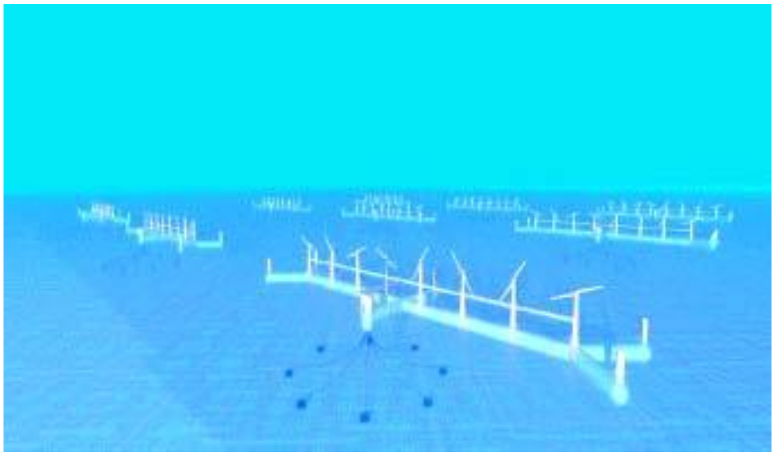

Figure 4. Wind Farm concept using floating islands.

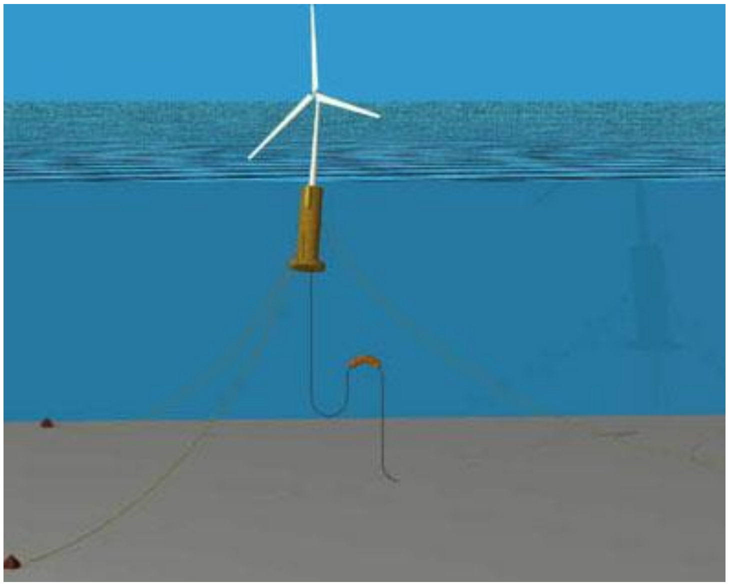

Figure 5. Floating spar buoy wind turbine.

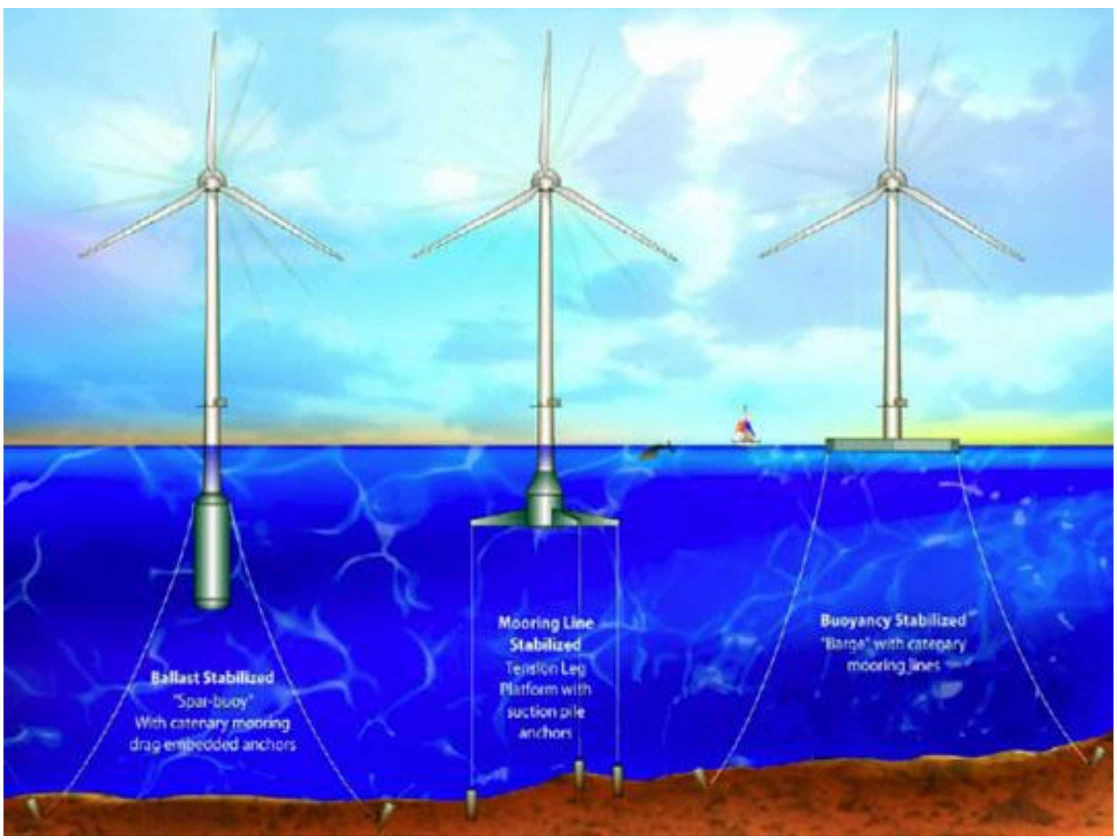

Figure 6. Oil rigs moored wind turbine concepts: Ballast stabilized, Mooring-line stabilized and Buoyancy stabilized. Source: MIT.

Floating islands carrying multiple wind turbines have been proposed for shallows waters up to 15 m in depth.

Using oil rigs construction technology, three types of deep water wind mill rigs for depths larger 15 m have been suggested:

1. Ballast stabilized using a spar buoy with catenary mooring drag embedded anchor.
2. Mooring line stabilized rigs with a tension leg platform with suction gale anchors.
3. Buoyancy stabilized barge with catenary mooring lines.

These large turbines reaching the size of 5 MW would be barged away from the coastal lines up to 100 miles at sea.

The availability of both water and electricity in offshore locations immediately suggests the production of hydrogen through the dissociation of water through the electrolysis process:

$$2H_2O \xrightarrow{electrolysis} O_2 + 2H_2 \quad (1)$$

Hydrogen would then act as an energy carrier for use with fuel cells as a transportation fuel. It would be transferred to the consumption centers through pipelines or using container ships.

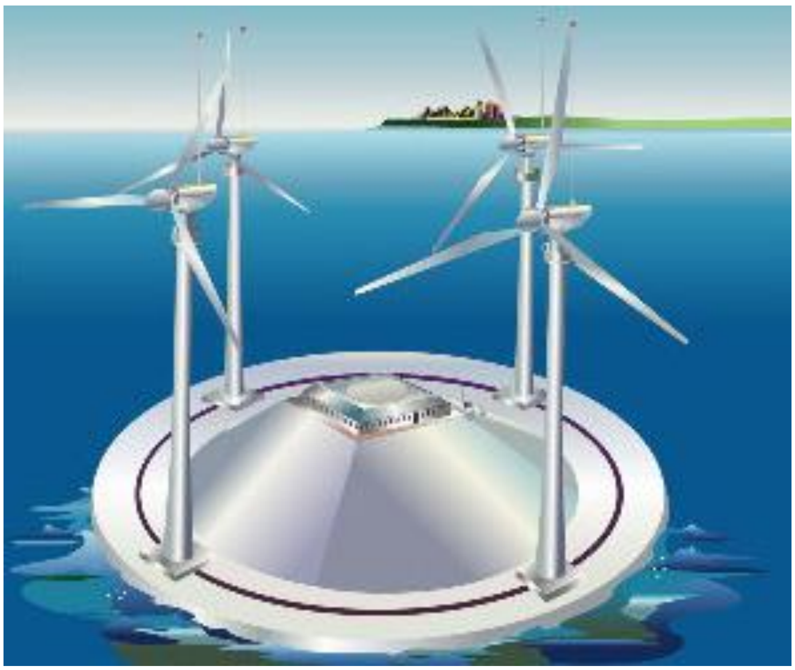

Figure 7. Hydrogen production and storage offshore wind turbines. Source: Stanbury Resources.

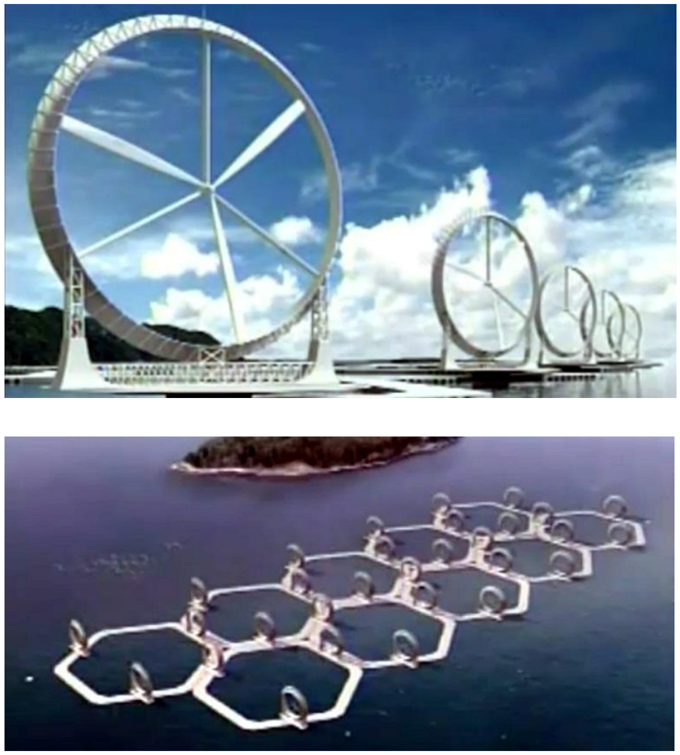

Figure 8. Conceptual floating diffuser wind turbines off the coast of Japan.

Table 2. Comparison of the parameters of onshore and an offshore wind farms.

	Onshore	Offshore
Project name	Hagshaw Hill	Middelgrunden
Project location	50 km South of Glasgow in the Southern Highlands of Scotland	Near Copenhagen, Denmark
Site features	High moorland surrounded by deep valleys.	Water depth of 2-6 meters
Turbines	26, each 600 kW	20, each 2 MW
Project power rating	15.6 MW	40 MW
Turbine size	35 m hub height, 41m rotor diameter	60 m hub height, 76 m rotor diameter.
Special features of turbines	Turbine structure modified for high extreme gust wind speed; special low noise features of blades.	Modified corrosion protection, internal climate control, built in service cranes.
Turbines siting	Irregular pattern with two main groups, typical spacing 3 rotor diameters.	180 m apart in a curve and a total wind farm length of 3.4 km.

Annual energy production	57,000 MW.hr	85 000 MW.hr (3 percent of Copenhagen's needs)
Construction period	August to November 1995	March 2000 to March 2001

Figure 9. Vindeby, Denmark, first offshore wind farm.

REQUIREMENTS OF OFFSHORE WIND MACHINES

CORROSION PROTECTION

The extended turbine components should be painted with off shore grade painting systems that minimize corrosion caused by salty water and air. The nacelle and tower should be fully enclosed with climate control using dehumidifiers that constantly maintain the internal humidity below the 60 percent corrosion threshold.

SAFETY

Lightning protection is more important off shore than onshore because of its higher frequency. The turbines must be fitted with navigational lights and aerial warning lights meeting the required safety criteria. Rescue equipment is made available for the maintenance crews at the foundation level.

COOLING SYSTEMS

Cooling of off shore wind turbines uses air to air heat exchangers. Ambient air which is quite humid is not allowed to circulate through the nacelle or tower. It is limited to flow only through the external part of the heat exchanger controlling the internal climate in the nacelle enclosure.

OFFSHORE FOUNDATIONS

DISADVANTAGES OF CONCRETE FOUNDATIONS

The use of traditional concrete foundation techniques results in that the cost of the completed foundation follows the quadratic rule:

$$Cost \ \alpha_{\ell} \ D_{water}^{2} \tag{2}$$

which states that the foundation cost is proportional to the square of the water depth.

The water depths at some offshore wind farms such as Vindeby and Tunoe Knob vary from 2.5 m to 7.5 m with the concrete foundation reaching an average weight of 1,050 metric tonnes.

According to the quadratic rule the concrete platforms tend to become prohibitively heavy and expensive to install at water depths above 10 meters. Therefore, alternative techniques must be developed in order to break through the cost barrier.

Figure 10. Steel foundation for offshore wind turbine.

Figure 11. Prototype Multibrid M5000 offshore wind turbine with foundation.

Figure 12. Steel tower manufacture for offshore wind turbine in the Baltic Sea.

STEEL GRAVITY FOUNDATION

Most of the existing offshore wind parks use gravitation foundations. The new technology offers a similar method to that of the concrete gravity caisson. Instead of reinforced concrete it uses a cylindrical steel tube placed on a flat steel box on the sea bed.

Figure 13. Monopile support for offshore wind turbine.

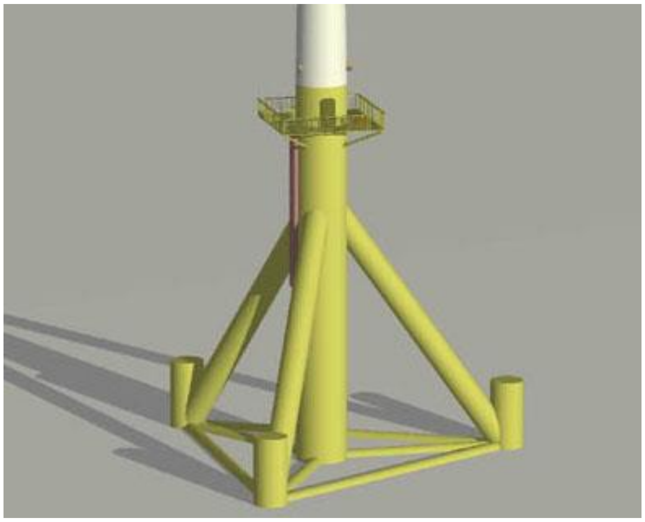

Figure 14. Tripod foundation for offshore wind turbine.

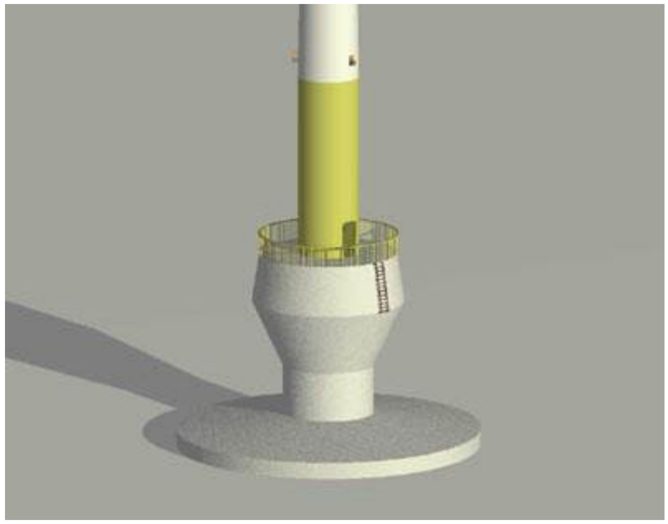

Figure 15. Gravity support foundation for offshore wind turbine.

Figure 16. Foundations welding for North Sea wind farms installations, Germany. Source: DPA.

Figure 17. Riffgat wind farm, North Sea, Germany. Source: DPA

A steel gravity foundation is considerably lighter than a concrete foundation. Although the finished foundation has to have a weight of around 1,000 metric tonnes, the steel structure will only weigh about 80-100 metric tonnes for water depths between 4 and

10 m. An extra 10 metric tonnes have to be added for structures in the Baltic Sea, which require pack ice protection.

The relatively low weight allows barges to transport and install many foundations rapidly, using the same fairly light weight crane used for the erection of the turbines. The gravity foundations are filled with olivine, a very dense mineral, which gives the foundations sufficient weight to withstand waves and ice pressure. The base of a foundation of this type for a wind turbine with a 65 m rotor diameter will be 14x14 m, or a diameter of 15 m for a circular base, for water depths in the range of 4-10 m.

The advantage of the steel caisson solution is that the foundation can be built onshore, and may be used on all types of seabed although seabed preparations are required. Silt has to be removed and a smooth horizontal bed of shingles has to be prepared by divers before the foundation can be placed at the site.

The seabed around the base of the foundation will normally have to be protected against erosion by placing boulders or rocks around the edges of the base. This is also the case for the concrete version of the gravitation foundation. This makes this foundation-type relatively costlier in areas with significant erosion.

JACK UP BARGES

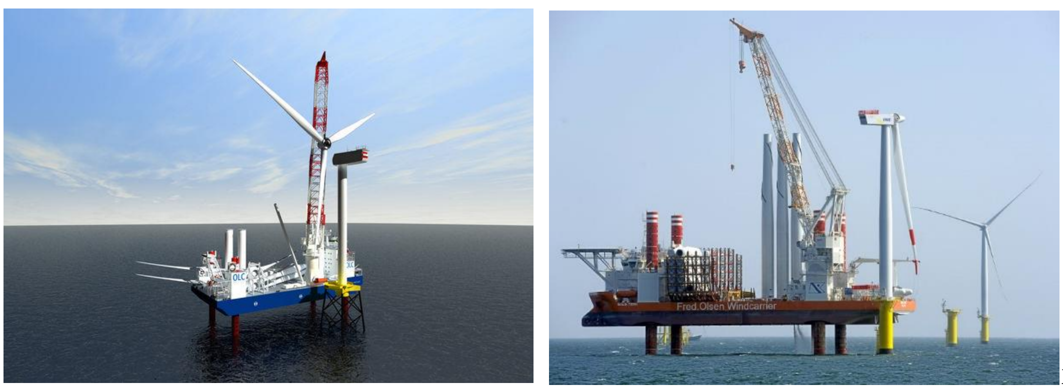
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Figure 18. Jack-up barge for offshore wind turbines installation. Source: DPA.

Offshore wind-power producers are building custom ships at record rates to reduce the cost of offshore wind turbines installations. As many as 20 vessels are coming online, some with movable jack-up legs that reach the sea floor.

A lack of specialized installation ships has forced companies to hire barges designed for oil exploration, holding up work at projects. They allow operation in higher water depths, and in more inclement water conditions. They allow the job to get done faster and more safely. The custom-made craft can operate in waters 45 meters or 148 feet in depth. The vessels, known as jack-up barges, have platforms supported by legs that can be adjusted to fit different water depths and heights for the towers that support wind turbines.

OFFSHORE WIND FARM SITES

MIDDELGRUNDEN OFFSHORE WIND FARM

Figure 19. Middelgrunden Offshore wind farm, Copenhagen, Denmark.

The developer is Middelgrunden Vindmollelaug, Kobenhavns Energi, Copenhagen, Denmark. The farm consists of 20 turbines emplaced in a large arc of 3.4 km in length with turbines spacing of 172 m. The project has a rating of 40 MW using the 2 MW Siemens SWT-2.0-76 turbine design.

The energy production potential is 85 GW.hr/year. The construction lasted over the period June 2000 – December 2000.

The Middelgrunden offshore wind farm was the largest offshore wind farm at the time of its completion. The turbines were assembled onshore in three parts then floated to their foundations where they were erected with cranes fitted to a jack-up barge.

NYSTED OFFSHORE WIND FARM, DENMARK

Figure 20. Nysted offshore wind farm, Denmark.

The developer is Energi E2 A/S with a construction period from May 2003 to September 2003 with the turbines installed in 81 days. The project is composed of 72 offshore wind turbines emplaced as a parallelogram in 8 rows with 9 units each. The turbines are placed 10 kms from the shore.

The turbines are the Siemens SWT-2.3-82 with a rated power of 2.3 MW for a total installed capacity of 165.6 MWe and an annual energy production potential of 600 GW.hr.

ALPHA VENTUS WIND FARM, GERMANY

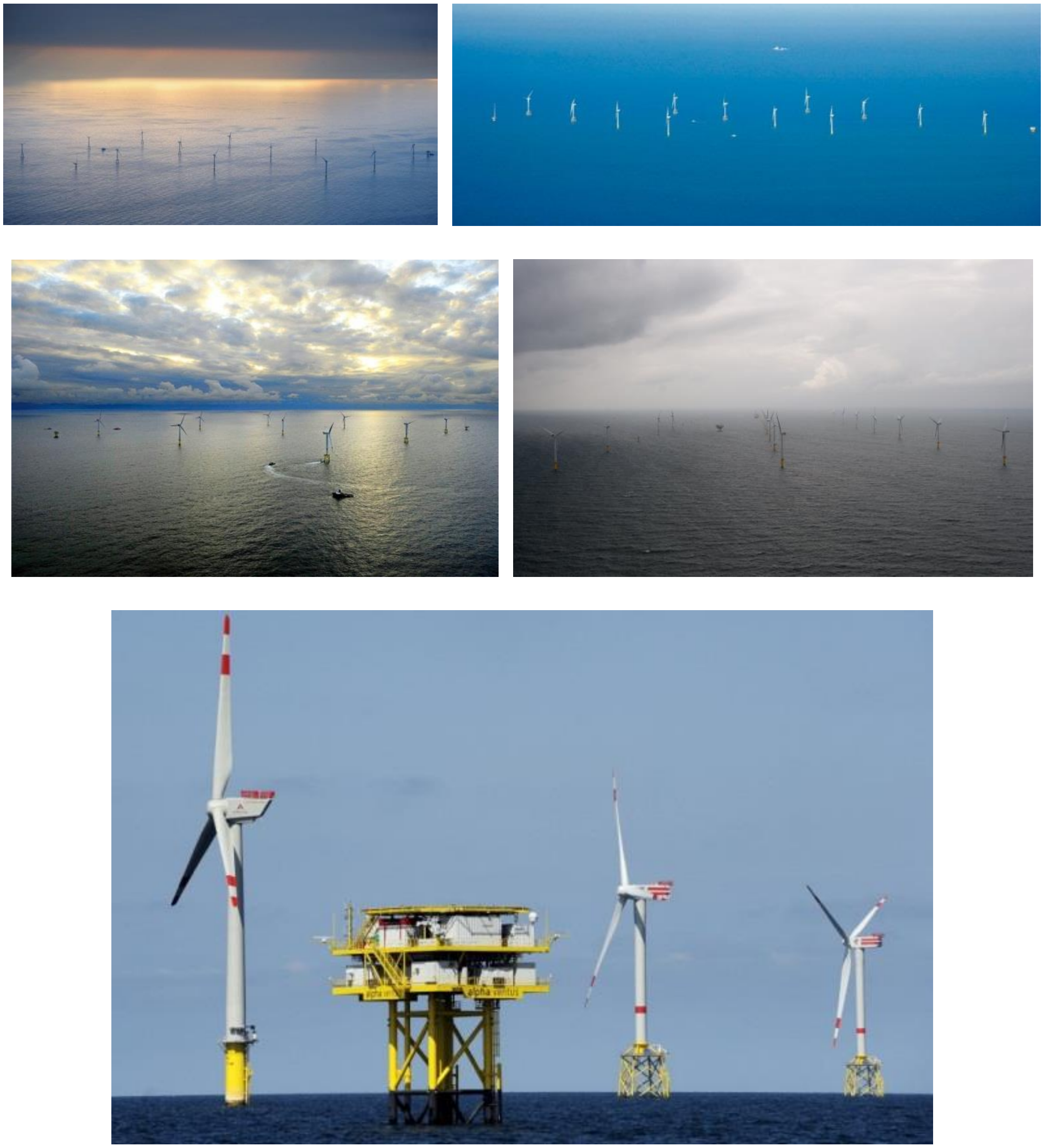

Figure 21. Alpha Ventus offshore wind farm by the Borkum island in the North Sea in Germany, started operation in April 2010 with a projected yearly energy production of 220 GW.hrs.

Germany planned to increase the share of green power to 35 percent of power consumption by 2020 from 20 percent in 2012. A substantial part of that increase was to originate from offshore wind farms, seen as particularly suitable because the wind blows constantly at sea, which makes it a more reliable source of power than solar energy or wind turbines on land.

Germany’s plan is to have 10,000 wind turbines in operation off Germany's coasts by 2030. By 2012 it had only 27. The aim is for the wind farms to produce 25,000 MWs of power. By 2012 it was just 135 MWs. The energy companies E.on and RWE complained about delays in transmission power lines construction. They are forced to stop investing in offshore power as the grid operators did not keep up with their construction of power lines to transport the power generated by the wind farms. The grid operator Tennet at some point was 15 months behind with work on linking the Amrumbank offshore wind farm, operated by E.on, to the grid.

The grid operators overestimated their capabilities and underestimated the problems. They did not possess sufficient financial incentives as the regulatory authorities did not allow them a high enough return on their investments. In addition, the suppliers did not provide the required hardware such as cables.

USA OFFSHORE PROJECTS

The USA General Electric (GE) leading manufacturer of wind-power turbines scaled back its efforts to expand its presence in the offshore wind power market. The rationale: there is no meaningful offshore wind market to speak-of yet in the USA. Given slower-than-expected industry growth, the offshore market may not mature as rapidly as many wind enthusiasts once believed.

Figure 22. Offshore wind turbines. Source: GE.

Figure 23. Projected 10 MW GE wind turbine for offshore applications.

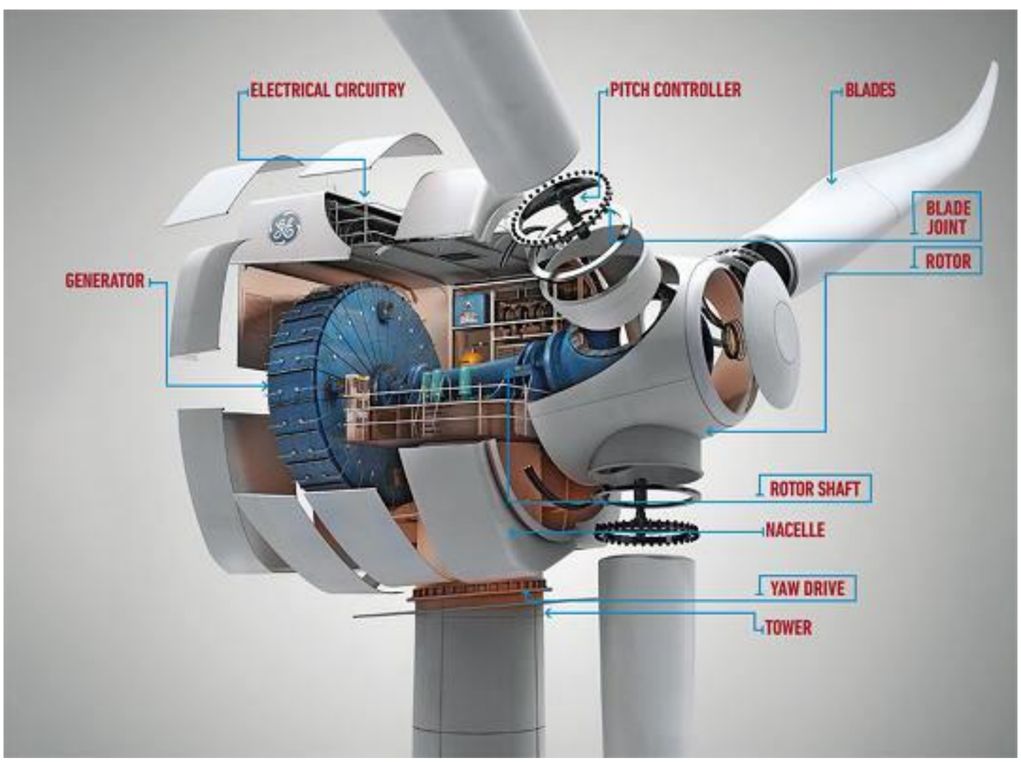

Figure 24. Direct drive generator 10 MW offshore wind turbine design eliminates the need for a gearbox or transmission. Source: GE.

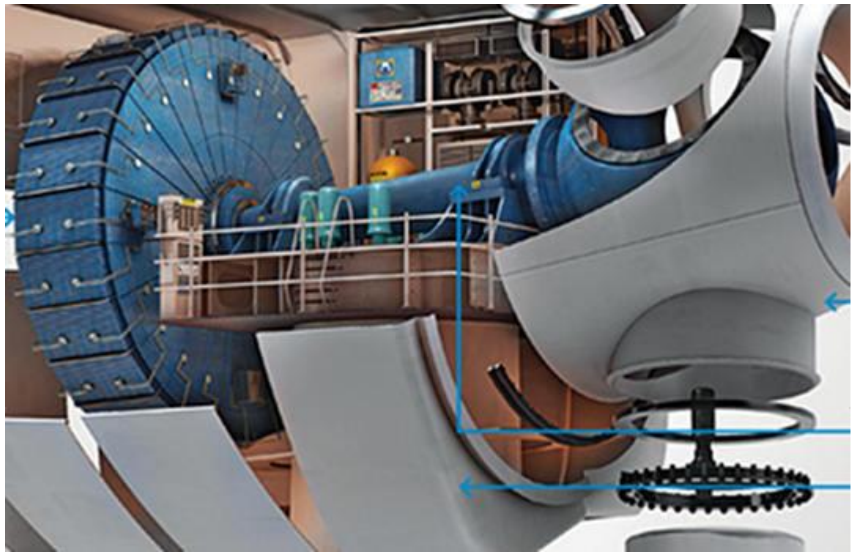

Figure 25. Direct drive electrical generator shaft for GE 10 MW offshore wind turbine.

In 2009, GE moved into the offshore market by acquiring Norway’s ScanWind, a developer of direct-drive turbines, based in the city of Trondheim. GE suspended plans to construct a manufacturing facility in the UK indefinitely.

The 4.1-113 4-MW direct-drive offshore turbine developed by GE in Norway performs well in shallow waters, but leaves a lot to be desired in deeper waters. GE has shifted its focus in the deep-water space to developing a 10-15 MW turbine using permanent or superconducting magnets, which has received additional funding support from the USA Department of Energy (DOE).

In a GE’s strategic shift, plans to deploy the first 4.1-MW prototype in Gothenberg harbor proceeded on track.

FLOATING WIND TURBINE, PORTUGAL

Floating wind farms are tested with a prototype seaborne turbine off the coast of Agucadoura, Portugal. The 54-meter tall structure sits atop a semi-submersible platform known as a WindFloat situated five kilometers offshore.

It has been manufactured by WindPlus, a consortium of energy and clean-tech companies including Principle Power, Energias de Portugal and Vestas. The group hopes their primary success will help secure European Union funding to add another five turbines alongside the existing model, with greater electrical production. The prototype turbine is capable of producing 2 MWs of rated power.

Figure 26. Floating wind turbine at Agucadoura, Portugal.

An undersea cable transmits the energy produced on site back ashore. The costs for transporting electricity rise the further out to sea the structures are placed with the ideal distance is out of sight from land, typically 12-18 miles," says Weinstein. The distance mitigates visual concerns yet decreases the exposure to exorbitant transmission costs. The WindPlus turbine cost $24.9 million to build and install.

The floating turbines and their platforms can be assembled on land, unlike bottom-fixed devices which are assembled at sea on specialized vessels and cost as much as $250,000 a day.

REFERENCE

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