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Review Article

Prospects and Economics of Offshore Wind Turbine Systems

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KEY WORDS: Floating offshore wind turbine, Bottom-fixed offshore wind turbine, Levelized cost of energy, Plant-level cost, Integrated cost, Social cost

ABSTRACT: *In recent years, floating offshore wind turbines have attracted more attention as a new renewable energy resource while bottom-fixed offshore wind turbines reach their limit of water depth. Various projects have been proposed with the rapid increase in installed floating wind power capacity, but the economic aspect remains as a biggest issue. To figure out sensible approaches for saving costs, a comparison analysis of the levelized cost of electricity (LCOE) between floating and bottom-fixed offshore wind turbines was carried out. The LCOE was reviewed from a social perspective and a cost breakdown and a literature review analysis were used to itemize the costs into its various components in each level of power plant and system integration. The results show that the highest proportion in capital expenditure of a floating offshore wind turbine results in the substructure part, which is the main difference from a bottom-fixed wind turbine. A floating offshore wind turbine was found to have several advantages over a bottom-fixed wind turbine. Although a similarity in operation and maintenance cost structure is revealed, a floating wind turbine still has the benefit of being able to be maintained at a seaport. After emphasizing the cost-reduction advantages of a floating wind turbine, its LCOE outlook is provided to give a brief overview in the following years. Finally, some estimated cost drivers, such as economics of scale, wind turbine rating, a floater with mooring system, and grid connection cost, are outlined as proposals for floating wind LCOE reduction.*

1. Introduction

The share of offshore wind power has increased steadily in recent years because large offshore wind farms can be developed with the advantages of faster and steadier wind speeds. In particular, bottom-fixed offshore wind farms are now becoming more competitive due to significant cost reduction. According to the 2019 IRENA (International Renewable Energy Agency) report, the LCOE (levelized cost of electricity) for onshore wind power was reported to be about 50-170 USD/MWh (IRENA, 2019) which is competitive compared to that of fossil fueled power. The report revealed that the LCOE of bottom-fixed offshore wind power was 53-94 USD/MWh in the European wind farms. The ARENA report predicted that the LCOE will be lower than that of fossil fuels.

As reported by Wind Europe, approximately 80% of potential offshore wind power is distributed in offshore area deeper than 60 m water depth (Wind Europe, 2017). This equates to 4,000 GW in Europe, 2,450 GW in the United States, and 500 GW in Japan, respectively. Larger foundation substructures and higher strength steels are necessary at such a water depth, which inevitably induce for the bottom-fixed offshore wind turbines to be less economical. Therefore, the interest in floating offshore wind turbines (FOWT) is growing rapidly as an alternative to untapped offshore wind potential.

Floating offshore wind power is a method of generating electricity by combining a wind generator and a floating substructure called a floater, which is not fixed to the seabed. The floating offshore wind started in 2009 with the installation of the first prototype in the world called the Hywind Demo, which is a 2.3-MW floating turbine with a rotor diameter of 82.4 m in the southeast of Karmoy in Norway at a water depth of about 220 m. After the commission of the Hywind Demo, the total installed floating offshore wind capacity has increased speedily and reached about 124 MW in 2020 (Spearman and Strivens, 2020). The pilot FOWT projects are in commissioning or have been completed. They are mainly located in Norway, Portugal, England, France, Japan, and the United States.

The FOWTs are capable of not only increasing the total production

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of renewable energy at deep sea areas but also minimizing ecosystem degradation, civil complaints, noise problems, etc. Consequently, it has shown a trend of focusing on floating offshore wind power all over the world.

In spite of those advantages of the FOWTs, they remain nascent technically compared to the bottom-fixed offshore wind turbines. It still makes investors very concerned about its economic feasibility. In this context, the LCOEs of floating and bottom-fixed offshore wind power were analyzed to understand the economic feasibility. In addition, we intended to identify major LCOE cost drivers of floating offshore wind power generation through an analysis, and we outlined some suggestions.

2. Floating Offshore Wind Market Reviews

2.1 Global Market Reviews

After the commissioning of the world’s first floating offshore wind turbine, the Hywind Demo, in 2009, the total electricity production by floating offshore wind turbines has grown steadily up to 124 MW in 2020 of which 90% of total installations is in Europe. The United States, Japan, and Korea are preparing to carry out pilot projects, and they are expected to accelerate the development of floating offshore wind power by the early 2020s (Table 1). Installation of FOWT is forecasted to reach 10-30 GW in 2030 and up to 250 GW in 2050 (Fig. 1 and Table 2).

Among the FOWT pilot projects, the Equinor's Hywind and the PPI's WindFloat are considered as the most pioneering ones. After the success of the Hywind Demo in 2009, Equinor constructed a pilot park called Hywind Scotland to demonstrate world's first offshore floating wind farm (Fig. 2). The Hywind Scotland finished installation of five 6 MW capacity wind turbines mounted on a spar type of floater at depth of 95−120 m in October 2017, and it has been actively operating since then.

PPI installed a 2 MW capacity wind turbine on a semi-submersible type of floater, which is called the WindFloat 1 project. The successful completion of the project paved the way for the development of a FOWT wind farm, the WindFloat Atlantic project (Fig. 3). The new floating offshore wind farm is located 20 km off the coast of Portugal

Table 1 Floating offshore wind farms expected to be commissioned by 2022 (Spearman and Strivens, 2020)

Project	Country	Capacity [Turbine rating]	Commissioning date
Hywind Scotland	UK	30 MW [6 MW × 5]	2017 (in operation)
Wind Float Atlantic	Portugal	25 MW [8.3 MW × 3]	2020 (in operation)
Kincardine	UK	50 MW [2 MW × 1, 9.6 MW × 5]	2021
Groix and Belle-Ile	France	28.5 MW [9.5 MW × 3]	2021/2022
EFGL	France	30 MW [10 MW × 3]	2021/2022
EolMed	France	30 MW [10 MW × 3]	2021/2022
PGL wind farm	France	25.2 MW [8.4 MW × 3]	2021/2022
Goto City	Japan	22 MW [2MW × 1, 5 MW × 4]	2021/2022
Hywind Tampen	Norway	88 MW [8 MW × 11]	2021/2022

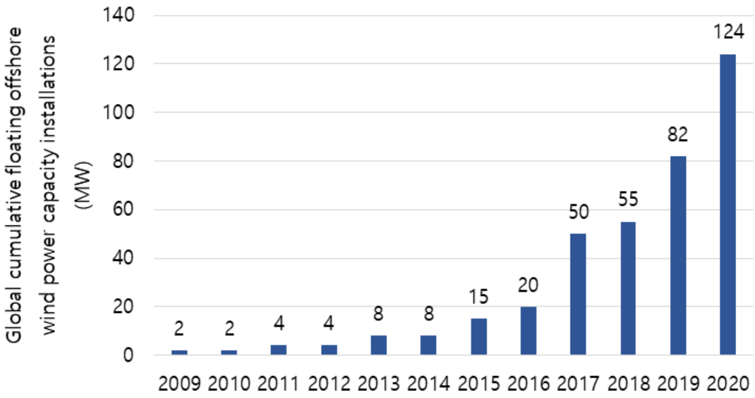

Fig. 1 Global cumulative floating offshore wind power capacity installation (Spearman and Strivens, 2020)

Table 2 Global wind energy growth (IRENA, 2019)

Wind turbine type	2030	2050
Onshore wind	1,787 GW	5,044 GW
Bottom-fixed offshore wind	228 GW	1,000 GW
Floating offshore wind	5-30 GW	250 GW

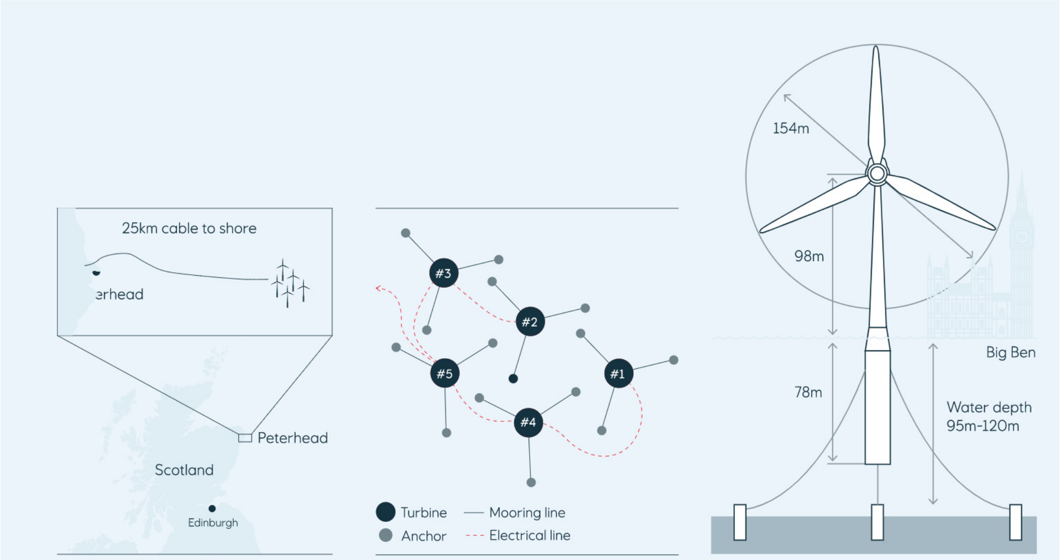

Fig. 2 Hywind Scotland floating wind turbine concept by Equinor

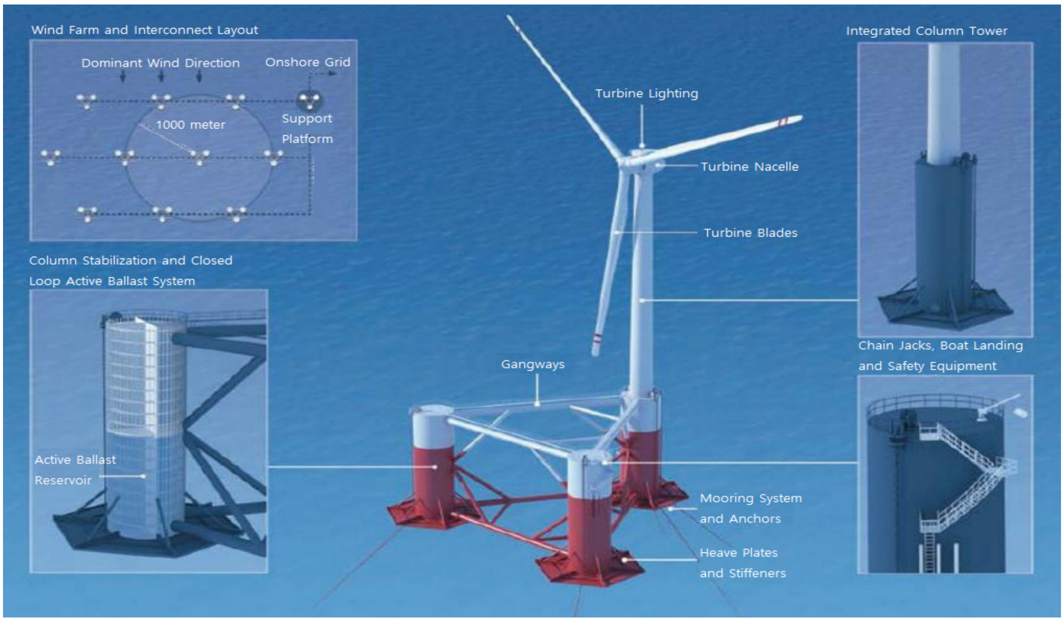

Fig. 3 WindFloat Atlantic floating wind turbine concept by PPI

and was commissioned in the middle of 2020. The project is considered to be the world's first semi-submersible floating wind farm to include three 8.4 MW capacity wind turbines.

During first 5 years of operation, the WindFloat 1 generated more than 11 GWh of electricity with a five-year average capacity factor of 47% (Weinstein, 2014). It experienced an extreme wave height of 18 m for this period and no structural damages were reported. The Hywind Demo has survived against 19 m wave height and produced about 55 GWh of electricity with an annual average capacity factor of about 50% in 2011 (Equinor, n.d.). After the commission in 2017, the Hywind Scotland recorded a capacity factor of up to 65% for the first three months and an average factor of 56% for first two years of operation (Equinor, 2020). With such huge capacity factors, floating offshore wind power has shown strong competitiveness compared to bottom-fixed offshore wind power which has a capacity factor of less than 40%.

2.2 Korean Market Reviews

According to data from the Korea Energy Agency (2020), the potential capacity of offshore wind power in the Korean Peninsula is estimated to be 41 GW based on the minimum economic feasibility. The potential of offshore wind resources on the Korean Peninsula is estimated to be 41GW based on the minimum economic feasibility. The sea area southeast of the Korean Peninsula and offshore area of the Jeju Island have a wide continental shelf for which water depth is suitable for floating offshore wind power generation. The average annual wind speed in these areas is over 8 m/s, and it is known as the best places for floating offshore wind power generation as shown in Fig. 4.

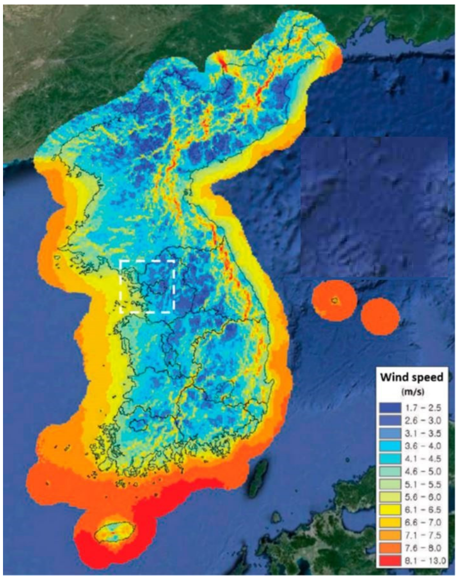

Fig. 4 Wind resource map of Korean Peninsula of mean wind speed at 100 m height above ground (Korea Institute of Energy Research, 2015)

As of 2019, 28 units of offshore wind turbines with 72 MW capacity were installed at 5 locations, accounting for 4.8% of the total installed wind power capacity (Korea Energy Agency, 2020). In the same year, the Korean government supported development of the first 750-kW FOWT project, which will be installed in the sea at 2.6 km in front of Sin-ri, Ulju-gun, Metropolitan Ulsan (Fig. 5). Since then, the development research of a MW-size FOWT has been continuously promoted. Recently, the government has continuously funded 50 billion KRW for the project of developing and manufacturing the Korea's first 8 MW FOWT from 2020 to 2026. In the report of the Ministry of Trade, Industry and Energy (MOTIE), the government also plans to install a 200 MW floating offshore wind farm in 2023, a 1.4 GW FOWT farm in Ulsan, and a 4.6 GW FOWT farm in the southeast region after 2030 (Ministry of Trade, Industry and Energy, 2020).

3. LCOE of FOWT

The economics of energy resources are based on LCOE which is the average power generation cost over the lifetime of the generator and means the average real power generation cost (KRW) per unit of power (kWh) produced by a power plant (Lee and Kim, 2020). LCOE is calculated as the ratio between the present value of the total cost of the generator and the present value of the total amount of electricity generated (Lee, 2017) and is expressed as Eq. (1):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Q}{(1+i)^t}} \tag{1}$$

Where C_t is the total cost for energy generation in year t, Q_t is the total generated electricity during year t and i is the discount rate. As specified by Samadi (2017), the costs related to power generation can be divided into three levels: power plant costs, systems integration costs, and social costs (or external costs).

3.1 Power Plant Cost

Power plant costs include capital costs, fuel costs, operating and maintenance costs, and market costs of greenhouse gas (GHG) emissions (Samadi, 2017). In the case of renewable energy, such as floating offshore wind power, only capital costs and operating and maintenance costs are considered because fuel costs and market costs of greenhouse gas emissions are not produced. Table 3 shows the main components of capital costs through reference analyses (Harries and Grace, 2015; Rhodri and Marc, 2015; Benveniste, et al., 2016; Valpy et al., 2017; Tyler et al., 2019, Lerch, 2019). The capital cost comparison between bottom-fixed and floating offshore wind power may not be accurate since the data is collected from different sizes of installations, but some general conclusions can be drawn.

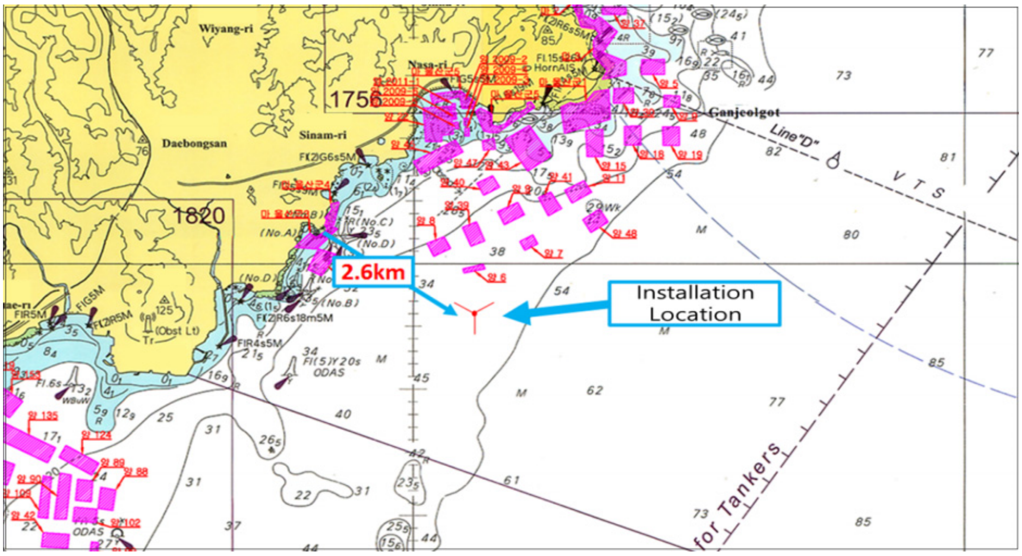

Fig. 5 Installation location of the first 750-kW floating offshore wind turbine in Korea

Table 3 Capex break-down according to some researches

Research	Bottom-fixed wind	Floating wind	Note
Harries and Grace, 2015	- Development: 4% - Windturbine: 45% - Balance of plant: 33% - Installation: 18%	- Development: 2% - Windturbine: 21% - Balance of plant: 73% - Installation: 4%	Based on 2015 data for bottom-fixed offshore wind turbine Based on assumption of 2020 projection for floating wind turbine
Rhodri and Marc, 2015	- Wind turbine: 40% - Balance of plant: 37% - Installation: 23%	- Wind turbine: 42% - Balance of plant: 45.5% - Installation: 12.5%	Based on assumption of a bottom-fixed offshore wind farm Based on assumption of a floating offshore wind farm
Benveniste, et al., 2016	- Development: 4% - Windturbine: 39% - Balance of plant: 31% - Installation: 26%	- Development: 4.8% - Windturbine: 37.6% - Balance of plant: 44.5% - Installation: 13.1%	Based on assumption of a 10 MW bottom-fixed offshore wind turbine Based on assumption of a 10 MW floating offshore wind turbine
Valpy et al., 2017	- Development: 4.7% - Windturbine: 51.3% - Balance of plant: 27.9% - Installation: 16.1%		Based on assumption of a 500 MW bottom-fixed offshore wind farm
Tyler et al., 2019	- Development: 5.1% - Windturbine: 31.9% - Balance of plant :40.9% - Installation: 22.1%	- Development: 4.7% - Windturbine: 24.4% - Balance of plant: 47.1% - Installation: 23.8%	Based on assumption of a 600 MW bottom-fixed offshore wind farm Based on assumption of a 600 MW floating offshore wind farm
Lerch, 2019	- Development: 5% - Windturbine: 40% - Balance of plant: 31% - Installation: 25%	- Development: 5% - Windturbine: 39% - Balance of plant: 50% - Installation: 6%	Based on a 4.14 MW bottom-fixed offshore wind turbine Based on a 10 MW floating offshore wind turbine

As shown in Table 3, the capital costs usually consist of four types of costs: costs for development and management, wind turbine, balance of plant (BOP), and transportation and installation, even though Rhodri and Marc (2015) did not classify development and management cost separately. The development and management cost includes expenses such as development, design, marine environment surveys, management, construction insurance, etc. and varies with the size of the project. In the case of FOWTs, the scope and intensity for a seabed environment survey are less considerable than those in case of bottom-fixed offshore wind turbines since a FOWT is not fixed on the seabed, but the cost of analyzing the weather for deep sea installation may be higher.

The wind turbine cost consists of three elements: rotor, nacelle, and tower. Rotor contains blades, hub, auxiliary systems, and blade bearings, while nacelle is a cover housing that houses most turbine components such as generator, gearbox, drive train, power take-off, control system, and other assemblies. The nacelle and contained components account for the largest share of wind turbine cost, followed by the rotor cost. The compositions of the 5 MW and 10 MW wind turbines' costs are shown in Table 4. When upscaling a wind turbine, while other parts' proportions show small changes, the nacelle cost increases significantly due to especially the generator cost rise. In the case of a gearless-type 10 MW wind turbine, the generator cost is even double that of one with the gearbox (Offshore Renewable Energy Catapult, 2019).

The BOP cost includes floater of wind turbine, mooring system, anchor, and connecting cable. More than 40 concepts of floaters have been proposed (Spearman and Strivens, 2020), but they can be segmented into 3 main types: spar, semi-submersible and tension leg platform (TLP) (Fig. 6). A spar-type floater is ballast-stabilized structure with a large draft that is suitable for deep water. A TLP is a

Table 4 Offshore wind turbine cost break-down

Wind turbine cost	5 MW turbine[1)]	10 MW turbine[2)]
Nacelle:	41.70%	60.61%
- Bedplate and shaft	3.70%	6.06%
- Main bearing	1.30%	3.03%
- Gearbox	16.70%	10.61%
- Generator	4.20%	15.15%
- Power take-off	6.70%	10.61%
- Control system	2.80%	3.79%
- Others	6.30%	11.06%
Rotor:	25.00%	28.79%
- Blade	17.50%	19.70%
- Hub casting	1.30%	2.27%
- Pitch system	2.50%	1.52%
- Others	3.70%	5.15%
Tower:	16.70%	10.61%
- Tower	16.70%	10.61%
Miscellaneous components:	16.70%	NA

[1)] Bjerkseter and Agotnes (2013)
[2)] Offshore Renewable Energy Catapult (2019)

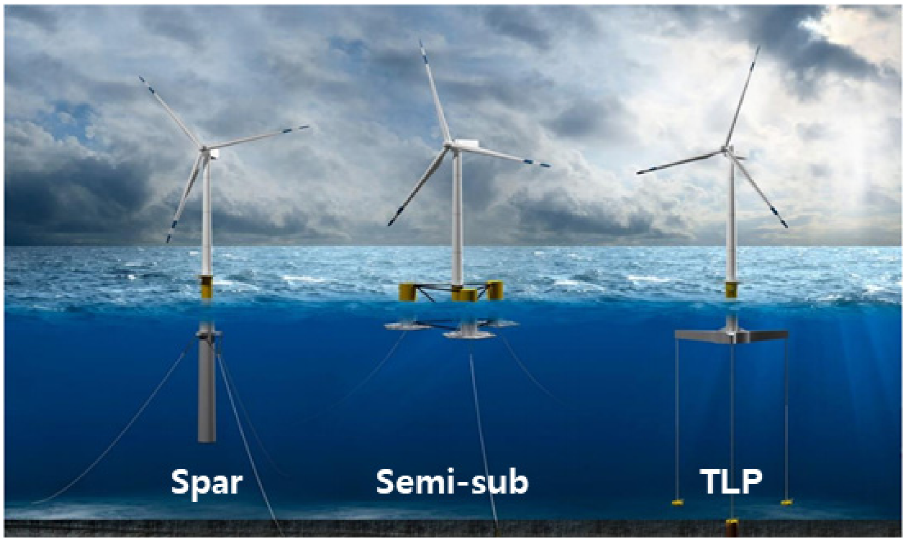

Fig. 6 Main substructure types of offshore floating wind turbine

Table 5 Offshore wind turbine cost breakdown[1)]

Item	Spar	Semi-submersible	TLP
Weight	heavy	heavy	light
Wave sensitivity	low	high	low
Pitch stability	ballast	buoyancy	mooring
MCF[2)]	120%	200%	130%
Water depth	> 100 m	> 50 m	> 50 m

[1)] Jung and Lee (2020)

[2)] MCF (Manufacturing complexity factor): The relative complexity of manufacturing in compare with the bottom-fixed monopile type.

tension-stabilized structure that uses tendons, so the seabed surface needs to be hard enough for tendon installation, and the installation cost increases with water depth. In the case of a semi-submersible substructure, with catenary mooring-stabilized structure, it is suitable for relatively shallow to deep water depth (Table 5).

According to Global Wind energy Council (GWEC) database, by the end of 2020, 67% of floating offshore wind turbines in the market use a semi-submersible floater (Lee and Zhao, 2020). Although spars and TLPs could reduce manufacturing cost due to lighter weight, transportation and installation procedures are more complicated than semi-submersibles' one. A semi-submersible platform needs more complicated manufacturing process and requires more amount of steel but has advantages such as ease of transportation and installation. It can be also installed in shallow water depth.

Bottom-fixed and floating offshore wind turbines show a meaningful difference in the BOP costs. Due to the low complexity of the BOP design, turbine cost accounts for the largest share of the total cost of fixed-bottom offshore wind power generation. In other words, the foundation design of onshore wind power can be applied again to that of fixed-bottom offshore wind turbine. Since it costs so much to design and build a floating substructure, most of the references estimate higher BOP cost t. For instance, according to the research results of the National Renewable Energy Laboratory (NREL) based on a 6 MW wind turbine (Lerch, 2019), the difference between the turbine cost and BOP cost of bottom-fixed offshore wind power is only 9%, but that of FOWT is up to 22.7% as shown in Table 3. The reason for this is that the floating substructure occupies a large share of the BOP cost. As the floating substructure technology develops in terms of design and production, the BOP cost is expected to be reduced gradually.

The transportation and installation cost include the costs for transportation, installation, and decommissioning (Sun, 2020). Transportation and installation cost mainly depend on the types of floating structures. Since a semi-submersible FOWT is assembled on the ground or at the quayside and towed to an installation offshore site, the installation process is simpler and therefore the transportation and installation costs of the semi-submersible FOWTs are more competitive than other types of floaters. A spar floater should be towed a certain distance to have a sufficient water depth and positioned to upright position by a ballasting operation. After then, tower, nacelle, and rotor are assembled to the spar floater step by step. A fully assembled spar-type FOWT is towed to the installation site.

In the case of a TLP-type floater, there are various ways of installation methods. For example, the Germany's GICON TLP can be assembled on the ground by mounting the tower and RNA (rotor nacelle assembly) on the floater and towed by tugboats (wet towing) or transported by special transportation vessel (dry towing) to an installation site or floating slab/towing vessel. Therefore, unlike bottom-fixed offshore wind power, there is no need to hire heavy lift vessel in the installation process of FOWT. The rental fee for a heavy lift vessel is about 150,000 £ or 230 million KRW per day, while that for a fleet of tugboats is only around 30,000 £ (about 47 million KRW) per day (Jame and Costa Ros, 2015).

The operation and maintenance cost is necessary for operating and maintaining a wind turbine over its lifetime. This cost is mainly classified into operation cost and maintenance cost. The portion of the costs are almost same as that of the bottom-fixed offshore wind turbine,

Table 6 Operation and Maintenance cost break-down

O&M cost		Components	% in LCOE
500 MW wind farm[1]	Bottom-fixed	- Material: 15% - Labour: 10% - Equipment: 75%	22.0% (average)
	Floating	- Material: 13% - Labour: 9% - Equipment: 79%	25.0% (average)
600 MW wind farm[2]	Bottom-fixed	- Operation: 23% - Maintenance: 77%	34.3%
	Floating	- Operation: 22% - Maintenance: 78%	29.5%

[1] Bjerkseter and Agotnes (2013)
[2] Tyler et al. (2019)

accounting for about 22–34% of the LCOE (refer to Table 6). A large proportion of operating and maintenance cost is maintenance costs. It is known that the maintenance cost of a geared type turbine is higher than that of a gearless type turbine (direct-driven type turbine) due to complexity of gear system. The semi-submersible FOWT is possible to tow it back to a repair yard whenever maintenance is required. Therefore the semi-submersible FOWT is more advantageous than the bottom-fixed one in terms of the maintenance cost.

3.2 System Integration Cost

System integration cost is commonly referred to the cost of integrating an individual power plant into an electricity system (Lee, 2017). It is classified according to the type of renewable energy system: balancing cost, grid cost, and profile cost (Jang, 2019). The balancing cost comes from the renewable power generation due to weather forecast uncertainty. The grid cost includes connection costs and system reinforcement costs for connecting the generator to the transmission/distribution network. Finally, the profile cost, which is also called utilization cost or backup cost is the cost incurred by the variability of renewable generation.

Even though the LCOE always includes capital expenditure (CAPEX) and operating expenditure (OPEX), the formulas for calculating the system integration cost may be different by country or by project, which may affect the estimation of the LCOE (EWEA, 2016). When the average consumption of wind energy was about 10.2% in Europe in 2014, the balancing cost of wind energy was about 2–3 €/MWh. However, when the consumption increased to 20%, the balancing cost increased to about 4.5 €/MWh (EWEA, 2016). The profile cost, similarly to the balancing cost, elevates as the use of wind energy increases (Jang, 2019). However, these data are based on an onshore wind turbines only and there are few analytical studies on the profile cost of offshore wind case.

The FOWTs usually require higher grid cost than the bottom-fixed offshore wind turbines or onshore wind turbines because they are located farther from the energy consumption sites. According to the OECD NEA (Organization for Economic Co-operation and Development Nuclear Energy Agency), the grid cost in the system integration cost shares about 70% and 46% corresponding to the use of offshore wind power of 10% and 30%, respectively (OECD NEA, 2018). The grid cost of a FOWT is about 24% of the LCOE and can be influenced largely by environmental conditions, the distance from land, water depth, etc. (Myhr et al., 2014).

3.3 Social Cost

In the case of renewable energy, the social cost is not significant since carbon dioxide, air pollution, and radionuclide emissions are not produced. According to the LCOE calculation standard of the Korean Society of Industrial Organization, the social costs include only policy cost. Policy cost includes residential and environmental compensations (Korea Electric Power Corporation, 2018). The project developers of bottom-fixed offshore wind projects have to pay much policy cost to solve the problems related to costal ecosystem, underwater noise, and resident complaints. In contrast, a floating offshore wind turbine installed in the deep sea far from land is relatively free from these problems, and the compensation payment can be minimized.

The policy cost by the Japan Committee of Cost Verification includes human resource development, technology development for efficiency improvement, promotion, additional profits related to FIT (feed-in tariff) purchase price (Choi et al., 2019). A FIT purchase price, also called renewable energy payments, is a policy system designed to support renewable energy producers when market price of renewable energy is lower than the price announced by the government. It is mainly applied in the United States, Japan, and Germany. The Japanese FIT purchase price was maintained at 36 ￥/kWh from 2018 to 2020 for the FOWTs (Korea Energy Economics Institute, 2019).

The Korean Government also used to operate the FIT policy till 2012. The renewable energy portfolio standard (RPS) is now in acts in Korea. The RPS is a system that requires power generation companies with more than 500 MW power generation facilities to produce renewable energy by a certain percentage of total power generation. A power generation operator must either produce renewable energy directly or purchase a renewable energy certificate (REC) to meet the RPS obligation (Yoo, 2018). The REC certifies that power suppliers produced renewable energy. It has different weighting factors according to the renewable energy types (Song, 2012). As shown in Table 7, the weighting factors for the offshore wind power turbines ranges from 2.0 to 3.5 according to the grid connection distances.

Table 7 REC for offshore wind turbines[1]

Grid connection (km)	REC weighting factor
$d < 5$	2.0
$5.0 \leq d < 10.0$	2.5
$10.0 \leq d < 15.0$	3.0
$d \geq 15.0$	3.5

[1] Korea Energy Agency Renewable Energy Center (n.d.)

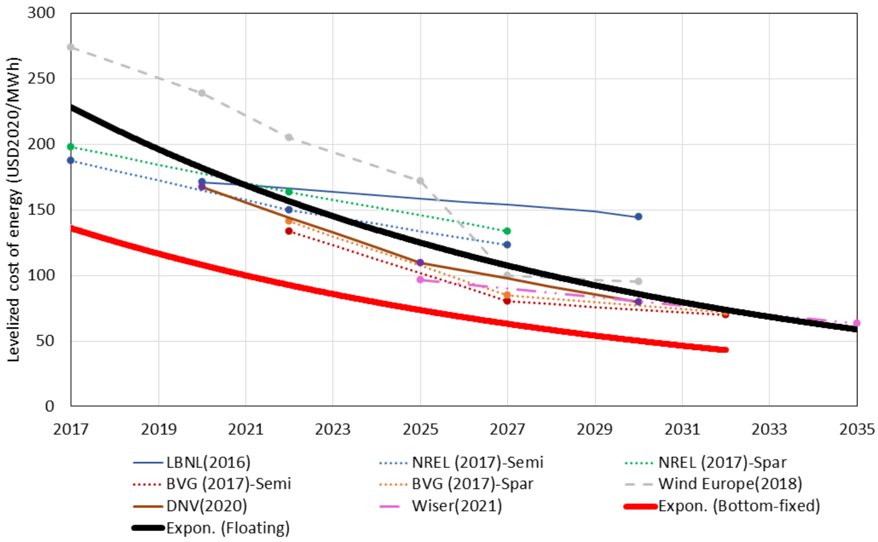

Fig. 7 Global LCOE estimates

3.4 Solutions for Cost Reductions in Offshore Wind Energy Production

As shown in Fig. 7, the LCOEs of the bottom-fixed and floating offshore wind turbines are predicted based on several references (Wiser et al., 2016; Beiter et al., 2017; Hundleby et al., 2017; WindEurope, 2018; DNV GL, 2020; Wiser et al., 2021). The red and black thick solid lines are exponential trend lines for the bottom-fixed and floating offshore wind turbines, respectively. The black thick solid line is more rapid reduction in the LOCE than the red one. This means the LCOE of the FOWTs could decrease faster than that of bottom-fixed wind turbines.

Although the data are based on some pilot farm projects, the LCOE of floating offshore wind farms is about 180–275 $/MWh (Wiser et al., 2016; WindEurope, 2018), which is almost double that of the bottom-fixed wind turbines (130 $/MWh in 2018). The LCOE of floating offshore wind farms is expected to reduce by 135–175 $/MWh after 2022 (Hundleby et al., 2017; WindEurope, 2018). Wiser et al. (2021) even forecasted that the floating offshore wind turbines' LCOE will decrease to about 60 $/MWh by 2035, eliminating the difference between the LCOEs of the bottom-fixed and floating offshore wind turbines.

There are various cost raisers of floating offshore wind power, such as the scale of development, turbine rating, cost of BOP, grid cost, etc. (OREC, 2021). For instance, compared to a pilot project, the capital costs of a commercial-scale project are significantly reduced. As shown in Fig. 8, Carbon Trust (Rhodri and Marc, 2015) estimated that CAPEX of floating offshore wind farm could be reduced by 48% when scaled up from a pilot project to a large commercial farm. Equinor reported that the CAPEX of the world's first floating offshore wind farm Hywind Scotland was reduced by 60–70% compared to the single-unit demonstration project (Equinor, n.d.).

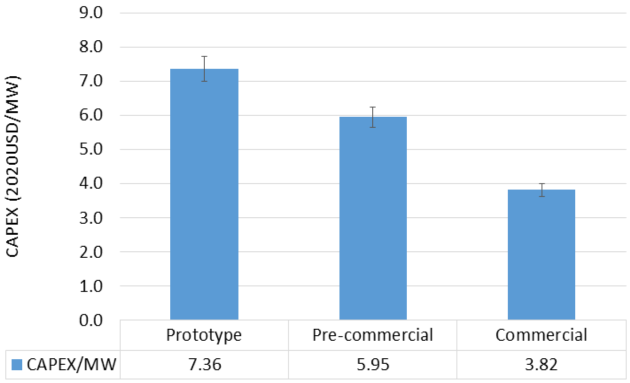

Fig. 8 Capex for floating wind devices by development stages (Rhodri and Marc, 2015)

The largest cost saving for the offshore wind farm projects is in the turbine sizes. The turbine capacity has continued to increase, but the floater capacity to support a turbine should follow it. Nevertheless, the commercial maturity of the wind turbine market continues to increase, and the design and manufacturing technology of large turbines continue to advance. As of 2021, 9.6 MW turbines were used in the floating offshore wind farm of WindFloat Kincadine project, and it is expected that 15 MW wind turbines will be used from 2030 in England, along with 20 MW wind turbines from 2037 (Offshore Renewable Energy Catapult, 2021).

Continuous innovation in the design and performance of the floating substructure, which accounted for a large proportion in CAPEX, will have significant impact on total costs. In addition, the development of mooring line material and design standardization all have cost-reduction potential. The integrated design concept of an anchor, mooring system, and floating substructure could not only help to reduce cost, but also lessen the time for transportation, installation, and maintenance. For example, the objective of the COREWIND (COst REduction and increase performance of floating WIND technology) project promoted by Horizon 2020 is to reduce the LCOE of floating offshore wind power by 15% through improvements in anchor systems and power cables (Ramboll Group, n.d.).

Currently, because most offshore wind turbines for floaters are modified from the onshore wind turbines, it is necessary to develop some specialized turbines for FOWTs. The geared wind turbines are dominant in markets, but the gearboxes require higher maintenance cost than direct-driven turbines. The gearless or direct-driven turbines wind turbines are more suitable for offshore because it will require low maintenance cost for the rotor parts being directly connected to the generator.

Grid costs make up a large portion of the LCOE. Recently, the Swedish government announced a proposal to reduce the cost of connecting offshore power plants to the national electricity grid for electricity suppliers (Swedish Wind energy Association, 2021). According to the research by Bulder et al. (2021), it is predicted that the LCOE can be reduced by 7.7% through the development and integration of offshore grids for the European markets. Moreover, by producing green hydrogen with electricity produced from floating offshore wind plants, it is possible to dramatically reduce the grid cost of floating offshore wind power. The Dolphyn project in the UK is an example of producing green hydrogen through floating offshore wind power. After starting a 2 MW demonstration in 2024, a 10 MW platform will be installed at the Kincardine floating offshore wind farm in 2027 (Scottish Government, n.d.).

4. Conclusion

Floating offshore wind turbine is developing with a fast-maturing technology, while bottom-fixed offshore wind turbine has many restrictions related to water depth and seabed conditions. Recently, the global cumulative installation capacity of the FOWTs has continued to increase through many studies and pilot/wind-farm projects, but the economic feasibility is still uncertain. For the purpose of confirming the possibility of reducing floating offshore wind power's LCOE, a comparative analysis between bottom-fixed and floating offshore wind power was performed. From a social cost perspective, the LCOE was classified into power plant costs, system integration costs, and social costs. The sub-categories of these costs are broken down and shown in Table 8.

Table 8 LCOE break down under social perspective

Primary category	Second category	Tertiary category
Plant-level cost	Capital cost	Development & management cost
		Turbine cost
		BOP cost
		Transportation & Installation cost
	O&M cost	Operation cost
		Maintenance cost
System integration cost (System cost)	Balancing cost	
	Grid cost	
	Profile cost	
Social cost	Compensation cost	

The main difference between bottom-fixed and floating offshore wind turbines was identified as the proportion of the BOP cost in the power plant level. The wind turbine cost is the largest for the bottom-fixed offshore wind turbines, while the floating offshore wind turbines require much BOP cost among all of costs. Since there are various types of floating substructures, the BOP cost and operation and maintenance cost can also be reduced by technical choice or development of advanced floating substructures that are most suitable for the conditions of the sea area. Floating offshore wind power is expected to be more competitive than bottom-fixed offshore wind power since it has lower ecological survey cost, transportation and installation cost, and maintenance cost.

At the system integration level, analyses of balancing cost and profile cost are still insufficient, and further studies are needed to assess this part. In the case of floating wind power, the competitiveness would be low in terms of grid cost due to the long connecting distance compared to a bottom-fixed one. However, it is predicted that the grid cost of floating wind power can be dramatically reduced through new technology in electricity generation, such as green hydrogen (Power to gas, P2G).

The social costs related to the environment of floating offshore wind power are relatively low because the bottom-fixed offshore wind power requires more compensation for ecosystem impacts, civil complaints, etc. Currently, floating offshore wind power's LCOE is more than double that of bottom-fixed offshore wind power, but through continuous technology development and cost reduction, floating offshore wind power is expected to have an LCOE that is approximately equivalent to that of bottom-fixed offshore wind power by 2035. By reducing LCOE through several methods related to development scale, wind turbine rating, BOP cost reduction, grid cost reduction, it is expected that floating offshore wind power can be a significant driver that can support energy transition in the future.

Conflict of Interest

No potential conflict of interest relevant to this article is reported.

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