Levelized Cost of Energy for a 200 MW Floating Wind Farm with Variance Analysis

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ABSTRACT

The technology to engineer, fabricate and install floating wind exists and is feasible for all components, turbines or foundation. Applying lessons learned from offshore oil and gas projects with respect to engineering execution options, competitive supply and reduction in life cycle costs makes offshore floating wind a commercially viable energy supply in regions with moderate to high electricity prices or in regions that have other geographical or resource constraints to bringing additional energy supply on-line. For this study, a 200 MW floating wind farm located 50 km SE off the coast of Ulsan City is considered. The considered farm consists of 40 units of Y-Wind semi type floating platform with 5 MW turbine. The Levelized Cost of Energy (LCoE) of the farm is calculated according to the U.S. NREL method. The LCoE is also compared against existing electricity prices of Korea to assess project feasibility. The results indicate that a 200MW wind farm with Y-Wind foundations will have an LCoE value of around \$0.162 / kWh, as compared to an LCoE value of \$0.114 / kWH for the current Korea residential electricity price. Several LCoE factors are then varied to determine the sensitivity of LCoE to those factors and to identify which factors are critical to control and reduce in order to bring the wind farm cost to be competitive against existing electricity prices in Korea. Additional socio-economic benefits are discussed that can justify the LCoE of a floating wind development in markets with low electricity prices, such as in Korea. The successful implementation of offshore floating wind requires developing and implementing business, engineering and execution strategies and plans in a careful manner in order to achieve the benefits of floating offshore wind energy, namely, diversity and security of energy supply, access to large amounts of energy where needed, low carbon technology and of course, lower total energy costs.

Keywords : Y-Wind, Floating Wind Turbine, LCoE, Floating Foundation, Wind Farm, Semi-Submersible

1. Introduction

The first true floating wind farm, the Hywind Scotland project consisting of five units of 6MW, was installed in 2017 and is now producing electricity. Although Hywind Scotland is not economically competitive today without government subsidies, it represents an important step in proving the technology of offshore floating wind. The success of this first commercial project, together with lessons learned from offshore oil and gas projects and a number of prototype floating wind projects, demonstrates that the technology to engineer, fabricate and install floating wind exists and is feasible for all components, turbines and foundations. Given industry confidence in floating wind technology, the challenge for widespread implementation is to continue to reduce the total life-cycle cost.

In 2017, the authors evaluated a 200MW floating wind farm located approximately 11km offshore and presented that while floating offshore wind is technically viable, it is not quite cost effective [1].

The results in 2017 showed that a 5MW wind farm with Y-Wind foundations will have an LCoE value of between $0.102 to $0.142 / kWh, as compared to an LCoE value of $0.117/kWh for the Korea residential electricity price. This 2017 study assumed a production life span of 25 years.

For the present study a 200 MW wind farm situated 50 km offshore, in water depths of 200m is also considered. The LCoE value is again calculated and variances are applied in order to identify key factors for the LCoE. The wind farm for this study is also using the 5-MW Y-Wind semi-submersible floating foundation design. The project life time for this study is assumed to be 20 years.

It is found that the LCoE value for this wind farm is greater than the LCoE from the 2017 study. The further distance offshore increased export power costs, installation costs and public use fees, and the reduction in project life all contributed to the increase in the LCoE value compared to the near shore wind farm of the 2017 study.

Nevertheless, the results of this study still put offshore floating wind in the range of current retail electricity prices in Korea. Another study by the authors that focused on net project value and internal rate of return shows that with the inclusion of the value of renewable energy certificates (RECs) in the economics, which is the current Korean approach to subsidizing renewable energy development, a 200 MW wind farm at the location will be commercially feasible [2].

As the next step to bring the wind farm cost to be competitive against existing electricity prices in Korea, this paper summarizes the results of a detailed evaluation of the sensitivity of the LCoE values for this wind farm to key cost elements contributing to LCoE. The parameters evaluated consist of:

- Capital costs (CAPEX)
- Operations and Maintenance (O&M) Costs (OPEX)
- Capacity Factor or Turbine Power Rating
- Production Life
- Cost Escalation Rate
- Discount Rate
- Distance Offshore

Based on the results, critical areas are identified that have the greatest potential to reduce the LCoE or conversely that can result in significant increases in the LCoE.

Additional socio-economic benefits are discussed that can help justify the LCoE of a floating wind development in the interim time frame and help ensure that supply chains are developed, cost reductions can be realized, and economics of scale can be introduced.

2. Floating Wind Farm Site and Design Life

A 200 MW wind farm is located 50 km offshore the SE coast of Korea in water depths of 200m (Fig. 1). This offshore wind farm site has abundant wind resources [3] [4], as shown in Fig. 2. This location provides convenient access to existing high power grid node of Gori nuclear power plants as shown in Fig. 3.

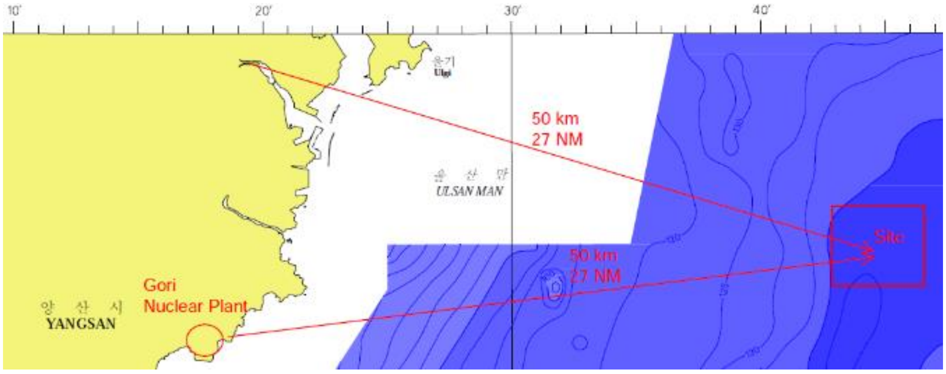
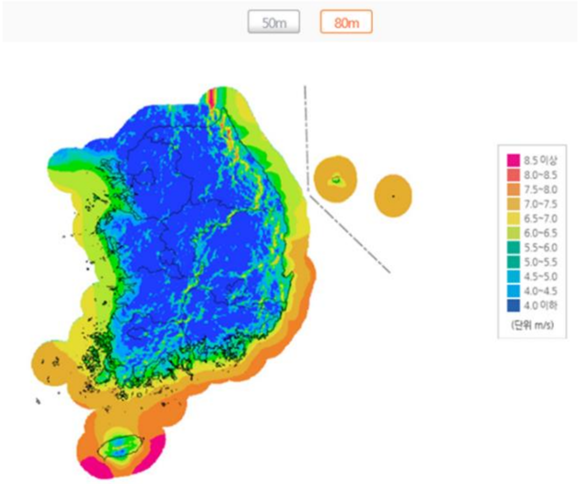


Fig. 1. Floating Wind Farm Site for the Study

The wind farm considered can benefit from the world class infrastructure in terms of offshore platform fabrication capability and a highly educated and well-trained work force. The wind farm for this study is using the 5-MW Y-Wind semi-submersible floating foundation.

The project life time for this study is assumed to be 20 years.



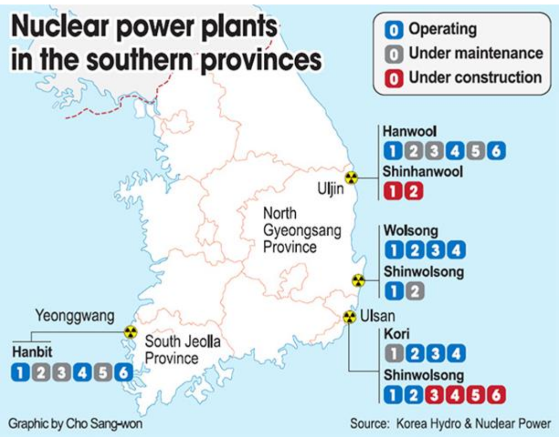


Fig. 2. Wind Resources Offshore Korea

Fig. 3. Location of Nuclear Power Plants

3. Factors Affecting Wind Farm and Offshore Floating Wind Design

In a previous study [1] the authors classified factors that affect wind farm and floating foundation design, namely:

a) Field Factors which include site specific metocean and wind characteristics, commercial factors, such as price targets and availability of subsidies, proximity to grid connections and the availability of suppliers for key equipment.

b) Foundation Factors which are characteristics specific to the floating foundation to be used including the simplicity or complexity of fabrication and operation, tolerance of foundation to different turbine designs, fit in available fabrication yards and integration ports and ability to use vessels of opportunity.

c) Execution Factors which comprise all logistical factors such as how and where to integrate the turbine onto the floating foundation, how to maintain the turbine performance and undertake repairs when necessary, etc. As O&M costs can be 25% or more of the total lifetime costs of a windfarm ([5], [6]) execution factors need to be optimized for a wind farm in order to avoid unexpected cost overruns.

Controlling of Field Factor costs or inputs is difficult as once a site is selected the developer or operator of that site has little control over the site conditions and has to accept them as they are. Operators also have to work within existing market prices and subsidies as available.

Wind farm developers have more control over the Foundation Factors, starting of course with the floating foundation design and turbine selected for the proposed wind farm site. Developers also have considerable control over choosing which fabricators and service providers will be used for various elements of the project.

From deep-water offshore experience it is the Execution Factors that can have the greatest impact on the cost of a project and can also add considerable risk. Often though, Execution Factors are considered after Filed and Foundation Factors are considered. This is an unfortunate approach: Execution Factors actually dominate Field and Foundation Factors in terms of cost impact to the project. For example, the trend in offshore wind is to move to bigger turbines. This is a Foundation Factor as larger turbines generate proportionally more power and thus revenue. However, this ignores the Execution Factor: Very large turbines require large foundations and in many areas of the world available fabrication yards cannot accommodate the large foundations required to support the very large turbines. Another example concerns the logistics (supply, transport and handling) of the very large blades required for the very large turbines. Wind turbine blade manufacturers that are not located next to a seaport will find it difficult to ship and deliver large turbine blades using existing road and rail access. The inter-relationship of Field, Foundation and Execution Factors is currently being studied by the authors and may be presented in a future paper.

4. Y-Wind Semi-Submersible Foundation

Examining the state of existing semi-submersible foundation designs, the authors identified several key improvements in design and technology that will make semi-submersibles cost effective for offshore floating wind:

- Reduction of dynamic responses of the foundation
- Shallow draft during tower and turbine lift and integration, in order to be accessible to as many ports, fabrication yards and drydocks as possible
- Hydrostatic stability during all conditions including transit and in-place
- Using non-special vessels of opportunity for towing and installation operations
- Simple, braceless structural design to allow for low cost and fast series production
- No active ballasting for operations
- Detachable mooring to allow for disconnect and tow back to port to facilitate quayside major maintenance and repair of the turbine

Incorporating these technology factors, the Y-Wind semi-submersible foundation has been developed by the authors as depicted in Fig. 4. These design features are in response to many of the design objectives identified by the NREL as necessary to reduce offshore floating wind costs as described in Section 7.3 [7] (see also Section 1.2 [5]). Though the NREL report focused on U.S. offshore wind energy, we applied the strategy to a design which can then be used globally.

The Y-Wind semi type foundation is engineered to be the most efficient foundation possible with excellent stability and dynamic performance with motion attenuation structures. It is designed for ease of fabrication and simplicity of operation in order to minimize capital and operating costs to the greatest extent possible. In addition, the combination of shallow floating draft and a mooring system that is designed to be detachable allows for quayside major maintenance or repair of the turbine system.

Fig. 4. Y-Wind Semi Configuration with Turbine on Center Column

5. Parameters of LCoE Estimate for Wind Farm

The LCoE parameters summarized in Table 1 are used for evaluation of a wind farm with forty (40) Y-Wind units, each with a 5MW turbine installed. In addition, one Y-Wind foundation is used for a floating power substation offshore. These are the same parameters used by the authors for an NPV and IRR analysis in another recent paper [2]. The wind turbine particulars for the 5MW turbine designs are based on the data in references [8]. Detailed design and analysis results of the 5MW unit can be found in references [9] and [10].

Table 1. LCoE Parameters for Offshore Korea Floating Wind Farm with Y-Wind Semi

	Input Values	Basis
Capital Cost (CAPEX)	40 units of floating platforms Inter-array cables 1 floating substation 1 export cable	Y-Wind cost components using NREL unit costs [3] (Construction learning curve improvements and bulk procurement factors are considered)
Pre-Production and Planning Phase	3 years prior to project start	
Occupied Area Lease Fees	Annual for occupied space and one time for fisheries	
Production and Field Life	20 years	Typical announced life span for proposed offshore wind projects
Discount Rate (Real)	5.0%	Assuming Korea is similar to US Federal [1]**오류! 참조 원본을 찾을 수 없습니다.** plus a small margin for anticipated future increases
Capacity Factor	42.5%	As per range of values for east offshore of Korea between 24% to 48% [1]

Fixed O&M Cost	$15.0/kWyr	Typical Life Cycle Cost Values [1]
Variable O&M Cost	$0.025/kWh	
Electricity Price	$0.093 / kWh (A Series of Residential Prices are input and compared to the LCoE of the renewable energy system)	Korea Residential Gross Domestic Product (GDP) Based [1]
Cost Escalation Rate	2.3%	Average rate of inflation, Korea, past year [1]

There are also some decommissioning engineering, planning and demobilization costs included in the CAPEX. Demobilization includes disconnecting the platforms from mooring at site and towing them back to a quayside or harbor. Decommissioning costs to remove turbines from foundations, to remove mooring piles, to remove the export power cable and to remedy the site are not included. REC selling costs are also not included in LCoE calculations and are therefore not included in Table 1. The project is assumed to be financed internally by the operator, and loan finance charges and capitalized interest costs are not included.

For this study, platform spacing is based upon turbine rotor diameter, D, and is 10 D laterally and 10 D for turbines downstream, which is more conservative than industry norms in terms of density to the mean array density of 19 operating offshore wind power projects in Europe [3]. The resulting wind farm arrangement offshore is then approximately square, with the offshore power substation being to the shore side of the wind farm array.

6. Method of Calculating LCoE

The LCoE is calculated with all components of the wind farm, from floating foundations, turbines, inter-array and export power cables all the way to the shore connection, but not including the shore connector.

The method of calculating the LCoE is based on the simple LCoE method defined by the U.S. National Renewable Energy Laboratory [11] [12].

$$LCoE = \frac{\sum_{t=1}^{n} \frac{(I_{t} + M_{t} + F_{t})}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{(E_{t})}{(1+r)^{t}}} \tag{Eq. 5-1}$$

Where:

I_t = investment expenditures in year t

M_t = Operations and Maintenance expenditures in year t

F_t = Fuel expenditures in year t, equal to 0 in the case of a wind turbine generator

E_t = Electricity generation in year t

r = Discount rate

n = life of the system

For the LCoE calculation electricity production is not uniform over the life of the of the project. Losses in production due to turbine wear out are incorporated, as well as transmission losses.

In terms of electricity production, it should also be noted that for this study we assumed three years pre-operation duration to account for project planning and capital expenditures during which no electricity is generated. Therefore, Eq. 5-1 was applied in such a manner as to account for the different durations, with the numerator values having a life of n=23 and the denominator having a project life of n=20 with power production commencing three years after project expenditures begin.

7. Results and Discussion

Using the input parameters of Section 4 and the methodology of Section 5, the resulting LCoE value is $0.162 / kWh. The LCoE of the existing Korea residential electricity price is $0.114 / kWh. Thus, simply comparing LCoE would suggest that the subject 200 MW wind farm is not economically competitive.

However, to better understand the sensitivity of this result to the input assumptions, we grouped several of the main input factors and independently varied their values by 5% increments:

- Capital costs (CAPEX)
    - Wind Units
    - Substation and Export Cable
    - Distance Offshore
- Operations and Maintenance Costs (OPEX)
    - Variable O&M
    - Fixed O&M
- Capacity Factor or Turbine Power Rating
- Investment Factors
    - Cost Escalation Rate
    - Discount Rate
    - Production Life

The results are indicated in the following Fig. 5 to Fig. 8, with all the variation of all factors plotted in Fig. 9.

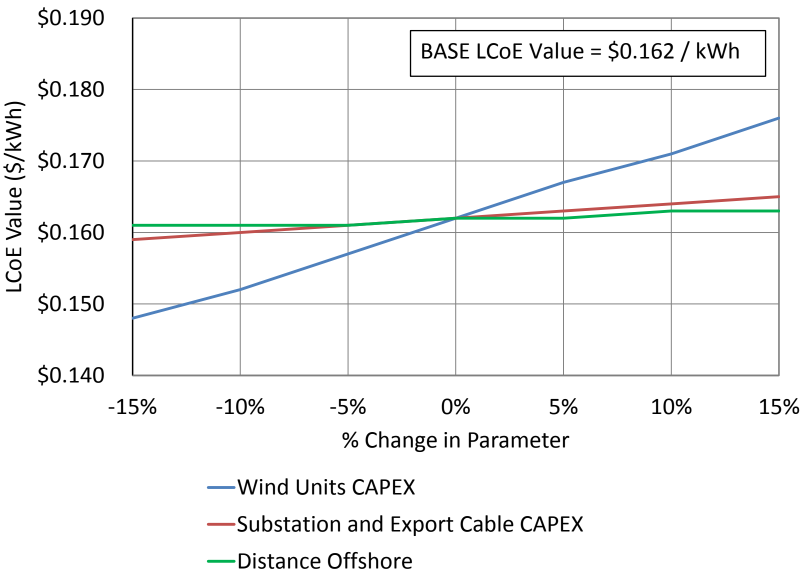


Fig. 5 LCoE Variance due to Changes in CAPEX Factors

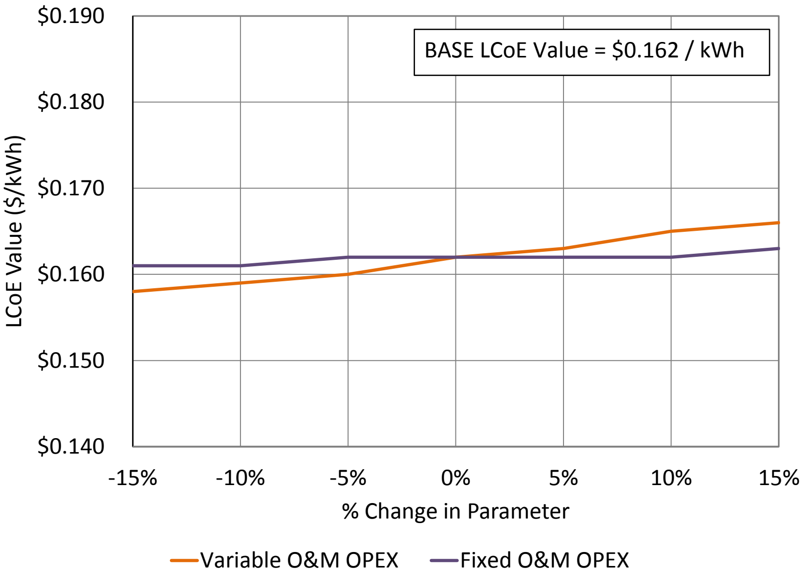


Fig. 6 LCoE Variance due to Changes in OPEX Factors

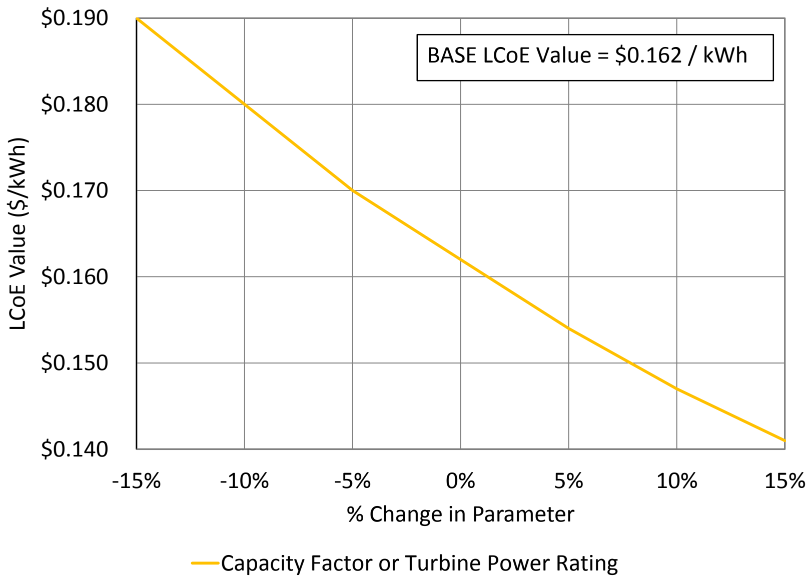


Fig. 7 LCoE Variance due to Changes in Power Production

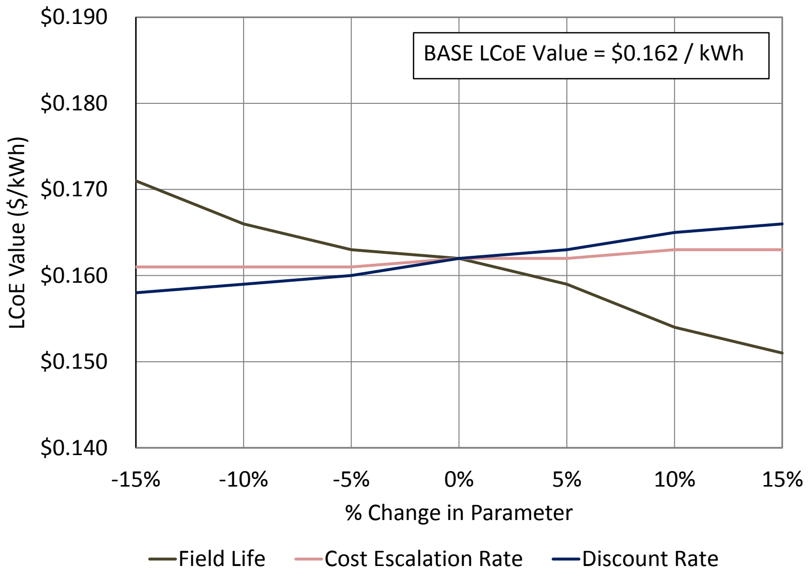


Fig. 8 LCoE Variance due to Changes in Investment Factors

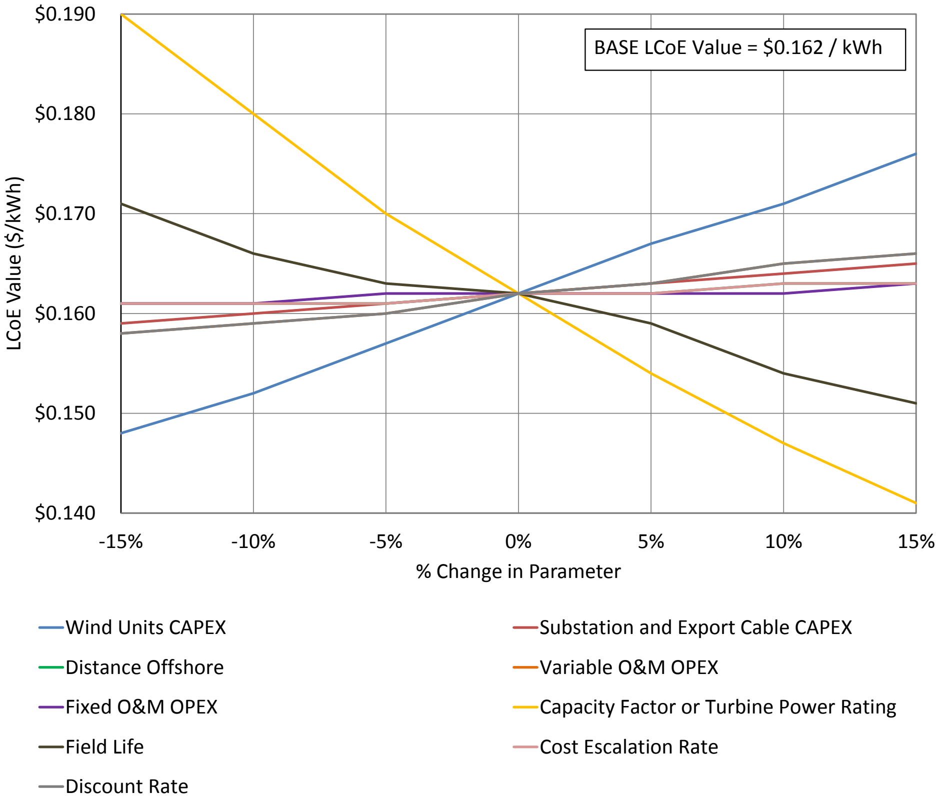


Fig. 9 LCoE Variance of All Factors Considered

Examining Fig. 5 to Fig. 8, the factors that have the most effect on LCoE can then be identified. These are: Wind Units CAPEX, Variable O&M, Power Output and Field Life (Project Life). These four factors were then combined to create a broad “wind farm performance factor” so that the impact on LCoE for 5%, 10% and 15% ranges could be calculated. The results are plotted in Figure 6-6 and summarized in Table 2.

Table 2. LCoE Variance Ranges

Input Performance Factor Variance	LCoE Value ($/kWH)
-15%	0.112
-10%	0.126
-5%	0.144
0%	0.162
5%	0.177
10%	0.196
15%	0.217

From Fig. 10, it can be seen that a reduction in cost factors of 5% is insufficient to bring the LCoE of the floating wind farm to be at or below the LCoE cost of the electricity price. Fig. 10 indicates that in order to be commercially viable on cost alone, the performance factor for the wind farm needs to improve by at least 10%.

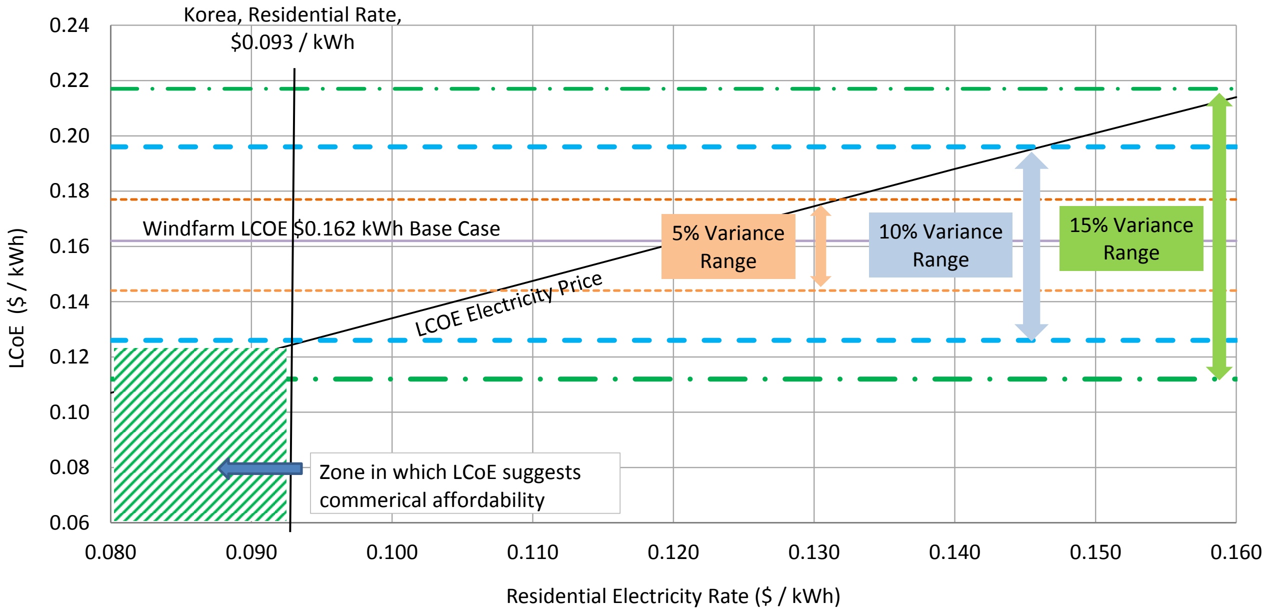


Fig. 10 LCoE 5%, 10% and 15% Performance Factor Variance Ranges

8. Means to Reduce the Cost of the Windfarm

As previously mentioned, other initiatives advocate going with larger and larger turbines as the best solution to driving LCoE costs to below current electricity prices. While this is a valid approach, it may not be an optimum approach. Considering the 200MW wind farm example in this study, choosing a 6MW turbine design instead of a 5MW turbine design will reduce the capital cost of the turbines on a per-MW basis and reduce the number of floating foundations. However, upsizing the turbine platform in this way may limit fabrication to only the largest fabrication yards with the deepest quayside drafts and largest drydocks and lifting cranes, which will increase foundation costs. In addition, it may also increase the other cost factors including in-field power components and O&M costs. Furthermore, the supply of very large offshore turbines is limited to only a few non-Korean firms and these turbines will either need to be imported into Korea or significant investment in infrastructure investments will need to be completed in Korea in order to facilitate the use of such large offshore turbines in Korea. It is not an automatic answer to use ever larger turbines offshore, but it is worth studying on a case-by-case basis.

Probably one of the quickest means to reduce the LCoE of the windfarm would be to extend the farm’s production life. From Fig. 8, every 1 year increase in field life will reduce LCoE by about 5%, all other things being equal. Increasing field life will require increasing the life of the platforms and, in particular, the offshore wind turbines. This needs to begin at the engineering stage in order to design and specify components that can achieve the desired life span.

Another area that could help reduce LCoE values for the wind farm relates to the arrangement of the individual units within the wind farm. Separation of the units is currently driven by empirical guidelines. If ongoing research can optimize the spacing to minimize down-turbine wake effects, thus increasing the capacity factor, or can reduce turbine spacing in order to decrease in-field cables lengths, LCoE values can be further reduced.

Sensitivity of Costs to Execution Factors

The offshore oil and gas industry, as well as other major infrastructure developments around the world, has shown that it is far easier to unintentionally increase project costs than it is to intentionally achieve project cost reductions.

As mentioned in Section 3, execution costs are often the last cost group considered when planning for offshore projects. Y-Wind has been designed to be have the minimal amount of activities occurring offshore. For Y-Wind, the turbine integration occurs quayside, and then the complete platform is towed to site and connected to its mooring. This type of execution strategy for turbine integration is the lowest cost method of lifting and setting a turbine on a floating foundation [14].

However, if a developer chooses a floating foundation design that does not allow for quayside integration of the turbine, turbine integration will need to occur afloat near-shore in sheltered waters, or offshore in open waters. The further that an execution strategy moves from quayside, the more expensive it becomes. The rough order of magnitude change in execution costs is as shown in Fig. 11.

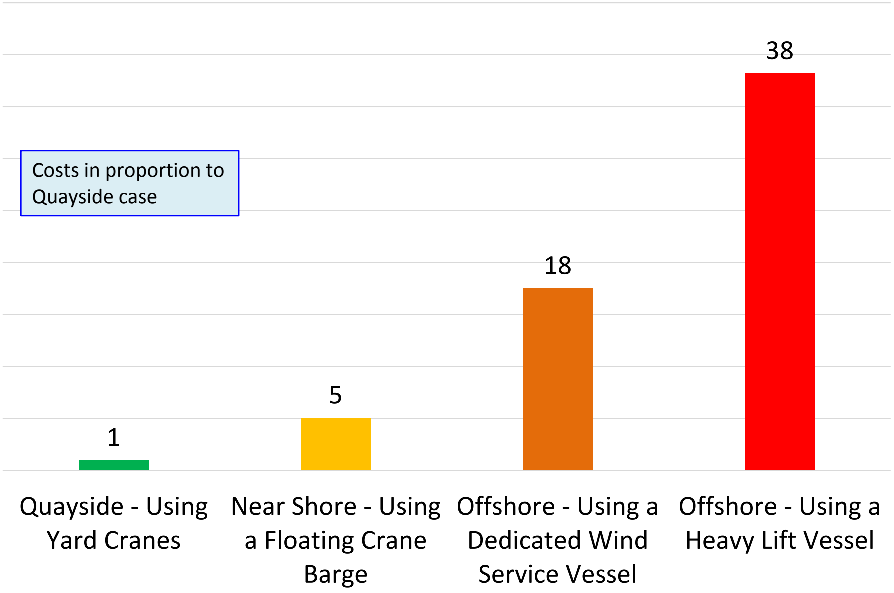


Fig. 11 Order of Magnitude Increase in Execution Costs for Turbine Integration

For the Y-Wind design, approximately 1.0% of CAPEX is for quayside services (including turbine integration) and 7.5% for the remainder of activities afloat. If a developer chooses a yard that cannot support quayside integration, the next available option, near shore integration, would raise total Y-Wind CAPEX by about 4.0%. This example illustrates the importance of carefully evaluating execution factors during project planning.

9. Social Benefits and Costs

The above discussion has only addressed issues surrounding the cost of offshore floating wind installations and how to make them commercially viable for the current retail price of electricity in Korea. Given that Korea has a relatively low cost of electricity, this is a significant challenge. However, Korea has demonstrated through its Renewable Portfolio Standard (RPS) [14] that it is committed to steadily increasing the amount of renewable energy in its energy mix. Under the RPS, large power companies must either invest in new sources of renewable energy or purchase RECs. As mentioned in Section 1, the inclusion of the cost of RECs in project economics makes offshore wind projects viable today.

The following additional socio-economic benefits are provided by offshore wind developments:

1) Reduction in carbon dioxide emissions that contribute to climate change. Currently, the cost of mitigating any climate induced impacts due to rising sea levels or ever more severe weather is borne indirectly by consumers through taxes, insurance premiums, healthcare costs and premature deaths. Offshore wind power will offset generation from traditional

electrical generating facilities that burn fossil fuel and thus reduce the amount of man-made carbon dioxide emissions to the atmosphere. .

2) Improved health. Atmospheric emissions from the burning of coal to generate electricity have been shown to impact people’s health and can be linked statistically to mortality rates. This creates a burden on healthcare systems and leads to shortened lifespans, both of which impact a country’s economic potential. As with carbon dioxide emissions, offshore wind energy will offset traditional power generation.

3) Local jobs. A change from burning fossil fuels for generating electricity to renewable sources shifts expenditures on procurement of fuel to procurement of equipment. For a country like Korea, fuel must be imported while the workforce to build equipment is national.

4) Balance of trade. Since Korea has few fossil fuel resources, these must be imported. By saving the cost of fuel, Korea will have more money available to purchase other international goods and products.

5) National security. Energy independence has been a key component of national security throughout history. Shifting from external sources of fuel to locally generated power reduces dependence on other countries, some of whom may be potential adversaries in future global conflicts.

It should be mentioned that opponents to wind developments often quote negative impacts such as turbine noise, turbine blade shadow flicker, vista impairment, bird fatalities, destruction of fish habitat, and risk to aircraft and vessels. Offshore wind farms resolve the first 3 of these by locating the facilities away from people. Modern turbines rotate much more slowly than the early land turbines, and pre-development site surveys require consideration of bird migration routes, both of which mitigate bird fatalities. Offshore oil and gas developments have demonstrated that rather than damage fish habitats, platforms actually become artificial reefs that attract fish and improve fishing. And modern technologies including radar, communications, global positioning systems, and graphic information system (GIS) mapping help reduce already low risks of collision between vessels and fixed offshore facilities.

The net of all these socio-economic benefits and costs is a significant benefit, but one that is hard to quantify. While one can subjectively justify a deficit of several cents per kilowatt-hour on a pure cost basis, most investment decision processes don’t generally allow such subjectivity. That is slowly starting to change, however. In addition to governments providing a variety of subsidies for renewable power generation, cities and corporations are now beginning to influence decisions on type and location of generation facilities.

10. Summary and Recommendations

Offshore floating wind energy is commercially acceptable in areas with moderate to high electricity prices and in areas that have other geographical or resource constraints to bringing additional energy supply on-line.

For an estimate of LCoE of the floating offshore of Korea, a wind farm of 200MW capacity located about 50km off the southeast offshore of Korea was considered. The farm was assumed configured with the Y-Wind semi-submersible foundation designed for a 5MW turbine. The wind farm design life considered is 20 years. The LCoE values calculated for the configurations is compared against the LCoEs of a range of electricity prices, including the Korea residential electricity price. The results suggest that a 200MW wind farm with Y-Wind foundations will have an LCoE value of $0.162 / kWh, with a 5% range between $0.144 to $0.177 / kWh, a 10% range between $0.126 and $0.196 /kWh and a 15% range between $ 0.112 and $ 0.217 / kWh. In order to compete against existing residential electricity prices, the LCoE of the wind farm will need to be reduced by more than 10%.

The floating wind farm LCoE can vary depending on several other factors such as total capacity of the wind farm, design life of the foundation, site and metocean conditions, wind farm layout and infrastructure. Using high efficiency floating foundations and mooring technology along with competitive supply, robust execution engineering and a competitive supply and manufacturing strategy can drive the offshore wind farm LCoE within range of the current electricity prices. Additional offshore wind farm cost reductions for the export cable and substation will help reduce wind costs even further. However, Execution Factors need to be considered as early as possible as changes in execution options can have large effects on LCoE cost factors. Detailed analysis of the LCoE factors for the specific site of the wind farm for Korean offshore is recommended.

Finally, consideration of additional socio-economic impacts as part of the decision making process will close the apparent cost gap between current market prices for electricity and floating offshore wind investments. If one takes into consideration these important socio-economic benefits, a strong case can be made that offshore wind developments are the right investment today for Korea.

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