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Comparing Levelized Cost of Energy for a 200 MW Floating Wind Farm using Vertical and Horizontal Axis Turbines in the Northeast U.S.A.

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Abstract

The technology to engineer, fabricate and install offshore floating wind turbine exists and is feasible for all components. 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 relatively high electricity prices or in regions that have other geographical or resource constraints to bringing additional energy supply on-line.

However, while horizontal wind turbine (HAWT) technology is developing rapidly and driving down cost, it may be possible to further drive down offshore floating wind costs by choosing a vertical axis wind turbine (VAWT) technology. VL Offshore has developed a cost effective 5 MW floating foundation, Y-Wind semi for HAWT. In this study, the LCoE (Levelized Cost of Energy) of the Y-Wind semi with 5 MW HAWT is compared against the same foundation type with a 5 MW VAWT. For the present work, a 200 MW wind farm, located about 10km off shore the Northeast U.S. at a water depth of 100m is selected. This water depth exceeds the current commercial limits for fixed foundations for offshore wind. LCoE is estimated using the tool developed by NREL, considering all the cost parameters of foundation and mooring CAPEX, installation, operation and maintenances, in-field and export power cables, capacity factors, turbine layouts, substation, discount rate, cost escalation rate, current electricity price and design life. The LCoE results indicate that a 5 MW VAWT foundation will be more commercially viable than a comparable 5 MW HAWT foundation. The LCoE values compare favorably to the LCoE values for most electricity prices in the Northeast states.

Introduction

The U.S. Northeast, offshore from Pennsylvania north to Maine, faces the problem of growing populations with increasing power demand while having fewer options available for supplying that power. There are no nuclear or coal power generating stations planned nor under construction, owing to both commercial factors, such as prohibitive costs and scarcity of available land, and socio-political objections, such as concerns about environmental quality and "Nimbyism". To meet increasing power demands, states in other regions, such as Texas and Colorado are successfully investing in large scale onshore wind farms.

In fact, onshore wind power has emerged as a significant source of clean renewable energy. Onshore wind energy is much more cost effective, in terms of Levelized Cost of Energy (LCoE) than new coal powered thermal generating plants, and in some parts of the world onshore wind energy is already as cost effective, if not more cost effective, than the most efficient new gas powered (combined cycle) generating plants.

However onshore wind does have some limits. In densely populated areas such as the Northeast of the United States, it is difficult to find locations for wind power installations. Therefore, any onshore wind power farms must be located further afield and will entail greater logistical and transmission challenges, including higher cost and power loss. Such is the situation in California, where there are large populations and energy consuming clusters near the coast which are separated by large mountain ranges from the prime wind power areas of the American Midwest states such as Texas and Wyoming.

A proposed solution for supplying power in the Northeast that is gaining more political and commercial attention is to install floating wind power offshore. This has been the solution in Europe where the Northern European states, in particular the United Kingdom, have been rapidly pushing wind power offshore. At the beginning of 2018 there was approximately 14 GW of offshore wind generation capacity installed in the European North Sea. The vast majority of this capacity is in the form of fixed foundation wind turbines located in shallow waters, which is the current plan for the first offshore wind farms proposed for the U.S. Northeast.

More recently, European power producers have begun to focus on deeper water and the use of floating foundations, with the Hywind Scotland project, the first true floating wind farm of 30MW rated output, installed in 2017. More floating windfarms are already being planned for Europe and being discussed for the U.S. By taking advantage of technology developed overseas and leveraging U.S. fabrication infrastructure, it may be commercially feasible for the U.S. to more quickly utilize floating offshore wind farms without having to follow the European development path of thousands of fixed units first. There are several advantages to floating offshore windfarms:

- They can be located further offshore, thereby minimizing impact to coastal fisheries, and abating line of sight issues
- There is significantly more energy available further offshore in deeper waters due to stronger and more consistent winds
- They can be more easily decommissioned than fixed foundation windfarms
- They can be maintained at port, depending upon the design of the platform (foundation)

The problem is to make offshore wind power commercially acceptable. For fixed installations in shallow depth and near onshore grid connections, this has already been achieved. Offshore floating wind costs have, until recently, been too high to be economically attractive for utilities, especially without the benefits of feed-in-tariffs or rate guarantees. The solution is the careful application and combination of offshore engineering technology with execution strategy.

In this study, a representative 200 MW floating wind farm is considered to evaluate the LCoE of the electrical power. The wind farm location is selected about 10km off the Northeast coast of the U.S. This location has good wind resources, water depths in the ranges of 80m to 100m that is too deep for fixed foundation wind turbines. Two types of wind turbines are considered, a Horizontal Axis Wind Turbine (HAWT) of the type extensively used for wind farms and a Vertical Axis Wind Turbine (VAWT). Although only a few large VAWT prototypes have been evaluated and most power production units are of a much smaller scale than HAWTs, a preliminary 5 MW VAWT design for offshore work has been developed by Sandia National Laboratory (Fowler, et. al, 2011; Griffith et. al, 2016). For this study, both turbine units are rated at 5 MW capacity and the Y-Wind semi-submersible foundation, developed by VL Offshore (VLO), is sized for each configuration. Along with turbine and floating foundation data various other appropriate input parameters are used to calculate the LCoE values for the two configurations and then compared.

Opportunity for Offshore Floating Wind in the United States

The National Renewable Energy Laboratory (NREL) has estimated that offshore wind resources in the United States have the technical potential to provide up to 2,058 GW of capacity or 7,203 TWh/year (Musial, et. al, 2016). This is over two times the total current installed electrical generation capacity in the United States of just over 1,000 GW. Fig. 1 shows the summary of technical potential on a per state basis. While these values are significant in themselves, it should be noted that they are based on excluding areas with water depths greater than 1,000 m, based on consultation with industry technology developers. Given that the offshore oil and gas industry has developed fields in water depths greater than 2,000 m, it would seem that appropriate application of technology relating to the floating platform component could push this technical boundary to deeper water.

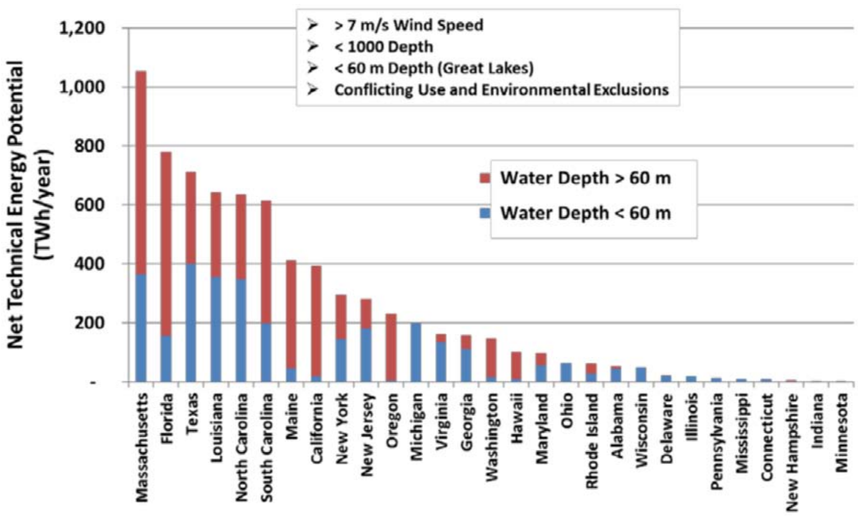

Figure 1—Offshore Wind Net Technical Energy Potential by States for Depths of More than and Less than 60m (Musial et. al, 2016, Fig. ES-4)

The tremendous impact of such an expansion of offshore wind technical potential can be visualized in Fig. 2, where the gross area associated with this deeper tranche of offshore is significantly greater than area considered by the NREL.

Figure 2—Gross Potential Resource Area Showing Excluded Water Depths of More than 1,000m in Dark Blue (Musial et. al, 2016, Fig. ES-1)

Given that the resource is available and the technology either exists or can be adapted from the deepwater oil and gas industry, the challenge for floating offshore wind comes down to economics. In 2016 the NREL issued its report "A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030" (Beiter, et. al, 2016) which is the most comprehensive analysis to date of the cost of offshore wind in the United States. This analysis assumes that the U.S. offshore wind industry can leverage European offshore wind technology and industry experience. This report looks at both fixed bottom and floating developments, accounts for important regulatory and economic differences between the U.S. and Europe, and considers the broad range of location specific variations across the U.S. that will impact offshore wind deployment. Two key conclusions from this report are:

- Although the LCOE for floating developments is significantly higher than for fixed bottom developments in 2015, the two technologies are expected to converge with floating developments possibly having lower LCOE for commercial operation dates in the late 2020's (Fig. 3).
- Considering Levelized Avoided Cost of Electricity (LACE) on a regional basis, offshore wind developments begin to show economic potential in the early 2020's (Fig. 4). It should be noted that these results are based on unsubsidized electricity prices. Factors such as the production tax credit, carbon pollution regulations, or state renewable portfolio standards would serve to increase the economic viability of a given development.

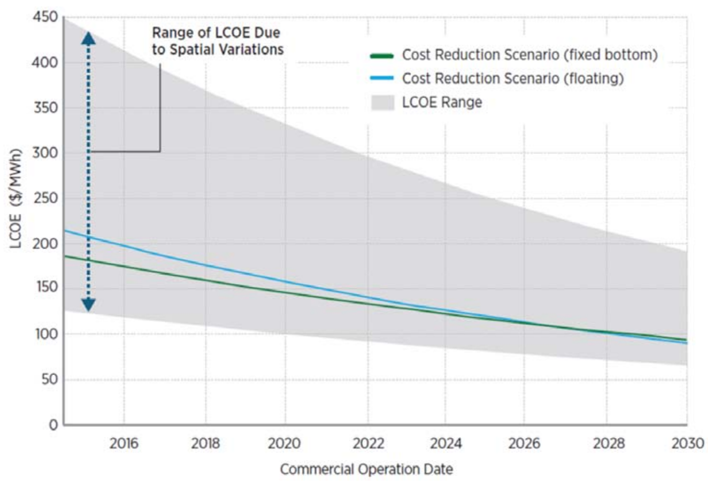

Figure 3—Levelized Cost of Energy for Potential Offshore Wind Power Projects from 2015-2030 throughout the U.S. Technical Resource Area (Beiter et. al, 2016, Fig. 44)

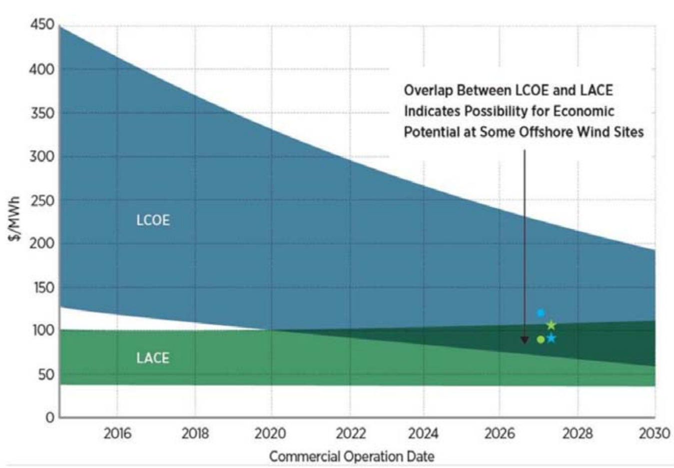

Figure 4—Comparison of LCoE and LACE of Energy Estimates from 2015-2030 (Beiter et. al, 2016, Fig. 45)

These studies by the NREL are based on the assumption that technological improvements and cost reductions will continue at their historic pace. What is needed to dramatically increase the opportunity for economic development of offshore wind resources is a step-change in technology.

Advancing Floating Wind Farms to Commercial Scale

While wind turbine costs are a large component of offshore wind costs, the floating foundation costs are an even larger component (Beiter et al., 2016; Shelley et al, 2017). Considerable wind turbine technology advancements are being made to reduce their costs and improve their operability and reliability offshore. To more significantly reduce floating offshore wind cost, similar advancements in cost, operability and reliability for floating foundations need to be achieved. This was the motivation in developing the Y-Wind floating foundation technology: To have excellent hydrodynamic performance, to be the most economical floating foundation possible and to allow for flexible execution (Boo et. al, 2017a, 2017b).

The size of a floating foundation is determined by the size and characteristics of the turbine that needs to be supported. To date, all floating offshore wind installations, whether technology demonstrators or small scale wind farms, have used HAWT turbines. This is due mainly to availability of HAWT turbines up to 6MW rating. Even larger HAWTs are being considered for future offshore floating wind farms. Commercial scale VAWT turbines exist only up to a few hundred KW ratings, though engineering designs up to 1 and 2MW are begin considered by some European firms, and Sandia National Laboratory (SNL) has developed its preliminary 5 MW VAWT design for offshore (Fowler, et. al, 2011; Griffith et. al, 2016).

A VAWT has several key differences from a HAWT that have a significant impact on foundation size. In particular, the centers of gravity and wind load of the VAWT are lower, thus reducing overturning loads on the foundation and resulting in a smaller foundation size and displacement. Furthermore, a smaller foundation will require a smaller mooring system. As the floating foundation is such a large component of overall floating wind costs, any reduction in the hull and mooring size, and thus cost, because of improvement or changes in the wind turbine technology will be consequential. An additional advantage could arise in execution costs with a smaller foundation making available more construction and integration options. Field costs may also be reduced by using a VAWT design. Spacing between turbines in a wind farm is governed by turbine blade swept area (generating wake downstream). A VAWT has a smaller swept area than a HAWT, and thus it could be possible to reduce field spacing, which in turn will reduce power cable costs. Finally, advocates of VAWTs argue that the placement of the gear boxes and generating equipment down low, on the floating foundation (instead of on top of a tower as for a HAWT) will result in reduced operating and maintenance (O&M) costs over the wind farm life. Offsetting these potential cost savings are the higher initial capital costs of a VAWT compared to a HAWT (Akimoto et al., 2011).

Platform Configurations and Design Conditions

For the present study, the Y-Wind foundations (platforms) with 5 MW HAWT and VAWT are used. The Y-wind semi foundation consists of three outboard columns and one center column to support the wind turbine as depicted in Fig. 5. At the design stage, a mean heel angle of the platform due to the peak rotor thrust at the rated wind speed is considered such that the mean heel angle is maintained below 4 deg. In addition, it is checked if the platform has a sufficient positive metacentric height specifically in wet-tow but with a shallow tow draft.

Figure 5—Y-Wind Semi with HAWT Turbine on Center Column

NREL 5 MW HAWT and SNL VAWT properties summarized in Table 1 are used for the Y-Wind foundations. The 5 MW HAWT and VAWT turbines are described in Jonkman et al. (2010) and Fowler et al (2011), respectively.

Table 1—Wind Turbine Data

Items	HAWT (NREL)	VAWT (SNL)
Power (MW)	5	5
Number of Blades	3	3
Thrust (Peak, kN)	819	550
Pressure Center above SWL (m)	90	67
Total Weight including Tower (tonnes)	600	600
Total Weight CoG above SWL (m)	70.4	54.9

Detailed design and analysis results of Y-Wind semi foundation with HAWT can be found in Boo et al (2017a, 2017b). The 5 MW VAWT Y-Wind semi is sized considering the turbine weight and peak thrust but maintaining similar mean heel angle and tow draft as the 5 MW HAWT Y-Wind. Both foundation's particulars are summarized in Table 2. The platform configuration sketches are compared in Figure 6. The same size of mooring chain of 120 mm diameter and 800 m long is used for the moorings of the foundations.

Table 2—Y-Wind 5 MW Floating Foundation Particulars

Items	Y-Wind Semi 5 MW HAWT	Y-Wind Semi 5 MW VAWT
Displacement (tonnes)	7,770	6,500
Draft – Design (m)	18.0	18.0
Offset Column Center Radius (m)	35.0	30.0
Column OD (m)	10.5	9.5
Column Height (m)	29.5	29.5
Center Column Height (m)	28.0	28.0
Pontoon width, Height (m)	4.5, 4.0	4.5, 4.0

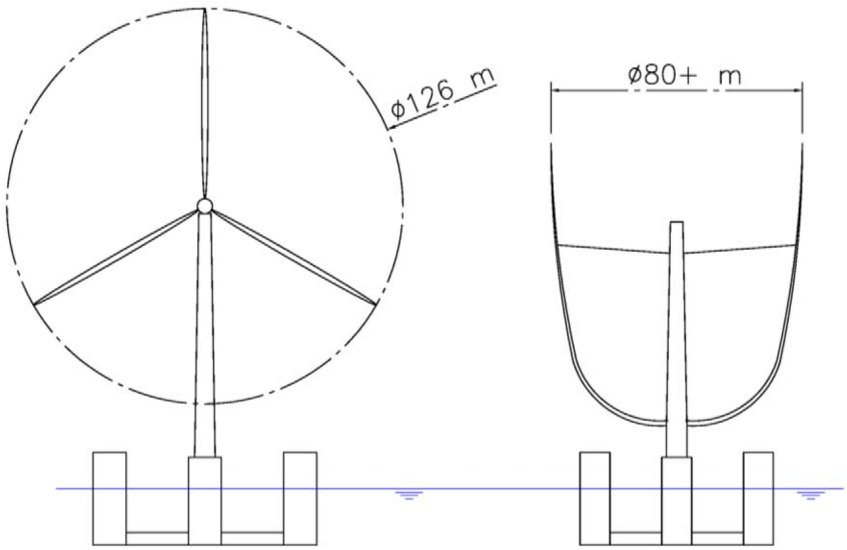

Figure 6—Y-Wind Semi Foundations with 5 MW HAWT and VAWT

Foundation hull and mooring design basis are based on ABS requirements (ABS, 2015). Metocean conditions used are derived from the US offshore data summarized in Table 3

Table 3—Metocean Data

Platform Condition	Operating	Extreme	Survival
ABS DLCs	1.3	6.1	SLC
Environment Condition	Rated	50-yr	500-yr
Turbine Condition	Production	Parked	Parked
Wind @ hub (m/s)	11.4	40.0	45.0
Wave Hs (m)	7.5	12.5	15.0
Tp (s)	11.5	14.2	15.3
Current @ Surface (m/s)	0.4	0.8	1.0

Wind Farm Layouts

A representative Y-Wind foundation farm in offshore Northeast U.S. is assumed for the LCOE evaluations. The farm layout is highlighted in Table 4 and Figure 7. Floating wind farm arrangement is in a radial orientation with respect to the substation. Spacing between the turbines is 8 times the rotor diameter (8 D) laterally and 10 times the rotor diameter (10 D) for turbines downstream. Such geometry is consistent with large offshore wind farms developed recently in the North Sea. Approximately 50 km2 are required for the HAWT wind farm, whereas approximately 30 km2 are required for the VAWT wind farm. Power cable lengths are calculated as twice the water depth plus the separation (10 D) with an additional 25% margin.

Table 4—Offshore Floating Wind Farm with Y-Wind Semi, HAWT and VAWT Turbines

	5 MW HAWT Y-Wind Semi	5 MW VAWT Y-Wind Semi
Wind farm power capacity (MW)	200	20
Number of units	40	40
Distance from shore (km)	10	10
Water depth (m)	100	100
Number of Offshore Substations	1	1
Number of Export Cables to Shore	1	1

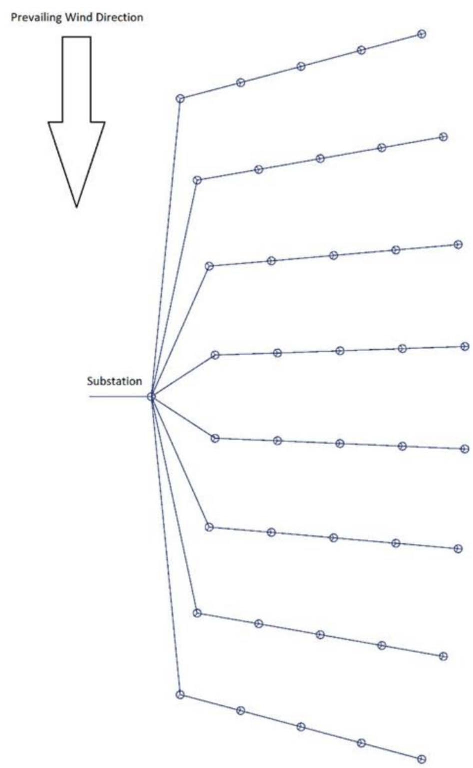

Figure 7—Floating Wind Farm Radial Layout for 5 MW Turbines (HAWTs or VAWTs)

LCOE Factors

Common factors for LCoE calculation are summarized in Table 5. The LCoE of the electricity generated by the wind farm is calculated using the NREL on-line LCoE calculator (https://www.nrel.gov/analysis/tech_lcoe.html). LCoE costs include all costs from project sanction (assumed to be 2019) until delivery, installation and connect of the last platform. While a 5 MW VAWT is not commercially available at this time nor forecast to be available by 2019, for the purposes of this study, engineering designs for a 5 MW VAWT exist and therefore this engineering data is used to size the foundations accordingly and to calculate the LCoE values.

Table 5—Input Factors of Common LCoE Calculation

Factors		Sources
Capital Cost	Foundation	Y-Wind cost components using NREL unit costs (Beiter et a., 2016)
		Construction learning curve improvements and bulk procurement factors are considered.
	HAWT	NREL unit costs (Beiter et. al, 2016)
	VAWT	VAWT turbine cost is assumed in the same proportion to the NREL HAWT costs as indicated in the study by Akimoto et. al. (2011)
Operating Lifetime	25 years	Based on typical offshore platform life time
Capacity Factor	42.5%	Assumed similar to observed North Sea values (http://energynumbers.info/capacity-factors-at-danish-offshore-wind-farms)
Fixed O&M Cost	$15.00 / kWyr	Typical Life Cycle Cost Values (Myhr et. all, 2014)
Variable O&M Cost	$0.025 / kWh	
Electricity Price	Series of Prices	https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

For each configuration, the LCoE includes capital and operating costs for the wind turbines, floating foundation fabrication, tow and installation, mooring and in-field power cables, the substation, export power cable, shore grid connection and field component O&M. Pre-sanction costs, such as project approvals and permitting, seabed surveys, and site specific metocean data collection are not included. Finance costs are incorporated in the discount factor, an overall project insurance cost of 2.3% is included, and there are no Feed-in Tariffs, Production Tax Credits or other forms of subsidies included in the LCoE values calculated. All costs are US dollar denominated.

Both lower and upper bound LCoEs are calculated for each configuration. The differences in input for these ranges are summarized in Table 6.

Table 6—LCoE Calculation Input Factors for Lower and Upper Bounds

Items	Lower Bound	Upper Bound
Discount Factor	4.05%	5.75%
Inflation (Cost Escalating Factor)	2.30% (https://data.bls.gov/timeseries/CUUR0000SA0L1E?output_view=pct_12mths)	4.00%
Mooring Anchor	Drag-Embedded Anchors	Suction Pile Anchors
Execution Strategy	Hull build in Northeast yard; turbine integrated in Northeast port or yard	Hull build in Gulf of Mexico, transport to integration yard or port; turbine integrated in Northeast yard or port.
	Local vessels of opportunity used for installation offshore	Local vessels of opportunity used for installation offshore

Results and Discussion

The LCoE calculation results are plotted for the Y-Wind HAWT and VAWT wind farm configurations in Fig. 8. The electricity price LCoE lower bound curve (solid) shows the 25-year levelized cost of electricity for a given set of electricity prices and the lower bound assumptions. The upper bound curve (dashed) shows the levelized cost of electricity for the upper bound assumptions. Current electricity prices for New England States (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont) and Mid-Atlantic States (New Jersey, New York and Pennsylvania) are based on U.S. Department of Energy data (https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a) and the average prices and LCoE values are indicated as shown. When the LCoE values for the floating wind farm are less than the LCoE for the electricity prices, the wind farm is the more economical power supply for that particular region or application. For example, Figure 8 indicates that the 5 MW HAWT solution with lower bound assumptions is more economical than current electricity rates above about \$0.13/kWh with lower bound assumptions while the VAWT breakeven price is approximately 8% lower at \$0.12/kWh. (It should be noted that current electricity prices do not include other utility company on-shore costs, such as transmission costs and overhead, that might be appropriate depending on the project under consideration.)

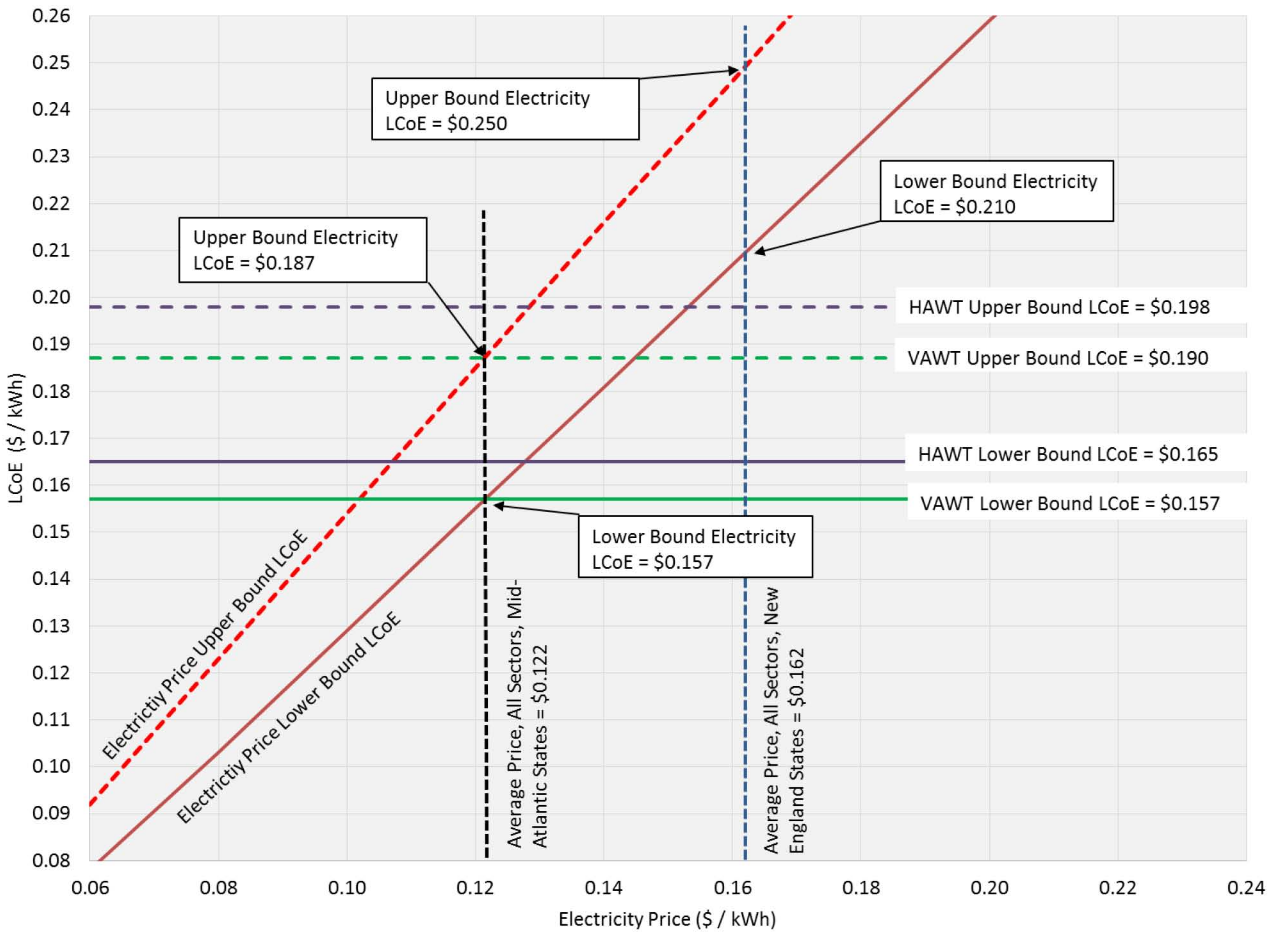

Figure 8—Floating Wind Farm LCoE for HAWT and VAWT Configurations Compared to Electricity Price LCoE Values

From Fig. 8, it should be noted that VAWT platform LCoE values are lower than the HAWT platform values throughout the range. Comparing the HAWT and VAWT LCoE values against the LCoE values of the electricity prices, it can be seen that both platform configurations will have lower LCoEs than the average electricity price in New England. This suggests that a floating wind farm will be commercially feasible in New England, given the assumptions herein. For the Mid-Atlantic States, it is likely that a VAWT based wind farm will be commercially feasible, but that the cost of a HAWT based wind farm will not be commercially feasible at either the lower or upper bound ranges. However, depending upon specific details of the development, the floating wind farm could be cost effective in select areas and for select purposes in the Mid-Atlantic States. Further analysis will be required to confirm the feasibility envelop of the 200 MW wind farm for the Mid-Atlantic States.

Fig. 9 provides a breakdown of LCoE cost for each configuration. Export substation, cable and shore connection costs are not included but are essentially identical for the two cases. The breakdown of the LCoE costs is such that turbines are included as a procured item while the Y-Wind foundations are included as a constructed item. The procured LCoE values include the turbines and foundation materials, systems and outfitting and are similar across configurations. However, the reduction in the LCoE of the constructed items, which consists predominantly of the fabrication of the foundation, for the VAWT is lower, suggesting that savings in foundation cost are could be significant when choosing between a HAWT and VAWT. Other potential benefits of VAWTs as discussed in the section, Advancing Floating Windfarms to Commercial Scale, which are not yet quantified are not included in this evaluation.

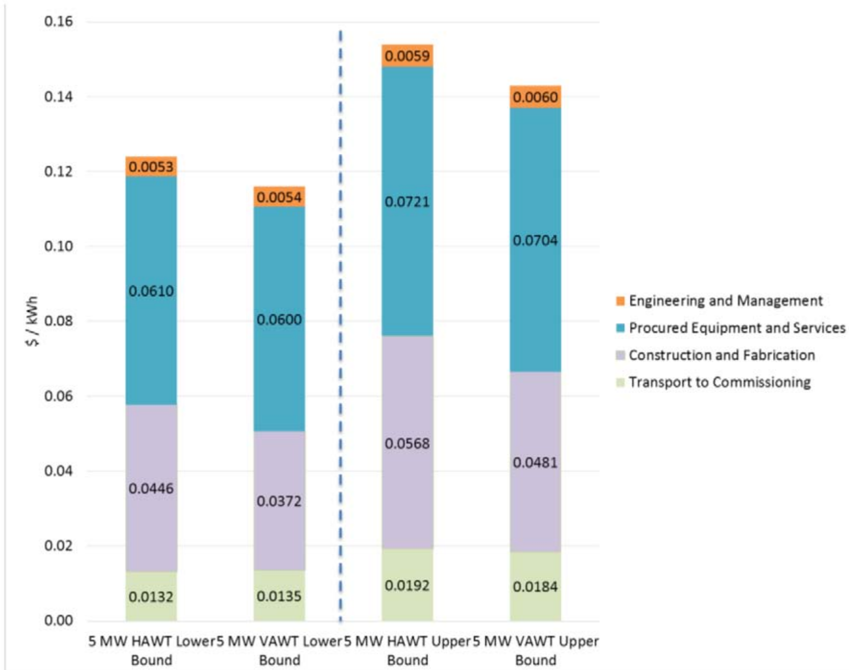

Figure 9—LCoE Breakdown for HAWT and VAWT Foundations, Lower Bound and Upper Bound

Ways and Means to Reduce Wind Farm LCoEs

Although the current work might not quite meet the level of a step-change in technology as discussed in the section Opportunity for Floating Offshore Wind in the United States, it does provide a significant improvement in cost that will help enable offshore wind developments. It is interesting to compare results with the NREL projection of LCoE for offshore wind (Betier et al, 2016). Figure 10 superimposes the calculated LCoE ranges for the Y-Wind with HAWT and VAWT configurations on the NREL plot from Figure 3, assuming the 200 MW turbine farm development commences in 2019 and achieves a commercial operation date (COD) in 2022. The Y-Wind data ranges are within the overall NREL LCoE range forecast and close to the NREL Cost Reduction Pathway for that year. Given that there is only a single commercial floating wind farm in operation at this time, an estimate of $0.25/kWh can be inferred as current unsubsidized LCoE based on published data. Such a value exceeds the NREL vision, but helps put the current research into perspective. Achieving the projected Y-Wind improvements over other floating wind foundations aligns with the NREL vision for offshore wind.

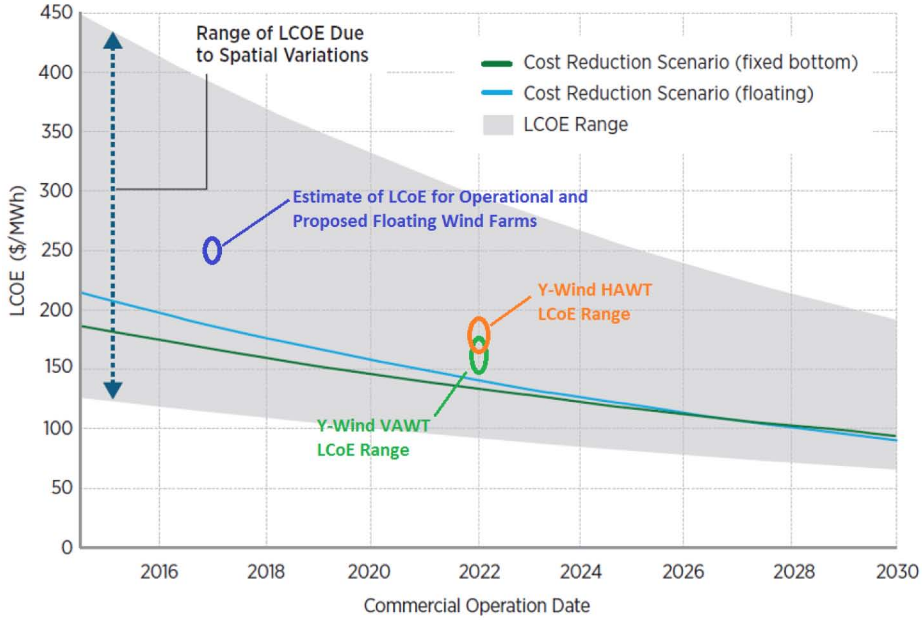

Figure 10—LCoE (Unsubsidized) of US Offshore Wind by NREL (Betier, et. al, 2016, Fig. ES-3) vs. LCoE of Y-Wind for Northeast U.S.

Continuing advances in turbine and blade technologies are resulting in incremental increases in power output, efficiency improvements and cost reductions. These continual improvements will continue to reduce the LCoE costs of the floating wind farm.

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. Further, for this study, spacing of the VAWT turbines is based upon HAWT empirical guidelines while some researchers (for example, Kinzel, et al, 2015) suggest that closer spacing of VAWTs may even result in improved power output.

The above discussion is solely focused on the cost of offshore floating wind installations and how to make them commercially viable in today's socio-economic climate. However, a number of fundamental considerations beyond pure cost are worth considering in any decision process regarding an investment in a new energy source including: reduction of carbon dioxide emissions, health impact from air emissions, local jobs and energy security. All of these factors add value to renewable resources such as offshore wind and can be factored into project economics to help justify a deficit on a pure cost basis as compared to a fossil fuel based energy developments.

Summary and Recommendations

An estimate of LCoE for a floating wind farm of 200 MW capacity located about 10km off the Northeast offshore of the U.S. in 100 m water depth was developed. The wind farm was assumed configured with two different Y-Wind semi-submersible foundations designed for a 5 MW HAWT turbine and a 5 MW VAWT turbine. The LCoE values calculated for those configurations are compared against the LCoEs of a range of electricity prices for the New England and Mid-Atlantic states. Two bounds were also considered: a lower bound assuming Northeast execution, low discount rates and good soil conditions for mooring, and an upper bound assuming higher discount rates, a split execution and poor soil conditions for mooring.

The results suggest that a 5 MW HAWT wind farm with Y-Wind foundations will have an LCoE value of between $0.165 to $0.198/kWh. For a 5 MW VAWT configuration, the range of LCoE values is $0.157

to \$0.190 / kWh. These LCoE values compare favorably to the LCoE values for most electricity prices in New England and the Mid-Atlantic States, suggesting that floating offshore wind in some form is already commercially viable in those regions. In addition, these values suggest that a VAWT solution at 5 MW will be more commercially viable than a comparable 5 MW HAWT solution.

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, turbine spacing 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 below the LCoE of current electricity prices, in some regions. Any cost reductions for the export cable, substation and shore grid connection will also help reduce wind costs even further. Additional research into optimizing wind farm arrangements and layouts could realize increases in power production and additional reductions in the in-field costs. 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.

The technology for offshore floating wind has advanced sufficiently that using high efficiency foundation designs, low cost mooring and series production results in commercially viable development opportunities near shore in water depths that cannot support fixed-bottom solutions. In addition, floating wind technology has the potential to extend offshore wind developments further offshore into significantly deeper water and unlock the potential for clean, renewable energy of a magnitude many times greater than total electricity usage today in the U.S. While engineers can improve technology including every factor from equipment performance to how things are built, transported and installed, macroeconomic factors also affect wind farm developments and need to be evaluated carefully before investing in or sanctioning an offshore wind farm project.

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