IEEE Power and Energy Technology Systems Journal

Received 25 June 2018; revised 26 November 2018; accepted 29 January 2019. Date of publication 12 February 2019; date of current version 25 March 2019.

Digital Object Identifier 10.1109/JPETS.2019.2898688

Transmission Design and Analysis for Large-Scale Offshore Wind Energy Development

ELPINIKI APOSTOLAKI-IOSIFIDOU [1], REGINA MCCORMACK [2], WILLETT KEMPTON [3], PAUL MCCOY [4] (Life Member, IEEE), AND DENIZ OZKAN [5]

[1] Transportation Sustainability Research Center, University of California at Berkeley, Berkeley, CA 94704 USA
[2] College of Earth, Ocean, and Environment, University of Delaware, Newark, DE 19716 USA
[3] Integrated Science and Engineering, College of Earth, Ocean, and Environment, University of Delaware, Newark, DE 19716 USA
[4] McCoy Energy Consulting, LLC, Western Springs, IL 60558 USA
[5] Atlantic Grid Development, LLC, Silver Spring, MD 20910 USA

CORRESPONDING AUTHOR: E. APOSTOLAKI-IOSIFIDOU (elpiniki.apostolaki@gmail.com)

This work was supported by the US Department of Energy, grant DE-EE0005366, Mid-Atlantic Offshore Wind Integration & Transmission (MAOWIT), with W. Kempton as Principal Investigator. Publication made possible in part by support from the Berkeley Research Impact Initiative (BRII) sponsored by the UC Berkeley Library.

ABSTRACT The offshore wind resource is very large in many coastal regions, over 80,000 MW capacity in the region studied here. However, the resource cannot be utilized unless distant offshore wind generation can be effectively collected and brought to shore. Based on extensive oceanographic, environmental, and shipping data, a realistic wind energy deployment layout is designed with 160 wind power plants each 500 MW. The power collection and transmission infrastructure required to bring this power to shore and connect it to the electricity grid is designed and analyzed. Three types of connection to shore are compared; high voltage AC to the nearest onshore point of interconnection (POI), high voltage DC with voltage-source converter (HVDC-VSC) to the nearest onshore POI, and connecting to an offshore HVDC backbone running parallel to shore that interconnects multiple wind power plants and multiple POIs ashore. The electrical transmission losses are estimated step by step from the wind turbines to the POI. The results show that such a large system can be built with existing technology in near-load resources, and that losses in the HVDC-VSC systems are approximately 1%–2% lower than that in the AC system for a distance about 120 km from shore.

INDEX TERMS Power system interconnection, transmission losses, high-voltage alternating current (HVAC), high-voltage direct current (HVDC), offshore wind power, transmission design.

I. INTRODUCTION

Interest in offshore wind power is growing worldwide due to environmental and energy security concerns and rapidly declining price. The leading world region, Europe, had built 11,027 MW capacity of 84 offshore wind power plants by 2015 [1]. The resource in U.S. waters has been shown to be very large. For example, in the shallow Atlantic waters of the Northeast, proximate to large load centers, offshore wind could provide all the electricity now consumed by all Northeast coastal states three times over [2]. Although only one 30 MW US commercial offshore wind power plant is in operation as we write in 2017 [3], another 450 MW of capacity are contracted and recent state commitments by MA and NY will add an additional 5,000 MW over the next 12 years [4], [5]. Yet there is no plan for the electrical collection and transmission systems that might make most sense for such large builds. Rather, to date, planning has been based on each individual offshore wind power plant, independently linking to the nearest point of interconnection (POI) on land.

This paper begins with an estimate of the resource in the Atlantic Ocean adjacent to the Transmission System Operator (TSO) named PJM Interconnection (hence PJM), the largest US TSO in terms of peak load.[1] After a detailed

[1] In the US, TSOs are referred to as Regional Transmission Operator (RTO) or Independent System Operators (ISO). In this paper, the term TSO is used.

analysis of ocean uses and depths to establish areas available and an hourly wind speed analysis over four years, a layout of individual wind power plants is proposed, power output is calculated, and alternatives for electrical interconnection are designed to collect the power and bring it to the shore. The authors include both academic wind power analysts and experienced designers and planners from the wind and transmission industries.

In this paper, three transmission scenarios are compared; 1) using high-voltage alternating current (HVAC), 2) using high-voltage direct current with Voltage-Source Converter (HVDC-VSC), and 3) using a combination of HVAC and HVDC-VSC assuming an HVDC cable that runs parallel to the coastline. The transmission cable assumed on the third scenario creates a structure with several offshore wind projects connected to a straight run, like ribs connected to a backbone. Connecting wind output over 1,000 km north-south along this coast, using a backbone structure, has been shown to greatly reduce offshore wind fluctuations [6]. Commercially, Atlantic Wind Connection, LLC (AWC) has designed and proposed such structures including HVDC backbone for the U.S. Mid-Atlantic [7]. In the third scenario, this HVDC cable is considered as part of the electric power transmission, so it becomes the POI.

The contributions of the paper include the following: a) A realistic ocean space was used, b) wind power installation almost eighty times larger than any previous study or design was considered, c) the transmission infrastructure design and the academic analysis were conducted in collaboration with designers and planners from the wind and transmission industries, and d) an HVDC cable, backbone, running parallel to shore is considered as part of the grid; to the best of our knowledge there are no previous studies that considers such a configuration.

The outline of the paper is as follows. Section II is a literature review, and Section III is a description of the wind power plant design, including the wind power plant layout and its transmission infrastructure. Section IV presents the methodology used for the electrical loss calculation of the transmission infrastructure. The results are described in section V, while conclusions are presented in section VI.

II. LITERATURE REVIEW

In the past, most offshore wind farms were connected to the onshore grid via HVAC cables. As offshore wind power plants continue to increase in scale and are located further from shore, designs with HVDC transmission potentially become optimal because of those longer distances and higher power levels [8]. According to a 2014 review on challenges and opportunities in development of offshore wind power [9], HVDC transmission systems are more attractive and efficient compared to HVAC system, especially when transmitting large amount of power in distances over 50 km - 100 km. A more recent review concludes that an HVDC line (bipolar or tripolar) can transmit from 1.80 to 2.24 more power compared to the AC line in each case [10]. Another study of grid interconnection of offshore wind power plants states that HVDC offers the following advantages for long distances (>50 km) [11]:

- power flow is fully controlled,
- AC faults are not transferred to the rest of the network,
- there are no issues of cable charging currents, which for AC cables reduce the active power rating, and
- DC cable power losses are less.

Several studies have been conducted to compare HVAC and HVDC transmission systems for hypothetical offshore wind power plants with somewhat different conclusions. In [12], HVAC and HVDC interconnections are compared based on transmission fault simulations in an offshore wind power plant of 184 MW. All systems recover from a 100 ms fault, however, during a 625 ms fault the HVAC system was not able to recover, giving an advantage to HVDC [12]. In [13], wind power plants of 100 MW, 200 MW, and 500 MW are compared with three transmission connection systems, including HVAC and HVDC. This study found that HVDC is more economical than HVAC for distances more than 90 km, for a 100 MW wind power plant [13]. Another study makes a comparison between HVAC and HVDC [14], with different distance cutoffs. This concludes that HVAC is a better choice for wind power plants less than 300 MW unless very long distances are considered (>200 km) [14]. For more than 300 MW, this study finds the HVDC solution more feasible with critical distances between the range of 40 km - 60 km (depending on wind farm capacity) [14]. Similarly, in [15], HVAC and HVDC are compared, concluding that for a 400 MW wind power plant HVDC is less expensive if the distance from the shore is more than 52 km. Another study calculates the economic decision threshold between HVDC-VSC and HVAC for a 300 MW offshore wind farm in two different investment scenarios. If the investor for the transmission infrastructure and the wind turbines is a different party (this is the most common scenario), HVAC is preferable for cable lengths shorter than 80 km and HVDC-VSC for longer cables. If the investor for the transmission infrastructure and the wind turbines is the same entity, HVDC-VSC is chosen for 35 km and higher cable lengths [16].

In [17], HVAC and HVDC system losses are compared, using a wind power plant of 117 MW capacity. This study finds that the HVAC transmission loss is 12% more for distance to shore of 150 km, a large penalty in electric losses [17]. A recent study using forward-looking designs calculates the losses of offshore wind power plants for three different transmission topologies: HVAC, HVDC with a Line-Commutated Converter (HVDC-LCC) and HVDC-VSC [18]. The wind farm sizes are 500 MW and 1,000 MW and the distances from the shore are 50 km, 100 km, 150 km, and 200 km [18]. The losses were calculated for different submarine cable and converter station ratings. The losses for a 500 MW wind farm with 200 km distance to shore, can reach almost 18% for the HVAC scenario (1 × 400 kV cable) compared with only 6% for the HVDC-VSC scenario (500 MW converter station) [18].

For a 1,000 MW wind farm, the maximum losses are slightly less; they can reach about 15% for the HVAC (2×400 kV cables) and 5.5% for the HVDC-VSC (2×500 MW converter stations) [18]. The HVDC-LCC has less losses compared to the HVDC-VSC, with both having significantly less loss than HVAC. Lastly, a 2015 study on transmission losses of offshore wind farms presents transmission losses under steady state for a 640 MW offshore wind farm for distances 50, 100, and 159 km [19]. HVAC cables are the main contributors to the total losses in the HVAC configuration [19]. In the HVDC configuration, the converters represent almost all of the total losses [19].

Older studies analyze wind power plant capacities up to 1,000 MW. However, as of 2018, the largest offshore wind power plant in operation is 659 MW and the whole clusters of farms in the same installation reach 1,000 MW [20]. Since previous studies consider installations almost eighty times smaller than today's new designs, we felt an updated, larger study was needed.

When transmission is designed in advance for a cluster of wind power plants, the literature suggests that HVDC may be preferred; here we propose that an integrated transmission topology solution may be optimal as compared to each project being developed separately and incrementally over time. Moreover, all prior studies refer to hypothetical distances and wind farm layouts, whereas this study is based on real ocean space configurations and thus the conclusions may also be of more practical application. Lastly, we do not find in literature HVDC backbone configurations.

In this study, a realistic ocean space to lay out a very large-scale offshore wind installation is analyzed, almost eighty times larger than any prior studies or designs. Three electrical infrastructure solutions to transfer the power from the offshore wind power plant to shore are designed. The transmission losses of all the system components including substations, converters, cables, are calculated and presented in electrical power. The calculations include the entire installation from the wind turbines to the POI.

III. WIND POWER PLANT DESIGN

A. OFFSHORE WIND POWER PLANT LAYOUT

The offshore wind resource analyzed here is located in the ocean adjacent to the PJM territory. Wind development is suggested only where consistent with water depths, environmental parameters, and lack of conflicts with other human use, per an earlier analysis [21]. The area is delimited by 8 km from shore to minimize visual impact [22], and no more than 60 m of water depth, to accommodate current and near-term bottom-mounted technology. Based on a Weather Research and Forecasting model, the hourly wind speeds at hub height throughout all the non-excluded areas were estimated, providing high spatial and time resolution of wind speeds throughout the region [23].

In an actual buildout, agencies may exclude some areas that are not excluded in these assumptions, resulting in smaller areas than in this analysis. On the other hand, building closer to shore or using floating structures beyond 60 m depth would increase the estimated potential resource. Nevertheless, as a review of prior offshore wind resource demonstrates, the methods used here are much more accurate than prior estimates of the offshore wind resource, most of which surprisingly do not use detailed estimates of either exclusions or water depth. A map of exclusion areas [21] and remaining potential wind resource areas can be seen in Fig. 1. This figure also shows a proposed HVDC transmission line by AWC [7] running through the area that will be discussed later in the paper.

FIGURE 1. Potential wind power plant development areas. Green Areas: offshore wind power plants up to 60 m water depth and excluding use conflicts [17] [24]. Black Lines: HVDC backbone proposed by Atlantic Wind Connection, LLC [7], with Point of Interconnections (POIs) shown as dots.

Two other studies analyze different aspects of the offshore build-out developed in this article, using our results. In the first, differing build-out levels are used to evaluate how much offshore wind power can be integrated into PJM, under varying assumptions [23]. The second [25] finds that the multipoint HVDC backbone with multiple POIs on land has a significant dispatch advantage over direct connection to each POI. The converter station(s) at each POI of the HVDC backbone can be separately controlled to inject a needed amount at that point in the network. The present article analyzes the offshore grid itself, and was used in the other two studies [23], [25].

The Mid-Atlantic Ocean adjacent to PJM contains approximately 24,700 km^2 of available space for bottom-mounted offshore wind power development. The available area is divided into clusters of wind power plants. Each power plant has capacity 500 MW (100×5 MW turbines). Fig. 2 illustrates the base layout analysis configuration, 10 rows of 10 turbines, spaced 10 rotor diameters apart in each direction (10Dx10D). Development of the entire region is treated as a hypothetical sequential build-out, ordered from nearer-shore to further away from shore. The wind speed at

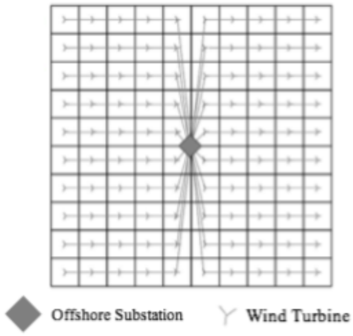

FIGURE 2. Wind power plant layout of 500 MW capacity (100 turbines ×5 MW).

the center of each plant is used for power calculations. The total capacity for the whole region, given itemized exclusions, is about 80 GW. As we finalize this article, typical offshore turbine sizes have grown from 5 MW to 8 or 12 MW; however, as spacing is a function of rotor diameter, larger turbines have minimal effect on the power capacity in GW of a given ocean area in km^2 [2].

Rotor spacing is an optimization tradeoff for which greater spacing reduces wake at the downstream turbine and thus increases the energy produced, but greater spacing also consumes more ocean space per MW capacity. For example, to reduce array losses to less than 10%, in a location with prevailing winds from a single direction, suggested spacing is 8 to 10 rotor diameters apart in the direction of the prevailing wind and 5 rotor diameters apart in the crosswind direction [26]. A similar rule of thumb, based on velocity, is that the ratio of original velocity to downwind one is between 80% and 90% for distances of 10 and 15 rotor diameters [27].

In this region, prevailing winds are out of northwest or southwest, thus the turbine alignment should minimize wake losses in these directions. Because prevailing winds are from two directions, 90 degrees apart, a simple pattern of rows perpendicular to the wind does not apply. Here a square pattern aligned north-south is suggested, as it maximizes wake recovery time along both diagonals in a square of 10 × 10. The diagonals are 14 rotor diameters apart. The basic layout shape shown in Fig. 2. An offshore AC substation is placed in the middle of each wind power plant (Figs. 2). The location of the substation was a design decision to achieve reliability and reduce the length and power flow for each one array cable.

The wind power plants are clustered in groups of 2, 4, and 9 depending on the location's available space. These clusters are assumed to populate the available area for offshore wind energy development in the Mid-Atlantic. The layout of the wind power plants is the same for all scenarios of electrical transmission infrastructure presented later in this paper. This is an illustrative layout to calculate losses. In an actual build-out, shapes of individual wind power plants would vary, and actual cable layouts would use more rigorous optimization such as [27]. The capacity factor is conservatively assumed at 35%.

B. ELECTRICAL INFRASTRUCTURE

In Fig. 2, the transmission cable layout is shown within each wind power plant. Five turbines in each row are connected to the same cable. By connecting five wind turbines to the same cable instead of ten, higher reliability is achieved, a smaller cable is required, and, in case of a single fault anywhere in the row, less generation will be lost. The interconnection cable voltage is 35 kV, 3-phase, a typical cable today. For the coming generation of 8- to 12-MW offshore turbines, higher voltages, such as 65 kV or 69 kV will be optimal for array cables.

Each wind power plant contains one offshore platform in the center of the plant with a 35 kV/230 kV substation system. Twenty feeders of 35 kV are connected to each substation. According to an ABB study [28], by installing one substation platform per wind power plant, instead of using a single platform for multiple wind power plants, ''single point of failure'' is avoided. In case one platform is shut down, only 500 MW will be lost.

After the turbines and collectors to the offshore AC substation (35 kV to 230 kV), we analyze three different scenarios, 1) HVAC To Shore POI, 2) HVDC-VSC to shore POI, and 3) HVAC to HVDC-VSC offshore backbone. These are modeled and explained below. Note that in all scenarios, all electrical components, substations and converters, are designed for storm conditions in the area installed.

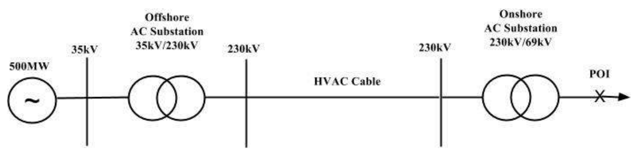

FIGURE 3. One line diagram for the connection of one wind power plant in the HVAC to Shore POI scenario.

1) HVAC TO SHORE POI

In this scenario, Fig. 3, the wind power plants, after the first offshore AC substation, are connected to an onshore AC substation with 230 kV HVAC cables. According to an ABB study [28] and power engineering collaborators, HVAC at 230 kV is an economically feasible option for US systems. Choosing a lower kV rate would increase current, as a result ohmic losses. Choosing a higher rate, e.g. 550 kV would result in more capacitive reactive power making this option less practical [28]. The use of a 230 kV submarine cable was confirmed based on the maximum power generation, the current rate and the cable specifications.

For this design, an HVAC 230 kV submarine cable is installed from the offshore AC substations to the shore, where it changes to an onshore underground 230 kV cable until reaching the onshore substation. The onshore HVAC cables are modeled to connect to the PJM interconnection points close to the cities of New York, Philadelphia, Annapolis, and Norfolk, with an onshore AC substation which steps down to local high voltage, in this model, the onshore AC substation

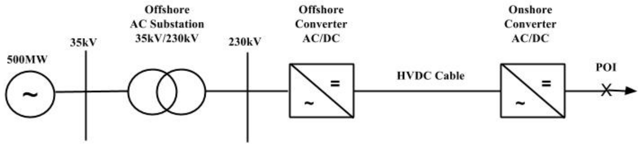

FIGURE 4. **One line diagram for the connection of one wind power plant in the HVDC-VSC to Shore POI scenario.**

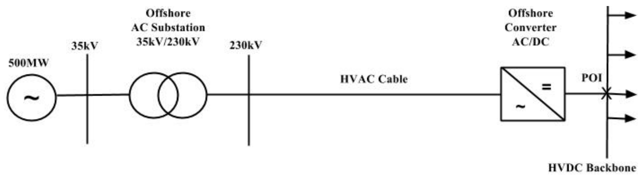

FIGURE 5. **One line diagram for the connection of one wind power plant in the HVAC to HVDC-VSC offshore backbone scenario. Note that two wind power plants are connected to each converter station.**

transforms the 230 kV voltage to a lower voltage, corresponding to the POI grid (e.g. to 69 kV). The POI is assumed to be just after the onshore substation. This scenario's one line diagram for one wind power plant connection is shown in Fig. 3.

2) HVDC-VSC TO SHORE POI

In this configuration, Fig. 4, the wind power plants, after the offshore AC substation (35/230 kV), are connected to an offshore converter via AC transmission cables of 230 kV. As described by ABB [28], the collector system is still an AC system. The voltage is stepped up to 230 kV and connected to HVDC-VSC converter.

The rating of each converter is assumed approximately 1,000 MW [28], therefore two wind power plants are connected per converter. Two poles of HVDC cables, one +320 kV and one −320 kV per converter station, carry power to an onshore converter station. The maximum power generation and current rate were compared with the specifications of the HVDC submarine cable to confirm that the 320 kV is appropriate.

The POI is assumed to be just after the onshore converter station. This scenario's one line diagram for one wind power plant is shown Fig. 4.

3) HVAC TO HVDC-VSC OFFSHORE BACKBONE

In this configuration, Fig. 5, the offshore 230 kV cable connects an AC-DC converter station located on the HVDC backbone, running along the coast. Again, there is one converter station per two wind power plants, because the converter maximum capacity is 1,000 MW [28]. The converter stations are located on the HVDC backbone, thus the step up to 320 kV need not to be aligned with the connection to the POI ashore. For the 2-plant configuration, one converter station is used. For the 4-plant configuration, two converter stations are used. For the 9-plant configuration, five converter stations are used. The POI is assumed to be just after the backbone converter station. The one-line diagram is shown in Fig. 5.

Although the comparison of one-line diagrams of scenarios 1 and 2 is a simple substitution of DC for AC for the high voltage transmission to shore, in one-line diagram of scenario 3 the HVDC cable is quite different because it allows movement of high power north-south along the line with very low losses. This was illustrated in the map of Fig. 1, showing one layout for such a system, the planned Atlantic Wind Connection (AWC) [7]. Atlantic Wind Connection: Grid Resiliency, Its Economic and Security Impacts, and the Implications of AWC, overlaid on our areas in which offshore wind power plants could be built. Whether this line is built in precisely these locations or not, this analysis uses the AWC line for an HVAC-HVDC system that has gone through detailed electrical planning. The AWC capacity would be far less than the total build-out of the 80 GW resource calculated here, and as the figure shows, it is aligned more to serve the shallower, closer to shore wind areas. This could be expanded in the future with additional lines going through the outer wind energy areas.

From the backbone, HVDC offshore submarine cables are assumed to be installed. The AWC HVDC cable is proposed to be a symmetrical monopole, that is, there is a plus and a minus conductor, with voltage of ±320 kV. There is no ground return. For this configuration though the losses are calculated up to the backbone converter.

IV. METHODOLOGY

A. AC CABLE LOSSES

As described by [29], losses can be analyzed as active losses and reactive losses. Active losses include ohmic and dielectric losses while reactive losses include capacitive and inductive losses [29]. Cable ohmic losses are calculated using the power equation as follows [29]:

$$P_{ohmic} = n_{cables} \times n_{phases} \times I_{rated}^2 \times R \tag{1}$$

I_{rated} is the current running through the one phase and R is the resistance of the cable. The number of phases, n_{phases}, and the number of cables, n_{cables}, per phases are also considered in this equation. The current through one phase, rated current, is calculated by using the formula:

$$I_{rated} = \frac{P}{V \times \sqrt{3}} \tag{2}$$

where I_{rated} is the rated current, P is the power and V is the nominal voltage. The power (P) used in (2) is calculated as the 35% capacity factor times the 500 MW wind power plant capacity times the number of wind power plants per cluster.

When calculating the cable losses within the wind power plant (35 kV), only the ohmic losses are considered. As noted above this provides an approximation due to small distances, with far less calculation effort. A simpler ohmic loss calculation is used because, for short cable lengths ohmic losses can give an approximation likely to be no less than 1/2 the actual value. Given the large size of this proposed build-out, the owners may well seek to optimize cable sizes within wind power plant collector systems. That is, the cable furthest from the step-up platform would be smaller and increase in size as each segment between turbines got closer to the platform. Smaller cable would have higher ohmic losses but the current flowing through them would be much smaller, and $I^2 \times R$ would be much smaller yet. Thus, the use of ohmic losses only is a reasonable approximation for the MV collector system.

For within the wind power plant, the losses were calculated for each connection individually, as transmission losses vary across each row and increase as each additional wind turbine is connected to the 35 kV cable. The total cable length within one wind power plant is about 165 km. Therefore, the cables needed within the power plant to connect the wind turbines with the substations are 330 km, 660 km and 1485 km for the 2-, 4- and 9-plant respectively.

After the substation 35/230 kV, cables are rated for 230 kV. For those, the formulas (1) and (2) are applied for the ohmic losses. Due to the high voltage, the 230 kV cable is treated as an insulated cable, and not as an ohmic resistance. The dielectric insulation behaves as capacitor, and each time the voltage direction changes, the electric dipoles are realigned resulting in losses. This loss is known as dielectric, $P_{dielectric}$ (W/m) and calculated as follows [29]:

$$P_{dielectric} = n_{cables} \times n_{phases} \times \pi f \times tan\delta \times (\frac{V_{rms}}{\sqrt{3}})^2 \quad (3)$$

where C is the cable capacity [F], f is the frequency [Hz], V_{rms} is the voltage rms [V] and $tan\delta$ is the insulation loss factor, typically around 0.004. The reactive component causes charging current, which increases with cable distance due to the cable capacitive and inductive elements. The following formulas are used for the charging current (i_c) and loss calculations [29].

$$i_c = \frac{q_{tot}}{\sqrt{3} \times V_{rms} \times n_{cables}} \quad (4)$$

$$P^{charging}_{Ohmic,HVACtot} = \int_0^{d_{tot}} n_{cables} \times 3l^2 \frac{{i_c}^2}{4} \times R_{ac} dl$$

$$= \frac{3 \times n_{cables} \times R_{ac} \times {i_c}^2}{12} dtot^3 \quad (5)$$

where q_{tot} is total reactive power generated by the cables [VAr], d_{tot}: is the total distance after integration of variable l and R_{ac}: is the ac resistance $[\Omega/km]$.

The total reactive power generated by the cables q_{tot}, is calculated as follows [29]:

$$q_{tot} = |q_L - q_C| \quad (6)$$

where q_L is the reactive power produced by inductive effects [VAr] and q_C is the reactive power produced by capacitive effects [VAr]. The formulas of these can be found at [29].

Another way reactive losses are captured is in the capital cost of the network as the AC export cables are commonly compensated at shore with inductors to mitigate effects on the shore network and to hold down the cable voltages. Long export cables may also need inductance installed on the offshore AC platform. This drives up capital costs and would be captured in the design's fixed costs.

TABLE 1. AC cable 230 kV parameters.

Voltage (kV)	Current rating (A)	Capacitance (μF/km)	Resistance (Ohm/km)	Charging Current (A/km)
230	825	0.19	0.0335	7.4

TABLE 2. DC cable 320 kV parameters.

Voltage (kV)	Current rating (A)	Resistance (Ohm/km)
320	1720	0.0140

Regarding 230 kV losses, bundles of three conductors per phase are assumed for each 500 MW wind power plant. As described above, cable ohmic losses, dielectric losses and charging current losses are calculated. Table 1 shows the HVAC loss calculation parameters used in this study [30].

B. AC SUBSTATION LOSSES

The transformer losses consist of iron losses (non-load losses) and copper losses (load losses). The rule of thumb the industry uses as a value for the substation loss is 0.1% of the input power entering the substation. In this study, a conservative loss of 0.4% which is 99.6% efficiency (0.2% non-load losses and 0.2% load losses) is considered [29].

C. AC/DC AND DC/AC CONVERTER LOSSES

At the HVDC-VSC to shore POI scenario, two converter stations are used (offshore AC/DC and onshore DC/AC). Each converter station serves two wind power plants (1,000 MW). The converter no-load and load losses are 1.3% of the rated power (no load and load 0.1% and 1.2% respectively) [31]. Different arrangements such as the Cascaded Two Level (CTL) converters have total losses even less than 1% [32]. Losses used are based on VSC converter. The estimates for converter losses presented here include all losses associated with conversion. The comparison between HVDC-LCC and HVDC-VSC is out of scope of this study.

D. DC CABLE LOSSES

The HVDC losses include only the ohmic loss component. This is calculated using Formula (1). The power rate per cable is approximately 1,000 MW. Based on this limit the appropriate number of cables per pole is used, and the losses are calculated accordingly. The parameters are shown in Table 2 [33]:

V. RESULTS

A. TRANSMISSION LOSSES

The losses for the HVAC to Shore POI scenario are presented at Table 3. For the distances to the shore, an average is assumed for each case of 2-, 4- and 9-plant installation based

TABLE 3. HVAC to SHORE POI losses (Scenario 1).

Power capacity (MW)	Interconnection losses (%)	Losses at 36/230kV substation (%)	Losses at 230kV HVAC cable (%)	Losses at onshore substation (%)	Average distance from POI (km)	Total transmission losses (%)
1000	0.068	0.400	3.740	0.400	117.3	4.57
2000	0.068	0.400	3.453	0.400	113.7	4.29
4500	0.068	0.400	4.692	0.400	137.3	5.52

TABLE 4. HVDC-VSC to shore POI losses (Scenario 2).

Power capacity (MW)	Interconnection losses (%)	Losses at 36/230kV substation (%)	Losses at 230kV HVAC cable (%)	Losses at AC/DC converter (%)	Losses at 320kV HVDC cable (%)	Losses at onshore converter (%)	Average distance from POI (km)	Total transmission losses (%)
1000	0.068	0.400	0.204	1.309	0.286	1.330	117.3	3.55
2000	0.068	0.400	0.333	1.310	0.277	1.332	113.7	3.67
4500	0.068	0.400	0.513	1.312	0.303	1.334	137.3	3.87

TABLE 5. HVAC to HVDC-VSC offshore backbone losses (Scenario 3).

Power capacity (MW)	Interconnection losses (%)	Losses at 36/230kV substation (%)	Losses at 230kV HVAC cable (%)	Losses at backbone converter (%)	Average distance from POI (km)	Total transmission losses (%)
1000	0.068	0.400	0.447	1.312	10.6	2.21
2000	0.068	0.400	0.682	1.315	16.2	2.45
4500	0.068	0.400	1.065	1.320	25.2	2.83

on the layout proposed. The transmission losses to the shore are about 4.3% - 5.5%, while most of the losses occur at the 230 kV HVAC cable. For the HVDC-VSC to Shore POI scenario, the results are shown in Table 4. The transmission losses from the wind power plants to the onshore converter are approximately 3.6% to 3.9%. The losses for the HVAC to HVDC-VSC offshore backbone scenario are presented in Table 5. An average distance from to the converter stations of the HVDC backbone of each configuration is assumed. The transmission losses are between 2.2% and 2.8%.

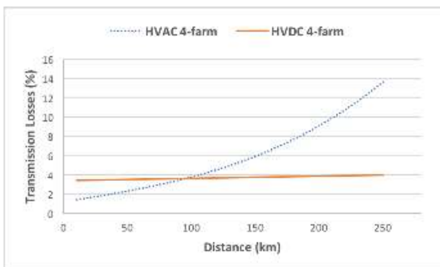

FIGURE 6. HVAC and HVDC-VSC transmission losses for 4-plant layout, 1,000 MW, for different distances.

B. COMPARISON BETWEEN SYSTEMS

The study analyzes three configurations in real ocean space. For the first two scenarios the distances to the POI are equal and HVDC-VSC is more efficient. In the third scenario, with an HVDC-VSC backbone transmission line assumed to be part of the electric grid, the losses are approximately 2.5%. If we add about 1% for eventual converter losses ashore (plus a small amount of DC line losses), the two DC configurations are of about equal efficiency. The two HVDC systems are a little more efficient at the distances of this offshore resource.

A comparison between the first two scenarios for 4-plant layout is presented in Fig. 6 for distances between 10 km and 250 km from the POI. The efficiency crossover distance is 95 km. The results were similar for 2- and 9-plant layouts.

For HVAC, Fig. 7 shows the losses of the different HVAC layouts for distances from 10 km to 250 km. Losses become quite large for longer distances. Losses are similar for different capacities.

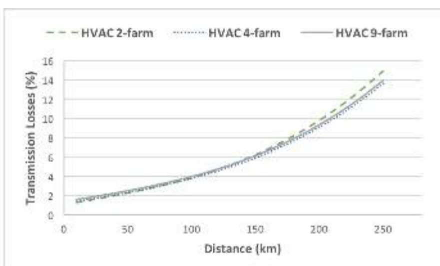

FIGURE 7. HVAC transmission losses for 2-, 4- and 9-plant layouts.

For HVDC-VSC systems (Fig. 8), the distance plays a minor role, since the HVDC cable losses are so low that they do not show a noticeable increase with distance, as compared with converter losses or HVAC losses.

Four additional factors would be considered in an actual choice among these transmission systems. First, cost was

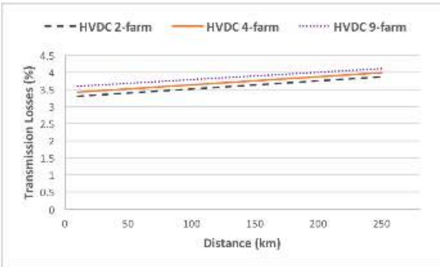

FIGURE 8. HVDC-VSC transmission losses for 2-, 4- and 9-plant layouts.

TABLE 6. Power output at POI of the 80GW wind power plant installation.

Capacity Installed (MW)	HVAC (MW)	HVDC-VSC (MW)	HVAC to HVDC-VSC to Backbone (MW)
80000	26603	26942	27257

not analyzed here but is significantly more for HVDC-VSC systems, so a project analyst could use the losses in this article and net the efficiency savings against higher capital cost. Second, the HVDC backbone is only practical with an HVDC system, due to both charging currents and losses over longer distances, which leads to two further considerations. Third, the HVDC backbone has a demonstrated advantage of considerable smoothing of power output, although that has been demonstrated only for longer distances [6] than the shorter PJM coast analyzed here [23]. Fourth, another advantage of a backbone based on multi-terminal HVDC is that each POI to shore can be dispatched independently as if it were a separate power plant. This independent dispatch at the shoreside POI enables considerable improvement in the ability to integrate large amounts of wind power by matching wind power plant output to local electric network needs [25].

Given these multiple considerations of cost, efficiency, wind smoothing and improved integration, a cost versus benefits comparison of these systems is beyond the scope of this analysis. Rather, we have provided a plausible system topology and equipment needed, for an offshore wind transmission system much larger than any currently designed or studied. We also have calculated efficiency losses to define the scope of the problem and provide a basis for future analyses such us [23], [25].

The comparison of results in power transmitted by the whole installation are shown in table 6. The difference in output between HVAC and HVDC-VSC is about 300 MW, while between HVAC and HVAC to HVDC-VSC to Backbone about 600 MW. The two HVDC systems are better than the HVAC, with the backbone system output approximately 300 MW higher than the HVDC-VSC.

C. RESULT VALIDATION

The above results are consistent with previous related work. More specifically, [17] finds HVAC losses about 5% and 19% for distances 50 km and 150 km respectively, however the results are for a small-scale wind power plant of 117 MW capacity. For the same wind power plant, the HVDC losses are approximately 4.5% [17]. According to [34], configurations of 1,000 MW wind power plants using HVAC show losses in the range of 1.3% (50 km) to 7.3% (200 km), while when using HVDC only, the losses are from 2.4% (50 km) to 3.3% (200 km). Lastly, the study [16] finds that for a 1,000 MW wind farm, using 2×220 kV AC cables, the losses are 1.96% for 50 km and 7.58% for 200 km. For the HVDC-VSC scenario, for a 1,000 MW wind farm, the losses are approximately 4% and 5.5% for 50 km and 200 km respectively [18].

The HVAC and HVDC results from our analysis are consistent with the losses from above studies, however, we believe that no prior work compares standard topologies to a backbone, running parallel to shore as part of the grid, nor have prior works analyzed a realistic resource of this scale.

VI. CONCLUSION

This study uses a more careful mapping with an advanced meteorological model for more precise wind speeds, and considers ocean use conflicts, to produce a map of the offshore wind resource adjacent to PJM. This article analyzes a set of potential wind power plants, including areas not yet permitted but potential given water depths and minimizing other use conflicts, for a total of 80 GW capacity. In this study sample wind power plant configurations are designed, along with the system of cables and transformers that would carry power to shore. From the specified cables and converters, the power loss from an HVAC, an HVDC-VSC and an HVAC to HVDC-VSC offshore backbone transmission system is calculated in detail. The two HVDC-VSC solutions have fewer losses at the distances of the system analyzed here.

To summarize the contributions of this study, a realistic ocean space available for development is analyzed, using real distances from the wind power plants to the POIs. Three different transmission scenarios, HVAC to shore POI, HVDC-VSC to shore POI and HVAC to HVDC-VSC to offshore backbone are compared. The lattermost allows large-scale developments of offshore wind power plants and can be technically superior, but only makes sense when analyzed at a scale greater than a single project. If project design is done one at a time by each developer, an HVDC backbone would never make sense. Although this work focuses on a case of a large-scale offshore wind build-out in the US, this approach and methodology can be adapted to any location. This study is a result of academia and industry collaboration, includes a plausible topology, equipment needed, and transmission loss analysis, and provides a practical basis for future analysis.

ACKNOWLEDGMENT

Thanks to Scott Baker and Blaise Sheridan for the ocean space analysis underlying Figs. 1 and 6. Thanks to Mike Dvorak of Sailor's Energy for setting up and running the WRF models, and to Dr. Yiannis Perivolaris for the advice on the solution approach.

REFERENCES

[1] EWEA. (2016). *The European Offshore Wind Industry—Key Trends and Statistics 2015*. [Online]. Available: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-European-Offshore-Statistics-2015.pdf

[2] W. Kempton, C. L. Archer, A. Dhanju, R. W. Garvine, and M. Z. Jacobson, "Large CO_2 reductions via offshore wind power matched to inherent storage in energy end-uses," *Geophys. Res. Lett.*, vol. 34, 2007, Art. no. L02817. doi: 10.1029/2006GL028016.

[3] Deepwater Wind. (2017). *Block Island Wind Power Plant. America's First Offshore Wind power Plant*. [Online]. Available: http://dwwind.com/project/block-island-wind-farm/

[4] C. Harvey. (2016). Massachusetts just gave a huge boost to the offshore wind industry. Washington Post. [Online]. Available: https://www.washingtonpost.com/news/energy-environment/wp/2016/08/08/at-long-last-the-u-s-offshore-wind-industry-is-ramping-up/?utm_term=.0f082b6e627d

[5] K. E. Stromsta. (2017). *New York Unveils 2.4GW Offshore Wind Target for 2030*. [Online]. Available: http://www.rechargenews.com/wind/1205484/new-york-unveils-24gw-offshore-wind-target-for-2030

[6] W. Kempton, F. M. Pimenta, D. E. Veron, and B. A. Colle, "Electric power from offshore wind via synoptic-scale interconnection," *Proc. Nat. Acad. Sci. USA*, vol. 107, no. 16, pp. 7240–7245, Apr. 2010. doi: 10.1073/pnas.0909075107.

[7] Atlantic Wind Connection, Grid Resiliency. *Its Economic and Security Impacts, and the Implications of AWC*. Accessed: Apr. 1, 2017. [Online]. Available: http://atlanticwindconnection.com/projects/

[8] H. Ahmad, S. Coppens, and B. Uzunoglu, "Connection of an offshore wind park to HVDC converter platform without using offshore AC collector platforms," in *Proc. Green Technol. Conf.*, Apr. 2013, pp. 400–406. doi: 10.1109/GreenTech.2013.68.

[9] R. Perveen, N. Kishor, and S. R. Mohanty, "Off-shore wind farm development: Present status and challenges," *Reneable Sustain. Energy Rev.*, vol. 29, pp. 780–792, Jan. 2014. doi: 10.1016/j.rser.2013.08.108

[10] A. Kalair, N. Abas, and N. Khan, "Comparative study of HVAC and HVDC transmission systems," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1653–1675, Jun. 2016. doi: 10.1016/j.rser.2015.12.288.

[11] L. Xu and B. R. Andersen, "Grid connection of large offshore wind farms using HVDC," *Wind Energy*, vol. 9, no. 4, pp. 371–382, 2006. doi: 10.1002/we.185.

[12] A. Reidy and R. Watson, "Comparison of VSC based HVDC and HVAC interconnections to a large offshore wind farm," in *Proc. IEEE Power Eng. Society Gen. Meeting*, vol. 1, Jun. 2005, pp. 1–8. doi: 10.1109/PES.2005.1489081.

[13] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, R, "HVDC connection of offshore wind farms to the transmission system," *IEEE Trans. Energy Convers.* vol. 22, no. 1, pp. 37–43, Mar. 2007. doi: 10.1109/TEC.2006.889624.

[14] J. Machado, M. V. Neves, and P. J. Santos, "Economic limitations of the HVAC transmission system when applied to offshore wind farms," in *Proc. 9th Int. Conf. Compat. Power Electron. (CPE)*, Jun. 2015, pp. 69–75. doi: 10.1109/CPE.2015.7231051.

[15] G. F. Reed, H. A. Al Hassan, M. J. Korytowski, P. T. Lewis, and B. M. Grainger, "Comparison of HVAC and HVDC solutions for offshore wind farms with a procedure for system economic evaluation," in *Proc. IEEE Energytech*, May 2013, pp. 1–7.

[16] B. Van Eeckhout, D. Van Hertem, M. Reza, K. Srivastava, and R. Belmans, "Economic comparison of VSC HVDC and HVAC as transmission system for a 300 MW offshore wind farm," *Eur. Trans. Elect. Power*, vol. 20, no. 5, pp. 661–671, 2010. doi: 10.1002/etep.359.

[17] T. W. May, Y. M. Yeap, and A. Ukil, "Comparative evaluation of power loss in HVAC and HVDC transmission systems," in *Proc. IEEE Region 10 Conf. (TENCON)*, Nov. 2016, pp. 637–641. doi: 10.1109/TENCON.2016.7848080.

[18] N. B. Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms," *Electr. Power Syst. Res.*, vol. 76, no. 11, pp. 916–927, 2006. doi: 10.1016/j.epsr.2005.11.004.

[19] A. Papadopoulos, S. Rodrigues, E. Kontos, T. Todorcevic, P. Bauer, and R. T. Pinto, "Collection and transmission losses of offshore wind farms for optimization purposes," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Montreal, QC, Canada, Sep. 2015, pp. 6724–6732. doi: 10.1109/ECCE.2015.7310601.

[20] Orsted-Walney Extension. *Walney Extension, Green Electricity From the World's Biggest Offshore Wind Farm*. Accessed: 2018. [Online]. Available: https://walneyextension.co.uk/en

[21] S. Baker, "The atlantic offshore wind power potential in PJM: A regional offshore wind power resource assessment," M.S. thesis, Dept. Marine Studies, Univ. Delaware, Newark, DE, USA, 2011.

[22] R. G. Sullivan *et al.*, "Wind turbine visibility and visual impact threshold distances in western landscapes," in *Proc. 37th Annu. Conf. Nat. Assoc. Environ. Professionals*, 2012, pp. 21–24. [Online]. Available: https://www.researchgate.net/profile/Robert_Sullivan6/publication/279850731_Wind_Turbine_Visibility_and_Visual_Impact_Threshold_Distances_in_Western_Landscapes/links/559be4be08ae898ed650aa70/Wind-Turbine-Visibility-and-Visual-Impact-Threshold-Distances-in.pdf

[23] C. L. Archer, H. P. Simão, W. Kempton, W. B. Powell, and M. J. Dvorak, "The challenge of integrating offshore wind power in the U.S. electric grid. Part I: Wind forecast error," *Renew. Energy*, vol. 103, pp. 346–360, Apr. 2017. doi: 10.1016/j.renene.2016.11.047.

[24] B. Sheridan, S. D. Baker, N. S. Pearre, J. Firestone, and W. Kempton, "Calculating the offshore wind power resource: Robust assessment methods applied to the U.S. Atlantic Coast," *Renew. Energy*, vol. 43, pp. 224–233, Jul. 2012. doi: 10.1016/j.renene.2011.11.029.

[25] H. P. Simão, W. B. Powell, C. L. Archer, and W. Kempton, "The challenge of integrating offshore wind power in the U.S. electric grid. Part II: Simulation of electricity market operations," *Renew. Energy*, vol. 103, pp. 418–431, Apr. 2017. doi: 10.1016/j.renene.2016.11.049.

[26] P. B. S. Lissaman, A. Zalay, and G. W. Gyatt, "Critical issues in the design and assessment of wind turbine arrays," in *Proc. 4th Int. Symp. Wind Energy Syst.*, Stockholm, Sweden, 1982, pp. 411–423. [Online]. Available: https://www.osti.gov/etdeweb/biblio/5264590

[27] D. Smith and G. J. Taylor, "Further analysis of turbine wake development and interaction data," in *Proc. 13th Brit. Wind Energy Assoc. Conf.*, 1991, pp. 325–331.

[28] ABB Power Systems Consulting. (2011). *Dominion Virginia Power Offshore Wind Interconnection Study*. [Online]. Available: http://www.offshorewindhub.org/sites/default/files/resources/dominionva-abb_3-13-2012_oswintegration_0.pdf

[29] J. R. Lluch, "Power transmission systems for offshore wind power plants: Technical-economic analysis," M.S. thesis, School Ind. Eng., Universitat Politècnica de Catalunya, Barcelona, Spain, 2015. [Online]. Available: https://upcommons.upc.edu/handle/2117/77913

[30] ABB. *XLPE Submarine Cable Systems Attachment to XLPE Land Cable Systems–Users Guide*. Accessed: Apr. 1, 2017. [Online]. Available: https://library.e.abb.com/public/2fb0094306e48975c125777c00334767/XLPE%20Submarine%20Cable%20Systems%202GM5007%20rev%205.pdf

[31] M. Ali, D. P. Nedic, and J. V. Milanovic. *Robust Methodology for Cost-effective Design of Large Offshore Wind Power Plants*. Accessed: Apr. 1, 2017. [Online]. Available: http://w3.usa.siemens.com/smartgrid/us/en/newsletters/Documents/Design%20of%20Offshore%20WF-v5_EWEAtemp_R1.pdf

[32] B. Jacobson, P. Karlsson, G. Asplund, L. Harnefors, and T. Jonsson, "VSC-HVDC transmission with cascaded two-level converters," CIGRE, Paris, France, Tech. Rep. B4-110, 2010.

[33] ABB. *Submarine Cable Design Sheet-1,000 MW*. Accessed: Apr. 1, 2017. [Online]. Available: http://www.necplink.com/docs/Champlain_VT_electronic/04%20L.%20Eng/Exh.%20TDI-LE-4%20(HVDC%20Cable%20Design%20Sheet%20(ABB)).pdf

[34] L. Lazaridis. (2005). *Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Power Plants Under Special Consideration of Reliability*. [Online]. Available: http://www.diva-portal.org/smash/get/diva2:609080/FULLTEXT01.pdf

ELPINIKI APOSTOLAKI-IOSIFIDOU received the M.Eng. degree from the National Technical University of Athens, Greece, the M.Sc. degree in sustainable energy systems from The University of Edinburgh, U.K., and the Ph.D. degree in electrical and computer engineering from the University of Delaware, USA. She has collaborated with the Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, Siemens Gamesa Renewable Energy, and Twitter, Inc. She is currently a Post-Doctoral Scholar with the Transportation Sustainability Research Center, University of California at Berkeley.

REGINA MCCORMACK received the B.S. degree from the University of Notre Dame, USA, and the Master's degree in Marine Policy from the University of Delaware, USA. Her contributions to this analysis were completed while she was studying for her master's degree at the University of Delaware. She is currently with the Government and Regulatory Affairs Team, Invenergy LLC, an Independent Power Producer of clean energy. Her research interests include electric power markets, environmental law, and grid integrated vehicles.

WILLETT KEMPTON is Professor with the Department of Electrical and Computer Engineering, and with the College of Earth, Ocean, and Environment, University of Delaware. He directs 15 professional researchers and students in research on clean energy technologies. He lectures widely and publishes scientific and technical articles on offshore wind power, electric transportation, and energy analysis.

PAUL MCCOY was the Senior Vice President of Unicom and Commonwealth Edison (ComEd), Chicago, IL, USA. He led the Transmission Group of ComEd. He has working experience with several State Regulatory Agencies and the Federal Energy Regulatory Commission. He was the President of Trans-Elect Development Company, LLC, from 1999 to 2011. He is currently the Principal and the President of McCoy Energy Consulting, LLC, specializing in grid operations and maintenance practices. He also serves on New Brunswick Power's Board of Directors. He is one of the Principals of the Atlantic Wind Connection.

DENIZ OZKAN received the B.Sc. degree in industrial engineering from Marmara University, Istanbul, Turkey, the Ph.D. degree in engineering management/economics, finance and cost engineering from The George Washington University, and the M.B.A. degree in management and organization. She is currently the Director of analysis, research and systems engineering with the Atlantic Grid Development. She leads techno-economic studies, including system design, siting optimization, and project engineering analysis from the systems perspective. She has conducted more than ten years of research in renewable energy and integrated system analysis. She also has written articles, presentations, and technical reports on the offshore wind energy grid integration, including her dissertation on Financial Analysis and Cost Optimization of Offshore Wind Energy under Uncertainty and in Deregulated Power Markets.