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Electrical Collection and Transmission Systems for Offshore Wind Power

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Abstract

The electrical systems needed for offshore wind farms to collect power from wind turbines—and transmit it to shore—will be a significant cost element of these systems. This paper describes the development of a simplified model of the cost and performance of such systems. The performance prediction accounts for losses as a function of the power produced in the wind farm and the length and size of the cables. The cost prediction is flexibly formulated so wind farm configurations can be evaluated by parameters such as the number of wind turbines, wind turbine size, turbine array configuration and spacing, and distance from shore. The collection system—the medium-voltage electrical grid within the wind farm, and the transmission system—the high-voltage electrical connection to an on-shore transmission line—are treated independently in the model. Data sources for the model and limitations of the data are discussed, and comparison is made to costs reported by others. The choice of transmission system technology is also addressed. This electrical system model is intended for integration into a more comprehensive model of offshore wind farm design, cost, and performance that will be used for parametric studies and optimization of wind farm configurations. Because some concepts for future offshore wind installations in deep water use floating platforms, this paper briefly discusses the application of submarine cable technology to nonfixed termination points, a departure from current practice.

Introduction

The National Wind Technology Center (NWTC) of the National Renewable Energy Laboratory (NREL) in Golden, Colorado, has undertaken a series of concept studies to evaluate the cost and performance of offshore wind farms. The product of these studies will be a comprehensive model of offshore wind farm design, cost, and performance suitable for parametric studies and optimization of wind farm configurations. The overall goal of this effort is to help identify technology pathways for offshore wind energy development and deployment in the United States. Offshore wind farms present an attractive option because they allow for larger wind turbines that operate in higher wind resources than land-based [1,2]. Offshore installations are also more expensive, so an understanding of their performance, cost, and optimal configurations is needed.

This paper is an overview of one of these concept studies. It focuses on the power losses in wind farm electrical power collection and transmission systems, as well as the costs of the system components and their installation. A hypothetical system was based loosely on the Horns Rev offshore wind farm in Denmark. Inquiries were made with manufacturers about electrical and cost data on the required components, which were then compiled in a spreadsheet model. The performance prediction accounts for losses as a function of power output of the wind farm and length and size of the cables. The cost prediction is flexibly formulated so wind farm configurations can be evaluated by parameters such as the number of wind turbines, wind turbine size, turbine array configuration and spacing, and distance from shore.

Electrical System Overview

The electrical system for an offshore wind farm consists of a medium-voltage electrical collection grid within the wind farm and a high-voltage electrical transmission system to deliver the power to an onshore transmission line.

Collection System

The collection grid begins with transformers at each wind turbine, usually in the base of the tower, to step up from the generation voltage, typically 690 volts (V), to a medium voltage of typically 25–40 kilovolts (kV). This voltage range seems to be preferred because standardized equipment is available at competitive prices and because higher voltage transformers would be too big to fit readily into the tower cross sections. A grid of medium-voltage submarine cables, typically buried 1–2 meters (m) deep in the seabed, is used to connect the wind turbines to an offshore substation.

Transmission System

The transmission system begins at the offshore substation, which steps up the voltage to a transmission voltage of 130–150 kV, the highest voltages in use today for AC submarine cables. This higher voltage allows a much smaller diameter and lower cost submarine cables to be used for the long run to shore. Only three offshore wind farms in operation today have offshore substations. However, these stations are expected to be the least-cost option for wind farms that will be larger and further offshore than current practice. Such wind farms are the main target of this inquiry.

From the offshore substation, a high-voltage submarine cable (which is also buried in the seabed for protection) carries the power to shore. Once it makes landfall, the run continues, either underground or overhead, to an onshore substation for connection to a transmission line. An additional transformer may be used in this substation to step up the voltage to a higher level to match the transmission grid.

Two technology options are available for the transmission system: high-voltage AC (HVAC) and high-voltage DC (HVDC). The current consensus is that HVAC is the most economical option for distances shorter than 50 kilometers (km) [2,3,4]. This technology is assumed for our model. Between 50 and 80 km, HVAC and HVDC are expected to be similar in cost. Longer than 80 km, HVDC systems will likely be least cost, mainly because the capacity of a given HVAC cable drops off with distance due to the capacitive and inductive characteristics of the cable and their associated losses. DC transmission avoids these losses entirely, so it is the preferred technology for longer distances.

Obtaining Cost and Performance Data

Our study began by examining European offshore wind farms. One of the best documented is Horns Rev, a 160-megawatt (MW) farm that began operation off the coast of Denmark in 2002 [5]. Horns Rev is also one of the two largest offshore wind farms in operation and was the first to use an offshore substation. The collection and transmission cables are rated at 36 kV and 150 kV, respectively with XLPE (cross-linked polyethylene) insulation. We used these parameters to create a model of an example wind farm rated at 500 MW. Requests for high-voltage submarine power cable cost and performance were sent to five manufacturers. Three responded to our requests with preliminary engineering estimates. These estimates were converted to a value in U.S. $/m and loss, kilowatts (kW)/m, for application in our model. Similar methods were used to determine the shipping and installation costs for the cable.

Submarine power cables are custom manufactured to meet the requirements of each unique project; as a result, extensive electrical and cost data on specific cable sizes and types are not readily available. We found that performance and cost data are highly variable between manufacturers. In fact, one manufacturer provided cable prices about twice as high as the other two. We have concluded those prices are not representative of the market and we are not reporting them here. During interviews with manufacturers, we determined that this variability could arise for numerous reasons: high demand for cable from a particular company, rapid inflation in commodity prices, company policy to bid conservatively (especially when little is known about the application), the customized nature of cable design, and setup and tooling costs that are unique to each design.

Two manufacturers provided performance data for their cables. In addition to an inconsistency in these variables, we had too little information about the cables themselves to calculate losses from first principles. However, both data sets contained values for current rating or ampacity (amperes), I_{rated}, and power losses (kW) at full capacity, P_c. We developed a method for calculating power losses that relies on I_{rated}, P_c , and the resistance of the copper conductor, R (ohms). Although R was listed on only one data sheet, resistances are readily calculated for copper conductors of known size. The total losses were divided into two parts: losses (kW) that vary with current, which were modeled as a quadratic term, P_i; and a base loss (kW), P_b, that does not vary with current, modeled as a constant. P_i and P_b are calculated as follows:

$$P_i = I_{rated}{}^2 \times R$$

$$P_b = P_c - P_i$$

A transformer manufacturer was contacted to request cost and performance data for three transformer applications. These transformers contain a special type of liquid coolant that is biodegradable, nontoxic, and suitable for offshore use [6]. Transformer specifications were developed based on the system voltages and power levels throughout the collection and transmission systems. For installation in each wind turbine tower, we priced a 3.16-mega-volt-amperes (MVA) transformer to step up the voltage from an assumed 3-MW wind turbine's 690-V generation voltage to the collection system's 34 kV. The offshore substation contains three, 187-MVA transformers that step up the voltage from 34 kV to the transmission system voltage of 138 kV. (We selected operating voltages that are slightly lower than the cable voltage ratings.) Lastly, a single 560-MVA transformer is located at an onshore substation to step up to an assumed onshore transmission system voltage of 345 kV. This voltage level is typical of a transmission system that can receive 500 MW of generation.

Results

Unit Costs and Performance

Table 1 is a cost summary (in $/m) for submarine cables from two companies. All cables are AC, contain a single layer of steel armor, and are XLPE insulated. Table 2 is a cost summary for the transformers for the tower base, the offshore substation, and the onshore substation.

Table 1. Costs for cables with specific conductor sizes from two companies. Highlighted costs were extrapolated from known costs.

Conductor Size mm^2	Company A	Company B
	Cost ($/m)	Cost ($/m)
Collection System		
95	152	455
150	228	494
400	381	609
630	571	635
800	600	731
Transmission System		
630	755	860

Table 2. Transformer unit costs.

Location	Voltage & Capacity	Unit Cost
Wind Turbine	690/34 kV 3.16 MVA	$50,500
Offshore Substation	34/138 kV 187 MVA	$2,618,000
Onshore Substation	138/345 kV 560 MVA	$5,600,000

Figures 1 and 2 show performance data for submarine cables from two companies. The power losses in Figures 1 and 2 are computed at steps that correspond to 3 MW of additional power in a 34-kV line. As the power level increases, the current on the line and thus the power loss increases. Electrical data were not available for the transmission system cables, so no power loss estimation for high voltage operation is provided here. The actual losses for an operating wind farm, which are a function of power level (and in turn a function of wind speed), will be applied in the final wind farm model.

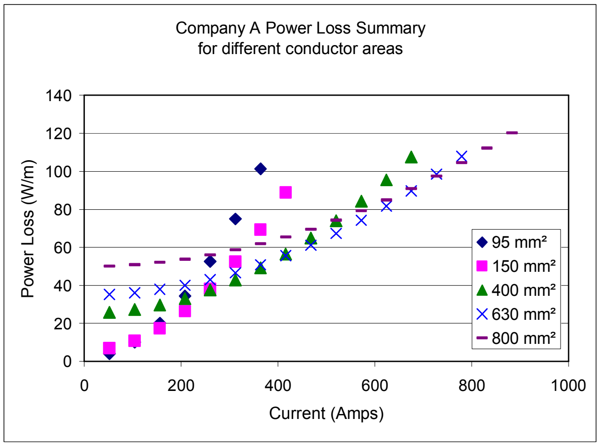

Figure 1. Loss results for Company A cables at various currents for several conductor sizes.

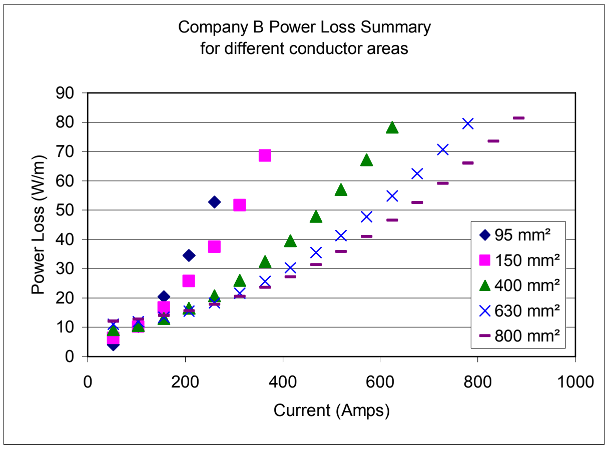

Figure 2. Loss results for Company B cables at various currents for several conductor sizes.

We also contacted a domestic submarine cable installer who provided us with a preliminary engineering estimate for cable shipping and installation, which we then converted to a base value and a $/m value to allow for variability in cable length (see Table 3). Mobilization, demobilization, marine route survey, and route engineering costs are given as fixed costs; shipping and cable laying costs vary with cable length.

Table 3. Installation cost breakdown.

	East Coast	West Coast
Marine Route Survey & Engineering	$1,500 K	$2,000 K
Cable Transport Via Freighter from Europe ($/m)	$58	$85
Mobilization/ Demobilization	$5,000 K	$6,000 K
Cable Laying Operations ($/m)	$94	$103

Cost for an offshore substation for a 240-MW farm was obtained from the SeaWind concept study [7]. We adjusted this number to account for the difference in size, foreign excahange rates, and inflation resulting in a value of $40.52 million (2006 $) for a 500 MW offshore substation.

500 MW Wind Farm

After we compiled the unit cost data in the spreadsheet, we considered alternative layouts for an example 500 MW wind farm to assess impacts on wind farm power losses and costs. All collection grid layouts investigated were radial from the offshore substation. The numbers of rows and number of turbines per row were varied for different layouts; see Figure 3 for a 21-row layout with eight turbines per row.

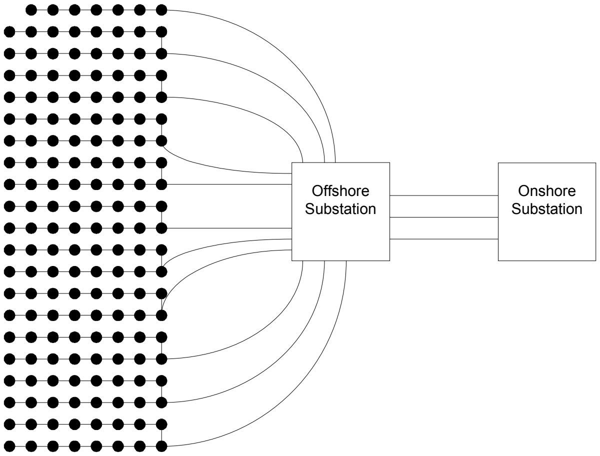

Figure 3. 500 MW wind farm layout with 3 MW qind turbines. Diagram not drawn to scale.

Table 4 summarizes the input parameters of this example wind farm. The 630 meter distance between rows and between turbines is 7 times the rotor diameter of 90 meters. A cable length between turbines of 830 meters allows ample room for installation and topographical differences in the ocean floor. The cables connecting the collection grid to the offshore substation vary in length based on their location but are each approximately 7 kilometers. The number of transformers and their costs for this 500 MW system are shown in Table 5.

Table 4. 500 MW wind farm parameters

Wind turbine rating	3 MW
Number of wind turbines	167
Rotor diameter	90 m
Water depth	20 m
Distance between turbines	630 m
Distance between rows	630 m
Cable length between turbines & between rows	830 m
Substation distance to shore	15 km
Length of onshore transmission	15 km

Table 5. Transformer cost summary for 500 MW wind farm.

Location	Quantity	Unit Cost	Total Cost
Wind Turbines	167	$50,500	$8,433,500
Offshore Substation	3	$2,618,000	$7,854,000
Onshore Substation	1	$5,600,000	$5,600,000

Table 6 is a summary of total wind farm costs and losses for Companies A and B. Cable cost, cable shipping and installation, tower transformers, offshore transformer substation, and onshore transmission and substation are included in these costs. Power losses are computed at the wind farm's rated power and, thus, are not representative of actual operating losses. (Transmission losses are based on extrapolations of losses at medium voltage and should be considered rough estimates.)

Table 6. Cost and performance summary for a 500 MW offshore wind farm. All costs are in millions $ and all power losses are in MW at rated power.

	Layout 1	Layout 2	Layout 3
Turbines per row	8	7	6
# of Rows	20.9	23.9	27.9
Turbine Transformer Cost	$8.43	$8.43	$8.43
Collection Cable Shipping & Install Cost	$36.53	$38.36	$42.84
Transmission Cable Shipping & Install Cost	$6.83	$6.83	$6.83
Offshore Substation w/Transformers	$40.52	$40.52	$40.52
Onshore Transmission & Substation	$29.37	$29.37	$29.37
Company A			
Collection Cable Cost	$82.85	$86.64	$78.78
Transmission Cable Cost	$33.98	$33.98	$33.98
Collection Losses (MW)	11.96	11.86	14.21
Transmission Losses (MW)	2.88	2.88	2.88
Total Cost and Unit Cost	$238.57 $477/kW	$244.13 $488/kW	$240.75 $482/kW
Total Losses (MW)	14.84	14.74	17.09
Company B			
Collection Cable Cost	$123.15	$122.54	$136.88
Transmission Cable Cost	$38.70	$38.70	$38.70
Collection Losses (MW)	7.81	8.29	11.27
Transmission Losses (MW)	2.88	2.88	2.88
Total Cost and Unit Cost	$283.53 $567/kW	$284.75 $570/kW	$303.57 $607/kW
Total Losses (MW)	10.69	11.17	14.15

Cost Comparison to Other Sources

The cost data used in this study were compared to the cost data reported by Neilson [7] and Gerdes et al. [8]. When a direct match could not be made between the cables used in these studies, the cable with the dimensions closest to those specified was used. The data was corrected for inflation and foreign exchange rates and are reported here as 2006 costs.

For this comparison, we did not create wind farm array configurations. We simply calculated total cost by multiplying the length of the cable from the Seawind study [7] by the $/m data from both of the manufactures in our study. Table 7 shows the individual cable costs and the total cost results for both Seawind and our study.

Table 7. Comparison to Seawind cable costs.

Length (m)	Voltage (kV)	Area (mm^2)	Cost $/m	Total ($M)
Seawind				
35,500	150	630	641	22.76
39,714	30	300	128	5.08
				27.84
Company A				
35,500	170	630	755	26.80
39,714	36	400	381	15.33
				42.13
Company B				
35,500	150	630	860	30.53
39,714	36	400	609	24.18
				54.71

All our cable costs are higher than those in the Seawind report. The price of copper increased significantly between 2003 (when the Seawind study was performed) and the summer of 2006 (when our data were collected), at one time by more than 300%. This increase may partially explain the differences between the costs in these two studies. A manufacturer reported that commodity prices are about one-third of the cable cost. Changing foreign exchange rates may also have been a factor

In addition, the results from our loss calculation method were compared to the results obtained by the Seawind study. The Seawind study provided the losses at full load for different wind farm sizes with a 300 mm^2 conductor cable at 30 kV. Table 8 show these losses for Seawind and the full load losses based on our data for a 400 mm^2 conductor cable at 36 kVa. There is a reasonable match between these data sets, although lower losses might have been expected from our data given the larger cable size and higher assumed operating voltage.

Table 8. Comparison to Seawind full load losses.

Size (MW)	Seawind (% lost)	Company A (% lost)	Company B (% lost)
15	0.603	1.253	0.690
30	1.203	1.234	0.950

Table 9 shows a comparison of the actual transmission system costs for Horns Rev [8] and the predicted costs from our study. Note: the dimensions of the onshore cables differ between Horns Rev and our data. Our costs compare reasonably well with Horns Rev.

Table 9. Comparison of transmission cable and substation costs to the actual cost for Horns Rev.

		Company	
	Actual	A	B
Onshore Cables		10.55	10.55
Offshore Cables		15.86	18.06
Offshore Substation w/Transformers		12.87	12.87
Total ($M)	39.45	39.28	41.48

Table 10 shows a similar comparison between the actual costs of the Nysted transmission system and our cost estimate. Note: the dimensions of the cables differ between Nysted and our study. Once again, the cost comparison is reasonably good.

Table 10. Comparison of transmission cable and substation costs to the actual costs at Nysted.

		Company	
	Actual	A	B
Onshore Substation & Transformer		8.4	8.4
Onshore Cables		5.59	5.59
Offshore Cables		8.31	9.46
Offshore Substation w/Transformers		13.32	13.32
Total ($M)	37.80	35.62	36.77

Reducing Cable Cost

Several options for reducing electrical system cost emerged in the course of our study. These options may be technically feasible, but each comes with some added risk of reduced reliability. Because submarine cables require significant capital investments and are relatively inaccessible for maintenance, buyers are conservative with a strong preference for designs with proven records.

1. Don’t bury the collection system cables in the seabed between wind turbines, since the risk of damage within the wind farm from boat anchors, commercial fishing, etc., is low compared to the more exposed transmission cable to shore. Laying cable on the seabed costs less than buried cable installation.
2. For copper conductors, the lead sheath is not strictly necessary. A copper wire sheath can be used instead to provide an effective electrical shield. Lead sheathing is commonly specified as a conservative approach that provides one more seawater barrier for the conductors. Lead sheathing is more expensive because it uses a larger volume of material applied in an extrusion process.
3. Alternatively, aluminum conductors can be used in place of copper can reduce both cost and weight. Conductor cost alone could be lower by about a factor of 6 (at 2006 commodity prices), and cable costs might be reduced 15%–20%. Seawater exposure of aluminum results in corrosion and off-gassing, so using a lead shield for maximum seawater isolation will be prudent.

4. Power cables for wind farms should be designed with cable thermal mass in mind. One manufacturer noted that a buried cable/soil system has a thermal time constant of about one week. Typically, wind farms are not at peak power continuously. Intermittency of the wind resource may allow cable thermal design to be based on current level less than that at peak wind farm output. Temperature monitoring of cables is feasible with fiber optics, though the optical fibers are reported to be less robust than the cables.
5. One cable manufacturer recommended that performance-based cable specifications be used instead of design-based specifications to give the manufacturers greater flexibility to use their knowledge and experience to explore cost-effective designs.

Cables for Floating Platforms

Some concepts for future offshore wind installations in deep water use floating platforms [1], which will not provide static termination points for submarine power cables. These cables will be subjected to some finite motion: heave, sway, torsion, or some combination of the three. Clearly the medium- and high-voltage submarine cable designs in use today will not be adequate for this service, primarily because the lead sheathing around the electrical conductors has very poor fatigue properties. This issue has not been addressed by the oil and gas industry because the risers typically used for floating oil and gas platforms are communications cables and pipelines for oil and gas, not high-voltage power cables. These platforms typically operate with 13.8-V power, not the higher voltages needed for offshore wind.

One option might be to switch from lead to copper sheathing around the electrical conductor. Removing the lead creates a much more fatigue-resistant cable. Of course, the fatigue properties of cables without lead sheathing will need to be determined and evaluated in light of the dynamic characteristics of particular floating platform designs. However, a copper sheath, typically a mesh of copper wires, which provides necessary electrical shielding, is not a seawater barrier as is a continuous lead sheath. Thus long-term resistance of the cable to seawater intrusion will be reduced. Other issues will include means to distribute cable bending, i.e. to limit bending radius; creating resistance to cable abrasion against the seabed; and finding suitable means to support cable weight if the cable must be used in a droop configuration. In contrast, experience with submarine cables is limited to stationary and fully supported installations, typically laid on or trenched into the seabed. Care is taken to protect cables from seabed scouring, in particular at the bottom of wind turbine towers, which could leave a length of cable suspended above the bottom and vulnerable to movement.

Conclusion

The NREL NWTC in Golden, Colorado, has undertaken a series of concept studies to evaluate the cost and performance of offshore wind farms. This paper reports on one of these concept studies that focused on the costs and losses in wind farm electrical power collection and transmission systems. We believe the cost and performance data reported here are well suited for parametric studies of wind farm size and configuration. However, we recommend some caution about the use of these data for estimating absolute costs. Uncertainties in absolute cost arise from factors such as changing commodity prices, changing foreign exchange rates, changing levels of demand for goods and service in this industry, and the impact of project-specific design parameters. Also, losses in submarine cables appear to depend on the specific cable design and, perhaps, the manufacturer. Submarine power cables are highly customized for each application, so generalizations about cost and performance are estimates at best.

This study was limited to electrical system components—submarine cables, the offshore substation, and transformers—that contribute the most to system cost. Devices we have not addressed, including switches, circuit protection, and compensation devices, have much lower costs, but are nonetheless important to wind farm operation. Our cost model can be improved with further research of the cost and performance of these devices. Our model also needs data about losses in high-voltage transmission cables, which were not available from manufacturers during our study.

Our studies illustrate how wind farm layout affects collection system cable losses and cost. Changes in cable size will move cable cost and performance in opposite directions. These tradeoffs between configuration, cost, and performance point to the importance of performing parametric studies of the entire system to seek optimum configurations. The comparisons we made of our transmission system cost data to published data for wind farms showed that our costs matched very well.

One critical research need for offshore wind farm electrical systems is technology for nonstatic power cable terminations. Submarine power cable technology is vulnerable to fatigue failures. Fatigue-resistant cable technology must be developed if floating platforms are to be used for offshore wind farms in deep water.

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