



Process-Based Balance-of-System Cost Modeling for Offshore Wind Power Plants in the United States

Preprint

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National Renewable Energy Laboratory

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Process-based balance-of-system cost modeling for offshore wind power plants in the United States

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Abstract. This paper describes the development of a process-based and open-source balance-of-system cost model that provides the capability to evaluate both existing and novel offshore wind technologies. Individual design and installation steps are represented with bottom-up engineering models that compute times and costs associated with the process; furthermore, operational constraints are assigned to each process so that delays caused by weather and presence of marine mammals may be accounted for in the overall project timeline. The model structure, assumptions, inputs, and results are vetted with industry partners and compared against actual projects for validation. Installation times show reasonable agreement with real data. Project cost sensitivities are investigated to compute the system-level impact of different design choices. First, individual vessel efficiencies are computed for varying numbers of installation vessels and weather time series to show the diminishing returns of more than two feeder barges. Then, array cable capital costs and installation times are determined for a representative project with different turbine sizes. These values quantify the cost-benefit trade-offs and show a net-cost savings of decreasing numbers of turbines, increased turbine spacing, and fewer turbine terminations. These results demonstrate that the balance-of-system model features the accuracy, functionality, and accessibility to serve as the foundation for a wide range of analyses to identify cost reduction potentials for offshore wind energy in the United States.

1. Introduction

The levelized cost of energy (LCOE) of offshore wind power plants comprises capital expenditures (CapEx), operational expenditures (OpEx), financial parameters, and annual energy production. CapEx costs are subdivided into the capital costs of the wind turbine generator (WTG) and the *balance-of-system* (BOS), which includes the CapEx of substructures, cables, and substations, as well as the times, delays, and costs required to install these components (including the turbine) at sea [Kaiser and Snyder, 2012]. BOS costs are estimated at 46% of the total costs of a fixed-bottom project and 60% of a floating project [Stehly et al., 2018]; while these contributions to LCOE are significant, the myriad of design options available to project developers provide an opportunity to optimize and innovate to reduce costs. Improvements in installation processes have the potential to be doubly beneficial as much of the risk of the project, and the subsequent financial structuring, is associated with uncertainty of the construction phase [Musial et al., 2019, Brindley, 2018]. Technological innovations and advancements along the learning curve have recently begun to achieve these improvements, and better modeling and analysis capabilities will promote increasingly efficient, predictable, and cheaper projects [Lacal-Arántegui et al., 2018]; however, the ability to conduct cost benefit analyses that capture

the competing effects of different technological and process innovations over many different projects is currently a challenge for the industry that requires the development of appropriate modeling tools.

A common cost modeling approach is to parameterize the costs of existing technologies in terms of several project parameters [Ioannou et al., 2018a, Ioannou et al., 2018b, Myhr et al., 2014]. These models are useful for comparing costs of existing wind plants but have a limited capacity to evaluate new innovations; for example, regression fits based on current turbine ratings become more uncertain as they are extrapolated to the larger turbines that are becoming standard in the industry. Furthermore, this approach typically does not directly capture the impact of weather delays on installation times. Other approaches can include expert elicitation of component or project costs [Wiser et al., 2016, Valpy and English, 2014, Valpy et al., 2017] or time series simulations [McAuliffe et al., 2018, Kikuchi and Ishihara, 2016, Paterson et al., 2018, Sevilla et al., 2014]; again, these can provide accurate representations of the current state of the industry but are typically not appropriate for mapping engineering design choices with overall project costs. A bottom-up approach is required that allows novel strategies or technologies to be defined and then evaluates the interaction between these new concepts and the remainder of the system to capture the net impact on LCOE.

In this work, the National Renewable Energy Laboratory’s (NREL’s) new process-based Offshore Renewables Balance-of-system Installation Tool (ORBIT) is described, wherein each phase of an offshore wind project development is defined by a series of discrete, weather-dependent processes. Durations and respective costs of each process are then calculated based on fundamental parameters of the turbine components and available vessels. This bottom-up framework permits technological and process innovations to be modeled for a range of offshore wind projects to compare the impact on cost. Furthermore, the open-source and modular ORBIT model is available to be used and adapted by a range of users within the industry. This provides a valuable tool for evaluating the cost reduction potential of new technologies and strategies within the offshore wind industry.

This paper first provides an overview of the methodology used to develop the process-based equations and process diagrams depicting the modeling framework for the modules. Next, validation results are presented to characterize the accuracy of the model. Finally, several case studies are run to compare the impact of different design and installation strategies on the duration and costs of a representative offshore wind project. Discussion and results presented in this paper are primarily intended to demonstrate the framework and functionality of ORBIT for a range of cost-benefit trade-offs.

2. Methodology

2.1. Offshore wind power plant installations

At the most basic level, the steps taken by a project developer during the construction of an offshore wind power plant involve:

- Obtaining site control/permits and conducting metocean and geotechnical site assessments.
- Purchasing project components (WTGs, substructures, cables, offshore substation) and staging them at port.
- Contracting construction vessels to transport and install components at sea.
- Constructing an onshore substation and connecting to the local electricity grid.
- Commissioning the wind power plant and beginning generation.

A number of factors contribute to the complexity of these processes, particularly those related to installing large and heavy components at sea. Each operation can only be conducted if metocean conditions are within the weather constraints of the individual vessel. These operations are also

highly dependent upon the characteristics of an individual site, including water depth, distance from shore, and soil conditions. Start times for each construction phase are constrained by the availability of the limited number of vessels that can conduct the complex tasks. Finally, offshore wind power plants are customized for an individual site, meaning that component, vessel, and methodology selections need to be evaluated for a specific project. Understanding how these design choices scale for different projects requires a bottom-up model that allows a user to modify these BOS aspects and then compute the impact on all related aspects of the project as well as the overall cost.

2.2. Process-based modeling approach

ORBIT is based on systems-level engineering models that calculate the durations of individual installation processes using project geospatial data, vessel and component data sheet specifications, component cost data, and industry standards. As a result, the installation times and costs output by the model scale with variables such as project size, turbine rating, site location, substructure technology, and vessel selection. Furthermore, each process is assigned weather and wildlife constraints and is compared against a wind and wave time series that spans the installation time frame. Delays accrue when weather conditions exceed the operational limits for a given operation. Finally, ORBIT is coded in Python using a modular framework that easily allows baseline values, assumptions, and technologies to be overwritten by a user. This framework allows novel technologies to be rapidly evaluated and compared with more conventional baseline scenarios. As such, the model is designed to have sufficient resolution to accurately reflect the current state of the industry as well as enough flexibility to analyze the effects of future innovations.

ORBIT has two primary modules: one that conducts a first-order engineering design of the wind power plant to calculate component costs and sizes; and a second that conducts a time series simulation of the construction process to calculate installation costs and duration. It is important to note that the design modules in ORBIT are not intended to provide detailed engineering representations of offshore wind components, which would introduce substantial complexity into the model without adding meaningful value to the results. Instead, the first-order designs are intended to capture how costs scale over different projects to identify trends and opportunities for cost reduction. For brevity, the detailed development of these design modules is not included in this paper but will be described in detail in a forthcoming NREL technical report as well as being documented in the GitHub repository that stores the ORBIT code [NREL, 2019]. A brief summary of the design and installation modules is included in the following sections to provide a perspective of the key dependencies for each component.

2.3. System design modules

2.3.1. Substructure design

Monopiles, which are steel tubes driven into the seabed to form a base for the turbine and tower, are the most common substructure used by offshore wind power plants [Musial et al., 2019]. In ORBIT, monopile design is based on a simplified 10-step process intended to conduct financial screening at the early phase of an offshore wind project [Arany et al., 2017]. The model considers wind characteristics, turbine properties, and soil stiffness to obtain the required diameter, length, and thickness of the monopile; these properties inform the selection of installation vessels that must have sufficient lifting capacity to install the component. The 10-step method is further simplified in ORBIT to reduce the number of inputs and complexity of the model; specifically, buckling modes are not investigated, and no design iteration is conducted to ensure conformity with acceptable ultimate load states. Currently, ORBIT only supports monopile design, but extension to jacket and floating substructures is under development.

2.3.2. Cable design Offshore wind power plants require array cables, which connect individual turbines on a “string” to transmit power to the offshore substation (OSS), and export cables, which transmits power from the OSS to the electrical grid on land. Using performance characteristics from cable manufacturer data sheets, ORBIT sizes three-phase alternating current cables, which are the most common designs in existing projects. These properties are specified at a range of burial depths, meaning that the impact of burying cables at different depths under the seafloor is implicitly captured by the subsequent reduction in ampacity. ORBIT allows cable types of increasing capacity to be defined for each string and then calculates the maximum number of turbines that the string can support. As a result, the number of strings varies with turbine rating, plant size, and cable specifications. The design modules output the total length and cost of both array and export cables required for a given project.

2.3.3. Offshore substation design The OSS is a facility located within the power plant that collects power from all turbines and transmits it to land via the export cable. The OSS design in ORBIT is retained from an older version of NREL’s BOS model [Maness et al., 2017]. The components of the substation (switchgear, shunt reactors, generators, structural mass, and ancillary equipment) are parameterized in terms of the number and rating of the main power transformers using empirical relationships from industry data. ORBIT estimates the mass and cost of the substation itself as well as the substructure required to support it on-site.

2.3.4. Onshore design Offshore wind power plants typically require some amount of onshore construction to connect the export cable to an electrical substation (which may also require upgrades or additions to accommodate the incoming power). Similar to the OSS design, the onshore construction and connection to the electrical grid are parameterized in terms of plant size, distance to the grid, and interconnection voltage [Maness et al., 2017]. ORBIT outputs the total costs associated with these construction activities.

2.3.5. Port logistics Offshore wind projects require substantial port capacity, including appropriate cranes that can lift turbine components onto vessels as well as staging areas to store components before shipping them to the project site [Kaiser and Snyder, 2012]. Project developers tend to enter into agreements with port operators in which a specific berth and crane are rented exclusively to the wind project throughout the duration of the construction phase. ORBIT calculates these costs by defining a monthly rental fee and applying this to the computed duration of the installation process.

2.4. Installation simulation module

For the installation modules of ORBIT, processes are modeled using SimPy, a discrete event simulation (DES) framework written in Python. DES allows for modeling of each individual subprocess and related constraints throughout the installation process at an hourly timescale. Constraints can be weather related (maximum operational wind speed or wave height), or related to other agents acting in the same simulation. For example, a wind turbine installation vessel (WTIV) may not be able to perform an action, such as lifting a blade, unless there is an acceptable weather window and a feeder barge with the blade already in position. This framework allows for the development of complex, process-based analysis of these installations, in which the constraints and their downstream implications are considered at every subprocess step.

The current version of this model permits a single WTIV to be paired with a user-specified number of feeder barges to install the substructures, turbines, and substations. Separate cable-lay vessels are defined for the array and export cable systems. Individual task durations are

calculated using process equations where appropriate, or values from literature if no equation is available; ongoing development of the model will systematically replace the hard-coded values with engineering models.

2.5. Industry review

The modules discussed in Sections 2.3 and 2.4 were presented to a number of industry practitioners for preliminary review of the scope, approach, and accuracy of the ORBIT model. The purpose of these reviews was to confirm that the processes included in the model reflect current industry best practices. The response from the reviewers substantiated the approach of the model and indicated that its proposed fidelity is valuable within the offshore wind industry for performing design trade-offs and evaluating cost trends over different sites or technologies. As previously stated, ORBIT is not intended to replace project-specific budgeting tools used in industry. Further reviews are planned in which the magnitude of the input values and the output results are reviewed more quantitatively by the same practitioners; however, the initial round of reviews provided confidence that the model serves a useful purpose in the offshore wind community and provides a meaningful and relevant level of fidelity in its approach.

3. ORBIT validation and application

The primary value of ORBIT is evaluating how varying design choices or project characteristics impact the costs of offshore wind power plants. In this section, ORBIT is first shown to provide a reasonable representation of actual project data as a preliminary validation case. An exploration of model sensitivities is then conducted for a representative project to demonstrate the potential impact of weather delays and increasing turbine size on project cost.

3.1. Validation case: Dudgeon wind power plant

The installation times calculated using ORBIT were compared with reported phase durations from the Dudgeon wind farm off the east coast of the United Kingdom [4C Offshore, 2019]. This project was selected as a reasonable validation case based on several criteria. The project has been fully commissioned, meaning that well-defined start and end dates are available for each installation phase; in addition, as construction was completed within the last 2 years, the vessel characteristics and installation strategies are similar to current industry practice. Dudgeon also features a straightforward project design, including a single offshore substation, monopiles in use for all substructures over a small range of depths, mostly uniform cable designs, and only a single installation vessel working on each major phase. Finally, wind and wave time series for the construction window are available from ERA5 reanalysis data [Copernicus Climate Change Service Climate Data Store (CDS), 2017]. The relevant project characteristics used to define the input parameters for ORBIT are tabulated in Table 1.

To conduct the validation testing, the average site specifications, vessel characteristics, and values from component data sheets (referred to in the “Dudgeon validation” column of Table 1) are defined as inputs to the ORBIT model; insofar as possible, these values match the inputs to the process diagrams described in Sections 2.3 and 2.4. Any values that are not publicly available are estimated from the offshore wind literature. ORBIT is then run and used to develop a first-order system design of monopiles and cables, and then calculates the duration of the major installation phases (foundation, turbines, and cabling). Installation times computed in ORBIT are compared with Dudgeon project information in Fig. 1.

Performance of the ORBIT model is primarily assessed based on the computed durations of the installation phases. Although the ultimate aim of the model is to estimate costs, the individual charter rates of the installation vessels are proprietary and not reported here; however, because total vessel cost is directly proportional to installation time, the main goal of the validation exercise is to establish the accuracy of the calculated times. This gives a model user

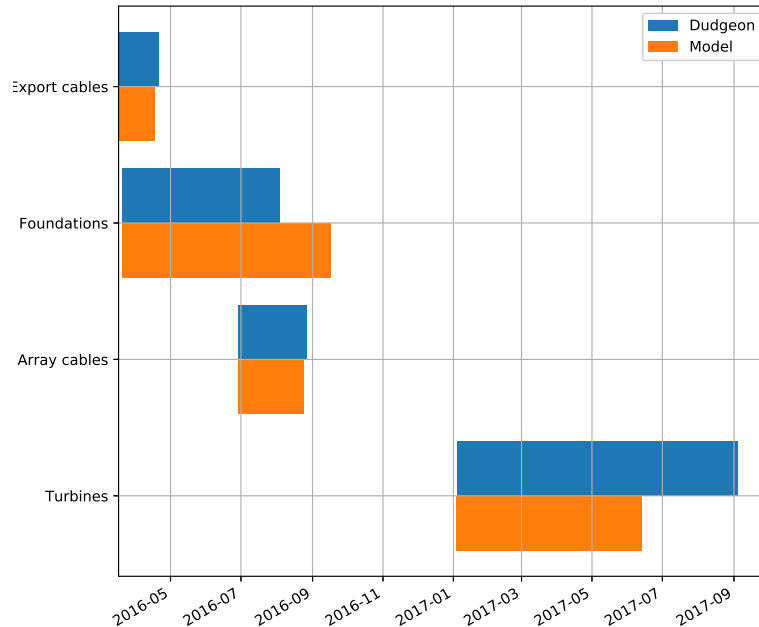


Figure 1. Comparison of calculated installation times with reported values from the Dudgeon wind farm.

confidence that total costs will be correctly estimated if a valid charter rate is assigned to each vessel. These calculations also implicitly depend on the first-order system designs described in Section 2.3.

The results from ORBIT’s estimation of installation times for export cables [-9%], foundations [+33%], array cables [-5%], and turbines [-34%] demonstrate reasonable agreement with the actual installation times of the Dudgeon project. It is likely that further modification of the input parameters (for instance, crane specifications or vessel transit rates) would allow these results to be more closely tuned to the exact Dudgeon values; however, it is important to reiterate here that the default values in ORBIT are intended to represent many sites and should not be calibrated too extensively toward one project. Any user can override the defaults with project-specific values for a more detailed comparison (assuming these values are available). For the purposes of this work, it is sufficient to know that the model outputs reasonable values for each phase; as previously stated, ORBIT is intended to capture cost trends over a range of projects and, as such, duration estimates within around 30% of actual values are sufficient. Future work will extend this exercise to additional wind farms to better understand the validity of ORBIT over a range of site and project conditions.

3.2. Balance-of-system cost sensitivities

A representative project was defined to demonstrate the ability of ORBIT to investigate the impact of design decisions and weather profiles on installation times and costs. This section is not intended to provide a detailed analysis of the results, but to show how cost and duration trends are appropriately captured within the model and to identify some of the insights that

become available through the process-based simulations. For instance, beginning an installation on October 1 is not standard in industry but is considered here to demonstrate how the model can account for different project start dates. Project and scenario data are contained in Table 1.

Table 1. Summary of scenario data.

	Dudgeon validation	Representative project
<i>Site</i>		
Distance to Port	185 km	80 km
Depth	20 m	40 m
<i>Turbine</i>		
Capacity	6 MW	9.5 MW
Number	67	50
<i>Monopile</i>		
Weight	1000 t	1200 t
Diameter	7.25 m	7 m
<i>Cables</i>		
Rated Voltage	33 kV [array], 132 kV [export]	36 kV, 220 kV [export]
Rated Current	470 A and 734 A [array], 655 A [export]	655 A [array], 710 A [export]
<i>WTIV</i>		
Transit Speed	25 km/h	13 km/h
Max Cargo	8500 t [monopile], 7400 t [turbine]	8400 t
Max Wind Speed	20 m/s	15 m/s
Max Wave Height	2.5 m [monopile], 3 m [turbine]	3 m
<i>Feeder Barge</i>		
Transit Speed	N/A	10 km/h
Max Cargo	N/A	1500 t
Max Wind Speed	N/A	20 m/s
Max Wave Height	N/A	2.5 m
<i>Cable Lay Vessel</i>		
Transit Speed	22 km/hr [array], 16 km/hr [export]	11.5 km/h
Cable Lay Speed	0.5 km/hr	0.5 km/h
Carousel Capacity	2000 t [array], 4400 t [export]	2000 t
Max Wind Speed	25 m/s	25 m/s
Max Wave Height	1.5 m	1.5 m

Table 2. Summary of weather data.

Season	Start Date	Mean Wind Speed (m/s)	Wind Speed Standard Dev.	Mean Sig. Wave Height (m)	Wave Height Standard Dev.
Summer	April 1	8.18	2.64	1.51	0.84
Winter	October 1	8.13	2.76	1.93	1.11

3.2.1. Impact of weather on installation time The first analysis explores installation strategies with a varying number of feeder barges (n=1, 2, 3) that are transporting monopile components to a WTIV located on-site. An additional scenario involving a hypothetical U.S.-flagged WTIV installation vessel (n=0) was also included; in this case, the WTIV is responsible for both

transporting and installing each component, requiring additional trips between the site and port. Ten hourly weather profiles (wind speed and significant wave height) were selected to study distributions in installation times across the four scenarios outlined earlier. Because ORBIT models the implications of weather at each discrete process step, the impacts of increased weather variability in winter can also be explored. The analysis was conducted with the project starting on April 1 (“summer” scenario) and October 1 (“winter” scenario) to demonstrate the impact of a delayed start date on total project times. Average wind speeds and standard deviations for both seasons are shown in Table 2.

Fig. 2 displays the distribution of monopile installation times for summer and winter start-date scenarios. The Single WTIV installation strategy (without feeder barges) has the highest installation time of all strategies, with a mean of 3400 h during the summer and 3977 h during the winter, indicating that the harsher weather experienced during winter causes more delays in the construction process as vessels have to wait to satisfy their operational limits. The strategy that uses one feeder barge to transport components from port to site decreases installation times to 2854 h during the summer and 3559 during the winter. Adding an additional feeder barge (n=2) further decreases the installation times to 2491 h and 2944 h. The addition of a third feeder barge does not decrease the installation times because the first two are appropriately able to keep the WTIV busy installing components at site.

Installation cost was calculated by tabulating the total number of days for which each vessel needed to be contracted and multiplying by a day rate for each vessel. The day rate for the WTIV was assumed to be the same as the day rate for jackup vessels from [Ioannou et al., 2018a]. The day rate of the feeder barges was assumed to be 20% of the WTIV. A summary of installation costs of each strategy is provided in Table 4. In summer, the addition of one feeder barge decreases the installation time enough to offset the additional cost of the feeder barge. However, in winter the total installation cost increases by \$1.5 million as the more challenging weather conditions lead to additional delays for the feeder barges, which accrues additional costs for the overall project. For both seasons, the decrease in total installation time from two feeder barges offsets the additional incurred costs of the barges.

Table 3. Summary of installation times per strategy and season.

Strategy	Summer Mean (h)	Summer Min. (h)	Summer Max. (h)	Winter Mean (h)	Winter Min. (h)	Winter Max. (h)
Single WTIV	3399	3184	4309	3978	3196	5838
1 Feeder Barge	2855	2377	4066	3559	2418	6133
2 Feeder Barges	2492	2096	3571	2944	2141	5410
3 Feeder Barges	2492	2096	3571	2932	2141	5410

Table 4. Summary of installation costs per strategy and season.

Strategy	Summer Mean (\$M)	Summer Min. (\$M)	Summer Max. (\$M)	Winter Mean (\$M)	Winter Min. (\$M)	Winter Max. (\$M)
Single WTIV	23.06	21.6	29.24	26.98	21.68	39.61
1 Feeder Barge	22.82	19.0	32.52	28.45	19.32	48.98
2 Feeder Barges	22.88	19.23	32.84	27.02	19.66	49.61
3 Feeder Barges	25.78	21.66	37.0	30.34	22.14	56.0

Fig. 3 expands upon this analysis by plotting the individual vessel efficiencies, η_{vessel} , for each scenario, as calculated by Eq. 1,

$$\eta_{\text{vessel}} = \frac{t_{\text{active}}}{t_{\text{total}}}, \quad (1)$$

where t_{active} is the duration in which a given vessel is active (installing components or in transit) and t_{total} is the total duration of the installation phase (including weather and operational delays). For the Single WTIV scenario, the vessel is operating above 90% efficiency; however, this includes transit to and from the site, which drives up the total installation time. In other words, although the WTIV is highly efficient because it is almost always moving, it is spending significant time in transit instead of installing components at the site, which is less effective for the overall project schedule. For the 1 feeder barge strategy, the efficiency of the WTIV decreases because it frequently spends time at site waiting for additional components to install, whereas with 2 feeder barges, all vessels are operating at 85%+ efficiency for most weather profiles. The addition of the third feeder barge drops the efficiencies for all barges because the WTIV can only install components as fast as two feeder barges can supply. Changing the project start date from April 1 to October 1 results in a greater spread in vessel efficiencies, reflecting the increased uncertainty in project duration as a result of weather. These data can be valuable to project developers looking to streamline their subcontracts and not overpay for inefficient vessels.

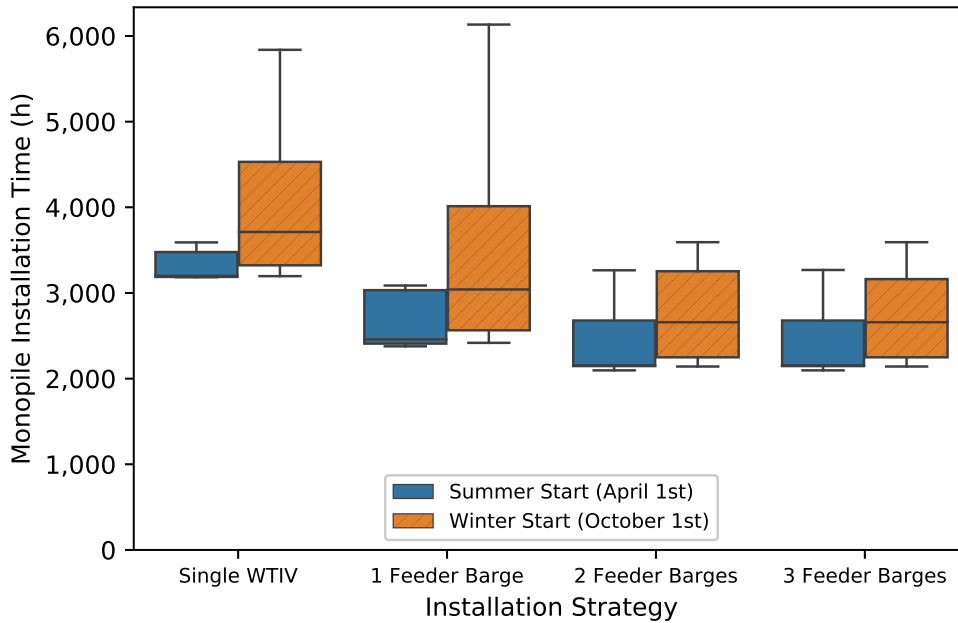


Figure 2. Total monopile installation times for strategies with an increasing number of feeder barges with installations starting in summer (April 1) and winter (October 1).

3.2.2. Impact of turbine scaling on array cable sizing and installation times ORBIT also allows users to perform first-order designs of specific subsystems and explore how these design changes affect system capital expenditures (CapEx) and installation times. The following analysis explores the change in array system costs (CapEx and installation) with increasing turbine sizes. This reflects the current trends in the offshore wind industry, which has seen 9.5-MW

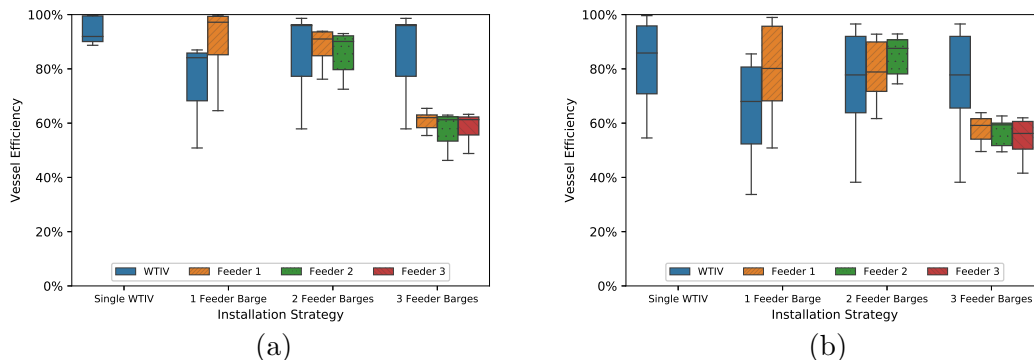


Figure 3. Individual vessel efficiencies for installation strategies with an increasing number of feeder barges with installations starting on (a) April 1 and (b) October 1.

machines installed in the last year and is expected to grow toward 12- or 15-MW turbines in the near future [Musial et al., 2019]. Increasing the turbine size requires fewer substructures and installation trips for a given plant capacity; however, changing the rating of the turbine can create competing effects throughout the project. As an example, the number of turbines that fit on an array cable string is limited by the ampacity of the cables and the turbine rating; therefore, larger turbines may require more strings and additional cable lengths and costs. ORBIT can be used to quantify what these impacts are on the overall project costs.

ORBIT’s array system design and installation module was run with five different turbine specifications (see Table 5) to calculate total cable length, CapEx, and installation costs and time. Turbines are arranged in a rectangular configuration and ORBIT recalculates the number of strings and their respective number of turbines. Plant size was held constant at 475 MW for this study to illustrate the effects of increasing turbine size and decreasing the number of turbines. However, plant size (and similar parameters) can be varied and all submodules automatically adjust to install additional turbines. Site parameters were the same as in Section 3.2 and are shown in Table 1. Cable costs from [Ioannou et al., 2018a] were used to calculate the total system capital cost, shown in Fig. 4.

Table 5. Summary of turbine data.

Capacity (MW)	Rotor Diameter (m)	Hub Height (m)	Number of Turbines
6	155	100	80
8	180	112	60
10	205	125	48
12	222	136	40
15	247	149	32

As the size of the turbine increases, the turbines are spaced farther apart, increasing the interturbine cable length for the array system. However, this is offset by the decrease in the total number of turbines, shown in Fig. 4. Total array system cable length decreases from 65-km to 35-km as the turbine rating increases from 6-MW to 15-MW; the varying lengths of the individual cable types defined for the strings are also calculated and plotted; the larger diameter cable (630-mm) can carry more power than the smaller cable (400-mm), but comes with an increased cost. As the turbine size increases, more of the 630-mm cable is required to support the additional power transmitted along each string. The higher percentage of more expensive cable reduces the cost savings realized between 8-MW and 12-MW; however, 15-MW

turbines require fewer strings and the 630-mm cable length drops. This particular scenario still demonstrates a monotonic decrease in cable CapEx for increasing turbine size; however, this is not necessarily true for other projects with different cable types or site characteristics. ORBIT is capable of evaluating these costs and determining potential breakpoints in cable costs associated with turbine rating.

The results plotted in Fig. 5 extend this analysis to include the implications of larger turbines in the installation process. The total array system installation time decreases from 1,250 h to 600 h because the cable installation vessel has fewer turbines at which to terminate the cable as well as a net decrease in the total length of cable to be installed. This time reduction is also reflected in a decrease in installation cost, from \$20 million to \$8 million. The total cost for the installed system (CapEx and installation) decreases from \$60 million to \$30 million as the turbine increases from 6-MW to 15-MW. While further investigation is necessary, these preliminary results support the industry trends toward larger turbines in order to decrease installation times and costs. ORBIT aims to incorporate this level of modeling fidelity for both the design and installation of all systems within an offshore wind power plant, ensuring that the impact of design choices with competing cost effects is quantitatively evaluated.

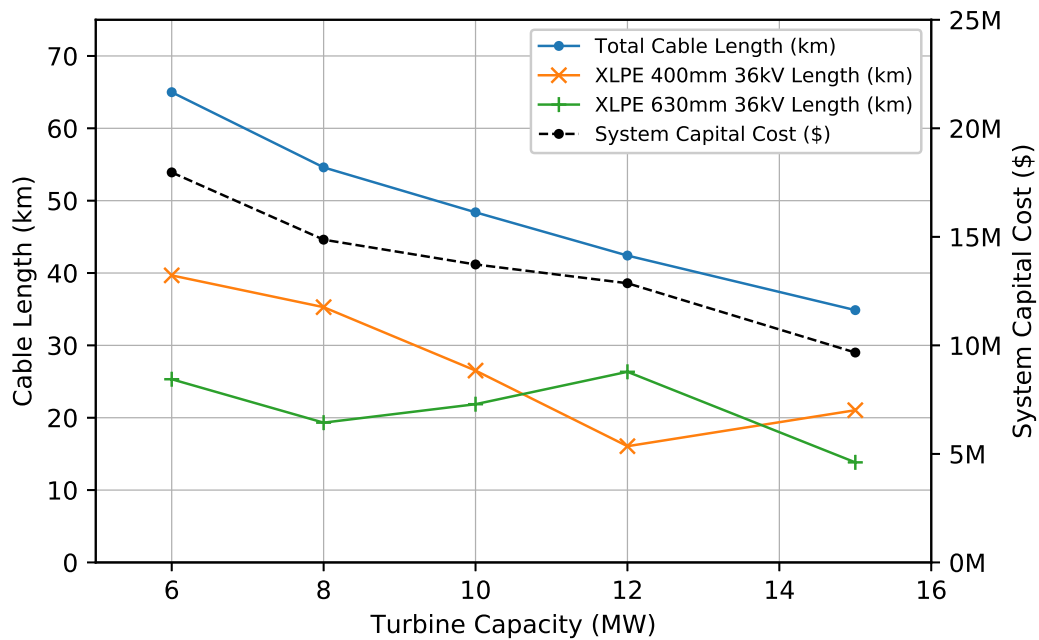


Figure 4. Array cable system size and total capital cost with increasing turbine size. Plant size is held constant at 475 MW.

4. Conclusion

This paper has presented the ORBIT model, newly developed by the National Renewable Energy Laboratory to estimate the BOS capital and installation costs of offshore wind power plants. The model features first-order design tools for sizing substructures, cables, and the offshore substation, as well as a time series installation simulation framework for computing construction times, costs, and delays. The Python code is structured to append new technologies or installation strategies, which can be compared with more conventional solutions. This

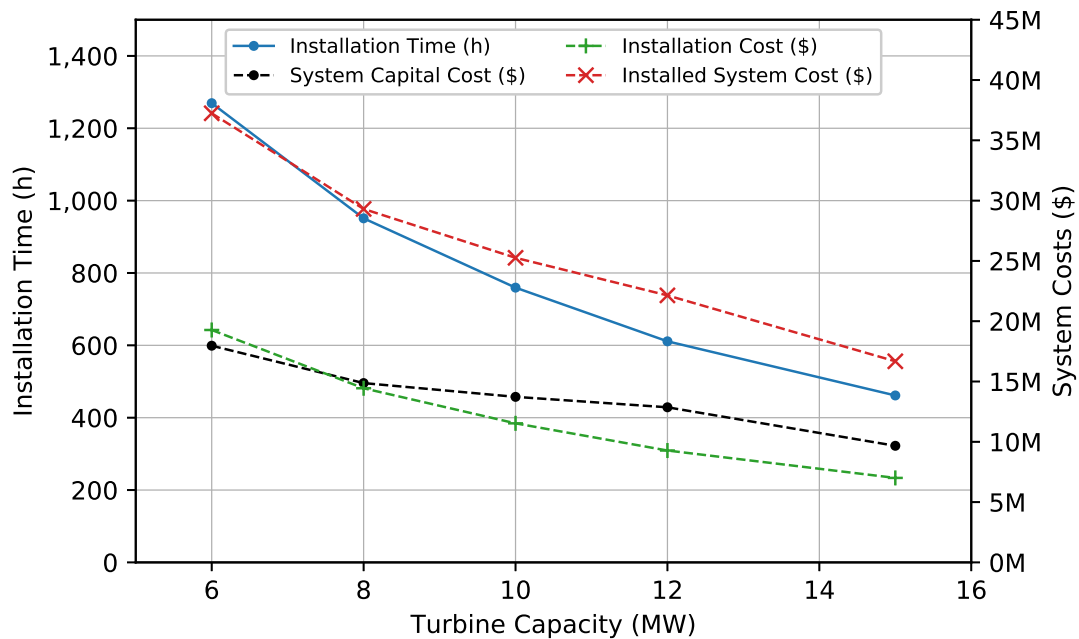


Figure 5. Array cable system installation time and total system costs with increasing turbine size. Plant size held constant at 475 MW.

architecture allows ORBIT to perform cost-benefit analyses for key aspects of the balance-of-system both for analyzing the current state of the industry and for evaluating the impact of proposed innovations on project cost; furthermore, as an open-source code, ORBIT has the potential to be widely used by a range of industry stakeholders. The model has been reviewed by members of the offshore wind industry to confirm its relevance to current best practices and to rectify any issues with the methodology. In addition, the model has been calibrated against actual data from the Dudgeon wind power plant in the United Kingdom and was shown to provide a reasonable estimate of installation times for major project phases.

After the model's validity was established, ORBIT was used in two sensitivity studies to demonstrate its functionality. In the first case, monopile installation times were simulated for a range of weather scenarios and selections of installation vessels. The resulting calculation of vessel efficiencies showed that two feeder barges present the most effective solution for the site in question; conversely, adding additional barges increases costs without reducing downtime of the installation vessel. Furthermore, the ability of ORBIT to capture the risks of weather delays was demonstrated by shifting the start date of the construction phase; this feature represents a valuable tool for evaluating how contractual delays can impact the overall uncertainty, and ultimate cost, of a project. Finally, the scalability of ORBIT was demonstrated by varying turbine size for a representative project and describing the impact on array cable length, cost, and installation time. The model balances the competing effects of plant layout and collection system requirements to quantify the cost reduction potential of increased turbine capacity for the array system. These analyses represent a subset of the spectrum of analyses that can be conducted with ORBIT to identify the best approaches to reducing the cost of offshore wind in the United States.

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