ORBIT: Offshore Renewables Balance-of-System and Installation Tool

Jake Nunemaker, Matt Shields, Robert Hammond, and Patrick Duffy

National Renewable Energy Laboratory

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List of Acronyms

BNEF	Bloomberg New Energy Finance
BOEM	Bureau of Ocean Energy Management
BOS	Balance of System
CapEx	Capital Expenditure
EOG	Extreme Operating Gust
LCOE	Levelized Cost of Energy
MPT	Main Power Transformer
NREL	National Renewable Energy Laboratory
ORBIT	Offshore Renewables Balance-of-system and Installation Tool
ROV	Remote Operated Vehicle
WISDEM	Wind-Plant Integrated System Design & Engineering Model
WTIV	Wind Turbine Installation Vessel

List of Variables

W_{required}	required tonnage to load component on vessel
$W_{\text{available}}$	available tonnage of a vessel
S_{required}	required deck space to load component on vessel
$S_{\text{available}}$	available deck space of a vessel
t_{transit}	vessel transit time
$t_{\text{jack-up}}$	vessel jack-up time
$d_{\text{port\_to\_site}}$	distance from port to site
s_{vessel}	vessel transit speed
$s_{\text{extension}}$	jacking system extension speed with no load
s_{lift}	jacking system extension speed with vessel load
e	jacking system extension
d_{site}	site depth
s_{crane}	crane lift speed
t_{upend}	time required to upend monopile on deck
$l_{\text{embedment}}$	monopile embedment length
l_{monopile}	total monopile length
t_{drive}	monopile drive time
r_{drive}	monopile drive rate
N_{sections}	number of tower sections
$t_{\text{lift,section}}$	time required to lift a tower section
$t_{\text{lift,hub}}$	time required to lift a component to hub height
h_{hub}	turbine hub height above mean sea level
$l_{\text{available}}$	length of configured cable that can be loaded on the vessel
λ_{cable}	linear density of a cable
P_P	plant power capacity
d_R	turbine rotor diameter
d_{turb}	spacing between adjacent turbines on a string
d_{row}	spacing between strings (used for rectangular grid layout)
V_r	rated line-to-line voltage
I_r	rated capacity at desired burial depth
R_{AC}	resistance at 90°C and 60 Hz
L_{AC}	inductance
F_{AC}	capacitance
m_{cable}	mass of cable in air
C_{cable}	unit cost for cable
Z	characteristic impedance
Λ	integral length scale
ρ	air density
γ_L	load factor
γ_M	pile material factor
η_h	horizontal coefficient of subgrade reaction
A_r	swept area of rotor
AS_{cost}	offshore substation ancillary system costs
BG_{cost}	offshore substation backup generator costs
C_T	thrust coefficient
D_p	pile diameter
f_{yk}	pile material yield strength

$F_{wind,EOG}$	horizontal force caused by the extreme operating gust at rated wind speed
K	Weibull scale parameter
I_p	second area moment of inertia for pile cross section
l_{air}	length of air gap above mean sea level
L_p	pile embedment length
$\mu_E OG$	50-year extreme operating gust
n_{MPT}	number of main power transformers
MPT_{cost}	cost of main power transformers
MPT_{rating}	main power transformer rating
n_{turbines}	number of turbines in the project
$OSS_{\text{assemb cost}}$	offshore substation assembly cost
$OSS_{\text{sub mass}}$	mass of the offshore substation substructure
$OSS_{\text{sub mass, pile}}$	mass of the required piles for the offshore substation substructure
$OSS_{\text{sub cost}}$	cost of the offshore substation substructure
$OSS_{\text{sub cost rate}}$	cost rate associated with the primary substructure material
$OSS_{\text{sub pile cost rate}}$	cost rate associated with the required pile material
OSS_{cost}	total cost of the offshore susbtation(s)
OA_{cost}	other ancillary system costs associated with the offshore substation
P_{error}	percentage error
r_{turbine}	turbine rating in MW
S	Weibull shape factor
SR_{cost}	cost of the shunt reactor for the offshore substation
$shunt\_reactor_{\text{cost\_rate}}$	cost rate of the shunt reactor for the offshore substation
SG_{cost}	cost of the switchgears for the offshore substation
$SG_{\text{cost rate}}$	cost rate of the switchgears of the offshore substation
t_p	pile thickness
$t_{predicted}$	predicted phase installation time
$t_{reported}$	reported phase installation time
TS_{mass}	mass of the topside
TS_{cost}	cost of the topside
$TS_{\text{assemb factor}}$	topside assembly factor
$U_{\text{10,50-year}}$	50-year maximum 10-minute mean wind speed
U_R	rated wind speed
WS_{cost}	offshore substation work space cost
z_{hub}	turbine hub height

Executive Summary

This report describes the Offshore Renewables Balance-of-system and Installation Tool (ORBIT), the National Renewable Energy Laboratory's newly released model for assessing the balance-of-system (BOS) costs of an offshore wind power plant. BOS costs include the capital costs of all project components other than the turbine's rotor nacelle assembly, tower, and all installation and project development costs. The costs of these components typically contribute more than 50% of the overall project capital expenditures for offshore wind projects. ORBIT is a medium-fidelity, bottom-up, design trade-off tool that computes BOS costs for a theoretical project and can be used to evaluate the impact of technological and process innovations relative to baseline project scenarios. The model is open source and is intended to provide a tool for offshore wind industry stakeholders to evaluate the impact of project design decisions and installation strategies on BOS costs.

ORBIT uses simple and scalable representations of major project components, such as the turbine substructure, electrical system infrastructure, and offshore substation. These first-order designs are lower fidelity than those produced by detailed engineering models, but they provide reasonable estimates of component costs, sizes, and masses using a limited number of user inputs. More importantly, these estimates scale with key project design parameters—such as plant capacity, turbine rating, and site characteristics—which enables comparison of BOS costs for different project configurations. ORBIT also simulates the installation process of the offshore wind project on an hourly timescale. A user can customize the number and type of installation vessels, the weather conditions throughout the duration of the installation, the operational constraints of vessels and/or individual operations, and the start dates and sequencing of major installation phases. The model outputs component size, mass, costs, installation times, and associated weather delays.

This report details the functionality, background theory, and performance of ORBIT. It begins by providing a top-level description for the motivation and requirements of the publicly available BOS model. The report describes the detailed installation methodologies for the different phases of the project and the underlying theory used to size components. Finally, the report includes a summary of the external review process along with a representative set of results demonstrating the functionality of the ORBIT simulation engine.

ORBIT is continuously under development, with new functionality and updated methodologies frequently being introduced into the model. This report corresponds to the current publicly available version of the model, ORBIT v0.4.2, which is available at https://github.com/WISDEM/ORBIT. The reader is referred to the GitHub repository for the most current version of the software along with online code documentation and notifications of major model changes.

Table of Contents

List of Figures

List of Tables

Introduction

Offshore wind energy has developed into a robust industry with more than 22,000 MW of installed capacity and a global pipeline of 272,000 MW as of the end of 2018 (Musial et al., 2019). This growth has been characterized by rapidly evolving technologies, including larger turbines, which have contributed to a significant reduction in electricity prices (Musial et al., 2019), and it provides an encouraging long-term outlook for offshore wind. The U.S. Department of Energy has targeted 86 GW of installed offshore wind capacity by 2050 (DOE, 2015). Still, the offshore wind industry must address many challenges to realize this target.

This report describes the Offshore Renewables Balance-of-system Installation Tool (ORBIT), a new model developed by the National Renewable Energy Laboratory (NREL) to evaluate the balance-of-system (BOS) costs associated with offshore wind projects. In the context of wind energy projects, BOS costs encompass all expenses required to construct a project other than the capital expenditures (CapEx) of the turbines and towers; BOS costs include the procurement costs for all other components (such as substructures, cables, and electrical infrastructure), offshore and land-based construction costs, port costs, site surveying fees, permitting fees, and leasing fees (BVG Associates, 2019). BOS costs significantly contribute to the levelized cost of energy (LCOE) for offshore wind, typically comprising more than 50% of the CapEx for a fixed-bottom offshore wind project and 60% for a floating project (Stehly et al., 2018). In addition, technology solutions and installation methods vary drastically among projects because they are impacted by factors such as vessel availability, geographic considerations, and site geotechnical conditions (Kaiser and Snyder, 2012). These effects require a model with appropriate fidelity to understand how these costs scale as turbine rating increases and the offshore wind supply chain, particularly offshore construction vessels, is expanded. For offshore wind, cost savings attributed to increased turbine rating are realized primarily through BOS procurement and project installation as projects require fewer substructures and less cable (BVG Associates, 2019). BOS costs represent both a modeling challenge and an opportunity for project developers to optimize solutions to reduce costs. It is critical to understand how these costs are affected by novel technologies, innovative installation processes, and operational constraints to identify meaningful cost reductions for offshore wind energy.

Offshore Wind Balance-of-System Modeling Approaches

Balance-of-System Components

The top-level components comprising the BOS are summarized as follows:

- BOS CapEx components:
  - The *substructure* connects the wind turbine tower to the seafloor. This report considers the foundation (the direct connection to the seafloor) to be part of the substructure.
  - The *array cables* connect individual turbines through strings of cable and transfer generated electricity to the offshore substation.
  - The *offshore substation* collects the electricity generated by individual turbines and transfers it to the onshore distribution system through the export cable system.
  - The *export cables* connect the offshore substation with the onshore distribution system.
- Installation costs:
  - The *vessel costs* are the rates paid to the installation vessels based on their time spent at sea or in delays as a result of adverse weather.
  - *Port fees* are paid to rent space at a construction port, which can include staging components and loading them onto installation vessels using port crane infrastructure. This can also include entrance/exit fees to access port infrastructure.
- Development costs:

– *Auction fees* are paid by the developer to the U.S. Department of Interior Bureau of Ocean Energy Management to obtain rights to develop the site.

– *Permitting and surveys* are conducted by the developer after obtaining site control to be granted permission by the Bureau of Ocean Energy Management to begin construction.

– *Commissioning* is the process by which the wind power plant is tested and approved to begin producing power.

– *Decommissioning* is the process by which the wind power plant is taken down at the end of its life.

This is not a comprehensive list of every BOS component for an offshore wind project; however, these items represent common primary BOS cost drivers for LCOE and should be considered in any modeling approach. The reader is referred to BVG Associates (2019) for a more detailed description of offshore wind BOS.

Balance-of-System Cost Modeling Approaches

A number of modeling approaches exist in the offshore wind literature to evaluate BOS costs. These models typically estimate costs using one (or more) of three techniques: expert elicitation, cost curves/regression to empirical data, or bottom-up analysis.

Expert elicitation solicits available data from industry practitioners related to the costs associated with offshore wind projects. The resolution of these data varies among models. For example, Wiser et al. (2016) obtained expert estimates of LCOE, CapEx, operational expenditure, capacity factor, and financing costs for hypothetical fixed-bottom and floating projects expected to be built between 2020 and 2050. Kempton, Levitt, and Bowers (2017) used more granular data by obtaining direct quotes from contractors for a conceived project off the coast of Delaware. Their work discretizes costs into more specific categories, including the turbine, foundation, sea work, and electrical. This approach is taken with even higher granularity by Valpy et al. (2017), in which the surveyed experts provided anticipated cost reductions for more than 50 cost categories relative to baseline values. Because the results from expert elicitation are obtained directly from industry practitioners, they can provide an estimate cost of a representative project. These data points can be accurate for specific projects, but they do not easily translate to alternate project locations, nor do they allow the modeler to compare the effects of different technologies or installation strategies. The expert elicitation approach is often used to project future costs, as in Wiser et al. (2016) and Valpy et al. (2017), so it is difficult to explore different deployment or technology scenarios because the elicitations are specifically tuned to the representative project definition.

Another strategy is to compile data from a range of projects and develop cost curves using regression methods. These cost curves parameterize desired outputs such as LCOE or CapEx in terms of a range of project-specific parameters. This approach was taken by Ioannou, Angus, and Brennan (2018), who characterized CapEx, operational expenditure, and LCOE in terms of turbine rating, water depth, distance to shore, and plant capacity to demonstrate key sensitivities of the cost variables. This approach was taken to develop parts of the prior NREL Offshore Balance-of-System Model (Maness, Maples, and Smith, 2017), which solicited cost estimates for more than 100 offshore wind cost components. These data were used either directly in cost calculations or to develop engineering models for component costs and installation times. This model served as the basis for analyses conducted in Beiter et al. (2016). Cost curves offer insight into how costs vary among different projects and how costs will scale with standard parameters such as turbine choice and water depth. Similar to the expert elicitation approach, this method does not easily permit a modeler to evaluate the impact of innovations because the cost curves implicitly depend on a specified set of technology assumptions. Further, the applicability of the model to a specific site of interest depends on the accuracy of the regression fit.

The last technique is bottom-up cost modeling, which involves developing cost estimates or engineering models for constituent components of an offshore wind power plant to obtain total project costs. An example of this approach is taken in Bortolotti et al. (2019) to derive the cost of fabricating 30-m to 100-m blades by estimating the direct costs of labor, overhead, buildings, tooling, equipment, maintenance, and material costs. The bottom-up approach can also be used to estimate costs for an overall project, such as the study done by Ioannou, Angus, and Brennan (2018) to evaluate the life-cycle costs for a fixed-bottom offshore wind project. The clear advantages of a bottom-up modeling approach are the ability to evaluate costs at high resolution and to introduce new technologies or innovations into the model to determine how they impact the overall project. The drawbacks of this methodology are the added complexity, the additional opportunities for errors or inaccuracies, and the amount of required data.

ORBIT Scope and Report Overview

ORBIT is designed as a medium-fidelity trade-off tool that builds on the capabilities of the original NREL BOS model. The goal of this model is to evaluate how major BOS costs vary as project characteristics, technology solutions, and installation methodologies change. This requires component designs (such as substructures and cable layouts) to scale as project parameters (such as turbine rating, plant size, and water depth) vary.

The model permits a modular investigation into constituent cost components not possible with the expert elicitation and cost curve approaches. First, ORBIT takes a process-based approach to modeling the installation process, which was not a feature of the prior NREL models and allows the user to directly compute the impact of weather delays on the project installation time. Further, sequencing between different installation phases can be imposed by the user to understand the impact on the overall installation time line. ORBIT is an open-source model written in Python and is intentionally designed to permit users to introduce new technologies or strategies into the model to compare them to the user-defined scenarios. This design also allows integration with NREL's system design tool Wind-Plant Integrated System Design & Engineering Model (WISDEM) (NREL, 2015), which enables the ability to run system-level engineering and cost optimizations of a wind power plant. Finally, analysts updated the input cost parameters to represent recently installed offshore wind projects.

This report details the functionality of ORBIT v0.4.2 and provides the underlying engineering process models used to size components such as substructures and cables. The simulation framework, which is used to model all installation processes and evaluate weather delays, is described at a high level followed by specific installation procedures of each component. Finally, model reviews and demonstrations are provided to demonstrate the accuracy and flexibility of ORBIT. The open-source code can be accessed through the WISDEM GitHub organization (https://github.com/WISDEM/ORBIT); future releases of the model, which will enable ORBIT to evaluate jacket and floating substructures, will become available in the same GitHub repository. Note that ORBIT is continuously under development, and a number of the modules described in this report will be periodically improved. ORBIT users are encouraged to refer to the GitHub repository for the most recent version of the code and associated online documentation.

1 ORBIT Functionality

ORBIT is designed to enable researchers, students, and academic partners to model the offshore wind BOS process by configuring a wind power plant and simulating its design and installation. Modules in ORBIT represent the design and procurement of required components of an offshore wind plant (e.g., substructures and electrical infrastructure) as well as the installation of these components (e.g., substructure installation and cable installation). Each module has been developed to consider the relevant engineering constraints and broad scaling trends expected as the offshore wind industry develops. As such, each module dynamically calculates component costs, installation times, and vessel downtime resulting from weather based on a configured set of inputs. The following modules are available:

- Project development: upfront capital costs associated with project development, e.g., lease auction price, site assessment, environmental review
- Monopile design: monopile sizing tool
- Scour protection design: scour protection material scaling tool
- Array system design: designs an array system given the input plant layout, cable types, and site parameters
- Export system design: designs an export system based on input cable type, site parameters, and interconnection voltage
- Offshore substation design: sizes an offshore substation and substructure based on input electrical parameters, site parameters, and project capacity
- Monopile installation: simulates the installation of monopiles and transition pieces
- Scour protection installation: simulates the installation of scour protection material
- Array system installation: simulates the installation of array system cables at a site
- Export system installation: simulates the installation of export system cables and land-based construction required for interconnection
- Offshore substation installation: simulates the installation of the offshore substation(s)
- Turbine installation: simulates the installation of turbines at the site.

Note that each module is optional and user-configurable. For example, installation modules can often simulate different installation strategies.

1.1 Discrete Event Simulation

To simulate the the installation processes, ORBIT uses a discrete event simulation framework in which the operations of a collection of agents are modeled as a discrete sequence of events. In the context of the offshore wind BOS processes, each major vessel involved in the installation of a subsystem is modeled as an individual agent with its own list of discrete tasks to complete. For example, the installation of a rotor nacelle assembly using a wind turbine installation vessel (WTIV) at the project site could be discretized by the following tasks:

- Load turbine components at port.
- Transit to site.
- Release tower section from deck.
- Upend, lift, and position section above substructure.
- Attach section to substructure.

- Repeat for remaining tower sections.
- Swap crane lifting equipment.
- Release nacelle from deck.
- Lift nacelle to hub height and position above tower.
- Attach nacelle to top of tower.
- Release Blade 1 from deck.
- Lift blade to hub height and position at hub.
- Attach blade to hub.
- Release Blade 2 from dec.
- (continued)
- Installation is complete when all components are installed.
- Transit back to port.

Although this list does not fully capture all the detailed process steps required to install a rotor nacelle assembly at sea, it splits the installation process into a manageable number of discretized tasks that can be modeled individually. The framework of ORBIT extends this principle, applying operational constraints to each task and allowing the effects of weather, wildlife interactions, and interactions with other vessels to be studied temporally. Each installation module in ORBIT uses these concepts, building a set of discrete tasks and constraints that represent the installation of a subsystem of the offshore wind plant.

1.2 User-Defined Installation Vessels

As outlined, ORBIT includes the ability to model individual vessels of an installation process. These vessels can be defined and configured to represent vessels currently available or vessels that might be available in the future. This functionality allows the user to study the impacts of new vessels on the installation time and weather downtime. For example, an increase in vessel storage capacity directly affects the number of substructure components that a vessel can transport during an installation simulation.

To facilitate this type of analysis, ORBIT splits the vessel definition into multiple subsystems (e.g., crane, jacking system, and storage). These subsystems change how the vessel is configured and allow the vessel to perform related tasks. The following subsystems are currently available in ORBIT:

- Crane: Allows the vessel to perform primary offshore lifts required for monopile and turbine installation. The crane must be configured with a maximum lift capacity, hook lift height, and maximum operating wind speed.
- Jacking system: Allows the vessel to jack-up to a stable working platform at sea, allowing the vessel to lift and install heavy components. Currently required for monopile and turbine installation modules. The jacking system configuration is based on a maximum leg extension, maximum operating depth, and a maximum operating wave height.
- Vessel cargo capacity: This system allows the vessel to transport objects from the port to the site. The capacity of this system is parameterized by cargo weight capacity (tonnage), deck space available (m^2), and deck loading limits (kg/m^2).
- Cable storage: This system allows the vessel to transport spooled cable from the port to the site. The capacity of this system depends on the cargo weight capacity of the vessel and the capacity of the cable spool. This system represents specialized cable spools found on cable installation vessels.

Two vessel types are referenced frequently in this report: a WTIV and a feeder barge. Using these available components as context, a WTIV is equipped with a crane, jacking system, and vessel storage; a feeder barge is outfitted with a jacking system and vessel storage.

1.3 Jones Act

The legal landscape in the United States presents additional challenges to the offshore wind installation industry. In particular, the Jones Act of 1920 prohibits foreign-flagged vessels from transporting goods between U.S. ports. This presents a challenge for the installation of U.S. offshore wind plants because no current U.S.-flagged vessels are capable of installing the larger components, i.e., turbines and foundations. Further descriptions of these implications are discussed in Douglas Westwood (2013).

It is expected that installation strategies involving feeder barges will be used to adhere to the restrictions of the Jones Act. Internationally flagged vessels are required to travel to the project site and wait for U.S.-flagged feeder barges to transport components from the U.S.-based construction port to the project site. ORBIT was designed with these logistical complexities in mind to allow the user to simultaneously explore weather effects and required vessel interactions.

1.4 Customizable and Scalable Process Times

Process times in ORBIT are a mix of constant values and dynamic engineering models based on a combination of component size (length, mass, etc.), vessel design (maximum lift capacity, maximum lift height, transport, speed, etc.), geospatial parameters (depth, distance to port, etc.), as well as the current operating conditions at the site (wind speed and significant wave height). A user can either implement the default process values defined or computed in ORBIT or can override these with their own inputs to better reflect a particular project. Throughout the simulation, each process performed by a vessel is modeled using the framework described in Section 1.1. Section 1.6 covers the default constant values and the underlying equations used in each installation module.

1.5 Detailed Accounting of Weather Delays

Meteorological ocean (metocean) conditions are an important driver of the duration, cost, and uncertainty in the installation of offshore wind projects. The operational limits of a vessel (e.g., average significant wave height and wind speed) are frequently within the range of typical sea conditions, and weather delays are common throughout the installation process. These delays also highly depend on the specific vessel because the operational limits typically vary between significant wave heights of 1.5–3.2 m and wind speeds of 12–30 m/s for installation vessels common to the industry (4COffshore, 2019h).

ORBIT considers the significant wave height and wind speed at a temporal resolution of 1 hour. To simplify the data processing and number of inputs required, ORBIT currently considers only the metocean conditions at the site when applying constraints to the operations performed by the vessel, including the transit between the installation port and the project site. This simplified approach does not consider spatially dependent weather profiles along the transit route, but it is a reasonable approximation because the most weather-sensitive operations occur at the project site.

ORBIT uses two methods to calculate weather delays for a particular process. For tasks that have a high risk associated with being interrupted (e.g., crane operations or other actions involving unsecured cargo), a vessel must wait for a complete weather window that satisfies the operational constraints for the entire duration of the work. Until this window is found, the vessel will sit idle before initiating any work. For example, for a vessel to perform 4 hours of crane work, a 4-hour window of time where the the wave height is less than the operational limit of the vessel and the wind speed is less than the operational limit of the crane must be satisfied. The vessel will time-out while waiting for an appropriate weather window, logging the time spent waiting as an operational delay. After the delay, the vessel is then cleared to proceed with the process. Operational limits in ORBIT can be either configured on a per-vessel basis or specific to the component and operation being performed. For tasks that can be interrupted (e.g., transit to/from site), the vessel will initiate the task when the weather is acceptable and shut down when conditions exceed operational limits. For interruptible tasks, the vessel might start/stop any number of times until the total amount of time required for the task is completed under acceptable weather conditions. In both cases, ORBIT assumes perfect weather forecasting, meaning that the vessel does not consider any probability in the weather profile being accurate when the next weather window is searched.

1.5.1 Crane Lift Rates

Cranes play a key role in the construction of offshore wind plants, both to load vessels and to lift components into place for installation. For safety reasons, the use of cranes in offshore environments in extreme weather is limited. ORBIT assumes that cranes can operate as long as weather conditions do not exceed vessel operational limits. The default crane lift rate in ORBIT is 100 m/h; however, this value is easily overridden by the user.

1.6 Configurable Installation and Design Modules

The installation modules in ORBIT aim to discretize the construction logistics into a set of subprocesses that represent the overall time and complexity of real-world installation as well as how these subprocesses scale with larger turbines or different site conditions. As such, the time associated with some processes is dynamically calculated, whereas others are static, user-configurable inputs. Static values are generally used where the value is not expected to change with increased turbine size, new substructures, or future development of vessel technology. For example, the time associated with a vessel positioning itself at a site is assumed to be a static value; however, these values are still configurable by the user and can be overridden to study future innovations.

To perform these installation sequences, ORBIT needs to know the relevant geometric properties of the wind plant structures to appropriately allocate component sets to installation vessels. Further, to evaluate how BOS costs and installation times scale among projects, these component designs should scale with project characteristics such as plant capacity and water depth. To facilitate this, ORBIT includes basic sizing tools for monopiles, array and export cables, offshore substations, scour protection, and project development. These modules do not approach the fidelity required for an engineering design of these components, which would vastly overcomplicate the model and require more inputs than a typical cost modeler would have data for; however, the sizing equations described in the following sections provide estimates for component sizes and masses based on user inputs, which results in values that scale among projects and better inform the installation modules.

2 Component Design Modules

2.1 Project Development

The project development module accounts for upfront permitting, review, and engineering steps that are required before construction can begin. This module does not perform any calculations and is used only as a place for the user to provide values for the time and cost associated with the project development processes.

A site auction refers to the process that a developer would undertake to lease an available offshore area. Although the the documentation of this model typically follows the nuances of the development process in the United States, this input could be configured to represent a purchase of a development area in a different market. In the United States, the price for development area leases has increased rapidly during the last few years and represents a significant portion of project CapEx (Musial et al., 2019).

The remaining configurations available represent steps a developer could take to fully develop a completed site auction. For example, the development and execution of a site assessment plan in conjunction with local stakeholders defaults to take 6 years and >$50M. The default values for these and the other configurable project development steps are presented in Table 1.

Table 1. Default Values for the ORBIT Project Development Module

Process	Completion Time (h)	Cost to Developer (USD)
Site auction	0	$100M
Site assessment plan	8,760	$500,000
Site assessment	43,800	$50M
Construction operations plan	43,800	$1M
Bureau of Ocean Energy Management review	8,760	0
Design and installation plan	8,760	$250,000

2.2 Monopile Design

The monopile design module in ORBIT allows a user to model and capture the scaling trends of monopile substructures using a limited set of inputs, without requiring a rigorous engineering design. The following section outlines the methodology used in this module, including any relevant limitations. The more detailed input variables (load factors, wind resource shape parameters, soil conditions, etc.) are not expected to be known by an average user and are assigned as defaults in ORBIT; however, all values in Eq. 2.1–Eq. 2.5 can also be overridden if project-specific data are available. The important takeaway of this section is that even with the standard defaults in ORBIT, the monopile diameter, thickness, and length will scale with rotor diameter, hub height, and water depth to size site-specific monopiles for a given project.

This model is based on initial pile dimension calculations presented in Arany et al. (2017). The pile dimensions are designed to withstand the bending moment induced by the 50-year extreme operating gust (EOG), μ_{EOG}. This corresponds to the wind scenario U-3 in Section 2.2.1 of Arany et al. (2017) and is calculated using the the cumulative density function of the site's wind speed by Eq. 2.1, where K and S are the Weibull scale and shape factors, respectively:

$$U_{10,50\text{-year}} = K(-ln(1-0.98^{\frac{1}{52596}}))^{\frac{1}{S}} \tag{2.1}$$

Using this distribution, the extreme gust $\mu_E OG$ at rated wind speed U_R can be calculated as the minimum of Eq. 2.2 and Eq. 2.3:

$$1.35(0.8U_{10,50\text{-year}} - U_R) \tag{2.2}$$

$$\frac{3.3 * 0.11 * 0.8 U_{10,50\text{-year}}}{1 + \frac{0.1D}{\Lambda}} \tag{2.3}$$

where Λ is the integral length scale, and D is the rotor diameter of the turbine. The total wind load can be calculated by Eq. 2.4 and the mud line bending moment by Eq. 2.5:

$$F_{wind,EOG} = \frac{1}{2}\rho A_r C_T (U_R + \mu_{EOG})^2 \tag{2.4}$$

$$M_{wind,EOG} = \gamma_L F_{wind,EOG}(d_{\text{site}} + z_{hub}) \tag{2.5}$$

where ρ is the air density, A_r is the swept area of the turbine, C_T is the coefficient of thrust, γ_L is the load factor, and d_{site} and z_{hub} represent the total moment arm from the mud line to the hub height.

With this calculation for the extreme operating moment, the initial pile dimensions can be calculated. An expression for the initial value of wall thickness is given Eq. 2.6, outlined in American Petroleum Institute (API) standards (API, 2005).

$$t_p \geq .00635 + \frac{D_p}{100} \tag{2.6}$$

where t_p is the initial pile wall thickness (m), and D_p is the pile diameter (m).

This inequality can be introduced into the expression for the moment of inertia for the pile, Eq. 2.7:

$$I_p = \frac{1}{8}(D_p - t_p)^3 t_p \pi, \tag{2.7}$$

to yield an equation for the pile moment of inertia as a function of pile diameter in Eq. 2.8:

$$I_p = \frac{1}{8}(D_p - 6.35 - \frac{D_p}{100})^3(6.35 + \frac{D_p}{100})\pi \tag{2.8}$$

where I_p is the area moment of inertia of the pile cross section. To avoid pile yield during the load case described, the following condition must be satisfied:

$$\sigma = \frac{M_{wind,EOG}}{I_p}\frac{D_p}{2} < \frac{f_{yk}}{\gamma_M} \tag{2.9}$$

where f_{yk} is the yield strength of the material, and γ_M is the material factor of the steel pile. The required diameter can be solved for using the combination of Eq. 2.8 and Eq. 2.9.

Using the calculated pile diameter, the required embedment length can be calculated using the following formula given by Poulos and Davis (1980):

$$L_p = 4.0(\frac{E_p I_p}{\eta_h})^{\frac{1}{5}} \tag{2.10}$$

where L_p is the embedment length of the pile; E_p is the modulus of the pile; and η_h is the horizontal coefficient of the subgrade reaction, a measure of the ability of the seabed to resist deformation caused by horizontal loading. The total monopile length can then be calculated as:

$$l_{\text{monopile}} = L_p + d_{\text{site}} + l_{\text{air}} \tag{2.11}$$

where l_{monopile} is the total monopile length, and l_{air} is the length of the air gap (the distance from mean sea level to the top of the monopile.

2.3 Array System Design

In an offshore wind power plant, the electricity generated by the turbines flows to the offshore substation via array cables. To reduce the total amount and cost of cabling required, turbines are connected to strings instead of being individually linked to the substation. The number of turbines on each string is limited by the capacity of the constituent cables, which must be able to transmit the power being produced by every connected turbine. A common design practice is to design the strings with increasing cable capacities closer to the substation to allow additional turbines to be appended onto the string. A sample turbine string is depicted in Figure 1. Reducing the overall number of strings can decrease costs by reducing the length of the cable required to connect the final turbine in the string with the substation; however, this can create competing effects because larger (and more expensive) cables are required to design a plant with fewer strings. Cable lengths and costs are also heavily influenced by the spacing between turbines and the electrical characteristics of the individual cables.

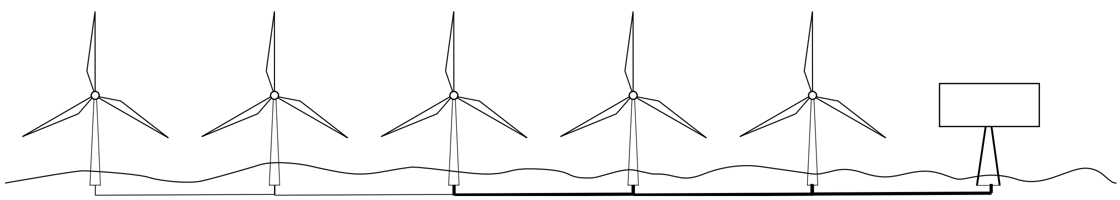

Figure 1. Turbine string with increasing cable capacity closer to offshore substation

The array system design module in ORBIT allows a user to vary input parameters such as cable type, turbine spacing, plant size, and turbine rating. It designs the strings to incorporate the maximum number of turbines that the defined cable types will allow, and then allocates all turbines in the plant to strings. Plants can orient strings in a rectangular grid, radial, or custom layout. The module then calculates the length and cost of each type of cable required for the given plant design parameters. This methodology allows cable costs to scale with project, site, and cable characteristics, which allows a user to conduct design trade-off studies by varying these parameters.

2.3.1 Input Parameters and Model Assumptions

ORBIT assumes that the array cable system transmits balanced, three-phase AC power. A user must populate the inputs described in Table 2 to design an array cable system in ORBIT.

2.3.2 Calculating Cable Power Transmission

The power capacity of each defined cable type is calculated to determine the maximum number of turbines that it can support (Manwell, McGowan, and Rogers, 2002). The cable transmission line is represented as an equivalent circuit using the Telegrapher's Equation, in which the characteristic impedance, Z, is given by:

$$Z = \sqrt{\frac{R_{AC} + jL_{AC}\omega}{\frac{1}{R_{AC}} + jF_{AC}\omega}} \tag{2.12}$$

where j is the imaginary unit, ω is the natural AC frequency, and all other parameters are defined in Table 2. This representation of the transmission line allows the active and reactive power components to be computed using per-unit-length cable specifications, thereby solving for the actual power that the cable can transmit. This useful power is defined using the power factor, PF, of the cable:

Table 2. Default Values for the ORBIT Array System Design Module

Parameter	Units	Symbol	Description
Project and site characteristics			
Plant capacity	MW	P_p	Plant power capacity
Turbine rating	MW	r_{turbine}	Individual turbine rating
Rotor diameter	m	d_R	Turbine rotor diameter
Turbine spacing	Rotor diameters	d_{turb}	Spacing between adjacent turbines in a string
Row spacing	Rotor diameters	d_{row}	Spacing between strings (Only used for rectangular grid layout)
Water depth	m	d_{site}	Average water depth at site
Individual cable characteristics			
Rated voltage	kV	V_r	Rated line-to-line voltage
Current capacity	A	I_r	Rated capacity at desired burial depth
AC resistance	Ohms/km	R_{AC}	Resistance at 90°C and 60 Hz
Inductance	mH/km	L_{AC}	Inductance
Capacitance	nF/km	F_{AC}	Capacitance
Mass	kg/km	m_{cable}	Mass of cable in air
Cost	$USD/km	C_{cable}	Unit cost for cable

$$PF = \cos\left(\tan^{-1}\left(\frac{Im(Z)}{Re(Z)}\right)\right) \tag{2.13}$$

For a balanced three-phase AC power line with power per i^{th} phase of $P_i = V_r I_i \cos\phi$ and a total current of $I_r = \sqrt{3}I_i$, the total power transmission through the cable at rated current and voltage is:

$$P_{\text{cable}} = 3P_i = \sqrt{3}V_r I_r PF \tag{2.14}$$

2.3.3 Defining String Properties

The maximum number of turbines that an individual cable can support is given by:

$$n_{t,i} = \left\lfloor \frac{P_{\text{cable}}}{r_{\text{turbine}}} \right\rfloor \tag{2.15}$$

ORBIT conducts the following algorithm to define a string:

1. Calculate $n_{t,i}$ for all cable types defined by the user.
2. Assign $n_{t,1}$ turbines to the smallest cable type; this will be the part of the string farthest from the substation.
3. Compute the number of turbines that can be added to the next largest cable in the string as $n_{t,2}$ - $n_{t,1}$. This accounts for the power produced by the turbines connected with the smallest cable type.
4. Repeat for all cable types defined by the user.

This process defines the number of turbines, $n_{\text{t,string}}$, and number of sections, $n_{\text{s,string}}$, of each cable type that comprise a single string in the wind power plant. The power transmission capacity of this string is then:

$$P_{\text{string}} = n_{\text{t,string}} \times r_{\text{turbine}} \tag{2.16}$$

ORBIT then calculates the number of full (n_{full}) and partial (n_{partial}) strings required to support all turbines at the wind power plant. The full strings connect $n_{\text{t,string}}$ turbines; and if there are remaining turbines required to meet the plant capacity, they are added to a single partial string. The number of full and partial strings are computed as:

$$n_{\text{full}} = \left\lfloor \frac{P_p}{P_{\text{string}}} \right\rfloor$$
$$n_{\text{partial}} = P_p \mod P_{\text{string}} \tag{2.17}$$

Full and partial string designs generated by ORBIT are shown in Figure 2 for grid and radial layouts. In both examples, turbine rating is held constant at 10 MW, and two 36-kV cables are defined with current capacities of 610 A and 750 A, respectively. The project with the grid layout is assigned a capacity of 440 MW, corresponding to 44 turbines. The project with the radial layout is assigned a capacity of 420 MW, corresponding to 42 turbines. ORBIT calculates that $n_{\text{t,string}} = 4$, meaning that the radial plant layout will require one partial string. The ORBIT-determined layouts for these two examples are shown in Figure 2. Further, the transition from the smaller to the larger cable is required only to complete the link from the string to the substation. The partial string requires only the smaller cable. These calculations are automatically performed in ORBIT, meaning that string designs and the associated cable lengths scale with the plant design.

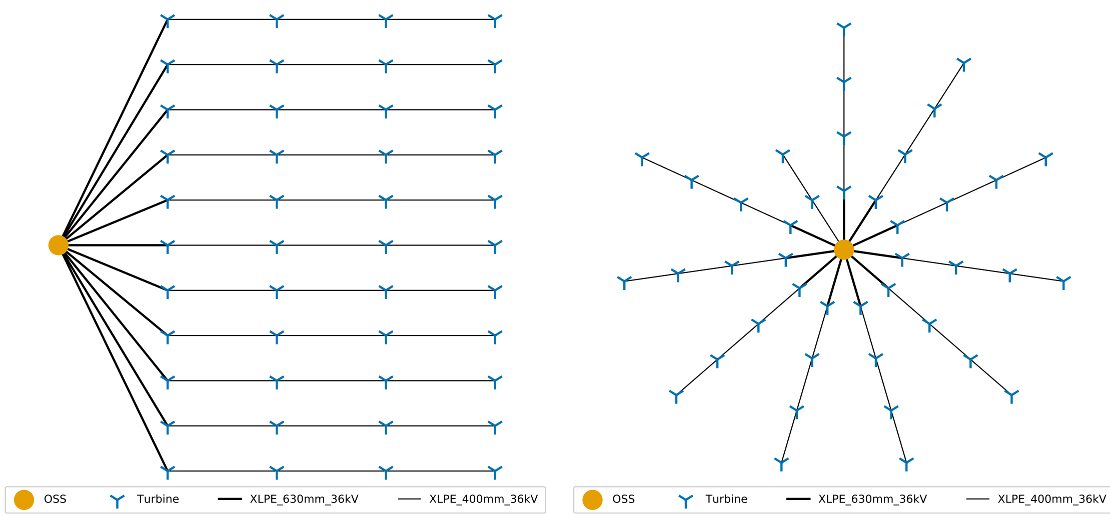

Figure 2. ORBIT plant designs for a rectangular grid layout with 44 turbines (left) and a radial plant layout with 42 turbines (right).

ORBIT also allows a user to input a .CSV file with customized substation and turbine locations, cable segment lengths, and cable burial speeds; these input values override the cable lengths calculated in this section. This method requires the user to know a priori how many turbines can be allocated to a given string.

2.3.4 Determining Cable Lengths and Costs

The final step in the array system design module is to calculate the total length of the cable required to connect all the turbines in the wind power plant. Overall cable lengths are calculated by adding the segments that connect individual turbines; this makes it possible to separate the lengths of each type of cable used to create a string. The length of each segment, l_{seg}, is given by:

$$l_{\text{seg}} = 2 \times d_{\text{site}} + (d_R \times d_{\text{turb}} \times (1 + exclusion)) \tag{2.18}$$

where *exclusion* represents an additional factor to account for added length resulting from exclusion zones (environmental, geotechnical, etc.) at the site.

The parameters used to calculate Eq. 2.18 are provided in Table 2. This simple representation assumes that the cables run from the mean waterline to the seafloor at each turbine and that they are linearly connected between the turbines. These lengths are therefore affected by the assumed turbine spacing, d_{turb}.

The distance from the final turbine in the string to the offshore substation must also considered. If the user selects a grid layout, the distance from each string to the substation is calculated as the hypotenuse of the right triangle located between the end of the string, the midpoint of the plant, and the substation. This requires the spacing between rows, d_{row}, to be defined. The substation is assumed to maintain the same spacing in the horizontal direction as the individual turbines in the string, i.e., $d_R \times d_{\text{turb}}$, and it is located at the geometric center of the vertical direction.

If the user selects a radial layout, the substation is located at the geometric center of the plant, and the direct displacement between the final turbine and the substation is again assumed to be $d_R \times d_{\text{turb}}$. In this case, the radial spacing between strings does not affect the cable length required to connect each string to the substation.

Finally, the total capital cost of the array cable system is calculated by multiplying the total length of each cable type, l_i, by its unit cost, $C_{\text{cable,i}}$, and combining the results for all N cable types:

$$C_{\text{cable}} = \sum_{i=1}^{N} l_i \times C_{\text{cable,i}} \tag{2.19}$$

2.4 Export System Design

The power collected at the offshore substation is transmitted onshore via export cables and then connected to the local electric grid. A typical offshore wind project has two to three export cables buried separately under the seafloor; the cable route must avoid underwater obstructions, such as fishing areas, extreme terrain, or shipwrecks. Sizing export cables involves a trade-off between capital costs and redundancy; adding capacity or extra cables allows a wind power plant to transmit power to shore in case of a failure of an individual cable, but the costs of these cables are high. Most projects installed to date have used HVAC export cables; however, HVDC export systems have recently gained interest for longer transmission distances (typically more than 100 km) because no reactive power compensation is required, which reduces costs and electrical losses (Beiter et al., 2016). ORBIT currently assumes HVAC transmission, although a future version will extend the model to include HVDC solutions.

The export system design module in ORBIT allows a user to define the characteristics of the export cable and determines the number of cables required to support the plant capacity. In an actual offshore wind project, the export cables are custom designed to account for varying geotechnical conditions (and the resulting heat transfer implications) along the cable route; because these extensive geotechnical data are not commonly available, ORBIT assumes a constant composition along the length of the export cable. It also requires information about the linear distance from the project to the cable landfall location; a user can adjust a redundancy parameter to increase this length and thus account for any potential underwater exclusion zones. Export cable design trade-off studies are therefore a function of project location, plant capacity, and cable composition.

2.4.1 Input Parameters and Model Assumptions

ORBIT assumes that the export cable system transmits balanced, three-phase AC power; a future release will extend the model to include HVDC power. A user must define the inputs shown in Table 3 to design an export cable system in ORBIT.

The cable characteristics are used to calculate the rated power that can be transmitted by a single export cable following the method described in Section 2.3.2.

Table 3. Default Values for the ORBIT Export System Design module

Parameter	Units	Symbol	Description
Project and site characteristics			
Plant capacity	MW	P_p	Plant power capacity
Distance to landfall	km	d_l	Distance from offshore substation to cable landfall
Distance to interconnection	km	d_i	Distance from cable landfall to point of interconnection
Water depth	m	d_{site}	Average water depth at site
Cable characteristics			
Rated voltage	kV	V_r	Rated line-to-line voltage
Current capacity	A	I_r	Rated capacity at desired burial depth
AC resistance	Ohms/km	R_{AC}	Resistance at 90°C and 60 Hz
Inductance	mH/km	L_{AC}	Inductance
Capacitance	nF/km	F_{AC}	Capacitance
Mass	kg/km	m_{cable}	Mass per length of cable in air
Cost	$USD/km	C_{cable}	Unit cost for cable

2.4.2 Computing the Number of Export Cables

The export system must include a sufficient number of cables to transmit the maximum amount of power that the offshore wind power plant is capable of producing. For each cable type defined by the user, the rated power transmission through the cable, P_{cable}, is computed using Eq. 2.14. The number of cables required to transmit the rated capacity of the power plant, P_p, is then:

$$n_{\text{cables}} = \left\lceil \frac{P_p}{P_{\text{cable}}} \right\rceil \tag{2.20}$$

The ceiling operator in Eq. 2.20 requires some consideration on the part of the operator; for instance, consider a scenario in which the rated power of the export cable is computed to be $P_{\text{cable}} = 333$ MW, and the plant capacity is $P_p = 1000$ MW. Evaluation of Eq. 2.20 would require a fourth export cable that would transmit only 1% of the rated plant capacity; in reality, a project developer would simply size a slightly larger cable. ORBIT currently requires the user to check this cable efficiency, although future versions will automatically check this.

2.5 Offshore Substation Design

ORBIT includes a simple module for designing an offshore substation based on a previous model developed by NREL (Maness, Maples, and Smith, 2017). This module encompasses several regression fits of industry data, primarily parameterized by the number and size of the main power transformers (MPTs), calculated using Eq. 2.21 and Eq. 2.22:

$$n_{\text{MPT}} = \lceil n_{\text{turbines}} \times r_{\text{turbine}} \rceil \tag{2.21}$$

$$MPT_{\text{rating}} = \frac{\lceil n_{\text{turbines}} \times r_{\text{turbine}} \times 1.15 \rceil}{n_{\text{MPT}}} \tag{2.22}$$

where n_{MPT} is the number of MPTs; n_{turbines} is the number of turbines in the project; r_{turbine} is the turbine rating; and MPT_{rating} is the MPT rating. The size and cost of individual substation components are calculated as factors of these results. ORBIT supplies default factors; however, these values can also be supplied by the user. This module will see continued development in the future and will be expanded to include HVDC substation solutions.

2.5.1 Offshore Substation Cost

The total cost of the substation, OSS_{cost}, is calculated using Eq. 2.23:

$$OSS_{\text{cost}} = MPT_{\text{cost}} + TS_{\text{cost}} + SR_{\text{cost}} + SG_{\text{cost}} + AS_{\text{cost}} + OSS_{\text{assemb cost}} + OSS_{\text{sub cost}} \tag{2.23}$$

where MPT_{cost} is the cost of the main power transformers, Eq. 2.24; TS_{cost} is the total cost of the topside, Eq. 2.26; SR_{cost} is the total cost of the shunt reactors, Eq. 2.27; SG_{cost} is the cost of the switchgears, Eq. 2.28; AS_{cost} is the cost of the ancillary systems, Eq. 2.29; $OSS_{\text{assemb cost}}$ is the substation assembly costs, Eq. 2.30; and $OSS_{\text{sub cost}}$ is the cost of the substation substructure, Eq. 2.33.

2.5.2 Component Costs

The cost of the MPTs is calculated using the relationship presented in Eq. 2.24:

$$MPT_{\text{cost}} = MPT_{\text{cost\_rate}} \times MPT_{\text{rating}} \times n_{\text{MPT}} \tag{2.24}$$

where $MPT_{\text{cost\_rate}}$ is the cost of an MPT as a function of the rating. The default cost rate for the MPTs is 12,500 USD/MW.

The mass and cost of the substation topsides are calculated using Eq. 2.25 and Eq. 2.26:

$$TS_{\text{mass}} = 3.85 \times MPT_{\text{rating}} \times n_{\text{MPT}} + 285 \tag{2.25}$$

$$TS_{\text{cost}} = TS_{\text{mass}} \times TS_{\text{fab\_rate}} + TS_{\text{design\_cost}} \tag{2.26}$$

where $TS_{\text{fab\_rate}}$ is the cost of the topside fabrication parameterized by the mass of the topside (default: 14,500 USD/t), and $TS_{\text{design\_cost}}$ is the cost to design the topside (default: 4.5M USD).

The cost of the shunt reactor is calculated using Eq. 2.27:

$$SR_{\text{cost}} = \frac{n_{\text{MPT}} \times MPT_{\text{rating}} \times SR_{\text{cost rate}}}{2} \tag{2.27}$$

where $SR_{\text{cost rate}}$ is the cost rate of the shunt reactor parameterized by the total rating of all MPTs. The default value for this cost rate is 35,000 USD/MW.

The cost of the switchgear is calculated using Eq. 2.28:

$$SG_{\text{cost}} = n_{\text{MPT}} \times SG_{\text{cost rate}} \tag{2.28}$$

where $SG_{\text{cost rate}}$ is the cost rate of the required switchgears, parameterized by the number of power transformers. The default switchgear cost rate is 145,000 USD/MPT.

Ancillary system costs include any additional costs associated with backup generators, work spaces, or other systems needed in the construction of the topside. The summation of these additional costs is shown in Eq. 2.29:

$$AS_{\text{cost}} = BG_{\text{cost}} + WS_{\text{cost}} + OA_{\text{cost}} \tag{2.29}$$

where the backup generator costs, BG_{cost}, default to 1M USD; the work space costs, WS_{cost}, default to 2M USD; and other ancillary costs, OA_{cost}, default to 3M USD.

2.5.3 Offshore Substation Assembly

The cost associated with assembling the topside components on land is summarized in Eq. 2.30:

$$OSS_{\text{assemb cost}} = (SG_{\text{cost}} + SR_{\text{cost}} + AS_{\text{cost}}) \times TS_{\text{assemb factor}} \tag{2.30}$$

where $TS_{\text{assemb factor}}$ encompasses the cost adder to assemble the topside on land; this factor defaults to 0.075, but it can be configured by the user.

2.5.4 Offshore Substation Substructure

The offshore substation design module assumes that a monopile substructure will act as the base for the topsides, although a simple scaling relationship exists to consider the additional mass and cost of a jacket. The mass of the substructure is calculated using Eq. 2.31; if the substructure is a jacket, the weight of the required piles is calculated using Eq. 2.32:

$$OSS_{\text{sub mass}} = 0.4 \times TS_{\text{mass}} \tag{2.31}$$

$$OSS_{\text{sub mass, pile}} = 8 \times (OSS_{\text{sub mass}})^{0.5574} \tag{2.32}$$

The total cost of the substructure can then be calculated with Eq. 2.33:

$$OSS_{\text{sub cost}} = OSS_{\text{sub mass}} \times OSS_{\text{sub cost rate}} + OSS_{\text{sub mass, pile}} \times OSS_{\text{sub pile cost rate}} \tag{2.33}$$

where $OSS_{\text{sub cost rate}}$ is the cost rate associated with the primary substructure material (default: 6,250 USD/t for jackets and 3,000 USD/t for monopiles), and $OSS_{\text{sub pile cost rate}}$ is the cost rate associated with the required pile material (default: 2,250 USD/t for jackets and 0 USD/t for monopiles.).

2.6 Scour Protection Design

Fixed substructures installed in the seabed are subject to the erosion of seabed material around their base; this process is referred to as hydrodynamic scour. Over time, the development of scour around the substructure decreases the embedment depth and can significantly impact the structural integrity and dynamics of the substructure. Marine engineers can limit the development of scour, typically by installing a layer of rocks, sand, or similar material as protection around the base of the substructure. This layer, typically ranging from 0.3–2 m thick, decreases the ability for fine sediment to be removed by turbulent flow.

The design of scour protection in ORBIT is a simplified representation of a DNV GL standard from 2014 (DNV GL, 2014). This module is not intended to represent a full engineering design of scour protection but to capture the broad scaling trends seen in scour protection installation. As scour protection provides a relatively small contribution to the overall BOS costs, an overly complex model would not align with the intended fidelity of ORBIT; as a result, several calculations from the DNV GL standard are replaced with user inputs (BVG Associates, 2019; Catapult, 2019).

ORBIT calculates the maximum scour depth that will develop using Eq. 2.34:

$$S = 1.3D \tag{2.34}$$

where D is the monopile diameter, and S is the scour depth. This calculation assumes a steady current for simplicity. Using the scour depth calculated in Eq. 2.34 and an assumed soil friction coefficient, the radius of the scour pit can be calculated with Eq. 2.35:

$$r = \frac{D}{2} + \frac{S}{tan(\phi)} \tag{2.35}$$

where ϕ represents the soil friction angle. This value defaults to 33.5°(for medium-density sand), but it can be overridden by the user for a different sediment.

The volume of scour protection material needed for each substructure is then calculated with Eq. 2.36:

$$V = \pi t r^2 \tag{2.36}$$

where t is the user-defined depth of scour protection material installed. The total volume of scour protection ultimately impacts the installation time based on the maximum cargo capacity of the scour protection installation vessel. The value of t tends to vary between 1 m and 2 m depending on site conditions (Vineyard Wind LLC, 2018); a value of 1 m is set as the default ORBIT input. By allowing this parameter to be an input, the user can investigate the downstream effects (e.g., installation time, required vessel specifications) of increased scour protection without needing a complete design.

3 Project Installation Modules

3.1 Monopile Installation

Installation of substructures is one of the first phases to occur during project construction because the substructures are critical infrastructure that need to be in place before many other components can be installed. ORBIT currently considers only the installation of monopile substructures, but upcoming releases will be expanded to include jackets and floating substructures.

ORBIT models monopile substructures in two pieces: the monopile and the transition piece, an additional steel structure installed on the top of the monopile to provide a level platform for the tower to be installed. Monopiles are typically constrained to depths less than 60 m and might be economical only for depths less than 40 m (Musial et al., 2019). They can be installed in many geotechnical conditions, though the complexity of the installation can increase if the seafloor consists of rocky or hard material (Sevilla et al., 2014).

Monopile designs for current turbines typically range from 5–8 m in diameter, 35–75 m in length, and 450–900-t mass (Sif, 2019; Bladt Industries, 2019). Monopiles for future turbines are expected to grow to 10 m in diameter, 90 m length, and 1,300 t (Gaertner et al., 2020). Vessels with high cargo capacity are required to transport them to the site, and the installation vessel requires a crane with sufficient lifting capacity to upend them and lower them to the seafloor. The total times and costs associated with the transport process depend on the number of monopiles that can be stored on a vessel; this is constrained by the available deck space and maximum cargo capacity of the vessel.

The monopile installation module evaluates the impact of monopile size, distance to port, and vessel specifications to estimate the time and cost required to install the substructures. ORBIT models the underlying subprocesses dynamically, meaning that the total number of vessel trips required, total installation time, and overall cost scale with project size and vessel specifications. This is primarily handled by calculating the number of substructure components that can fit on a vessel based on component size and vessel parameters.

The monopile installation module can be configured to transport and install monopiles using a single WTIV, or it can be configured to use barges to transport the monopiles and transition pieces from the port to the site. An overview of the installation strategy involving a lone WTIV is shown in Figure 3. A process diagram for the installation strategy using a WTIV and feeder barges is shown in Figure 4. Subprocesses for the actual installation of the monopile are presented in Figure 5. ORBIT currently assumes that a jack-up vessel is used for monopile installation; an alternate scenario using a dynamically positioned vessel can be considered by setting the jack-up speeds to an unrealistically high value, effectively setting the jack-up time to zero.

3.1.1 Port Operations

The vessel configured for transportation of the monopile components begins the installation process at port. Depending on the installation strategy selected by the user, this could be the WTIV or a feeder barge. The number of component sets (monopile and transition piece) that can be transported on a vessel can be calculated as:

$$n_{\text{sets}} = min\left(\left\lfloor \frac{W_{\text{available}}}{W_{\text{required}}} \right\rfloor, \left\lfloor \frac{S_{\text{available}}}{S_{\text{required}}} \right\rfloor\right) \tag{3.1}$$

where W_{required} is the required tonnage for one set of components; $W_{\text{available}}$ is the current available tonnage of the configured vessel; S_{required} is the required deck space for one set of components; and $S_{\text{available}}$ is the current available deck space on the configured vessel. The $\lfloor X \rfloor$ operator signifies the floor of the argument X.

Vessels in ORBIT are currently restricted to transporting entire sets instead of making separate trips for each type of component. The vessel will then fasten each component in the number of sets calculated by Eq. 3.1 to its deck. The default fastening operation times are presented in Table 4; however, these times can be overridden by the user.

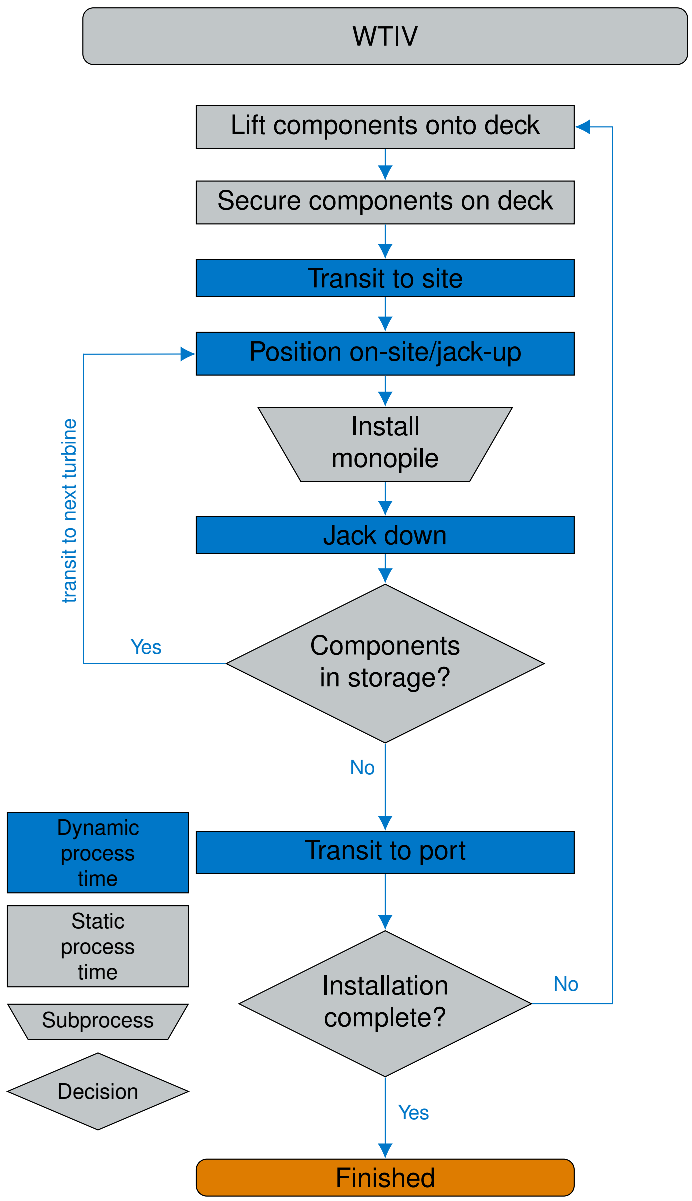

Figure 3. **Monopile installation logistics with single WTIV**

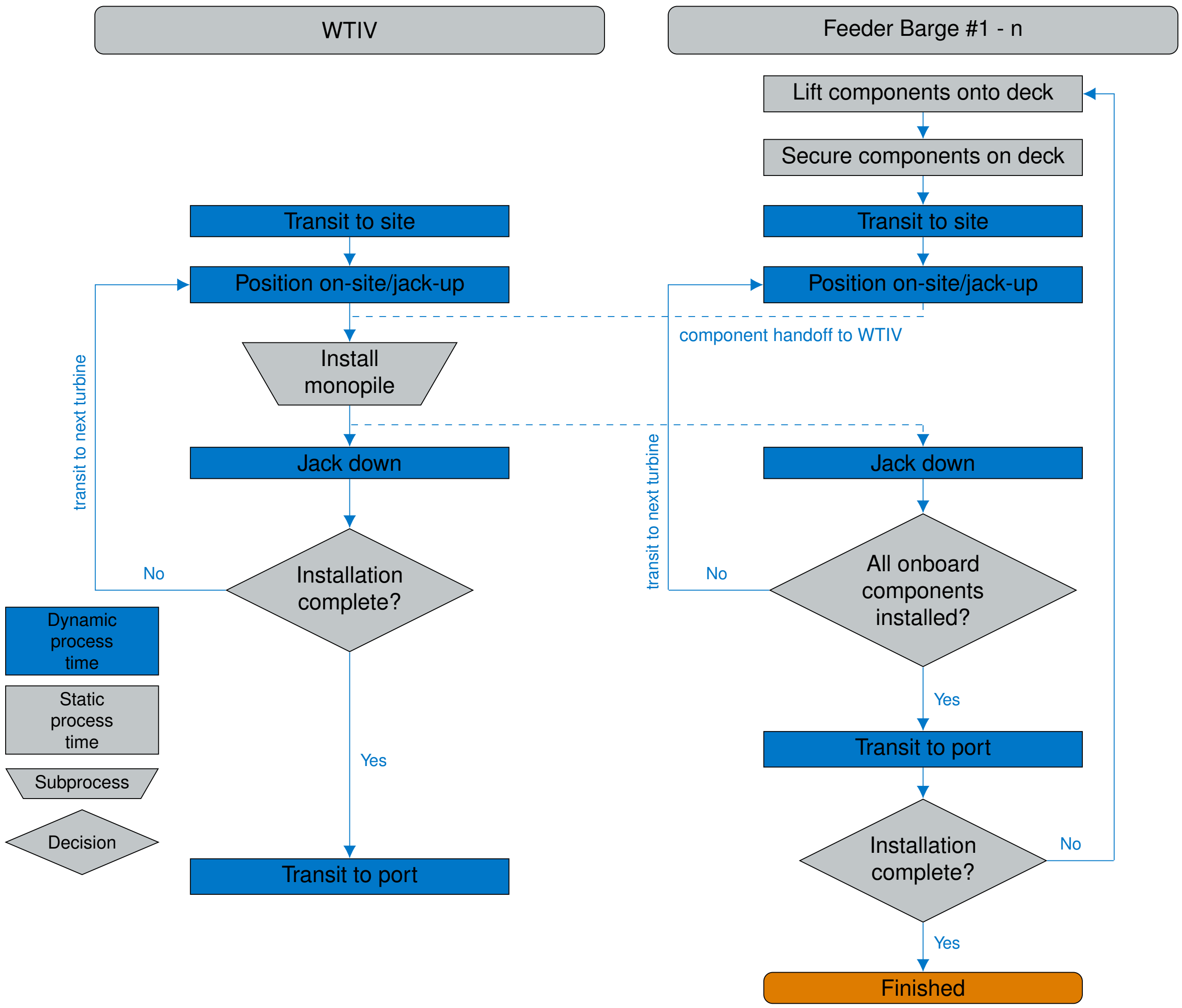

Figure 4. Monopile installation logistics with WTIV and feeder barge(s)

Table 4. Monopile and Transition Piece Static Process Times

Process	Default Time (h)
Fasten monopile on deck	12
Fasten transition piece on deck	8
Position on-site	2
Perform ROV survey	1
Release monopile from fittings	3
Release transition piece from fittings	2
Bolt transition piece	4
Grout transition piece	2
Grout cure time	24

Transit

After all possible components are fastened on deck, the transportation vessel leaves the port and transits to the site. The process time for transit is dynamically calculated using Eq. 3.2:

$$t_{\text{transit}} = \frac{d_{\text{port\_to\_site}}}{s_{\text{vessel}}} \tag{3.2}$$

where t_{transit} is the time for a vessel to transit from the port to the site; $d_{\text{port\_to\_site}}$ is the transit distance from the port to the site; and s_{vessel} is the transit speed of the transportation vessel. The transit process is treated as a suspendable task, meaning that the vessel can begin transit without needing to look for a weather window of length t_{transit} and will pause operations if the weather exceeds the operational limits of the vessel.

3.1.2 Site Preparation

Once on-site with a substructure component set (monopile and transition piece) available (either stored on the WTIV or on a feeder barge), the WTIV will begin the site preparation process by positioning itself at the substructure location, jacking-up to a stable position, and completing a remote operated vehicle (ROV) survey of the seabed. The process times for positioning and performing the ROV survey are assumed to be constant values (summarized in Table 4), whereas the time to jack-up is dynamically calculated using Eq. 3.3:

$$t_{\text{jack-up}} = \frac{d_{\text{site}}}{s_{\text{extension}}} + \frac{(e - d_{\text{site}})}{s_{\text{lift}}} \tag{3.3}$$

where $t_{\text{jack-up}}$ is the time for a vessel to jack-up; d_{site} is the site depth; $s_{\text{extension}}$ is the jacking system extension speed not under load; e is the eventual extension of the jacking system; and s_{lift} is the jacking system extension speed while lifting the vessel.

Monopile Installation

Once the vessel(s) are positioned on-site and have performed the site preparation tasks, the monopile installation process can be initiated. The subprocesses of the installation are detailed in Figure 5:

First, the monopile is released from the fittings on the vessel deck. The time required for this process is assumed to be constant throughout the installation and can be configured by the user. Default values for the release of the monopile and the transition piece from a vessel deck are summarized in Table 4. After it is released, the installation vessel will upend the monopile using the main onboard crane. Note: Ancillary vessel components that are required for operations (i.e., secondary assist crane) are not discretely modeled by ORBIT. The time required to upend the monopile is calculated using the defined lift speed (s_{crane}) and Eq. 3.4:

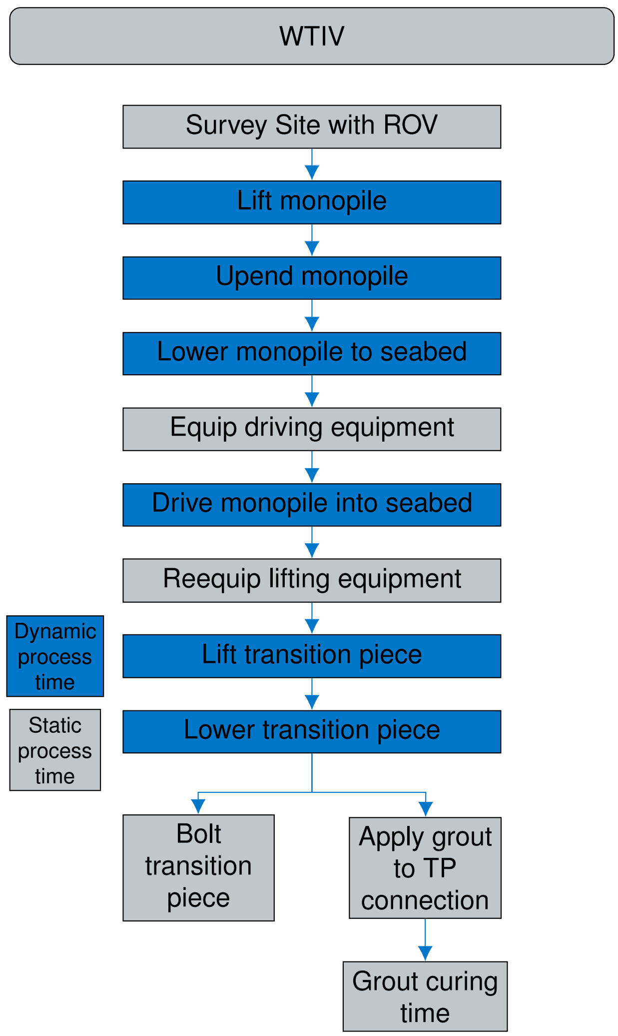

Figure 5. **Monopile and transition piece installation process**

$$t_{\text{upend}} = \frac{l_{\text{monopile}}}{s_{\text{crane}}}, \tag{3.4}$$

where t_{upend} is the time required to upend the monopile, and l_{monopile} is the total length of the monopile. Using the same crane rate, the time required to lower the monopile to the seabed is calculated with Eq. 3.5:

$$t_{\text{lower}} = \frac{e}{s_{\text{crane}}}, \tag{3.5}$$

where t_{lower} is the time required to lower the monopile to the seafloor. While holding the monopile on the seabed with the assistance of a support vessel, the driving equipment is attached to the crane with a default process time summarized in Table 4. The monopile is then driven into the seabed using Eq. 3.6 to calculate the time required for this process:

$$t_{\text{drive}} = \frac{l_{\text{embedment}}}{r_{\text{drive}}} \tag{3.6}$$

where t_{drive} is the time required to drive the monopile into the seabed; $l_{\text{embedment}}$ is the embedment length of the monopile; and r_{drive} is the rate at which the monopile can be driven. By adjusting the drive rate, an ORBIT user can implicitly account for soil and seabed conditions.

3.1.3 Transition Piece Installation

Once the monopile is driven into the seabed, the WTIV begins the installation of the transition piece. The subprocesses for the transition piece installation are also outlined in Figure 5.

After the crane equipment is changed out, the transition piece is released from the deck, lifted over the edge of the vessel, and lowered onto the monopile. By default, the transition piece is attached to the monopile with a bolted connection; however, the model can also be configured to use a grouted connection. Default process times for these actions are summarized in Table 4. It is assumed that the WTIV stays at the turbine for the duration of the bolting or grouting operations. After the transition piece is secured to the monopile, the vessel jacks-down and continues on to the next monopile installation. The jack-down process is also represented by Eq. 3.3. ORBIT loops through the processes described in Sections 3.1.1–3.1.3 until all monopiles required for the project have been installed.

3.2 Turbine Installation

Turbine installation for offshore wind plants is a complex operation that can account for nearly 10% of total BOS costs (BVG Associates, 2019). This process imparts more risk to the project schedule than the substructure installation described in Section 3.1 because it involves lifting and installing components at hub height (100–150 m above sea level), resulting in more frequent weather limitations. Despite this, the offshore wind industry is trending toward larger turbines to decrease overall BOS costs by reducing the total number of turbines for a given project size (Musial et al., 2019). ORBIT is uniquely designed to quantitatively evaluate the trade-offs and overall cost impacts associated with larger turbines.

The turbine installation phase encompasses the installation of the tower, nacelle, rotor, and blades onto an already installed substructure. Historically, there have been many methods for installing these components, varying in the amount that the turbine is preassembled at port. With smaller turbines, the nacelle, hub, and blades could be fully assembled at port and transported to the site in this configuration, decreasing the number of lifts required at sea to two: the tower and the preassembled rotor "star" (Kaiser and Snyder, 2012). Alternatively, the "bunny-ears" method involves preassembly of the nacelle, hub, and two of the blades at port; the remainder of the construction is completed at the site with as few as three lifts (tower, bunny-ears assembly, and remaining blade) (Kaiser and Snyder, 2012). It is expected, however, that these installation methods will be less relevant for larger turbines because of crane size and lifting capacity constraints. For this reason, ORBIT models the installation of turbine components one-by-one; this method involves a minimum of five lifts to hub height (tower, nacelle and hub, and three individual blades); however, for larger turbines, the tower is often split into multiple sections, resulting in additional lifts at sea. This component-by-component lifting strategy will likely be consistently employed regardless of turbine scaling, and it provides a baseline to compare future vessel and strategy development to. An image of a jack-up WTIV installing a single blade is shown in Figure 6.

Figure 6. **WTIV installing a blade at an offshore wind power plant.** ***Photo from Siemens AG, NREL 27858***

Similar to the monopile installation module described in Section 3.1, ORBIT allows the user to select the vessel(s) that will transport the turbine components to the site: the installation vessel itself or optional feeder barges. The process diagram for the installation of turbines with a single WTIV is provided in Figure 7; the process diagram using feeder barges is provided in Figure 8.

3.2.1 Port Operations

Port operations for the turbine installation module are similar to those in the monopile installation module described in Section 3.1.1. The number of turbine component sets (tower, nacelle, and three blades) that can be transported by the vessel is calculated using Eq. 3.1, where W_{required} and S_{required} represent the tonnage and deck space required for a set of turbine components. These components are then fastened to the deck of the transportation vessel using the default fasten times listed in Table 5.

3.2.2 Transit

After all turbine components are fastened to the deck, the transportation vessel will transit to the site using the methodology presented in Section 3.1.1 and using Eq. 3.2 to calculate the time required to transit to the site based on the distance and the speed of the transportation vessel.

3.2.3 Turbine Installation

Once the WTIV and a turbine component set are on-site, the installation process is initiated, beginning with the WTIV and an optional configured feeder barge jacking-up at a preinstalled substructure. Once the vessels are stable,

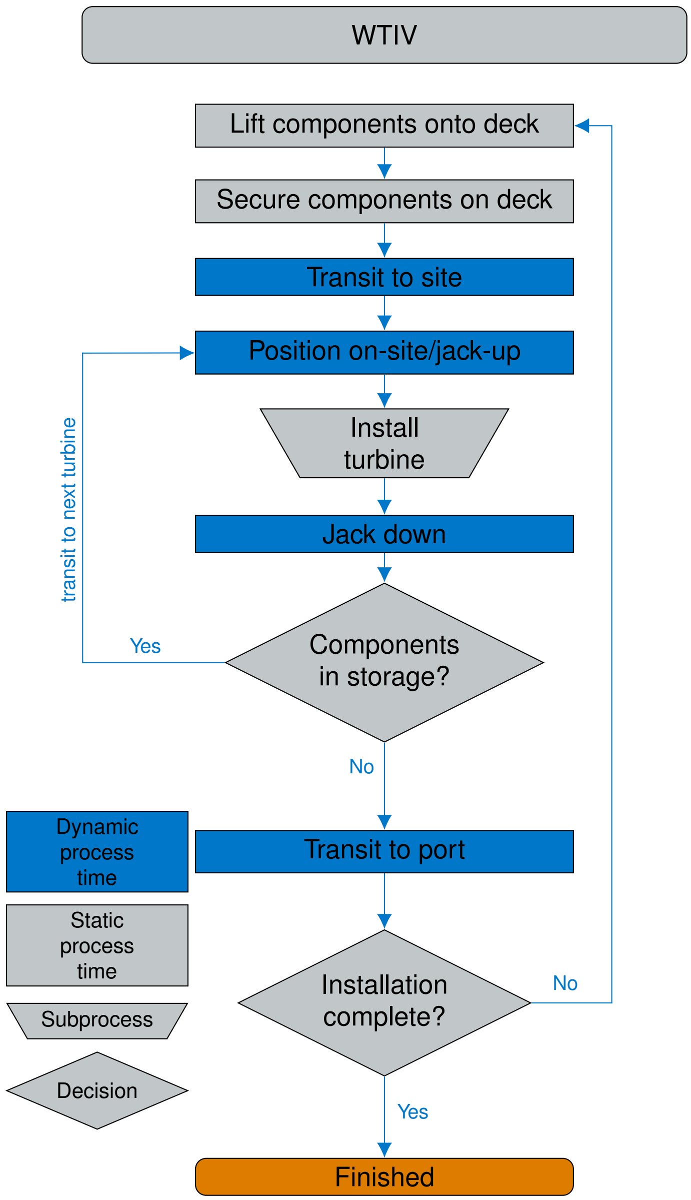

Figure 7. **Turbine installation logistics using a WTIV without feeder barge(s)**

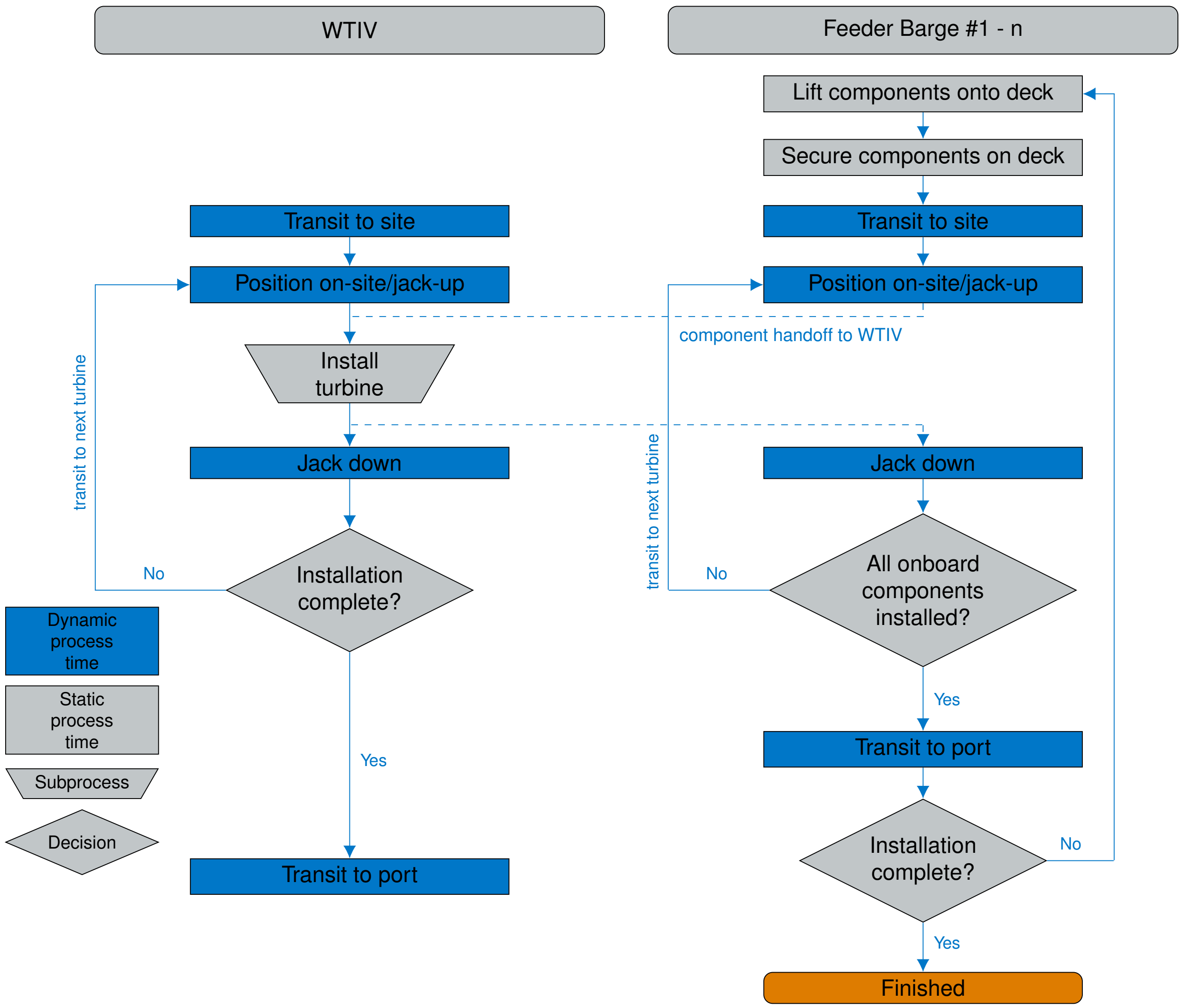

Figure 8. **Turbine installation logistics using a WTIV and feeder barge(s)**

Table 5. Default Turbine Component Process Times

Component	Default Time (h)
Fasten tower section to deck	4
Fasten nacelle to deck	4
Fasten blade to deck	1.5
Release tower section from fittings	3
Release nacelle from fittings	3
Release blade from fittings	1
Attach tower section to substructure/tower	6
Attach nacelle to tower	6
Attach blade to nacelle/hub assembly	3.5

the first tower section is released from its fitting, and the turbine assembly begins. The steps of the component-by-component installation are summarized in Figure 9. Default times for releasing each turbine component from deck storage are summarized in Table 5.

Each tower section is then lifted into place with a process time calculated with Eq. 3.7:

$$t_{\text{lift,tower}} = \frac{h_{\text{hub}} \times (\frac{n}{N_{\text{sections}}})}{s_{\text{crane}}} \tag{3.7}$$

where $t_{\text{lift,section}}$ is the time required to lift a tower section; h_{hub} is the hub height of the turbine above mean sea level; n is the current tower section; N_{sections} is the total number of tower sections; and s_{crane} is the defined lift rate. The base tower section is attached to the substructure, and subsequent tower sections are attached to the tower.; default times for attaching a component are summarized in Table 5.

The release-lift-attach process is repeated for each component: other tower sections, nacelle/hub assembly, and three turbine blades. The time required to lift a component to hub height is calculated with Eq. 3.8:

$$t_{\text{lift,hub}} = \frac{h_{\text{hub}}}{s_{\text{crane}}} \tag{3.8}$$

ORBIT loops through the processes described in Sections 3.2.1–3.2.3 until all turbines in the project have been installed at the site.

3.2.4 Weather Limits

As the turbine installation process involves significant crane operation time at hub height, an additional operational constraint is enforced on these processes: maximum crane operating wind speed. This parameter can be configured to be different than the maximum vessel operating speed, further limiting the installation process during times of high wind speed.

3.3 Scour Protection Installation

The scour protection installation module models the installation of additional material on the seabed surrounding a fixed substructure to minimize the effects of hydrodynamic scour. The most common technique, and the one modeled in ORBIT, is the installation of a layer of loose rock large enough to not be removed by hydrodynamic forces (Whitehouse, 1998; Whitehouse et al., 2011). This module is intended to capture a rough estimate of time and cost associated with this part of the installation phase and scale with the amount of material required, distance from port, vessel specifications, and project capacity.

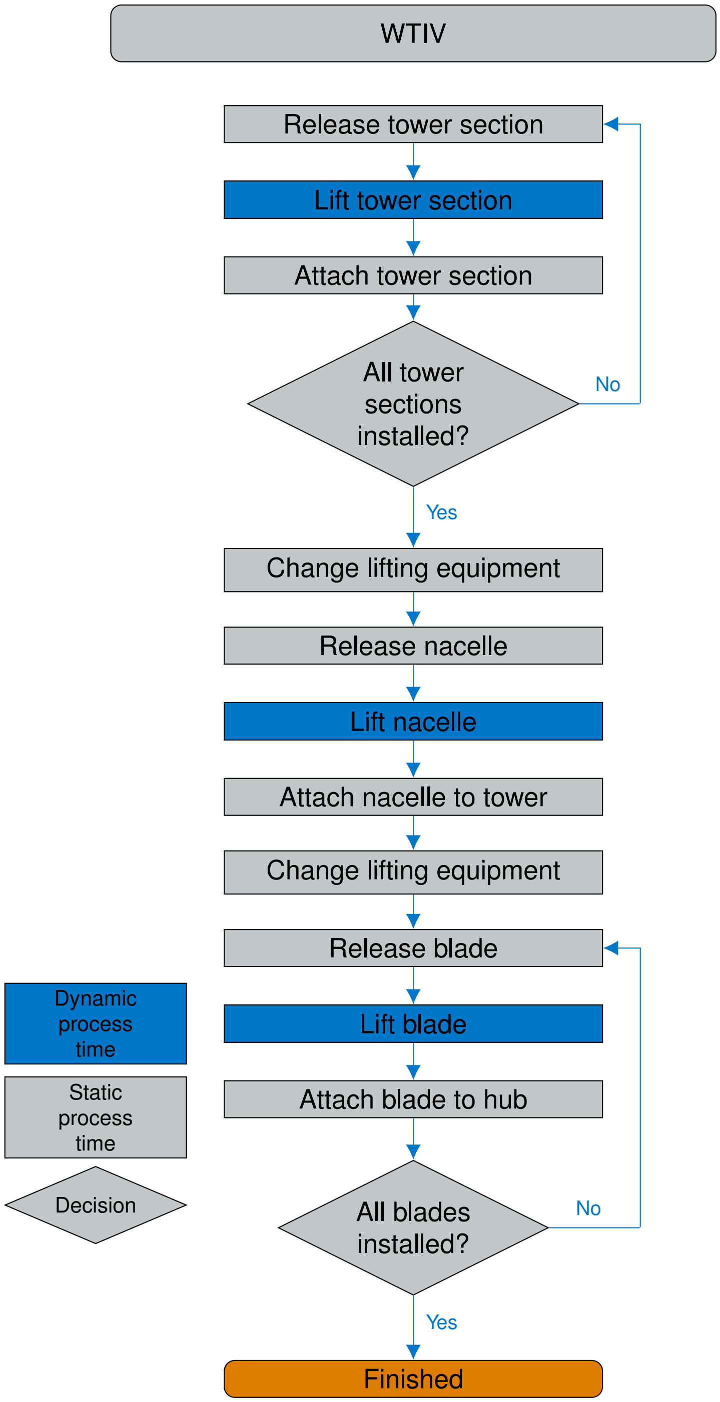

Figure 9. **Turbine installation processes**

3.3.1 Port Operations

This module includes only one vessel: a scour protection installation vessel, which begins at port. The main parameter of the vessel is the tonnage of the material that can be loaded on the vessel, which dictates the number of trips required to complete the installation. The default time to load the material at port is listed in Table 6.

Table 6. Default Scour Protection Installation Process Times

Process	Default Time (h)
Load material at port	4
Position on-site	2
Drop material at site	10

3.3.2 Transit

Transit between the port and site used the same methodology as Sec. 3.1.1, using Eq. 3.2 to calculate the time required to transit from the port to the site.

Material Installation

Several methods for the installation of scour protection material are used in industry. The most prevalent is side stone dumping vessels or fall pipe vessels, which enable more accurate material placement. ORBIT does not currently specify scour protection installation at the site; instead, it provides a user-configurable static value for the time required to complete an installation. The default is listed in Table 6. After the vessel completes this operation, if it still has enough material onboard, it will move to the next substructure and repeat the installation. Otherwise, the vessel will return to port to load more material before continuing with the installation. All the processes at the site outlined in this module are subject to the operational constraints of the installation vessel.

3.4 Array System Installation

The array system installation module models the installation of inter-turbine array cables at the site, a critical phase of the installation process because many of the project commissioning steps require a functional array system to be in place. For fixed substructures, this process involves pulling the cable into the substructure, completing the electrical connection and required testing, laying the cable on the seabed following a predetermined route to the next turbine in the chain, and repeating the electrical connection and testing procedures. The array cables can be installed in either a single process where the cable is laid and buried simultaneously or in a separated laying process and burial process involving a secondary vessel. The cable-laying process can be very time intensive, highly dependent on the geotechnical parameters of the site, and often requires specialized equipment and vessels. Speeds of this process can range from 50 m/h to 500 m/h, depending on the soil conditions and machinery used, with a typical burial speed of 200 m/h (KIS-ORCA, 2019).

The array system installation module evaluates the impacts of array cable types, cable section lengths, vessel specifications, installation strategy, distance to port, and the time and cost required to fully connect the offshore wind farm. The underlying subprocesses are also subject to weather constraints, allowing the user to study the impacts of weather throughout the installation processes.

3.4.1 Port Operations

The cable installation process begins at port, where cable is loaded onto the installation vessel. The vessel must be configured with cable storage parameterized by the available tonnage for the loaded cable. The length of cable that can be loaded onto the cable is calculated using Eq. 3.9:

$$l_{\text{available}} = \frac{W_{\text{available}}}{\lambda_{\text{cable}}} \tag{3.9}$$

where $l_{\text{available}}$ is the length of cable that can be loaded onto the vessel; $W_{\text{available}}$ is the available tonnage of the the installation vessel; and λ_{cable} is the linear density of the cable to be installed. The time associated with loading the cable onto the vessel is listed in Table 7.

Table 7. Default Cable Process Times

Process	Default Time (h)
Load cable at port	6
Prepare cable	1
Lower cable	1
Raise cable	0.5
Pull in cable	5.5
Terminate cable	5.5
Splice cable	48

3.4.2 Transit

After the cable is loaded, the installation vessel transits to the site using the same methodology from Section 3.1.1 using Eq. 3.2 to calculate the time required to transit to the site based on the distance and the speed of the cable installation vessel.

3.4.3 Array Cable Installation

Once the installation vessel has arrived on-site, the cable-laying process can begin. Figure 10 shows an overview of the steps involved in the installation process for a simultaneous lay and bury process. First, the installation vessel positions itself at a turbine location. Then, the cable end is prepared for pull-in, pulled into the turbine, terminated, and tested. After the cable is secured at the beginning of the route, the installation vessel lays the cable (and simultaneously buries the cable if configured) on the seabed along the route to the next turbine in the string sequence. Once the vessel reaches the destination turbine, it positions itself, prepares the cable for pull-in, pulls the cable into the destination turbine, and terminates/tests the cable section. This process is repeated until the carousel is empty. At that point, the vessel returns to the port for another carousel, until all the turbines have been connected to the offshore substation. If a separate laying and burial process is being used, a second cable installation vessel will travel to each cable section and bury the cables in a separate process. The default times associated with the operations at each substructure are summarized in Table 7. Default cable process speeds are summarized in Table 8. The vessel repeats these actions for each cable section of one size, returning to the port to load more cable if needed or to load a new cable size as required.

Table 8. Default cable-laying/burial speeds

Process	Default Time (km/h)
Lay cable	1 km/h
Simultaneous lay/burial	0.3 km/h
Pre-cable trenching	0.1 km/h
Bury cable	0.5 km/h
Pull winch at cable landfall	5 km/h

3.4.4 Trenching Vessel

ORBIT also includes an optional configuration for an additional vessel to clear the cable route and perform any required trenching operation. The process times associated with this task are calculated using the configured trenching speed and the length of the cable sections. The default value for the trenching speed is listed in Table 8.

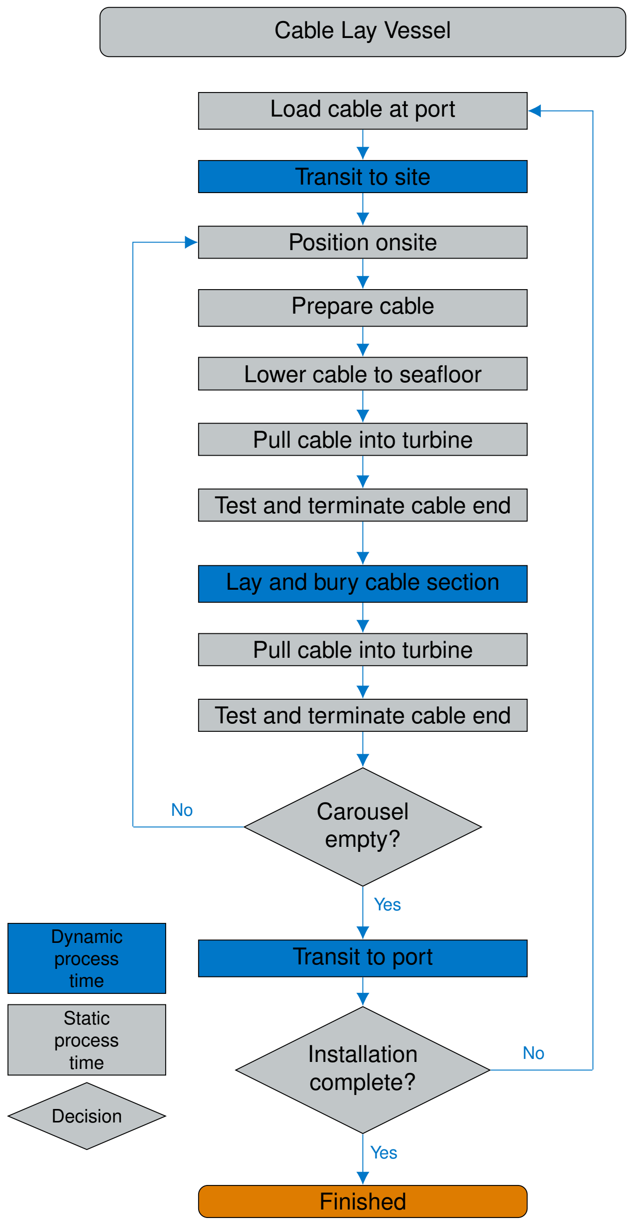

Figure 10. **Array cable installation logistics using the simultaneous lay/bury strategy**

3.4.5 Weather Limits

All operations that occur at the site are subject to the operational constraints of the cable installation vessel, including the maximum wave height and maximum wind speed. The cable-laying and burial processes are treated as suspendable tasks, allowing the vessel to pause if the weather exceeds the limit and resume as it clears up. The operational limits of the cable-laying process can be configured by the user to be stricter than the limits imposed on the vessel during transit.

3.5 Export System Installation

The export system installation module models the installation of the configured export cables from the offshore substation to the land-based grid connection. The installation of the cable along the predetermined route can be installed using simultaneous or separate lay/burial strategies, as presented in Section 3.4. By default, the installation speed will remain constant along the length of the cable; however, a user can configure different speeds for any number of cable sections to account for the impact of different soil conditions along the route on the local cable-trenching burial speeds. The cost associated with the land-based construction uses the relationships presented in Maness, Maples, and Smith (2017) based on the interconnection distance (from cable landfall to interconnection point) and the interconnection voltage.

3.5.1 Export Cable Installation

An overview of the export system installation process is shown in Figure 11. The installation of the export cable begins at the cable landfall point. It is assumed that required land-based construction (including the construction of a trench across the beach) was completed prior to the installation vessel arriving at cable landfall. Upon arrival to the cable landfall point, the end of the loaded cable is pulled onshore through the trench using a winch wire. This end is terminated at the land-based interconnection point and tested before the installation vessel proceeds with offshore installation.

Once the land-based cable termination process is completed, the vessel begins to install the export cable, moving toward the offshore substation. The default speeds at which this process can occur are summarized in Table 8. If the export cable route distance is greater than the length of the loaded cable, the vessel will transit back to the port to load more cable, then transit back to the cable route and perform a cable splice operation. The transit times are calculated dynamically using Eq. 3.2 and the distance along the cable route. The times to load the cable at the port and perform the splice operation are summarized in Table 7. The export cable-laying and cable burial processes are subject to the same weather constraints referenced in Section 3.4.5.

3.6 Offshore Substation Installation

The installation of the offshore substation is a critical part of the offshore electrical infrastructure construction. Although there are typically only two to three substations per wind farm, they are a significant contributor to the BOS CapEx; Bloomberg New Energy Finance (BNEF) reports that the substation can account for 14% of the total BOS CapEx. The installation of substation topsides is also a complex process, often requiring contracting expensive heavy-lift vessels that typically service the oil and gas industry. As the industry moves toward larger plant sizes, new electrical infrastructure standards and new substation technologies along with novel installation strategies provide opportunity for future cost reductions.

The offshore substation installation module in ORBIT allows the user to explore how scaling the substation topside mass affects the installation vessel selection, the installation time and cost, as well as weather delay impacts. In the offshore substation installation module, the substations are discretized as a large topside mass that houses all the high-voltage electrical equipment, supported by a fixed substructure (typically monopile or jacket). ORBIT currently supports the use of a monopile for the substation substructure, though a future release will extend this module to include jackets. The installation of the substation is modeled using an installation vessel and a feeder barge using the process logic outlined in Figure 4.

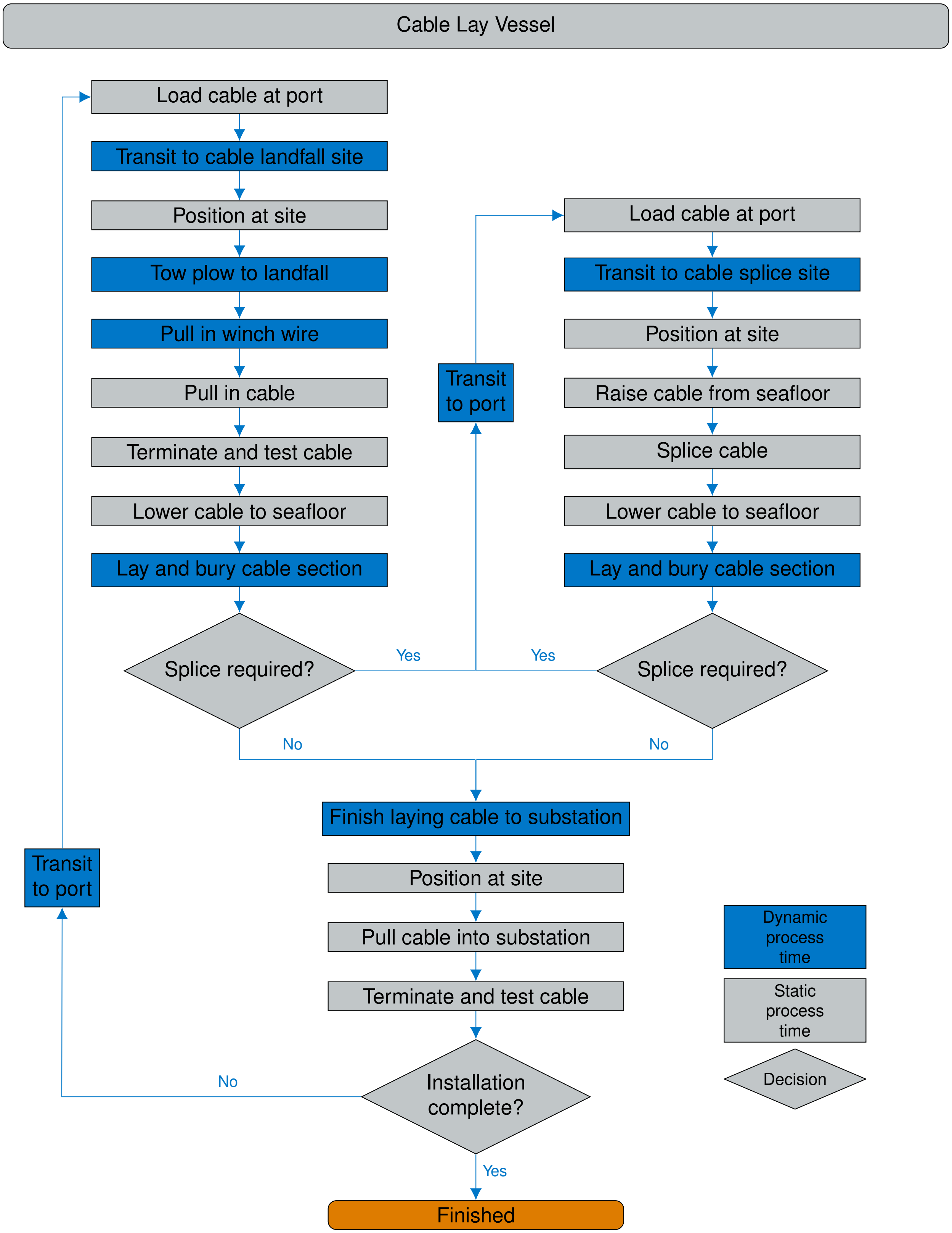

Figure 11. **Export cable installation with simultaneous lay and burial**

3.6.1 Port Operations

Port operations for the offshore substation installation module are similar to those in the monopile installation module, Section 3.1.1. The number of substations and associated monopile sets that can be transported by the feeder barge is calculated using Eq. 3.1, where W_{required} and S_{required} represent the cargo weight and deck space required for a topside and monopile. These components are then fastened to the deck of the transportation vessel using the default fasten times listed in Table 9.

3.6.2 Transit

After the substructure and topside are fastened to the deck, the transportation vessel will transit to the site using the same methodology presented in Section 3.1.1 using Eq. 3.2 to calculate the time required to transit to the site based on the distance and the speed of the transportation vessel.

3.6.3 Offshore Substation Installation

Once the installation vessel and the feeder barge with a substructure and topside are on-site, the installation process can begin. The steps of the component-by-component installation are summarized in Figure 12. First, the substructure is released from the its fittings; default times for releasing each component from deck storage are summarized in Table 9. The monopile installation procedure follows the same process steps outlined in Section 3.1.2. Once the substructure is in place, the substation topside is released from the feeder vessel, lifted into place with the heavy-lift vessel, and fastened to the substructure. The times associated with these process steps are summarized in Table 9.

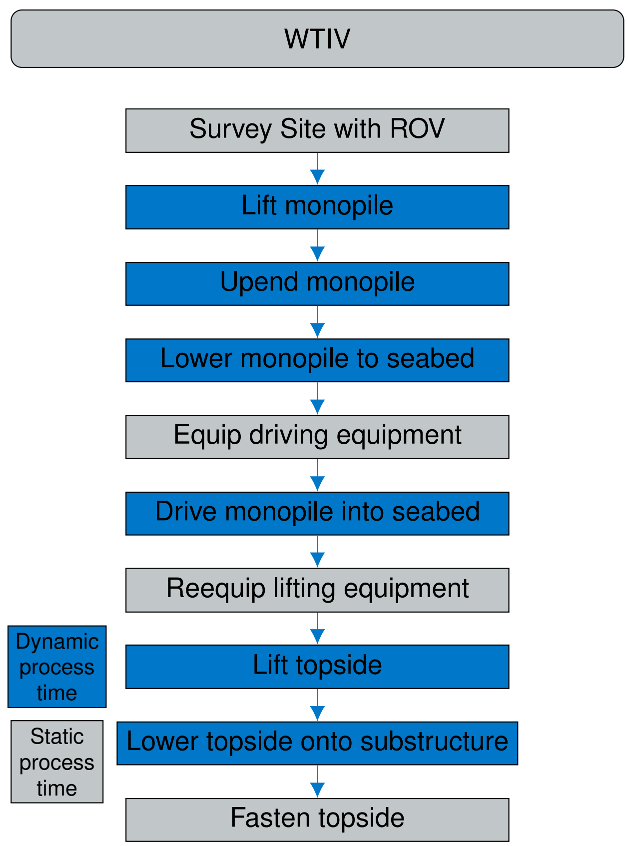

Figure 12. **Offshore substation installation processes**

Table 9. Default Offshore Substation Component Process Times

Process	Default Times (h)
Fasten monopile	12
Fasten topside	12
Release monopile	3
Release substation topside	2
Attach topside	6

4 Model Review

Several phases of ORBIT model verification and review were conducted to evaluate the model's results and sensitivities. An inherent challenge in validating cost models is the proprietary nature of industry cost data; the authors are not aware of a public resource that provides offshore wind project cost data at the resolution output by ORBIT. As a result, model validation included multiple phases of review by industry practitioners along with comparison against limited publicly available project data.

ORBIT is intended to provide a medium-fidelity representation of how offshore wind BOS costs scale among different projects, but it is not designed to have the resolution of a detailed project planning or bid preparation tool. The goal of this section is to summarize the steps taken to review the validity of the model and to convey that the baseline (not overly customized) ORBIT model produces reasonable estimates of project costs and installation times; it is not intended to provide a comprehensive suite of validation results or sensitivities around key cost drivers, which will be the focus of future publications. The diverse nature of offshore wind projects means that calibrating ORBIT specifically to one scenario does not mean that the same model configuration can represent other projects with equal accuracy. Instead, the following sections convey that the baseline cost assumptions and simulation methodologies are representative of current industry practices; the modular nature of the ORBIT model means that it can be easily customized for more detailed project analyses given that the user has sufficiently resolved input data.

4.1 Industry Review of Model Inputs and Outputs

The input cost data and model structure were reviewed by industry practitioners, including project developers, consultants, and offshore logistics specialists. Because these reviews and discussions focused on proprietary cost data and best practices, the reviewers requested to remain anonymous. The reviews took part in two phases: the first focused on the conceptual model structure, and the second evaluated the input/output magnitudes.

4.1.1 Conceptual Review

The conceptual review involved presenting process diagrams, such as the diagram shown in Figure 4, to the industry reviewers and requesting feedback and discussion for each component of the model. This included both the design modules discussed in Section 2 and the installation modules presented in Section 3. The reviewers were asked to identify any major omissions or errors in the inputs, assumptions, and processes of the model. Further, the sensitivities to key model parameters were discussed within the context of the offshore wind industry to confirm that significant scaling trends between projects are appropriately captured in ORBIT. Finally, the reviewers were asked about the relevance of the model to industry and their opinions of how the model could contribute to the offshore wind community.

The major comments from the anonymous reviewers included:

- The scope of ORBIT is appropriate and useful for preliminary comparison studies.
- ORBIT could potentially be used by project developers for site screening, policymakers for evaluating the cost impact of state procurement or development targets, marine logistics operators for comparing different installation options, and academics for evaluating system costs of novel innovations.
- The offshore wind industry would value a planning tool that is validated, reliable, and broadly accepted. This would not replace the detailed budgeting tools currently used by developers, but a publicly available and industry-vetted model would be valuable for analyzing potential cost-benefit trade-offs.
- Updates to default model parameters to better reflect current industry practices including replacing grouted connections between the monopile and transition piece with bolted connections; assuming that array cables are 66 kV; and condensing all port costs into a monthly fee instead of separate line items for cranes, vessel trips, berthing, and lay-down area.

The responses from the industry reviewers did not reveal any major concerns with the model, and they provided confidence that ORBIT will add value to the offshore wind community. Appropriate updates were made to the model design based on comments from the reviewers; after several months of software development and estimation of cost data from the literature, the same practitioners were engaged for the second phase of review.

4.1.2 Quantitative Review

The goal of the second review phase was to evaluate the accuracy of the baseline model inputs (e.g., cost rates and vessel specifications) and calculated outputs (e.g., total component costs and component installation times). An input/output spreadsheet was compiled for a representative project; the spreadsheet included definitions of project characteristics and user-defined inputs (e.g., water depth, distance to shore, project size, turbine rating, cable specifications), intermediate calculations (e.g., number of array cable strings, installation hours per substructure, duration of weather delays, vessel operational efficiencies), and module outputs (e.g., component costs and phase installation times). Each input/output row included a dropdown menu that allowed the reviewer to provide a range of accuracy for the individual value; reviewers also had the option to suggest a better value if appropriate. This allowed the reviewers to provide quantitative feedback without explicitly revealing proprietary data. A sample of the initial inputs and feedback for example WTIV parameters is provided in Table 10.

Table 10. Representative Sample of Industry Feedback Spreadsheet.

Variable Name	Input Value	Units	Accuracy of Value	Suggested Value
WTIV				
max_windspeed_crane	17.0	m/s	Too high, 10%-30%	15.0
max_windspeed_transit	20.0	m/s	Just right, ±10%	
max_waveheight_transit	2.5	m	Just right, ±10%	
day_rate	500,000	USD/day	Just right, ±10%	

Note: The proposed model inputs are provided on the left, and sample responses from industry reviewers are shown on the right.

4.2 Validation of ORBIT Discrete Event Simulation

This report described the simulation framework ORBIT uses to model the installation of an offshore wind plant. The goal of this framework is to appropriately capture how installation strategies and weather downtime affect the duration of specific construction phases because these present significant challenges to the offshore wind industry (McAuliffe, Murphy, and Lynch, 2018). Although approximately 15 GW of offshore wind have been installed and commissioned since 2015 (Musial et al., 2019), reported information on phase-specific installation times and methodologies are sparse and vary substantially from one project to another. As such, attempting to directly calibrate installation times modeled by ORBIT to publicly available data is impractical because the significant variability among projects could result in overfitting the model to match the expected results. Instead, the approach here is to use the baseline ORBIT model with no modifications and show that modifying high-level input parameters—such as site geospatial characteristics and the number of installation vessels—reasonably agrees with a wide range of projects. This approach is intended to ensure that the installation processes and weather delays are appropriately considered in ORBIT. Figures 13 and 14 present results for monopile and turbine installation times for seven representative European projects; although other installation phases (such as cable laying or substation installation) are not reported here for brevity, they should be viewed with a similar confidence level because the underlying model architecture has been reviewed with the same rigor and the discrete event simulation framework is identical.

4.2.1 Methodology

Seven fully commissioned European projects were identified based on the following criteria:

- Exclusive use of monopiles
- Capacity of at least 400 MW

- Availability of wind and wave time-series data at the project location
- Availability of project level installation data.

The selected projects are summarized in Table 11. In addition to the spectrum of plant and turbine sizes, each project employed a variety of vessel spreads comprising varying numbers of installation vessels and/or feeder barges. For each case, the reported installation time for monopiles and turbines (defined as the total number of days the installation vessels worked or were prepared to work) were collected from 4C Offshore. Additional data relating to vessel and site characteristics were collected from a variety of public sources. The baseline ORBIT installation methodologies described in Section 3 were used to conduct the simulation in conjunction with wind and wave time-series data from the ERA5 global reanalysis dataset (Hersbach et al., 2020). The following model input values were customized as appropriate for each scenario:

- Vessel specifications
- Number of foundations/turbines installed
- Average water depth at the site (m)
- Distance to port (km)
- Turbine hub height (m)
- Monopile length (m), diameter (m), deck space (m^2), and mass (t)
- Transition piece length (m), diameter (m), deck space (m^2), and mass (t)
- Turbine hub height (m)
- Turbine tower weight (t) and deck space (m^2)
- Nacelle weight (t) and deck space (m^2)
- Blade weight (t) and deck space (m^2)
- Installation phase start date(s) for each vessel
- Hourly wind and wave data for the installation period.

Table 11. Seven Offshore Wind Farms for Foundation and Turbine Installation Validation

Project	Location	Plant Cap. (MW)	Turbines	Turbine Model	Commissioned
Anholt[1]	Denmark	400	111	SWT-3.6-120	2013
Gemini[2]	The Netherlands	600	150	SWT-4.0-130	2017
Gode Wind 1 and 2[3]	Germany	582	97	SWT-6.0-154	2017
Greater Gabbard[4]	UK	504	140	SWT-3.6-107	2013
Walney Extension[5]	UK	659	87	V164-8.25, SWT-7.0-154	2018
Horns Rev 3[6]	Denmark	407	49	V164-8.3	2019
Merkur[7]	Germany	396	66	Haliade 150-6MW	2019

Figures 13 and 14 plots the predicted installation times from ORBIT against the reported project installation times; the percentage error between the respective values is tabulated in Table 12. The turbine installation module tends to perform better than the monopile installation module, with relative errors less than 33% and 55%, respectively. Although the model does not match all the project data, it is critical to remember that these estimates are derived from generic project installation assumptions and still provide a reasonable estimate of installation times. If additional project data are known—such as the number of feeder barges, the number of component sets per vessel, or the specific weather constraints for a given vessel operator—ORBIT can produce results more closely aligned with a specific project.

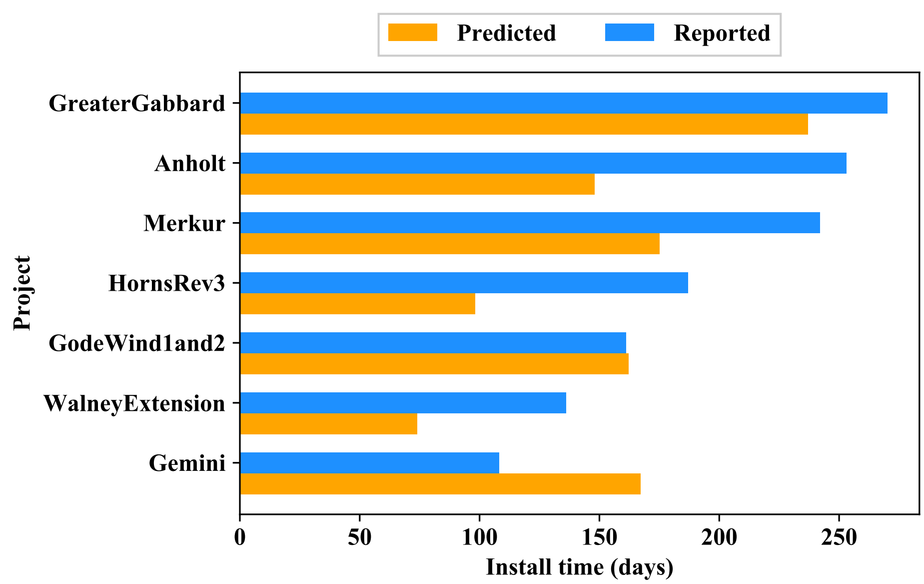

Figure 13. **Predicted and reported foundation installation times for seven offshore wind projects**

[1]Data compiled from 4COffshore (2019a), offshoreWIND.biz (2012), Dong Energy (Ørsted) (2012), Subsea World News (2012), Reece Williams (2014), and Dong Energy (Ørsted) (2013).

[6]Data compiled from 4COffshore (2019b), Gemini Wind Park (2016), Northland Power (2015), Sif (2019), and Gemini Wind Park (2016).

[7]Data compiled from 4COffshore (2019c), offshoreWIND.biz (2016), wind-turbine-models.com (2013), Siemens Gamesa (2019), and Bladt Industries (2019).

[8]Data compiled from 4COffshore, 2019d; Siemens AG, 2011; offshoreWIND.biz, 2010; The Wind Power, 2018.

[9]Data compiled from 4COffshore, 2019g; SAL Heavy Lift, 2019; Ørsted, 2018; Siemens Gamesa, 2019; Bladt Industries, 2019.

[10]Data compiled from 4COffshore, 2019e; Bladt Industries, 2019; MHI Vestas, 2015; MHI Vestas, 2017; Vattenfall, 2019.

[11]Data compiled from 4COffshore, 2019f; GE Renewable Energy, 2015; Teknisk Ukeblad, 2016; Merkur Offshore, 2019.

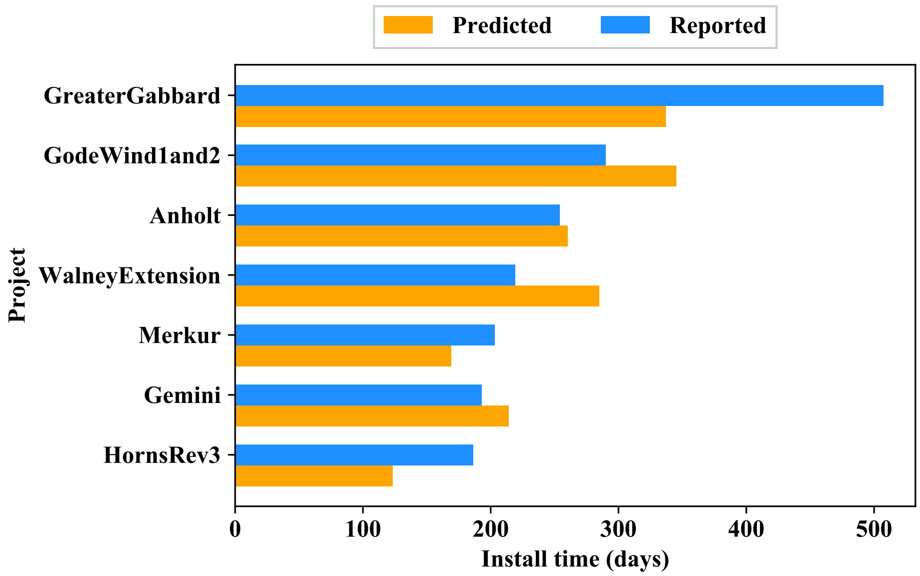

Figure 14. **Predicted and reported turbine installation times for seven offshore wind projects**

Table 12. Percentage Error on Foundation and Turbine Installation Times

Project	Percentage error (Foundations)	Percentage Difference (Turbines)
Anholt	41.5	-2.4
Gemini	-54.6	-10.9
Gode Wind 1 and 2	-0.6	-19.0
Greater Gabbard	12.2	33.5
Walney Extension	45.6	-30.14
Horns Rev 3	47.6	33.9
Merkur	27.7	16.8

Conclusions and Future Work

4.3 Discussion of Results

This report provides detailed documentation for the initial public release of ORBIT: a bottom-up, process-based modeling tool developed by NREL for studying the times and costs associated with the BOS processes for offshore wind projects. ORBIT expands on the capabilities of other open-source BOS models by enabling discrete steps of offshore installation procedures as well as their relevant weather limits. The fidelity of ORBIT allows users to quantitatively evaluate how turbine scaling, installation vessel technologies, installation methods, and other innovations might impact a project's installation time, cost, and risk.

Sections 1–2 outline the overall approach of ORBIT and describe each module, including any relevant literature. These sections also include detailed process diagrams that describe the installation procedures implemented in the model and the default values assumed for process times and design parameters. Although detailed code examples are not included in this report, the online documentation for ORBIT (https://orbit-nrel.readthedocs.io/en/latest/) includes several tutorials for getting started and how to customize ORBIT to model different development scenarios.

Section 4 provided a high-level validation study and industry review of the ORBIT functionality and defaults by comparing the modeled and reported installation times of seven recent European projects. The focus on the installation of wind plant substructures and turbines was selected because these categories had limited publicly available data. Each project was modeled assuming parameters such as distance to shore, water depth, turbine size, and weather profile. The default process times in ORBIT were used for each installation. This study was not intended to be an exhaustive validation and verification of all available inputs in ORBIT. The intention of this study was to confirm that the default ORBIT configuration accurately captures the installation times of BOS components and scales with site-specific parameters.

The model results for turbine installations closely aligned with publicly available installation timing data among the seven offshore projects. The maximum percentage difference for turbine installation time was 33.9%, and four of seven projects were within 20%. The percentage error in foundation installation time resulted in a maximum of 54.6%. Note that these results represent the default values in ORBIT because of a lack of publicly available process times. It is likely that these results could be significantly improved given more detailed input assumptions per project, including vessel- and component-specific installation process times.

4.4 Future Work

ORBIT is still in active development and will continue to see future releases. The model was designed to be modular, allowing model improvements as the offshore wind industry continues to evolve. As such, there are many options for future ORBIT development, including:

- More detailed validation and verification of the modeling framework and assumptions.
- NREL is actively working on an analysis that uses ORBIT to explore how turbine scaling impacts the BOS process timeline and costs. It is expected that this work, in combination with continued industry collaboration, will improve the capabilities and accuracy of the current modules.
- Stochastic analysis. One of the highest impact capabilities of ORBIT is the ability to analyze installation methods and technologies to capture the effects of weather downtime. The preliminary results of this report are presented using one weather profile; however, an ORBIT project could be run against a range of other weather profiles to statistically evaluate the impacts of weather delays and inform project risk characteristics.
- Floating offshore wind support (in development). NREL is actively working on expanding the functionality of ORBIT to include the installation of floating offshore wind turbines. Preliminary development of the new floating modules is expected to be complete in summer 2020.
- Expansion of current modules. The modular nature of ORBIT allows each module, representing the design or installation of a single BOS component, to be expanded separately from the overall model. As new data or

resources become available, ORBIT modules can be expanded to include them, increasing the confidence of the model over time.

- New modules. As new technologies or standards are implemented, additional ORBIT modules can be created to allow users to study their impacts quantitatively.

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