An Assessment of Vessel Characteristics for the Installation of Offshore Wind Farms

E. Barlow[1,2,*], D. Tezcaner Ozturk[1,2], S. Day[1], E. Boulougouris[1], M. Revie[2] and K. Akartunali[2]

1. Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, UK
2. Department of Management Science, University of Strathclyde, UK

Abstract: Offshore wind farms are moving further offshore and increasing in size, which brings new challenges in identifying efficient installation scenarios. Uncertain weather conditions give rise to uncertainties in the expected duration and cost of any installation operation. This paper investigates the impact of key vessel characteristics in the installation of an offshore wind farm. A simulation tool is employed which combines a model of the installation with a weather model and enables realistic assessments of installation durations to be realised. This tool is applied to investigate the impact of key installation vessel characteristics on the duration of the installation. Vessel characteristics that can be expected to have a substantial impact on the installation duration are identified, and this information could enable decision makers to make substantial savings in the OWF installation.

Keywords: offshore wind farm, logistical simulation, vessel characteristics
Article ID: RE-SU-G

1 Introduction

1.1 Background

The installed capacity of offshore wind energy has been steadily increasing in Europe over the last five to ten years, with the majority of offshore wind farms (OWFs) developed in the North Sea (European Wind Energy Association, 2013). Since 2008 the UK has had the largest installed offshore wind capacity worldwide (European Wind Energy Association, 2011). As of mid-2013 this stood at 4.7 GW capacity in operational or commissioned OWF sites (Renewable UK, 2013), and the UK government has targeted an operational capacity of 16 GW by 2020 (UK Department of Energy and Climate Change, 2013). To meet this target OWF development has progressed to the Round 3 and Scottish territorial OWF sites. These sites are further from shore which enables large scale OWFs to be developed, with the number of wind turbines (WTs) typically over a hundred; however, developing these sites gives rise to a new set of challenges. Being situated further from shore these sites are exposed to more severe weather conditions, which increases the complexity of offshore operations and increases the uncertainty around managing these operations. Additionally, the large scale of these developments amplifies the impact of any operational decisions as these are repeated many times across the OWF site.

Received date:
***Corresponding author Email: euan.barlow@strath.ac.uk**

The UK government's industry-led Offshore Wind Cost Reduction Task Force has identified installation and logistics as an area where substantial cost-reductions can be achieved through innovation (Offshore Wind Cost Reduction Task Force, 2012). The installation of an OWF is particularly susceptible to the new challenges arising through developments larger in size and further offshore. Challenges facing decision makers in the planning and installation stage of an OWF include determining what impact the selection of ports and vessels to be utilised during the installation will have on the length of the installation process and the resulting costs. As the duration of installation operations are subject to the uncertain weather conditions as well as the specific vessels used for the installation, assessing the comparative benefits of two installation scenarios over an entire OWF installation is challenging. An improved understanding of the impact of vessel selection on an OWF installation is therefore required to enable cost-efficient installation scenarios to be identified.

1.2 Wind turbine generators

There are several major assets which comprise an OWF, and the installation of each asset requires specific capabilities from the installation vessel(s) used. An overview of the different assets and their associated vessel requirements can be found in (European Wind Energy Association, 2011). Wind turbine generators (WTGs) are perhaps the most identifiable OWF assets. WTGs are the large tower structures that are responsible for converting the kinetic energy of the wind into electrical energy. The standard

WTG design consists of the tower section(s) which are large metal tubes housing any electrical connections, the nacelle which contains the gearbox and performs the conversion from kinetic to electrical energy, the hub which connects the blades to the nacelle, and the blades which are highly engineered aerodynamic structures designed to minimise air resistance and maximise the return from the wind-speed. The hub and blades comprise the WTG rotor section. Offshore WTGs are similar in design to the onshore turbines commonly seen today, and initial OWFs employed the same WTGs as their onshore counterparts. Whereas onshore WTGs are restricted in size due to transportation logistics and planning and consent issues, offshore WTGs are continually increasing in size and generating capacity. The largest offshore WTGs today have a 10 MW generating capacity and have a rotor diameter of 170 m (European Wind Energy Association, 2011), although the average size used in current developments is a 4 MW capacity (European Wind Energy Association, 2013). The installation of the WTGs are amongst the most sensitive operations to weather conditions, as installing the blades is a very intricate process and the aerodynamic design of the blades is such that even moderate wind speeds can generate too much movement in the blades and prove to be restrictive. There are various options available as to how WTGs are installed, depending on the degree of onshore assembly. After the WTG is installed a series of completion operations are required including mechanical and electrical completion, commissioning, testing and release.

WTGs are installed with jack-up vessels which are specialised vessels that have retractable legs which can be lowered into the seabed to jack-up the vessel above the surface of the water and provide a stable platform which reduces the sensitivity of operations to the sea conditions. The specialist nature of these vessels coupled with the relatively recent growth in the OWF industry means that there are a limited number of jack-up vessels available for installation; as of 2011 only 17 different jack-up vessels had been utilised in the installation of offshore WTGs (European Wind Energy Association, 2011)., although several more vessels are expected to become operational over the next few years (Roberts et al. 2013).

1.3 Existing literature

Studies on the logistics of OWF vessels are to the best of our knowledge limited to the following recent papers. Scholz-Reiter et al. (2010) look at the short-term vessel planning for the installation of an offshore wind farm. They use a mixed-integer linear programming model which takes weather forecast as an input rather than directly incorporating the uncertainty. A single installation vessel and four operations related to the installation of 12 turbine substructures and WTGs are considered. Three scenarios of vessel scheduling are considered in the model. In Lutjen and Karimi (2012), a two-level simulation which has a port inventory control system coupled with a reactive scheduling component is used to determine loads and operations based on forecast weather conditions. They incorporate a medium-term weather forecast to determine the installation schedule which is updated with a short-term forecast, and five categorical weather states are considered ranging from very bad to very good. A single vessel is considered to perform all installation operations. Seven installation operations are considered and the focus of this work is on the effect that different levels of inventory have on the progress of the installation of 12 turbine substructures and WTGs and the resulting duration. Similarly to Scholz-Reiter et al. (2010), Ait-Alla et al. (2013) frame the problem as a mixed-integer linear programming model with five categorical weather states. The proportion of occurrence of each weather state is determined beforehand and fed into the optimisation model. In this case ten installation operations are considered related to the installation of turbine substructures, WTGs and inter-array cables. Three different types of vessel are potentially used to complete different categories of the ten installation tasks. Three vessel scheduling scenarios are considered for the installation of 30 turbines.

Barlow et al. (2014) present a simulation tool to model the OWF installation logistics problem. The tool incorporates a model of the installation process developed in collaboration with a group of OWF installation industry experts, and a synthetic hourly weather time-series model generated from real data. This combination enables a detailed and realistic assessment of the expected duration and costs associated with a particular installation scenario. The simulation tool is capable of analysing installation vessel scheduling, installation fleet composition and port selection for the installation of all major assets of an OWF. Additionally, Barlow et al (2014) provide a comprehensive review of the small number of studies concerning offshore support vessels for the oil and gas industry, which have several similarities with the problem discussed here. In these problems the offshore supply vessels have a series of operations which must be completed, where these operations are subject to weather limitations. In comparison with the works by Scholz-Reiter et al. (2010), Lutjen and Karimi (2012) and Ait-Alla et al. (2013), the model developed by Barlow et al. (2014) provides a more realistic representation of the installation process. This provides a framework for detailed analysis of the impact of logistical installation decisions and is the method applied here.

1.4 Overview

This paper presents an application of the simulation tool presented in Barlow et al. (2014), in determining the key characteristics of an installation vessel for reducing the duration of the OWF installation. To clearly depict the impact of each vessel characteristic the OWF installation is restricted to the installation of WTGs and a single installation vessel is considered.

2 Offshore wind farm installation logistics model

The tool developed in Barlow et al. (2014) for simulating the impact of an OWF installation logistics scenario is employed here. A brief description of the relevant components of this tool is presented below; for a full description see Barlow et al. (2014).

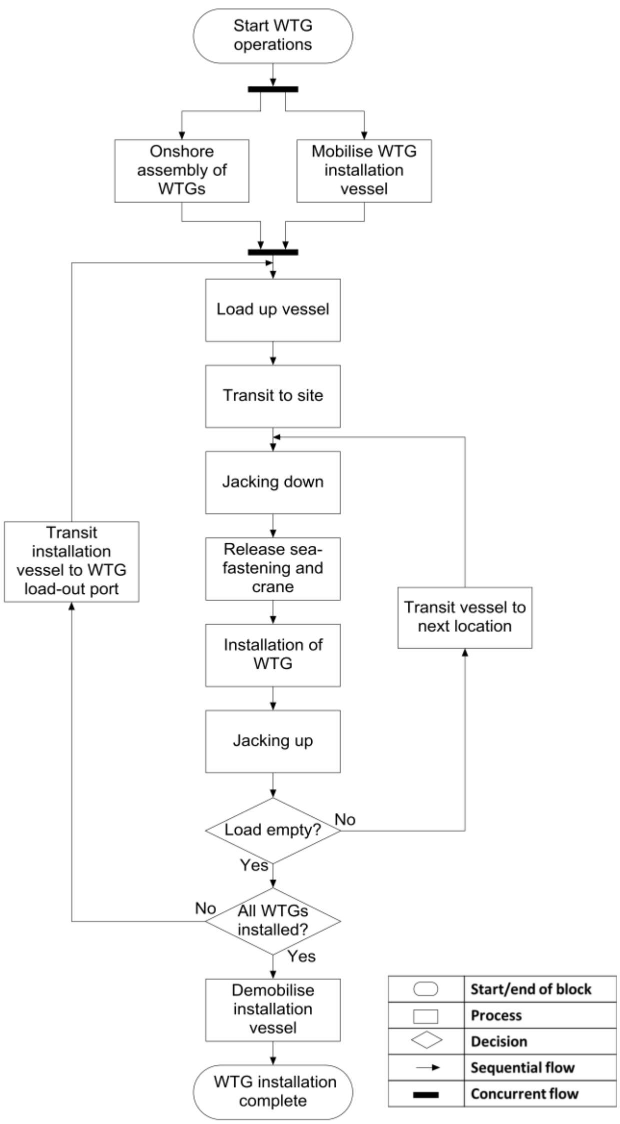

Fig. 1 Flow-chart for the installation of wind turbine generators

The installation model in Barlow et al. (2014) is developed through close collaboration with experts from three companies with direct experience of the European OWF industry, with a particular emphasis on providing an accurate representation of the current industry practices and experiences. The model is designed to cover the main aspects of an OWF installation with a detailed breakdown of the associated installation tasks and the flexibility to model the wide variety of installation scenarios which could potentially be considered for current and future OWF developments. Figure 1 displays a high-level overview of the WTG installation with the key installation operations and their precedence relationships identified. Each individual operation will have a specific set of operational limits including daylight and weather restrictions which are dependent on the operation and the particular vessel used.

The uncertain weather conditions are modelled through a correlated auto-regression model, similar to the approach taken in Dinwoodie et al. (2012). This enables multiple data-sets of synthetic weather data to be generated from a hindcast weather data-set, which retain the underlying statistical properties of the original data-set. The weather properties included here are significant wave height and wind speed, which can be appropriately correlated in the synthetic weather data-sets.

An installation scenario is assessed by simulating the progress of the installation subject to each synthetic weather series. Simulating this progress over many synthetic weather series provides a realistic assessment of the expected duration and thus the expected costs of the installation. Ross (2013) provides a general discussion of applying simulation models to real-world problems and gives an introduction to various simulation methods.

Probabilistic performance measures used to evaluate an installation scenario include a cost breakdown of the installation, the expected duration of each installation operation and expected delays during the installation.

3 Results

To demonstrate the potential decision support provided by the OWF installation logistics simulation tool outlined in Section 2, the impact of a selection of key vessel characteristics on an example OWF installation are explored. The four key vessel characteristics explored here are capacity, average operational transit speed, wave limits for vessel transiting and wave limits for jacking operations. Each vessel characteristic is varied over a range of values which have been identified as appropriate by industry experts. The ranges used are typical of current WTG installation vessels and vessels which are expected to be available on the open market in the next few years. The installation is simulated over 1000 runs as described in Section 2, for each value of each of the four key characteristics across the range explored.

The example OWF used here is designed to be typical of the next phase of OWF developments in the UK, namely Round Three and Scottish territorial sites which are situated further offshore in deeper waters and are larger in scale than current developments. The OWF is situated 150 NM from the WTG load-out port, where this port is either the WTG fabrication and supply port, or is a marshalling port situated closer to the OWF site. There are 100 WTGs to be installed, and the average distance between two WTGs is 1 km. The supply rate of the WTGs and storage space at the load-out port are assumed to be sufficient that the installation will never be delayed by these factors. There are assumed to be no other vessels requiring access to the load-out port so there will be no loading delays to the installation. Onshore pre-assembly operations are assumed to be subject to no weather restrictions and are initiated prior to the mobilisation of the installation vessel so that these operations will not delay the installation vessel.

The main delays to the WTG installation captured here are therefore delays due to adverse weather conditions. Data from the FINO1 weather station (Bundesamt fur Seeschifffahrt und Hydrographieis FINO database) is used to generate the synthetic weather series as described in Section 2; the FINO1 weather station is an offshore weather research platform located in the North Sea 45 km off the coast of Germany with high-quality publicly available weather time-series recorded since 2003. Due to differences in location and proximity to shore, weather conditions recorded at FINO1 may not be representative of weather conditions at specific UK Round 3 and Scottish territorial OWF sites; however, this data-set enables the capability of the simulation tool to be demonstrated in the analysis of the test example outlined above.

The onshore pre-assembly of WTGs is assumed to include combining tower sections, nacelle and hub into a single component, with the three blades unassembled. Installation operations therefore involve installation of the combined tower, nacelle and hub component (5-lift), followed by the installation of each of the three blades. Until recently WTG manufacturers required that the blades of each WTG are installed immediately following the installation of the combined tower component to minimise the weather exposure of uncompleted connections. This requirement is assumed here and each WTG is therefore completely installed in series. It should be noted, however, that one turbine manufacturer has recently indicated that the blades can be installed a short period after the combined tower component has been installed. Future work could therefore explore the impact of different WTG assembly options on the installation duration.

To explore the impact of the key vessel characteristics on the WTG installation, a base-case installation vessel is defined which exhibits typical characteristics of the WTG installation vessels commonly used to date. The impact of each of the four key vessel characteristics is explored separately; in each case the vessel is equivalent to the base-case vessel except for the key characteristic under investigation. The base-case installation vessel is defined in Table 1.

The duration of mobilisation and demobilisation operations are fixed across all investigations as these are assumed to have a straightforward impact on the duration of installation operations. The load-out rate is fixed as this is assumed to be driven by the port selected for load-out and to be approximately consistent across all vessel choices. Pre-installation operations such as the release of seafastenings and cranes prior to each WTG installation are fixed across all investigations as these are assumed to be relatively consistent between vessels. The duration and weather limits of the installation are fixed as these are assumed to be dependent on the model of WTG installed.

Table 1 Characteristics of the base-case installation vessel

Vessel capacity (no. of WTGs)	5
Average vessel speed (kn)	10
Max wave limit for vessel transits (m)	2
Max wave limit for jacking operations (m)	2

3.1 Vessel capacity

The capacity of a WTG installation vessel is defined here as the number of WTGs which can be carried in a single load, given the pre-assembly and installation definitions above. The capacity is dependent on the free deck-space of the vessel and the deck-footprint of all WTG components, and considering the capacity therefore provides a general means to account for both of these factors. The vessel capacity will determine how frequently the vessel has to re-load and influences the amount of time which can be dedicated to installation activities rather than replenishing the load. The range of capacity values considered here is 2-12 WTGs. A capacity of two WTGs would represent a small installation vessel, with five typical of the majority of installation vessels with current WTG dimensions, eight representing the larger installation vessels which have been recently developed, and twelve potentially achievable from the largest vessels transporting smaller turbines. The impact of each capacity on the duration of the example WTG installation is displayed in Figure 2. It is clear from Figure 2 that increasing the vessel capacity from two WTGs to five WTGs could be expected to have a substantial impact on the duration of the installation – a reduction of approximately 120 days. Increasing the vessel capacity beyond five WTGs, however, provides diminishing returns with a capacity of 12 WTGs only reducing the installation duration by a further 50 days. One reason for this behaviour is that increasing the vessel capacity has a diminishing impact on reducing the total vessel transition time due to the non-linear reduction in the number of trips required. Beyond a certain limit, the time spent on on-site installation activities will therefore dominate the decreases in the transition duration and further increases to the vessel capacity have reduced impact.

Increased vessel capacity can be expected to come at an increased price, and the results in Figure 2 suggest that the benefits of increased vessel capacity should be carefully considered.

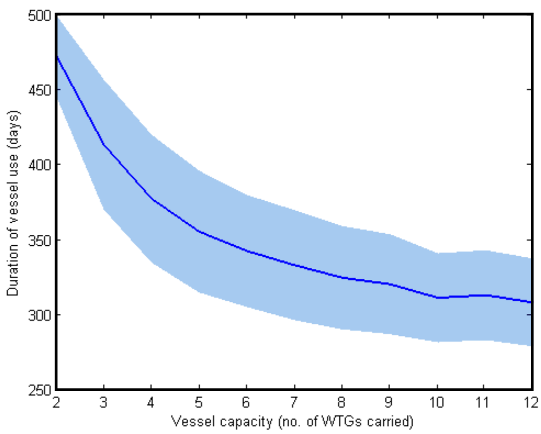

Fig. 2 The effect of varying vessel capacity on the duration of the WTG installation. Mean duration is shown bounded by the standard deviation.

3.2 Average vessel transit speed

A typical OWF installation will consider various WTG models and manufacture ports, with the average vessel speed determining the time taken to transit between the load-out port and the OWF site. The time taken to transit on-site between WTG locations will be influenced to a lesser extent due to the proximity of locations, and in this investigation the transit time between on-site locations is assumed to be constant. In Figure 3 the average vessel speed is varied between 5 kn and 12 kn, with 5 kn representative of a slow transit typical of a towed jack-up rig, 10 kn representative of common self-propelled jack-up vessels, and 12 kn representative of recently developed high-performance installation vessels. Figure 3 shows that improvements in average vessel speed can be expected to provide consistent gains in terms of installation duration. The use of a self-propelled jack-up vessel compared with a towed jack-up barge could be expected to reduce the installation duration by approximately 80 days, and further increases in vessel speed provide consistent returns in terms of reduction in installation duration.

3.3 Wave limit for vessel transitions

The wave limit for vessel transits is defined here as the maximum significant wave height at which vessels can safely transit between the OWF and the load-out port, and between locations on-site. This limit is vessel specific and will be provided by the vessel operators. The wave limit will influence the proportion of time for which the vessel is delayed by weather, with lower limits more susceptible to weather delays. A range of 1 m to 3 m wave limits are considered here, with 1 m representing relatively restrictive conditions, 2 m common in currently operating installation

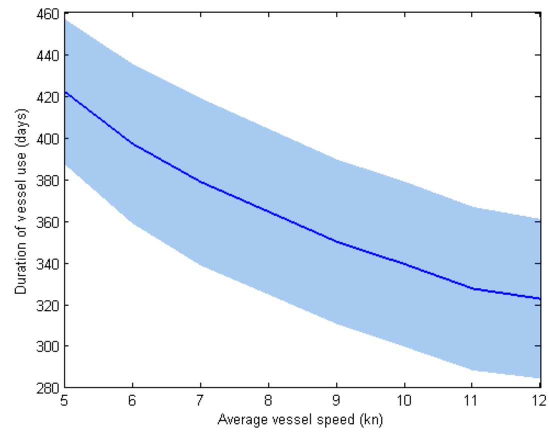

Fig. 3 The effect of varying vessel speed on the duration of the WTG installation. Mean duration is shown bounded by the standard deviation

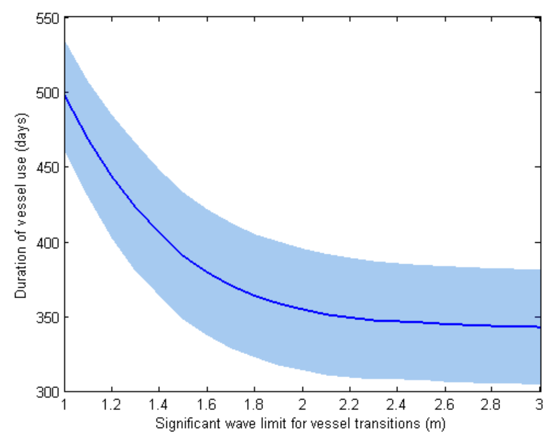

Fig. 4 The effect of varying the significant wave limit for vessel transitions on the duration of the WTG installation. Mean duration is shown bounded by the standard deviation.

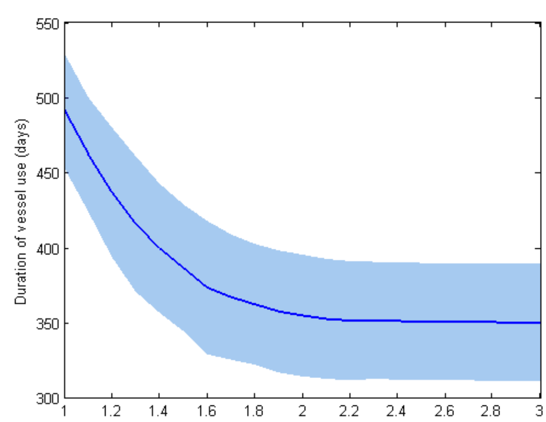

Fig. 5 The effect of varying the significant wave limit for jacking operations on the duration of the WTG installation. Mean duration is shown bounded by the standard deviation.

vessels and 3 m representing vessels with relatively high operating limits. Figure 4 indicates that the difference in average installation duration between vessels with relatively poor performance and average performance is relatively substantial at approximately 140 days. Additional reductions are limited, however, with the average difference between vessels with average performance and high performance only 10 days. This behavior can be expected as higher wave conditions will be observed less frequently. Improvements in the proportion of time the vessel can operate will therefore decrease as the wave limit increases, once the vessel has achieved a relatively high proportion of operability. Naturally both operability limits and expected duration will influence the time taken to complete a vessel transition. Comparing Figures 3 and 4, however, demonstrates the different impacts that these vessel characteristics can be expected to produce.

3.4 Wave limit for jacking operations

The wave limit for jacking operations is defined as the maximum significant wave height at which jacking operations can be safely performed. Similarly to the wave limit for vessel transitions, this limit is ranged here from 1 m to 3 m. Figure 5 demonstrates that a vessel with a jacking wave limit of 1.8 m could be expected to provide a reduction in installation duration of approximately 140 days in comparison to a vessel with a jacking wave limit of 1 m. As in Section 3.3, further improvements in wave limit are shown to provide reduced benefits as a vessel with a capability of 3 m jacking wave limit only provides a further expected reduction in installation duration of only 3 days. In comparison with the wave limit for vessel transitions, the wave limit for jacking operations will impact on the required duration to complete on-site installation operations. The impact of the wave limit is particularly dependent on the weather conditions at the OWF site; however, Figures 3 and 4 provide an indication of the typical behaviour which could be expected. These figures suggest that beyond a certain limit improvements in the wave limit for operations are unlikely to be substantially beneficial.

3.5 Discussion

An OWF developer has two key objectives when selecting an installation vessel: minimising the cost of the installation campaign, and maximising the rate at which WTGs come on-line and begin to produce revenue. The installation costs are influenced by the duration of the installation and the vessel day-rate, and the rate at which revenue production increases is influenced by the duration of the installation. The analysis of the test-case WTG installation in Sections 3.1-3.4 demonstrates that improvements in vessel performance could potentially provide minimal reductions to the installation duration. As higher performance vessels can be expected to come at a higher day-rate than lower performance vessels, minimal improvements to the rate at which revenue production increases could potentially be offset by higher vessel costs over the entire WTG installation campaign. Conversely, the analysis in Sections 3.1-3.4 demonstrates that relatively small improvements in vessel performance could potentially provide substantial reductions to the installation duration which could improve both the installation costs and the rate of production increase over an entire WTG installation campaign. The installation logistics simulation tool developed by Barlow et al. (2014) could therefore enable decision makers to build a realistic assessment of the advantages associated with a particular vessel and to guide and justify their choice of installation vessel.

The analysis of vessel characteristics presented in Sections 3.1-3.4 could also be used by an OWF developer to explore the impact on the expected installation duration if values of the vessel characteristics are in practice less than expected. This situation could arise through vessel operators advertising optimal operational performance, or through a warranty officer imposing stricter operational limits. Applying the simulation tool in this way would enable the risks to the installation schedule associated with a particular choice of vessel to be identified prior to the installation.

A further use of the analysis in Sections 3.1-3.4 is demonstrated by the standard deviations displayed in Figures 2-5. These provide an understanding of the uncertainty associated with the expected installation duration for each vessel characteristic value. This information could be used by OWF developers to identify the risks of selecting a particular installation vessel, such as the risk that an installation project will run significantly off-schedule, or the range of installation costs and revenue production increases which could potentially be obtained with a particular vessel choice. Understanding the risks associated with the choice of installation vessels enables an OWF developer to take these risks into consideration when planning the installation project and to reasonably account for possible outcomes.

4 Conclusions

This paper presents the application of an offshore wind farm (OWF) simulation tool to a test-case installation project. The simulation tool combines a realistic model of an OWF installation developed through collaboration between academic and industrial partners, with a synthetic weather model which enables a realistic assessment of the duration of the OWF installation and associated costs. The test-case presented here is used to demonstrate the impact of four key vessel characteristics on the duration of the installation. This application demonstrates the potential of the simulation tool to provide OWF planners with a framework to compare the impact of vessel selection on the installation strategy in terms of the duration and costs of the installation.

The study presented here is part of a larger project investigating decision support for the installation of OWFs. This project has developed two complimentary tools for decision support: a simulation tool and an optimisation tool. Interested readers can see Barlow et al. (2014) and Tezcaner Ozturk et al. (2014) for further information on each tool, respectively.

Acknowledgements

This study was funded through the University of Strathclyde Technology and Innovation Centre, grant reference TIC/LCPE/FI03. The authors would like to thank Kambiz Gindesgaard, Installation & Logistics, Scottish Power Renewables, Sol Judah Head of Offshore Marine and Construction Engineering, Scottish and Southern Energy and Dave Thompson, Engineering Manager, Technip Offshore Wind Limited.

References

Ait-Alla A, Quandt M, Lutjen M (2013). Aggregate installation planning of offshore wind farms. *Proceedings of the 7th international conference on communications and information technology*, Cambridge, MA, USA, January 30 – February 1, 2013, 130-135.

Barlow E, Tezcaner Ozturk D, Day S, Boulougouris E, Revie M, Akartunali K (2014). Simulation of the offshore wind farm installation logistics problem. *In preparation.*

Bundesamt fur Seeschifffahrt und Hydrographieis FINO database, available from: http://www.fino1.de/en/

Dinwoodie IA., Quail F, McMillan D (2012). Analysis of offshore wind turbine operation & maintenance using a novel time domain meteo-ocean modeling approach. Paper GT2012-68985, ASME Turbo Expo 2012, Copenhagen 2012.

European Wind Energy Association (2011). Wind in our sails, available from: http://www.ewea.org/publications/reports/wind-in-our-sails/

European Wind Energy Association (2013). Deep Water, available from: http://www.ewea.org/publications/reports/deep-water/

Lutjen M, Karimi HR (2012). Approach of a port inventory control system for the offshore installation of wind turbines. *Proceedings of the twenty-second international offshore and polar engineering conference*, Rhodes, Greece, June 17-22, 2012. 502-508.

Offshore Wind Cost Reduction Task Force (2012). Offshore wind cost reduction task force report, available from: https://www.gov.uk/government/groups/offshore-wind-cost-reduction-task-force

Renewable UK (2013). Wind energy in the UK; state of the industry report, available from: http://www.renewableuk.com/en/publications/reports.cfm/state-of-the-industry-report-2012-13

Roberts A, Weston J, Valpy B (2013). Offshore wind: a 2013 supply chain health check; a report prepared by BVG associates for the Crown Estate, available from: http://www.thecrownestate.co.uk/energy-infrastructure/offshore-wind-energy/working-with-us/strategic-workstreams/supply-chain-and-skills/

Ross SM (2013). *Simulation.* Academic Press, London UK.

Scholz-Reiter B, Lutjen M, Heger J, Schweizer A (2010) Planning and control of logistics for offshore wind farms. *Proceedings of the 12th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering*, Faro, Portugal, November 3-5, 2010, 242-247.

Tezcaner Ozturk D, Barlow E, Day S, Boulougouris E, Revie M, Akartunali K (2014). A rolling horizon optimisation model for offshore wind farm installation logistics. *In preparation.*

UK Department of Energy and Climate Change (2013). UK renewable energy roadmap update 2013, available from: https://www.gov.uk/government/publications/uk-renewaren-energy-roadmap-second-update