Project 107: Final Report

Comparative Operability of Floating Feeder Solutions

F I N A L

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Acronyms and Abbreviations

AWEA	American Wind Energy Association
CBP	U.S. Customs and Border Protection
CNS	Central North Sea
COG	Centre of Gravity
deg	degrees
DOE	Department of Energy
DOF	Degrees of Freedom
DOI	Department of the Interior
DP	Dynamic Positioning
EPCI	Engineering Procurement Construction Installation
FMEA	Failure Mode and Effect Analysis
GAO	Government Accountability Office
GW	Gigawatt (one thousand megawatts)
HC	Heave Compensation
HLCV	Heavy Lift Crane Vessel
m	meter
mHs	Significant Wave Height (in meters)
MW	Megawatt (one million watts)
LF	Low Frequency
Lpp	Length between perpendiculars
MPM	Most Probable Maxima
NDA	Non-Disclosure Agreement
NNS	North North Sea
NOWRDC	National Offshore Wind Research and Development Consortium
NYSERDA	New York State Energy Research and Development Authority
OCS	Outer Continental Shelf
OSHA	Occupational Safety and Health Administration
RMS	Root Mean Square
s	second
SNS	Southern North Sea
t	Metric Tonnes
TRIR	Total Recordable Incident Rate
U.K.	United Kingdom
U.S.	United States
WFO	World Forum Offshore Wind
WIV	Windfarm Installation Vessel
WTG	Wind Turbine Generator

EXECUTIVE SUMMARY

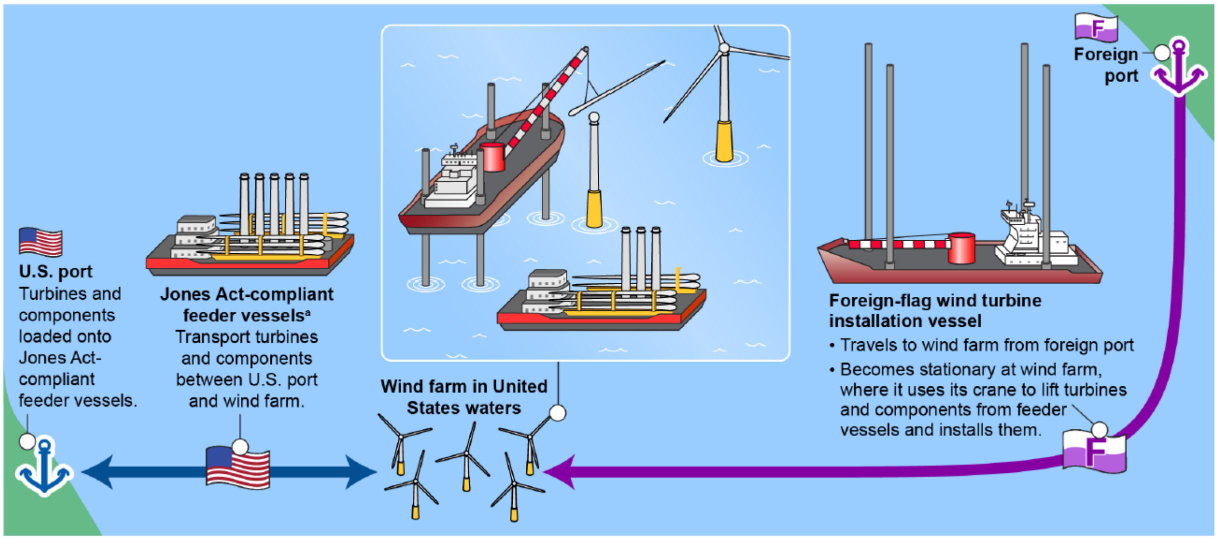
The U.S. offshore wind industry is on the verge of making a significant transition from its initial start-up exploratory pilot phase into full-scale commercial industrialization. A wide variety of vessels, tools and equipment will be needed to install the wind turbines. Current practice uses windfarm installation vessels (WIVs) that can transport required components from a load-out port to the offshore sites and proceed with installation. It is unlikely that sufficient Jones Act-compliant WIVs will be available on short notice and bridges or other overhead obstructions further limit accessibility of most U.S. ports for jack-up vessels.

Consequently, Jones Act-compliant feeder solutions that are able to sustain the safe and efficient supply of offshore wind turbine components to foreign-flagged WIVs on the Atlantic outer continental shelf (OCS) will be a critical part of offshore windfarm development in the U.S. over the near to mid-term. These solutions could also be used to supply U.S.-flagged WIVs in the future if needed. As the use of feeders in this way is unconventional in both the global maritime and offshore wind industries, this project has sought to obtain a greater understanding of differences in the operability characteristics of various feeder concepts, especially as it relates to the component lift from feeder to WIV.

The diagram in Figure 1 from a U.S. Government Accountability Office (GAO) report on Offshore Wind Energy [1], which was submitted to the U.S. Congress in December 2020, provides a graphical representation of how a Jones Act-compliant feeder solution is intended to support a foreign-flagged WIV on the OCS.

Figure 1: Graphic of Jones Act-compliant feeder concept on the U.S. Outer Continental Shelf

Source: U.S. Government Accountability Office (GAO), GA-21-153



Methods developed in this study enable an initial high-level determination to be made about the potential suitability of different feeder solutions for a given project. Those preliminary findings can then be used as precursor inputs to more comprehensive studies that should be carried out on a project-by-project basis. Such detailed further studies should be based on data that is specific to the particular vessels, assets and equipment that will be deployed, as well as geotechnical, geophysical, and met-ocean data that is location, and site-specific.

Section 1 of this report outlines the context that underpins the project and details the level of industry support the study has garnered. It describes the goals of the U.S. offshore wind industry, evaluates the likely requirements for installation assets to achieve those goals and discusses the methodology of offshore logistics that will be involved, including a range of operational risks. The influence of port infrastructure and unique environmental conditions are also discussed, as are human factor considerations.

The report then goes on in Section 2 to outline the approach that was taken to evaluate lifting operations in an offshore environment and then describes how the comparative assessment of different feeder solutions was carried out. Findings, observations, and recommendations are then discussed, including the influence that a feeder's size has on overall seasonal operability and the increase in operational uptime that is achieved by the application of heave and/or motion compensation systems. As expected for the region, the study's findings also determined that all feeder solutions that were analyzed in the simulations have higher operability during the summer months of June, July, and August on the U.S. northeast Atlantic coast.

Given the unconventional nature of feeder-based offshore logistics considered in this study, a range of unique risk factors are also highlighted. These include the method of connecting a lifting arrangement that is attached to a component on a feeder's moving deck to the lowered crane hook of the installation asset, which in this study is considered earth-fixed. Another is releasing the sea-fastening that secures a component to the feeder's deck during transit, as the crane starts to lift the component. Due to the complexity of modelling and detailed analysis required to adequately evaluate these elements, this study applied the assumptions that a) the crane-component connection can safely be made, and b) that sea-fastening is safely released when required.

However, relative motions between and the mass of items involved in this scenario create significant risks, particularly for any personnel who would typically be part of such an operation. This raises the imperative that industry will need to ensure safety, both through the development of suitable technological solutions and facilitating the availability of advanced training capabilities. The magnitude of risk to personnel in feeder-based offshore logistics is also seen as a worthwhile area of further study.

Following the discussion on findings, observations and recommendations, Section 3 expands on lessons learned during the study and prospective further feeder-related improvements that could help provide greater levels of understanding. These include station-keeping of feeders, horizontal motion of components, movement of the WIV crane and a brief discussion on the use of floating feeders to supply components to floating installation assets.

Benefits of the project are outlined in Section 4 and potential implementation scenarios are considered in Section 5. To close out the report, a number of potential new innovations that could potentially further improve the operability of floating feeder solutions are explored in Section 6.

1 PROJECT CONTEXT

As offshore wind in the U.S. continues to coalesce into more clearly definable market opportunities, the need for greater understanding of how the industry will achieve its ambitious goals has become more immediate. This project was initiated to provide greater insight into one aspect of the unique risks that need to be addressed. From unprecedented installed-capacity targets to legislative complexity and non-standard installation methodologies, the industry's challenges are considerable and warrant collective deliberation.

An initial cadre of nine (9) supporting companies at inception of the proposal , has since grown to now include a wide-ranging pool of twenty-seven (27) stakeholders across all related sectors of the industry. They include developers, turbine manufacturers, EPCI contractors, vessel designers, vessel owners, and vessel operators, along with manufacturers of specialized equipment and systems. The diversity of organizations involved demonstrates industry's broad interest in gaining a greater understanding about the risks associated with deploying floating feeder solutions into the rapidly growing U.S. offshore wind industry.

An alphabetical arrangement of stakeholders is available in Appendix 1. In addition, Table 1 on the next page provides a breakdown of stakeholders, into broad categories of their interests in or capabilities that relate to floating feeder solutions. These category listings are again arranged alphabetically. It should also be noted that some stakeholders may not directly align with a defined category or may alternatively fall into multiple categories. For example, some organizations listed under EPCI contractor may also own and operate a mix of floating and/or jack-up installation assets, while others listed in this category may provide only engineering and/or consulting services. In any case, stakeholders have been listed under what is considered to most closely describe their primary role, within the range of available categories.

To alleviate potential confidentiality concerns for a number of direct competitors that are supporting the study, the project team implemented non-disclosure agreements (NDAs) with more than half of all participating stakeholders. This has enabled the sharing of proprietary and/or sensitive details that has better informed the study and ensures that it is able to provide industry-relevant results. The level of engagement the study has been able to foster further emphasizes the immediacy of the issue.

Table 1: Broad categorization of industry stakeholders supporting the project

Developer	Turbine Manufacturer	EPCI Contractor	WIV Owner/Operator	Vessel Designer	Feeder Owner/Operator	Crane-based Compensation	Feeder-based Compensation	Specialized Tool Solutions	Propulsion Systems	Ports & Logistics
Avangrid	GE	Jan De Nul	Cadeler	C-Job	Crowley	Cranemaster	Amplemann	Osbit	Thrustmaster	Keystone Shipping
EDF Renewables	Vestas	Ramboll	Seajacks	GustoMSC (NOV)	Green Shipping Line	Seaqualize	Bargemaster		Voith	
Mayflower Wind		Saipem		Neptun Ship Design	Maersk Supply Service					
Orsted		Van Oord								
Shell										

Disclaimer:
The opinions expressed in this report are those of the authors. They do not purport to reflect the opinions or views of all industry stakeholders.

1.1 U.S. Offshore Wind Goals

The Department of Energy (DOE) Offshore Wind Market Report: 2021 Edition [2] indicates that by the end of 2020, the pipeline of offshore wind projects in the U.S. had grown to a little over 35GW. To give that figure some context, the Global Offshore Wind Report 2020 [3] from the World Forum Offshore Wind (WFO) indicates that total installed global offshore wind capacity stood at 32.5GW at the end of 2020 and is forecast to rapidly increase, reaching 234GW by 2030.

In March 2021, the current U.S. Administration established a target of deploying 30GW of offshore wind generating capacity in the U.S. by 2030, as a key driver of economic growth, reinvigorating U.S. manufacturing, combating climate change, and creating employment. With the first offshore wind farm having been installed in Denmark in 1991, it has taken the global offshore wind industry just over 30 years to install slightly more that the U.S. is aiming to achieve in less than 8 years. The target of 30-by-30 essentially means that the U.S. is looking to install nearly the same amount of offshore wind generating capacity that currently exists globally, in about a quarter of the time.

1.2 Installation Vessel Requirements

It is widely considered that the current generation of wind farm installation vessels (WIVs) can install about sixty (60) complete offshore wind turbines per year. Given the goal of achieving 30GW of offshore wind capacity by 2030 and based on a nominal turbine size of 15MW, a total of 2,000 turbines will need to be installed. At an installation rate of 60 turbines per year, slightly over 33 years of WIV capacity is needed. For that level of WIV capacity to be realized by 2030, there would need to be five (5) WIVs currently deployed on installing U.S. offshore wind projects, using a standard installation methodology.

In addition to the very short timeframe in which the U.S. wants to achieve the ambitious goal of 30-by-30, global market pressures will add a further layer of complexity to the overall equation. In a February 2022 report, Rystad Energy [4] projected that global demand for WIVs will increase significantly, from 11 vessel-years in 2021 to a staggering 79 vessel-years by 2030. This will make the prospect of securing WIVs for U.S. offshore wind projects increasingly more difficult.

1.3 Offshore Logistics Methodology

Complicating the situation even further, is that there is currently just one (1) Jones Act-compliant WIV that is only scheduled to be come into service early in 2024. As such, construction of offshore wind farms in the U.S. will necessarily be dependent on deploying foreign-flagged WIVs over the near to mid-term. As the Jones Act does not permit those vessels to operate from U.S. ports, suitable Jones Act-compliant feeder vessels will be needed to transport offshore wind turbine components from U.S. ports to the foreign-flagged WIVs, as they remain stationed offshore on the outer continental shelf (OCS).

The use of feeders in this way, for the nature and sizes of components that will be transported, and at the scale that will be required, has not been done previously anywhere in the world. This introduces further unknowns in terms of both the annual installation rates for WIVs supported by feeders, and the additional operational risk that those projects will incur due to the non-standard offshore logistics methodology.

Current generation WIVs can jack-up and refloat in sea conditions of about 2.5mHs. These vessels also attract charter rates in the order of $170,000 to $250,000 per day. If the supply of turbine components to foreign-flagged WIVs deployed on U.S. offshore wind projects cannot be reliably maintained, the economic viability of those projects will be significantly impacted. Ensuring there are suitably capable and reliable floating feeder solutions available, will be key to mitigating that risk and speaks to the wide-ranging support this study has been able to secure from industry stakeholders.

An additional complicating factor is that the Jones Act prevents foreign-flagged WIVs from “transporting” any turbine “merchandise” between different “points” on the OCS. This means that using extended weather windows that are favorable for transferring turbine components from feeder vessels to load all required components for multiple turbine installation locations, is not permitted. Under current interpretation of Jones Act provisions, a foreign-flagged jack-up WIV may transfer components from a Jones Act-compliant feeder to the WIV’s deck, prior to then installing those components at the turbine location on which it is elevated at that time. Similarly, foreign-flagged floating heavy lift crane vessels (HLCVs) are permitted to make short distance lateral moves with a load that has been taken to its crane hook from a Jones Act-compliant feeder, but only for the purpose of completing the installation lift at that specific turbine location.

U.S. Customs and Border Protection (CBP), the agency responsible for enforcing Jones Act provisions, issued a ruling in July 2020 stating that items incidental to the installation of turbine components are deemed to constitute “vessel equipment” and therefore are not considered “merchandise” under the Act. This will enable items such as WTG transport frames and blade racks to remain onboard a foreign-flagged WIV as it moves from one installation location to the next, where they can then be back-loaded to a feeder for return to the project’s loadout port. As more projects move closer towards the construction phase, additional requests for CBP rulings may provide further guidance for foreign-flagged WIVs operating on the OCS.

Through discussions with stakeholders, it was established that a range of approaches are being taken regarding how feeders will maintain their position while components are transferred to WIVs. These include by means of an integral dynamic positioning (DP) system; by mooring to the seabed after having been towed to the site by tug(s); by DP-equipped tugs that are hipped-up alongside and/or maintaining tension on towing bridles; and lastly, by being moored alongside the WIV’s hull that has been lowered towards but not into the water, with an extended vertical-height fendering arrangement fitted to the feeder.

The complexity of interactive forces between a hull-at-the-water WIV and a feeder moored alongside necessitates that asset, case and site-specific data would need to be used and is beyond the scope of this study. Similarly, the tightness of station-keeping footprint that can be maintained by other approaches that have been described, are also not able to be established without asset-specific data and analysis, which this study was unable to accommodate. Notwithstanding, each approach involves unique considerations that may affect its ability to deliver required performance of limiting excursions of the feeder to no more than about 3m (10ft). The integrity of mooring connections for a feeder moored either alongside a WIV or to the seabed should be evaluated for both their ongoing physical condition and the continued serviceability of any constant-tension winch systems that may be in use. Potential requirement for additional redundancies should also be considered. For DP-equipped feeders, their Failure Mode Effects and Analysis (FMEA) document should be up to date, with any changes to the vessel or other considerations taken into account during the vessel’s most recent annual DP trial.

In terms of feeder station-keeping, this study applies the assumption that the feeder can maintain position with sufficient accuracy to enable lifting operations to be carried out.

For purposes of this study, the overall offshore logistics methodology consists of a feeder that is either a ship-shaped DP2 vessel or a dumb barge that is towed by tug(s) and may or may not be fitted with an integral DP2 system. The feeder loads components at the project's U.S. loadout port and transits to the offshore site. After components have been transferred to the WIV and any backload taken onboard, the feeder then returns to the loadout port where it is again loaded, and the cycle continues until the project is completed.

1.4 Port Infrastructure

The heavily built-out nature of the U.S. coastline significantly limits the number of locations that might be able to support the marshalling and loadout of offshore wind turbine components. A proliferation of overhead obstructions also significantly encumbers air-draft clearances and further reduces the number of waterways in which WIVs can operate. Consequently, even when a greater number of Jones Act-compliant WIVs does become available, suitable ports for them to operate from that are in reasonable proximity to offshore wind project sites, is another major challenge for the industry. These factors place further emphasis on the need for viable feeder solutions to support the U.S. offshore wind industry, as well as a clearer understanding of the risks involved with a feeder-based offshore logistics methodology.

1.5 Environmental Conditions

A further consideration in optimizing floating feeder solutions, is the influence of environmental conditions in which they will need to operate. Most existing offshore wind projects to date have been constructed in Europe, predominantly in the North Sea. Near to mid-term projects in the U.S. will be constructed off the Atlantic Coast.

Figure 2 is based on ERA-40 reanalysis and depicts hindcast seasonal variation in wind speed at 10m elevation in the North Atlantic Basin. Similarly, Figure 3 is also based on ERA-40 reanalysis and depicts hindcast seasonal variation in significant wave height. These diagrams demonstrate the difference in conditions experienced in the North Sea compared to those off the U.S. Atlantic Coast.

In addition to wind speed and significant wave height, another factor with implications for the design of feeder solutions is wave period, or the time it takes for the crest of one wave to pass the position of the wave that precedes it. Different average wave periods impart different hydrodynamic forces onto the structure of a vessel's hull and behavior. The cumulative effect of this over time needs to be considered by vessel designers.

Figure 2: ERA-40 diagram of hindcast seasonal wind data in the North Atlantic Basin

Winter (top) and summer (Bottom), mean wind speed (U10 m/s) and direction (arrows) in the NA

Source: United Kingdom Health & Safety Executive, Offshore Technology Report 2001/030 [5]

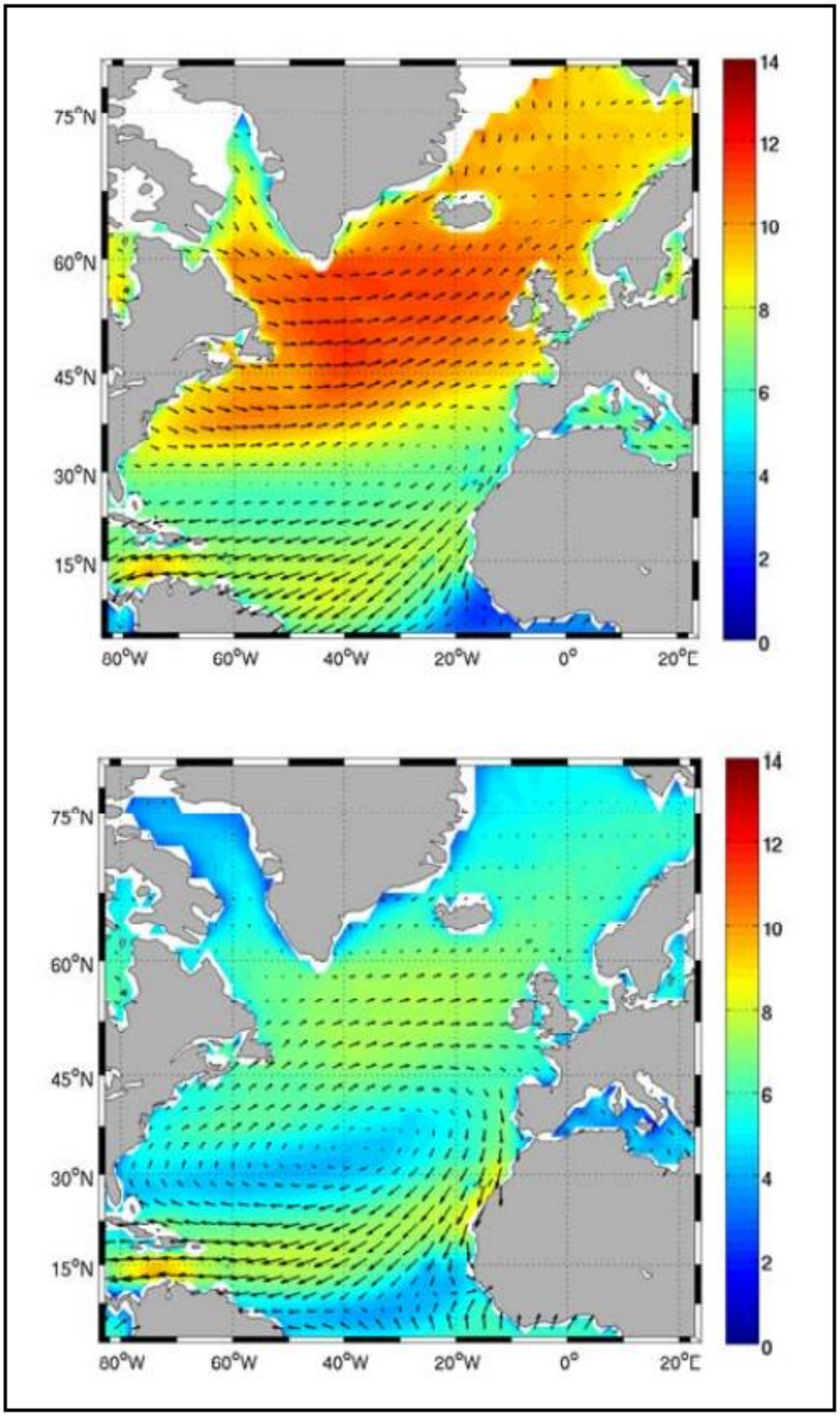


Figure 3: ERA-40 diagram of hindcast seasonal wave data in the North Atlantic Basin

Winter (top) and summer (Bottom), mean wave height (mHs) and direction (arrows) in the NA

Source: United Kingdom Health & Safety Executive, Offshore Technology Report 2001/030 [5]

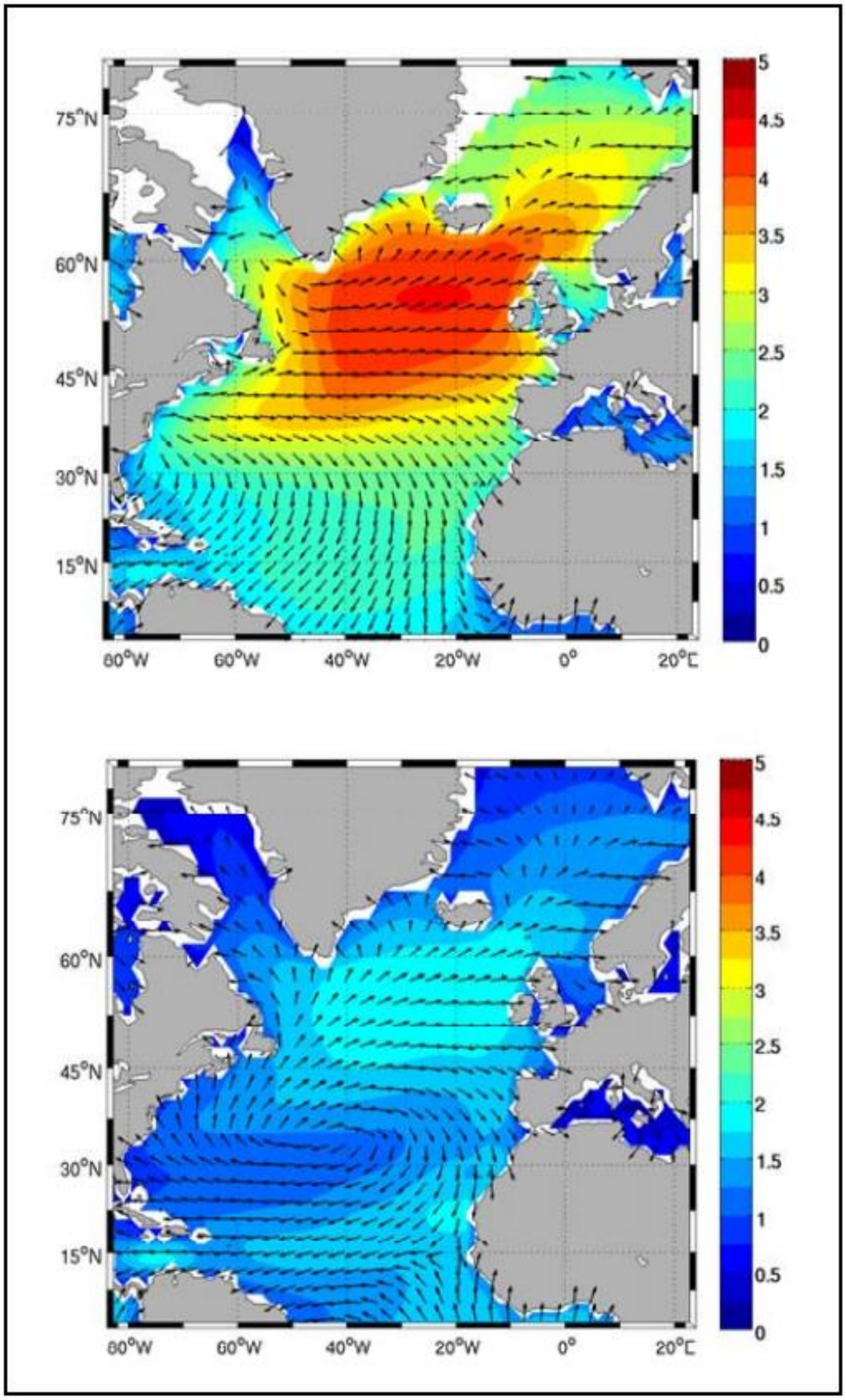
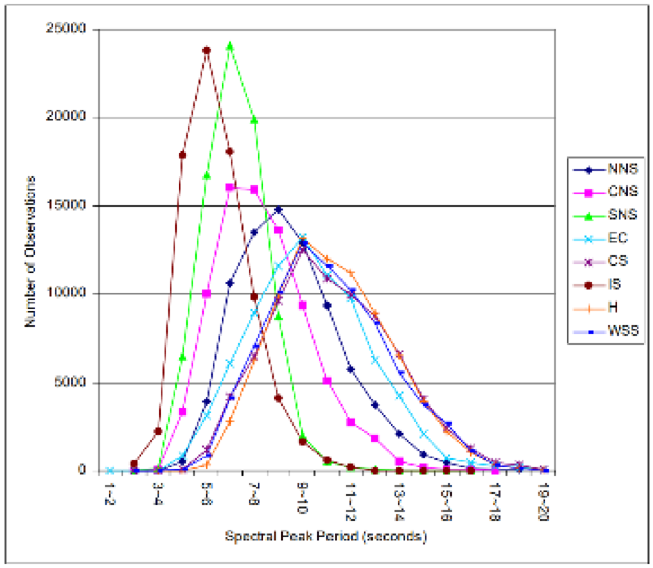


Figure 4 from the U.K. Health and Safety Executive Offshore Technology Report 2001/030 [6] shows hindcast wave period data across the North Sea.

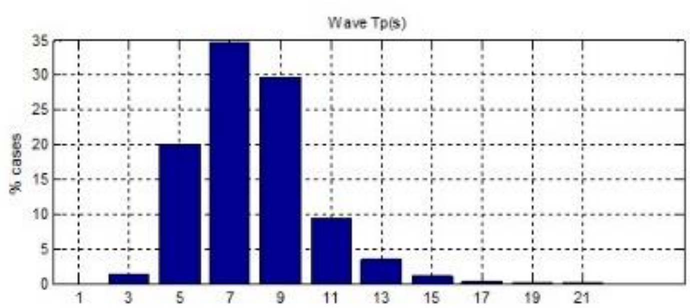
Figure 4: Line graph of hindcast wave period data across the North Sea



NNS = Northern North Sea; CNS = Central North Sea; SNS = Southern North Sea; EC = English Channel; CS = Celtic Sea; IS = Irish Sea; H = Hebrides; WSS = West Shetland Shelf

As a comparison, Figure 5 shows hindcast wave period data in position 40.99° N 70.75° W. This is a location offshore southern Massachusetts on the Northeast U.S Atlantic Coast, and was the basis used to evaluate feeder operability in this study.

Figure 5: Bar graph of hindcast wave period data offshore Massachusetts

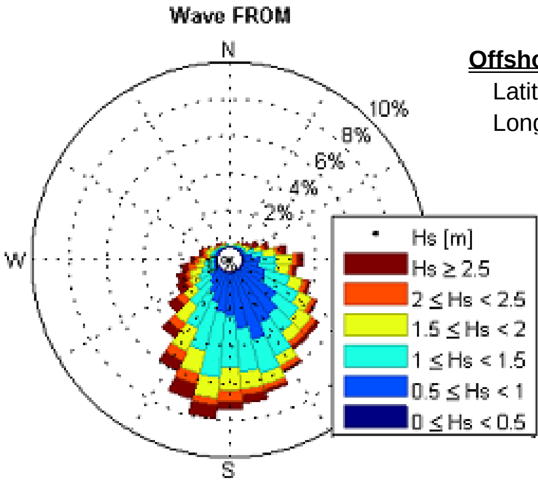


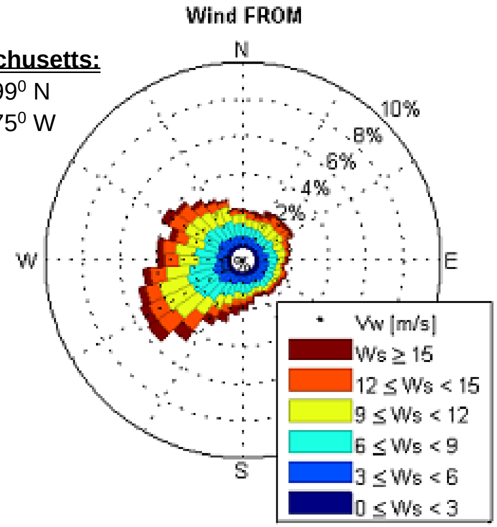
In addition to the above contrast in transatlantic conditions, it is also useful to consider regional variations. To that end, the rose diagrams in Figure 6 show hindcast wind and wave data for three different east coast locations.

Figure 6: Rose diagrams of hindcast wind & wave data on the US east coast

Offshore Massachusetts:

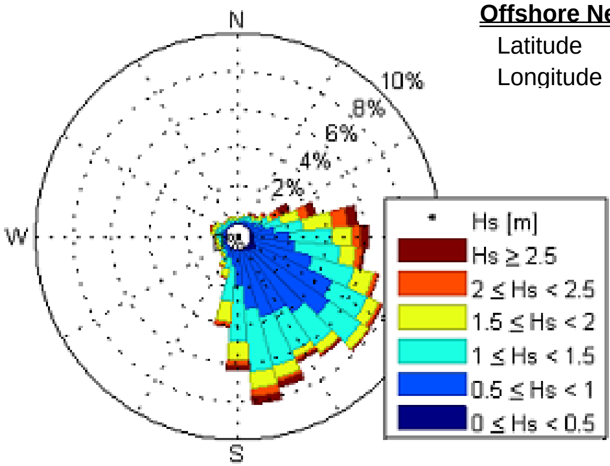
Latitude 40.99^0 N
Longitude 70.75^0 W

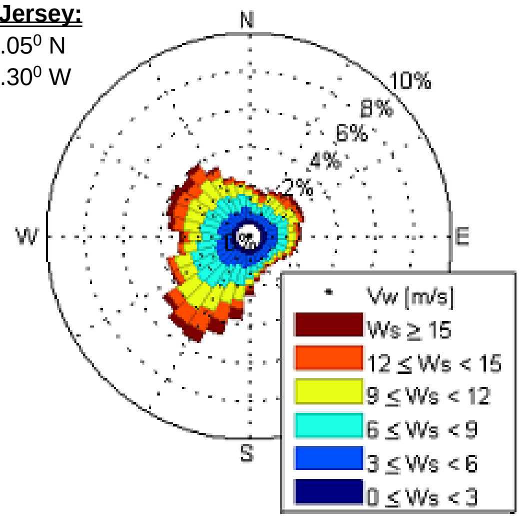




Offshore New Jersey:

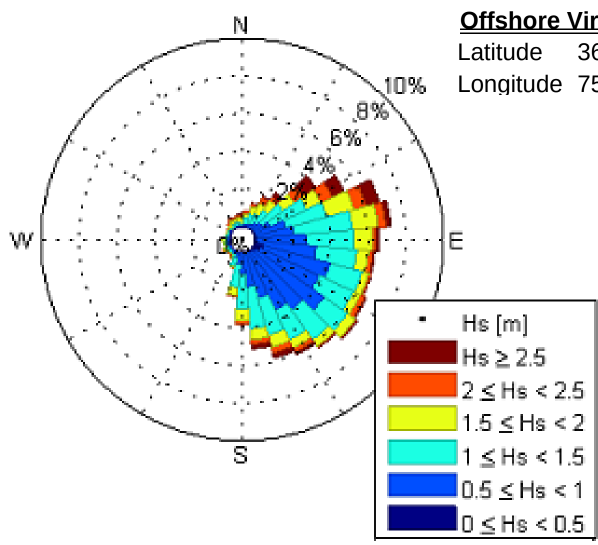
Latitude 39.05^0 N
Longitude 74.30^0 W

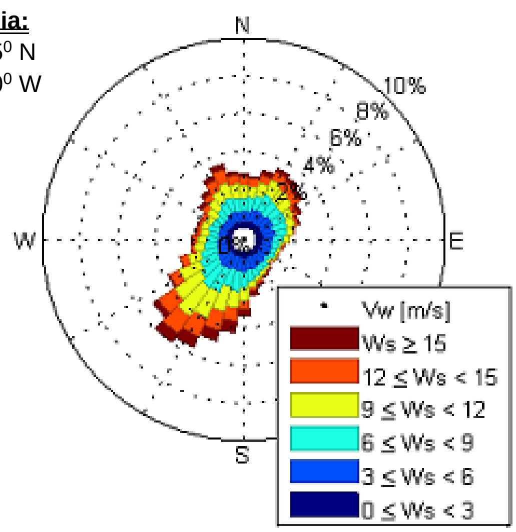




Offshore Virginia:

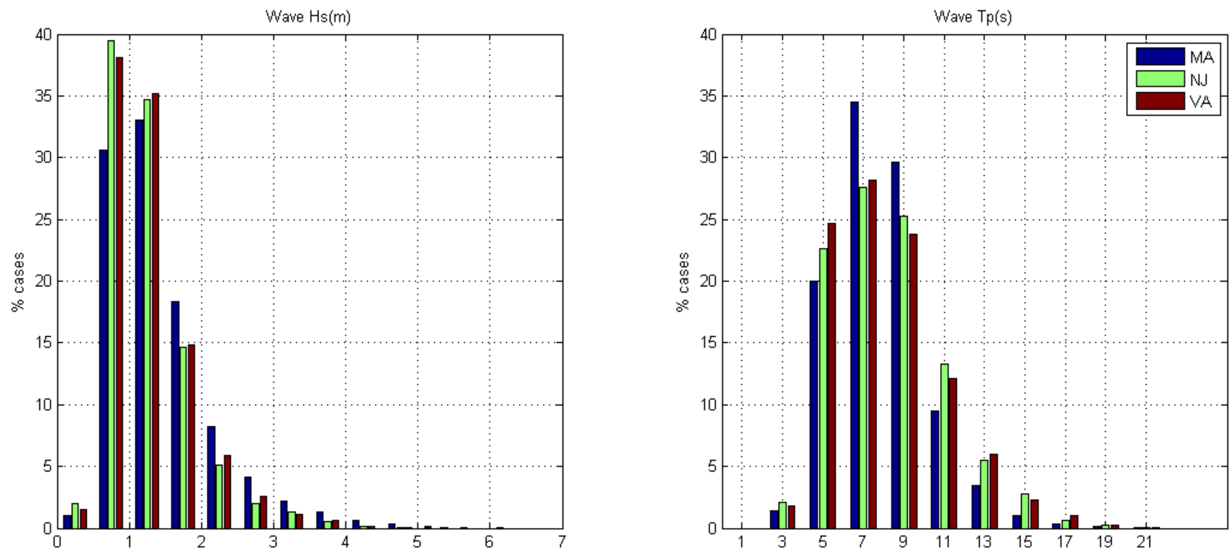
Latitude 36.85^0 N
Longitude 75.30^0 W





Similarly, the bar graphs in Figure 7 show hindcast wave height and wave period data for the same three east coast offshore locations in Massachusetts, New Jersey, and Virginia respectively.

Figure 7: Bar graphs of hindcast wave height & period data on the US east coast



Vessel responses, in particular heave and pitch, are generally higher in longer waves. Roll response depends on the natural roll period of the vessel. Feeders considered in this study have roll periods in the range of 8-12s. The Central-North-Sea (CNS) and North-North-Sea (NNS) regions experience longer waves than the South North-Sea. The wave period distribution used in this study is similar to the CNS and NNS regions.

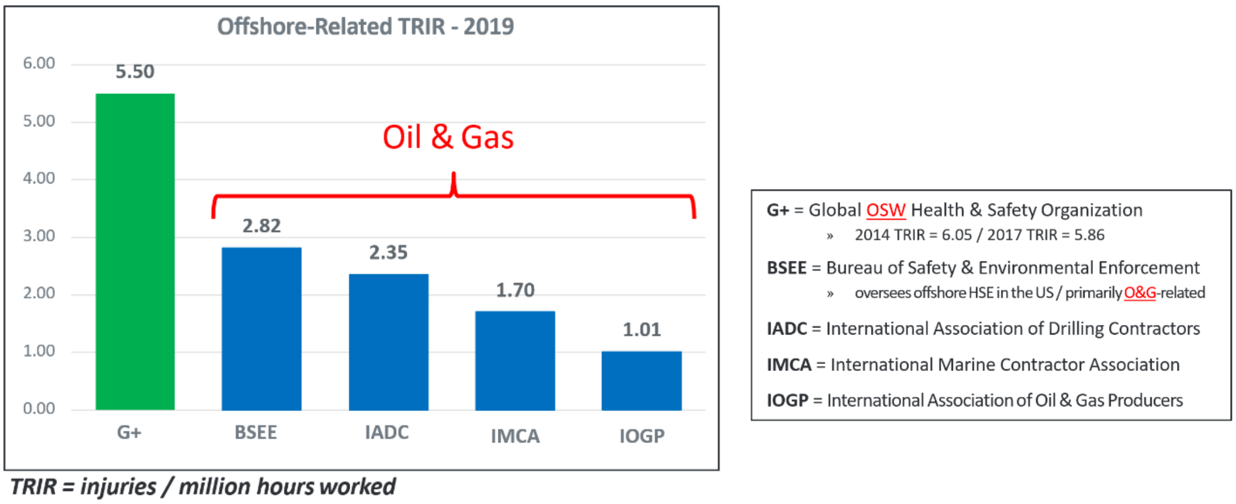
1.6 Human Factor Considerations

The very ambitious goal of installing 30GW of offshore wind by 2030, will be predicated on the U.S. also undertaking a significant and comprehensive workforce development effort. Estimates by the Department of the Interior (DOI) [6] and the American Wind Energy Association (AWEA) [7] indicate that up to 45,000 full-time-equivalent positions will need to be filled by 2025, with that number becoming up to 83,000 by 2030. This clearly presents a considerable job creation opportunity, but also brings a range of sizeable challenges.

As U.S. immigration policy prevents large-scale deployment of foreign skilled workers, most of the workforce required to support the U.S. offshore wind industry will need to be developed domestically. While a range of skills are transferrable from adjacent industries such as offshore Oil & Gas and land-based wind, there are nuanced risks associated with offshore wind that bring additional and unique hazards. To put this into some context, it is helpful to evaluate some relevant cross-sector industry data.

Total Recordable Incident Rate (TRIR) is a measure devised by the U.S. Occupation Safety and Health Administration (OSHA) to compare working conditions in different workplaces and industries. Figure 8 shows 2019 metrics for a number of organizations across the offshore wind and Oil & Gas industries.

Figure 8: Offshore wind and Oil & Gas cross-sector TRIR data for 2019



The U.S. is well experienced in both offshore Oil & Gas and land-based wind but has very limited experience in offshore wind. In contrast, Europe currently dominates the global offshore wind industry and also has considerable experience in both offshore Oil & Gas and land-based wind. Historical data for the global offshore wind industry shows a downward trend in annual TRIR results, but the figure still remains almost double that of the next nearest Oil & Gas-related metric. If the rate of improvement in the global offshore wind industry's TRIR data continues to reflect the 5-year trend in the above diagram, it would take in the order of 25 years for that figure to reach parity with the next nearest Oil & Gas industry metric, presuming the latter remains unchanged.

To mitigate additional risks to personnel in the U.S. offshore wind industry, appropriate training is progressively being made available but will need to expand considerably in order to meet the forecast levels of demand. In addition, suitable systems and safeguards are also required to effectively manage the various operational activities that need to be undertaken. Relevant considerations include but are not limited to:

- Worksite orientation & familiarization
    - Manufacturing / Intermediate & Marshalling Ports / Vessel & Helicopter Safety Induction
- High-risk + high-consequence task-specific proficiency development
    - Feeder-based Operations / Crane & Banksman / CTV-SOV-WIV / Helicopter Operations
- Procedural development & pre-deployment operational verification
    - How does it need to be done? / Is everybody involved on the same page?
- Risk mitigation planning & proof-of-concept validation
    - HIL elements associated with operational decision-making in feeder-based operations

The magnitude and extent of unique risks associated with floating feeder-based offshore logistics cannot be overstated. From undertaking heavy-lift crane operations with sensitive components in a dynamic open sea environment, to having personnel not only transfer onto the deck of a floating feeder in that scenario, but also exposed to the relative motions between and the mass of items involved, the prospect of potentially negative outcomes is considerable.

Industry is endeavoring to develop suitable technological solutions to help mitigate some of the risks involved. However, the gravity of consequences that could result from an incident tends to indicate that risk to personnel in feeder-based offshore logistics is an area worthy of further detailed study.

2 FINDINGS | OBSERVATIONS | RECOMMENDATIONS

Computer simulations were carried out to model the lifting of WTG components and for evaluating the comparative operability of different feeder solutions. Project report M1.1 titled "Comparative operability of Floating Feeder Solutions" [8] explains the simulation inputs, model, criteria, and results in detail. Project report M1.2 titled "Operability Analysis Approach" [9] explains the methodology that was followed to do the comparative operability analysis. This chapter gives a brief review of those two reports and highlights some of the crucial observations, findings, and recommendations from the study.

The study used a combination of time-domain and frequency-domain analysis. MARIN's in-house software Diffrac and Anysim were used. Diffrac is a linear diffraction theory program where the added mass, damping and wave loads on a vessel can be calculated in frequency-domain. Anysim is a non-linear time domain simulation software for offshore applications where the response of floating bodies due to hydrodynamic and mechanical forces can be calculated.

The feeder gets loaded with WTG components (towers, nacelle, blades) at a U.S. port, travels offshore to the installation location (either under own power or towed by tugs) and gets positioned (with DP system or tugs) next to a jacked-up WIV, before the various components are lifted off using a crane on the WIV. The most critical part of the operation is the actual lifting of the WTG components from the floating feeder vessel by a WIV crane. Since the lift involves changing draft and metacentric height of the feeder (as component is lifted off), potential re-hits of the WTG components, varying winch speeds of the WIV crane and other nonlinearities, it is best handled with time-domain simulations. Results of the time-domain simulations were then related back to the motions of the feeder vessel. Since motions of the feeder itself can be quickly calculated in frequency-domain, these motion limits were then used to find the operability of a wide range of feeder solutions (different feeder sizes, presence/absence of motion and heave compensation, additional damping from advanced thruster solutions etc.).

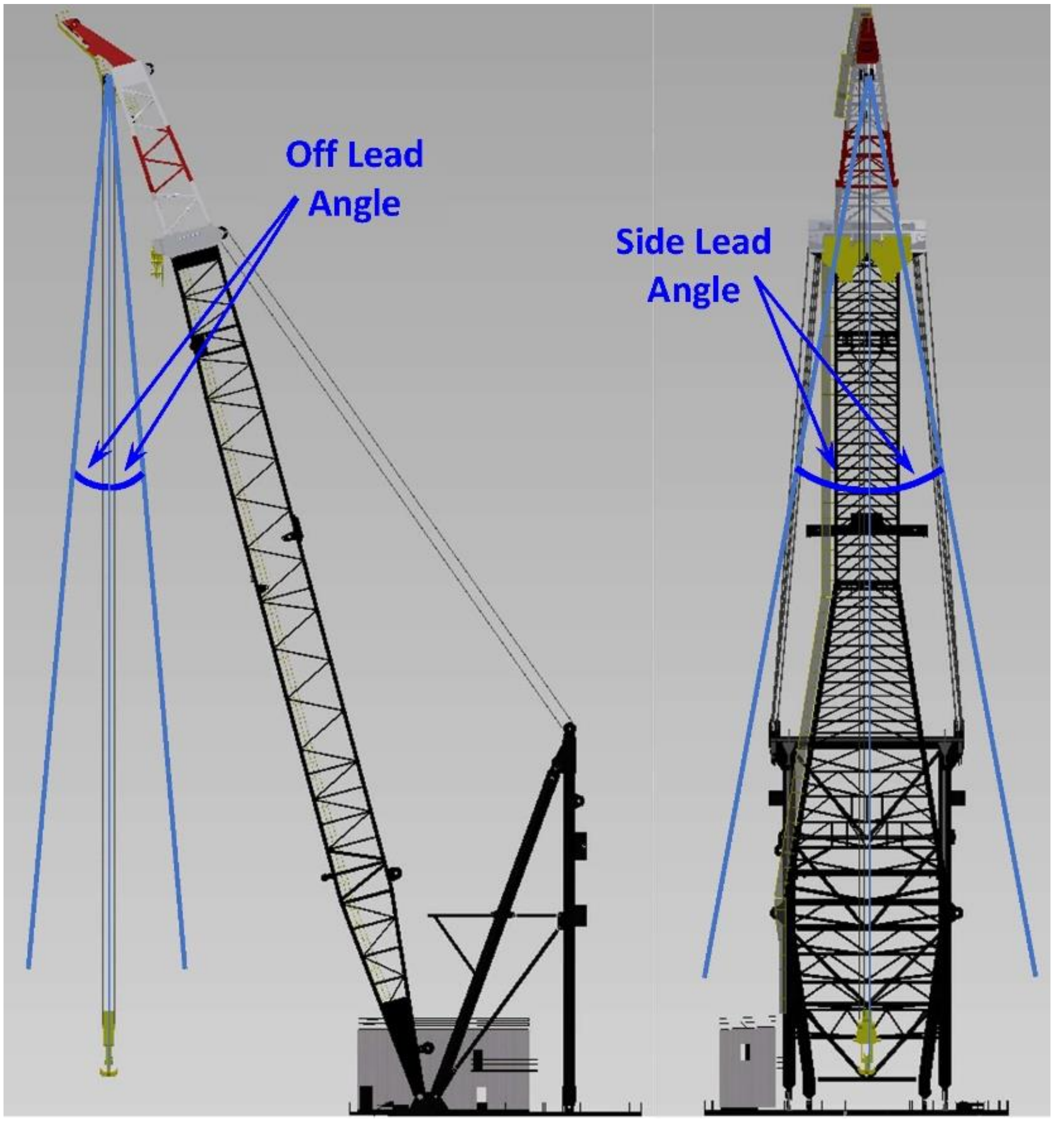
2.1 Evaluation of Critical Lifting Operation

Time domain simulations were carried out to model lifts of various WTG components from a floating feeder using the crane of a jack-up WIV. The WIV will be jacked-up with sufficient air-gap when the feeder arrives at the site. Therefore, wave forces are only considered on the feeder vessel. The base of the crane is considered earth-fixed and the stiffness of the crane structure (truss, crane house etc.) is included in the equivalent stiffness modelling of the hoist arrangement. Figure 9 shows a rendering of the ship shaped feeder vessel carrying the four (4) WTG components. The feeder had a length of 100m, beam of 25m and loaded draft of 5m (displacement of 10,000t). These dimensions were defined based on the averaged data of a number of different feeder concepts provided by stakeholders. The feeder carried a 15MW turbine in four sections (2 tower sections, nacelle, and blade set). The lightest component was the smaller tower section at 219t while the heaviest component was the nacelle at 777t.

Figure 9: Rendering of feeder vessel with WTG components

The lifting simulations were performed for each WTG component (4 lifts). The loading condition (draft) of the feeder was varied for each lift. This study considered only first order motions of the feeder, as that generates the greatest motions and accelerations in a vertical direction. Low frequency (LF) motions might lead to high crane lead-angles (see Figure 10) as the feeder drifts in surge/sway/yaw, but they occur over a large enough period of time (~70-100s) that the crane operator/lift superintendent can decide to start the lift when the lead angles are close to zero. The presence of a DP system on a feeder can also significantly reduce LF motions.

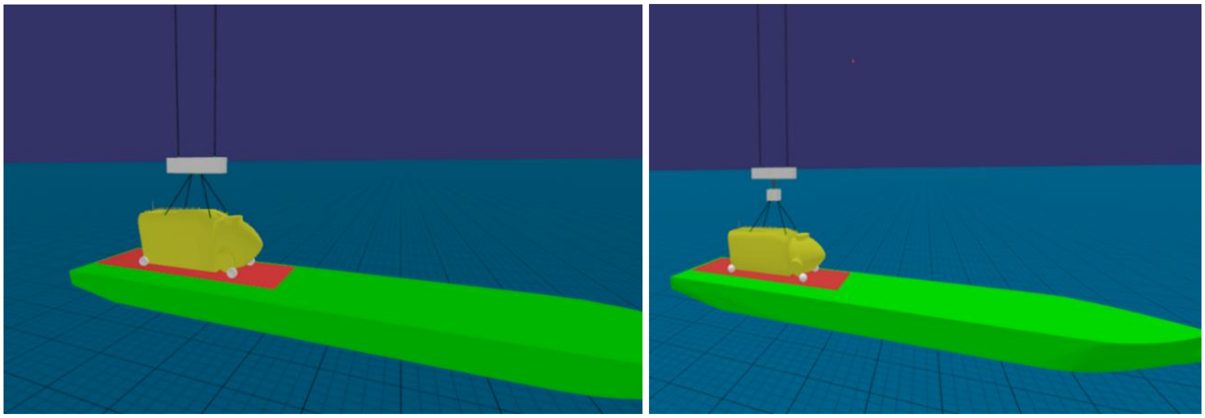
Figure 10: Diagram showing crane lead angles



Simulations were started with the crane lines and slings already connected to the WTG components. Springs and dampers were used to model the sea-fastening between the base of the WTG components and the feeder deck. Rigging can be a significant safety risk during any heavy lift but rigging when there is relative motion between the hook or rigging and the work surface is even more dangerous. That risk should be considered by anyone considering this installation method but was not considered in this study.

Lifts were performed with and without heave compensation on the crane. Figure 11 shows the lifting set-up for a nacelle. The model on the right has a heave compensation device. These devices can reduce the occurrence of shock-loading.

Figure 11: Time domain model of nacelle lift



Lifting simulations were done for a range of wave heights, peak periods, and directions (252 environments were considered with heave compensation and 168 environments without heave compensation). Wave heights were varied from 0.25m to 2.5m, peak periods from 5s to 17s and wave direction from 90deg to 180deg (directly abeam to head-on). The lifts in each environment were repeated for 10 different seeds, which represented different instances in time at which the lift is started. Each simulation was run for 1080s. The initial 600s were used to allow the system to reach equilibrium. Waves were started at 600s. From 600-900s (5 minutes), the feeder is moving in the waves. After 900s, the sea-fastening is released, and the lifting starts. When heave compensation is present, the lifts are started at the top of the heave motion at the location of the WTG component. When no heave compensation is present, the lifts are started at a random point in time. The WIV crane winch in this study has a speed of 10 meters per minute. The study used a heave compensation device that has a quick lift functionality and can lift at 24meters per minute (up to a stroke of 2m).

Results of the time-domain simulations were analyzed with respect to relevant criteria applied on the accelerations of various components, crane line loads and the occurrence of re-hits during the lifts. Amongst the criterion considered, it was found that re-hits occurred most often. A clear correlation existed between the number of lifts that exceed a criterion and vertical motions of the feeder at the 4 corner base points of the WTG components. These vertical motions were evaluated both before and after each lift considering the instantaneous center of gravity and center of floatation. Doing so enabled changes in the feeder’s natural roll period to be taken into account, as feeder motion characteristics can alter quite substantially depending on the component being lifted.

Figure 12 shows results from time-domain simulations related to vertical motions of the feeder. The x-axis shows maximum heave RMS values at the 4 corner base points of WTG components (the maximum value from before and after the lift is taken). RMS motions are split into bins that are 0.1m wide and the center of the bins is shown in the figure. Each bin contains at least 10 lift simulations with different seeds in a particular sea condition, but different sea conditions can result in similar heave RMS resulting in many more cases in most bins. The y-axis shows the percentage of simulations that exceed any of the criteria considered (component accelerations, crane line tensions, re-hits) during the lift.

Figure 12: Percentage of lift simulations that exceed criteria with increasing heave motions

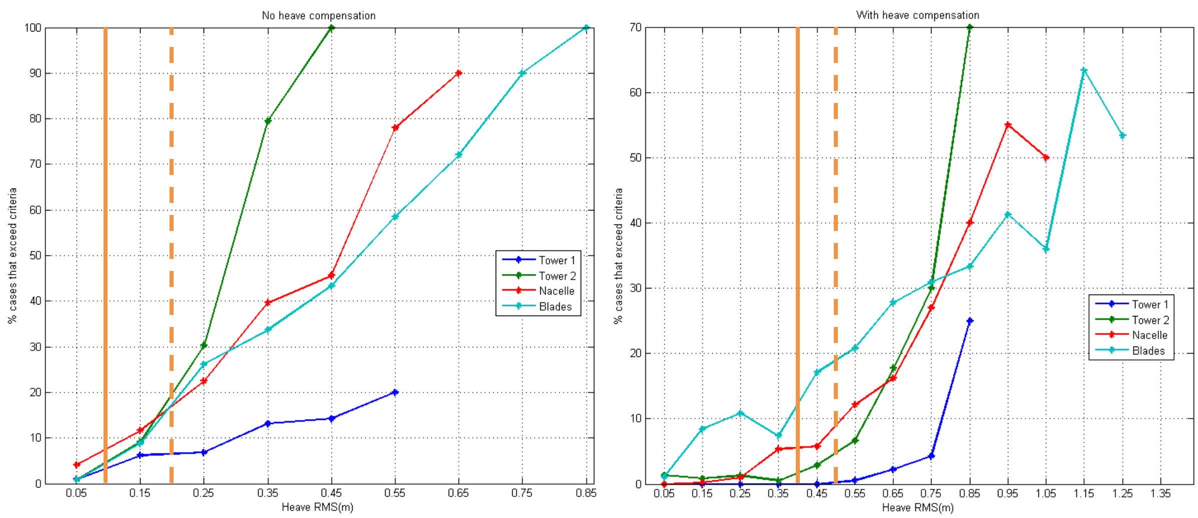
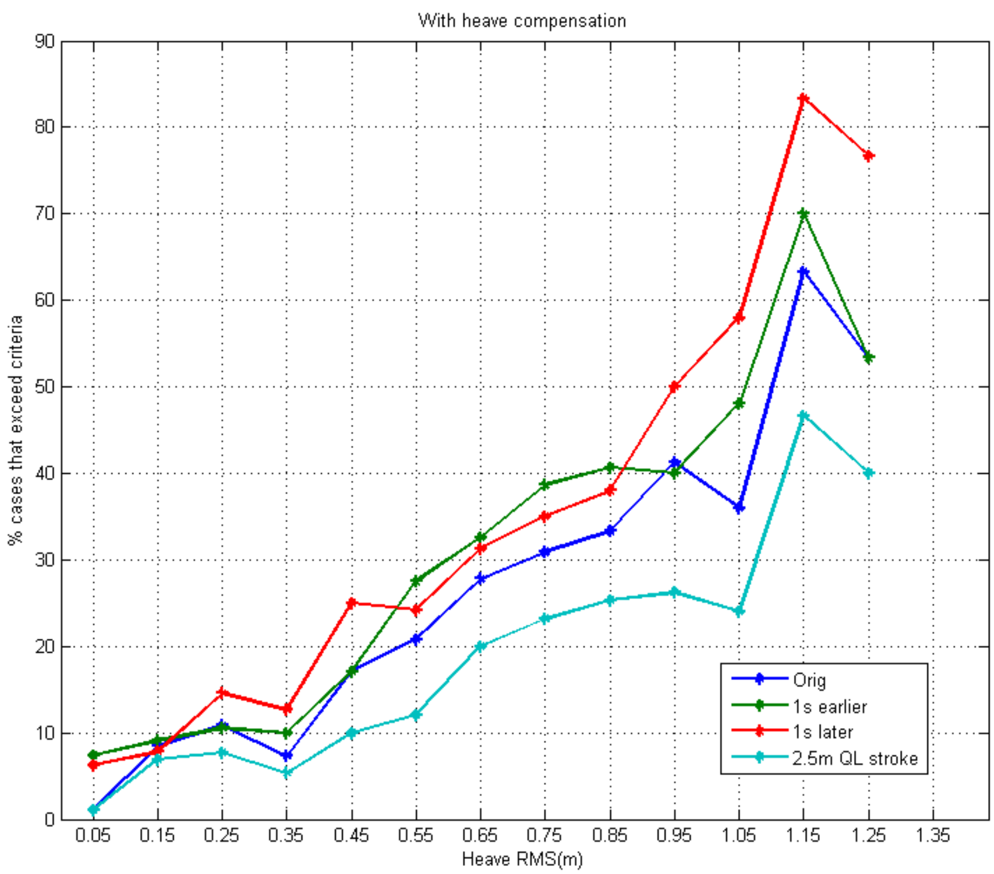


Figure 12 shows that heave compensation in the crane increases acceptable heave motion RMS values from 0.1m to 0.4m. It is noted that not all lifts are successful below these limits, which could be associated with low probability events such as waves with very short periods but large height from random wave generation. It is assumed that those periods can be avoided by a skilled lift operator, especially when wave prediction systems are present to aid the operation. A sensitivity analysis for 0.2m and 0.5m is included in the main report M1.1 [8] and helps to identify the expected uptime range.

It is also worth noting that the level of improvement achieved for blades with crane heave compensation is less pronounced. This is due to the large longitudinal footprint that was considered in this study, where blade racks are positioned about 70m apart on the feeder's deck. That configuration understandably increases the risk of re-hits due to pitch motions of the feeder. Alternative blade rack configurations that have a smaller longitudinal footprint on the feeder's deck would be less susceptible to this occurring.

Blade lifts with heave compensation were re-done with some variations in the quick-lift process to check the sensitivity. In the base case, quick-lifts were started at the top of the local heave motion. In the sensitivity cases, quick lifts were started 1s before and 1s after the local heave maxima. Another variation was to increase the quick-lift stroke from 2.0m to 2.5m. Figure 13 shows the effect of these variations on the results. Changing the quick-lift start time slightly increases the number of simulations that exceed the criteria while increasing the stroke length improves the results.

Figure 13: Percentage of cases that exceed criteria at different heave motions – Blades



2.2 Comparative Assessment of Feeder Solutions

Time domain simulations were used to derive acceptable heave RMS values of the feeder at the base corners of WTG components. These limits depend on the lifting configuration used, i.e., the limits are different with or without crane-based heave compensation. These heave motions can be easily derived in frequency-domain for a large variety of feeder solutions. This ensures that operability of a wide range of feeder solutions can now be calculated.

The following variations were considered in the comparative operability study:

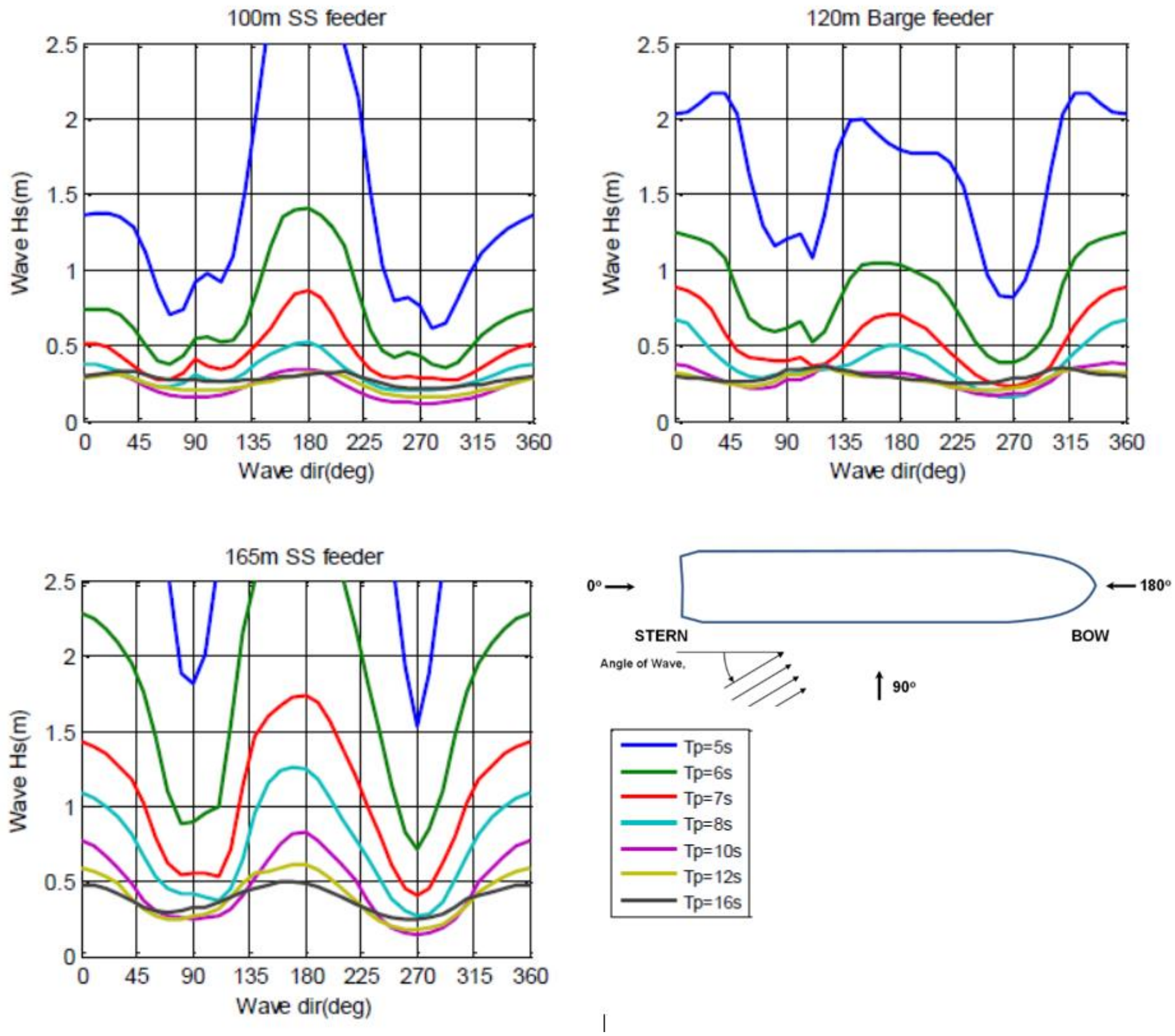
- *3 different feeders* – One barge and two ship shaped vessels. Table 2 shows the main particulars. Diffraction analyses were performed for these feeders at various drafts (corresponding to the draft/displacement before each WTG component lift).
- *Presence of advanced thruster systems or anti-roll devices, modelled as additional roll damping*
This study only looked at wave frequency motions. Therefore, only the effect of advanced thruster systems with regard to their ability to reduce roll motions was considered. While the default case had 3% roll damping, the effect of advanced thruster systems was considered with 12% roll damping. These estimates were for basic/notional feeder vessels. Purpose-built vessels can potentially improve on the amount and effectiveness of roll dampening.
- *Presence of rails on the deck to assist placement of WTG components at the start of the lift*
Since motions are generally lower near the centerline of a vessel, the effect of moving components to the centerline before a lift starts were evaluated. Both results with and without rails are presented for all feeders. It should be noted that load transfers like this require specially designed ballast systems which are difficult to add to generic feeders.
- *Presence of feeder-based compensation systems.*
Motion compensation comes in different flavors – systems that compensate in 2 (roll/pitch), 3 (heave/roll/pitch) and 6 degrees of freedom (DOF). 2-DOF systems work in combination with a crane-based heave compensation system. Generally, these deck-based systems have cylinders with defined maximum stroke lengths at their corners. They can compensate for deck motions as long as the stroke limits are not reached. This results in a reduction of the calculated heave RMS at the 4 corners of the WTG component. The applied reduction level is chosen such that the corresponding one-hour heave MPM does not exceed the stroke length. A stroke length of 2.2m (half stroke/stroke amplitude of 1.1m) was considered in the study. This effectively increases the allowable heave RMS by about 0.3m.

Table 2: Main particulars of feeder vessels (loaded drafts)

Parameter	Units	100m Ship shaped feeder	Barge feeder	165m Ship shaped feeder
Length Overall	[m]	100.2	122	165
Beam	[m]	24.9	32	35
Loaded Draft	[m]	5	3.4	6
Loaded Mass	[t]	10,223	11,689	26,084

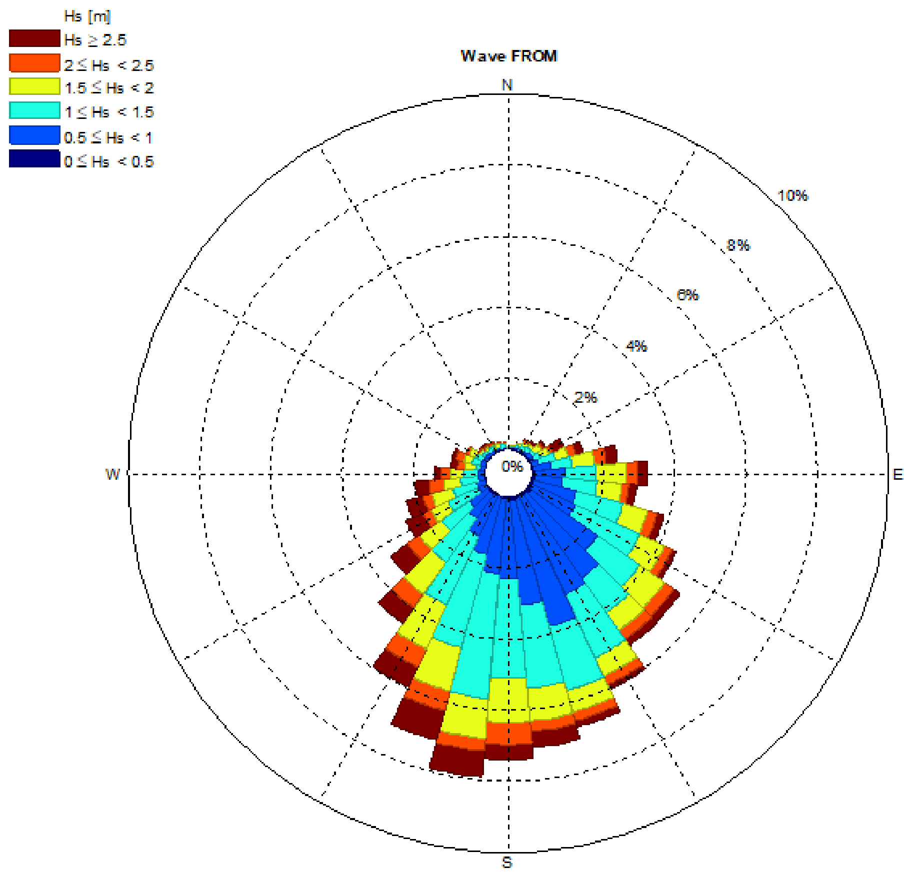
Since vessel motions for each configuration above are different, identical heave RMS value criteria result in different wave height limits for each vessel. Figure 14 shows wave height as a function of direction and period that results in a heave motion RMS value of 0.1m. This limit was identified from Figure 12 for the configuration without heave compensation. With motion compensation on the feeder or heave compensation in the crane, allowable wave heights increase by a factor 4. It should be noted that these limits are based on vertical motions only and do not consider the increased challenges of connecting the rigging or transferring personnel in the increased wave height.

Figure 14: Wave height limits for vessels without heave compensation or motion reduction



Hourly hind-cast data for a location offshore Massachusetts was selected for this comparative study. Figure 15 shows the wave distribution. Most waves come from the South, South-West and South-East. Feeders have been assumed to head into the dominant wave direction for the comparative operability study, i.e., the feeder heading is always 180deg (due South). This means that the waves are from a head-on sector (within a 45deg sector each side of head-on) in about 60% of the environments. Although a feeder on DP might be able to adjust its heading in each environment, its actual heading will depend on orientation of the WIV, which is limited in the location and heading it can jack-up by exclusion zones around each foundation.

Figure 15: Distribution of waves in Offshore Massachusetts



Heave RMS values at the base corners of various WTG components was calculated for different feeders and every wave condition in the hindcast data set. This value was compared against the allowable heave RMS criteria (0.4m RMS with heave compensation, 0.1m without heave compensation) to find the environments where the lifts are possible. In addition, a 16-hour total duration was considered (4 hours for each lift) necessary to lift all the components from the feeder.

Based on this methodology, uptime was derived by looking at the number of days in a given month or year where a 16-hour block was available for the component transfer. The reader is again urged to refer to report M1.1 [8] for a more detailed description of the methodology and results.

2.3 Comparative Operability, Findings

Table 3 shows the uptime for different feeder solutions considering an allowable heave RMS value of 0.4m. This value is derived in Section 2.1 for crane-based heave compensation systems and is 0.3m higher than the limit without heave compensation. Coincidentally, this difference equals the reduction obtained from deck-based compensation. Therefore, comparative operability results are similar for either compensation method. Overall uptime (with motion compensation and no additional anti-roll or rail systems) of the smaller feeders is about 55-60%. This increases significantly to 80% with the 165m feeder.

Most waves at the site range from 6-10s. This corresponds to wave lengths from 60-160m. Heave and pitch motions of a 165m feeder will generally be lower in these waves (roll depends on the natural roll period). Using advanced thruster/anti-roll systems can improve uptime by 3-5%, while using rails to transfer components to the center of the feeder before the lifts could increase uptime by 6-8%.

Table 3: Uptime values (as percentage) with heave compensation in the hoist wire

Vessel	**100m SS feeder**				**Barge feeder**				**165m SS feeder**			
Rails	**No**		**Yes**		**No**		**Yes**		**No**		**Yes**	
Roll	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Jan	39.8	45.2	46.2	48.4	48.4	48.4	52.7	54.8	68.8	75.3	80.6	81.7
Feb	43.5	45.9	48.2	49.4	42.4	43.5	44.7	47.1	80.0	84.7	85.9	87.1
Mar	48.4	49.5	52.7	57.0	50.5	52.7	57.0	57.0	79.6	81.7	84.9	87.1
Apr	37.8	45.6	47.8	52.2	42.2	47.8	56.7	57.8	67.8	73.3	80.0	82.2
May	59.1	66.7	74.2	77.4	63.4	66.7	71.0	75.3	77.4	80.6	88.2	89.2
Jun	87.8	94.4	95.6	96.7	87.8	92.2	95.6	95.6	100.0	100.0	100.0	100.0
Jul	86.5	91.9	93.2	94.6	83.8	91.9	91.9	91.9	97.3	97.3	97.3	97.3
Aug	83.9	85.5	88.7	88.7	87.1	87.1	88.7	90.3	93.5	93.5	95.2	96.8
Sep	53.3	63.3	63.3	66.7	56.7	60.0	63.3	63.3	71.7	78.3	80.0	80.0
Oct	32.3	35.5	48.4	50.0	35.5	40.3	46.8	51.6	66.1	67.7	67.7	71.0
Nov	51.7	56.7	60.0	60.0	58.3	63.3	66.7	66.7	78.3	83.3	85.0	86.7
Dec	43.5	50.0	50.0	56.5	48.4	50.0	53.2	56.5	66.1	69.4	77.4	79.0
Total	55.5	60.7	63.9	66.3	58.5	61.8	65.6	67.2	79.1	82.4	85.6	86.9

Anti-roll devices or feeder-based motion compensation acting in directions other than heave, such as the case with roll/pitch compensation platforms, has very limited influence on the heave at the base of the component, but they are effective in reducing horizontal motions at the top of the component. This increases the safety of the operation but is not considered in any detail in the presented comparative operability analysis (see also Section 2.4 #6).

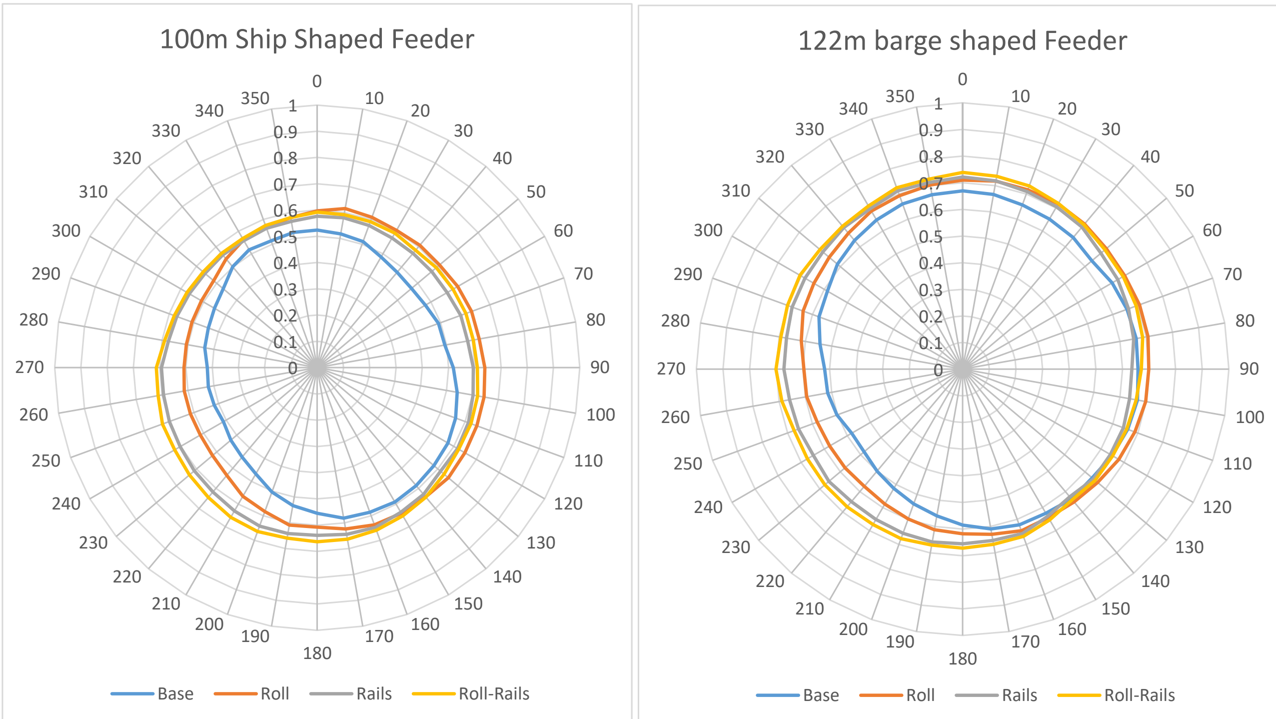
The amount of available uptime is very limited without any compensation (~10% annual for the smaller vessels and ~30% for the 165m vessel), see Table 4. Additional uptime values are included in report M1.1 [8] and show the range of values that can be expected if an additional 0.1m heave RMS would be allowable.

Table 4: Uptime values (as percentage) without heave compensation

Vessel	100m SS feeder				Barge shaped feeder				165m SS feeder			
Rails	No		Yes		No		Yes		No		Yes	
Roll	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Jan	3.2	3.2	3.2	3.2	4.3	4.3	4.3	4.3	18.3	19.4	21.5	21.5
Feb	2.4	2.4	2.4	2.4	3.5	3.5	4.7	4.7	18.8	18.8	18.8	18.8
Mar	6.5	6.5	6.5	6.5	3.2	3.2	3.2	3.2	19.4	19.4	22.6	22.6
Apr	5.6	5.6	5.6	5.6	2.2	2.2	2.2	2.2	21.1	21.1	21.1	21.1
May	9.7	9.7	9.7	9.7	7.5	7.5	7.5	7.5	46.2	46.2	46.2	46.2
Jun	25.6	25.6	25.6	25.6	21.1	22.2	20.0	21.1	67.8	67.8	67.8	67.8
Jul	29.7	31.1	31.1	31.1	21.6	20.3	20.3	20.3	62.2	62.2	62.2	62.2
Aug	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	50.0	53.2	61.3	61.3
Sep	1.7	1.7	1.7	1.7	1.7	1.7	5.0	5.0	20.0	21.7	23.3	25.0
Oct	1.6	1.6	1.6	1.6	0.0	1.6	3.2	3.2	11.3	12.9	14.5	14.5
Nov	8.3	8.3	8.3	8.3	11.7	11.7	11.7	11.7	25.0	25.0	26.7	26.7
Dec	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	17.7	17.7	17.7	17.7
Total	9.3	9.4	9.4	9.4	7.7	7.8	8.0	8.1	32.0	32.6	34.0	34.1

The results discussed above only considered the motion limits established in section 2.1 and assumed the feeder would be able to head into the dominant wave direction (i.e. South). The effect of roll suppression devices and advanced skidding systems to lift components from the midship centerline location is more significant in beam waves. This sensitivity to wave heading is shown in Figure 16, for annual uptime value as a function of the orientation of the feeder. It should be noted that these results maintain the same vessel heading for all weather conditions, resulting in some head wave and some beam wave scenarios. Uptime values would be further suppressed if the worst heading for each weather condition were considered.

Figure 16: Annual uptime as a function of feeder vessel heading



2.4 Observations and Recommendations

1) Based on criteria considered in this study (component accelerations, re-hits, and line load limits), re-hits are most important. Among the different components (tower, nacelle, blades) that were considered, blades experienced the most re-hits. This is due to the large longitudinal footprint (support structures ~70m apart) on the feeder's deck considered in this study. A smaller longitudinal footprint would reduce this risk.

2) Feeder motions before and after lifts need to be considered during these operations, as roll periods and/or vessel motions can change after a component is lifted off the feeder's deck. This was done for every component lift in this study and was particularly important for the lift of tower 1 due to its high COG.

3) Overall uptime is very limited without any sort of compensation systems. Crane-based heave compensation with quick-lift functionality and/or deck-based compensation on the feeder can significantly improve the available uptime.

4) Uptime also increases significantly with vessel size. Most of the wave periods are around 6-10s which correspond to wave lengths from 60-160m. Heave and pitch motions of the 165m feeder will generally be lower in these waves (roll depends on natural roll periods).

5) Additional roll damping does not significantly reduce the vertical heave motions and thus has limited effect on the calculated uptime. However, roll damping will be most effective for beam waves. In most

cases in this study, waves were from a head-on sector. In addition, horizontal motions at the tower-top were not considered. Roll mitigation can be useful to limit tower-top motions. Roll mitigation reduces risks related to rigging, increases safety and will improve operability by reducing sea-fastening moments and load swing.

6) Relative motions between components or personnel on a feeder's deck and a lowered WIV's crane hook may be substantial. This presents a significant challenge to avoid risk to personnel who may be tasked with attaching a component's lifting arrangement to the crane hook. These relative motions are a significant risk that needs to be addressed by anyone considering the installation method. A range of technical solutions are currently being explored and developed by industry, varying from motion compensation on the barge to fully autonomous connections between the crane and the WTG component. These advanced systems should be seriously considered to reduce the safety risk involved in rigging activities on floating feeders in offshore conditions. It is imperative that appropriate procedures are developed, and relevant personnel provided intensive training in them to further reduce safety risk.

7) Release of sea-fastening that secures components to the feeder's deck during transit so it can be lifted by a WIV crane, is another significant risk factor. This is particularly the case for taller components on a feeder in a beam-on aspect to the prevailing wave direction, as the component's higher COG may be susceptible to an overturning moment due to feeder roll motions. Feeder-based motion compensation or fully automated connect and release systems are being developed and should be considered to reduce this risk.

8) Some stakeholders consider personnel transfer between the fixed WIV and the floating feeder, while others purposely exclude this scenario. Safe walk to work gangways with motion compensation systems are available and should be considered to reduce the safety risk involved with transferring personnel in offshore conditions.

9) The safe transfer of transport frames and other items when backloading a feeder for its return to port is expected to be less critical than WTG components but should nonetheless also be considered in a project-specific risk analysis and comprehensive operability assessment.

10) Safe transfer of turbine components from floating feeders to WIVs on the OCS will depend on close and effective communication and coordination between the WIV's lifting supervisor and operators of the WIV crane and any crane-based heave compensation device that may be in use, along with the feeder's DP operator, the operator of any motion-compensation system on the feeder's deck and the operators of any remote crane-to-component connection system and/or remotely-activated quick-release sea-fastening mechanisms that may be fitted. Additional studies to examine the human factor elements of these complex operations is warranted. The objective being to optimize execution protocols, develop standard operating procedures and determine appropriate training requirements, which collectively will substantially increase overall operational safety.

11) Purpose-built active control systems can greatly improve uptime and the safety of component transfer operations. However, station-keeping redundancy is required and FMEAs should be an inherent part of the project planning process to eliminate the risk of cascading failures.

12) The results discussed above only considered the motion limits established in section 2.1. These motion limits are based on criteria set for the component accelerations and hoist line loads, and on the occurrence of re-hits. When using crane-based heave compensation or motion compensation on the feeder's deck, the operation can proceed with larger motions and thus in increased wave heights. Those larger wave heights are often accompanied by higher wind speeds, and as all WTG components have an upper wind speed limit in which they can be lifted safely, this in itself could also limit these operations. Table 5 shows monthly and annual uptime values when a wind speed limit of 12m/s is considered for the full operation. When compared to the identical configurations shown in Table 3, for which no wind limit was applied, it can be seen that uptime is reduced by 15 to 30%.

Table 5: Uptime values (as percentage) with heave compensation and 12m/s wind speed limit

Vessel	100 SS feeder				Barge Shaped Feeder				165m SS feeder			
Rails	No		Yes		No		Yes		No		Yes	
Roll	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Jan	28.0	35.5	37.6	39.8	35.5	35.5	40.9	41.9	47.3	51.6	54.8	55.9
Feb	32.9	36.5	36.5	37.6	35.3	36.5	36.5	37.6	57.6	62.4	61.2	62.4
Mar	29.0	30.1	32.3	34.4	30.1	31.2	34.4	34.4	44.1	47.3	49.5	49.5
Apr	23.3	28.9	31.1	36.7	24.4	28.9	36.7	37.8	32.2	36.7	44.4	45.6
May	37.6	44.1	49.5	52.7	39.8	41.9	48.4	49.5	48.4	51.6	53.8	53.8
Jun	60.0	66.7	68.9	68.9	60.0	64.4	68.9	68.9	71.1	71.1	71.1	71.1
Jul	78.4	82.4	83.8	85.1	75.7	82.4	82.4	82.4	87.8	87.8	87.8	87.8
Aug	79.0	80.6	80.6	82.3	80.6	80.6	80.6	80.6	83.9	85.5	85.5	87.1
Sep	41.7	51.7	53.3	56.7	45.0	48.3	53.3	53.3	56.7	63.3	65.0	65.0
Oct	21.0	24.2	35.5	37.1	22.6	27.4	32.3	37.1	40.3	41.9	41.9	45.2
Nov	33.3	38.3	40.0	41.7	35.0	41.7	43.3	45.0	43.3	50.0	53.3	55.0
Dec	25.8	30.6	29.0	37.1	27.4	29.0	30.6	32.3	37.1	37.1	43.5	45.2
Total	40.3	45.2	47.6	50.2	42.1	45.0	48.6	49.6	53.8	56.8	59.0	59.8

3 LESSONS LEARNED | FURTHER IMPROVEMENTS

A comparative operability method was proposed and used to find the operability of different feeder solutions to transfer WTG components from a floating feeder vessel to a jack-up WIV for environments offshore Massachusetts. This study and method can serve as a useful reference for developers and other stakeholders to do a quick comparison of different solutions. It was expected at the study outset that accelerations of components might be most crucial, but among the criteria considered, re-hits proved to be the most predominant risk. It was observed that having some form of compensation system and bigger feeders will improve the operability.

It should also be noted that while the methodology proposed in the study can be used to get a quick high-level comparison, once a concept is selected, more detailed time-domain evaluations and possibly model tests and bridge simulations will have to be performed. Bridge simulations will be key to making sure that all the different operational staff are on the same page and can act in good coordination with each other.

Topics not considered in the simulations carried out in this study, but that are viewed as being relevant in potential further evaluations are outlined below:

3.1 Station-keeping

This study only considered first order forces and motions. Second order wave forces, wind and current forces are countered by station-keeping systems. Some of the different concepts being considered for station-keeping are:

1. Feeder vessel on DP
2. Feeder vessel held in position by tugs
3. Feeder vessel moored to earth
4. Feeder vessel moored to the WIV

In all these cases, station-keeping capability and accuracy in the environments considered for offloading need to be evaluated. It is expected that DP can be more accurate than using tugs for positioning or mooring to earth. However, the DP system on a feeder must be tuned well and needs to take into account components as they are lifted off, to ensure there are no unexpected responses from the feeder's DP system. Some stakeholders have indicated that they are considering an approach of mooring feeder vessels directly alongside a WIV, using fenders and lines. In addition to station-keeping accuracy, the ability of WIV legs, jacking system components and surrounding hull structure to withstand the lateral loads that would be induced from movement of the feeder in a seaway also needs to be considered.

3.2 Component horizontal motions

Simulations start with the crane lines already connected to WTG components. However, motions at the top of a WTG component can be critical in the connection phase. Only defined amounts of motion will be acceptable if a successful connection is to take place, although there are stakeholders working on special tools to aid this. With a 1deg roll of the feeder, the top of an 80m high tower will move ~1.4m horizontally. Roll mitigation devices and deck-based compensation systems can also help to decrease tower-top motions.

WIV cranes also have off-lead-angle and side-lead-angle criteria, which can limit how far a crane hook can safely move laterally, relative to a vertical hoist wire. Generally, side-angle limits are around 2deg while lead-angle limits can be in the order of 5deg. When lifting taller tower sections, the crane hook is about 80m below the top of the crane, which means that a 2deg lead limit would translate into an allowable horizontal hook motion of ~2.8m. WIV cranes are typically equipped with winch-based tugger lines to help control horizontal motions of the crane hook, but these were not modelled in this study. In addition, once sea-fastening is released and the component is being lifted, there should not be any significant relative motions between the component and the feeder. This is to prevent a lifted component from coming into contact with any other components onboard the feeder or any part of the feeder's structure.

3.3 Jack-Up Motions

Motions of a WIV that is jacked-up are expected to be small, especially when compared to motions of a floating feeder. However, depending on WIV construction, water depth and seabed type, a WIV's crane can move due to wave action. Although this study has not considered the WIV, stiffness of its crane structure was included when modelling the lines. It is possible to have a communication link between motion compensated platforms and crane hook to further minimize or eliminate relative motions. This technology improves workability and can accommodate some hook motions on both fixed and floating WIVs.

3.4 Floating-to-Floating feeder operations

Although most current development is considering jack-up WIVs, floating installation assets may need to be used in the future. Floating installation assets are already used for installing foundations and transition pieces. It was seen in this study that the operability of feeder operations is limited even with jack-up vessels. It is to be expected that floating installation assets will have larger crane tip motions. This will have to be minimized as much as possible. Floating installation assets can be mono-hull, multi-hull or semi-submersible. Semis might have better motion characteristics than monohulls in this regard. Station-keeping also becomes more important since floating installation assets will also likely be on DP. There will need to be close coordination with the feeder vessel.

4 PROJECT BENEFITS

This project has developed methodology on lifting simulations and an efficient comparative assessment approach for evaluating the operability of floating feeder solutions. A guidance document has also been developed with the involvement of the project's stakeholders. These products will benefit the offshore wind industry by advancing the ability of floating feeder solutions to safely install offshore wind turbine components. They also provide insight on novel motion compensation solutions and can help accelerate time-to-market of floating feeder solutions. Some detailed benefits are provided in the subsections below.

It is acknowledged that while some of the benefits from the lifting simulation study are general, such as procedures for comparative study, the applicability of the findings may be limited to the scope of the desk study of the project. For those lifting operations with specific features that are outside the scope of the simulation study, additional considerations should be included in the evaluation of the operability of floating feeder solutions.

4.1 Determine Capability of Current Technical Solutions

The time-domain lifting simulation combined with frequency-domain comparative methodology can be used by industry to evaluate the operability of current technical solutions. Factors considered include size of feeders, effectiveness of motion compensation platforms on feeders, and the effectiveness of heave compensation devices on lifting cranes. These solutions enable owner/operators to quickly evaluate potential feeder uptime with given environmental conditions.

The lifting simulations can provide insight on lifting operations, such as the effect of lifting time and lifting speed on the re-hit phenomena. They also provide transparency on the performance of lifting systems and feeders so stakeholders can have a better understanding of anticipated operability of these assets. It is recognized that the simulations focus on performance of lifting systems and motions of feeder vessels under the specified analysis conditions. Therefore, users should understand the limitations of using the simulations for assessment of feeder solutions, especially with regard to operational factors, station-keeping performance, and any assumptions in the simulation models.

4.2 Consistent Assessment of Feeder Solutions

The ABS Consensus-based Guidance Document [10] provides an industry standard operability analysis procedure. The guidance document includes considerations of combined time-domain and frequency-domain methodologies, environmental conditions, numerical modelling details, processing of analysis results, and limiting conditions for lifting operations. The standardized analysis procedures could provide users with a robust and easy comparison of feeder and lifting system performance. Using a common assessment methodology will aid in minimizing uncertainties and help level the playing field.

4.3 Optimize Feeder Asset Selection

The operability assessment methodology developed in this project provides owner/operators with many features that can be used to optimize their feeder asset selection. The frequency-domain comparative approach can evaluate feeder performance effectively in a timely manner. Owner/operators can evaluate many variables, such as feeder size, feeder hull form, turbine component locations, feeder loading conditions, motion compensation, damping effects, heading control etc., to maximize cost-benefit.

5 POTENTIAL IMPLEMENTATION SCENARIOS

The technical reports [8] [9] and ABS Consensus-based Guidance Document [10] will be publicly available to benefit the global offshore wind community. The project team has organized workshops to introduce the assessment methodology and guidance document to stakeholders and has incorporated their feedback into project documents. These workshops help increase industry awareness of the assessment methodology and its implementations. Some implementation scenarios are provided in the subsections below.

5.1 Vessel Evaluation Using the Methodology Developed and Guidance Document

This project developed and demonstrated a process of time-domain lifting simulation and frequency-domain comparative evaluations for a lifting system with/without heave compensation and different feeder designs. Industry can use the methodology developed in this project and the ABS Consensus-based Guidance Document [10] to evaluate prospective feeder solutions. This can form a standardized transparent assessment process and minimize uncertainties in a consistent manner. Time-domain lifting simulation involves intense technical skills on modelling and needs special software with simulation capabilities. Once the time-domain simulation is performed for a given lifting system, comparative performance of feeder solutions is more of a typical vessel motion analysis, so owner/operators can evaluate different feeder solutions in a timely manner. The evaluation can provide industry with a better picture on the capability status of lifting systems and floating feeder solutions, within the scope presented in the analysis methodology and the Guidance Document [10].

5.2 Offshore Logistics Asset Selection

Comparative analysis of three feeder designs using the same lifting system was performed in this study. Results were presented in a way so performance of different feeder designs, lifting systems with/without heave compensation, and weather seasonality can be easily identified. Such a benchmark analysis can be utilized by owner/operators of lifting systems and feeders to help them with selection of offshore logistics assets. That in turn will allow respective systems to be presented against the spectrum of operability across comparable and/or similar capabilities in the emerging U.S. offshore wind industry.

5.3 Marine Operations Manual

From the vessel evaluation process, limiting conditions on the vessel's operability, such as allowable motions and accelerations, wave heights, wave period, and headings are obtained. That information can be included in the Marine Operations Manual for onboard operational support. Simulation procedures used, such as initial lifting time, lifting speed, pretension setup, initial control on motions of the WTG components before fully lifted, can also be included in the operations manual, so the operators can have a better understanding of the lifting performance.

6 NEW INNOVATIONS

Engagement with the project's Advisory Board and stakeholders, along with discussions within the project team, revealed several considerations to improve the feasibility of feeder solutions. It was beyond the scope of this project to study these ideas in detail, but we discuss them at a high level in this section. Potentially this will motivate others to study these concepts further and bring appropriate solutions to market.

6.1 Sacrificial Interface Components

As the time domain analyses discussed in section 2 showed, it will be difficult to eliminate the risk of re-hits between the wind turbine component (load) and the feeder. Due to stiffness of the crane and hoist systems, the load departs the deck slowly compared to the motions of the feeder vessel. This can be improved by quick lift systems in the hoist wire or by feeder deck-based compensation systems which quickly retract the compensated platform when the load is lifted, but without those tools the risk of premature departure and/or re-contact with the deck is substantial, even in relatively benign sea states of 0.5mHs. A member of the project's Advisory Board suggested that if it were possible to install turbine components on sacrificial interface arrangements, which would immediately collapse if the weight from the component is no longer carried by the interface, this could rapidly increase the air gap between a lifted component and the feeder's deck. Ideally this interface arrangement would be completely passive, so it always automatically collapses once the load is supported by the hoist wire, which would eliminate the potential additional risk of control failures.

Discussions with stakeholders and within the team also considered if certain re-hits could be permissible. One could argue that if the accelerations are sufficiently low, the re-hit itself might not be a problem. However, the challenge with this approach is that it shifts the acceptable re-hit quantifications to a complex response of the load to the structural stiffness of the deck. This requires a significant reduction in time step of the simulations to account for the rather stiff deck and it requires an accurate understanding of the local stiffness of the deck. This type of modelling was not considered in the scope of this project. Instead, soft supports were added to the corners of the load in the time domain simulations. Once all corners are lifted off the deck, recontact with any corner is considered unacceptable in our analysis, even though the accelerations are relatively low. If it would be possible to include fenders or sacrificial components on the deck that would crumble on recontact with the load, it might be possible to limit the accelerations of the components in a real application as well. This concept would need a thorough design and review to ensure it indeed results in acceptable loads on the wind turbine components.

6.2 Novel Feeder Concepts

Several design firms are considering novel feeder concepts, in which the relative motions between the feeder and wind turbine installation vessel are significantly reduced or completely eliminated, before any wind turbine components are lifted. Several systems are patented in which the feeder is either lifted inside a moon-pool with lines or lifted out of the water with a cradle on the stern of the installation vessel. These systems shift the challenge of relative motions to the mounting phase of the feeder into the wind turbine installation vessel. None of these systems are readily available, but existing WIVs could be modified, or new ones developed for these particular kinds of application.

6.3 Autonomous Crane-Component Connection

A number of companies are actively pursuing the development of systems to enable connections to be made between a WIV crane's hook and WTG components on the deck of a floating feeder. If successful, such systems would eliminate the need to potentially expose personnel to the very dangerous task of attaching a component's pre-rigged lifting arrangement to a heavy crane hook that is moving relative to a feeder's deck.

Some of the challenges associated with this kind of technology include but are not limited to:

- Component-specific mating receivers & lifting tools
- Mating receiver proximity tracking & targeting
- Lifting tool docking activation & status verification
- System redundancies & FMEA

6.4 Remote Quick-Release Sea-fastening

Similarly, companies are also endeavoring to develop systems that would enable sea-fastening to be released remotely by means of quick-response hydraulic actuators. This would eliminate the need to either; release the sea-fastening that secures WTG components to a feeder's deck during transit, prior to the load being taken by a WIV's crane; or for personnel to undertake the time-consuming task of manually removing heavy sea-fastening securing mechanisms with the load attached to a WIV's crane. Challenges presented for such systems would include but not be limited to:

- Component-specific interface requirements & interchangeability
- Actuation response timing & fail-safe interlock
- System redundancies & FMEA

6.5 Inter-System Telemetry & Data Synthesis

The advent of additional technological systems to facilitate the safe transfer of WTG components from floating feeders to WIV's offshore, also raises the need to ensure there is effective communication and transfer of relevant data between those systems. After having successfully achieved an autonomous connection of a WIV crane to a component on the feeder's deck, the component's sea-fastening would need to release at the appropriate time to allow the weight of the component to transfer from the feeder to the crane. Should that not occur, there would be significant risk of damage to the WIV crane and/or feeder, as well as potentially serious injury to personnel.

As highlighted in Section 2.4 #10 above, safe transfer of turbine components from floating feeders to a WIV will depend on close and effective communication and coordination between all personnel involved. To enable those personnel to make effective operational decisions, it would also be prudent for them to have access to the same information of any systems that are being relied on to complete their respective task. This would require sharing of data between systems and presentation of information in a suitable user interface.

Some of the challenges associated with this kind of technology include but are not limited to:

- Data string convention & format standardization
- Interoperability & bandwidth spectrum conflicts
- System redundancies & FMEA

6.6 High-Behavioral Realism Simulation

Innovations in simulation technology allow virtual environments to be created with a high degree of visual fidelity. Advanced physics modelling also enables the behavior of objects and activities within those virtual environments to reflect real-world behaviors very closely. Immersive display technologies such as virtual and/or mixed reality, enable users to experience highly realistic exposure to what would be potentially dangerous situations in a real-world scenario, without the risk of real-world consequences.

Areas in which these combined technologies could be leveraged for the U.S. offshore wind industry include:

- Proof-of-concept / engineering validation / risk mitigation planning
- Human factors in operational decision-making for feeder-based operations
- Procedure development & pre-deployment operational verification
- High-risk + high-consequence task-specific training & proficiency development

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[9] NOWRDC Project #107: Operability Analysis Approach (M1.2)

[10] NOWRDC Project #107: Consensus –based Document (M2.1), Guidance on Operability Analysis of Floating Feeder Solutions

Appendix 1: Industry Stakeholders

AMPELMANN

AVANGRID RENEWABLES

BARGE MASTER

C-JOB

CADELER

Cranemaster

CROWLEY
People Who Know

eDF renewables

GE Renewable Energy

GREEN SHIPPING LINE

GustoMSC | NOV

Jan De Nul GROUP

MAERSK SUPPLY SERVICE

KEYSTONE SHIPPING CO.

MAYFLOWER WIND

NEPTUN SHIP DESIGN

Ørsted

OSBIT

RAMBØLL

SAIPEM

seajacks

SEAQUALIZE

Shell

Thrustmaster

Van Oord
Marine ingenuity

Vestas

VOITH