Industrializing Offshore Wind Power
with Serial Assembly and Lower-cost Deployment[1]

Final Report, 11 December 2017

Lead Institution:

University of Delaware
Principal Investigator: Willett Kempton,
UD Project Managers: Andrew Levitt, Richard Bowers

Participating Contractors and Companies:

Mammoet, Weeks Marine, SPT Offshore, Moffatt & Nichol, Atlantic Grid Development, EEW Steel, CG Power Solutions, Clipper Marine, Saipem Group, Signal International, Steel Suppliers Erectors, Inc., Universal Foundation/Aalborg University, XKP Visual Engineers

Additional contributing scientists & engineers:

David L. Burris, Mike Dvorak, Jeremy Firestone, John Madsen, Deniz Ozkan, Alberto Tono, Bruce Williams

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[1] This work is the result of a proposal originally titled "A System Design Study for Wilmington Canyon Offshore Wind Farm". The title of this final report, shown at the top of this title page and abbreviated as the running head, has been made more descriptive.

"**We need to build turbines like we build cars**." [… in order to achieve the European goal of 60 GW of offshore wind by 2030]
- Pieter van Oord, CEO, Van Oord (at Offshore WIND 2017, Amsterdam)

"Substantial cost savings could be achieved by constructing several hundred wind turbines continuously, like an offshore assembly line, which would allow the industry to learn how to do offshore wind at scale…"
- Mark Gainsborough, Exec. VP, New Energies, Shell (at Offshore Wind Energy 2017, London)

"**The cheapest way to build something at sea is to assemble it on land.**"
- Richard Palmer, Vice President, Weeks Marine

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Abbreviations

AEP – Annual Energy Production
BOEM – Bureau of Ocean Energy Management, of the US Department of Interior
COE – cost of electricity, expressed in ¢/kWh
CPT – Cone penetration test, used for geotechnical analysis
DP2 - Dynamic Positioning of a vessel. DP2 is the second level of redundancy and thus ability to hold in place during operations.
FOA – Funding Opportunity Announcement
GBP – Ground bearing pressure
ha – hectare, 1 ha= 0.405 acre
LCOE – levelized cost of energy, in ¢/kWh given a level price throughout the project life
NBMCT – New Bedford Marine Commerce Terminal
nm – nautical mile; 1 nm = 1.15 statute miles = 1.85 km
PON – Program Opportunity Notice, a request for proposals to a Program
SOPO – Statement of Project Objectives, an agreement between DOE and grantee
Ton or Tonne - Metric ton = 1,000 kg ("US ton" refers to 2,000 pounds.)
WCP – Wilmington Canyon Project, original name of the project reported on here; also used to refer to the designated ocean area here analyzed for development
WEA – Wind Energy Area, as designed by BOEM
WTG - Wind Turbine Generator, often referring to all of tower, nacelle and blades

Summary

A team of engineers and contractors has developed a method to move offshore wind installation toward lower cost, faster deployment, and lower environmental impact. A combination of methods, some incremental and some breaks from past practice, interact to yield multiple improvements.

Three designs were evaluated based on detailed engineering: 1) a 5 MW turbine on a jacket with pin piles (base case), 2) a 10 MW turbine on a conventional jacket with pin piles, assembled at sea, and 3) a 10 MW turbine on tripod jacket with suction buckets (caissons) and with complete turbine assembly on-shore. The larger turbine, assembly ashore, and the use of suction buckets together substantially reduce capital cost of offshore wind projects. Notable capital cost reductions are: changing from 5 MW to 10 MW turbine, a 31% capital cost reduction, and assembly on land then single-piece install at sea an additional 9% capital cost reduction. An estimated Design 4) estimates further cost reduction when equipment and processes of Design 3) are optimized, rather than adapted to existing equipment and process. Cost of energy for each of the four Designs are also calculated, yielding approximately the same percentage reductions.

The methods of Design 3) analyzed here include accepted structures such as suction buckets used in new ways, innovations conceived but previously without engineering and economic validation, combined with new methods not previously proposed. Analysis of Designs 2) and 3) are based on extensive engineering calculations and detailed cost estimates. All design methods can be done with existing equipment, including lift equipment, ports and ships (except that design 4 assumes a more optimized ship). The design team consists of experienced offshore structure designers, heavy lift engineers, wind turbine designers, vessel operators, and marine construction contractors.

Comparing the methods based on criteria of cost and deployment speed, the study selected the third design. That design is, in brief: a conventional turbine and tubular tower is mounted on a tripod jacket, in turn atop three suction buckets. Blades are mounted on the tower, not on the hub. The entire structure is built in port, from the bottom up, then assembled structures are queued in the port for deployment. During weather windows, the fully-assembled structures are lifted off the quay, lashed to the vessel, and transported to the deployment site. The vessel analyzed is a shear leg crane vessel with dynamic positioning like the existing Gulliver, or it could be a US-built crane barge. On site, the entire structure is lowered to the bottom by the crane vessel, then pumping of the suction buckets is managed by smaller service vessels. Blades are lifted into place by small winches operated by workers in the nacelle without lift vessel support.

Advantages of the selected design include: cost and time at sea of the expensive lift vessel are significantly reduced; no jack up vessel is required; the weather window required for each installation is shorter; turbine structure construction is continuous with a queue feeding the weather-dependent installation process; pre-installation geotechnical work is faster and less expensive; there are no sound impacts on marine mammals, thus minimal spotting and no work stoppage

for mammal passage; the entire structure can be removed for decommissioning or major repairs; the method has been validated for current turbines up to 10 MW, and a calculation using simple scaling shows it usable up to 20 MW turbines.

Introduction

Objectives

This project's objective, as defined by the US Department of Energy, was to develop a cost-optimized, integrated system design of an offshore wind plant, bottom-mounted and capable of mid-depths, in order to reduce the Cost of Energy (COE) and to shorten the deployment timeline of offshore wind power. Competing designs were developed to fit a specific Mid-Atlantic (US) ocean area for realism, but the selected design and methods developed here are widely applicable to fixed-bottom offshore wind in a range of areas currently leased or under consideration for development.

Scope of DOE award

As defined in the Statement of Project Objectives (SOPO) for this project, the scope is to create an integrated design of a wind farm of 1,000 MW for a specific site of mid-depths, the specific site to be proposed by the applicant. The site here designed is in water depths between 20 m and 40 m, located between Delaware and the oceanographic feature "Wilmington Canyon", the target design wind project being between 40km and 70km offshore. (See map in section "Project Site and Characteristics").

The project work comprised four types of activities:

1. Engineering in the specialties represented in the team members, with each effort considered in the context of the entire offshore wind plant system. This effort includes requirements definition, design work, and analysis to determine that designs meet requirements.
2. Cost analysis of component designs, based on the engineering of 1.
3. Several analyses of the system as a whole: integrated engineering review, cost, deployment time, environmental impact, and feasibility.
4. Definition, design, and cost analysis of the baseline system. The baseline design need not meet all the engineering requirements of the proposed design, and therefore may have less detail than the proposed design, however both baseline and proposed designs have the same breadth of scope. Baseline design is drawn as much as possible from public information rather than our own design efforts.

The SOPO further requires that design decisions must be based on COE, feasibility, and deployment time. In no case will a solution with an unacceptable or immitigable environmental impact be chosen.

Contents of this report

The final deliverables include the following, all of which are contained in this report and its appendices. Besides this report, we produced from this project numerous technical dissemination efforts for target audiences and conference presentations (see Appendix G, Dissemination).

- Final design, described herein.
- Gross AEP calculated based on power curve as specified in Appendix E of the FOA.
- Precise cost estimates.
- Data compilation and final COE and breakeven price calculations by UD.
- Matching component cost breakdown and COE calculation for baseline design. Depending on the detail previously achieved, this analysis may not need to be extended from the previous phase.

In addition to the above deliverables from the SOPO, we have added a construction animation video for the lowest-cost variant we have developed, as a supplement to this written report

Substantive description of approach

In order to reduce costs and reduce installation time, the guideline of the funding DOE program, with which we agree, is that the design should be "integrated", that is, that design of each component and system is re-evaluated in light of the other components and processes. There are forces in the industry counter to this. Like any large construction project, operators of construction equipment, suppliers of common components, and structure designers each operate independently and come together at the project level. But by the time they come together for the next project, many design decisions have already been made based on previous projects. Decisions made by a single industry, for example a turbine manufacturer's need to standardize parts, may limit even a simple addition such as a bracket that would reduce cost and risk for materials handlers, especially if the handling in question related to a minority number of projects. An independent constraint is that even if a new process saves money or time, the first use in production is always perceived to be risky and thus raises the risk premium on finance. All these factors limit the degrees of freedom of any one project, restrain innovation, and in particular reduce integration so that design of each supplier's components reduce cost of the next series of projects.

In the offshore wind industry in particular, very large capital investments are required for designing and building the turbine itself, the construction vessel, and the deployment port. The turbine is the most expensive component – a new offshore wind turbine can require well above $100M to design and test a full-sized

prototype[2], followed by additional investment in supply chain, fabrication and logistics. This makes it difficult for the turbine manufacturer to make custom modifications for any one project. Adding to this, the turbine manufacturer often has the strongest voice in choice of additional components and processes, and of course does not want to risk its component (the turbine) on new or untested support systems or deployment innovations—the turbine itself both being the most expensive single component and having the strongest brand identification. This analysis of limits to innovation supports the value of a Federal Agency calling for, and funding, the type of integrated design which we have here tried to carry out.

On a budget of about ½ M$, we have done proof-of-concept engineering, not final design engineering. For example, we have determined that existing lifting equipment is appropriate for weights and loads, that a few existing ports and vessels can bear those loads, that wind and wave forces in the Mid-Atlantic site region are not excessive for equipment when queued in port, during transport to site or for installation, that an existing (not hypothetical) vessel can deploy using the process we have designed, etc. We have completed an engineering and cost analysis that is much more extensive than typical conceptual comparisons across offshore wind options. The results of this process is that the integrated designs proposed here have been validated as reasonable and cost-effective. We did not carry out final engineering that would prepare for every component and every detail to be ready to manufacture, assemble, and deploy; that would have been an expensive additional effort unnecessary to validate the integrated design and to show that design 3 is most cost-effective.

The design selected for lowest cost and fast deployment, we feel, represents an attractive opportunity. Current designs and installation methods, carried forward from the very first offshore wind farms, start with a pile-driven base, then lift and attach each major component separately from a jackup vessel. Even at first inspection, there are several disadvantages of this method. It requires jack-up vessels (originally designed as mobile platforms for offshore oil and gas drilling and operations); these are expensive, depth- and weather-limited, and require time to jack up to achieve stability before working at each turbine site. Offshore construction is generally estimated as 5x more expensive than land construction, or as one of this project's marine contracting partners said, "The cheapest way to build something at sea is to assemble it on land"[3]. In both land-based and offshore wind industry, larger capacity turbines have been one important factor leading to dramatic price reductions. Our primary designs were developed around a 10 MW turbine, a size just beginning to be commercially offered as we finish the project in 2017.

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[2] Personal communication, James G. P. Dehlsen.

[3] Rick Palmer, Weeks Marine, class lecture at U Delaware, Fall 2016. (Also quoted on cover sheet.)

The Department of Energy's Wind Vision (DOE 2015) seeks to achieve a deployment of 22 gigawatts (GW) by 2030, and 86 GW by 2050, at costs substantially lower than today. To do so would require both lower costs per GW capacity, and a faster timeline than today's installation methods provide. Our selected design and installation process meets both these benchmarks—it can deploy 1 GW per construction season per port, at 37% lower capital costs and 35% lower LCOE than today's methods.

Team

A diverse team of scientists, engineers, and industry experts is required for a project such as this. The initial team and their expertise at time of UD's proposal were: University of Delaware (UD), with researchers covering coastal geology (Madsen), wind power meteorology (Dvorak, UD consultant), drive train (Burris), policy (Firestone), met ocean conditions (Williams), and wind project economics (Ozkan, Kempton). On the original proposal, company team members were Clipper Windpower and Clipper Marine, covering advanced turbine design and systems engineering (Clipper); Moffatt & Nichol, marine structural engineering (M&N); Signal International, steel structure fabrication for offshore (Signal); Saipem, vessel deployment, logistics and offshore engineering (Saipem); CG Power Solutions, AC electrical system (CG); and Atlantic Grid Developers, HVDC electrical system and LCOE (AGD). After the project was awarded, design reviews by initial participants led to evaluating design concepts of suction bucket–based foundation, for that purpose both Universal Foundation/Aalborg U was added for monobucket foundation (Universal), and and SPT Offshore for multi-bucket designs (SPT). Additional company additions were EEG and Steel Erectors and Fabricators for steel supply and fabrication, Weeks Marine for vessel operations (Weeks), and Mammoet for heavy lift and transport on land (Mammoet).

In considering the design of the entire offshore wind park system, the research team utilized integrated design, a process that brings together design of different subsystems usually considered separately. In this project, fabrication, onshore assembly, transport from port to site, offshore installation, subsea support structure design, and turbine design choices and methods are all considered as they interact with each other, with the goal of innovation that reduces project costs.

Four Designs Analyzed

The result of these multiple analyses resulted in four design approaches, quantitatively compared for this project:

1. Conventional jacket structure, 5 MW turbine (base case). First, the design used as a comparison base, was originally proposed to follow the Ormonde offshore wind

plant in the Irish Sea[4], but given development of the US offshore industry and to make a more relevant US comparison, many elements from the US Block Island project, including experience of their contractors and bidders, were incorporated into the base case. As the base case turbines, we used 200 of the 5 MW REPower turbine. The National Renewable Energy Laboratory (NREL) turbine model is based on this turbine. As the base structure, this turbine is mounted on a tubular tower mounted on a quadrapod piled jacket foundation. ("Jacket" is the common industry term for a steel-lattice subsea structure.) Assembly is carried out offshore, with transport done by non-powered jack-up vessel. The electrical system is a 34 kV collector array with a single substation.

2. Conventional jacket structure, 10 MW Turbines. Second, the baseline concept is scaled up to 10 MW turbines, thus 100 turbines are used for the same power plant capacity of 1,000 MW. This design used the Britannia (Dvorak 2010) project turbine as the reference turbine, mounted on a tubular tower attached to a quadrapod piled jacket foundation. Assembly is completed offshore, with transport done by non-powered jack-up vessel. The conventional structure design was not simply scaled from the 5 MW, rather, it was fully designed by M&N and included several cost-saving design features based on the design firm's experience with both oil & gas and offshore wind structures. At the time of the proposal, only Clipper Marine had designed a 10 MW turbine; they were a key project participant and provided detailed mass, load and output data critical for design of a realistic offshore structure for a 10 MW machine. Even through Clipper Marine has ultimately not succeeded commercially, during the calculation phase of the project there was no commercial turbine with 10 MW capacity and certainly none that would provide such detailed data for a project like this. We expect that two offshore turbine slightly larger than 10 MW will be announced and offered for sale by the fourth quarter 2017, as described subsequently.

3. Suction-bucket jacket with in-port assembly, 10 MW turbines. Third, the same 100 of the 10 MW turbines, again mounted on a tubular tower attached to a jacket. But for this design the jacket is a tripod and is mounted on the ocean bottom by a three suction bucket foundation base. (A suction bucket, also called caisson or suction pile, is a cylinder shape with open bottom, pulled into the ocean floor by pumping water out of the enclosure.) Assembly is almost completely onshore, with transport to deployment site done with a shear leg crane vessel. Blades are attached to the tower in port and installed offshore using novel blade mounting and lifting techniques. Detailed cost analysis is based on using existing equipment and vessels, with a second cost analysis calculated from assumption of more purpose-built vessels and operations.

4. A modification of the third design is achieved by relaxing the restriction to use only existing equipment and processes. In Design 4, a vessel is to be built and

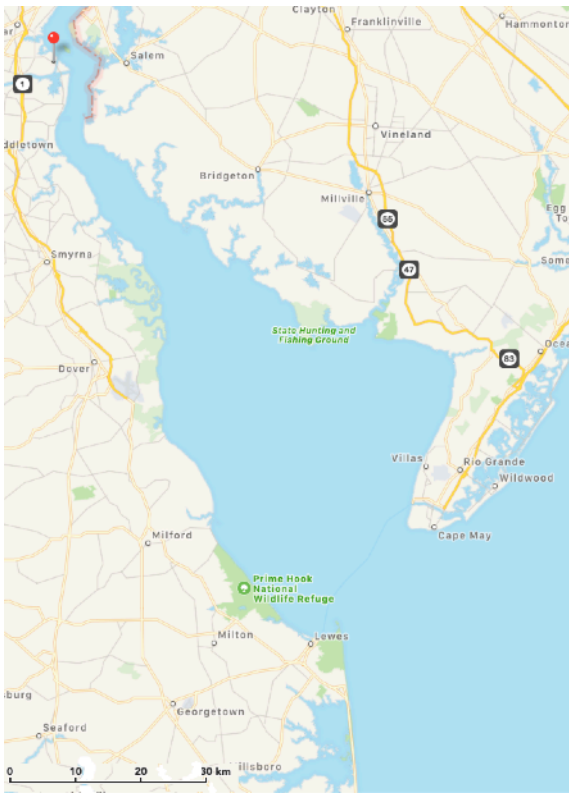
4 Ormonde specifications in 4C Offshore global data base, see http://www.4coffshore.com/windfarms/, accessed 2011.

processes are more tailored, for the express purpose of port-assembled, one-piece suction bucket installation.

One key aspect of the third (and thus fourth) design is that a floating vessel can be used yet there is never a lift from a moving vessel to a stationary structure. This is how the lift vessel is avoided. In the most populated areas of the US East Coast, like the North Sea, the ocean floor is soft enough to tolerate a large hard structure being placed there by a crane vessel undergoing wave motion. The only other attachment operation is the three blades, which were already attached to the tower in port, thus at sea they are lifted from stationary bracket to stationary hub, then attached. Quite differently from today's methods, there is no piling, parts transfer, or attachment operations between the installation vessel and the bottom-mounted structure. So our new approach is fundamentally different in that we literally mount everything together on land, then only the unitary whole structure is installed at sea.

Project Site and Characteristics

The Wilmington Canyon project site (**Figure 1a** Delaware Bay, and **Figure 1b**, Study Area in black outline) overlaps the BOEM-permitted Delaware wind energy area (WEA), in yellow. The project site for the analysis is approximately 212 km^2 in which



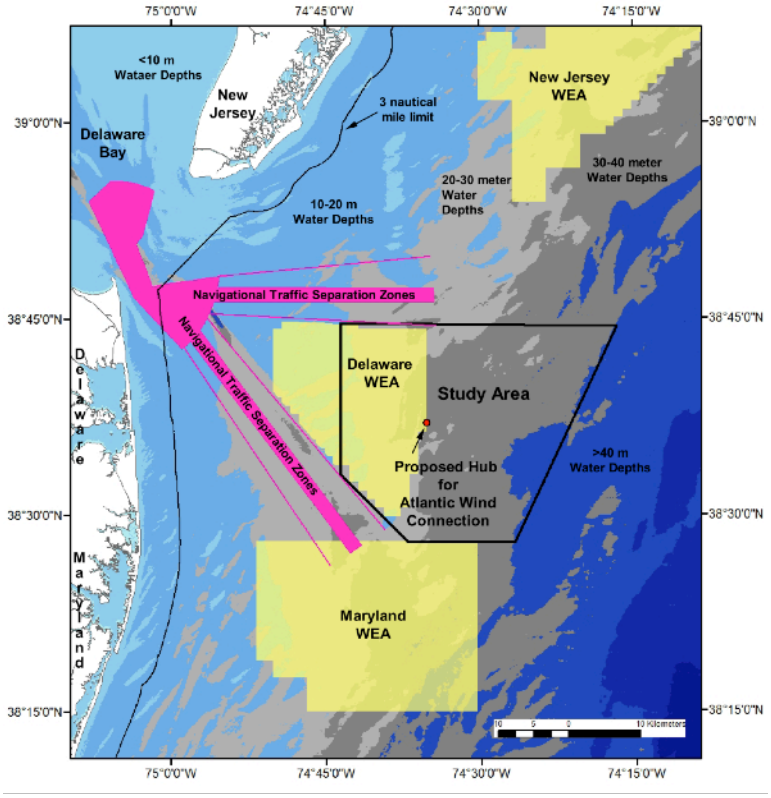


Figure 1a (left). Delaware Bay, showing Delaware City port at red pin. Figure 1b (right), Study area and Delaware WEA in ocean, outside mouth of Delaware Bay.

either 200 or 100 wind turbines will be located (the count depending on whether 5 or 10 MW turbines). The port selected for analysis (red pin in Figure 1a) is an undeveloped industrial area just north of Delaware City, an area adjacent to an operating oil refinery. It has rail, highway, and nearby deepwater channel access, and room for a large laydown area. The location is about 66 nm (122 km) to the sea, but this is the closest already-developed potential port to the site—closer areas are totally undeveloped or are protected, and most lack strong transportation access. There are no overhead obstructions from port to the sea.

Prior to performing the integrated design process, the research team analyzed the site characteristics, including geological, geotechnical, metocean, wind speed, and environmental considerations. These are summarized below.

Geological and Geotechnical Analysis

The geological setting governs the types and areal and vertical variability of sediments that will be encountered within any prospective offshore wind project area. As specified in the PON and SOPO, we conduct geological analysis to insure that the turbine and subsea solutions are realistic; because soils are similar within the Mid-Atlantic Bight, this means that the solution is also likely workable, with some local variations, through the area from Cape Cod to Cape Hatteras. We then consider acquisition of geotechnical data.

Geological Environment

Within the study region, the Wilmington Canyon Project (WCP) area, the bathymetric data indicates that the water depths vary between 10 and 50 meters. The geological data utilized for this analysis is composed primarily of bottom sediments obtained from grab samples. The geophysical data indicate the presence of four major paleochannels within the WCP area which are a result of infill associated with greater variability in the type and distribution of sub-bottom sediments. Subsequent transgressions and regressions result in reworking and erosion of previously preserved sequences, a pronounced three-dimensional variation in the types and distribution of surficial and sub-bottom sediments occur in the region encompassing the WCP area.

Given the coastal setting, the sedimentary environments encountered in the region are shallow marine, beach/barrier beach, estuarine, lagoonal, marsh, fluvial (river) and headlands. The predominant sediment types associated with these environments are: shallow marine - medium- to fine-grained sands to silts; beach/ barrier beach – coarse- to fine-grained sands; estuarine – fine-grained sands to silts and clays; lagoonal – fine-grained sands to silts and some clays; marsh – silts to organic-rich clays; fluvial – coarser-grained sediments (mostly cobbles to pebbles) to sands to silts; headlands – mostly coarser- to medium-grained sands.

Within the WCP area and bordering to the west, the Cape May Shelf Valley and Delaware Shelf Valley, respectively, are a relict expression of river valleys that served as pathways for the transport of sediments to the outer shelf (Figure 1). The Delaware Shelf Valley denotes the retreat path for the Delaware Estuary during the most recent Holocene transgression (Swift 1973). As sea-level has risen these valleys have been partially in-filled with sediments (e.g., Knebel 1981). The Inner Shelf Shoal Massif (Figure 2), which extends along the western edge of the WCP area and forms the northeastern border of the Delaware Shelf Valley (Figure 1) was formed as a result of the paleo-Delaware Bay interrupting the predominantly southwestward longshore sediment drift resulting in deposition of primarily sand-sized deposits in this area (Swift et al., 1972). A modern analog of the Inner Shelf Shoal Massif is the Cape May Shoal Complex where large volumes of sands are being transported and subsequently deposited along the southernmost New Jersey coast (**Figure 2**). Bordering the WCP area, the Cape May Shoal Complex and the Delaware Inner Shelf Platform, including the Hen and Chickens Shoal, and the ebb and flood tidal channels of the Delaware Shelf Valley (Figure 1) represent the now flooded land surface being reworked by both erosional and depositional marine processes.

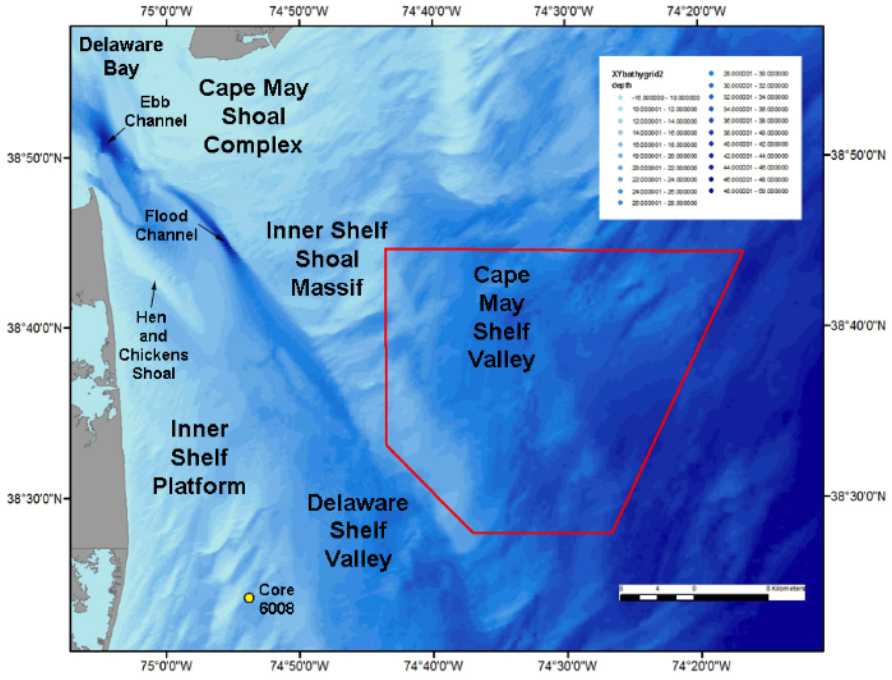


Figure 2: Major geomorphologic features in the vicinity of the WCP area. Red lines show boundary of the WCP area. Water depths are color-coded with shallower depths lighter and deeper depths darker blues. The project's original namesake, Wilmington Canyon, is actually at the Eastern (right) edge of this figure, aligned N-S with the state boundary, that is, deeper and outside the ultimate red WCP study area.

A rather thorough search of publicly available data indicated that eight sediment bottom grab samples have been collected in the WCP area (**Figure 3**); one in the southeastern corner of the project area (sample number 1873); one in the northern central portion (sample number 1789); and six samples in the northwestern portion of the survey area (sample numbers 5421, 5422, 5423, 5424, 5425 and 5890). The grab samples were compiled as part of the US Geological Survey's east-coast

sediment database (Poppe and Paskevich 2005). Of the eight bottom sediment samples in the WCP area, five are classified as sands; the three others are classified as gravelly sediments (**Table 1**).

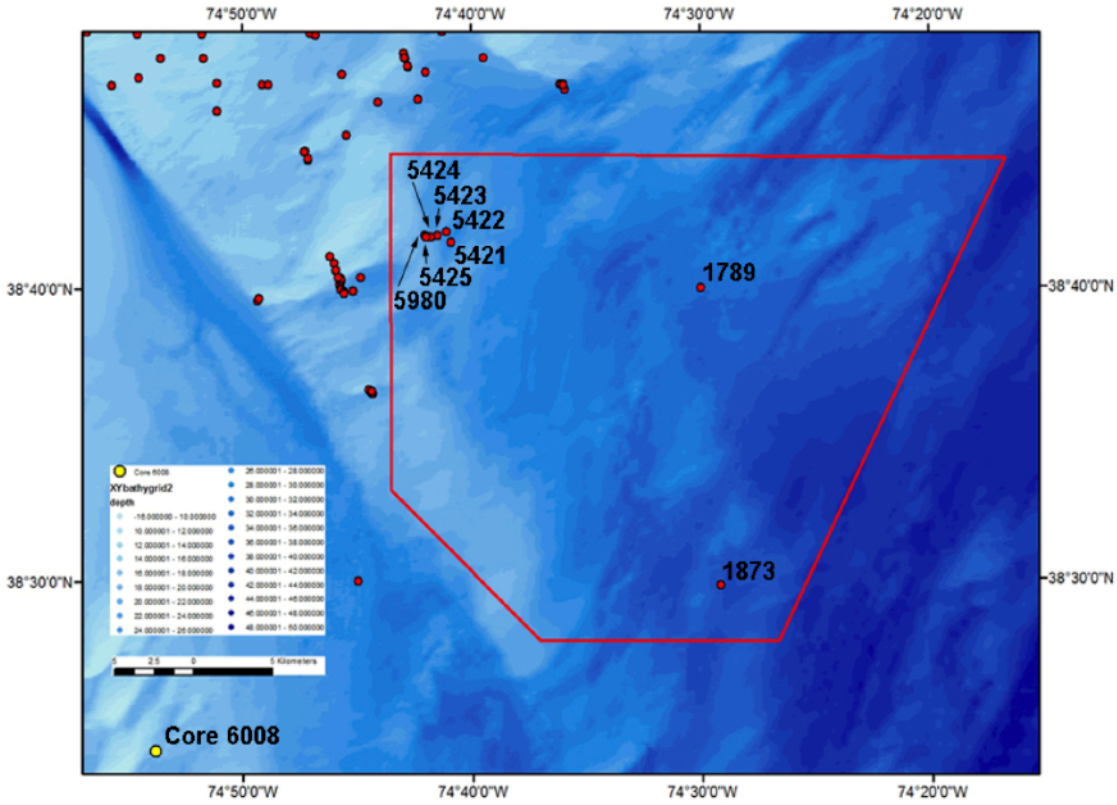


Figure 3: Bottom sediment grab samples in the WCP area. Red circles are publicly available sediment grab samples as complied by Poppe and Paskevich (2005)

Table 1: Sample locations shown in Figure 3

Sample #	% Gravel	% Sand	% Silt	% Clay	Classification
1789	0	100	0	0	Sand
1873	0	100	0	0	Sand
5421	0	98.7	0.83	0.47	Sand
5422	0.72	98.29	0.68	0.31	Sand
5423	1.09	97.96	0.66	0.29	Sand
5424	39.46	59.97	0.48	0.10	Gravelly Sediment
5425	24.88	74.59	0.38	0.15	Gravelly Sediment
5980	16.9	82.99	0.07	0.04	Gravelly Sediment

An additional source of information concerning bottom sediment types along the continental shelf of the eastern United States is available from the CONMAPSG: Continental Margin Mapping sediments grain size distribution for the United States East Coast Continental Margin project. The CONMAPSG project integrated available sources of sediment grain size distribution, including the grab sample data shown in **Figure 3**, to generate a regional map of the generalized distribution of bottom

sediment types (Poppe and Paskevich 2005). A map encompassing the WCP area from the CONMAPSG project is shown in **Figure 4**. The map indicates that the dominant inferred bottom sediment type in the WCP area is sand with a small area of gravelly sand along the southern boundary of the area. As noted by Poppe and Paskevich (2005), the CONMAPSG dataset upon which the inferred bottom sediment types were generated are somewhat sparse, and thus much greater local variability is to be expected.

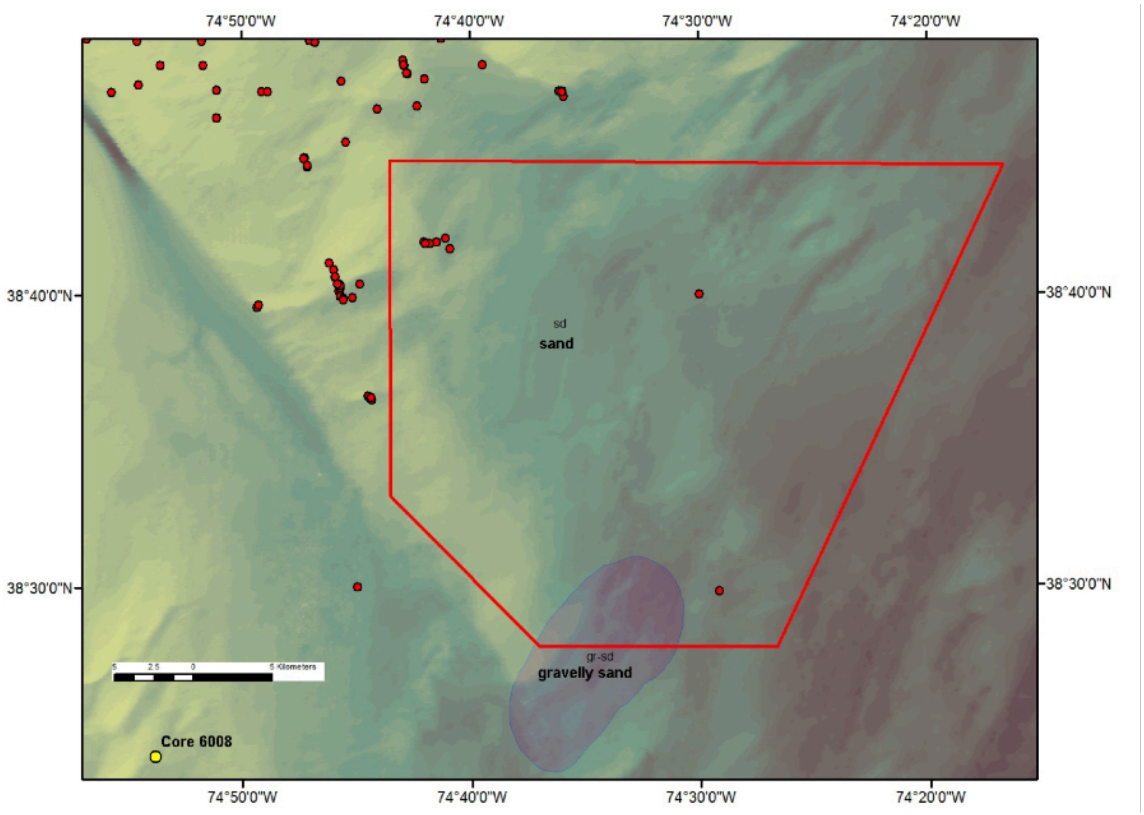


Figure 4: Generalized map of bottom sediment type in the WCP area. Red circles are publicly available sediment grab samples complied by Poppe et al. (2005). Map is generated from CONMAPSG: Continental Margin Mapping (CONMAP) sediments grain size distribution for the United States East Coast Continental Margin (Poppe et al., 2005). Note that there are only two types of bottom sediment shown: sand (sd) and gravelly sand (gr sd).

Using the Multipurpose Marine Cadastre dataset of the United States' Bureau of Ocean Energy Management and National Oceanic and Atmospheric Administration[5] a map was generated of the obstructions, including fish havens and known shipwrecks, and the major navigational zones within and in the vicinity of the WCP area (**Figure 5**). Within the WCP area, there are eleven known shipwrecks, two obstructions, and the portions of two fish havens. Buffer zones around these areas would presumably be considered during a commercial siting process to locate individual turbine foundations. There are two major ship traffic separation zones within the vicinity of the northern and western portions of the WCP area. These separation zones delineate pathways for ships bound to and from the Delaware Bay

5 The Multipurpose Marine Cadastre can be accessed at http://csc-s-webp.csc.noaa.gov/MMC/#

and River.

The practical outcome of the geological analysis is that any of monopole, pin pile, or suction bucket can be used at this site (and through the MAB region) for anchoring turbines to the sea floor.

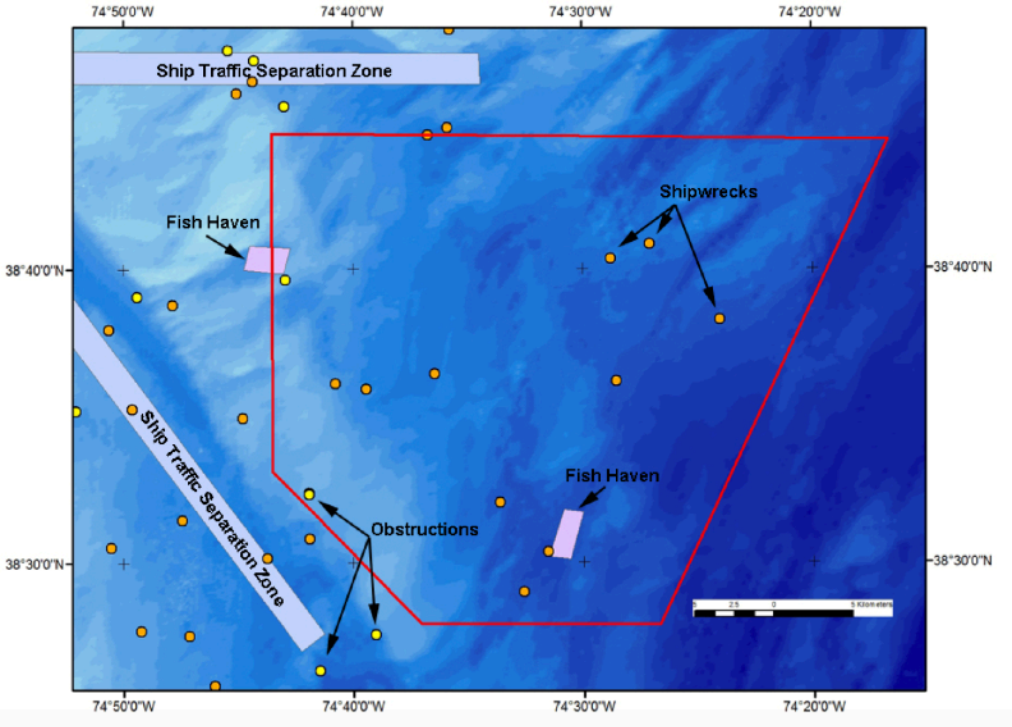


Figure 5: Location of bottom obstructions and major navigational approaches within and near the WCP area. Yellow circles are bottom obstructions. Orange circles are shipwrecks. Data from Multipurpose Marine Cadastre (http://csc-s-web-p.csc.noaa.gov/MMC/#).

Project site geotechnical data needs

The above geophysical background data is sufficient to confirm that specific bottom-mounting technology is appropriate for the area, with the result being that any of the major bottom mounting technologies could be used. Prior to installing wind turbine structures, more detailed geotechnical analysis would need to be done. This is needed to insure that each individual piling or suction structure will not encounter anomalies such as voids, loose or much more finely grained material, which would reduce the holding ability or require deeper buckets or piles, or conversely, boulders which could interfere with penetration of the pile or bucket.

Geotechnical requirements vary considerably for piled versus suction bucket mounting technologies. For either monopoles or pin piles, which may penetrate 50 m into the sea floor, common practice is to require a coring for each pile location. Furthermore, for safety of the large jackup vessel to be used for installation, a core may be required for each spud (leg) placement on the bottom. This requires a small

jack up vessel with drilling rig for each location and a great many core samples from that jackup. about 8 cores drilled for each turbine.

Suction buckets (3rd design studied), given the soils of this region, would penetrate only 10 m. By BOEM requirements the geotech analysis must go 10 m below the penetration, so that would require only a 20 m penetration analysis versus about 50 m for pilings. Also, SPT for example, requires only a handful of drilled core samples for the entire wind farm; per turbine, only a Cone Penetration Test (CPT) is needed at each bucket location. This is a substantial cost savings, as CPT can be done from a portable device lowered to the bottom from a vessel, then moved for each bucket location, all without jackup. In addition to penetration, the soil's water permeability must be tested for the suction bucket technology. The added cost of the permeability test is far less than the cost of multiple core drillings. Thus, the lighter geotechnical requirements of suction buckets amount to a considerable vessel and operational cost and time savings during the pre-installation phase. This is noted but not included in the cost savings calculation.

Wind Resource Analysis

We used the Weather Research and Forecasting (WRF) Model, Advanced Research WRF (WRF-ARW) version 3.2.1, to model the winds over the Wilmington Canyon area. Maps of the 90-m mean wind speed (**Figure 6**), mean power density (**Figure 7**), and capacity factor (**Figure 8**) were created from high resolution (5x5 km^2) hourly wind data for the 5 years of 2006-2010. No wake or transmission losses have been assumed in resource data. These wind speeds were validated using available National Data Buoy Center buoy and tall tower data in an article by Dvorak, et al. (2012). The closest buoy validation point to the Wilmington Canyon area is the 44009 buoy (5 m anemometer height), located 5 km from the SW corner of the study area and the closest tower is Chesapeake Lighthouse (43 m height) located 198 km SSW. A slightly higher wind energy resource exists on the E side of the project area, with differences being approximately 0.2 ms^{-1}, 46 Wm^{-2}, and 1%—in mean wind speed, mean power density, and capacity factor, respectively. This difference could be more dramatic during specific months and seasons but the overall effect on AEP would be very small or insignificant.

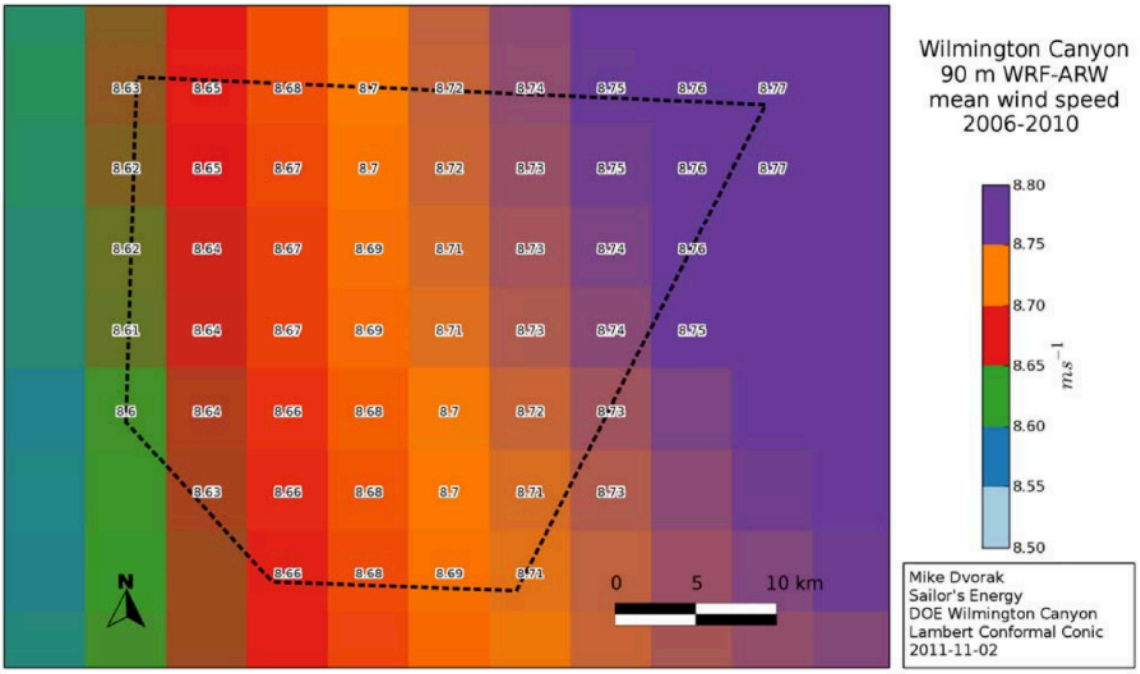


Figure 6: WRF-ARW 90m mean wind speed for 2006-2010 in the WCP area

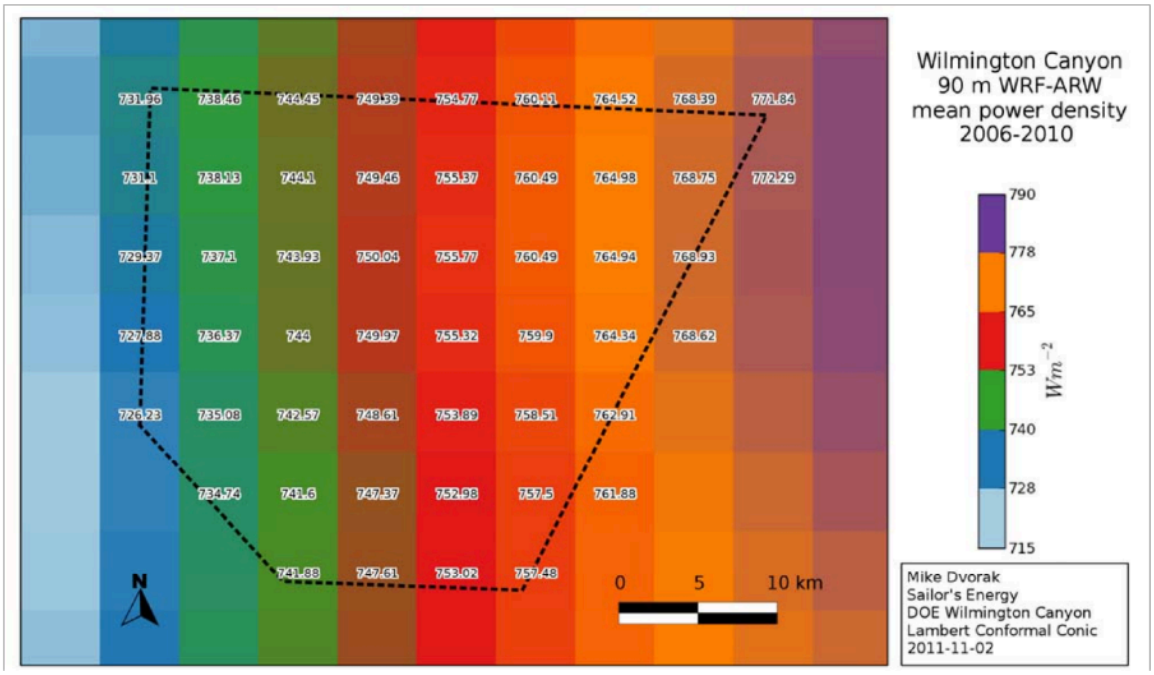


Figure 7: WRF-ARW 90m mean power density for 2006-2010 in the WCP area

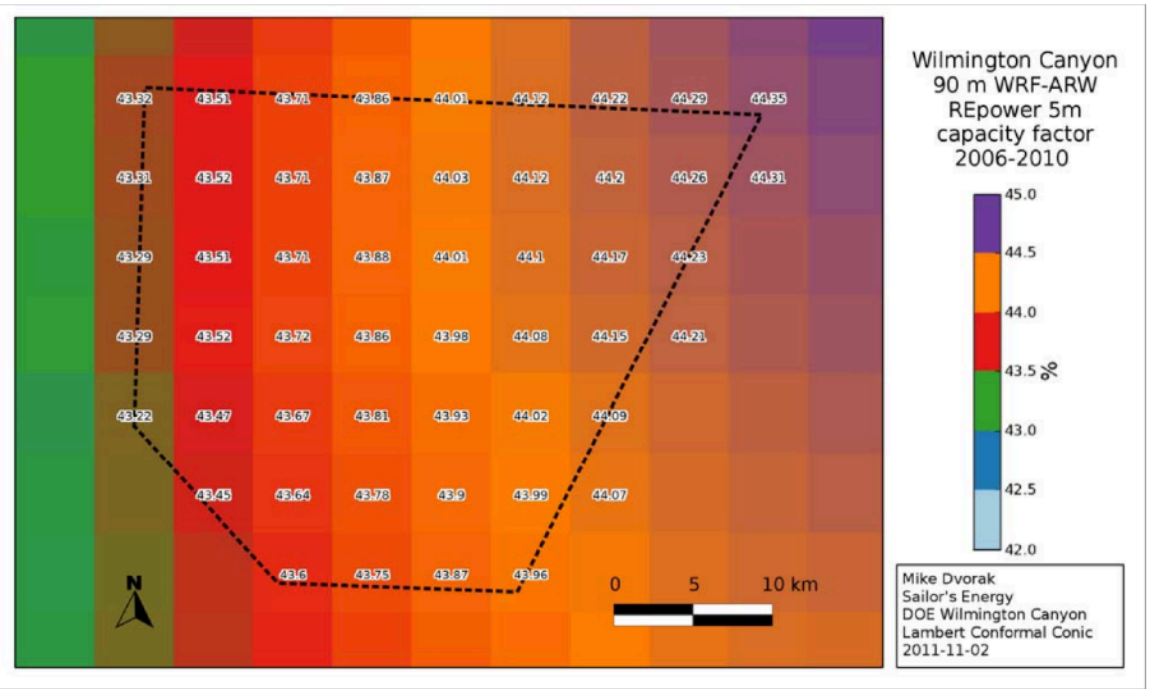


Figure 8: WRF-ARW 90m capacity factor for 2006-2010 in the WCP area

Metocean Analysis

In order to estimate loads during extreme wind and wave events, these events must be defined. The design life of a wind turbine is 20 – 25 years and the structures are classified as low to medium consequence of failure by BOEM (unlike an oil platform, offshore turbines are very unlikely to be occupied during a storm). In light of the consequence, designing for a 100 year storm would be excessive, so a 50 year return period is used for extreme loading, in line with IEC recommendations. This section summarizes a first order estimate of the primary environmental parameters that define extreme loading in the study area, based on published data and studies, using the 50 year event for each of the following:

- Peak 3 second gust (10m, 90m)
- Peak 1 min average(10m, 90m)
- Peak 10 min average(10m, 90m)
- Peak wave height – H_{max}
- Significant wave height - H_s
- Peak wave period
- Significant wave period

Average and extreme currents are also estimated for the 50 year event, at the surface, at the seafloor, and depth averaged. Tidal ranges and extreme water levels from storm surge were also investigated and estimated for the study area, and can

be found along with more detailed analysis in a white paper by Bruce Williams (Williams 2013).

The methodology is to examine historic in situ data sets and hindcast modeling to arrive at a reasonable yet conservative estimate of future extreme conditions. Published data from NOAA NDBC buoys, WIS wave hindcasting studies, the National Hurricane Center, and other sources were evaluated and compared, and discrepancies discussed.

This study did not treat wave spectral analysis, extreme wind shear, veer, clocking, turbulence intensity, or other parameters recommended by wind turbine certification agencies such as DNV in order to properly calculate all limit states and satisfy design certification criteria, nor does it provide a climatology, wind rose, or Weibull parameters for wind speed distribution.

Table 2 below gives the primary peak wind values for tropical storms, which produce the highest peak winds in the study area (although Nor'Easters produce the highest waves).

Table 2. Primary peak wind speed calculations.

PEAK WIND SPEED CALCULATIONS - TROPICAL STORMS						
Hub Height =	90	m				
Input Shear Exponent =	0.08	for extreme winds				
Gust Factor =	1.12	(1 min to 10 min)		**All data in m/s**		
All data in m/s	**NHC Data -1min, 10m, 50 year return (*)**			**Convert to Hub Height**		
Averaging Time	3 sec	1 min	10 min	3 sec	1 min	10min
Height Above Sea Level	10m	10m	10m	90m	90m	90m
Peak wind speed (m/s)	52	45	40	62	54	48
(*)- 3 second and 10 minute values were derived per Powell and Hsu, equations below.						

It should be noted that these values are highly dependent on the shear model (shear exponent) and gust factor selected.

Peak Wind Speed Data and Design Considerations

- Peak wind speeds in the study area are defined by tropical storms, and the strongest tropical storms to impact the study area have been Cat2 hurricanes.

- In the last 160 years, one Cat1 and one Cat2 hurricane have passed directly through the study area, producing peak winds within the study area. Assuming the NDBC hindcasted hurricane tracks are reasonably accurate, all others have passed far enough to the east that they do not produce hurricane level winds in the study area.

- The closest Cat3 track passed about 100 km to the east, too far away (and on the wrong side) to produce Cat3 or even Cat2 wind speeds at the study area.

- Peak observed gust speeds (5s avg.) were 33 m/s at buoy 44009, and this has occurred twice since 1984 (e.g., hurricanes Gloria and Charlie). Peak gusts from Sandy reached 30.2 m/s. A database query confirmed that these gust events plus the 6 Mar 2013 Noreaster, are the only four events that exceeded gust speeds of 30 m/s between 1984 and 2012, a period of 28 years.

- Nor'easters can reach peak gusts of 26 m/s at buoy sensor height of 2 to 3 m.

The National Hurricane Center estimates that the return period for a major hurricane (exceeding the upper threshold of a Cat2) making landfall in Delmarva or NJ ranges from about 58 years at the southern tip of Delmarva to about 76 years in northern NJ. However, it is unclear how this estimate was generated, given that a Cat3 has not made landfall on Delmarva in over 160 years.

A reasonable first order estimate for an extreme 50 year event in the study area would therefore be a direct hit from a weak Category 2 hurricane (which would have the same impact as a near miss from a strong Cat2 hurricane), with peak one minute gusts up to 45 m/s at 10 m ASL. Although a Cat2 has tracked through the study area only once in the last 160 years, climatological trends would indicate a conservative approach—yesterday's 100 year event is likely to be tomorrow's 50 year event. In addition, the relatively short time series of buoy data (29 years) is insufficient for an accurate 50 year return period climatology, so uncertainty would also suggest a higher safety margin. To translate this event into sustained and peak gust wind speeds at hub height, extrapolation was used.

Extreme Waves

Extreme Wave events are recorded fairly accurately by the NDBC buoys, so a peak over threshold analysis is used to assess their frequency and magnitude.

NDBC Buoy Wave Data

The wave data record of NDBC 44012 only goes back to October 1986, and wave data are not available for 1985 at NDBC 44009, so Hurricane Gloria wave data were not available from these stations. This may not have any effect on the analysis since the highest waves normally occur during Nor'easters, not tropical storms. NDBC 44012 was deactivated in 1992, so only 44009 data are available for Hurricane Sandy. The waves generated from Hurricane Charlie did not exceed Hs=4.5m, so that event was not included in the wave analysis.

Peak Over Threshold Analysis 8.0 m Hs

To check peak wave events, NDBC wave height records from buoy 44012 from 1986 to 1992 were converted to hourly averages and filtered using a criteria of wave height exceeding 8 meters (~24 feet). Out of 28 years of records, only two events exceeded the threshold—the Jan 1992 Nor'easter, and the 2009 Nor'easter,

Peak Over Threshold Analysis – 7.0 m Hs

The database for NDBC 444009 was queried for significant wave heights above 7m, and 9 events (34 hours) were identified between 1986 and 2012, a period of 26 years. It is notable that all of these large wave events were extratropical storms, with the exception of Sandy. It is likely that Gloria in 1985 produced wave heights well over 7 m, but the buoys were not measuring wave data at the time.

Table 3 below shows the study estimates for the significant and maximum wave heights and the average and dominant periods for extreme (50 year return) tropical and extratropical storms in the study area.

Table 3. Significant and maximum wave heights, avg and dominant period for extreme storms.

	ExTrop	Trop
H_s (m)	9	7.5
N =	150	110
H_{max} (m)	14.2	11.5
DPD (sec)	11 to 15	12 to 15
APD (sec)	7 to 10	7 to 9

Extreme Currents - Summary and Conclusions

1. **Average, one year peak current velocity** – Based on the literature search, annual average estimates range from 15 to 20 cm/s, which is slightly higher than found by Kuang et al (2011) due to the inclusion of winter months when winds are higher. A reasonable estimate for the average current velocity in the study area is 15 to 20 cm/s at the surface and 10 to 15 cm/s depth averaged. Peak one year return surface velocity is estimated at 40 cm/s, with about 25 cm/s depth averaged.

2. **50 year current event** – The storm investigated by Miles et al (Nor'Ida of 2009) produced peak 10 min. avg winds of 20.5 m/s at NDBC 44025, which is about half of what the 50 year event (a Cat 2 Hurricane) would produce at the buoy (NHC 2013). As a rough approximation, this could be expected to produce 50% higher depth averaged and surface velocities. Since the peak

surface vector velocity observed by Miles et al was about 1.0 m/s, the 50 year event could be expected to produce surface currents of around 1.5 m/s for several hours at least[6]. Based on the shear profiles observed in CMO 2007, this could be expected to produce depth averaged current of about 90 cm/s. Based on the literature survey in the Levitt scour study, this would attenuate to about 40 to 50 cm/s at the seabed.

These findings for site currents are summarized in Table 4 below.

The wave and wind data were used in analysis of turbine foundations, determination of which vessels were most suitable, and in the analysis of how many days, on average, would be excluded from transit or installation work due to ocean conditions.

Table 4. Site Currents: average, 1-year peak, and 50-year peak.

	Average Current	One Yr Event Peak	50 Yr Event Peak
Surface Velocity(cm/s)	15-20	40	150
Depth Average Velocity (cm/s)	10-15	25	90
Nearbed Velocity (cm/s)	5-10	10-20	40-50

Design Process and Design Comparison

This section describes the approach taken to design, a brief summary of the designs evaluated but rejected, the four designs evaluated and the LCOE calculations for each one. Each integrated design includes the turbine, the turbine support structure, the deployment port, and the vessel used.

Rejected design concepts

Many concepts either in the original proposal or advanced by the engineering team were discarded based on engineering analysis, or based on review by other disciplines, prior to detailed engineering. These are briefly described below. Each is a rejected design concept.

Horizontal transport of assembled turbine structure. This would solve the problem of bridge and other overhead clearance and would enable several more vessel types, including "tip up" vessel and installation. However, many items inside the nacelle would need to be re-designed for horizontal placement, and for

[6] Rough estimate was validated as reasonable by Bruce Lipphardt of Physical Ocean Science and Engineering (CEOE, UD), March 2013.

horizontal transport. Also, if the blade is attached during these operations, loads in the main bearing and (if present) gearbox could cause damage and premature failure (see next item). Our turbine manufacturer partner, as well as other turbine manufacturers we consulted, strongly recommended against horizontal transport.

Upright transport with pre-installed blades. Although transport with blades attached has been used, for example, for the Beatrice Demonstrator (one and two) and for Hywind, we do not think it prudent. Our proposed method installs the blades on-site, after transport, for multiple reasons. During transport, our recommended method of blades mounted on the tower makes the structure shorter, more stable, and with a lower center of gravity. Independent of weight distribution, vessel operators did not want either yaw or a rotating (freewheeling) blade adding dynamics to the ship's load. Under high wind conditions, the mounted blade cross-section makes overturning moment, both in the yard and in transit, a greater concern. If the blades are freewheeling it reduces some forms of bearing damage (see "with blades locked" below). Attached freewheeling blades were used in Hywind Scotland Pilot Park, where the five 6-MW turbines had blades mounted on the hub and the turbine vendor insisted on unlocked rotor, but allowed locked yaw. However, when freewheeling, bearing skidding and wear become an issue because the bearings are being alternatively loaded and unloaded. When unloaded, they lose traction and then skid during 'landing' (think about the smoke from the tire when a jet lands - this is happening to your bearings). A recent paper (N. Garabedian, B. Gould, G. Doll, D. Burris, n.d.) shows that in normal wind turbine operations, rotor torque prevents the skidding problem. Burris et al's research shows that over-loading is not a huge concern—under-loading is the larger problem. Wind turbines spend way more time at low wind speed, thus low torque, and this causes skidding once per cycle 40-60% of the time of operation. The same thing will happen during transport but over a short enough time-frame that it may be a small rather than a huge concern. Locking the rotor during turbine movement is not a solution, see "blades locked" below. In short, with further analysis it could be determined that a freewheeling rotor during transport causes an acceptably low amount of bearing damage—however, if that were demonstrated in subsequent study, attached blades would still have the problems of overturning moment in port and transport, instability (including unpredictably rotating blades) during transport, and added height conflicting with overhead obstruction or intrusion in prescribed airspace.

Upright transport with pre-installed blades, and blades locked. As noted above, transport instability would be modestly improved by locking blades. Turbine manufacturers (including partner Clipper Marine) advised against transport with blades on and locked, due to potential bearing damage. Consistently, our tribology advisor (Prof. Dave Burris) explains: If locked, bearings are not designed for load carrying without motion. When rolling element bearings are loaded statically, the lubricant is squeezed from the contact, metal surfaces touch, and the vibratory nature of transport causes fretting or false brinelling, which can and will compromise performance in the field. Rotational motion is important for replenishing lubrication. In sum, a locked rotor is worse for bearings than freewheeling, but best is no blades attached on rotor during transport.

Lattice structure extending to nacelle, no separate tubular tower. This redesign would eliminate the transitional stresses on the transition piece and would reduce wind loading against the tower. This concept was rejected because it would make little difference in loads, as this structure's primary loads are water force (wave and current) against the lattice below water line and the wind force against the rotor disk. A minor point is that turbine manufacturers depend on the tower to provide some shelter for switchgear and would have to re-design the interface to the nacelle—although those can be re-done, the substantial effort to induce turbine manufacturers to re-think the tower is not worth the modest payoff.

Concrete gravity base. By casting a concrete base with compartments for flotation, it is possible to build and float the entire base structure, then void air chambers to fill with water at the site, and lower to bottom with winches or a crane for stability. The weight of the base holds it to the seafloor without specific attachment processes. Only brief consideration was given to this option because of the high mass of concrete, the elapsed time to cast it and let it cure, and the need to move that greater mass on shore, to transfer to the deployment vessel, and on board the vessel.

Monopile rather than jacket. At the time the work was proposed, jackets were considered necessary for depths over about 20 m water depth. Now monopoles are sometimes used in waters of 30 m and deeper. However, monopolies require pile driving and grouting, both of which limit other construction changes and thus prevent several substantial cost reductions. Although a monopile might work in some locations, we discarded full engineering analysis of monopile because we did not feel that monopile could expand to deeper waters of the US Continental Shelves, and because it failed to meet the FOA criteria of being able to expand to mid-depths and larger turbines.

Monobucket rather than tri-bucket. Universal Foundation joined the team early in the project. Universal Foundation's design is a single large suction bucket with compartments, with suction differential among compartments during pumping used to align the tower to the vertical. Given that we wanted to scale above 10 MW and deeper waters, a very simple loading analysis left us concerned about overturning moment of a single large bucket and monopile, given the planned water depth, tower height, and 10 MW nacelle mass. We believe, especially as turbines become larger, that the sea floor mounting seems more stable from first principles if it uses three (or more) buckets. For further stability, multiple buckets can be separated as much as needed by extending the struts of the tripod foundation—difficult to do with a single bucket.

In-port assembly (of tri-bucket and jacket) in shallow water adjacent to quay. We considered building the buckets, jacket, then entire turbine structure, on the harbor floor adjacent to the quay. This would have allowed using a crane with hook height about 8 m shorter and reduced the lift requirement of the transport vessel crane pick. However, it would have required preparation of harbor floor for a added weight bearing (2500 metric tons for the fully assembled structure). Also it would have complicated worker transfer to the structure during assembly. These reasons led to the final design's location of the assembly area as being on land near the quay, using areas reinforced for higher ground bearing pressure.

Alternative vessels. The vessel selected for the cost modeling for suction buckets installation with existing equipment is a sheer-leg crane barge with azimuth thrusters for dynamic positioning (DP2), like the Gulliver. This is an existing vessel that can be used for our recommended procedure of one-piece pick of the entire structure off the quay, transport, and placing on bottom. This meets our "existing equipment" criterion and, unlike the above concepts in this section, was not discarded. However, Gulliver can carry only one structure at a time, thus many trips for large wind farms, which is not economical for development far removed from the port. Appendix F describes several vessel alternatives, some of which might be either lower cost, and/or which might be more efficient for serial installation of many turbines—for example a vessel similar to Gulliver but able to carry several assembled turbines, or a vessel like either the low-cost *UD winch pontoon barge*, or the *bridged A-frame*, both described in Appendix F. Since the non-optimized Gulliver vessel would not be used in larger serial installation, we consider, as a fourth design concept, alternatives such as those in Appendix F for the suction bucket with "adapted equipment" that is, with equipment more targeted to our new installation method.

Summary of four design concepts to be compared

In this section, each design concept is summarized, briefly covering its design, assembly, and installation method. For this project, two designs were fully engineered and cost-estimated (2 and 3), and four design concepts are compared. Each of the four is covered in detail in the subsequent four subsections.

First is the baseline concept, a 5 MW piled jacket. This was originally planned to follow the Ormonde offshore wind plant, which was based on 5MW turbine and quadrapod jackets in 21 m of water, in the Irish Sea.[7] During the course of this project, the DeepWater Wind Block Island project was built using similar technology and turbine size, so some aspects of the Deepwater project were used to make the baseline more comparable—in that it is in US waters, deployed from a US port, with US handling, deployment, and marine construction equipment. The baseline, following the SOPO, assumes 200 of the "NREL model" 5 MW REpower turbines, and assumes they are mounted on a tubular tower atop a quadrapod piled jacket foundation. Following today's processes, assembly is carried out offshore, with transport done by a non-powered jack-up vessel. The electrical system is a 34 kV array voltage with a single AC substation.

For the second design, the baseline concept is scaled up to 10 MW turbines, thus 100 turbines for the same 1 GW. We used the Britannia preproduction turbine specifications from Clipper Marine as the reference turbine—see early public documentation of Britannia in Dvorak 2010; a confirming reference is the somewhat heavier DTU 10 MW reference turbine, see Desmond et al (2016). For design 2, the 10 MW Britannia is mounted on a tubular tower mounted on a quadrapod piled

[7] See 4C Offshore, 2011, or Wikipedia https://en.wikipedia.org/wiki/Ormonde_Wind_Farm

jacket foundation. Assembly is completed offshore, with transport done by non-powered jack-up vessel.

The third design also uses 100, 10 MW turbines, again using the Britannia preproduction turbine as the reference turbine, and again mounted on a tubular tower mounted on a subsea jacket structure. The difference is that the subsea structure is a tripod with a three suction bucket foundation base. Also, assembly is almost entirely done onshore, with transport to deployment site done with shearleg crane vessel like the Gulliver[8]. Blades are mounted on the tower in port, then installed on the hub offshore using novel blade mounting techniques.

The fourth design concept is identical to the third, except that a customized vessel is assumed to be built, and handling in port and at sea are assumed to have developed further in order to optimize this new deployment method. By contrast, the third concept, as planned and quoted, uses existing vessels and does not assume development of supply or equipment tailored for the purpose.

Each of the four is below described, in turn.

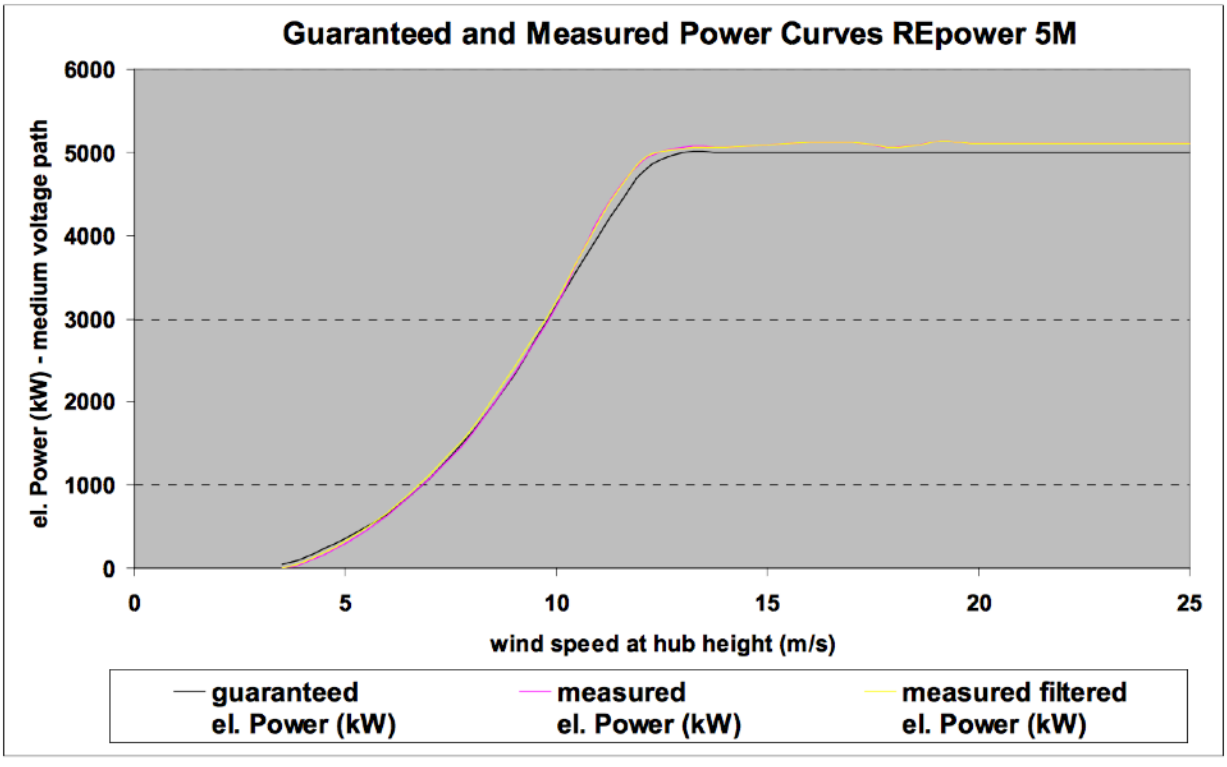


Figure 9: REpower Power Curve (Goesswein 2006)

[8] Specifications for the Gulliver are in Appendix D, with sources at http://www.ship-technology.com/projects/gulliver-heavy-lift-vessel/ Also at http://www.maritimejournal.com/news101/vessel-build-and-maintenance/ship-and-boatbuilding/scaldis-heavy-lift-vessel-gulliver

Design 1: 5 MW Piled Jacket (Base Case)

The baseline concept for this analysis, following the DOE SOPO and our proposed base case, is a 1 GW project utilizing 200 turbines, 5 MW each. The REpower 5 MW turbine, which is the NREL reference turbine (Jonkman et al 2009), is used as the base case. (Arguably, the GE/Haliade 5 MW would be a more contemporary base, but this choice does not greatly affect the conclusions.) Turbine power curve is shown in **Figure 9**. Quadrapod piled lattice jacket foundations were selected for this design, as this is the method utilized for the Block Island project and plausibly could be specified for planned offshore projects in the US Atlantic coast. The installation method is based on the marine transport method utilized by Block Island, as reported by our contractor Weeks Marine, and in-port storage and loading, as reported by contractor Mammoet. The following narrative details the design, installation, and assembly method for the baseline case.

Pilings, subsea structure, tower segments, nacelle, and blades are all delivered and staged prior to the start of construction. Staging all components prior to the start of construction, or in two batches in the case of larger projects, reduces not only time of construction, but also reduces the risk of project delays caused by supply-chain logistics issues with crews and cranes on site but lacking one or more components for construction. This staging is specified for all designs.

Cranes at port will load four pilings, weighing 120 tonnes each, onto a single barge, a process that will take 12 hours per piling set at port. Direct distance to the center of the selected site is about 82.5 nm, 150 km, the majority, 122 km, from the port to the mouth of the bay. For travel calculations, we assume the far side of the site, yielding a conservative steaming distance of 113 nm. Thus, at 113 nautical miles, with the loaded transit speed is 5 knots, it is expected that the barge will take 22.5 hours to reach the 500 ton, 335' class jack-up at the installation site (jack-up vessels are also called liftboats).

The 500 ton, 335' class jack-up takes 4.5 days per piling set to install (which assumes a 40% weather delay) or 2.7 days in good weather. After approximately 3.375 days (or 2 days in good weather) the barge carrying the pilings can return to port since at that time the last piling has been lifted and removed from the barge, but not yet driven.[9]

The barge, now unloaded returns to port at a transit speed of 6 knots, taking 16 hours to return to port.

The piling process is performed with two installation jack-ups and 6 feeder jack-ups, eight vessels in total, for the 5 MW piled jacket foundation. These vessels will

[9] This calculation based on the installation times (4.5 days or 2.7 days in good weather) divided by 4 pilings, yielding 1.125 days per piling or 0.675 days per piling in good weather, and then multiplying by 3 pilings to determine the time until the forth piling and lifted and removed.

operate the entirety of season one and then all installation vessels and half of the feeder vessels operating a portion of season two to accomplish the task within the schedule.

Figure 10. Traditional installation (base case): Lifting a 5 MW nacelle at Block Island, using the Brave Tern jackup vessel. From MarineLog, August 2016, © 2017 Simmons-Boardman Publishing Inc.

Cranes at port load and lash one jacket, weighing 553 tonnes, onto a single barge, a process that will take 24 hours per jacket. Given that the deployment site is 113 nautical miles from the port, and the loaded transit speed is 5 knots, it is expected that the barge will take 22.5 hours to reach the 1000-ton European jack-up at the installation site. The 1000ton European jack-up takes 2.25 days to install the one jacket (which assumes a 40% weather delay) or 1.6 days in good weather. The barge, now unloaded again returns to port at a transit speed of 6 knots, taking 16 hours.

The jacket installation is performed with two 1000-ton European jack-up vessels and utilizes the same six feeder jack-ups for the 5 MW piled jacket foundation. The idea is to have the feeders set up so that they can transport either 4 pilings or one jacket, depending on what is needed, to the site. It is estimated that all the vessels are on site for approximately 7.5 months, with mobilization and demobilization outside of that window.

Grouting is expected to take 2.25 days per turbine (which assumes a 40% weather delay) or 1.6 days in good weather for each piled jacket foundation to be grouted, and 28 days are needed for the grout to cure before being able to erect the turbine onto the foundation.

Once turbine assembly has begun cranes at port will load two complete turbine component sets onto a feeder vessel. A complete turbine component set includes; two tower segments (4-in total), one nacelle (2-in total), and three blades (6-in total). This process should take approximately 24 hours per vessel. Figure 10 shows the nacelle lift for Block Island.

The turbines should be able to be erected in 2 days or less offshore in good weather conditions. We used 3.25 days per turbine for the first 20% of the units (learning curve) and 2.69 days per turbine for the remaining 80%.

This process is done with four 1500-ton European jack-ups and eight feeder jack-ups for the 5 MW piled jacket. Each spread has a 140-day installation schedule, installing 50 turbines during that period.

Once the turbine has been completely assembled it is commissioned on site.

Design 2: 10 MW Piled Jacket, with conventional offshore assembly

Design 2 assumes that 10 MW generators with larger rotor diameters are available. The MHI Vestas V164-8.0 MW turbine is generally seen to be the most cost-effective offshore turbine available today (early 2017), and continuing growth of turbine size is generally considered by the industry to be an important driver of lower costs (see Kempton, McClellan, Ozkan 2016).[10] Siemens' CEO Michael Hannibal said they will announce an offshore turbine over 10 MW[11], Senvion said they will announce specifications and delivery date for a 10 MW turbine in 2017, and have done so to date privately to potential buyers. Most concretely, MHI Vestas announced a scale-up of the V164 to a rated 9.5 MW at Offshore Wind Energy London, June 2017. One member of our team (Clipper) had a complete 10 MW turbine in advanced design at the beginning of this project, and provided load data, even though this turbine was not ever commercialized (see references to public specifications in above section).

For our Design 2 with the 10 MW piled jacket and offshore assembly, 1 GW installed capacity still is assumed, using 100 turbines, 10 MW each, installed on quadrapod piled jackets. We used the fully-designed Clipper Britannia 10 MW test turbine as an engineering reference, although costs (in section "Capital cost comparison") are based on per-kW costs of recent turbines about this size. The installation method for the 10MW piled jacket is based on the method utilized by Deepwater Wind for Block Island but without assuming the Block Island long supply barge run, as reported by team member Weeks Marine. The following narrative details the design, installation, and assembly method for the 10 MW piled jacket. Like the base case, the appearance of vessel and offshore lifts is as shown in Figure 10.

Pilings, subsea structure, tower segments, nacelle, and blades are all delivered and staged prior to the start of construction. By staging all components prior to the start of construction, or in two batches in the case of larger projects, this method reduces

[10] This machine is highly cost-effective in the North Sea with average winds of 9 m/s; arguably a turbine with larger rotor might be more cost-effective in the mid-Atlantic site studied here.

[11] WindPower Monthly, 22 June 2016, "Siemens teases a 10MW+ turbine". also at http://www.windpowermonthly.com/article/1399841/siemens-teases-10mw+-turbine

not only time of construction, but also reduces the risk of project delays caused by supply-chain logistics issues with crews and cranes on site but lacking one or more components for construction.

Cranes at port will load four pilings, weighing 120 tonnes each, onto a single barge, a process that will take 12 hours in port per set of 4 pilings. Given that the deployment site is 113 nautical miles from the port, and the loaded transit speed is 5 knots, it is expected that the barge will take 22.5 hours to reach the 500 ton, 335' class jack-up at the installation site.

The 500 ton, 335' class jack-up takes 4.5 days per piling set to install (including the added 40% weather delay) or 2.7 days in good weather. After approximately 3.375 days (or 2 days in good weather) the barge carrying the pilings can return to port since at that time the last piling has been lifted and removed from the barge, but not yet pile driven.[12]

The barge, now unloaded returns to port at a transit speed of 6 knots, taking 16 hours to return to port.

The piling process is performed with one installation jack-up and three feeder jack-ups, eight vessels in total, for the 10 MW piled jacket foundation. These vessels will operate the entirety of season one and then all installation vessels and half of the feeder vessels operating a portion of season two to accomplish the task within the schedule.

Cranes at port load and lash one jacket, weighing 704 tonnes, onto a single barge, a process that will take 24 hours per jacket. Given that the deployment site is 113 nautical miles from the port, and the loaded transit speed is 5 knots, it is expected that the barge will take 22.5 hours to reach the 1000-ton European jack-up at the installation site. The 1000 ton European jack-up takes 2.25 days to install the one jacket (which assumes a 40% weather delay) or 1.6 days in good weather.

The barge, now unloaded returns to port at a transit speed of 6 knots, taking 16 hours.

The jacket installation is performed with one 1000-ton European jack-up vessel and utilizes the same three feeder jack-ups for the 10 MW piled jacket foundation. The idea is to have the feeders set up so that they can transport either 4 pilings or one jacket, depending on what is needed, to the site. It is estimated that all the vessels are on site for approximately 7.5 months, with mobilization and demobilization outside of that window.

[12] This calculation based on the installation times (4.5 days or 2.7 days in good weather) divided by 4 pilings, yielding 1.125 days per piling or 0.675 days per piling in good weather.

Grouting is expected to take 2.25 days per turbine (which assumes a 40% weather delay) or 1.6 days in good weather for each piled jacket foundation to be grouted, and 28 days are needed for the grout to cure before being able to erect the turbine onto the foundation.

Once turbine assembly has begun cranes at port will load two complete turbine component sets onto a feeder vessel. A complete turbine component set includes: two tower segments (4-in total), one nacelle (2-in total), and three blades (6-in total). This process should take approximately 24 hours per vessel.

The turbines should be able to be erected in 2 days or less offshore in good weather conditions. We used 3.25 days per turbine for the first 20% of the units and, assuming a learning curve, 2.69 days per turbine for the remaining 80%.

This process is done with two 1500-ton European jack-ups and eight feeder jack-ups for the 10 MW piled jacket. Each spread has a 140-day installation schedule, installing 50 turbines during that period.

Once the turbine has been completely assembled it is commissioned on site.

Design 3: 10 MW Suction Bucket, in-port assembly, install with existing DP vessel

Design 3 is the result of the integrated design process performed by the research team and our subcontractors. In engaging in this process the research team started with the expectation that larger turbines would be the market standard in the near future, thus as in the 10 MW jacket Design, the 1 GW project size is achieved by 100 turbines, 10 MW each, with the Clipper Britannia 10 MW turbine as an engineering reference, and costs (in section "Capital cost comparison") based on recent large turbines as in Design 2.

Early work in the integrated design process suggested that desired cost savings could be achieved with a different foundation design, one that has the potential to eliminate the need for jack-up vessels, with their required jacking time and costly day rates. The suction caisson, combined with a well-designed installation process, can be installed without jack-up vessels, as we will illustrate. A lattice subsea structure foundation is still used, but the base is a tripod with suction buckets rather than a quadrapod with pilings. SPT Offshore had considerable experience with subsea structures using buckets and jacket, and had developed designs for the Carbon Trust proposing one-piece wind turbine installations from floating vessels, part of which we adapt here.

The design 3 description will refer to the following port areas: Staging area for components; assembly area (with mountings to place buckets upon and cranes); commissioning area; storage area for complete assemblies; and quay at water's edge

where assembled turbines are picked up by the crane vessel. The ultimate location is the deployment site where the crane vessel lowers the entire structure to the bottom.

Buckets, subsea structure, tower segments, nacelle, and blades are all delivered and stored in the staging area prior to the start of construction. By staging all components prior to the start of construction, or in seasonal batches in the case of multi-season builds, this method reduces not only time of construction, but also reduces the risk of project delays caused by supply-chain delays. In addition, the Design 3 method allows for continuous turbine builds during the winter months, queuing up for the weather-dependent maritime construction season.

To place and position buckets, a temporary support structure (about 2.5m high) with guide marks is positioned in the assembly area to place each bucket upon. The temporary support must be high enough to allow the self-propelled modular transporters (SPMT) to roll underneath the structure, lift, and carry the assembled turbine out. It must of course also have sufficient weight bearing so as to not crush. Several sets of supports are built to allow for the construction of multiple turbines at once. (Subsequent lift height numbers do not include the ~2.5m height of the support structure.)

The three suction buckets, each weighing 270 tonnes and 10 meters high, are individually picked and placed on support structures.

The subsea lattice structure, includes transition piece and auxiliary steel (J tubes, access ladders etc), and weighs 607 tonnes with a height of 55.5 meters (total lift on top of buckets is 65.5 meters). This is next lifted, aligned with attachment points on top of buckets, and welded to the buckets. The upper end of the transition piece has a preinstalled attachment point to be used by the crane on the transport vessel—this point must be above center of gravity of the entire structure.

Next, the two tower segments are lifted and bolted on. Each of these segments weighs approximately 208 tonnes with a height of 52 meters (total lift height of 117.5 meters for the first segment and 169.5 meters for the second segment). The tower segments are fitted with removable blade attachment brackets for the three blades to be mounted on the tower.

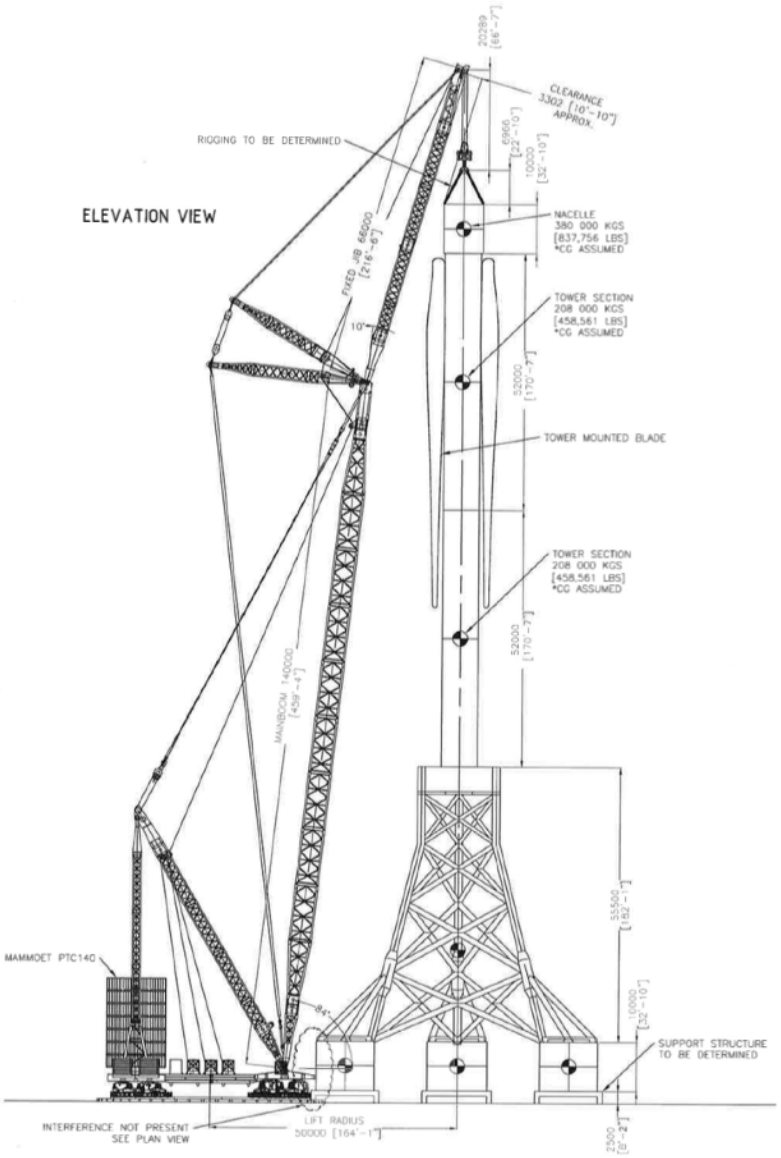


Figure 11. The highest lift, the nacelle at 180m, tops the complete turbine assembly on land in Design 3. Crane is Mammoet PTC140, see Appendix D, B02.

Each blade is lifted and lowered into the bracket on the tower.[13] Attaching blades to the stationary tower rather than the hub reduces wind load against the structure, and increases stability during storage in the yard and transport at sea. Blades off rotor also eliminates damage to bearings (see more detail in section "Design concepts rejected"). Each blade weighs 30 tonnes and will have a total lift height about the same as the total lift height of the second tower segment. (Note: Each blade has two winch connection points inside, on the hub end, to allow lifting blades to the rotor at sea, plus a smaller connection point near blade tip for a constant-tension winch used at sea for stability during the lift at sea; hub-side blade connection points may be helpful also for onshore lifting of the blades onto their bracket.)

The nacelle, weighing 380[14] tonnes and approximately 10 meters in height, is picked off the

[13] Two coated steel rings are attached around the tower to hold the blade mounts. The primary support ring, near the top of tower, holds three mounts, one for each blade's large end or root. These top mountings are an asymmetric "C" shape matching the asymmetric cross-section of the blade, allowing each blade to be gently lowered into its respective mount by the port crane and held in place primarily by gravity. Each blade is mounted at approximately 90-degree separation from another blade, leaving one side with approximately 180 degrees clear for affixing the entire tower to the crane vessel for marine transport. The lower steel ring holds three lower mounts, each a closed oval shape that matches the blade tip outline. The main purpose of the lower, oval mount is to prevent the blade from moving, although it may be tapered to provide some weight support. As with the top C-shaped mount, the oval shape enables the blade to be lifted in and out of this bottom mount. Both upper and lower mounts have a softer rubber-like inner surface material to protect the blade.

[14] Clipper Marine Datasheet for Britannia C150, Issue 2, November 2010, giving nacelle+hub weight. This is lighter than many 10MW-class nacelles, but a heavier nacelle and hub would not affect equipment needs. The PTC140 capacity is 1384 tonne, and the 380 tonne nacelle lift only imposes 12 tonne/m^2 GBP, so a heavier nacelle would not increase the requirements of either this crane or the port's GBP.

staging yard and placed on top of the tower. Per normal practice, the nacelle uses bolts on an interior flange to attach it to the top of the tower. Total lift height for the structure is 179.5 m, or now adding in the 2.5m support structure, is 182 meters total lift height. This can be seen, with total height and crane, in Figure 11 and with more detail, in Appendix D, Drawing B02. Note that the nacelle lift (and all assembly) in Figure 11 is quite different from that of Design 2 as shown in Figure 10.

This nacelle lift is the highest for any operation, in port or at sea. It is challenging—182 m (597 feet) is equivalent to a 47 story office building (at 3.9 m/story) or a 59 story residence (3.1 m/story). For comparison with another vertically-assembled structure, the Saturn V orbital lift vehicle is 111 m tall. As shown in Figure 11 and with detail in Appendix D, these lifts, culminating in the 182 m nacelle lift, can be done by existing cranes (here the Mammoet PTC 140), without requiring any new equipment nor any new methods. Once the nacelle is mounted, no lifts of this height are ever needed again in the whole installation sequence. Further, using the method we have developed, the entire structure is never picked up by port equipment (other than SPMTs), there is only the single departure pick by the crane vessel, and the lowering to sea floor, again by the crane vessel.

After the turbine structure is complete, multi-segment SPMTs move under the buckets, by rolling between supports on the ground, then lift against the buckets to carry the entire structure. The structure is moved from assembly to the commissioning area. For commissioning, internal electrical connections are made and most electric parts and controls can be tested in the yard. (In a future, more mature stage of this design, commissioning could use a motor atop a gantry crane to spin the hub and test the generator together with converters in-port.) After commissioning, the SPMTs again move the completed, now commissioned, turbine assembly to a storage area designated for complete assemblies.

The turbine structure is stable just resting on the surface during typical climate conditions based on our weather analysis. In the unlikely event of a 100-year storm (hurricane or Nor'easter), and if the cross-section of the nacelle is large, wind force could exceed overturning moment, in which case the assembled turbine structures would require lashing to the harbor surface prior to the storm event. It would be prudent when building the port to include recessed lash-down tie points in the storage areas for complete assemblies. For any specific project, the assembled structure, including tower height, nacelle cross-section, and extreme weather at that port, needs to be analyzed to determine whether lashing could ever be necessary.

When the next deployment vessel is ready and approaching the quay, the SPMT pick up an assembled turbine from the yard, and bring it to quayside to be ready for pickup. This allows pickup to proceed as fast as vessels can deploy, not restricted by turbine assembly operations. The crane vessel picks the entire turbine structure off

the SPMTs on the quay, lowers the buckets into the water, and lashes or attaches via sea mounts to the back side of the ship.[15]

The crane vessel transports the assembled turbine to the installation site. Once in the desired location, the mounting to the ship are uncoupled, and the crane lowers the turbine structure to the sea floor. The weight of the turbine sinks the buckets partially into the sea floor, 2 or 3 meters, depending on the sediment composition. Once the foundation base is resting into the sea floor, the crane lines can be slacked and pumping begins. We recommend using the service boats to supervise pumping but this may require transfer of control lines from crane vessel to a service boat. When the turbine structure is firm on the sea floor, the crane vessel removes the hook and returns to port to pick up the next turbine, while smaller support vessels can continue any further operation of the pumps, completing the process of mounting the turbine foundation in place. When pumping is complete, the service boats can remove the pumps and return them to port.

After the bottom mounting is complete, a small crew operating a winch in the nacelle can install the blades, supported by a small service vessel. A constant-tension winch at the bottom (attached near the blade tip) is recommended for stability. Blade installation by winch is very weather sensitive, but delay only costs labor of a few workers, not an expensive jack-up waiting to lift the blades.

This process is illustrated in a construction animation created as part of this project.

Design 4: 10 MW Suction Bucket, in-port assembly, with new adapted equipment

The Design 3 process, for in-port assembly and single-piece transport, has been calculated using only existing equipment and practices. However, existing equipment means a sheer leg crane vessel, the Gulliver, which allows only one complete turbine structure to be carried out at a time (for alternative vessels, see Appendix F).

Although the one-piece installation saves considerable time loading at port and deploying at sea, carrying only a single assembly costs in transit time over a vessel that can transport multiple turbines, per this calculation: The distance from the modeled port to the installation site is 113 nm, and speed of the Gulliver loaded is 5 knots, unloaded is 7 knots. That equates to 22.6 hours to transport out and 16.1

[15] The accompanying video shows a simplified schematic of these attachments, with the main lift of the assembled turbine+jacket via the two hooks on a transverse spreader bar clamped above the jacket, just above center of gravity. But that simplified visual would not provide stability along the longitudinal axis of the vessel (bow – stern). Better would be an X shaped spreader bar that goes to 4 point rigging under the two hooks, allowing the hooks to be well above the unit's CG in all cases. Another stability improvement would be rigging with attachment further down the jacket below the spreader bar, say, at the top of the buckets, which would maintain stability, notably when the lower sea fastening is released at the deployment site.

hours to transport back, a total of 38.7 hours in transit. If we assume approximately 6 hours to lift and lash each turbine structure in port, plus 6 hours to lower each turbine and wait for enough pumping to achieve stability, the existing-equipment method requires 50.7 hours per turbine. Or, given that two vessels were secured in order to complete the 1000 MW turbine facility in one construction season, that is 25.35 h/turbine (including transit time) with both vessels working. Due to our specified requirement of building the target 1 GW in one construction season, Design 3 specified two sheerleg crane vessels.

There are two ways to design and use these vessels more efficiently.

First, and a low-cost initial step, would be to use an existing US-built barge, and fit that barge with existing cranes to create a low-cost shear leg crane for initial builds. This option is described in Appendix F, section "Adjustable boom" vessels, which estimates that a US built vessel could be built for this installation method for $15 million if based on a barge, or for $30M if self-propelled DP2 with four azimuth thrusters. The use of existing equipment substantially lowers the cost. If this type of vessel is to later be expanded, additional vessels would be new custom vessels, perhaps with added operational efficiencies but at higher cost.

Second, a more highly customized vessel could be custom built for this installation method, for example, still using a large crane with similar lift capability, but able to carry six assembled turbines on deck rather than only one hanging from the crane, the transit time per turbine would be reduced by 83% (the loading and unloading time would be approximately equal). This would mean 6 turbines could be deployed in 38.7 h transit plus 6 * 12 hours load+install, or an average of 18.5 h/ turbine for the two vessels. The economies over a single lift become greater as the distance increases further than the modeled wind project at Wilmington Canyon, as the six-turbine transport essentially reduces steaming time by a factor of 6. These rough estimates of cost saving are used in the cost calculation of Design 4, a modified Design 3 with adapted equipment.

Specifying Ports for In-Port Assembly

Based on the above process, we can describe the requirements of a port that could deploy the method of Design 3 (and thus Design 4). Given that this is a new method with much heavier and taller assembly, one might reasonably ask whether the port requirements are difficult or impossible to meet.

Port Requirements

Each of the requirements below are described, and given some rationale for why needed for our new installation methods.

No overhead obstruction from in-port assembly to the sea. As noted, upright deployment of assembled turbine structures has many fewer concerns than horizontal deployment. This equates to a requirement of no overhead bridges, power lines or other obstructions of 182 m or 597 feet for the 10 MW turbine. Clearance is required from the assembly area in the port to the quay, and continuing from the quay to the ocean installation site. Clearance could be slightly reduced on the Gulliver by partial submersion of the buckets during transport, or conversely would be increased slightly by carrying the turbine structures on the deck. Our extrapolated 20 MW turbine would be 237m (computed below), and future larger turbines, and floating turbines, will require higher clearance. Thus, the simple guidance would be that the ideal port for now and the future should have a passage to the sea with no overhead obstructions at all.

Channel depth. The operating draft of the Gulliver heavy lift vessel, specified here as existing equipment for turbine lift, transport, and installation, is 4.5 m (15 feet). Draft of ocean-going ships delivering parts could be 9 meters (30 ft).

Channel width. The designed turbine structure has a width (across one side of its base triangle) of 53 m (174 ft). The Gulliver has a width of 49 m. The Rambiz 3000, which could lift the design 10 MW turbine structure but not a 20 MW one, has a width of 44 m. A transport vessel for 6 assembled structures would be wider than the Gulliver.

Aviation clearance. Because the assembled 10 MW structure is 182 m and a 20 MW is 237m, aviation clearance must be considered. This applies to the port area where the entire turbine structure is assembled, and to the path of deployment from port to the ocean site. The International Civil Aviation Organization (ICAO) sets standards for “prescribed airspace", specifically, the Obstacle Limitation Surface (OLS), generally 15 km from the airport, and the Procedures for Air Navigation Services-Operations (PANS-OPS) surface, roughly defined by a 2.5% grade up from the end of each runway. These “imaginary surface” limits apply to fixed, temporary, and mobile objects. A 2.5% grade to an 182 m structure is 7 km (the 20MW turbine is 237m height, so 9.5 km). This comparison shows that the OLS is the more restrictive for our structures. Thus, as a simple guideline, the port and the path to the sea should be more than 15 km from the closest airports.

Load bearing of quay. Based on the analysis of equipment by Mammoet (Appendix D), Table 5 describes load (ground bearing pressure or GBP) of each operation. Offloading of components received by the port is assumed to be less GBP than the assembly and support of the entire structure, and is not tabulated below. Operations requiring less GBP, such as carrying individual components to the assembly area, are not tabulated. Note that the entire structure is never lifted by port equipment (other than SPMTs), only by the crane on the installation vessel, with lift capability of 4,000 t. During transport, weight bearing is by lashings to the side and by the on-board cranes.

Table 5 summarizes the ground bearing pressure for each of the heavy operations. The blade transport and lift require far less of lift equipment and of GBP. Due to their small requirements, as shown in Appendix D, Mammoet drawing B08, and are not listed in the table here nor precisely calculated in the appendix. Note that the most severe GBP, 34.5 t/m^2 using a Demag/Terex CC2800-1 Crane to lift the buckets, can be reduced to 14.4 t/m^2 by using the larger PTC35 crane. After this adjustment, the greatest load bearing is the 24.9 t/m^2 (5,1000 psf) lift of the lattice structure. All remaining GBP requirements are less than 15 t/m^2. Since the position of the crane for the bucket lift will be fixed, during all assembly, the PTC35 can be located for lattice lift at a point of higher GBP support. For transport, even including the full turbine structure, the highest GBP is 13.2, so this would set the requirement for minimum GBP along all areas of port transport, concluding at the key for pickup by the vessel.

Table 5. Ground bearing pressure (GBP) of each major operation, based on Mammoet design calculations

Operation	Mammoet Drawing[a]	Weight of load (tonne)	Equipment	GBP Metric (tonne/m^2)	GBP Imperial (PSF)
Move bucket to assembly	B06	270	2 x 10 line SPMT	5.6	1,148
Bucket lift for placement (two alternative cranes calculated)	B09	270	PTC35 crane	14.4	2,953
			Demag/Terex CC2800-1 Crane	34.5	7,063
Move lattice to assembly	B05	607	3 x 10-line SPMT	7.9	1620
Lattice lift (no buckets)	B01	607	PTC35 crane	24.9	5,100
Move tower section to Assembly	B04	111	two[b] 2x 6-line SPMT	4.1	841
Tower Section lift	B02	208	PTC140-DS crane	10.9	2,242
Move nacelle to assembly	B07	380[c]	2x14 line SPMT	13.2	841
Nacelle lift	B02	380[c]	PTC140-DS crane	12.1	2,472
Move entire structure from assembly to commissioning and to quay	B03	2303	three 2x16 line SPMT	9.0	1,845

a. Mammoet drawings have numbers like 15029150-P153-D-Bxx. This column gives the Bxx part of the number.
b. A small inconsistency in drawing B04 shows 3 SPMT per lift point one place, another part shows two SPMT. In either case, this would not determine the critical GBP for the port.
c. This is weight of nacelle only; higher when hub is attached.

Port laydown area and quay length. Here we make only an approximate estimate of area requirements for a first scoping of ports. Kvitzau (2012) specified that for Cape wind loading and unloading, 1200 feet of quayside would be required, allowing one ocean-going transport and two installation vessels to dock simultaneously. For laydown of 40 × Siemens 3.6 MW turbines and towers, 28 acres were adequate; with 130 turbines in the project a 40 turbine capacity would have required > 3 staging waves (seemingly sub-optimal).

We use this on-record US port specification to estimate our port laydown requirement. Our selected design stages a 10 MW turbine, and would stage the subsea jacket at the same time as the turbine components. Adjusting turbine area for 3.6 MW to 10 MW is approximately 1.7 times, since linear area to power goes approximately with the square root. We require staging the jacket, which adds approximately a 0.4 multiple of the turbine components. Thus whereas Siemens approved 28 acres for 40 turbine storage at 0.7 acre/turbine (0.28 hectare/turbine), our 10 MW assembly in port would require laydown approximately 0.7acre×1.7×1.4 = 1.7 acres/turbine (0.67 hectare/turbine). We also require storage of assembled turbines, which we estimate at 2× the jacket storage area, or 0.95 acre/assembly (0.38 ha/assembly). Worst case for storage of full assemblies would be about 0.5 of the annual production (full winter build with no installations). Storage of components could require space for 0.5 per year assuming two supply waves/year or 100% if a more stringent full-year supply storage required. Space can be conserved by storing assemblies in laydown space freed up by components already assembled or by placing advanced delivery in areas not filled by other suppliers, and by requiring suppliers to make more waves of deliveries. Table 6 shows laydown space requirements under a range of these assumptions.

Table 6. Laydown area required (hectares) for 10 MW bucket, on-shore assembly

	Components ready to assemble (ha)	Assemblies ready to install at sea (ha)	Total laydown area	
			hectare	acres
500 MW project, 2 supply waves, assemblies replacing components	17	0	17	42
500 MW project, 2 supply waves	17	10	27	67
1 GW project, 2 supply waves	34	19	53	131
1 GW project, 1 supply wave	67	19	86	213

Example Ports

Two ports are used as examples of the above port requirements. New Bedford Marine Commerce Terminal is already built and can be used, although not optimal. The Delaware City area was specified in the proposal and is well-qualified, but would have to be built out.

New Bedford Marine Commerce Terminal

As an example evaluation of an already-built port, we take the New

Bedford Marine Commerce Terminal (NBMCT)[16]. This was recently designed in expectation of the traditional piece-assembly-at-sea planned for Cape Wind. How different are our requirements from that traditional design specification? The NBMCT has no overhead obstructions from quay to the sea. Load bearing is 4,100 lb/ft2 throughout most of the port (see "Crane loading area" on the port layout diagram at the end of Appendix D). The entire NBMCT area also can support concentrated loading of 20,485 PSF. By comparison to Table 5, the PCT35 crane would need to be at a more-reenforced point within the crane loading area, only for the lattice lift. Otherwise, all the areas in the NBMCT Crane loading area would be sufficient. The quayside draft is 9 meters, more than Gulliver's 5 m working draft. It has 26 acres (11 ha) of storage area, including the heavy lift and assembly areas, not nearly enough area for a 1 GW laydown, although a 500 MW build could be staged with four supply waves and/or some of the other adjustments mentioned above (see Table 6). Another issue at NBMCT is that the hurricane barrier protecting the harbor has a width of only 45.7 meter (150 ft). Our specified existing Gulliver vessel is 49 m, too wide. For the 10MW turbine (but not a 20 MW) the Rambiz 3000 could marginally be used, with a width of 44 m—of course this is marginal and would require special operational preparation and approvals. Other options would be widening of the entrance or a slightly narrower vessel designed for this barrier width.

The New Bedford Airport (EWB) is only 6 km to the North and has many commercial flights, so a closer examination of flight paths and prescribed airspace would be required.

In short, the existing NBMCT port itself could just barely accommodate the the in-port assembly and single-pick method developed here, with a 500 MW project and several adjustments. This does not mean to say that NBMCT is a perfect match, rather, we mean to demonstrate that our method does not make requirements beyond those an offshore wind port would be designed for, even if planned only for conventional deployment.

Delaware City area

The port designated to analyze for this project is an industrial area just north of Delaware City, DE, including the abandoned Occidental Chemical site, plus unused areas of the Valero refinery. This large site has excellent rail and highway access and has no overhead obstruction to the sea. Per Table 6, the unused land area at the two sites is much more than enough for deployment of one GW per year projects in a single wave of supply, build, and deployment.

Valero maintains a 40-50 foot draft channel with three births for offloading petroleum but that occupies only 1300 yards (1200m) of the 4000 yard total

[16] Data available from MA Clean Energy Center at http://www.masscec.com/nbmct and http://www.portofnewbedford.org/documents/freight_connectingshippers.pdf

waterside linear distance at the two sites (3650 m). Either the South or North of the unused portions of the combined site would be sufficient for a large offshore wind deployment port. There is a short deep channel beyond the last petroleum offloading birth, possibly enough for a small test quay, if the initial port were at the South end of the site. Extending the 40-50 foot channel up to the North, a 20 foot channel continues past the end of site, but that is further from land.

The North end of the combined site, formerly Occidental Chemical, is reported as 100 ha, about half of it (50 ha) non-wetland, and with 320 m waterside[17]. If one adjacent unused area of Valero were additionally used, that would be a total of 120 ha of laydown area and 1.6 km of waterside quay length for development.

In either North or South area, the waterside part of the site is undeveloped and for actual port activities would require creation of a heavy-lift quay and reenforcement of the laydown area. The existing dredged channel would need to be further extended for deep channel access to some or all all this waterside length, or to the North, the land could be filled out to reach the existing 20 foot channel.
The geology is amenable to support using cells (below), with fill on the surface, then 10-15 m of heterogeneous, medium to fine sand with discontinuous beds of coarse sand, gravel, silt, fine to very fine sand and organic-rich clayey silt to silty sand, on top of the Tertiary-age Calvert Formation (clayey silt to silty clay interbedded with silty to fine to coarse sands).

Air clearance would require more analysis. Wilmington Airport (ILG) is only 7 km to the north. ILG has had regular commercial flights but it currently support only general aviation. Summit Aviation, 10 km to the west, is only general aviation. The larger airport in the area, Dover Air Force Base, is a very comfortable 45 km south, and avoiding a 15 km radius from Dover during transit would just barely be achieved by staying in the deeper channel through the Delaware Bay.

As a rough estimate of cost, we draw from the cost to build the New Bedford Marine Commerce Terminal. Their construction method builds on tubular cells, driven into earth below the adjacent channel depth. For NBMCT, 25 cells were installed, each creating 62' of quay side, for a total cost of $113 million. NBMCT reports that these costs roughly scale, so $113M/25 cells would be $4.5M/cell. A small quay for only demonstration size projects might be 310 feet or 95m, enough to load one 10MW turbine and jacket and requiring 5 cells. Thus a full port at this site might be similar to NBMCT at $113, or a 5 cell test quay could cost $4.5M x 5 = $23M.

We develop the details for the Occidental Chemical/Valero site as it has many desirable characteristics and serves the DOE purpose of giving detailed information

[17] EPA Corrective Action information: https://www.epa.gov/hwcorrectiveaction/hazardous-waste-cleanup-occidental-chemical-corporation-new-castle-de . The EPA information was combined with wetland maps from Delaware Department of Natural Resources and Control, so area and distance calculations above exclude state-mapped wetlands.

to demonstrate plausible deployment of our selected design. That does not mean this is our primary recommendation for port location. We do not analyze here other potential sites in the Delaware Bay that we believe to be equally large, closer to the ocean, and with fewer potential flight path conflicts but possibly more environmental tradeoffs.

Capital Cost Calculations

Cost of components is developed in each of the subsections below, based on the design and estimation approach described above. Then, in the section "Combined cost of all components and major operations" below, each capital cost component is compared across the three different design approaches.

Cost Calculation of Components

Cost calculations for major components of the work and equipment are described in this section. In some cases more detailed background is provided in appendices.

Work in port

Mammoet designed the port process for all three designs and estimated the cost of each, making the port work costs highly comparable. The scope of work for each is described in the outline below.

The port work is for three distinct designs, for three proposed offshore wind turbine projects:

1. A 200 turbine project utilizing 5 MW Jacket Foundation turbines
2. A 100 turbine project utilizing 10 MW Jacket Foundation turbines
3. A 100 turbine project utilizing 10 MW Suction Bucket Foundation turbines

Assumptions and inputs:

- Assume all components will arrive by ship to quayside, need to unload
- Assume port location just North of Delaware city, you specify port needs for your approach (heavy lift quayside, sufficient soil support in laydown area, etc)
- You specify size of laydown area at which you can work efficiently
- You specify whether cranes would be Mammoet owned or rented
- Target time frame to complete project, based on timing of vessel and work at sea (one construction season)

The work includes:

- Unloading turbine components at the port
- Staging turbine components at the port site

- Assembling complete turbine on port land quay (only for suction bucket structure)
- Loading turbine or components onto transport vessel (only jacket structures)

Cost estimates consider:
- Personnel costs
- Equipment needed, and Ground Bearing Pressure (GBP) of each operation
- Desirable port size needed to complete project at least cost (you can specify as an output of analysis
- Separately tally cost of mobilization and demobilization; in our cost estimation we will assume that the setup is utilized for a five-year series of builds.

Deliverables:
- Port work estimate for 5 MW Piled Jacket Foundation project
- Port work estimate for 10 MW Piled Jacket Foundation Project
- Port work estimate for 10 MW Suction Bucket Project
- Elapsed time for each project
- Size of port necessary for each project.

The engineering specification of equipment and procedures for the 10 MW suction bucket port work is detailed in Appendix D.

Work at sea

For the 5 MW base build using 200 turbines, with conventional assembly at sea, costs for full 1GW build are calculated by Weeks Marine. The weather constraints for the 5 MW is based on their experience with Block Island, and thus perhaps a bit more constrained by weather than it would be at our Wilmington Canyon area. Note from the detailed description that more than one construction season is required for the 5 MW project, not meeting the goal of one construction season. Week's estimate for costs of work at sea is in Table 7.

1) A 500 ton, 335' class liftboat/jack-up will be used to install the pre-piling. The piles will be delivered on separate liftboat/jack-up feeder vessels of the same class. The liftboat will pick the pile and lower it through the template. The crane will then drive the pile and the process is repeated for the remaining three piles at each foundation location. Five liftboats / jack-ups will be needed to maintain the single season installation schedule.

2) A 1000 ton European Jack-up will be mobilized to the site. Jones Act compliant liftboats or jack-ups barges will deliver the jackets to the foreign-flagged jack-up. (The Jones act requires that shipping from US port to US port must use US-made vessels; in this case European-made jackup vessels can be used if not loaded in a US

port.) The jacket will be rigged , lifted and then lowered on to the pre-installed piles. Two jacket setting spreads will be required to maintain the schedule. The transport jack-ups will be shared with the pre-piling operation over the course of the first season.

3) A 215' Class Liftboat will be used to support the grouting operations. The Liftboat will be outfitted with a grout plant, mobilized to the site and jacked up. Grout hoses will be hooked up to the grout tubes on the jacket. The grout pumps will pump the grout to fill the annulus between the piles and the jacket. 2 grouting spreads will be required to maintain the schedule.

4) The WTGs will be installed using a 800 ton European Jack-up. The jackup vessel will be positioned at a jacket and jacked up out of the water. The WTG components will be delivered using Jones Act compliant feeder liftboats / jackups. The WTG tower sections will be lifted and set in place. The turbine generator will then be installed and finally the crew will install the blades. Four large jack-ups and eight feeder jack-ups will be used to to maintain the single season installation schedule. (Note that the WTGs are installed the year following the jacket installation)

Table 7. Cost of work at sea for Piled Jacket 5 MW.

BidItem	Bid Description	Bid Quantity	Units	Bid Total
100000	Foundation Mob/ Demob	1	LS	$9,999,285
200000	Pre-Piling Foundations	200	Ea	$157,823,622
300000	Jacket Structure	200	Ea	$216,724,665
400000	Grout Structures	200	Ea	$126,747,966
500000	WTG Installation	200	Ea	$226,627,501
700000	WTG Mob/Demob	1	LS	$144,617,555
Total				**$882,540,596**

Assumptions
- Storage/Port for component loadout will be on the Delaware River southeast of the Delaware Memorial Bridge.
- Transit speeds, loaded 5 Knots and unloaded 6 knots.
- Sea condition limitations, 2.4m Hs for transit and 1.2m Hs for jacking/moving on site.
- Grout tubes are pre-installed on the jackets.

For the Piled jacket 10 MW, with conventional assembly at sea, assembly steps are below, assumptions follow those, and costs are in Table 8 below, column labeled "Bid total"

1) A 500 ton, 335' class liftboat/jack-up will be used to install the pre-piling. The piles will be delivered on separate liftboat/jack-up feeder vessels of the same class. The liftboat will pick the pile and lower it through the template. The crane will then

drive the pile and the process is repeated for the remaining three piles at each foundation location. Three liftboats / jack-ups will be needed to maintain the single season installation schedule.

2) A 1000 ton European Jack-up will be mobilized to the site. Jones Act compliant liftboats / jack-ups will deliver the jackets to the foreign-flagged jack-up. The jacket will be rigged, lifted and then lowered on to the pre-installed piles. One jacket setting spread will be required to maintain the schedule. The transport jack-ups will be partially shared with the pre-piling operation over the course of the first season.

3) A 215' Class Liftboat will be used to support the grouting operations. The Liftboat will be outfitted with a grout plant, mobilized to the site and jacked up. Grout hoses will be hooked up to the grout tubes on the jacket. The grout pumps will pump the grout to fill the annulus between the piles and the jacket. One grouting spread will be required to maintain the schedule.

4) The WTGs will be installed using a 1500 ton European Jack-up. The jackup vessel will be positioned at a jacket and jacked up out of the water. The WTG components will be delivered using Jones Act compliant feeder jackups. The WTG tower sections will be lifted and set in place. The turbine generator will then be installed and finally the crew will install the blades. Two large jack-ups and four feeder jack-ups will be used to to maintain the single season installation schedule. (Note that the WTGs are installed the year following the jacket installation)

Assumptions
- Storage/Port for component loadout will be on the Delaware River southeast of the Delaware Memorial Bridge.
- Transit speeds, loaded 5 Knots and unloaded 6 knots.
- Sea condition limitations, 2.4m Hs for transit and 1.2m Hs for jacking/moving on site.
- Grout tubes are pre-installed on the jacket.

Table 8. Vessel work for the piled jacket with 10 MW turbine

BidItem	Bid Description	Takeoff Quantity	Units	Bid Total
100000	Foundation Mob/Demob	1	LS	$10,477,135.80
200000	Pre-Piling Foundations	100	Ea	$64,088,158.23
300000	Jacket Structure	100	Ea	$106,524,924.57
400000	Grout Structures	100	Ea	$62,509,465.41
500000	WTG Installation	100	Ea	$162,127,333.27
700000	WTG Mob/ Demob	1	LS	$69,826,447.43
Total				**$475,553,464.71**

NOTES on cost calculation:

Cranes at port will load four pilings onto a single barge, a process that will take 12 hours at port. Given that the deployment site is 113 nautical miles from the port, and the loaded transit speed is 5 knots, it is expected that the barge will take 22.5 hours to reach the 500 ton, 335' class jack-up at the installation site.

The 500 ton, 335' class jack-up takes 4.5 days to install the four pilings (which assumes a 40% weather delay) or 2.7 days in good weather. After approximately 3.375 days (or 2 days in good weather) the barge carrying the pilings can return to port since at that time the last piling has been lifted and removed from the barge, but not yet driven. (This calculation based on the installation times (4.5 days or 2.7 days in good weather) divided by 4 pilings, yielding 1.125 days per piling or 0.675 days per piling in good weather, and then multiplying by 3 pilings to determine the time until the fourth piling is lifted and removed. The barge, now unloaded, returns to port at a transit speed of 6 knots, taking 16 hours.

The vessel usage will be variable. Basic plan is to load out 4 piles per vessel in 12 hours each time a vessel comes into port. Total duration of pile loading should stretch over 7.5 months. 40% weather delay adds 1.8 days onto a 2.7 day neat schedule (.4 x 4.5 = 1.8) which gives the 4.5 day duration when weather is included.

Vessel count is one installation jackup and 3 feeder jackups, so there are 4 vessels in total. The money is in the budget for the production rates listed, but when that gets penciled out, the schedule stretches into the 2nd season if only one rig is driving all of the piles and there will be wasted time with the transport rigs. The goal is to use all of the available rigs as efficiently as possible, so we expect 2 rigs will need to be able to drive piles for a portion of the 1st season and two solely transport to make it work in the schedule.

<u>For Design 3, the suction bucket 10 MW with assembly in port</u>, the installation methods and assumptions are as follows.

Installation Methods
1) A 3500 ton shearleg vessel will load the Suction Bucket Foundation (SBF).
2) The shearleg will transport the SBF to the installation site.
3) Once properly located, the shearleg will lower the SBF to the sea floor.
4) Suction equipment will be activated pulling the SBF into the soil and anchor it to the seafloor.
5) The shearleg is then released and returns to port to load another SBF.
6) Two shearleg vessels will be used for the SBF installations to meet the single season installation schedule.
7) While the SBF installation is ongoing, a Jackup Accommodations barge will be onsite to support the crews installing the turbine blades which were attached to the WTG tower during transportation.

Assumptions
- Storage/Port for component loadout will be in Delaware City, DE.
- SBFs will always be available at the port and ready for loading and transport to the installation site when the Shearleg arrives back at the port.
- Assumed bare rent for each Shearleg is $5.83M per month. (Estimated based on $175M CAPEX)
- Blades will be attached to the WTG column and installed after Suction Bucket foundation installation. We have assumed no marine crane is required for this operation and the blade installation will be accomplished using an integrated lift system in the Nacelle.
- Transit speeds, loaded 5 Knots and unloaded 7 knots.
- Sea condition limitations, 3m Hs for transit and 1.5m for installing the suction Bucket foundation. (Notes: 1. Some team members believe that 2m Hs should be the limit for transport rather than 3m. 2. For both transport and installation, if we consider areas relevant but north of the study area, such as NY to MA, swell length could be an additional limit on marine operations, in addition to Hs and wind speed. This is not quantitatively evaluated here.)
- Installation period is April 15th through November 15th.

The suction bucket with assembly in port, costs for work at sea, as calculated based on existing vessels are in the second to last column of Table 9.

Table 9. Suction bucket with 10 MW, both Weeks' "bid total" and 6-turbine transport per text.

BidItem	Bid Description	Takeoff Quantity	Units	Bid Total (existing equipment)	Total modified for 6-turbine transport
100000	Mobilization/ Demobilization	1	LS	$16,083,046	$16,083,046
300000	Install SBF Foundation with preinstalled Turbine	100	Ea	$305,348,278	$222,904,243
400000	Install WTG Blades	100	Ea	$11,933,191	$11,933,191
Total				$333,364,515	$250,920,480

For Design 4, suction bucket 10 MW with six-turbine transport. The six-turbine transport adds an adjustment for a vessel capable of carrying six turbines per trip as calculated above, resulting in a reduction of the vessel work from 50.7 hours per one turbine to 110.7 hours for 6 turbines. This is used for our Design 4, which relaxes the requirement that all work is done with existing equipment. The one-turbine vessel required two vessels to compete 1000 MW in a construction season, here we simplistically assume that a single 6-turbine vessel would cost the same as the sum of two 1-turbine vessels. Thus, two vessels at 1 per trip is 152.1 h/turbine, versus a 6-pack vessel at 110.7 h/turbine, at approximately 73% of the time. Thus, the install estimate for the larger vessel is reduced to 73% of the existing equipment cost, as shown in the second to last column of Table 9.

Steel for jackets, piles and buckets

The mass of steel in the jacket, transition piece, and piles or buckets, is shown in Table 10, based on the detailed engineering costs for the two 10 MW structures. The 10 MW design by M&N is clearly very efficient, as lattice+piles weigh the same as the 5 MW structure.

Table 10. Foundation Steel Weights (tonnes per foundation), comparing three designs.

	Piled Jacket, 5 MW	Piled Jacket, 10 MW	Suction Bucket, 10 MW
Lattice: Worked Steel	553.4	684.3	587
Suction Bucket Steel	0	0	627
Piles: Rough/Extruded Steel	480.0	307.9	0
Transition Piece	0[1]	20	20
Total	1,033.4	1,012.2	1,234.0

[1] Transition piece included in jacket for 5 MW design.

For foundation costs calculated from steel cost estimates of $6000/tonne for worked steel used in lattice jacket, $2500/tonne for worked steel used in bucket construction, and $1500/tonne for extruded steel used in pilings. These values were provided by EEW in 2016, except costs of worked steel for buckets was provided by SPT. Note that the huge difference from pilings ($1500/t) to assembled jacket ($6000/t) is due to labor and how much is customized hand work. Thus the jacket and to some extent the buckets have the potential for substantial cost reduction (>>50% reduction) due to higher production volume, standardization, and partial automation. Costs for foundations are shown in Table 11.

Table 11. Foundation Steel Cost (per foundation and per kW), comparing three designs.

	Cost per foundation ($M)	Cost per kW ($/kW)
Piled Jacket, 5 MW	$4.04	$808.1
Piled Jacket, 10 MW	$4.62	$462.5
Suction Bucket, 10 MW	$5.15	$514.7

Electrical

Electrical engineering and cost estimate was done by CG Power Solutions. See the detailed layout, voltages and transformer specification in Appendix C. The 5 MW base design used a traditional 34.5 kV collector system and 230 kV transmission to shore.

In configuring the 10 MW turbines, available current carrying at standard 34.5 kV collector cables would have only allowed 3 or 4 10 MW turbine strings per cable. Therefore, we recommended, and CG agreed, that a 69 kV collector system should be used for the 10 MW turbine designs.

The higher voltage collector means less conductor mass per MW of capacity served —that, along with fewer connections to turbines (a 1 GW wind plant is 100 × 10 MW turbines rather than 200 × 5 MW ones) meant substantially lower cabling cost per MW of capacity for the two 10 MW turbine configurations. CG found that the electrical system for 200 × 5 MW turbines at 34.5 kV was $937.50 per kW capacity, compared with either of the 10 MW configurations at 69 kV, which cost $600/kW capacity. An additional operational savings from the higher voltage is that the 34.5 kV collector had 2.4% transmission losses, while the 69 kV cables had 1.61% losses (the latter savings are realized in our LCOE calculation, not capital cost).

The SOPO planned an analysis of the cost of HVAC converters and cable to shore compared with an HVDC at the point shown in Figure 1b. However, lack of data detail transferred from CG made this difficult to do accurately. Instead, the same team members (Ozkan and Kempton) carried out a similar analysis for offshore wind in New York (McClellan, Ozkan & Kempton, 2015). In that NY case, for a small number of wind projects, replacing AC with HVDC did not reduce cost, rather cost increased slightly (McClellan et al, Table 22). If we assumed that the HVDC backbone were already built, as we would have in this Delaware analysis, as suggested in Figure 1b, a modest cost reduction from HVDC would be likely.

Turbine, Tower, and Blades

The reference Clipper turbine for the 10 MW builds was never put into serial production and sales. Anyway, to compare the 5 and 10 MW turbines on an equivalent basis, the same metric would have to be used. Therefore, to estimate the cost of tower, nacelle, and blades, we used estimates based on expert elicitation in 2016 of developers who were getting quotations for builds in US waters, as reported in Kempton, McClellan and Ozkan (2016).

Combined cost of all components and major operations

Detailed calculations are based on analysis of existing methods and existing equipment. Of course, the piled jacket foundations have existing installation equipment that has been designed for installation with piling and lifts at sea. That equipment has been refined over three decades of OSW installations. The detailed cost analysis for the suction bucket installation was based on existing equipment and methods, including an existing vessel that can take only one assembled turbine at a time. Therefore a "adapted equipment" suction bucket cost has also been calculated as Design 4, based on a 6-turbine carrier vessel as described above. (As noted above and in Appendix F, the other cost saving approach would be to use simpler, lower cost vessels but retaining one-turbine carry per vessel.) For the adapted equipment, Valpy and English (2014) have estimated that using "whole turbine install" and "float and sink", when installation equipment and processes are adapted to this approach, will yield total capital cost savings of 4.5%, which would be $139.30 of the total capital costs in the table. To achieve a suction bucket estimate with more adapted equipment, the $139.30 would be realized in foundation, work at sea and port work (apportioned here as 17.4% savings of each), not turbine or electrical cost. The vessel improvement for adapted equipment has already been directly estimated based on use of a multi-turbine vessel, so the 17.4% savings is calculated only for capital cost of foundation and port work. This much saving is plausible because production of more foundations will lead to more use of jigs and lower cost to work the steel, and port work similarly will gain from repeating processes and standardization.

Table 10 compares capital costs of all four design methods. Look first at the total capital cost and percentage reduction on the right two columns of all four lines of Table 10. Notice that there is a substantial cost reduction in going from the 5 MW to the 10 MW turbines. Next down, going from the 10 MW piled jacket to the 10 MW suction bucket installation with existing equipment achieves only a small additional cost reduction. Moving to the last line, further cost reduction using equipment designed for the purpose and with expected economy as equipment and processes adjust to this method, compare to the base, yields a combined capital cost of 63% of the base design (47% reduction).

Table 10. Capital cost of all components. All figures in $/kW capacity

Design	Foundation	Work at sea	Port Work	Turbine and Tower	Electrical Infrastructure	Total Capital Cost [1]	% capital cost
Piled Jacket, 5 MW turbine	808.08	882.50	25.20	1952.00	937.50	4605.28	100%
Piled Jacket, 10 MW turbine	462.46	465.60	23.50	1615.00	600.00	3166.56	69%
Suction Bucket jacket, 10 MW turbine (existing equipment & processes)	514.65	333.40	32.55	1615.00	600.00	3095.60	67%
Suction Bucket jacket, 10 MW turbine (adapted equipment)	425.10	251.92[2]	26.89	1615.00	600.00	2918.91	63%

[1]Total capital costs does not include development, financing, insurance, engineering and management, contingency, or decommissioning costs, nor does it include costs of pre-development studies. These are covered in the LCOE calculation.
[2] Based on $251.92 for the 6-turbine vessel.

Next, comparing by columns, compare port work with work at sea. Comparing the 2nd, 3rd and 4th lines of the two 10MW turbines, we see that on-shore assembly increases the cost of work in port, but that higher cost in port is overwhelmed by the substantial reduction in work at sea, yielding a net savings for the in-port assembly.

The three pie charts in Figure 12 compare capital costs of Designs 1, 2 & 4: the 5 MW piled jacket base design, the 10 MW suction bucket with onshore assembly using existing equipment, then the same with adapted equipment. Savings are shown in grey. The slices of the pie are labelled with the $/kW capital cost.

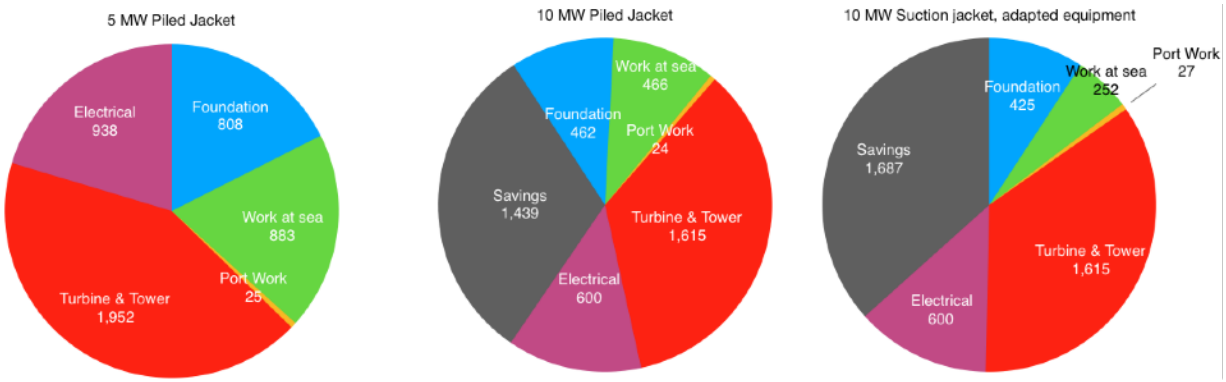


Figure 12. Capital costs of 5 MW base design (left), 10 MW suction bucket with existing equipment (middle) and 10 MW suction bucket with adapted equipment (right). Numbers are $/kW capacity, gray shows savings over base design.

Levelized Cost of Energy Calculation Methods

Calculations of the levelized cost of energy use the capital costs developed from the engineering analysis in the previous section. The component costs, LCOE results, and percentage changes across designs are shown in Table 13.

Amounts used for finance, development and other similar costs are taken from MA report by Kempton, McClellan and Ozkan (2016). However, offshore wind costs and bid prices have dropped more rapidly than forecast by Kempton et al in early 2016, and, the turbines we model have rotor diameters designed for the North Sea and are a bit small (lower CF) than optimum for the case study location. Thus, the LCOE calculations in Table 13 are unrealistically high, so are best used as percentages—that is, the calculated energy costs should not be used as $/MWh. Rather, the reader should use 100% as the current price, and look across the bottom-most column in Table 13 for the percentage changes in cost of energy due to each design change.

When calculating O&M, a 25% reduction per kW is predicted due to turbine increase from 5 MW to 10 MW; following Hofmann and Sperstad (2014), this reduction assumes that the size scaling does not lead to higher failure rates or longer down time. Although there are 50% as many turbines, the O&M reduction is less than 50%, because some large part replacements would be more difficult or slower.

When calculating power output, we use exactly the same power curve for the 5 MW turbine but just double the output for the 10 MW. This is not intended to be a precise calculation of power across turbine models, rather these simplifications focus the comparison of LCOE reductions across design concepts.

Table 13. LCOE. To compare row LCOEs of each design, use the percents across the lowes

	Cont.	5 MW Piled Jacket	10 MW Piled Jacket	10 MW Suction Bucket, Existing Equipment	10 MW Suction Bucket, Adapted equipment
Capital Costs ($/kW)					
Turbine and Nacelle ($/kW)		$1,952	$1,615	$1,615	$1,615
Foundation ($/kW)		$808	$462	$515	$425
Sea Work ($/kW)		$883	$466	$333	$252
Post Work ($/kW)		$25	$24	$33	$27
Electrical ($/kW)		$938	$600	$600	$600
Total Component & Installation ($/kW)		**$4,605**	**$3,167**	**$3,096**	**$2,919**
Development ($/kW)	5%	$230	$158	$155	$146
Total Cost ($/kW)		**$4,836**	**$3,325**	**$3,250**	**$3,065**
Contingency ($/kW)	10%	$484	$332	$325	$306
Total Cost inc. Contingency ($/kW)		**$5,319**	**$3,657**	**$3,575**	**$3,371**
Fixed O&M Expenses ($/kW-yr)		$95.45	$71.59	$71.59	$71.59
Contingency ($/kW-yr)	10%	$9.55	$7.16	$7.16	$7.16
Fixed O&M Expenses + Contingency ($/kW-yr		**$105.00**	**$78.75**	**$78.75**	**$78.75**
Project Info					
Installed Capacity (MW)		1000	1000	1000	1000
Turbine Size (MW)		5	10	10	10
Number of Turbines		200	100	100	100
Project Useful Life (yr)		25	25	25	25
Gross Capacity Factor (%)		46.9%	46.9%	46.9%	46.9%
Technical Losses inc. Wake Effects (%)		16.8%	16.8%	16.8%	16.8%
Transmission Losses (%)		2.40%	1.61%	1.61%	1.61%
Net Capacity Factor (%)		38.1%	38.4%	38.4%	38.4%
Financing Assumptions					
Percent Debt (%)		65%	65%	65%	65%
Precent Equity (%)		35%	35%	35%	35%
Debt Terms (Years)		15	15	15	15
Interest Rate on Debt Terms (%)		6%	6%	6%	6%
Target After Tax Equity IRR (%)		8%	8%	8%	8%
Capital Costs ($)					
Generation Equipment Cost ($)		$2,147,200,	$1,776,500,0	$1,776,500,000	$1,776,500,000
Balance of Plant ($)		$1,887,358,	$1,046,716,0	$968,660,000	$774,301,000
Interconnection ($)		$1,031,250,	$660,000,000	$660,000,000	$660,000,000
Development Costs & Fees ($)		$253,290,40	$174,160,800	$170,258,000	$160,540,050
Total Capital Cost ($)		**$5,319,098,**	**$3,657,376,8**	**$3,575,418,000**	**$3,371,341,050**
Decommissioning ($/kW) (inc. scrap value)		$20	$30	$10	$10
Decommissioning ($) (inc. scrap value)		$20,000,000	$30,000,000	$10,000,000	$10,000,000
LCOE ($/MWh)		**$200.5**	**$138.5**	**$135.5**	**$129.5**
Percentage of base case LCOE		**100%**	**69.1%**	**67.6%**	**64.6%**

Comparing LCOE of four designs

From the LCOE analysis, we see that the base design's energy cost (starting at 100%), is reduced to 67.6% for design 3, the recommended design and installation process, a 32.4% reduction. With equipment and processes more optimized for this design method (Design 4), the price is 64.6% of the base, a total of 35.4% reduction. Again, the specific $/MWh figures are dependent upon the many variables that enter into project cost, so the last row with % of base design energy cost is a more appropriate benchmark to compare designs. As shown with the capital cost savings, note that the largest saving in LCOE would be achieved by shifting from 5 MW to 10 MW turbine. Our integrated design, with adapted equipment, yields an additional 4.5% reduction in LCOE.

The following section describes further cost reductions that would be expected but have not been incorporated into our cost reduction calculations in Table 13. For example, our design may enable the shift to 15 MW and to 20 MW turbines, without requiring either port modification or expensive new jack-up vessels, with corresponding additional cost reductions of larger turbines not analyzed here.

Scaling estimates for lift, hook height, and cost up to 20MW turbines

Here we consider whether larger turbines can be installed by the method selected, Designs 3 and 4, for the 10 MW. This is not a "fifth Design" because larger than 10 MW turbines do not exist today and we cannot do either engineering or economic analysis. Rather, we here make scaling approximations to show that Design 4 should be expandable to larger turbines. In this section we consider whether this method could be adapted to 20 MW turbines, as might exist in roughly a 10-12 year time frame. The 20 MW estimation is based on very simplified scaling, not on detailed engineering like Designs 1 through 3. However it is illustrative of the adaptability of the selected method to future technologies.

For the subsea structure, SPT has found that a doubling of turbine capacity requires a 1.4 to 1.5 increased subsea structure mass with the same principal design foreseen. Here we more conservatively estimate that doubling the the turbine capacity, from 10 MW to 20 MW, would require about a 1.6 multiple in the mass of the tri-bucket jacket structure. Design 3, the 10 MW fully assembled structure—jacket, turbine and blades—is 2303 tonnes, so assuming a simple mass scaling by 1.6 for all components would yield 3685 tonne for a 20 MW turbine. For the in-port assembly, most of the lifts use less than 50% of the equipment lift or carrying capacity, so an estimated 1.6 scaling of parts for the 20MW turbine shows that all in-port lifts could be carried out with the same in-port equipment.

Sea work could use a similar vessel, the Gulliver. The Gulliver has a lift capability of 4,000 tonne, more than the full 20MW structure. Although its lift capacity is above the 3685 tonne of the 20 MW structure, considering crane reach

and the need to maintain safe margins in transit, a somewhat higher lift capacity vessel would be needed, possibly of the same design.

The lift height is set by the nacelle, not the top of the blade. In operation at sea, to maintain under-passage clearance for passing ships, the hub must be higher by the same amount as each blade is longer. Our specified 10 MW design blade is 72m length, with rotor diameter 150m, so the blade length is 48% of diameter (allowing for hub). Highest lift in port for 10MW is 180m. Since power captured goes with r^2, a proportional 20 MW machine would require swept diameter of 212 m thus a blade of 102 m. Thus by simple scaling the 20 MW machine would require nacelle lift of 52 m added for longer blade, plus perhaps 5 m for a taller nacelle, for a total lift 57 m higher than the detailed Design 3. Thus the 20 MW in-port assembly max lift height would be 180M+57m= 237m. Such cranes are already available today, such as the Liebherr - LR 13000, with a hoist height of 248 m and with a load capacity of 3,000 tonne.

To make a simplified scaling of cost, we draw from the costs in Table 10, which show the overall capital costs per kW when changing from 5 MW to 10 MW turbine. This includes all equipment and installation, and comparing with the same piled jacket foundation. Total capital costs are reduced from $4605/kW to $3165/kW, a substantial 31% reduction in per-kW cost, and we project a similar saving from moving from 10 MW to 20MW.

In short, with adjustments in some equipment, the selected Design 3 and its installation method appears usable with a 20 MW turbine. Without any other technology improvements other than this size, an approximation based on 5 - 10 MW scaling suggests that using this method with a 20 MW turbine could yield an additional 31% reduction in cost per kW. This approximation suggests that there is a substantial potential for cost reductions by adopting our proposed methods with today's turbines, and thus being able to achieve more cost savings by scaling continuously up to 20 MW as future turbines become available.

Additional Cost Savings from Integrated Design Not Calculated here

The cost calculations above do not reflect all cost reductions likely to be achieved in practice, as suction bucket and in-port assembly become industrialized. Additional cost savings, real and substantial but not quantified here, include:

- No pile-driving sound impact on marine mammals; no need for spotters.
- No unscheduled downtime for mammal passage.
- Seabed-placed CPT or acoustic scan sufficient;
- Significantly lower risk of worker injury or death because most construction is done on land
- At decommissioning, sub-floor structure can be removed completely, no remaining materials.
- Amenable to further serial processes and cost reduction

- Permanent, fixed-location cranes in port,
- Further commissioning in port,
- Co-location of component fabrication or assembly,
- Substantial further industrialization of assembly.

Conclusion

We here created an integrated design process, with contractors from each speciality involved in offshore wind deployment, and using site-specific, science-based data on bathymetry, shelf geology, wind resources, and sea conditions. When evaluated on cost, deployment speed, and feasibility, the result was a lower-cost, faster to install structure and method for deployment of offshore wind. The traditional method (here Design 1 or base case) uses an expensive jackup vessel with (relatively) low-weight-capacity crane, takes pieces to the site, and builds by adding one piece at a time offshore. In the base case, the problem of lifting from a vessel to a stationary, bottom-mounted platform is solved by the use of a jackup vessel, costing in vessel investment, time at sea per turbine, and exposure of workers to more hazardous and longer time at sea.

Three methods were evaluated in detail. The lowest-cost method, the "Design 3" that we now recommend, assembles all turbine and support structure components on land, in the port. The port crane requires higher reach than would be needed offshore (because the height of the subsea structure is added), but the port crane requires no higher lifting capacity than the traditional method. (Heavy load bearing of the full assembly in port is entirely done by SPMTs). The selected method uses 10 MW turbines with 69 kV array voltage, both larger than 2017 standard practice, but both are directions the industry has begun to move anyway, during the course of this project. We deploy using a floating (DP2) vessel with an on-board sheer leg crane requiring only half the hook height of the port lifts but requiring sufficient lifting capacity for the total assembly. The crane vessel picks the entire structure off SPMTs on the quay, carries out, and places on the sea floor. The problem of assembling a bottom mounted (stationary) structure from a floating vessel is solved by making only one placement from the floating vessel, the initial placement of the structure onto the soft bottom. No jackup vessel is needed for pile driving because there is no pile driving. On site at sea, the blades are already mounted (on the tower), thus their lift into place is entirely accomplished with winches in the nacelle, lifting from stationary tower to stationary hub.

An existing vessel was specified for the floating, offshore heavy lift. However, multiple purpose-built vessels are suggested in Appendix F if the industry were to build a vessel for this purpose, which would further reduce capital cost and LCOE. The capital cost of this vessel would also be significantly less than that of a jackup capable of a 10 MW turbine install. For initial projects, we also outline an approach to refitting a barge, at considerably lower cost than a new vessel.

As noted, our proposed method has advantages in vessel cost, less costly pre-construction work (shallower subsea profile, with CPT replacing most boring), reduced time, complexity and cost of construction at sea, better worker safety, and

reduced environmental impacts (due to no pile driving and complete removal at end of life). Perhaps most important, the processes in our proposed method are amenable to industrialization of the offshore wind production process, with attendant increase in volume and lowering of cost. The assembly process is like mass production in a factory, unlike today's practice which is like site-building a custom home. The US Wartime production of Liberty Ships illustrates the power of this approach to reduce cost and construction time well beyond that estimated here. Equally important, this method will extend to new turbines families, for example a simple calculation suggests these methods, and much of the same equipment, can deploy a 20 MW turbine, yielding an estimated further 31% reduction in cost.

Acknowledgment

We appreciate suggestions and improvement to this manuscript by Ketil Arveson, Henrik Carstens and Jonas Wittrup Jensen at Ørsted, Alana Duerr, Michael Hahn, Walt Musial and colleagues at NREL WTC, Gary Norton, Søren Juel Petersen and colleagues at Rambøll, Jayce Philpott, Aaron Smith and several commentators at conference presentations.

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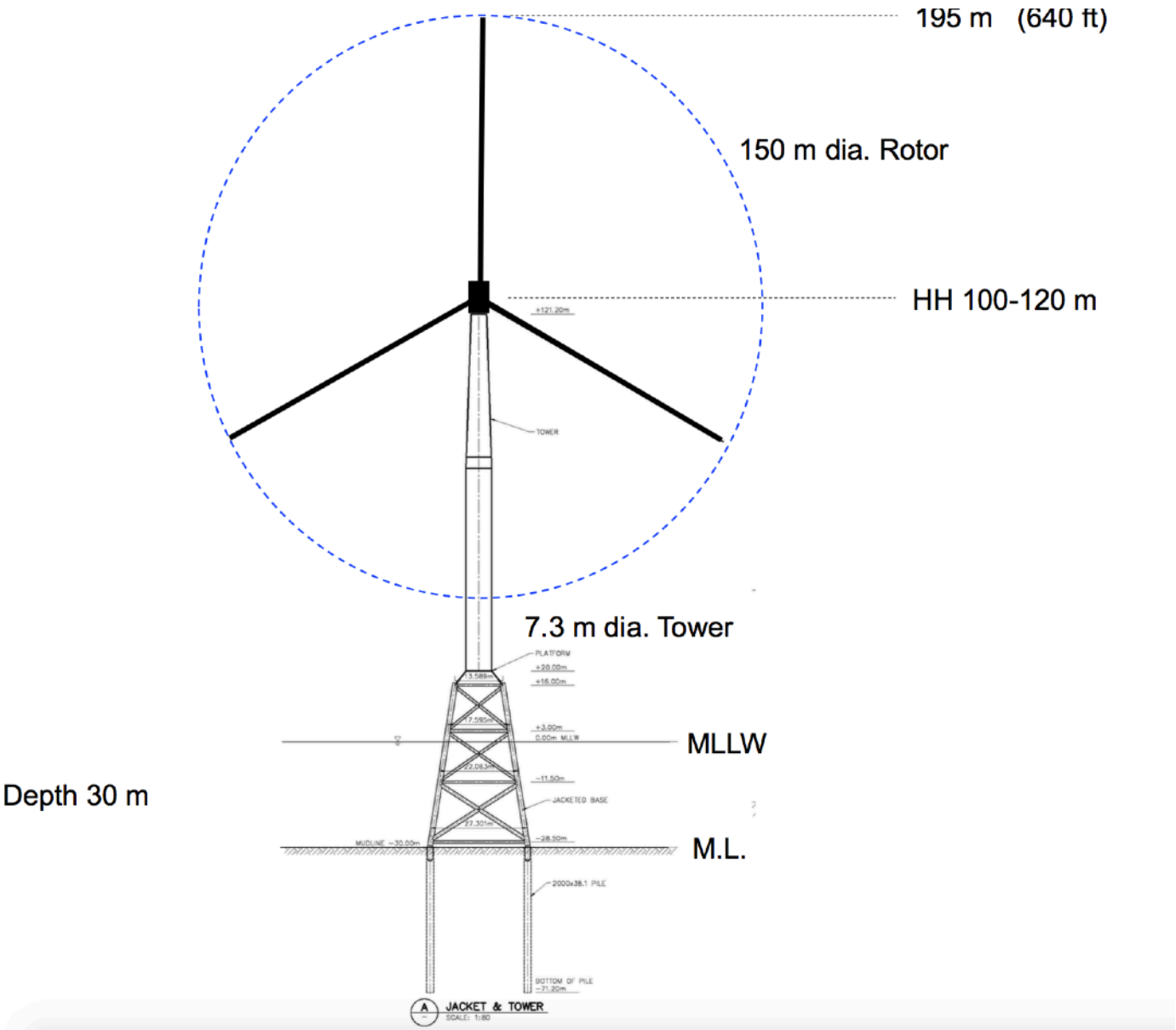
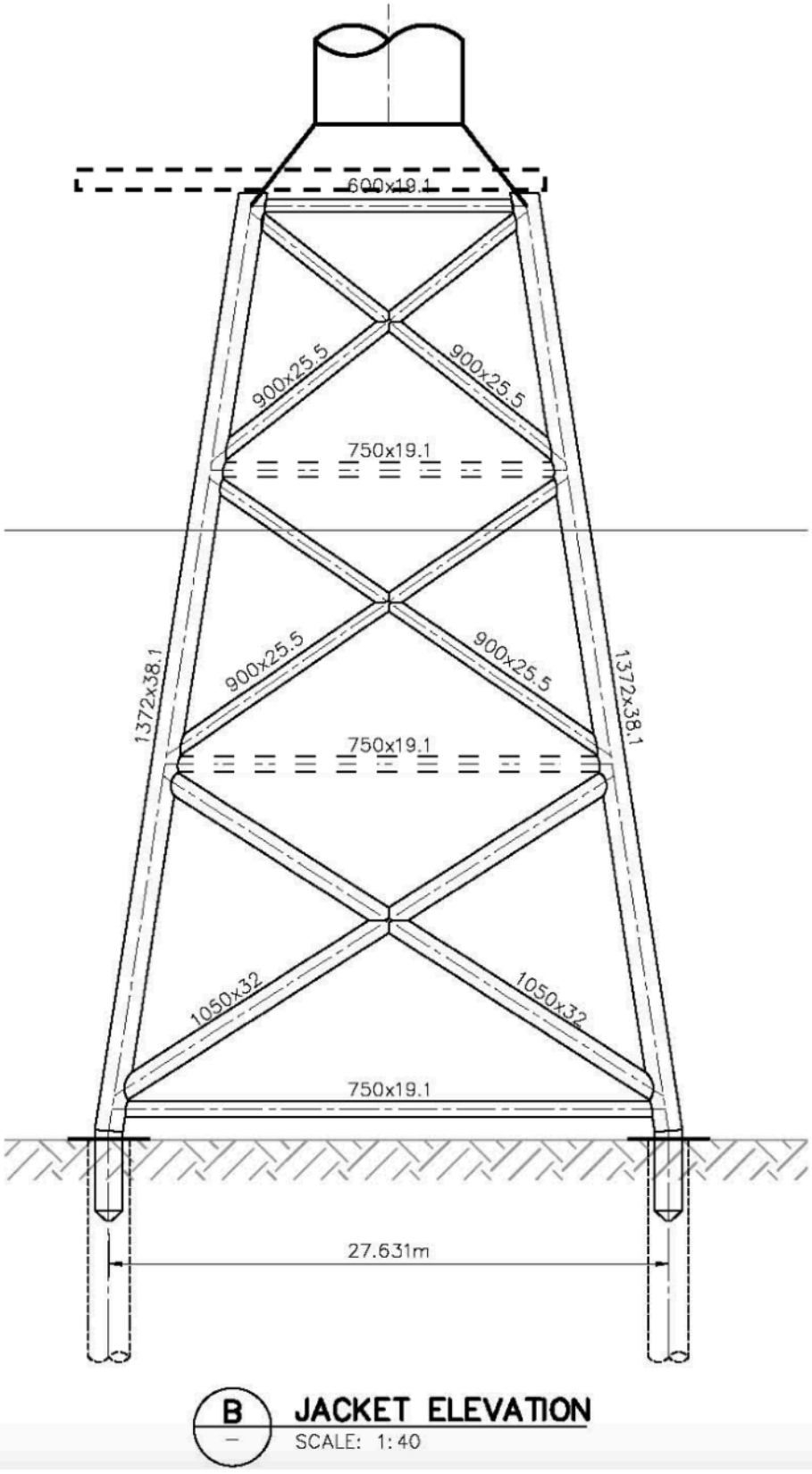
Appendices

A. Piled Jacket Structure

The Piled Jacket for the 10 MW turbine was designed for this project by Moffatt & Nichol, with Gerry Houlahan lead. Both jacket designers (Moffatt & Nichol and SPT) conducted static and dynamic analysis to insure that the subsea structure would support the loads of the 10 MW turbine, given the wind conditions and the wave and currents at the ocean site designated. For the piled jacket, the structure and mass analysis is shown but not all load analysis.



Entire structure with turbine, tower, jacket, and piles, installed in seabed.
Piled jacket structure, member sizes and configuration



Piled jacket structure, weights of each member

	length (mm)	size	unit weight (KN/m^3)	total weight (KN)	Mass (t)	
Legs	46650	1372x 38.1	78	2324		
anodes				26		
			SUM	**2349**	**239.6**	
Beams	13600	600 x 19.1	78	148		
	16200	750 x 19.1	78	222		
	22100	750 x 19.1	78	302		
	26000	750 x 19.1	78	356		
anodes				26		
			SUM	**1053**	**107.4**	
X braces	18400	900 x 25.5	78	804		
	22600	900 x 25.5	78	988		
	28100	1050 x 32	78	1794		
anodes				77		
			SUM	**2675**	**272.9**	
K braces	15200	750 x 19.1	78	104		
	18112	750 x 19.1	78	124		
	24710	750 x 19.1	78	169		
	29100	751 x 19.1	79	202		
anodes				13		
			SUM	**611**	**62.3**	
Jacket Total (Excl Contingency and Transition)				6688	**682.2**	
Piles	41200	2000 x 38.1	78	**3019**	**307.9**	**4 off**

B. Suction bucket jacket structure

The three-bucket lattice suction jacket structure was designed for this project by SPT Offshore (Oene Jeljer Dijkstra, design lead), based on prior designs by SPT. The loads from the turbine are based on detailed engineering specifications for a 10 MW offshore turbine designed by Clipper Marine, the "Britannia". The bottom mounting was designed for 20 and 40 m water depth, per the project specifications, and for the soils as determined by the geological data presented earlier.

Item Number	Title	Quantity	Mass Quantity
1	1700.0X25.0	3	49462 kg
2	Plate 50	2	53740 kg
3	Plate 20	3	34262 kg
4	1700.0X25.0	3	30911 kg
5	1700.0X25.0	3	128705 kg
6	Pile Dia 12 m, H 70 m	3	626521 kg
7	0800.0x25.0	3	25572 kg
10	0800.0x25.0	3	25655 kg
11	0800.0x25.0	3	2146 kg
12	0800.0x25.0	3	2146 kg
15	0600.0x45.0	3	13263 kg
16	0600.0x45.0	4	18740 kg
17	0600.0x45.0	3	771 kg
18	0700.0x45.0	3	28504 kg
19	0700.0x45.0	3	20597 kg
20	0700.0x45.0	3	25389 kg
21	0700.0x45.0	3	25565 kg
22	1700.0x50.0	3	36543 kg
23	7300.0X70.0	1	99633 kg
24	0600.0x45.0	6	22074 kg

General Information

Description	
Substructure	607 Ton
Piles	627 Ton
Total	1234 Ton

SPT Offshore

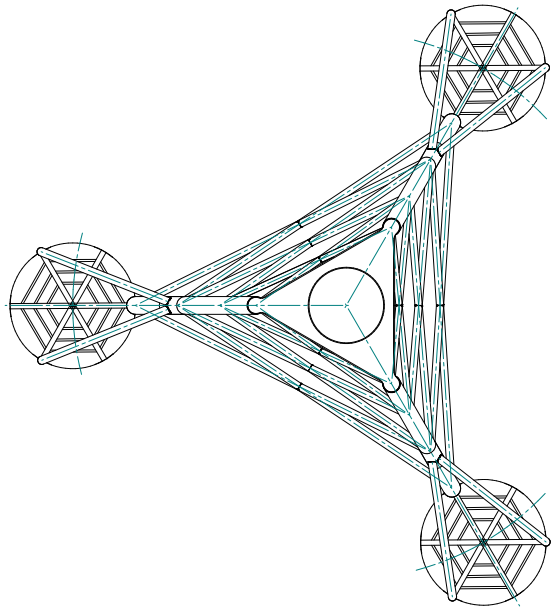
Client: University of Delaware

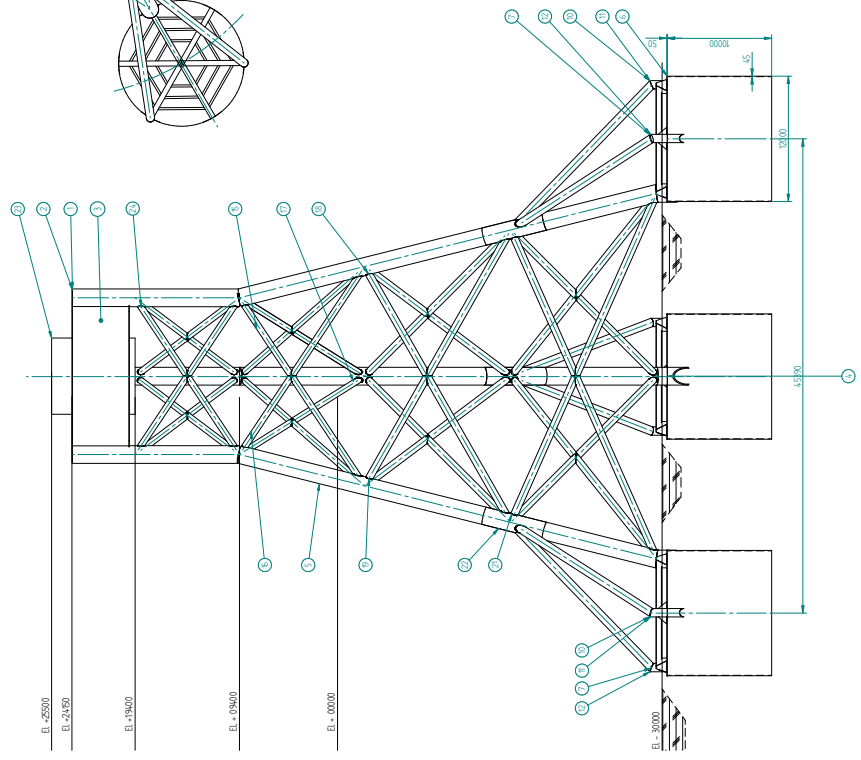
Project: Wilmington Canyon Offshore Wind Farm

Title: Substructure
General Arrangement

2012300l.001

A1

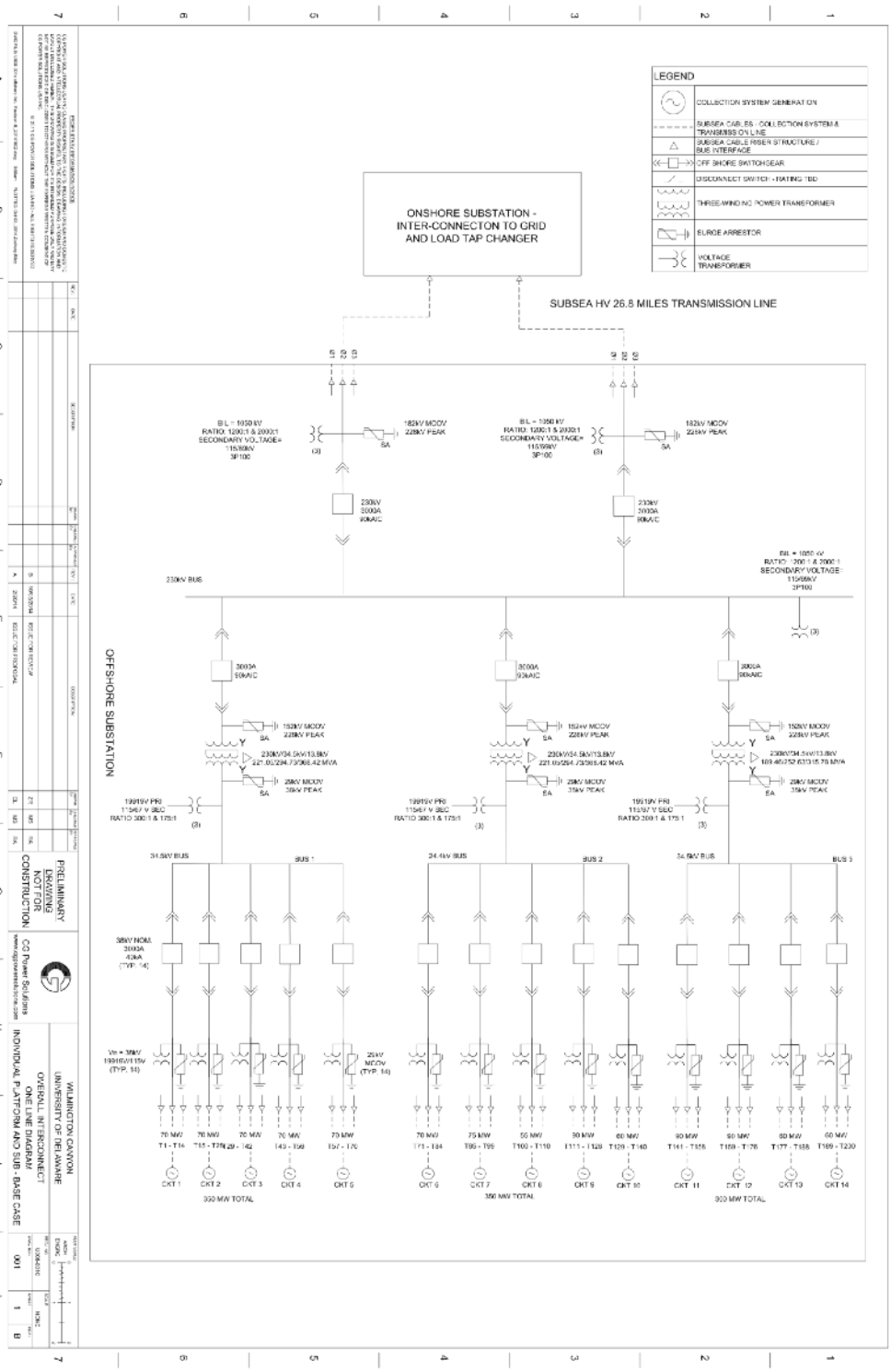




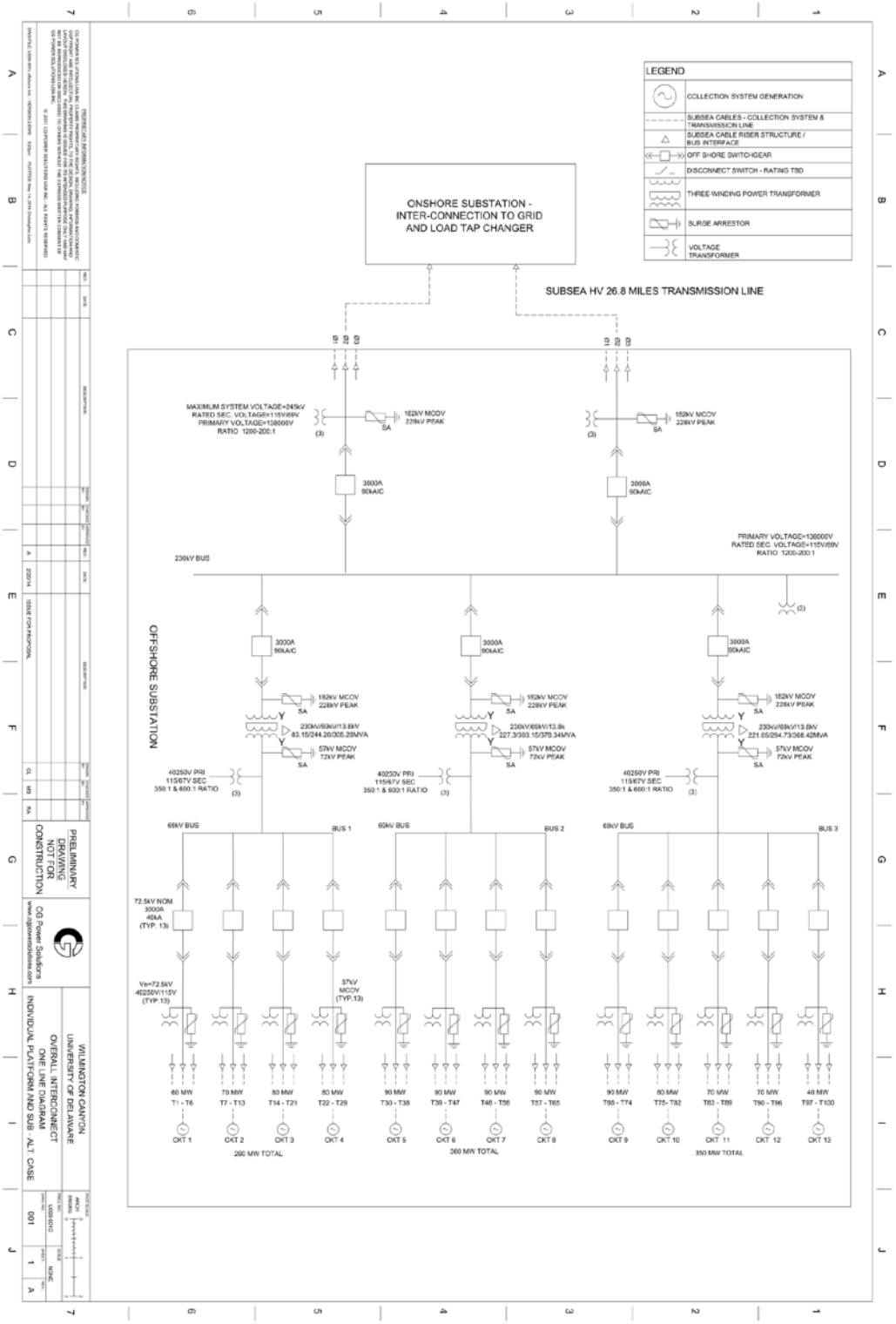
C. Electrical array

The electrical collection array for both 5 MW turbines and 10 MW turbines was designed and cost estimated by CG Power Solutions. Final cost figures are in the text, here we provide the detailed design drawings used. A primary difference in increasing the turbine size from 5 MW to 10 MW is that a traditional collector array cable voltage like 34 kV is no longer reasonable. Rather a 69 kV array is used in this design.

5 MW turbines, 34 kV array cable



10 MW turbines, 69 kV array cable



D. In-Port transport and assembly

Handling in port was designed and estimated by Mammoet. For the reference jacket assemblies with offshore assembly, both 5MW and 10 MW, Mammoet estimated loading of materials from parts transport into the laydown area, and then loading the materials from laydown onto a jackup vessel. For the 10MW jacket with assembly in port, Mammoet specified equipment and estimated the cost of assembly in port and lift onto the transport vessel.

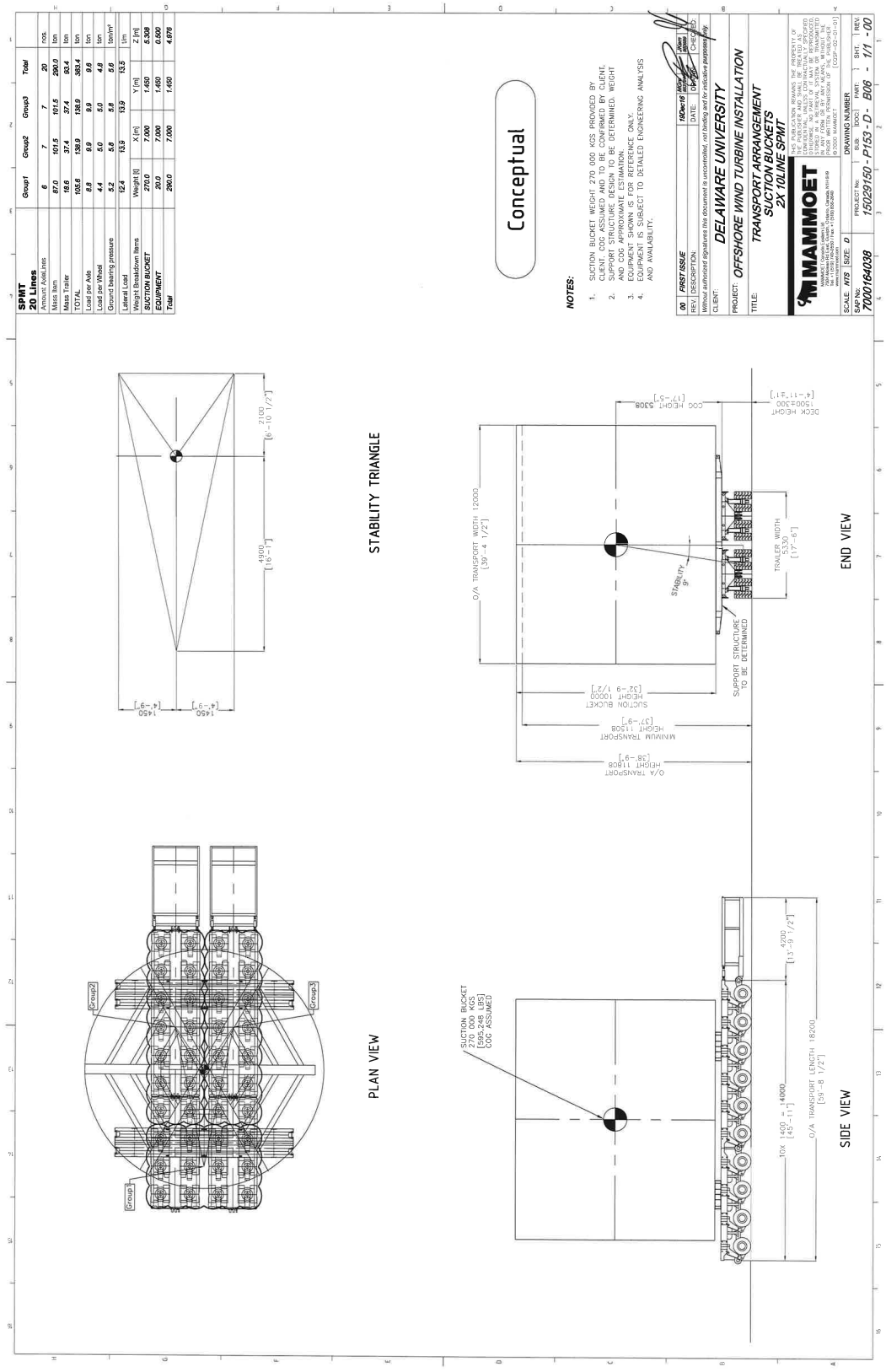
These are used for the "port work" part of the capital cost. The loading of parts from transport into the laydown area and from laydown area to jackup are conventional and are not itemized here. The 10 MW suction bucket with assembly in port and lift to vessel is un-conventional and needed to be more carefully investigated for feasibility and estimated closely. The equipment specified and requirements are specified here.

This appendix includes the drawings, with equipment to be used and ground bearing pressure calculations for the in-port assembly process for the 10 MW suction bucket design. In assembly order, indexed by the last two digits of the Mammoet drawings, these are:

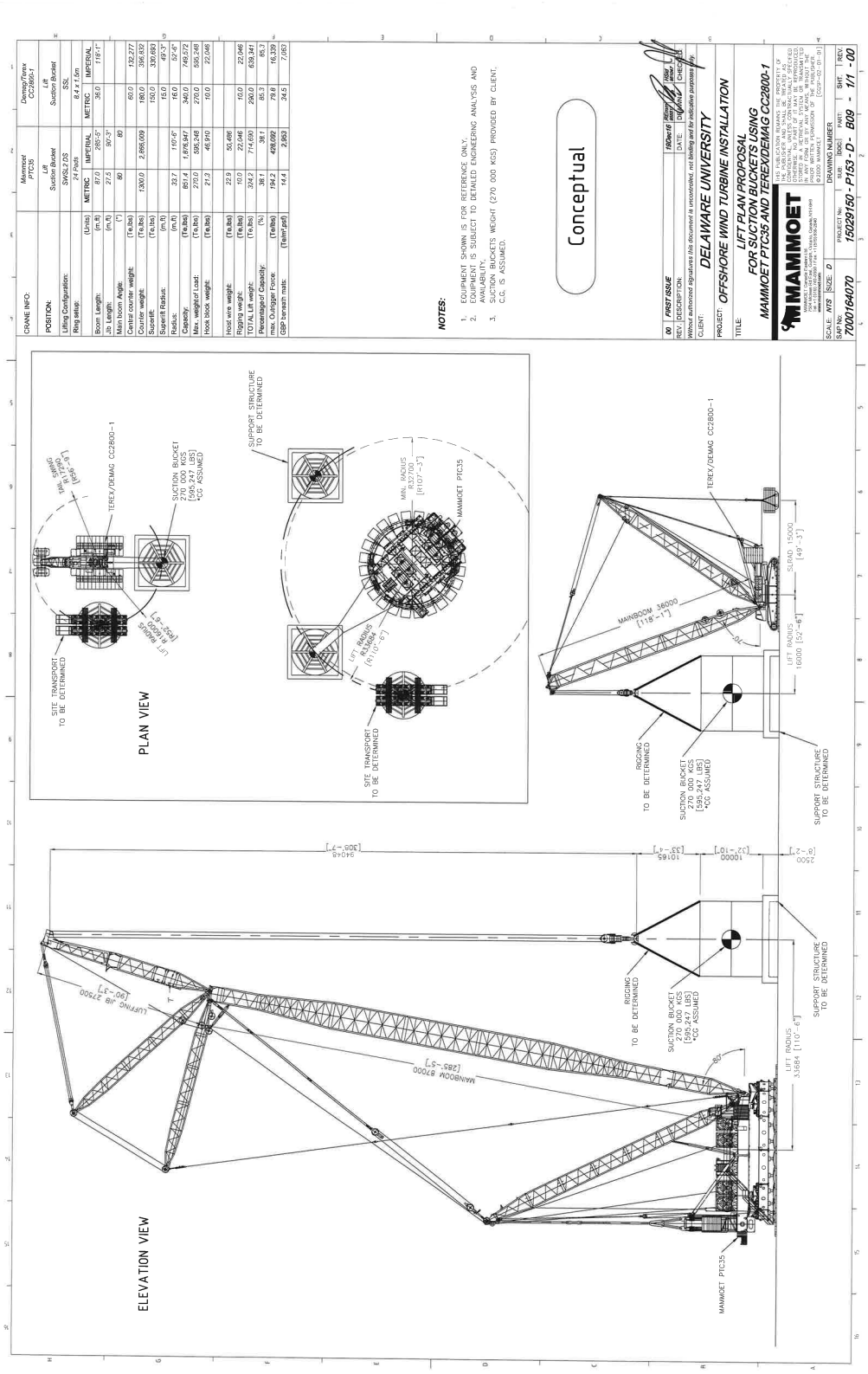
Move bucket to assembly	B06
Bucket lift for placement	B09
Move lattice to assembly	B05
Lattice lift (no buckets)	B01
Move tower section to assembly	B04
Blade transport	B08
Move nacelle to assembly	B07
Tower, Blade and Nacelle lift	B02
Move entire structure from assembly	B03

The last page of this appendix, following the equipment and lift drawings, is a plan of the one US offshore wind deployment port, the New Bedford Marine Commerce Terminal. Although this is not close to the deployment area calculated for this project, as noted the geological conditions would also allow our structure and installation in that area, and as an existing port it is a realistic check on the practicality of the ground-bearing pressure and other requirements of our selected methods.

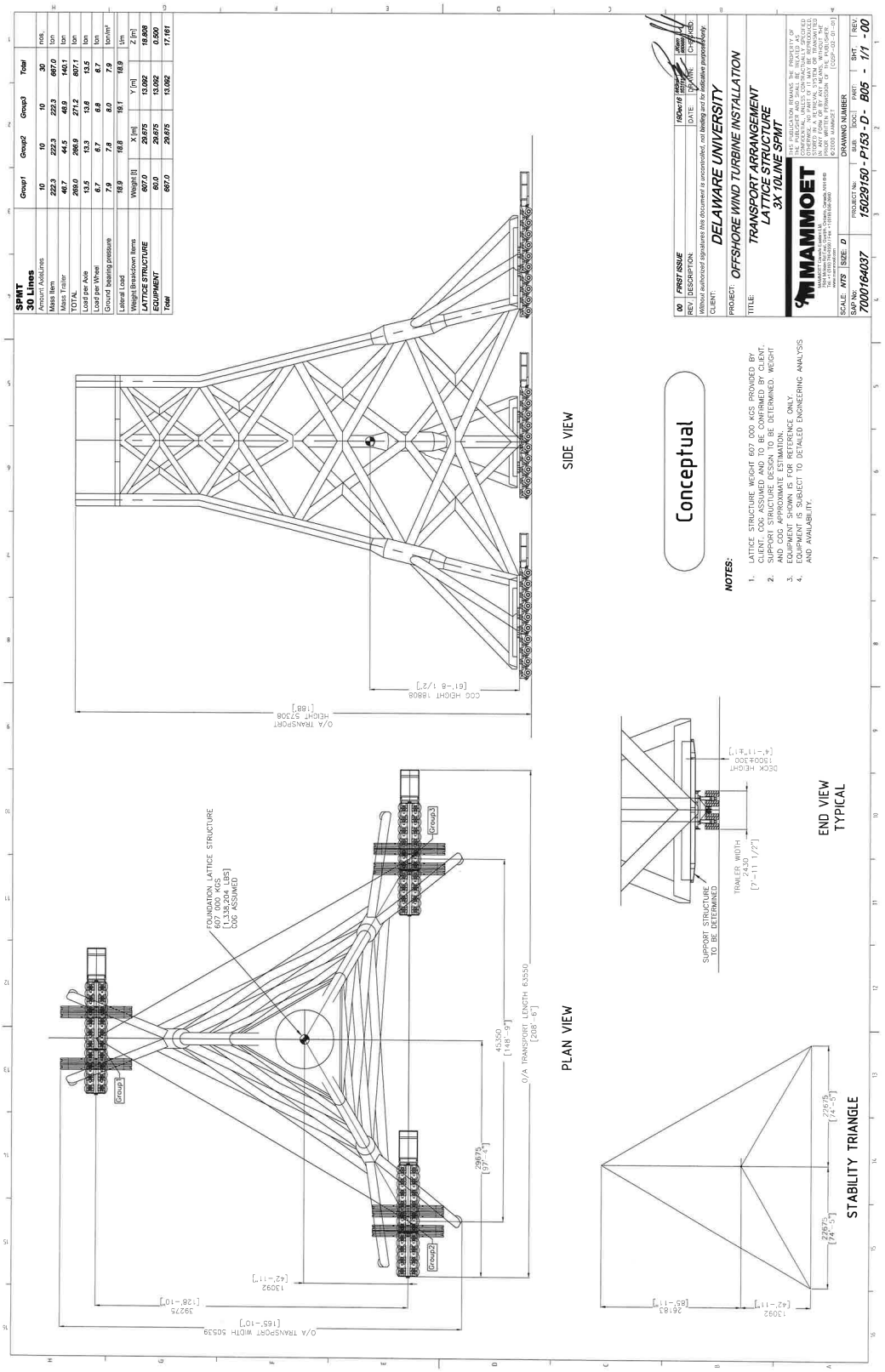
Move bucket to assembly B06



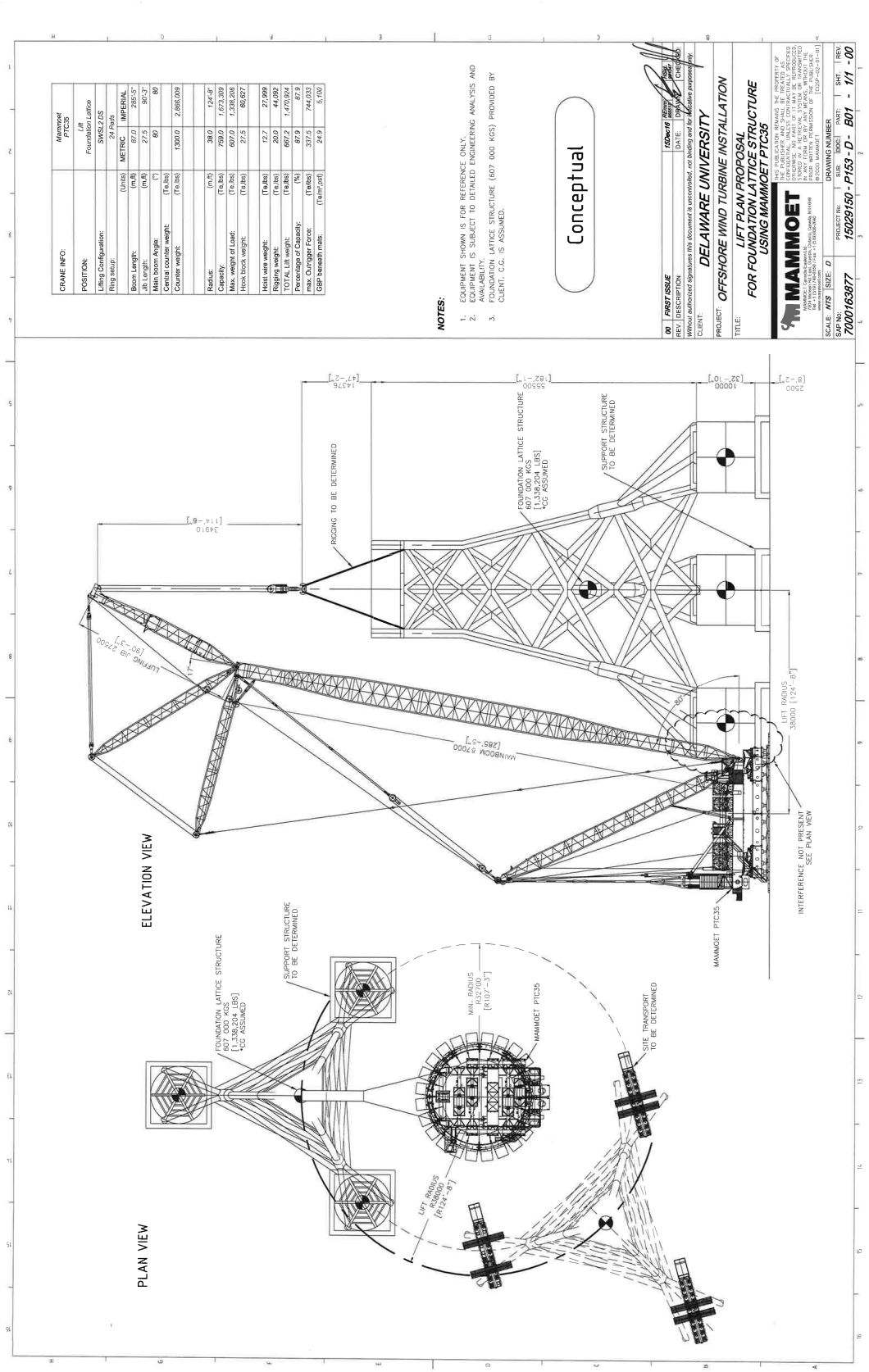
Bucket lift for placement B09



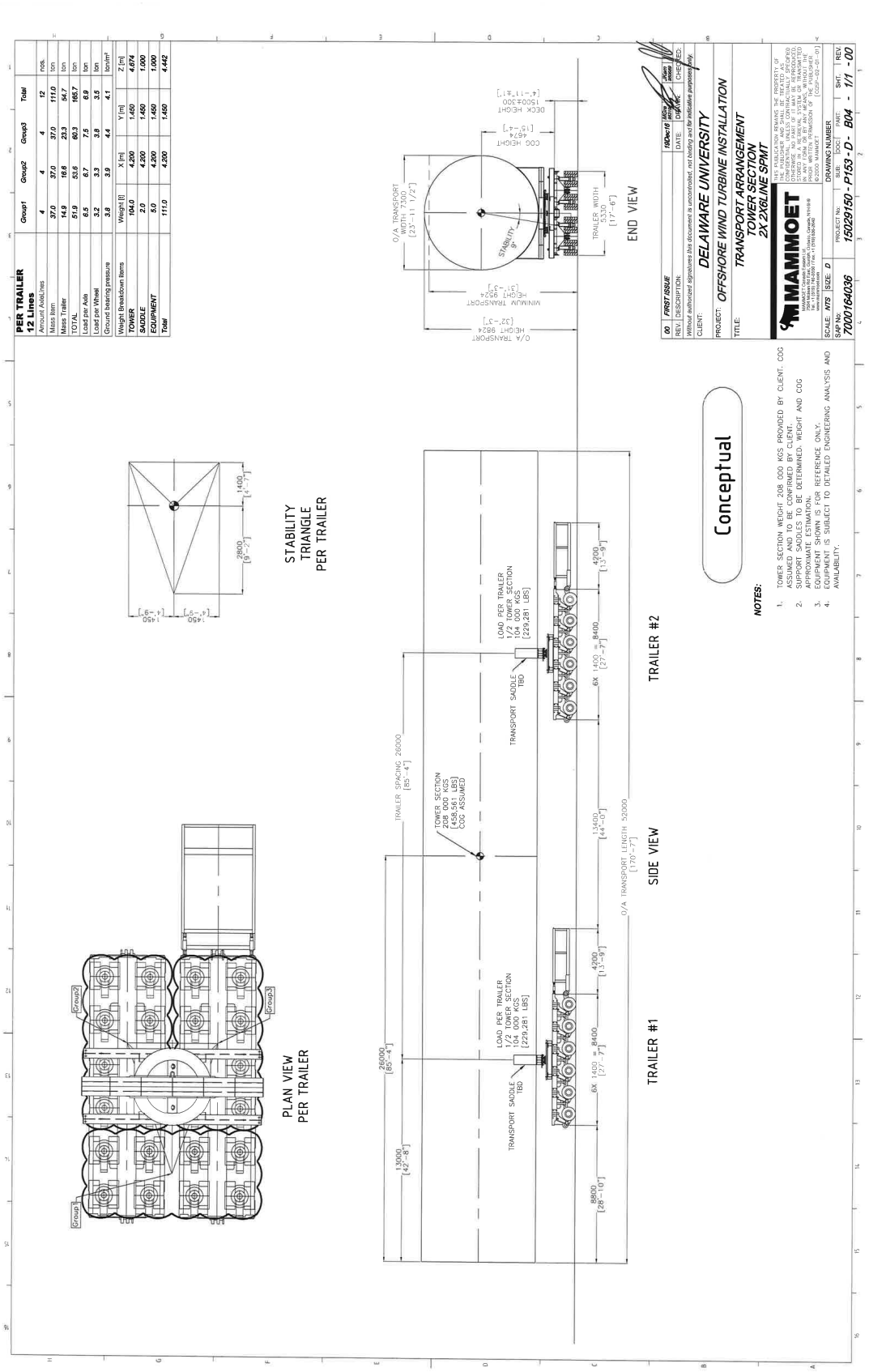
Move lattice to assembly B05



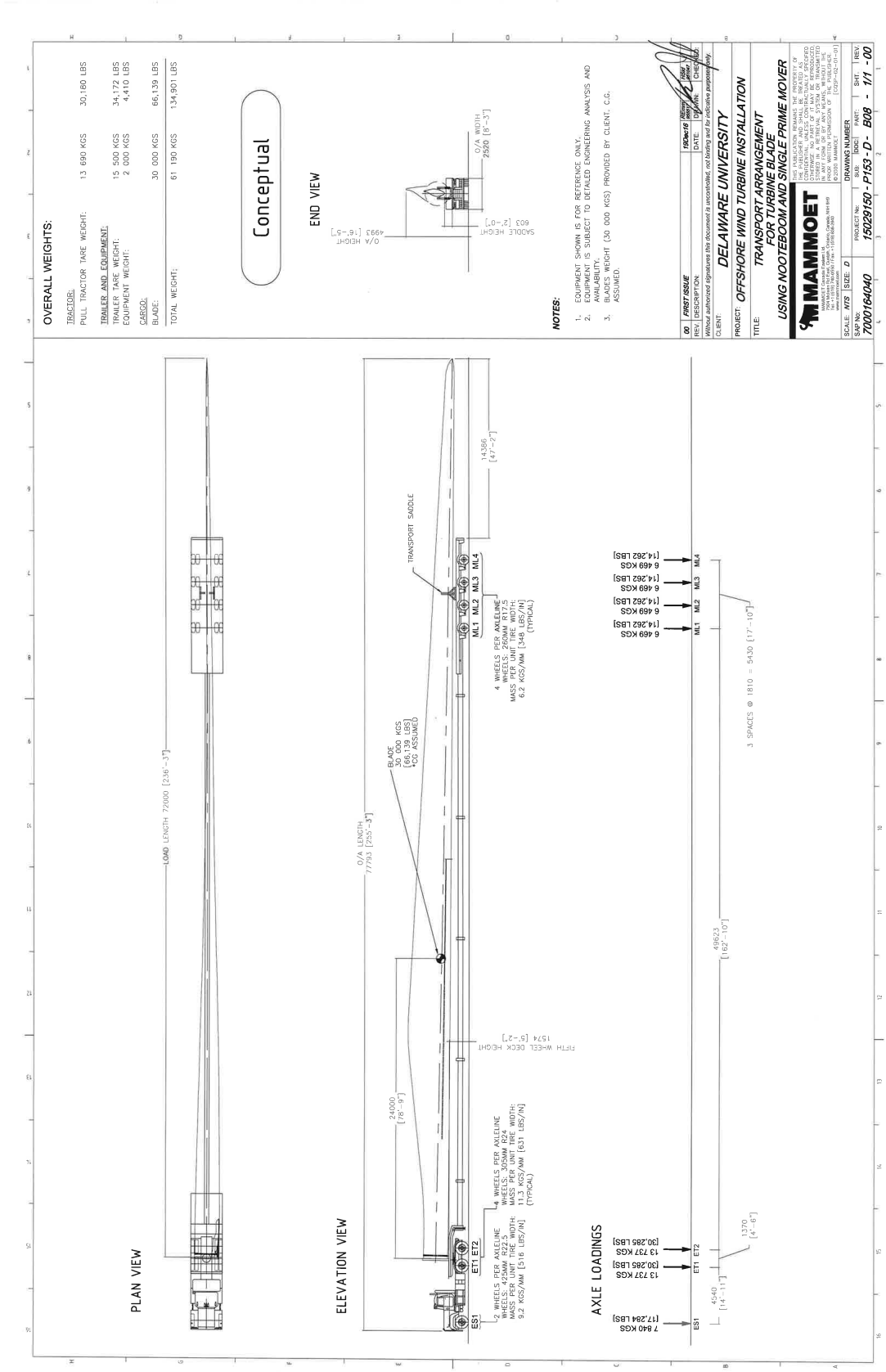
Lattice lift (no buckets) B01



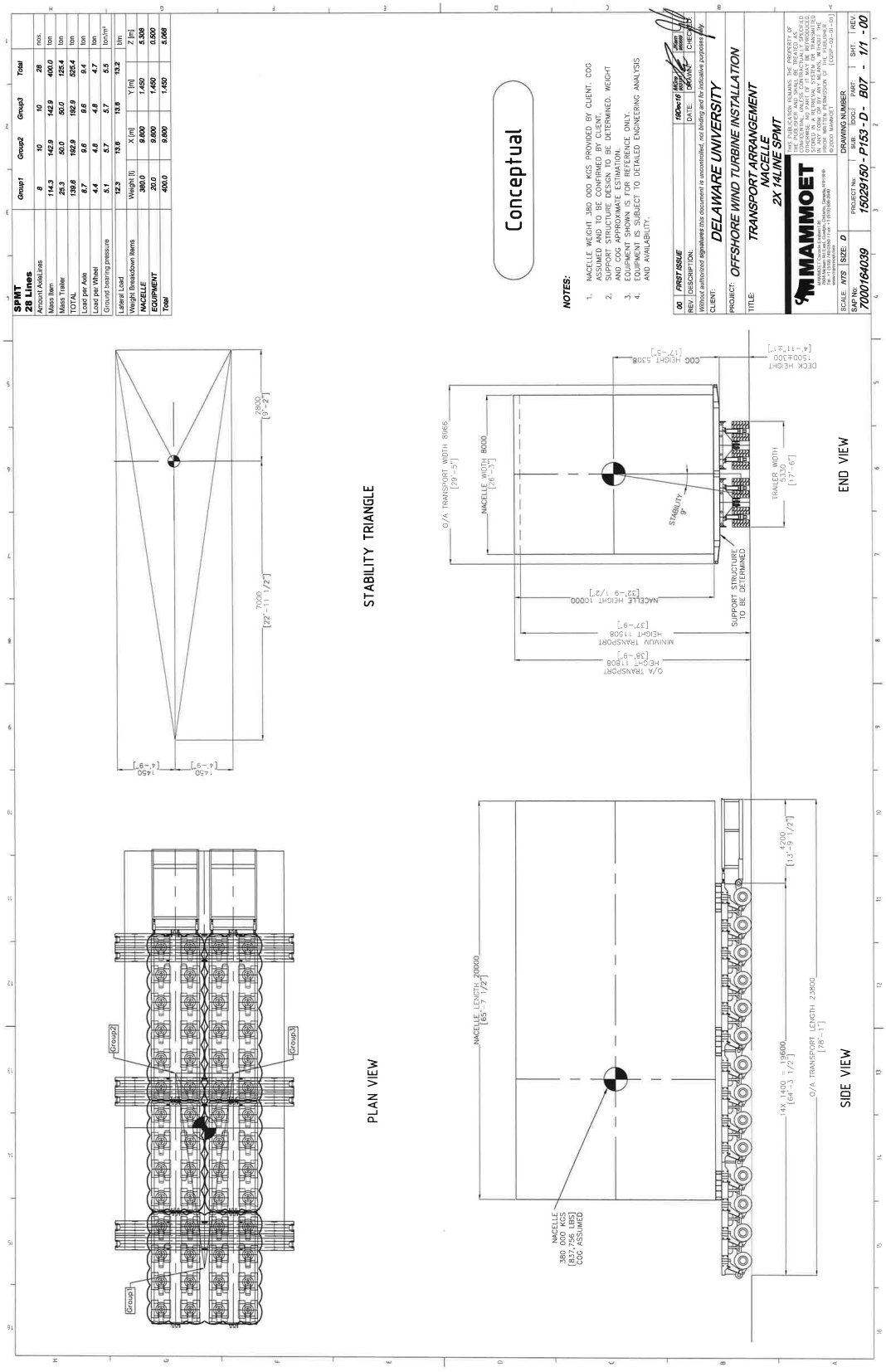
Move tower section to Assembly B04



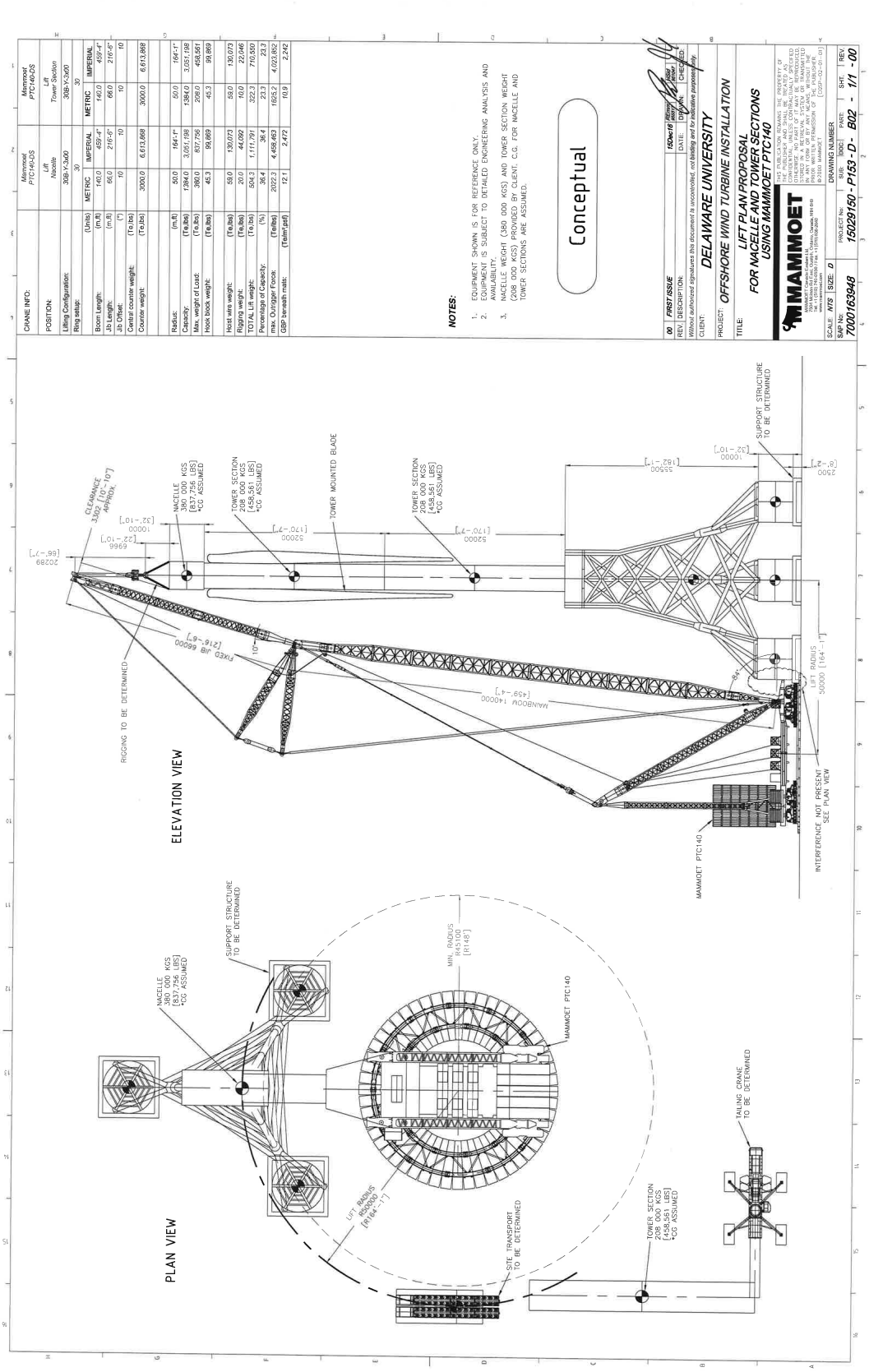
Blade transport B-08



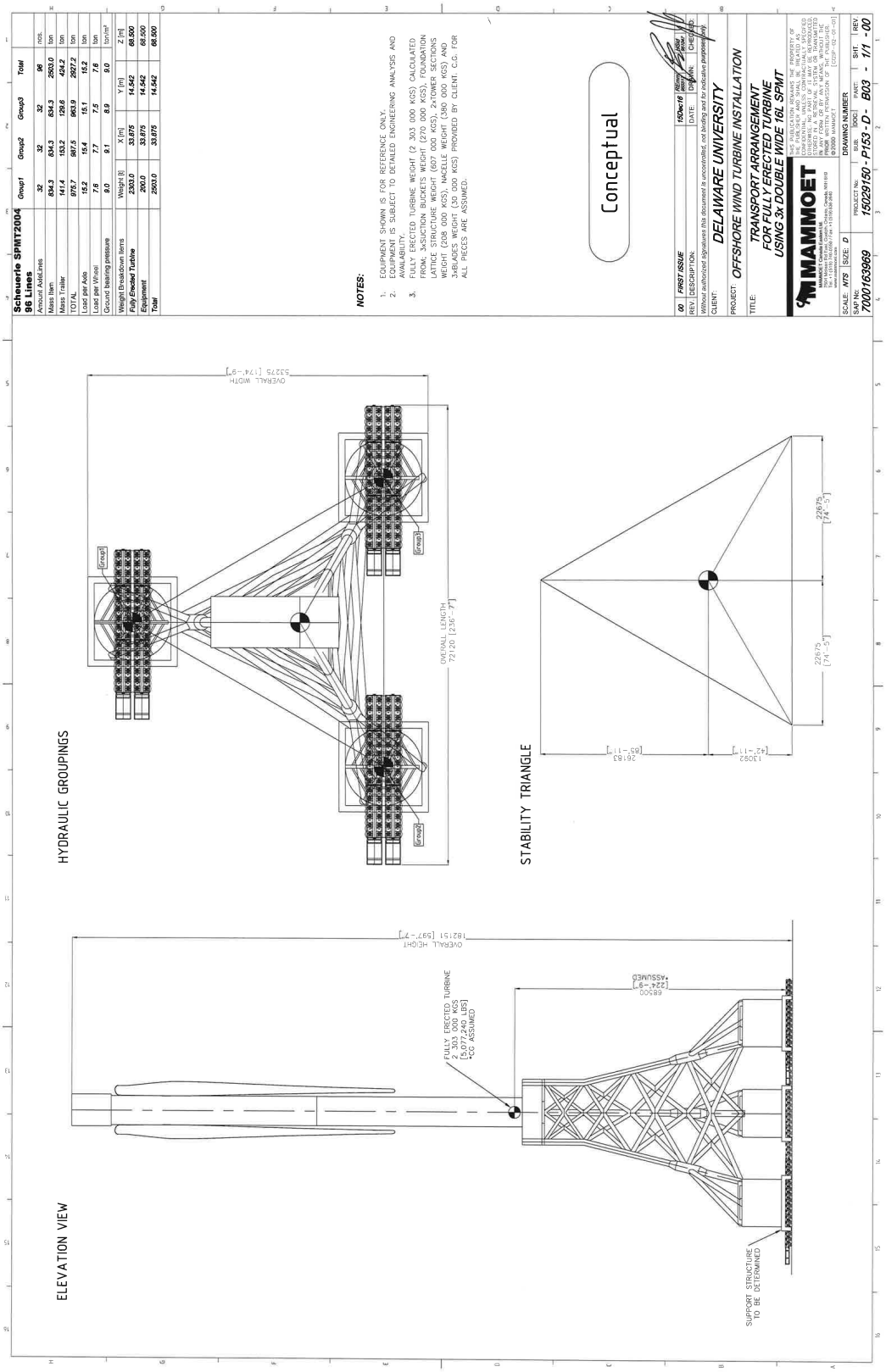
Move nacelle to assembly B07

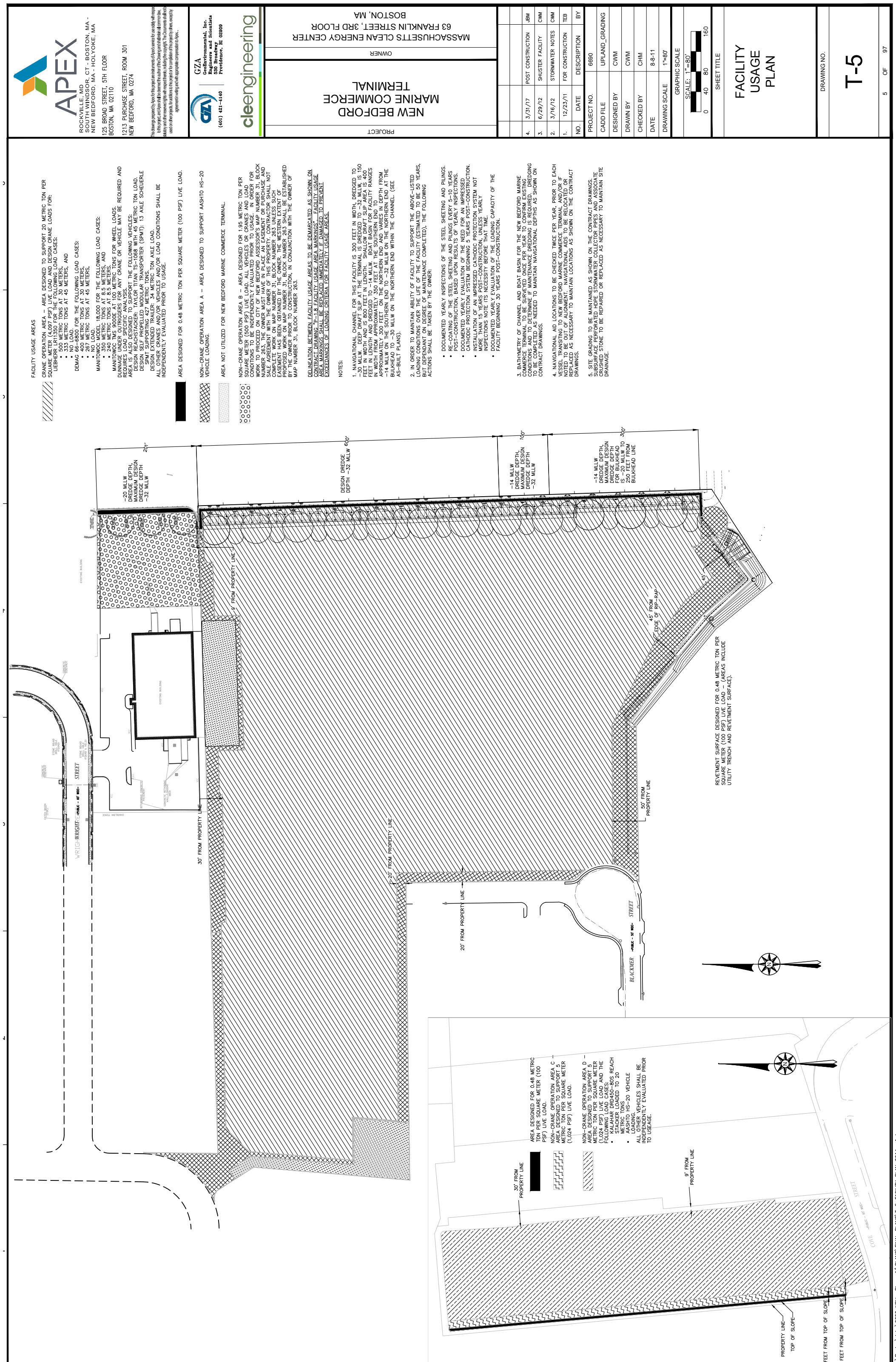


Tower, Blade and Nacelle lift B02



Move entire structure from assembly B03



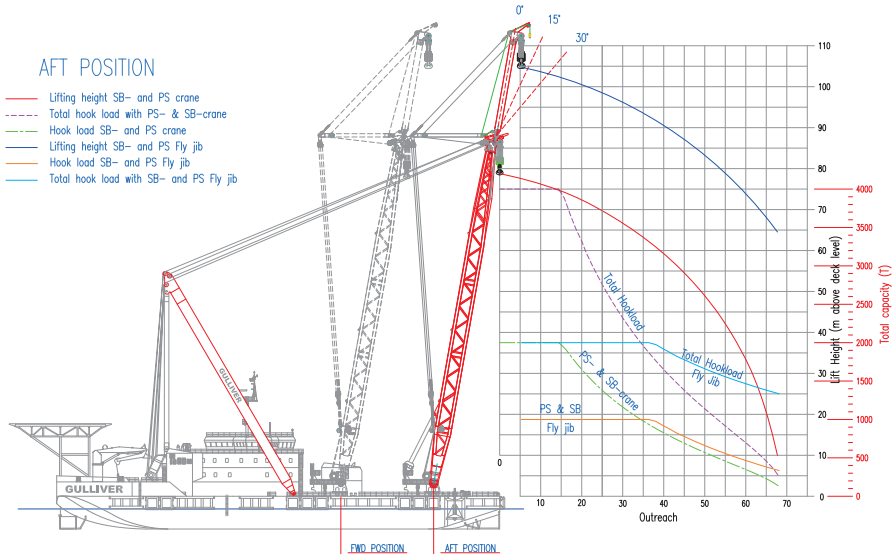

APEX
NEW BEDFORD
MARINE COMMERCE
TERMINAL
MASSACHUSETTS CLEAN ENERGY CENTER
63 FRANKLIN STREET, 3RD FLOOR
BOSTON, MA
FACILITY
USAGE
PLAN
T-5

E. Shear leg crane vessel specifications (Gulliver & Rambiz)

Gulliver

TECHNICAL INFORMATION

CHARACTERISTICS **DPII HEAVY LIFT VESSEL** GULLIVER



GENERAL PARTICULARS

Type of vessel	DP II Heavy Lift Vessel
Delivery	Spring 2017
Builders	IHC Offshore & Marine B.V.
Class	Lloyd's Register of shipping
Class Notation	• 100A1, Crane Ship, ShipRight(ACS(B)), LA, • IWS, LMC, UMS, DP(AA), CAC 3
Operators	SCALDIS-SMC NV
Flag	Belgian

LIFTING CAPACITY

Tandem lift	Max. 4,000t
Portside crane	Main hoist 2 x 1,000t Auxiliary hoist 2 x 15t
Starboard crane	Main hoist 2 x 1,000t Auxiliary hoist 2 x 15t
Max. lift height	78.5m above deck
Distance between crane booms	34.30m
Skidding System	

MAIN DIMENSIONS

Length overall	108m
Breadth moulded	49m
Depth moulded	8m
Min. Operating draft	4.9m
Displacement in operation	22,400t

POSITIONING

Type of propulsion	4 x Azimuth Thruster
Installed propulsion power	AFT: 2 x 1720 kW FWD: 2 x 1505 kW
Transit speed	7 knots
Mooring winches	FWD: - 2 x pcs mooring winches 80t - 1000m - Ø58mm - 2 x pcs mooring winches 50t - 1000m - Ø44mm AFT: - 2 x pcs mooring winches 80t - 1000m - Ø58mm - 2 x pcs mooring winches 80t - 1000m - Ø44mm

TANK CAPACITY

Fuel oil	1,342m³
Fresh water	935m³ + watermaker (20m³/day)
Water ballast	11,316m³

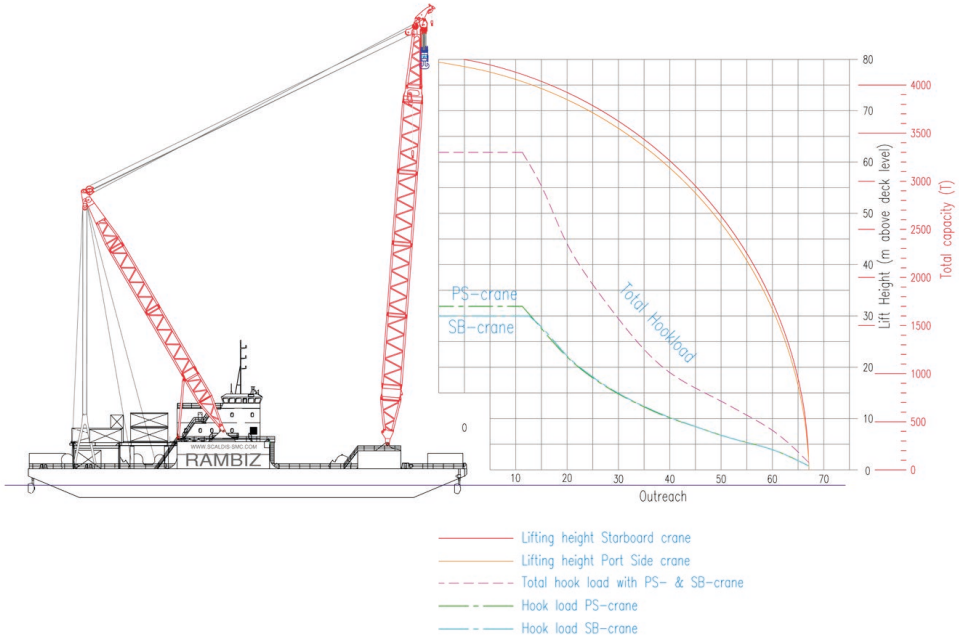
ACCOMMODATION

Max. persons	78 persons
Helicopter deck	
V-SAT internet and voip phone facilities	

Scaldis Salvage & Marine Contractors N.V. / North Trade Building Noorderlaan 133, box 31 / B-2030 Antwerp / Belgium
Tel. : +32 3 541 69 55 (24 hrs) / Fax : +32 3 541 81 93 / mail@scaldis-smc.com / www.scaldis-smc.com

TECHNICAL INFORMATION

CHARACTERISTICS **HEAVY LIFT VESSEL** RAMBIZ



GENERAL PARTICULARS

Type of vessel	Heavy Lift Vessel
Year of conversion	1999 - 2000
Builders	Huisman-Itrec / Schiedam
Class	Lloyd's Register of shipping
Class Notation	✠ 100AT non self-propelled crane pontoon, LA
Operators	SCALDIS-SMC NV
Flag	Belgian

LIFTING CAPACITY

Tandem lift	Max. 3,300t
Portside crane	Main hoist 1,700t Auxiliary hoist 2 x 15t
Starboard crane	Main hoist 1,600t Auxiliary hoist 2 x 15t
Max. lift height	78m above deck
Distance between crane booms	34.10m

MAIN DIMENSIONS

Length overall	85m
Breadth moulded	44m
Depth moulded	5.6m
Sailing draft	2.8m
Minimum operational draft	3.2m
Displacement	14,980t

POSITIONING

Type of propulsion	4 x Azimuth Thruster
Installed propulsion power	4 x 750 kW
Mooring winches	FWD: - 2x pcs mooring winches 80t -1000m - Ø52mm AFT: - 3x pcs mooring winches 80t - 1000m - Ø58mm

TANK CAPACITY

Fuel oil	420m³
Fresh water	400m³ + watermaker (10m³/day)
Water ballast	14,675m³

ACCOMMODATION

Max. persons	75 persons

V-SAT internet and voip phone facilities

Scaldis Salvage & Marine Contractors N.V. / North Trade Building Noorderlaan 133, box 31 / B-2030 Antwerp / Belgium
Tel. : +32 3 541 69 55 (24 hrs) / Fax : +32 3 541 81 93 / mail@scaldis-smc.com / www.scaldis-smc.com

F. Alternative Vessels

This appendix compares multiple alternative vessels in addition to the Sheer leg crane, it was written as a separate document in Nov 2013 by Andrew Levitt, Kevin Robinson, Alberto Tono, Nick Waite, and Willett Kempton. It has received minor updates mid-2017 by W. Kempton. Prices are equivalenced to 2013 dollars and when estimated rather than reported are conservative (that is, likely are too high). This analysis was an addition to the SOPO scope, and some part of the analysis are marked "pending", nevertheless, we believe it is of value in this form.

Vessel Concepts for Suction Installation

In this document we describe the conceptual decision-making process for a least-cost deployment method of a wind turbine fully assembled with sub-sea foundation on the quay.

Over the course of this design process, 5 categories of deployment were considered and assessed:

1. Self-buoyant tow ("float-out")
2. Auxiliary buoyancy tow
3. Semi-submersible installation vessel
4. Winch barge
5. Crane barge

These concepts are described here. Note that the ultimate vessel metric is not cost of the vessel (as assessed here), but rather total day rate, the factor more directly affecting the ultimate project metric, the cost of energy or COE.

In an integrated design study encompassing the entire offshore wind system, any consideration of installation vessel cost should consider that a $200 million vessel is equivalent to the cost of only five of the one hundred 10-MW turbines to be installed in the wind farm under study, and the vessel can be used for many more such wind farms — that is, vessel cost is relatively small. Nonetheless, it should also be recalled that installation costs today account for about 15% of total cost of energy, and so the overall installation concept, maximization of weather windows, and the installation time at sea are all very important. Also, a less expensive installation vessel may make the use of multiple vessels more practical, for example, one installing at sea, one loading at quay and another ready and loaded in harbor, in order to speed up the installation process.

For illustrative purposes, the below Conceptual Assessment Table summarizes informed guesses as to vessel cost for several approaches to solve the problem of transporting and lowering the entire structure for the tri-bucket design selected. On prices, we emphasize our description of "guesses", as these are not supplier provided values nor even estimates with a quantifiable accuracy.

Table 1. Conceptual Assessment Table

	Feasible?	Vessel cost	Transit speed	Transit wave/wind wind limit	Install wave / limit
Float-out	Unstable overturning	-	3 knots[a]	-	-
Auxilliary **buoyancy tow**	Unstable overturning	-	3 knots[a]	-	-
Semi-submersible installation	Yes	$200m	9 knots[b]	Assessment Pending[c]	Assessment Pending[c]
Winch barge	Likely	$40m tow $100m self-	3-8 knots tow[e] ~10 knots self-	Pending[c]	Pending[c]
A-frame crane barge	Likely	$75m	3-8 knots tow[e]	Assess Pending[c]	Assessment Pending[c]
"Svanen"-crane	Likely	$150m	3-8 knots tow[e]	Assess Pending[c]	Assessment Pending[c]
Sheerleg crane barge	Yes	$175m	3-8 knots tow[e]	Assess Pending[c]	Assessment Pending[c]

[a] Principle Power tow speed estimate (Principle Power, 2013)
[b] Based on Saipem S7000 specification sheet
[c] Alberto Tono estimate, personal communication.
[d] Specs from typical self-propelled deck barge
[e] Based on Ballast Nedam Svanen

	Pros	Cons
Semi-submersible installation vessel	• Elegant • Stable • Relatively fast	• High build cost • May be infeasible in port due to draft • Depth limited
U-shaped winch barge	• Low cost • Unlimited depth	• Further feasibility assessment required • May be low speed due to high COG • May be weather sensitive (or not)
Sheerleg Crane barge	• Better tested • Passive Stability • Unlimited depth	• Passive stability • Relatively fast • Higher build cost

Float-out

Figure 2. The Principle Power WindFloat semi-submersible wind turbine "foundation". Photos courtesy Principle Power.

The trio of 10m-diameter, 10m deep suction buckets in the design under study are sized to firmly anchor the turbine base given the sea bottom conditions on the mid-Atlantic continental shelf. Fortuitously, before the buckets are utilized for installation, this bucket size also displaces approximately 2,356 tonnes of water, or a bit more than the mass of the entire turbine/foundation assembly. The chamber inside the bucket is designed to be depressurized and pressurized for the suction

install and uninstall operations, and so the chamber could be pressurized for maximum displacement of water and therefore buoyancy.

Thus, the buckets can be used for buoyancy of the entire turbine system during float-out. When the assembly is on-site and ready for installation, the water can be gradually released from the buckets and the unit lowered at a controlled rate. The feasibility of controlled lowering by reducing buoyancy from below (e.g. filling the buckets during lowering) has not yet been examined. Additionally, the center of gravity during transport is high above the waterline, and, without doing a precise stability analysis, from first principles the assembly would be prone to overturning. For this reason, an entirely self-buoyant vertical deployment is unlikely to be practical without some additional stability. We examine that stability in other concepts below.

It is helpful to review the case of a floating structure that can be compared with our own. The Principle Power WindFloat, designed to be stable in a floating configuration, has been successfully operating off the coast of Portugal since 2011. Like the concept under consideration, it has three buoyant cans and it is fully assembled in-port. It is then commissioned in port and towed upright to its site. The WindFloat cans (for a 2MW machine) are about 27 meters high versus our 10 meters (for a 10MW machine), and lack our ~43 meters of lattice structure between the top of the cans and the bottom of the tower.

From American Institute of Chemical Engineers ChEnected magazine (Harrington, 2011): "The 1,200 ton WindFloat is designed to float half-submerged, moored in waters over 120 feet deep. The rig's three legs measure 90 feet high and 24 feet in diameter.

They are part-filled with 230 tons of static water ballast for stability."

WindFloat has demonstrated that installation of a fully onshore-assembled foundation and turbine is feasible. This may be a valuable approach for deeper waters. Nevertheless, there are some advantages of the present design over the WindFloat:

- No active ballast tank system (which pumps water between cans during operation), and no large heave plates (stabilizing the WindFloat on the bottom of each can).
- 1,200t of WindFloat for a 2MW turbine vs 1,200t of suction foundation for a 10MW turbine
- No foundation pitch during operation
- Bottom-mounted can be used in shallower water depth
- When installed, conventional cable management and no need for mooring

The considerably lower foundation mass would be expected to substantially lower the cost of our approach.

Auxiliary Buoyancy

Auxiliary buoyancy consists of attaching a tank or tanks to components of the

structure to increase buoyancy there. As the conceptual foundation design is refined, it may be the case that the cans change size—in the event that the buoyancy becomes inadequate to support the weight of the structure, auxiliary buoyancy could be used to supplement that. However, an auxiliary buoyancy system suffers from the same center-of-gravity stability issue as the self-buoyant case of the WindFloat. Moreover, the coupling and uncoupling of an auxiliary buoyancy system can add substantial complexity to the installation process.

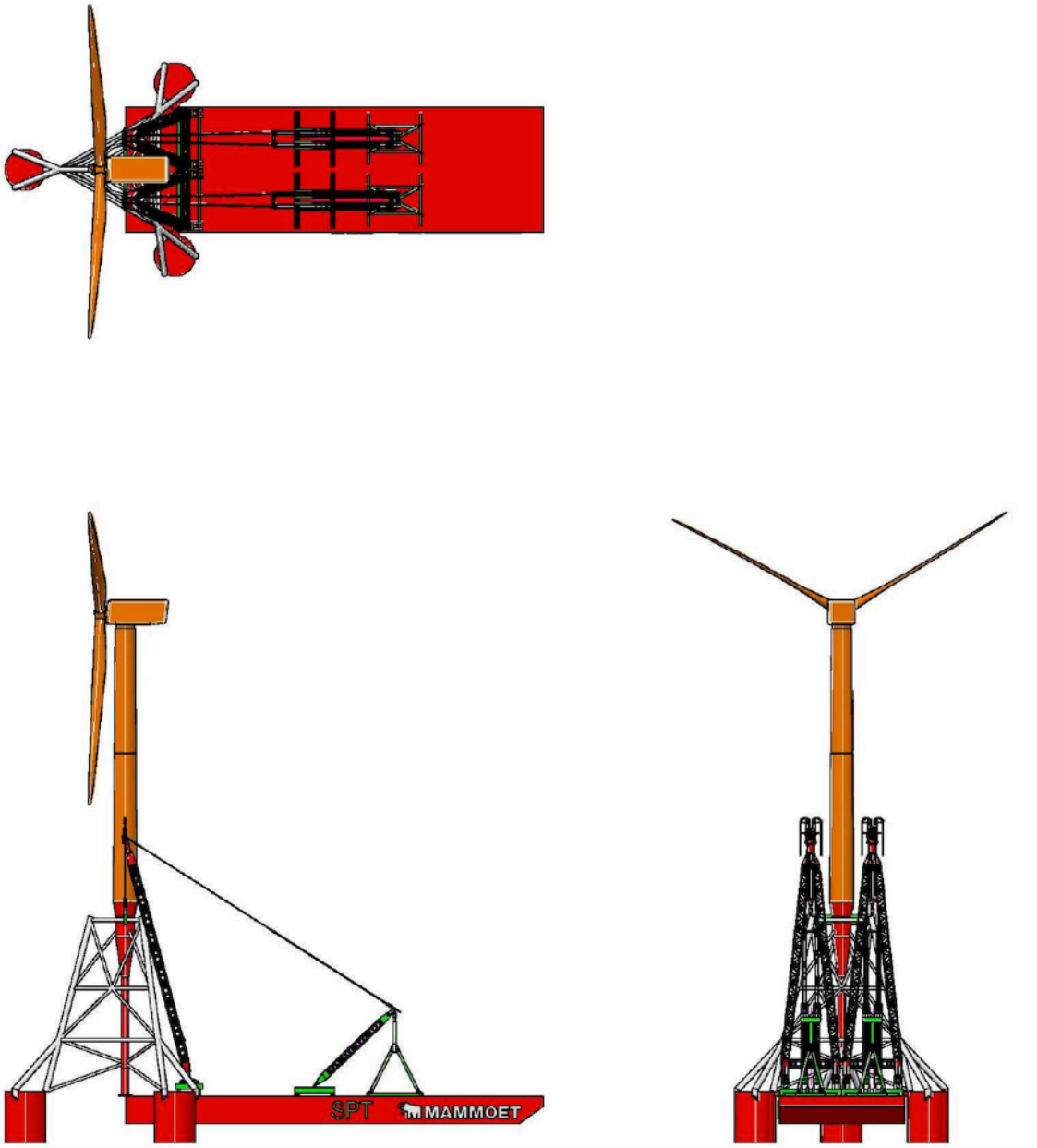
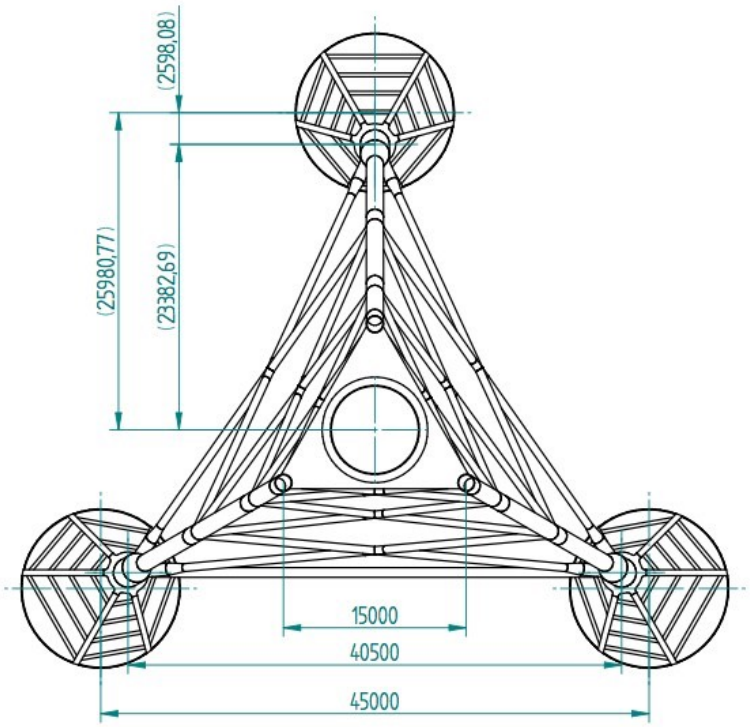


Figure 13. Multiview projection of SPT-Mammoet conceptual design for a shear leg crane barge.



If auxiliary buoyancy is desired in any of the subsequent vessel deployment concepts, one of several possible additions would be a triangular auxiliary buoyancy tank fabricated to fit between the suction buckets. This could, for example, be engaged with a lip on the buckets or perhaps a wire net, and slipped out after the assembly has been lowered and settled on the seabed, but before the cans have been suctioned into the sediment. A triangular prism with a side of 35m and a height of 5m displaces 2,652 cubic meters of water for 2,652 tonnes of buoyancy, and should allow sufficient clearance to be removed from under the foundation after the buckets are settled on the seabed.

Semi-submersible Installation Vessel

A very large auxiliary buoyancy system which can be easily coupled to the turbine/ foundation assembly is similar in concept to a semi-submersible installation vessel that is purpose-built to carry and lower the turbine assembly, not unlike a floating dry-dock. A similar vessel has been sketched by others for installation of a gravity-base foundation (Figure 3). Such a vessel, transporting the turbine assembly offshore, would sink itself to the seabed when it reaches the install site, thereby lowering the turbine assembly for installation. Such a vessel would be at least 50m per side, and for installation in water depths of 40m, approximately 50m deep. Very large existing semisubmersibles have similar depths (e.g., Thialf: 49.5m; Balder: 42m).

One drawback of this approach is the cost of the complex ballast system which counteracts roll, pitch and heave when lowering the barge, especially to the depths considered in this study (up to 40m).

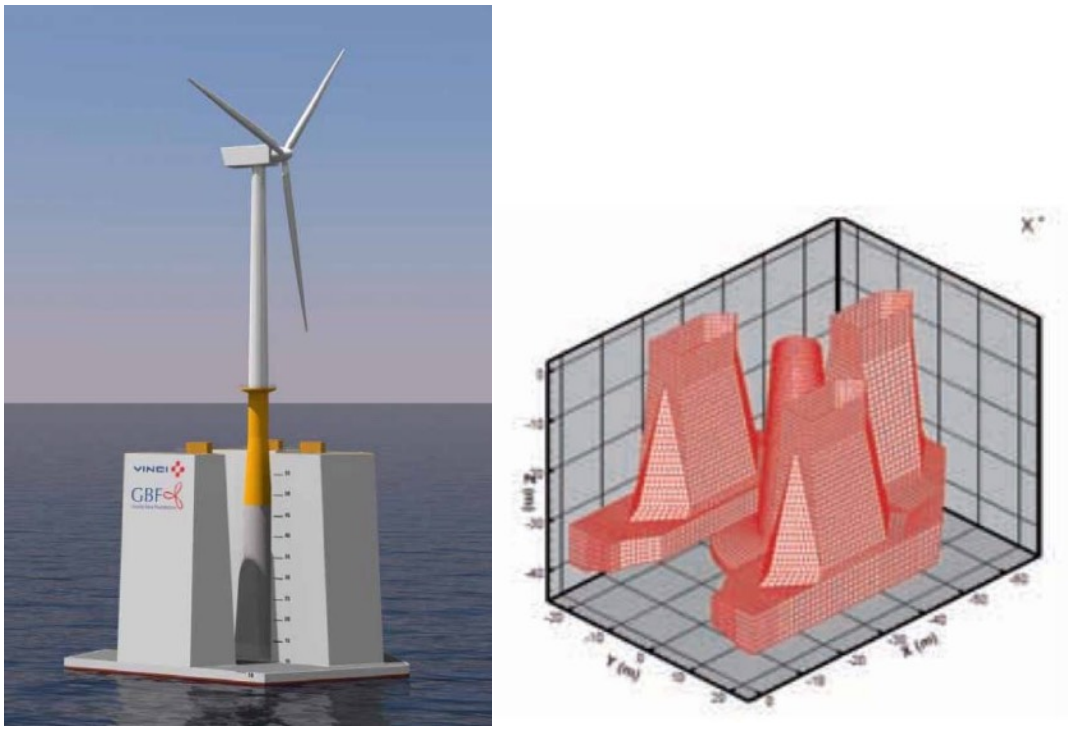


Figure 3. Purpose-built semi-submersible installation vessel concept for one-step install (in this case for a gravity-base foundation. Courtesy of Vinci Offshore Wind UK).

Semi-submersibles are generally costly compared to barges of a similar footprint. For comparison, the semi-submersible Q4000 is 95m x 63m x 30m deep and cost $180m to build in 2002 (ABS, 2013). (The Producer Price Index [PPI] for "Fabricated metal product mfg" is now 40% higher than in 2002, so the equivalent 2013 cost might be ~$250m). The L/P Odyssey when built was a 120m x 69m x 35m and cost $110m in 1982 (~$205m in 2013 using above PPI). It is important to understand that these costs are for illustration and approximate comparison, as these semi-submersibles include items such as decks, helipads, and drill rigs that would not apply on the same scale or at all in the current application. For the purposes of this conceptual-level assessment, we make a rough estimate of the cost of this vessel to be $200 million.

Pros

- Elegant, few moving parts
- Very stable, can operate in a wider weather window for transport and installation.

Cons

- Costly
- May be difficult to use this buoyant lift approach to pick up the assembly in harbor, where water depth is 10m or less.

Winch Barge

Figure 4. The ECEM Sultan.

A U-shaped catamaran barge could surround the turbine assembly with winches and thereby raise and lower it without need for a large crane boom or any cantilevering. This approach is commonly used for transporting and installing tunnel segments. For instance, the ECEM Sultan catamaran barge above has a 1,000-ton lift capacity using winches distributed around the perimeter of the space between the hulls.

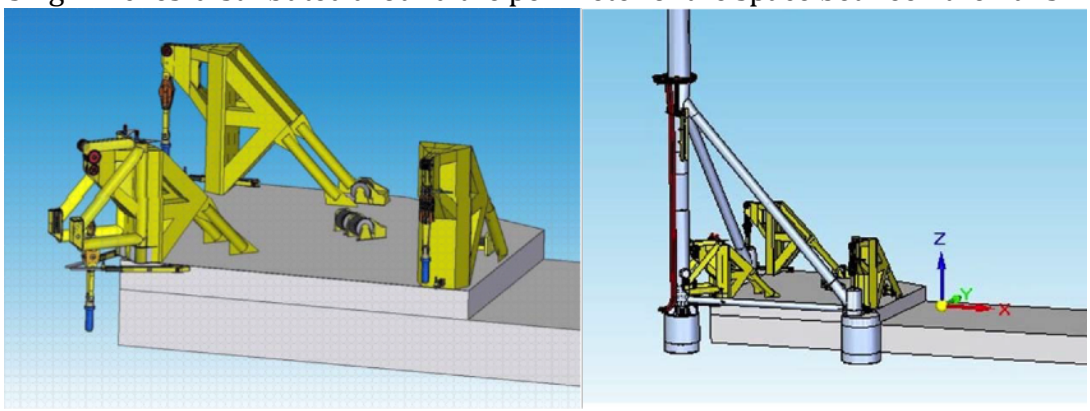


Figure 5. The SPT winch concept for the braced-tower Self-Installing Wind Turbine design funded by the Carbon Trust (courtesy SPT).

One challenge with the deck-mounted winch barge arrangement is that by supporting the assembly below its center of gravity, rather than above it as with a crane, passive stability is lost—like in the buoyant case, the assembly is prone to tipping over, both during transport and during lowering for installation. Such rotation relative to the vessel can be limited during transport by rigidly fixing the assembly to the barge at several points, but stability must be provided through other means during the lowering operation.

This could include something like a stabilizer bar that grasps the assembly with rollers that allow it to move vertically but not horizontally (see above figure from SPT for a non- U-shaped concept).

Another alternative to providing this rotational stability is to secure the assembly via guy wires that are tensioned with a winch at the deck. This provides horizontal stability both during transit (when the winches are essentially static) and during lowering (when winches are winding up the slack). As above, the bottom of the assembly is also held by winches. The resulting physical system is not unlike the horizontal stabilization provided for the mast of a sailboat by way of spreaders or, on a traditional sailing ship, the crosstrees and top.

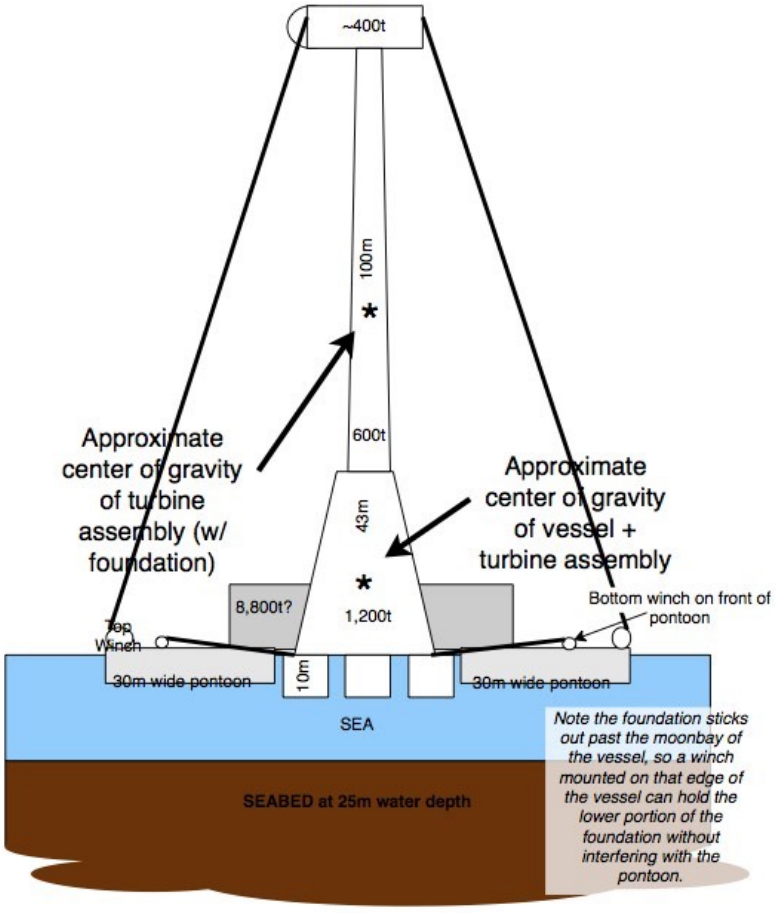


Figure 6. Scale sketch of the UD Integrated Design winch pontoon barge concept. This is a front view of the two pontoons, which are joined at the back by a bridge to form a single vessel. An alternative is a V-shaped vessel without a bridge. Blades would be attached to tower as described in text. Guys to top would mount to tower, not to nacelle as shown here.

While the winch system may work well on its own, it is more promising when coupled with the buoyancy provided by the buckets (see Figure 6 above), which as shown above is larger than the weight of the turbine-foundation assembly. In this case, the winches solely provide stability—the weight is entirely supported by buoyancy. Both the guy-wire winches connecting to the top of the turbine and the lowering winches attaching to the suction buckets provide horizontal stability.

Figure 7. The Ramform Titan research vessel. Photos at left from unknown source, photo at right courtesy Tom Gulbrandsen (2013).

Note that a wide aspect-ratio, triangular-shaped vessel, such as the one represented by the barge in this concept, has the capability of high speed if designed properly; the Ramform Titan pictured above is 104m long by 70m wide and travels at 16 knots (PGS, 2013).

That said, the concept under consideration has a substantial cross-section of suction buckets submerged by ~10m, possibly producing substantial drag in comparison to the Ramform Titan hull. In addition, each Ramform Titan costs ~$250m (PGS, 2012), including about $25m in specialized scientific equipment and a $26m electrical system. The cost of a self-propelled U-shaped winch barge is difficult to estimate. It can be built from two 30m x 100m barges plus a bridge, winches, and a self-propulsion system, and has the potential to be much lower cost than the other vessels in this document. US-flagged non- propelled barges of that size are available for sale for around $2m (Dredge Brokers, 2013).

Boom-mount Winch (i.e., Crane)

A high-mounted winch has the advantage of leveraging passive stability by holding the piece above its center of gravity, for the most part requiring no further mechanisms to prevent turbine system overturning during transit or install. In order to leverage this passive stability, the boom needs to be higher than the center of gravity of the piece it is holding.

Fixed boom (i.e., A-Frame)

Without a mechanism to raise or lower the boom, nor a slew mechanism to rotate, the A-frame vessel is the simplest (and presumably lowest-cost) form of crane vessel. This concept can be implemented in a simple barge with cantilever (as above), or with a U-shaped concept that accommodates the assembly in the center without the need to cantilever. The latter concept shares some characteristics with the Ballast Nedam Svanen, described below.

The cost for a simple, unpropelled A-frame crane barge with at least 80m hook height (to clear the center of gravity of the assembly) and several thousand ton capacity is guessed to be very roughly $75m, based on a reduction of the cost estimate for the sheerleg crane below to account for the simpler boom. Note that it is difficult to find

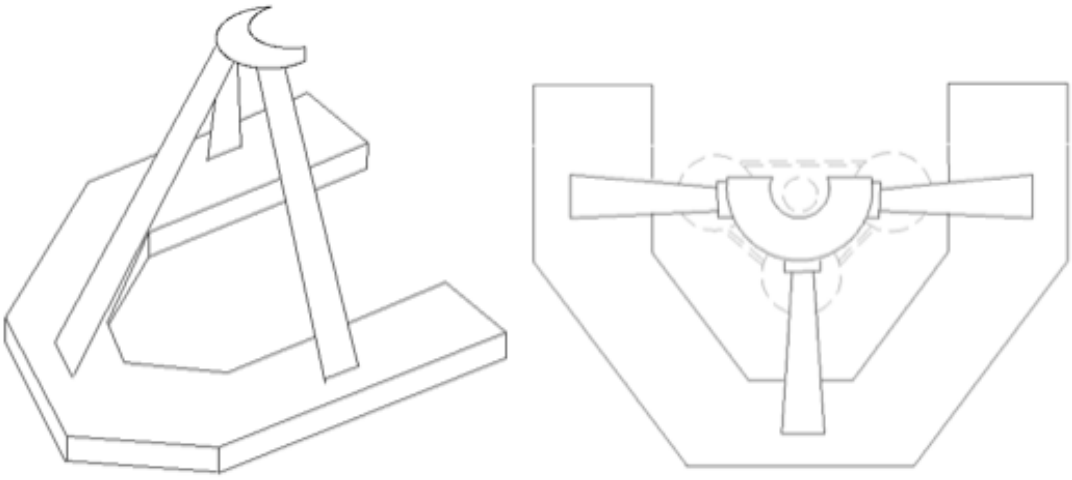


Figure 8. Image from UD design showing the bridged A-frame concept, isometric view (top) and plan view (bottom).

actual high-capacity A-frame cranes for cost comparison. A 600-tonne A-frame crane barge is listed by Dredge Brokers at a cost less than a third that for a 600-tonne sheerleg crane barge of similar age, though this could be due to considerations of geography, vessel condition, or other factors.

The Svanen

Figure 9.Ballast Nedam Svanen. Photo courtesy E. van de Brug.

The Ballast Nedam vessel Svanen is an example of a barge with hoist on top of a vertical support with a 76-m lift height. Remarkably for its relatively small size, the Svanen is considered to be the third-highest capacity lifting vessel in the world, with lift capacity of 8,700t. Ballast Nedam states that by lifting from its center of mass, the Svanen can efficiently achieve such high lift capacities.

The transit speed is listed as 2.8 knots in substantial winds, or 7.0 knots windless (Ballast Nedam, 2013). The Svanen is 103 m long by 72 m wide with a "moonbay" of 23 m x 64m. A similar vessel could be imagined that can accommodate the much wider cross- sectional area of the turbine assembly at the sea-line (~55m). The vertical structure on the vessel could either provide the lifting with a tower-mounted winch (as on the Svanen), or the tower could perform the less-stressful function of providing horizontal stability on the turbine tower, both in transit and as the assembly is lowered from deck-mounted winches.

Figure 10. Turbine install concept from Ballast Nedam (2013) for the Svanen. Though not illustrative of any of the approaches discussed here, with its partial onshore assembly and vertical deployment it does share some of the same conceptual underpinnings.

The Svanen cost £35 million to build in 1990 (Construction News, 1993). This cost would be higher in 2013 prices: based on available price indexes, ranging from £57m to £80.5m ($92m to $129m).[18] A mid escalation value of 2.0x results in a cost of $110m for the Svanen; a taller and wider version would be required for our 10 MW turbine.

For the purposes of this assessment, considering that our vessel would have to be slightly taller and substantially wider than the Svanen, we conservatively guess $150m as the 2013 cost for a non-propelled, U-shaped winch barge.

[18] The US Bureau of Labor Statistics Producer Price Index for "Fabricated metal product mfg" was 1.64x higher in 2013 than in 1990. This may be a conservative escalator: IHS CERA Upstream Upstream Capital Cost Index was 2.3x higher in 2013 than 2000 [IHS CERA, 2013], the ENR Construction Cost Index is about 1.8x higher in 2010 than 1990, and the PPI for Mining was up 2.3x between 1990 and 2013.

Adjustable boom

Figure 11. Asian Hercules II sheerleg crane, with (left) and without (right) luffing jib.

The most flexible (and complex) crane vessel considered here is the stiffleg or shear leg crane—it lacks the slewing of a typical crawler crane, but unlike the A-Frame vessel above, it does provide raising and lowering of the boom, and can provide an additional jib boom as well.

The Asian Hercules II pictured above has a 3,200-tonne lift capacity. Its successor, Asian Hercules III, is a 5,000-tonne capacity shear leg crane similar to the Asian Hercules II, only higher capacity. According to a press release from Keppel (the vessel builder, 2011), the 106mx52m self-propelled vessel with a 172m hook height will be built in China for S$143m ($115m USD). For a US manufactured vessel like this, we guess the domestic cost to be $175m.

SPT Offshore and Mammoet have conducted a preliminary design and assessment of a shear leg crane for a turbine deployment similar to (and partly inspiring) the one-piece ocean deployment of our own study. An example concept is shown in Figure 12. One advantage of this compared to A-frame is the ability to hold the boom closer to vertical during transport, which may allow for a lower-capacity system versus a more highly cantilevered A-frame crane (which must hold the piece sufficiently far out so that it can clear the deck barge for lowering).

As a practical matter for near-term US installations, Mammoet has cranes already available that could be used to fit an existing US-manufactured barge such as as the Weeks 531, to economically create a Jones-Act compliant shear leg crane barge similar to the drawing of Figure 12. Specifics require more analysis of sea conditions and how they affect alternatives for potential US-made barges. A back-of the envelope calculation by Mammoet, Weeks and STP estimated that, based on existing components, such a barge could be configured with cranes in less than a year for under $15 M. If self-propulsion is desired, that would add, for example, four Thrustmasters (https://www.thrustmaster.net) for an additional $15 M, yielding a self-propelled but retrofit DP2 vessel for under $30 M. Either barge or DP2 would accommodate lift, transport and deployment of a fully-assembled 10 MW turbine structure as proposed by this project.

Figure 12. SPT-Mammoet conceptual shear leg crane barge design to be made from US-made barge and existing crane.

In summary, we have reviewed concepts for vessel, buoyancy, mounting, and lowering of the turbine system, assuming a turbine system with a tri-bucket and jacket foundation. There are multiple possible approaches to the vessel, including several options for low-cost vessels for the near term, and more custom-built vessels that might be better suited for large builds later.

This review represents a conceptual design stage in the development of the vessel and installation methods for this integrated design project. Based on the conceptual

design comparisons, it appears that there may be substantial savings in mass, cost, and vessel complexity over jack-ups by use of the integrated design with assembly on shore.

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G. Dissemination

The table below provides a list of all dissemination of the project by the research team during the project period. These presentations and meetings served to obtain feedback and suggestions, to improve the project, and to disseminate the partial results during the time of the analysis. Other than the closeout presentation to US DOE, presentations and documents after the project period are not shown.

Event	Team member, Location and Date, Event Type	Dissemination Description	Feedback
American Wind Energy Association Offshore Windpower Conference	Kempton, Atlantic City, NJ 10/6/14-10/8/14, Industry Conference	Presented at high profile preliminary panel discussion titled "An integrated system design to lower cost of OSW energy deployment in the mid-Atlantic". This panel was attended by federal, state, and industry members.	
Meeting with Rambøll, Offshore Wind Engineering	Kempton, Copenhagen, Denmark 11/26/14, Expert Meeting	Meeting between the principal investigator and Rambøll representatives to get expert advice on the project and the technical approach	1. Due to mid-Atlantic sand waves, shifts could occur between survey time and deployment, which could then cause instability. A proposed solution from the Rambøll representatives would be to dredge shortly before bucket placement and then deposit a layer of rocks or similar material for scour protection. 2. If air is kept in buckets to reduce load on lowering equipment, the water level inside the bucket be monitored very closely during lowering operation, as water and bucket motion could cause some air to be lost which could lead to major stability issues (monitor with more direct measurement than a pressure valve for the bucket).

Meeting with DONG Energy (now Ørsted)	Kempton, Skærbæk, Fredercia, Denmark 11/28/14, Expert Meeting	Meeting between the principal investigator and DONG Energy 'Foundation and Structures' group to discuss the technical approach.	Float out using buckets for flotation too unstable for risk managers to accept.
Greenpower 2015	Kempton, Boston, MA 2/25/15, Lecture	Plenary lecture, by invitation, to present on panel "Technical lessons from 20 years of EU experience", in which a project overview was given.	
American Wind Energy Association Offshore Windpower Conference	Bowers, Baltimore, MD 9/29/15-9/30/15, Industry Conference	Poster titled "Calculated Cost Reductions from Integrated System Design" presented discussing the results of the project up to that point	
Offshore Wind Leadership Conference	Kempton, Boston, MA 2/29/16-3/1/16, Industry Conference	Detailed discussion with Ketil Arvesen of Fred Olsen vessels about the use of suction buckets for large builds of offshore wind coming up in the United State. Presented a project overview, summary, and ongoing results to three U.S. offshore wind developers also at attendance at the conference.	Expectation of increasing use of suction buckets in commercial installations.
American Wind Energy Association Offshore Windpower Conference	Bowers, Warwick, RI 10/25/16-10/26/16, Industry Conference	Poster titled "Calculated Cost Reductions from Integrated System Design" presented discussing the results of the project up to that point	
DOE Wind Program, at Headquarters	Kempton, Washington DC, 8/30/17, Report to Sponsor	Final Closeout Presentation at US-DOE, for award DE-EE0005484	No substantial problems identified. Potential next step would be a deployment of 2-6 turbines to demonstrate this method.