



A Comparison Study of Offshore Wind Support Structures with Monopiles and Jackets for U.S. Waters

Preprint

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*To be presented at "The Science of Making Torque from Wind"
(TORQUE 2016)
Munich, Germany
October 5–7, 2016*

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Conference Paper
NREL/CP-5000-66099
August 2016

Contract No. DE-AC36-08GO28308

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A comparison study of offshore wind support structures with monopiles and jackets for U.S. waters

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Abstract. U.S. experience in offshore wind is limited, and high costs are expected unless innovations are introduced in one or multiple aspects of the project, from the installed technology to the **balance of system (BOS)**. The substructure is the main single component responsible for the **BOS capital expenditure (CapEx)** and thus one that, if improved, could yield significant **levelized cost of energy (LCOE)** savings. For projects in U.S. waters, multimember, lattice structures (also known as jackets) can render required stiffness for transitional water depths at potentially lower costs than **monopiles (MPs)**. In this study, we used a systems engineering approach to evaluate the **LCOE** of prototypical wind power plants at six locations along the eastern seaboard and the Gulf of Mexico for both types of support structures. Using a reference wind turbine and actual metocean conditions for the selected sites, we calculated loads for a parked and an operational situation, and we optimized the **MP-** and jacket-based support structures to minimize their overall mass. Using a suite of cost models, we then computed their associated **LCOE**. For all water depths, the **MP-**based configurations were heavier than their jacket counterparts, but the overall costs for the **MPs** were less than they were for jackets up to depths of slightly less than 30 m. When the associated manufacturing and installation costs were included, jackets resulted in lower **LCOE** for depths greater than 40 m. These results can be used by U.S. stakeholders to understand the potential for different technologies at different sites, but the methodology illustrated in this study can be further employed to analyze the effects of innovations and design choices throughout wind power plant systems.

1. Introduction

Offshore wind power promises to deliver an essential contribution to a clean, robust, and diversified U.S. energy portfolio [1]. However, the lack of domestic experience with offshore wind technology has contributed to considerable uncertainty in estimates of the potential cost of domestic offshore wind energy, which remains high even in the most optimistic predictions. Significant cost drivers lie in the **BOS** activities. Experience in Europe has shown that costs are raised by project management inefficiencies, supply chain bottlenecks [2], as well as technology limitations. Offshore wind turbines have largely used maritized land-based machines mounted on **oil and gas (O&G)** derived platforms. Innovations in turbine and support structure design have the potential to streamline manufacturing and installation, and reduce material costs. According to [3], the substructure and foundation are responsible for 14% of the total offshore wind power plant **LCOE**, and the largest uncertainty in **LCOE** is attributable to its sensitivity to **CapEx**.

MPs and lattice structures (or jackets, a common term used for lattice substructures from the **O&G** industry experience) are among the most popular substructures for offshore wind.

Ninety-one percent of the 2014 installations were **MPs**, whereas some 5% were jackets [4]. **MPs** are easy to fabricate and to install in shallow waters (≤ 20 m), but they require progressively more material tonnage to guarantee modal performance in deeper waters, where installation also becomes more expensive. Lattice substructures can deliver needed structural stiffness by increasing the substructures footprint and by concentrating mass away from the neutral axis, but this is at the expense of more laborious fabrication than that of the **MPs**.

In the United States, analyses have shown that economic wind development would occur over transitional water depths (depths of 30–60 m and distances from shore of 5–50 nmi), where the estimated capacity potential for Class 4 wind and above exceeds 600 GW [5; 6]. Several studies, e.g., [7; 8], have shown that **MPs** are progressively unfeasible as projects are sited in deeper waters and use larger turbine sizes (6 MW+). Yet, in Europe, new extra-large and extra-extra-large **MPs** are being proposed and deployed in more challenging sites (depths > 30 m) and for larger turbines (ratings > 6 MW) [9].

Although the support structure plays an important role in defining the system’s reliability and performance characteristics, it also affects costs associated with the **BOS** as well as with the **operation and maintenance (O&M)**. The link between these costs and the main environmental design drivers must be recognized and understood (see also [10]) for the industry to flourish in the United States and to avoid mistakes observed in past experience. Selecting the proper support structure is one of the most important questions to address for U.S. offshore wind development, and it is one that must be resolved in a multidisciplinary context that encompasses both the technical aspects of the structural design and the **BOS** aspects of logistics and installation costs.

In this study, we made use of an integrated modeling tool, the **Wind-Plant Integrated System Design & Engineering Model (WISDEM™)** developed at the **National Renewable Energy Laboratory (NREL)**, to perform a system-level nonlinear optimization of wind power plants. Using an integrated model set with combined physics and cost modeling capabilities allows for the direct exploration of trade-offs in the design of different subsystems. We compared **LCOE** estimates for prototypical wind power plants composed of 100 5-MW turbines sited along the Eastern Seaboard and in the Gulf of Mexico. For each of the six sites, the analysis was conducted with both an **MP** and with a typical four-legged jacket as substructure configuration. The hub height was fixed throughout the sites, but the tower geometry was allowed to change depending on the structural requirements and the varying deck heights, which were identified based on the local wave crest conditions. Preliminary designs of the support structures were achieved via JacketSE and TowerSE (design tools within WISDEM) driven by a gradient-based optimization, which had the objective to minimize the support structure mass.

For this analysis, several plant cost models were used for the nonturbine cost elements of the **LCOE**. The **LCOE** analysis showed that jackets become more economical than **MPs** at sites in waters deeper than 45 m.

Section 2 presents the primary metocean conditions for the sites analyzed, whereas the details of the methods used and the results of the analysis are given in Section 3 and 4, respectively. Conclusions and areas of future work are presented in Section 5.

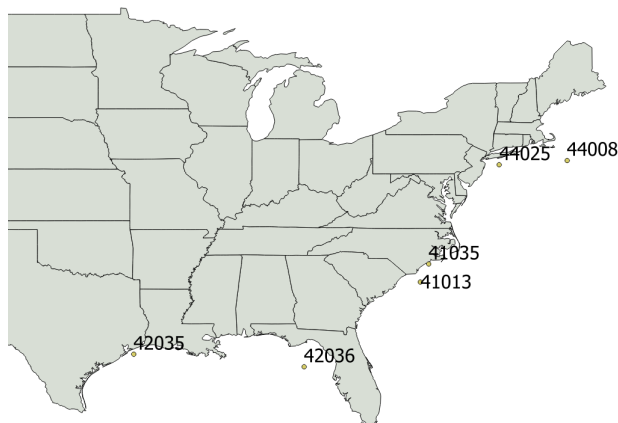
2. Metocean data

The modeling tool required information on wind and wave conditions at each site to establish wave loading, deck height, and other parameters. Six sites were chosen to represent a range of water depths. Each site was at (or very near, as in the case of Site 6) the location of a National Oceanic and Atmospheric Administration buoy to provide an accurate measure of the metocean climate at the site. Note that deck height was calculated for each location based on the wave conditions and supplied as an input to the support structure optimizations. The selected sites are identified in Table 1 and Fig. 1. The key metocean parameters are given in Table. 2.

Table 1. The six buoy sites analyzed^(a).

Case	Buoy ID	Name	Region	Lon (deg)	Lat (deg)
1	41013	‘FRYING PAN SHOALS’	‘atl’	-77.743	33.436
2	42035	‘GALVESTON’	‘gulf’	-94.413	29.232
3	44025	‘LONG ISLAND’	‘atl’	-73.164	40.251
4	41035	‘ONSLow BAY’	‘atl’	-77.280	34.476
5	44008	‘SE NANTUCKET’	‘atl’	-69.247	40.502
6	42036	‘W TAMPA’	‘gulf’	-84.517	28.500

^a From [National Data Buoy Center \(NDBC\) http://www.ndbc.noaa.gov/](http://www.ndbc.noaa.gov/) and [U.S. Army Corps of Engineers Wave Information Studies \(WIS\) http://wis.usace.army.mil/](http://wis.usace.army.mil/).

**Figure 1.** Locations of **NDBC** buoys.

2.1. Calculated parameters

A few parameters had to be extrapolated or calculated from the buoy and **WIS** records, including maximum and breaking wave heights, surge height, and maximum wave crests at different return periods.

The height of a breaking wave at a site is calculated as 0.78 times the water depth. Significant wave heights (H_{s50} and H_{s100}) with a return period of 50 and 100 yr are calculated by extrapolating from the largest wave events recorded at a site. If the breaking wave height at a site is lower than the extrapolated wave height, then the breaking wave height is used. Maximum wave heights (H_{mx50} and H_{mx100}) are also estimated for each return period by multiplying the respective significant wave height by 1.86.

The deck heights of the substructures were calculated to clear the 1000-yr wave-crest heights and accounting for a 1.5 m run-up. To determine the 1000-yr wave crests, highest astronomical tide (HAT), 1000-yr storm surge heights, and the 1000-yr maximum wave height had to be obtained. The 1000-yr wave heights and the HAT s were extrapolated from the maximum wave heights in the buoy records. Surge height is difficult to estimate at offshore sites. When data from nearby coastal water level measurement stations were available, the published extreme value distribution was used to compute the extreme surge height. These values can be regarded as conservative (high) because coastal areas will usually have higher surge heights than open ocean sites.

We utilized [11]¹, which includes the shape and scale parameters of a Gumbell Extreme Value distribution distribution to the data of each offshore station, to analyze two or three stations close to each of our proposed wind power plants. Through the R library `evd` [12], we computed the magnitudes of the 1000-yr surges.

These derived metocean parameters for the six sites are given in Table 2.

Table 2. Key metocean parameters for the six sites analyzed.

Case No.	$w_s^{(a)}$ m s ⁻¹	Water Depth m	$H_{s50}^{(b)}$ m	$H_{mx50}^{(b)}$ m	$T_{mx50}^{(c)}$ sec	$HAT^{(d)}$ m	$\delta_{1000}^{(d)}$ m	$H_{mx1000}^{(b)}$ m	Deck Height m
1	9.74	23.50	10.82	18.33	13.34	1.26	1.25	18.33	13.20
2	8.06	12.80	7.24	9.98	10.91	0.47	6.00	9.98	13.00
3	9.33	40.80	9.48	17.63	12.48	0.33	2.50	23.26	16.00
4	9.52	9.70	10.46	7.57	13.11	0.83	0.90	7.57	7.00
5	9.26	65.80	12.15	22.60	14.13	0.79	1.54	28.31	18.00
6	7.58	50.60	7.63	14.19	11.20	0.84	1.50	17.81	12.70

^a Annual average wind speed adjusted to 90 meters above sea level (MASL) using shear exponent of 0.12.

^b 50-yr significant wave height (H_{s50}), 50-yr maximum wave height (H_{mx50}), and 1000-yr maximum wave height (H_{mx1000}) are given as trough-to-peak differences in meters.

^c Peak wave spectral period (T_{mx50}) is in seconds.

^d Highest astronomical tide (HAT), 1000-yr storm surge (δ_{1000}) and deck height are given as MASL.

2.2. Wind data

Wind data for this study was licensed from AWS Truepower, Inc. (AWS) and consisted of gridded data at a resolution of 200 m, with separate shape files for annual, monthly, and diurnal distributions of wind speed and wind direction. Original wind data was at 100 MASL, but it was scaled downward slightly to adjust to 90 MASL.

3. Analysis method

The analysis carried out in this study made use of various tools available within the WISDEM software suite. WISDEM integrates a variety of models for the entire wind energy system, including turbine and plant equipment, O&M, energy production, and cost modeling [13]. The tool set allows for trade-off studies and guides the design of components as well as the overall system toward a configuration that minimizes the LCOE through multidisciplinary optimization. The main submodules used in this study include RotorSE, DriveSE, TowerSE, JacketSE [14], PlantEnergySE, TurbineCostsSE, and PlantCostsSE. RotorSE, a module that can calculate loads on rotor blades, has been described in detail in [15]. DriveSE [16] can calculate reaction loads at the interface with the tower, and together with RotorSE it was run a priori and produced the ultimate limit state loads that were inputs to the support structure sizing tools, i.e., TowerSE and JacketSE. The latter two modules, which were at the core of the optimization, are described in more detail in Section 3.1. PlantEnergySE, TurbineCostsSE, and PlantCostsSE are briefly described in Sections 3.2 and 3.3.

¹ The report is an analysis of data from 112 long-term stations from the National Water Level Observation Network.

3.1. TowerSE and JacketSE

TowerSE and JacketSE are preliminary sizing tools for support structures including towers, **MPs**, and jacket substructures. These tools are based on simplified physics and load case analyses and do not claim to be sufficient to arrive at final design details, but they offer a rapid and versatile way to analyze multiple effects of design choices and environmental conditions, which would be much more resource intensive with aeroelastic and finite element analysis tools.

JacketSE and TowerSE aid the designer in the search for an optimal preliminary configuration of the substructure and tower and for given metocean conditions, turbine loading, modal performance targets, and design standards' criteria. The two software programs are similar in framework and share some load calculation routines. JacketSE, includes the dimensioning of the tower component and uses the same structural code checks as TowerSE. The main difference lies in the treatment of the substructure, which in TowerSE is a continuation of the tower to the seabed (the pile) with the addition of a tubular **transition piece (TP)** to allow for the connection of the main pile to the tower. JacketSE solves for a multimember substructure (either three- or four-legged lattice) with a more complicated **TP** at the top [14].

The tools can size **outer diameters (ODs)** and **wall thicknesses (ts)** for piles, legs, braces, and tower; other design variables that may be optimized are batter angle, pile embedment, and tower tapering height. The design parameters (fixed inputs to the tools) include: water depth, deck and hub height, design wind speed, design wave height and period, and soil characteristics (stratigraphy of undrained shear strength, friction angles, and specific weight). Loads from the **rotor nacelle assembly (RNA)** can be input to the model either from other WISDEM modules or directly from the user. The user must also provide acceptable ranges for the design variables — for example, maximum tower diameter, minimum and maximum diameter-to-thickness ratios for the various members, and maximum allowed footprint at the seabed.

The common software framework primarily consists of the following submodules: geometry definition; load calculation; soil-pile interaction; finite element model; and structural code checks. A number of simplifications have been incorporated to allow for rapid analyses of multiple configurations on a personal computer. As such, complex hydrodynamics and associated variables (e.g., tidal range, marine growth, and member-to-member hydrodynamic interaction) are ignored, and fatigue assessments are not carried out by default. Although these aspects can very well drive the design of certain subcomponents and of the overall structure [17–19], it is believed that the main structural and mass characteristics should still be captured by the simplified models for the sake of preliminary design assessments and trade-off studies, and with a level of accuracy limited to those goals. More details on the codes can be found at <https://github.com/WISDEM> and [14].

Within WISDEM, these tools allow for the full gamut of component investigations to arrive at a minimum **LCOE** wind turbine and power plant layout. For example, together with a turbine rotor and blade model, JacketSE can produce a design that meets tower/substructure clearance criteria while also meeting mass or cost targets. In this study, the tools were used in stand-alone mode, wherein the preliminary design realizations for substructures, foundations, and towers, were based on minimizing the overall structural mass.

3.2. PlantEnergySE and AEP calculations

OpenWind Enterprise (<https://www.awstruepower.com/products/software/openwind/>) (**OE**) is a wind power plant micrositeing tool that has been incorporated into WISDEM via the PlantEnergySE module. PlantEnergySE was used to model wind power plant energy output and costs. For each of the prospective sites, the obtained wind data were used to create a **wind resource grid (WRG)** file. A 10-by-10 array of **NREL** 5-MW reference turbines was placed on the wind grid, and **OE** computed the expected **annual energy production (AEP)**. Turbine spacing was 1090m or 8.72 rotor diameters in each direction.

At full capacity (100% **capacity factor (CF)**), the wind power plant would produce $5 \text{ MW} * 8,766 \text{ h} * 100 \text{ turbines} = 4,383 \text{ GWh/yr}$.

Figure 2(a) shows the annual mean wind speed and the wind rose at 90 **MASL** for the site pertinent to Case 1. Divisions within each directional sector show the fraction of wind speeds less than 4, 8, 12 and 25 m/s (full sector). Figure 2(b) shows the variation in capacity factor across the wind power plant, primarily due to turbine wake effects and sheltering.

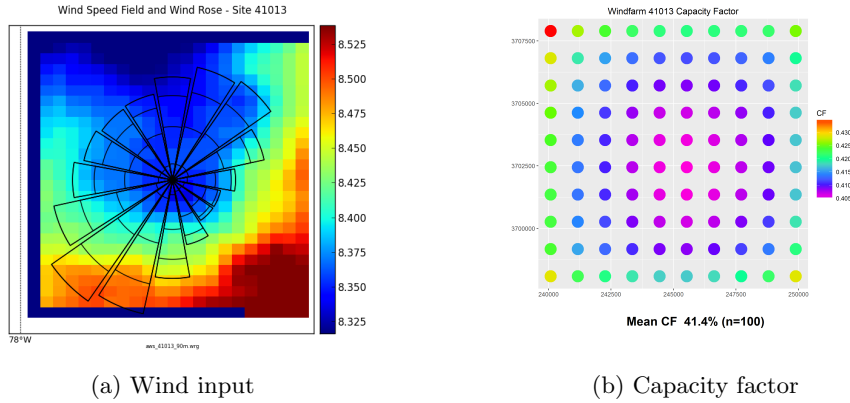


Figure 2. Wind resource and capacity factor for a wind power plant imagined located at the site corresponding to Case 1.

3.3. PlantCostsSE

Overall costs for the turbine and plant were modeled, and the overall wind power plant **LCOE** was calculated via Eq. (1):

$$LCOE = \frac{FR(TCC + BOS) + (1 - TR) OPEX}{AEP} \quad (1)$$

In this study, the effects of the designs on financing via financing rate (**FR**) were ignored and assumed to be a constant 9.8% based on [3]. In addition, the turbine capital costs were taken from reported industry averages [3] of \$1,952/kW, of which 18% is attributed to the tower or a split of U.S. \$1,600/kW for the rotor-nacelle-assembly and U.S. \$352/kW for the tower. This study used a fixed turbine configuration (see Section 3.4), and Case 1, a monopile at a water depth of 23.5 m, was taken as the baseline. Tower cost was then adjusted for each case based on the tower mass relative to the Case 1 tower mass for the monopile configuration. Summing the tower cost to the **RNA** cost gave the overall total turbine capital cost (**TCC**) for each case.

For the plant costs, two models that have been integrated into WISDEM were used. The first model is an empirical model of wind plant **BOS** costs, which has been recently developed by **NREL** [20]. Offshore **BOS** costs are determined based on input parameters that include the turbine configuration (rotor diameter, hub height, and rated power), plant characteristics (water depth, distance to shore, and meteorological-oceanographic data), and support structure characteristics (dimensions and component masses). For this study, the turbine configuration is static while each case is adapted for the particular plant and support structure characteristics. For the operational expenditure (**OPEX**), a model from the **Energy Research Center of the Netherlands (ECN)** was used. The **ECN O&M** calculator processes information that is similar to the **BOS** cost models along with metocean, time-series data [21]. Although the model does calculate maintenance costs for the support structure, the included version does not distinguish

Table 3. Baseline turbine parameters.

Parameter	Value	Unit
Rating	5	MW
Rotor diameter	125	m
Hub height	90	m
RNA mass	350	t
Unfactored peak thrust (DLC1/DLC2)	1.28e3/188	kN
Unfactored moment (DLC1/DLC2)	8.96e2/1.31e2	kN m
Nominal wind speed at max thrust (DLC1/DLC2)	30/70	m s ⁻¹
Target system first eigenfrequency	0.26	Hz

between support structure types, so the operational expenditures depend only on the case site and not on the substructure type. The setup for the model was based on a study of integrated installation and O&M [22]. The full set of plant costs for each case was then incorporated in the cost of energy equation, Eq. (1), to compare the impact of different support structures designs at different types of wind power plant sites with varied water depths.

3.4. Case study assumptions

The reference turbine used for this study was the **NREL** 5-MW turbine [23] with main parameters given in Table 3. The target first natural frequencies, based on a soft-stiff design approach [24], represent the modal performance requested for the various system layouts. Table 2 shows the range of main environmental parameters that were considered; for simplicity, soil characteristics were fixed throughout the various cases at an average stiffness soil profile (friction angles ≥ 35 deg).

Because of the simplifications in the physics of the used software programs, and because of the limited number of load cases considered, additional conservatism was provided by the employed drag (c_d) and added mass (c_m) coefficients, the choice of a worst-case loading scenario, and additional safety factors. Based on verification runs with other codes [14], the substructure c_d and c_m values were doubled with respect to those recommended by [25]; and for the tower, the wind c_d was set at 2 to account for transition piece drag; further, wave loads calculated on the main jacket legs were multiplied by a factor of 4 to account for hydrodynamics effects on secondary members of the substructure otherwise ignored.

Two characteristic load cases were investigated. One, similar to the **International Electrotechnical Commission (IEC) DLC 1.6** [26], assumes maximum turbine rotor thrust and maximum wave load aligned along the base of the structure. The other load case, similar to the **IEC DLC 6.1** [26], assumes the machine idling during an extreme (50-yr) wind and wave event. The loads from the **RNA** were precalculated by RotorSE and DriveSE as was stated earlier.

Both TowerSE and JacketSE were run in stand-alone mode to obtain minimum overall mass configurations of support structures based on **MPs** and jacket substructures, respectively, including the mass of the tower, four-legged jacket, transition piece, and pile(s).

3.5. Optimizer parameters

The optimization made use of **Sparse Nonlinear OPTimizer (SNOPT)**, a gradient-based, sparse sequential quadratic programming method as implemented in Python [27]. The final accuracy in the optimization and the feasibility tolerance were set at 10^{-3} . For each support structure type, the design variables and constraints are listed in Tables 4 and 5. Constraint functions were based on structural integrity and manufacturability criteria (see also [14]).

Table 4. Design variables and constraints for the monopile optimizations.

Description	# of Variables/Constraints
Tower and monopile ODs	3
Tower, TP , and MP ts	4
Utilization against shell and global buckling	68
Utilization against strength	34
Utilization against fatigue	34
Eigenfrequency lower limit	1
Tower taper ratio (manufacturability)	1
Diameter-to-thickness ratio (manufacturability)	7

4. Results

The overall support structure mass as computed by the optimizer is given in Table 6, where the comparison between **MP** and jacket includes the steel of the piles.

The first key finding is that the mass of monopile-tower combination is greater than the jacket-tower combination for all cases. For the **MP** in all cases, the frequency constraint proved to be the binding constraint and pushed the structure to a more massive configuration with diameters and thicknesses above the lower bounds of their respective, allotted ranges (with the exception of tower-top thickness). At low water depths, overall structural mass is similar among jackets and **MPs**, but for the deepest site, the support structure mass when using the **MPs** is nearly double that computed for jacket-based systems. A verification step showed good agreement between the optimization results and industry trends data for the **MPs** [28] (though there is mass underprediction for the **TP**), as shown in Figure 3. In general, we expect the **MP** mass to increase significantly with water depth; it is this increase in mass, along with the associated difficulties in the installation, that cause a decrease in the attractiveness for the **MPs** when moving to deeper water sites.

For the jacket substructure, the comparison to industry trends data [28] shows less agreement than for the **MP** (see Figure 4). Very few data points are available for jackets from the industry (four points on the graph), and it is striking that the data associated with the shallowest site (at a water depth less than 10 m) indicate a mass comparable to that at a site three times as deep. It is speculated that factors other than normal reliability sizing contributed to a larger than normal mass for the project in shallow water. Further, the industry data points at ~25 m are for 6-MW turbine installations, which are expected to be associated with higher loads than those from a 5-MW turbine as assumed in this study. If these data points are scaled by the ratio of the power ratings, they would align closer to the calculated jacket mass trend. The trend in the piles' mass might be affected by the same considerations, and, in addition, actual soil conditions might have promoted the use of larger piles than those calculated in this study for a generic soil.

Although the mass of the monopile-tower support structure is greater than the jacket-tower support structure for all cases, the overall cost impact on **LCOE** of the support structures results in the monopile being economically more favorable than the jacket for water depths up to 40 m. Summaries of the calculated costs are given in Table 7 and Table 8 for the **MP**- and jacket-based wind power plants, respectively.

Table 5. Design variables and constraints for the jacket optimizations.

Description	# of Variables/Constraints
Tower ODs and DTRs	4
Tower waist height	1
TP girder ODs and ts	2
TP deck width	1
Jacket batter	1
Jacket Leg, x-brace , mud-brace ODs , ts	6
Pile OD , t , length	3
Tower taper ratio (manufacturability)	1
Tower utilization against shell and global buckling	36
Tower utilization against strength	18
Tower and member DTRs (manufacturability)	5
Batter range (manufacturability)	1
Maximum footprint	1
Minimum jacket brace angle	1
Jacket member additional structural criteria	10
Jacket member utilization	316
Jacket joint utilization	48
Pile length (manufacturability and axial capacity)	2
Eigenfrequency range	1

Table 6. Computed overall masses in tonnes for the support structures and their towers for each design case.

Case No.	Monopile		Jacket	
	Total Mass	Tower Mass	Total Mass	Tower Mass
1	1,113	324	906	214
2	915	315	850	221
3	1,457	302	965	183
4	814	353	794	225
5	2,160	330	1,183	170
6	1,928	277	1,026	198

First, as noted in the tables, although the overall **LCOE** for plants with **MP** support structures is cheaper in shallow water depth sites, at some point around ~ 40 m, the jacket support structure

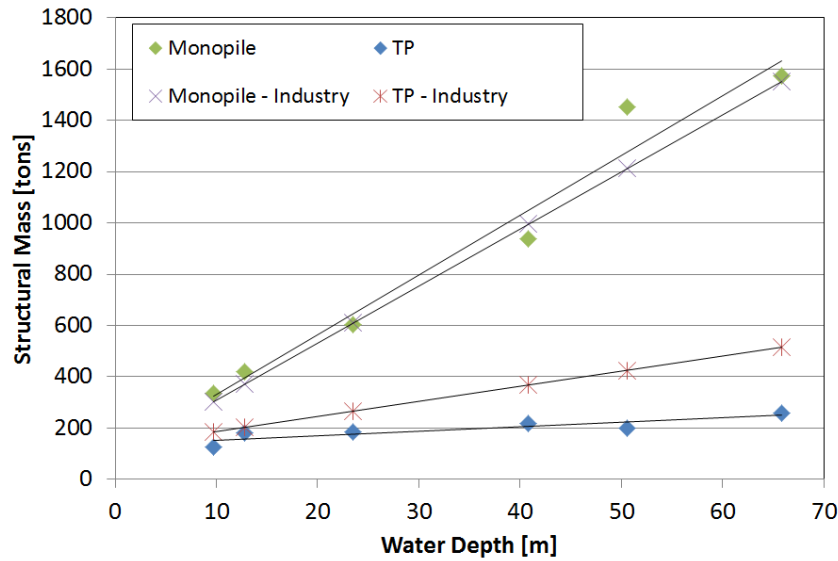


Figure 3. Comparison of optimization results for monopile and transition piece masses with industry data trends.

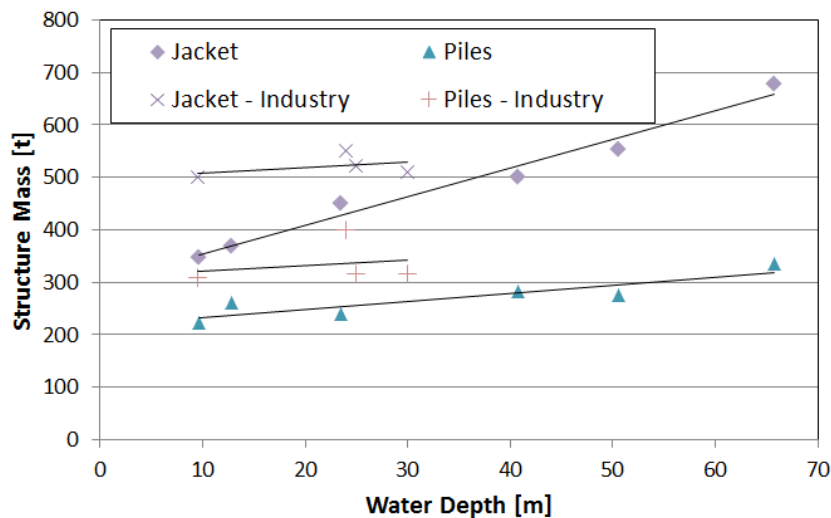


Figure 4. Comparison of optimization results for jacket and pile masses with industry data trends.

becomes the more cost-effective approach. For each case analyzed, Fig. 5 shows the structure BOS difference and the overall LCOE difference when using the MP compared to the jacket support structures. Fig. 5a shows that the crossover point from the calculated, linearized trends in BOS costs occurs around a water depth of ~ 35 m. Although MPs are much simpler to manufacture, as they become larger for deeper waters, the overall material costs overtake the manufacturing costs, and the overall MP BOS costs become greater than those for the jackets. However, the costs for MP installation and assembly are still cheaper than those of the jacket counterparts up to water depths of ~ 50 m. Beyond this depth, the extremely heavy MP would require a different type of vessel for transportation and installation, which is reflected in a step change in BOS cost. For this reason, and as shown in Fig. 5b, around ~ 45 m, the jackets

Table 7. Computed **AEP** and costs for the various cases with **MP** support structures.

Case No.	AEP GWh	TCC \$M	BOS \$B	O&M \$M	LCOE \$/MWh
1	1,815.65	976	2.21	70.28	195.1
2	1,544.88	971	1.71	65.70	195.8
3	2,071.86	964	2.07	70.51	163.9
4	1,638.29	992	1.37	67.24	166.9
5	2,240.18	979	3.48	74.31	215.0
6	1,214.24	950	2.89	65.70	342.4

Table 8. Computed **AEP** and costs for the various cases with jacket support structures.

Case No.	AEP GWh	TCC \$M	BOS \$B	O&M \$M	LCOE \$/MWh
1	1,815.65	916	2.44	70.3	204.6
2	1,544.88	920	1.90	65.7	204.6
3	2,071.86	900	2.18	70.5	166.0
4	1,638.29	922	1.59	67.2	175.2
5	2,240.18	892	3.50	74.3	212.1
6	1,214.24	908	2.81	65.7	332.3

become the cheaper option with respect to plant cost impacts and overall **LCOE**.

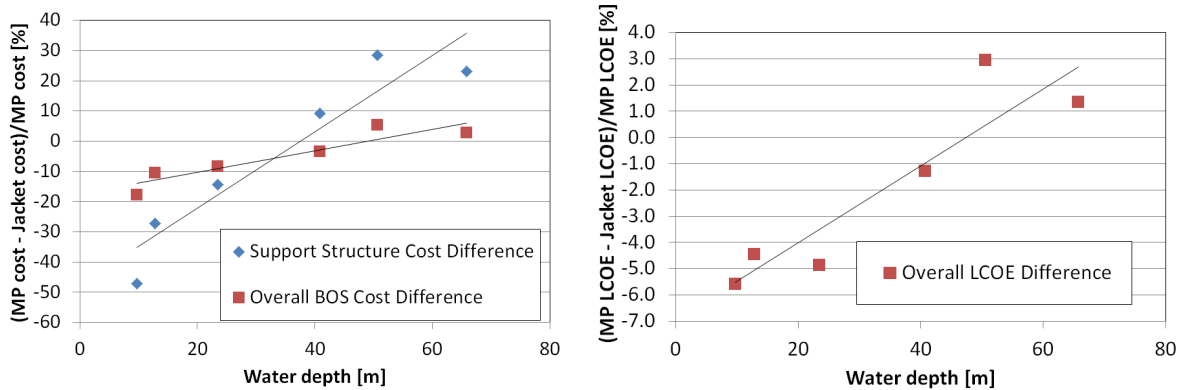


Figure 5. **BOS** costs (a) and **LCOE** difference (b) of the **MP**- and jacket-based support structures as a function of water depth.

5. Conclusions

We proposed a case study to assess the economical applicability of **MP** and jackets as substructure layouts for typical sites along the U.S. Eastern Seaboard and Gulf of Mexico. We used tools available within WISDEM combined with a gradient-based optimizer. One-hundred-turbine, 500-MW wind power plants were envisioned at six sites, where metocean conditions were collected from reliable buoy data and numerical reanalysis. Results showed that the **MP**

is preferable to jackets up to water depths of approximately 40 m. The first U.S. offshore wind power plant, which will use 6-MW turbines, is being built with jacket substructures, although water depth is lower than 40 m. This emphasizes the fact that other factors may have played a bigger role than pure economics in that case, such as the unavailability of large MP construction and installation entities in New England. Nevertheless, the methods proposed in this study can be used by U.S. stakeholders to evaluate various aspects of the project and their effects on the LCOE, including metocean conditions, turbine characteristics, and technology innovations. Future work will account for other DLCs and a full dynamic analysis of the turbine system, which will include the effect of fatigue loading and lead to more accurate estimates of the costs.

Acknowledgments

This work was supported by the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory (NREL). Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office. We acknowledge the insight and feedback on this paper by Aaron Smith and Ben Maples of NREL.

References

- [1] Musial W and Ram B 2010 Large-scale offshore wind power in the United States – Assessment of opportunities and barriers Tech. Rep. NREL/TP-500-40745 NREL Golden, CO
- [2] BVG Associates 2012 Offshore wind cost reduction pathways technology work stream Technical report The Crown Estate
- [3] Mone C, Smith A, Maples B and Hand M 2015 Cost of wind energy review Technical Report TP-5000-63267 NREL Golden, CO
- [4] EWEA 2015 The European offshore wind industry—key trends and statistics 2014 Tech. rep. European Wind Energy Association
- [5] Elliott D, Schwartz M, Haymes S, Heimiller D and Musial W 2011 Assessment of offshore wind energy potential in the United States National Renewable Energy Laboratory Poster PO-7A20-51332 NREL Golden, CO
- [6] Musial W and Butterfield S 2005 Deepwater offshore wind technology research requirements *WindPower 2005* (Denver, CO: AWEA)
- [7] Musial W D, Butterfield S and Ram B 2006 Energy from offshore wind *Offshore Technology Conference* (Houston, TX)
- [8] De Vries et al 2011 Final report WP4.2: Support structure concepts for deep water sites Technical Report UpWind.WP4.D4.2.8-Final Report project Upwind Contract No. 019945 (SES6)
- [9] A2SEA 2013 *A2SEA News* 6–9 Winter Edition
- [10] Damiani R, Ning A, Maples B, Smith A and Dykes K 2016 *Wind Energy* In review
- [11] Zervas C 2013 Extreme water levels of the United States 1893-2010 Tech. Rep. NOS CO-OPS 067 National Oceanic and Atmospheric Administration Silver Spring, MD URL http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_067a.pdf
- [12] Stephenson A G 2002 *R News* 2 31–32 URL http://cran.r-project.org/doc/Rnews/Rnews_2002-2.pdf
- [13] Dykes K, Meadows R, Felker F, Graf P, Hand M, Lunacek M, Michalakes J, Moriarty P, Musial W and Veers P 2011 Applications of systems engineering to the research, design,

- and development of wind energy systems Technical Report NREL/TP-5000-52616 NREL Golden, Colorado
- [14] Damiani R 2016 JacketSE—an offshore wind turbine jacket sizing tool—theory manual Technical Report NREL/TP-5000-65417 NREL Golden, CO
 - [15] Ning A, Damiani R and Moriarty P 2013 Objectives and constraints for wind turbine optimization *51st AIAA Aerospace Sciences Meeting and 31st ASME Wind Energy Symposium* (Houston, TX: AIAA)
 - [16] Guo Y, Parsons T, King R, Dykes K and Veers P 2015 An analytical formulation for sizing and estimating the dimensions and weight of wind turbine hub and drivetrain components Technical Report NREL/TP-5000-63008 NREL Golden, CO
 - [17] Cordle A, McCann G and de Vries W 2011 Design drivers for offshore wind turbine jacket support structures *ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering—OMAE2011* (Rotterdam, The Netherlands: ASME) pp 419–428
 - [18] Zwick D, Schafhirt S, Brommundt M, Muskulus M, Narasimhan S, Mechineau J and Haugsen P 2014 *J. of Physics: Conference Series* **555**
 - [19] Molde H, Zwick D and Muskulus M 2014 *J. of Physics: Conference Series* **555**
 - [20] Maness M, Maples B, Mone C and Stehly T 2016 The NREL offshore wind balance-of-system model: Modeling and analysis techniques Tech. Rep. TP-5000-xxxx NREL Golden, CO (forthcoming)
 - [21] ECN 2007 Accurate estimation of maintenance costs of offshore wind farms with ECN software tool Energy Center of the Netherlands URL <https://www.ecn.nl/news/item/accurate-estimation-of-maintenance-costs-offshore-wind-farms-with-ecn-software-tool/>
 - [22] Maples B, Saur G, Hand M, van de Pietermen R and Obdam T 2013 Installation, operation, and maintenance strategies to reduce the cost of offshore wind energy Technical Report TP-5000-57403 NREL Golden CO
 - [23] Jonkman J, Butterfield S, Musial W and Scott G 2015 Definition of a 5-MW reference wind turbine for offshore system development Tech. Rep. NREL/TP-500-38060 NREL Golden, CO
 - [24] Damiani R and Song H 2013 A jacket sizing tool for offshore wind turbines within the systems engineering initiative *Offshore Technology Conference* (Houston, Texas, USA: Offshore Technology Conference)
 - [25] API 2014 Planning, designing and constructing fixed offshore platforms - working stress design API Recommended Practice 2A-WSD
 - [26] IEC 2009 61400-3 wind turbines—part 3: Design requirements for offshore wind turbines
 - [27] Gill P E, Murray W and Saunders M A 2005 *SIAM REVIEW* **47** 99–131
 - [28] NREL Offshore wind project database internal, unpublished