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Feasibility of Ocean-Based Renewable Energy in the Gulf of Mexico

Walt Musial
Tessa Greco
National Renewable Energy Laboratory

Abstract

This paper summarizes a comprehensive feasibility assessment of six offshore renewable energy sources in the Gulf of Mexico (GOM) to potentially provide utility-scale electricity from the Outer Continental Shelf (federal waters) and state waters to land-based grids. The primary objective is to inform future energy planning. The authors evaluated offshore wind, wave energy, tidal energy, ocean-based solar photovoltaics (PV), ocean current, and ocean thermal energy conversion. Of these energy resources, offshore wind was the most viable option and was the focus of the second part of the study. The technical challenges of developing offshore wind in the GOM are discussed including hurricane design for turbines and substructures, as well as turbine solutions to overcome lower wind regimes. In addition, advantages to offshore wind development in the GOM are described including proximity to oil and gas supply chains. Economic analysis using established cost models at the National Renewable Energy Laboratory identified hypothetical project locations where net value of offshore wind was highest, and the levelized cost of energy (LCOE) was calculated for three sites: Port Isabel, Port Arthur, and Pensacola. Offshore wind LCOE in the GOM was found to be higher than sites along the north and mid-Atlantic coasts but decreasing cost trajectories indicate the possibility of economic viability for locations in Texas and west Louisiana after 2030. The extrapolated 2030 LCOE values range from $73/MWh (Site 1, Port Isabel) and $79/MWh (Site 3, Port Arthur) to $91/MWh (Site 5, Pensacola).

Keywords: offshore wind, Gulf of Mexico, renewable energy, cost

1 Introduction

Over the past 60 years, the Gulf of Mexico (GOM) has provided an abundant supply of energy to the United States with fossil fuels. Through this experience, the technologies and capabilities for installing robust structures in the ocean have been developed and matured. As we seek to diversify our renewable energy supply, we find that many possible sources are based in the ocean. Fortuitously, the oil and gas industries are now able to leverage their vast ocean-based capabilities to expand their markets and capitalize on these energy opportunities (Shell, 2020; Equinor, 2020; Ørsted, 2020; Total, 2020; BP, 2020). This linkage between oil and gas and the emerging renewable energy industry is most evident for domestic offshore wind projects that are moving quickly toward commercialization in the northeastern United States, where a regulatory pipeline that exceeds 25 gigawatts (GW) is propelling a wave of state policy commitments of nearly 30 GW (Musial et al., 2019).

This paper addresses the feasibility of renewable energy development in the GOM where it is less certain. It summarizes the findings of two recently published Bureau of Ocean Energy Management (BOEM) reports written by the National Renewable Energy Laboratory (NREL) (Musial et al., 2020a; Musial et al., 2020b). The first report, Musial et al., 2020a, is a broad survey of all renewable energy sources and evaluates them on their merits based on resource, technical maturity, and cost. The second report, Musial et al., 2020b, focuses on offshore wind energy that was found to be the most viable renewable energy source for the GOM.

From a national perspective, the GOM is one of five U.S. regions classified by the 2016 U.S. Department of Energy (DOE)/U.S. Department of the Interior (DOI) “National Offshore Wind Strategy,” which prescribes a scenario under which 86 GW of offshore wind energy capacity is installed in the United States by 2050 (Figure 1).

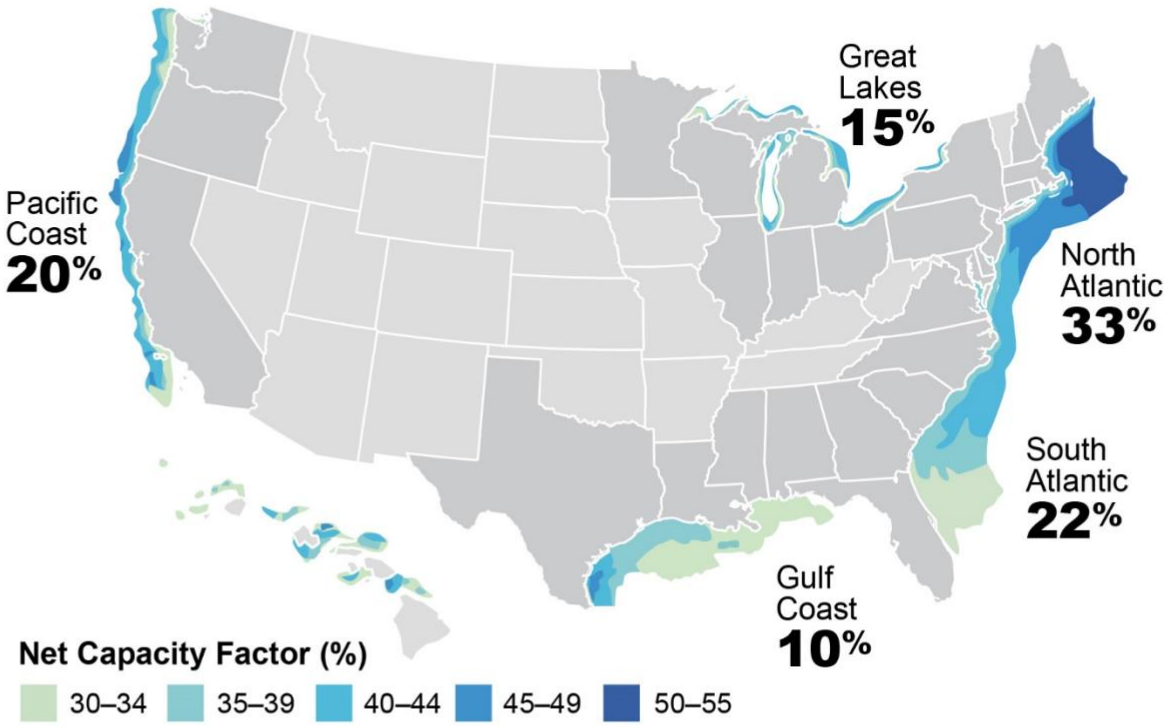

Figure 1. Offshore wind regions showing percentages of an 86-GW scenario that each region contributes by 2050 (Gilman et al., 2016)

At this level of deployment, offshore wind would account for 7% of all U.S. electricity generation (DOE, 2015; Gilman et al., 2016). To achieve 86 GW nationally, the offshore strategy identifies specific innovations and research that will address the challenges to lower the costs to where offshore wind can compete in all regional electricity markets, including the GOM, without subsidies; however, each region has unique challenges that must be specifically addressed.

The 86-GW scenario assumes the GOM would participate by providing 10% of the national total, or approximately 8.6 GW of offshore wind to the region. This target provides a reasonable deployment level to motivate the exploration of barriers to commercialization and cost competitiveness for the GOM. This paper evaluates both the technology and economic barriers and solutions. It does not reach final conclusions on technology or cost but illuminates critical areas for future study. In addition, because this paper was written more recently than the two BOEM reports, the recommendations herein may be more up to date.

2 Survey of Ocean-Based Renewable Energy Sources

In the first phase, we conducted a comprehensive feasibility assessment of the potential for offshore renewable resources to support future electric energy production to the GOM to inform BOEM's[1] strategic plans for possible renewable energy activities on the Outer Continental Shelf in the GOM (Musial et al., 2020a). The study considered potential renewable energy resources under the BOEM jurisdiction as well as coastal resources in state waters[2] focusing on potential offshore renewable energy applications that could be viable for utility-scale electric energy conversion to supply electricity to the land-based grid[3]. Six ocean-based resources were identified as having possible electric-generating potential for the GOM states[4] including:

- Offshore wind energy
- Wave energy
- Tidal energy
- Ocean current energy
- Offshore solar energy
- Ocean thermal energy conversion (OTEC).

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[1] The study was funded by the Bureau of Ocean Energy Management, Gulf of Mexico Division

[2] BOEM's jurisdiction extends from the 200-nm Exclusive Economic Zone to the state water boundary that is located 3 to 9 nautical miles from the shore, depending on the statutory agreements held between the individual states and the federal government (U.S. Congress, 2005; Thormahlen, 1999). Emphasis was on resources in federal waters.

[3] Distributed energy systems to supplement oil and gas production were not considered.

[4] Two other technologies, cold water source cooling and the potential for using the existing pipeline infrastructure to carry manufactured hydrogen to shore, were also considered in the original study but are not discussed in this paper because they are not considered independent energy sources. This discussion and analyses can be found in the full study report (Musial et al., 2020a).

We quantified the feasibility of each renewable energy resource type in the GOM using three factors: resource adequacy, technology maturity, and the potential for competitive cost.

2.1 Resource Adequacy

Resource adequacy was judged based on the quantities of gross and technically extractable resource. Professional judgments were based on the current progress of the technologies using the definitions and methodology for estimating resource potential provided by Musial et al. (Musial et al., 2016). In general, gross resource was calculated as the quantity of electric-generating potential within the geographic boundaries extending from the shore to the 200-nautical-mile (nm) Exclusive Economic Zone boundary with no additional filters applied. Technical resource is a subset of the gross potential resource considering practical depth limits, cut-offs for low power-generating potential, and percentage reductions to broadly account for competing uses. Note that over time technology advancements can potentially increase the technical resource potential by shifting gross resource over to technical resource as the technology evolves. However, the quantity of gross resource does not generally change. Therefore, if the gross resources are small, the technical resources are also small, which will limit market potential. In the ranking of each resource, the technical resource potential was weighted more heavily. However, we considered that a large gross resource potential could indicate a possible long-term opportunity even if the current technical resource is small (e.g., offshore solar).

Typically, we found that for renewable resources that are technically immature, the respective industry methods for calculating resource potential were also immature. In some cases, reasonable estimates could not be found in the literature, which required us to develop new methods to estimate the resource. This required computing nominal power density on a geospatial basis to quantify the gross and technical resource capacity potentials for certain renewable energy sources. The resource potential for each technology type is shown in Figure 2. Note that the vertical scale of the chart is logarithmic to enable resource quantities for all the technologies to be plotted over several orders of magnitude.

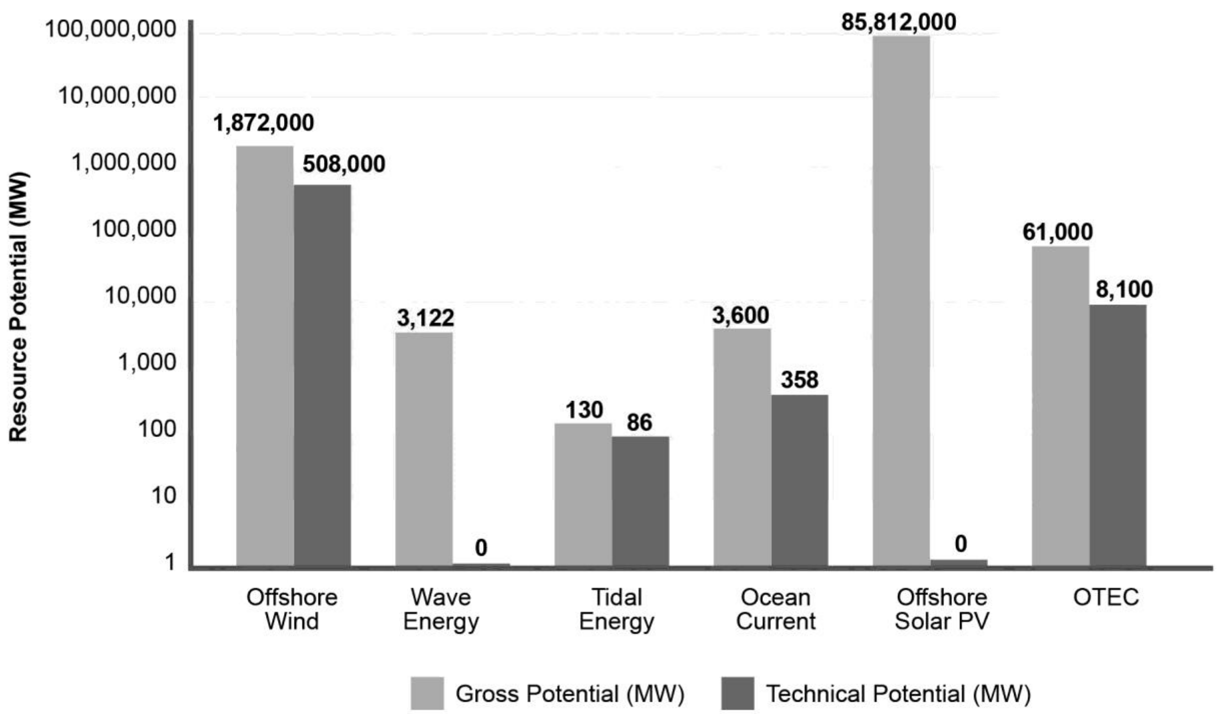

Figure 2. Gross and technical offshore renewable energy potential for the GOM by technology (Musial et al. 2020a)

The analysis revealed that offshore solar photovoltaics had the greatest gross potential resource but lacked a demonstrable method of surviving extreme waves on the open ocean. Therefore, none of that resource was counted as technical potential. This may not be entirely fair, however, because there are many sheltered bays in state waters that may be suitable for ruggedized versions of offshore solar, but this analysis was beyond the scope of this study.

Offshore wind had the largest quantity of technical resource potential, with 508 GW across all GOM states, although Texas and Louisiana provide the greatest contribution.

2.2 Technology Maturity

We assessed maturity based on industry reports, internet research, and correspondence with technology developers that provided evidence of the progress toward commercialization of each technology type. We classified technology maturity into four stages considering progress made over their entire global industries: 1) early-stage research and development, 2) proof of concept, 3) precommercial demonstration, and 4) commercially proven (DOE, 2011). The following observations on technology maturity are derived from Musial et al., 2020a.

Offshore wind has the highest technology maturity level, ranging from precommercial demonstration to commercially proven. Although there are more than 27 GW of offshore wind deployed globally, additional technology development is still needed for the GOM to deploy cost-competitive offshore wind turbines. Adapting turbines to survive major hurricanes and optimizing turbine rotors for the lower wind regimes found in this region[5] are the major challenges.

Wave technology maturity spans from early-stage research and development to precommercial demonstration. Although multiple wave energy devices have been deployed, the industry has not demonstrated commercial operation or predictable energy production profiles through sustained operation of any wave device. The industry is still actively engaged in developing new subscale concepts without significant commercial success.

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[5] Although there is a potential for hurricanes and large storms along the Atlantic Coast, it is likely that tropical storms in the GOM may be more severe and will introduce more extensive design challenges than projects currently being designed for the North Atlantic.

Tidal energy has had some precommercial success globally and is approaching commercialization in some projects, partly because of the underwater adaptation of horizontal-axis wind energy technology, which has similar engineering attributes. However, due to limited resources and siting options, industry maturation has been slow.

Ocean current technology uses similar technology as tidal turbines but has a unique open-ocean resource area. This technology has only been validated at the laboratory/prototype scale; no prototypes have yet been deployed at full scale to date.

Ocean-based solar PV are enabled by proven technology on land where PV has achieved vast commercial success. This success has been extended commercially to deployments over sheltered lakes and reservoirs where some potential has been identified especially in locations where land is scarce (Spencer et al., 2018). However, solar PV has yet to be commercially deployed or tested in open-ocean conditions or in sheltered sites where significant wave loading could occur. There are many sheltered bays and larger lakes where ocean based solar PV could potentially be feasible, but these sites are outside of the BOEM jurisdiction and were not evaluated.

OTEC technology has not demonstrated economic feasibility, and significant technical challenges are still unresolved. A major barrier to its development is that, according to studies, the scale of OTEC power plants must be on the order of 100 megawatts (MW) to realize cost reductions large enough for commercialization and technological success (Ascari, 2012). OTEC deployments to date have been at a scale 1/100th of that size. The OTEC technology requires significant additional research, prototyping and demonstration before it can be deployed commercially.

2.3 Potential for Competitive Cost

Cost information for this study relied on published industry data. The quality of available cost data was highly dependent on the stage of technology maturity. More mature technologies, such as offshore wind, have more accurate cost data because commercial-scale industry data exist. Nascent technologies (lower maturity) inherently have higher cost uncertainty and data are more difficult to obtain and verify. Most of the ocean-based renewable energy resources we examined are early-stage technologies. In these cases, commercial costs were estimated by extrapolating from prototype demonstrations or scale model tests. Therefore, most cost data exhibited high variability and uncertainty, and in many cases the methodology used could not be verified. For example, cost analyses for many technologies did not account for operation and maintenance, which cannot be assessed properly until there is significant deployment. We used the following ocean renewable energy technology cost data sources:

- Offshore wind: Beiter (2017) and Moné et al. (2017)
- Wave energy: International Energy Agency (IEA)-Ocean Energy Systems (OES) (2015), Neary et al. (2014) and Lewis et al. (2011)
- Tidal and ocean current energy: IEA-OES (2015); Neary et al. (2014); Lewis et al. (2011)
- Ocean solar: Bureau of Reclamation (2016); Barbusica (2016)
- Ocean thermal energy conversion: Lewis et al. (2011)
- Cold water source cooling: Vega (2016); Ascari et al. (2012).

2.4 Ocean Renewable Energy Survey Results

Based on the criteria established for three categories: 1) resource adequacy, 2) technology readiness, and 3) cost competitiveness, we conducted a down-select process to rank each offshore renewable technology. Figure 3 shows the results of the renewable energy rankings for the GOM.

Technology Type	Resource Adequacy	Tech Readiness	LCOE Range
Offshore Wind	HIGH	MATURE	$0.095/kWh to $0.19/kWh
Offshore Solar Photovoltaics (PV)	HIGH	EARLY	$0.14/kWh to $0.35/kWh
Ocean Current	MEDIUM	EARLY	$0.15/kWh to $0.38/kWh
Ocean Thermal Energy Conversion (OTEC)	MEDIUM	EARLY* *Small-scale demonstration	$0.14/kWh to $0.98/kWh
Tidal Energy	LOW	MEDIUM	$0.15/kWh to $0.31/kWh
Wave Energy	LOW	EARLY	$0.14/kWh to $1.00/kWh

Figure 3. Renewable energy technology sources and ranking for Gulf of Mexico

The figure shows that offshore wind scored the highest in all three categories. Out of all the renewable energy resources considered; offshore wind has the best potential to serve electric loads in the GOM. As a result, we conducted a more detailed study of offshore wind energy.

3 Comprehensive Offshore Wind Energy Evaluation

The cost of offshore wind energy is rapidly declining in European markets with some European auctions resulting in zero-subsidy bids (Musial et al., 2019). This cost trend appears to extend to the United States where contracted prices for the first commercial projects are near $80/megawatt-hour (MWh) for U.S. projects in the 2022–2023 timeframe (Beiter et al., 2019). These price declines have driven state policy support of nearly 30 GW from eight North Atlantic states as of March 2020. If built, this would result in a 100-billion-dollar industry by 2035 (Bloomberg New Energy Finance, 2018; 4C Offshore, 2018; McClellan, 2019). Potentially, the GOM can capitalize on this emerging offshore wind market by participating in the supply chain serving the North Atlantic. However, this paper focuses on the potential for regional offshore wind projects to serve the electric load in the GOM.

The GOM has a technical offshore wind resource capacity potential of 508 GW[6] and an energy-generating potential of 1,556 terawatt-hours (TWh)/year (yr) (Musial et al., 2016). This resource potential is double the electric usage of the five GOM states, which was about 779 TWh in 2018[7] (U.S. Energy Information Administration [EIA], 2020). Figure 4 shows the offshore wind resource in the GOM as an annual average wind speed heat map. The map shows the western regions (red colors) have higher-quality wind resources, with Texas and Louisiana each having over 200 GW of potential offshore wind electric-generating capacity.

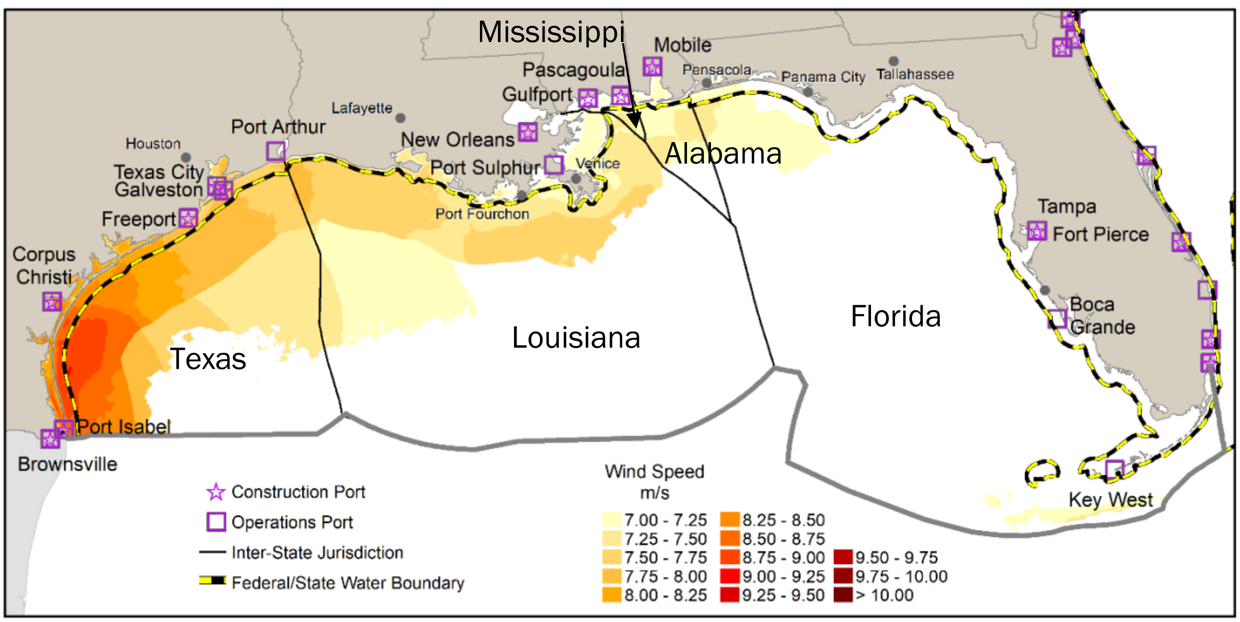

Figure 4. Technical offshore wind resource showing average annual wind speeds in the GOM (Musial et al., 2020b)

[6] The technical resource potential is the subset of capacity that is less than 1000 m depth and greater than 7 m/s average wind speed including all area from the shoreline to the exclusive economic zone.
[7] Note that Florida's electric usage in the GOM was estimated to be 50% of the entire state because half of its coastline is on the Atlantic Ocean.

State political boundaries limit the quantity of resource in Mississippi and Alabama significantly, and low wind speeds limit Florida's capacity. The quantities of resource by state are given in Table 1.

Table 1. Breakdown of GOM Offshore Wind Technical Resources by State and Depth*

State	Capacity < 60 m Depth (GW)	Capacity > 60 m Depth (GW)	Total Capacity (GW)
Florida	18.06	31.50	49.56
Alabama	14.82	3.94	18.76
Mississippi	3.49	0	3.49
Louisiana	119.92	99.82	219.74
Texas	117.46	98.52	215.98
Total	**273.75**	**233.78**	**507.53**

*Includes all area in both state and federal waters

The table also divides the resource by depth. The resource below a 60-meter (m) depth is 273.75 GW, which is 54% of the region's offshore wind resource. Compared to the national average of 42% less than 60 m, the GOM offshore wind resources are shallower and more compatible with fixed-bottom offshore wind technology.

3.1 Unique Challenges of Offshore Wind in the Gulf of Mexico

The commercial offshore wind industry has emerged over the past few years in the North Sea and Baltic Sea where predictable high winds, strong soils, and shallow waters prevail. In the U.S. North Atlantic, where the industry is now establishing itself, there are similar conditions. In the

GOM, offshore wind will encounter unique conditions that present technology challenges such as hurricane exposure, lower winds, and softer soils. Although some of these challenges are significant, they will generally require an adaptation of the existing technology to survive the load conditions and demonstrate cost competitiveness in the regional electric market.

3.1.1 Gulf of Mexico Wind Turbines

Most offshore wind turbines have been designed to operate in regions with high annual average wind speeds (greater than 9 meters per second [m/s]) but also where extreme winds and design loads are predictable and controlled to remain within the envelope prescribed by International Electrotechnical Commission (IEC) standards. All wind turbines are type-certified to these standards (IEC, 2020). GOM wind speeds are lower on average than other offshore wind sites but have higher extremes that are more difficult to predict over the life of the wind plant. This combination of low average winds and higher extremes presents a challenging design optimization problem. Mitigating hurricane exposure could drive designs toward reduced turbine and support structure profiles to minimize extreme drag loading under parked conditions. Conversely, lower wind speeds could drive designs toward larger rotors (lower specific power) to increase capture area. These competing objectives indicate that a new class of GOM wind turbines is needed to maximize energy production in lower winds, but with strengthened blades and support structures to withstand extreme conditions and lower technical risk. These GOM turbine design attributes may incrementally increase capital expenditures, but with an intelligent design optimization strategy, higher capital expenditures can be offset by net energy gains and technical risk management that supports economic competitiveness and financial investment.

3.1.2 Hurricane Exposure

The GOM is highly prone to hurricanes that have the potential to bring extreme wave heights and wind speeds that could exceed load envelopes prescribed by the governing design standards. Although the wind turbine and support structure are ultimately considered as a coupled system, the design process typically begins by separating the support structure and the wind turbine designs. Later they are brought together and analyzed holistically.

For support structures, which comprise the foundation, substructure, and tower in fixed-bottom systems, designs rely on the American Petroleum Institute (API) RP 2A design standard, which depends on regionally specific “hazard curves” to estimate the hurricane risk (API, 2019). The steepness of the regional hazard curves (e.g., the coefficient of variation) varies geographically, and must satisfy the API robustness criteria for defining hurricane risk, requiring understanding of return periods for 50, 100, and 500 years at the project site (Hall, 2015; IEC, 2019b). Therefore, all offshore wind projects use site-specific external conditions in the design basis for the support structure. The API RP 2A criteria have been recommended in the United States to ensure adequate safety for the design of fixed-bottom support structures on wind turbines (American Wind Energy Association, 2012). Dolan (2009) showed that IEC and API standards could deliver approximately the same level of safety for the turbine and support structure, respectively. However, API standards are limited to static structures and do not cover the wind turbine itself.

Unlike the support structure, wind turbines are not custom designed for site conditions. They are type-certified to IEC standards according to design classes that are detailed in IEC 61400-01 and 61400-3-1 (IEC, 2019a; IEC, 2019b). The most severe design class in earlier editions of IEC 61400-01, Class 1, specified an extreme 3-second (s) gust of 70 m/s. The existing Class 1 design extremes already cover maximum gust criteria for many hurricane-prone sites. For example, Hurricane Sandy that caused widespread destruction to the northeastern United States upon landfall in 2012, had recorded maximum wind speeds of only 115 miles per hour (mph), which all wind turbines are designed to survive (Blake, 2013; IEC, 2019a).

The challenge is that "major" hurricanes[8], which are more prevalent in the GOM, may embody conditions that are even more severe in terms of extreme gusts, waves, or events involving more complex combinations of these external load drivers. Site-specific risk assessments are needed in these high-hurricane-risk areas to determine more precisely where turbine designs need to be enhanced, or where additional hurricane load mitigation strategies (e.g., auxiliary on-board power supplies to maintain yaw authority during hurricanes) should be implemented.

The 2019 edition of the IEC 61400-01 wind turbine design standard added a wind turbine Typhoon Class that increases the 3-s gust criteria from 70 m/s to 80 m/s (179 mph). In many regions, this may be enough to adapt turbines to major hurricanes, but a full geospatial assessment of hurricane risk is needed to more accurately define the envelope of design conditions throughout these regions.

In the analysis, we did not account for the additional cost that would be added to the turbine itself to ruggedize it for hurricane resilience. We included a 25% increase in the insurance costs to account for hurricane uncertainty. In practice, wind turbine original equipment manufacturers hold liabilities associated with warranty provisions and may adjust the pricing structure for a

[8] The National Hurricane Center uses the Saffir-Simpson Hurricane Wind Scale, which is a 1 to 5 rating based on a hurricane's sustained wind speed. Hurricanes reaching Category 3 (sustained winds above 50 m/s (111 mph) at 10 m) and higher are considered major hurricanes (National Hurricane Center, 2020).

given site to account for the perceived level of risk associated with exposure to hurricanes. Follow-on studies should be done to assess the additional capital expenses to accommodate more stringent design standards required for hurricane-prone regions. These studies should also consider detailed assessments of the resulting technical risk and how it relates to possible increased insurance expenses and contingency levels.

3.1.3 Low Average Wind Speed

The offshore wind speeds in the GOM are lower than northern Atlantic and Pacific coastal states, which decreases the capacity factors and net energy yield. The conventional method of offsetting energy production at low-wind-speed sites is to increase the rotor diameter to make more kinetic energy available for conversion. Commercial land-based wind turbines typically come with different rotor size options corresponding to different wind regimes. A site with a lower annual average wind speed will generally require a larger rotor (larger capture area) to maximize energy generation, compensating for less power in the wind. Generally, a land-based site with lower average winds has lower extreme winds, which helps mitigate the cost of rotor upsizing.

Large rotors have lower specific power ratings[9], and higher capacity factors for a given site. Turbine specific power (SP) is defined as the turbine power nameplate rating (P_R) divided by the area swept by the rotor (A) in square meters, as shown in Equation 1:

$$SP = P_R/A \tag{1}$$

Offshore wind turbines have historically been deployed at European sites (e.g., North Sea), where typical annual average wind speeds are very high (i.e., annual average wind speeds greater

9 An analogy for specific power is in sailboats, where larger sails (e.g., spinnakers) are used during lower wind speeds to increase travel speeds.

than 10 m/s [33 feet (ft)/s] are typical). At these sites, most offshore wind turbines have relatively high specific power ratings.

In the GOM, annual average wind speeds range between 7 and 9 m/s (23 to 30 ft/s). Therefore, for optimum performance, larger rotors will be needed. These larger offshore wind turbine rotors may be implemented, like in the land-based wind industry, but the additional extreme loads imposed by hurricanes on larger blade profiles must also be considered. Therefore, the challenge is to design for higher loads resulting from extreme hurricane winds while accommodating longer blades for lower winds.

Figure 5 shows the result of a preliminary NREL study that relates average annual wind speed to specific power rating.

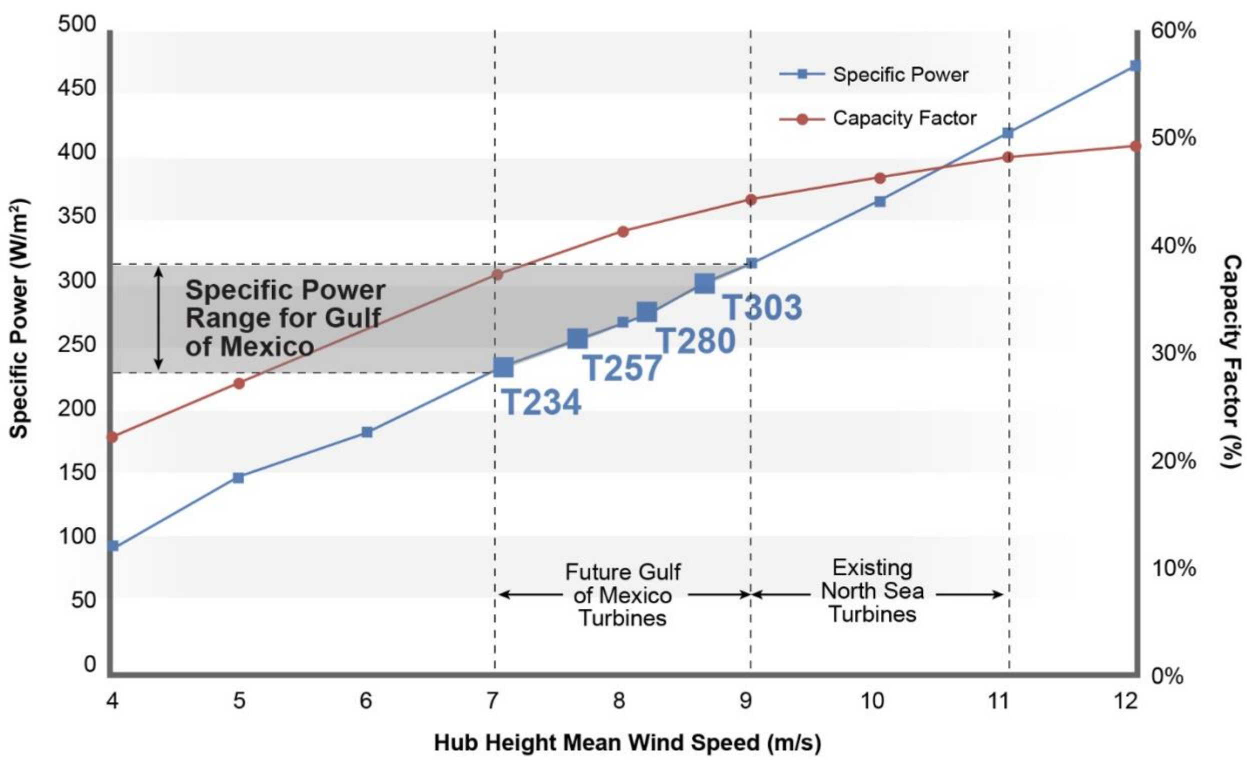

Figure 5. Specific power versus average annual wind speed showing lower-specific-power turbines are optimal between 230 W/m^2 and 320 W/m^2 for the GOM (Musial et al.,2020b)

It illustrates how optimal turbine specific power and corresponding capacity factors vary with annual average wind speed at hub height (Dykes et al., unpublished). Although this optimization study was conducted in the context of land-based wind turbines, the methodology was used for approximating the best specific power for offshore wind turbines. Using this analysis, the turbine specific power ratings for maximum energy production were estimated for various sites. For offshore wind turbines in the North Sea (9 to 11 m/s (30 to 36 ft/s) average annual wind speed) the analysis suggests the optimum is between 300 watts per square meter (W/m^2) and 400 W/m^2, close to the specific power of today's commercial fleet. For the GOM, with annual average wind speeds between 7 and 9 m/s, ideal specific power ratings for wind turbines range between 230 W/m^2 and 320 W/m^2. The data points labeled T234, T257, T280, and T303 represent the four hypothetical turbines used for this study. Table 2 gives the assigned rotor diameters, hub heights, generator nameplate ratings, and corresponding wind speed ranges of these turbines.

Table 2. Turbine Technology Assumptions for GOM Offshore Wind Cost Analysis

Turbine Designation	Baseline DTU 10 MW	T234	T257	T280	T303
Applicable Wind Speeds (m/s)	9.0	<7.25	7.25 to 7.75	7.75 to 8.25	> 8.25
Rotor Diameter (m/ft)	205/673	233/764	223/732	213/699	205/673
Specific Power (W/m2)	303	234	257	280	303
Hub Height (m/ft)	125/410	141.5/464	136.5/448	131.5/431	126.5/415
Turbine Rating (MW)	10	10	10	10	10

Figure 6 illustrates the relative scale of each of these turbine's rotors and hub heights to help visualize the subtle but important size differences among this set of wind turbines. Each turbine is a variant derived of the 10-MW Danish Technical University (DTU) reference turbine (Bak, 2013).

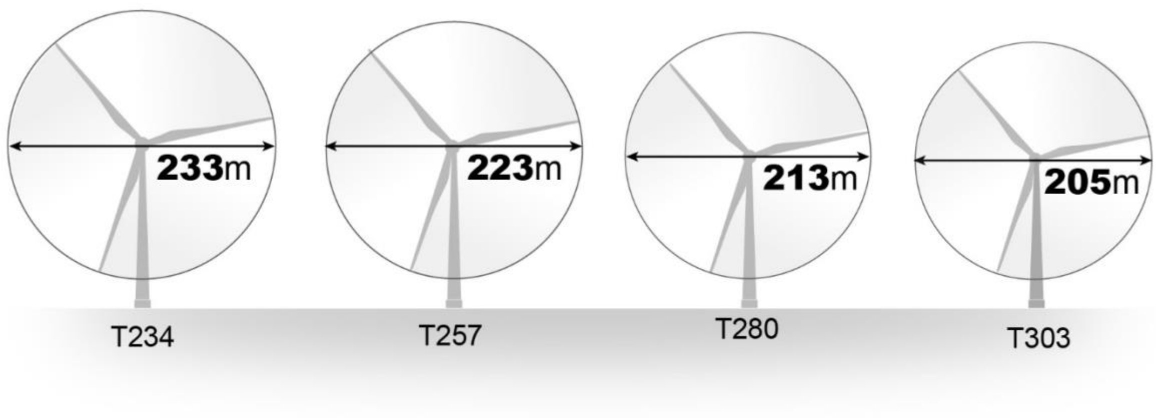

Figure 6. Comparative view of four 10-MW conceptual GOM turbines showing increasing rotor diameter with decreasing specific power (Musial et al 2020b)

The conceptual turbines all have nameplate ratings of 10 MW, but rotor diameters range in size from 205 (DTU reference turbine) to 233 m. The 233-m rotor has 29% more swept area than the DTU reference turbine, thereby allowing much greater energy yield but more challenging blade and turbine design.

The power curves corresponding to the four 10-MW turbines are described in Musial et al., (2020b). The primary observable difference in the power curves is that the lower-specific-power turbines with larger rotors reach rated power at a lower wind speed.

One of the most obvious industry technology trends is that turbine size continues to grow with time. Increasing turbine nameplate rating is a major driver helping to lower cost for offshore wind. Therefore, developers generally want the largest turbine nameplate rating available. When this study began the largest available turbine size was 8 MW. As a result, we selected a 10-MW wind turbine for this study because, conservatively, turbine ratings of this size would realistically be available for the years modeled out to 2030. However, recent market dynamics have stimulated turbine growth beyond the anticipated 10-MW wind turbines. Turbine sizes of 12 MW will be available for commercial use by 2022 and even larger turbines may be commercially available by 2030 (General Electric, 2018). Therefore, the use of a 10-MW turbine in this study may be overly conservative and estimated costs may be higher than if the costs were modeled today. Future cost analysis should examine the impact of larger turbines for the GOM to fully understand the cost reduction potential of turbine sizes up to at least 15 MW.

3.1.4 Softer Soils

The GOM has softer soils than other regions where offshore wind development has occurred or is being considered. Soft soils and the possibility of breaking waves in shallow waters may preclude monopiles, which is the most common offshore wind substructure type. Jacket substructures are commonly used by the oil and gas industry throughout the GOM and are more compatible with weak soils and breaking waves. However, even with jackets lower soil strength requires additional steel to react lateral forces that will increase their weight and cost. Proposed mitigation strategies include adding more steel and/or using longer piles to offset lower natural frequencies. This design adaptation is not complex but must be considered early in the design process and will add some cost. To account for these softer soils and reduced substructure stiffness, we artificially increased water depths by an additional 5 m (16.5 ft) to force additional substructure cost while maintaining the equivalent substructure stiffness as jackets designed to operate with stronger soils representative of the North Atlantic. This simple adjustment approximated the same cost change in the model to account for soil strength. For this study, the added cost to the support structure included the impact of larger rotors and softer soils. Generally, the study found that soft soil conditions, shallow waters, and the existing supply chain infrastructure in the GOM all favor the use of jacket-type substructures.

3.1.5 Summary of Gulf of Mexico Challenges

Turbines designed for the GOM will need to address the additional risk caused by hurricanes while simultaneously addressing the lower wind speed regime. Turbines that minimize project cost by balancing higher energy production and increased hurricane load resistance may have unique design features not found in the current fleet of turbines.

Although current, upwind, three-bladed yaw-controlled turbine architectures are likely to remain suitable for adapting to hurricane conditions, some additional features have been suggested for optimizing turbines to withstand extreme hurricane loads. These features include lower rotor solidity by increasing blade tip speed, low-solidity two-bladed rotors, highly ruggedized wind speed and yaw sensors to allow for continued operability under extreme conditions, active advanced load mitigation control systems, uninterruptible yaw power positioning, and downwind rotors. The development of hurricane-resilient turbines may be accelerated by offshore wind demand in other hurricane-prone markets such as the U.S. South Atlantic, southeast Asia, India, and Hawaii.

Future studies should address the hurricane resiliency of turbines that may be sited in the GOM, as well as the South Atlantic and other areas that my encounter severe tropical cyclones. There is a higher degree of uncertainty regarding the risk of wind turbines in these regions but with better design tools and experience the industry may be able to reduce uncertainty to the same level as non-hurricane-prone sites.

This study accounted for higher turbine costs caused by larger rotors associated with low-specific-power (low wind speed) turbines but did not account for additional costs related to hurricane resiliency.

3.2 Advantages of Offshore Wind Technologies in the Gulf of Mexico

Some technical advantages are also found in the GOM that may help offshore wind compete by offsetting increases caused by the technical challenges. These benefits include better turbine accessibility, shallow water, lower labor cost, and direct access to the existing industrial supply chains of the oil and gas industry.

Lower average wave heights allow construction and service vessels greater access and longer windows to perform installation and maintenance activities, resulting in lower capital cost as well as operation and maintenance costs for the project. In the northeastern United States, many marine operations are shut down during winter months, but expanded seasonal operations in the GOM will have a positive impact on cost.

GOM sites are characteristically shallower than sites in the northeastern United States and shallower water depths have a direct impact on lowering substructure cost. Shallow depths also might enable a wider range of vessel options for project construction and maintenance (Musial et al., 2020b).

According to the U.S. Department of Labor, the GOM has lower labors costs, which translates to lower capital costs for locally sourced components, service, and construction (EIA, 2016).

Finally, the GOM is the center of marine operations and manufacturing supply chain activities for the U.S. oil and gas industry. Offshore wind supply chains and marine operation requirements are very similar to the offshore oil and gas industry; therefore, the GOM is beginning at a higher level of maturity than other regions of the country. This advantage can allow GOM businesses to serve the other regions directly or lower costs for regional offshore wind industry development (Musial et al., 2020b).

3.3 Cost of Offshore Wind in the Gulf of Mexico

In this work, we quantified offshore wind energy resources in the GOM and determined its technical and economic potential to inform federal and GOM state strategic energy planning. The ability of offshore wind to serve the electric load in the GOM depends on overcoming the primary technical challenges and enabling lower costs commensurate with other regions.

3.3.1 Cost Modeling

We used NREL's Offshore Regional Cost Analyzer (ORCA) and geographic information system databases to estimate offshore wind energy development potential for the GOM states: Florida, Alabama, Mississippi, Louisiana, and Texas (Beiter et al., 2016).

We produced regional maps to document the offshore wind resources and economics. Further, we calculated the LCOE, levelized avoided cost of energy (LACE), and net value on a grid, approximately 10.8 by 10.8 kilometers (km) (6.7 by 6.7 miles [mi]), representing the approximate dimensions of a hypothetical 600-MW wind power plant for the target year of 2030 (Beiter et al., 2016). The four conceptual turbines described in Section 4.1.3, with different specific-power ratings at 234 W/m^2, 257 W/m^2, 280 W/m^2, and 303 W/m^2, respectively, were used in ORCA to maximize annual energy production at lower average wind speed regimes ranging from 7.0 to 9.0 m/s (23 to 30 ft/s).

ORCA is frequently upgraded and validated to keep up with industry progress. One of the limitations of this analysis is that the GOM results reflect the state of the art as of early 2018. Substantial improvements to the model have since been implemented. Generally, these more recent ORCA model improvements would result in lower costs relative to those reported herein.

For this analysis, we made the following assumptions for the GOM-specific model runs[10]. Many of these assumptions are unique to the GOM or reflect industry trends made evident after the publication of the 2016 and 2017 Beiter et al. reports (Beiter et al., 2016; Beiter et al., 2017). These assumptions are:

1. A relatively mature supply chains exists with the availability of U.S.-flagged vessels and suitable ports, harbors, and assembly areas.
2. Adapted low-wind-speed, hurricane-resilient turbines will be available for 2030 commercial operations.
3. A 25% increase in insurance costs is needed to account for hurricane uncertainty (although hurricane design criteria also need to be applied).
4. A fixed charge rate of 9.1% would apply for financing (previous rate was 10.5%). New evidence for fixed-bottom systems suggests that the fixed charge rate could now be as low as 7.1%.

[10] Note that the cost of offshore wind is rapidly changing, and the assumptions made for this paper would not reflect all the cost dynamics of this technology such as lower finance costs and larger turbines. Generally, the cost trends reflected in this study are conservative relative to costs obtained after the analysis was completed.

5. A 3 to 14% additional turbine cost accounts for larger rotors and enhanced support structures on the low-wind-speed turbines.
6. Increased annual energy production was realized because of reduced downtime and higher turbine availability, resulting from lower sea states and the milder GOM climate.
7. Wake losses, electrical transmission losses, and other loss parameters were the same as those used Musial et al. (2016) and were used to determine net capacity factor and net annual energy production.
8. To account for softer soils in the GOM and reduced substructure stiffness, we assumed water depths to be 5 m (16.5 ft) greater than the actual depth. The target was to achieve the equivalent substructure stiffness as jackets designed to operate with stronger soils such as the North Sea or northeastern United States. This had the intended effect of increasing cost to the substructure.
9. We applied supply chain cost reductions to some cost elements (e.g., jacket substructure) to account for closer proximity to substructure fabrication facilities, lower mobilization costs, and better access to U.S.-flagged vessels.

For this study, we ran ORCA with GOM site parameters inputs using modeled years 2015, 2022, and 2027. These data were then extrapolated to estimate costs for 2030.

3.3.2 Cost and Economic Potential of Offshore Wind

The cost analysis focused on sites that indicated the highest net value for the region. Offshore wind economics are typically evaluated based on LCOE, which reflects the total cost of generating a unit of electricity over the lifetime of the facility and is commonly expressed in dollars per megawatt-hour. LCOE varies by location because of geographic factors that affect energy production. However, LCOE is not enough to assess economic viability because it does not account for the value of the electric-generating asset to the electric system which varies geographically (Musial, 2018). To calculate economic potential, we determined the LACE for each offshore location (Beiter et al., 2017). LACE is a metric used to approximate the electric system value of a generation technology operating in each location over its expected lifetime and commonly expressed in \$/MWh. LACE is affected by unique parameters including coincidence with load, available transmission, forecast uncertainty, and variability of generation profiles (Hirth, 2013). The difference between LCOE and LACE at a given location is defined as net value, and is used to define economic potential, which is the subset of sites within the resource area in which net value is greater than zero.

As such, net value at a given site, i, is defined in Equation 2:

$$\text{Net value (\$/MWh)}_i = \text{LACE} - \text{LCOE} \quad (2)$$

For a given offshore wind site to have economic potential, net value must be a positive quantity (Beiter et al., 2017).

Figure 7 presents the results of the net value analysis for the GOM shown in a heat map estimated for a commercial operation date (COD) of 2030.

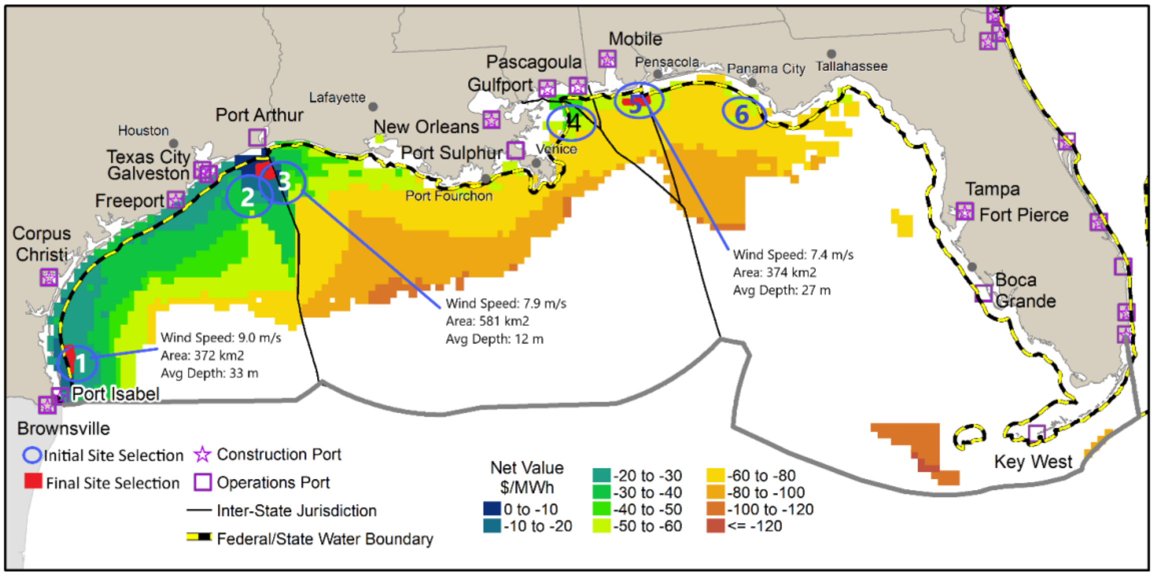

Figure 7. Estimated net value for GOM (2030 COD) (Musial et al., 2020b)

Note: 2030 data were extrapolated from modeled data for 2015, 2022, and 2027 in Beiter et al. (2017).

Net value ranged from -$5/MWh to -$125/MWh, indicating that LCOE from offshore wind was still greater than LACE at all GOM locations in 2030. However, declining LCOE trends are driving net value upward with time. Model results showed that many sites had a net value approaching 0 by 2030 and were within the margin of error for estimating economic potential. These nearshore sites off Texas and western Louisiana were near the municipal areas of Port Arthur and Corpus Christi. Regional clusters of locally high net value were also identified off Gulfport, Mississippi, and Pensacola, Florida.

Six sites were identified on this map as possible locations for further cost analysis: Site 1 (Port Isabel), Site 2 (Galveston), Site 3 (Port Arthur), Site 4 (New Orleans), Site 5 (Pensacola), and

Site 6 (Panama City). From these six sites, Site 1, Site 3, and Site 5 (Figure 7) were chosen by BOEM and NREL for more detailed cost analysis.

The three sites met the following selection criteria:

- High net value within its subregion.
- Area of at least 350 km^2/86,487 ac, large enough for a commercial-scale wind plant of at least 1,000 MW (assuming an array density of 3 MW/km^2)
- Low relative LCOE
- Located in federal waters but far enough from shore to avoid conflicts with coastal communities over viewshed issues
- Located in shallow waters less than 40 m [131 ft]) to enable low-cost installation.

Figure 8 shows the LCOE modeled by ORCA for the three GOM sites for the years 2015 through 2027 and extrapolated to 2030 (COD). ORCA estimated that the LCOE values for projects commissioned in 2015 would vary from $139/MWh at Site 1, to $149/MWh at Site 3, to $183/MWh at Site 5. The modeled LCOE values declined at each site out to 2030. The extrapolated 2030 LCOE values range from $73/MWh (Site 1), to $79/MWh (Site 3), to $91/MWh (Site 5).

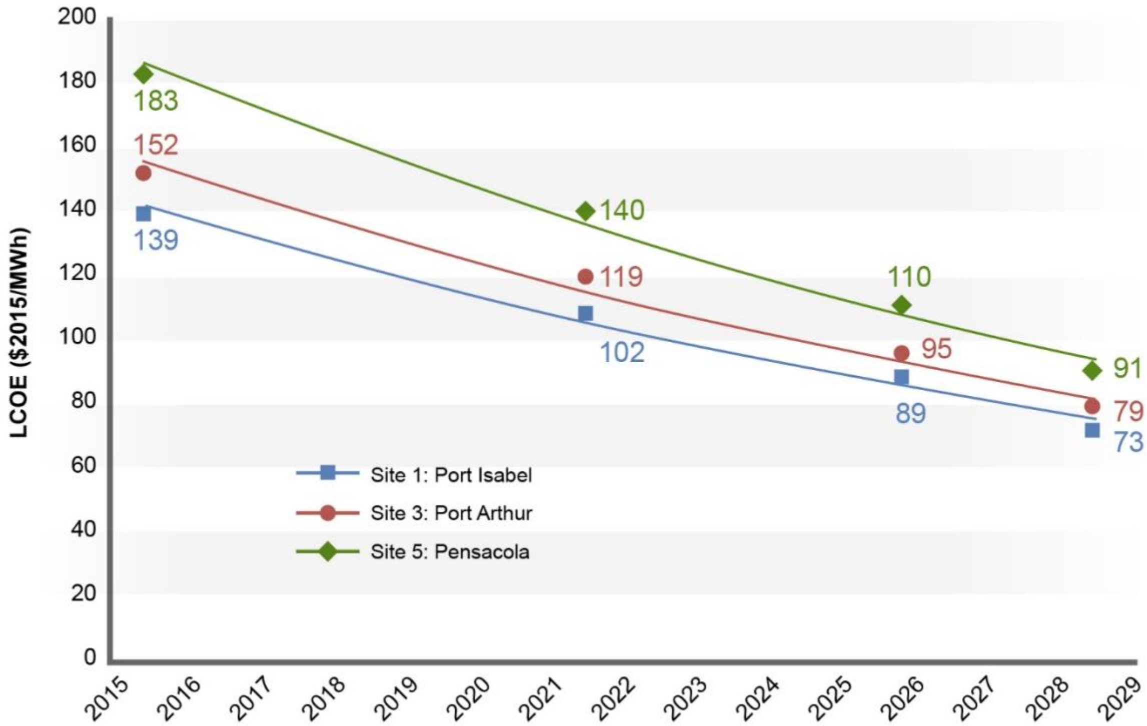

Figure 8. Estimated LCOE for the three modeled GOM sites from 2015 to 2030 (COD) (Musial et al 2020b)

These LCOE values indicate trends consistent with other cost declines seen in Europe and the northeastern United States, though at a slower pace (Musial et al., 2019). The slower pace can be attributed to the need for technology adaptations to address hurricanes and lower wind speeds that result in incrementally higher LCOE relative to the northeastern United States. Another important economic factor, not related to LCOE, is the lack of specific offshore wind state policy commitments in the GOM that are driving offshore wind development in other regions of the United States, such as the North Atlantic and the Pacific.

4 Conclusions

The Gulf of Mexico is characteristically different from other sites where offshore wind is being developed today. There are advantages and disadvantages of this location that require a more careful look to determine its technical and economic viability. Hurricane conditions and lower wind speeds are the primary technical challenges that need to be addressed but solutions are tenable with the proper investment and engineering.

Costs are higher than in the northeastern United States because of these challenges, but offshore wind costs are declining in all areas as a result of technology advancements, experience, increased competition, and lower project risk. GOM projects will benefit from the same macroscopic economic benefits as the rest of the industry. However, the unique preexisting oil and gas supply chains in the GOM could contribute to accelerated maturation of its offshore wind industry and consequently, lower costs.

The best opportunities for offshore wind in the GOM were in the western regions along the Texas coast and in western Louisiana. These subregions correspond to the most favorable winds and the best economics. Although none of the sites in the GOM were estimated to have positive net value, cost trends indicate that economic potential (development without subsidies) is possible at some sites after 2030.

The modeled (extrapolated) LCOE values for 2030 ranged between $73/MWh at Site 1, $79/MWh at Site 3, and $91/MWh at Site 5. These costs reflect the modeling assumptions in early 2018, which have been updated more recently in NREL's ORCA model. All indications are that costs today would reflect lower costs than those reported here.

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