OCS Study
BOEM 2020-018

Offshore Wind in the US Gulf of Mexico: Regional Economic Modeling and Site-Specific Analyses

U.S. Department of the Interior
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List of Abbreviations and Acronyms

Short Form	Long Form
A/C	air conditioning
AEP	annual energy production
AEP_{net}	net annual energy production
API	American Petroleum Institute
AWST	AWS Truepower
Bureau of Labor Statistics	BLS
BOEM	Bureau of Ocean Energy Management
BOS	balance of station
CapEx	capital expenditures
COD	commercial operation date
D	diameter
DOE	Department of Energy
DTU	Danish Technical University
EIA	Energy Information Administration
EEZ	Exclusive Economic Zone
EPAct	Energy Policy Act of 2005
EPCI	Engineering-Procurement-Construction-Installation
ERCOT	Electric Reliability Council of Texas
FCR	fixed charge rate
ft	feet
FTE	full-time equivalent
GCF	gross capacity factor
GDP	gross domestic product
GOM	Gulf of Mexico
GW	gigawatt
HTE	high temperature electrolyzer
IEC	International Electrotechnical Commission
IMPLAN	Impact Analysis for Planning
I-O	input-output
JEDI	Jobs and Economic Development Impact model
kWh	kilowatt-hour
kV	kilovolt
LACE	levelized avoided cost of energy
LCOE	levelized cost of energy
LSU	Louisiana State University
LTE	low temperature electrolyzer
M	meter
m/s	meters per second
MW	megawatt
NCF	net capacity factor
Nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OCS	outer continental shelf
OpEx	operational expenditures
ORCA	Offshore Regional Cost Analyzer
OTEC	Ocean Thermal Energy Conversion
PEM	Proton Exchange Membrane Electrolyzer
PPA	power purchase agreement
PV	photovoltaic
RE	renewable energy
S	second

Short Form	Long Form
SP	specific power
US	United States
W	watts
WACC	weighted average cost of capital
WEC	wave energy convertor
WRF	Weather research and forecasting model
WTK	WIND Toolkit
Yr	year

Summary

The goal of this study is to assess offshore wind energy resources in the Gulf of Mexico (GOM) and to quantify its technical and economic potential in order to inform Federal and GOM state strategic energy planning over the next decade. The objectives are to:

- Describe site-specific and regional benefits and challenges of deploying offshore wind in the GOM and discuss the current research to mitigate challenges;
- Review and quantify the wind resource capacity and energy potential in the GOM region for each GOM state including state and federal waters, distance from shore, and water depth;
- Perform geospatial regional economic assessments of levelized cost of energy (LCOE)[1], levelized avoided cost of energy (LACE)[2], and net value (Section 3.4.2);
- Evaluate three representative hypothetical locations for site-specific analysis;
- Perform a high-level assessment of local supporting infrastructure availability, including existing services (e.g., fabrication facilities, vessels, ports) and possible grid connection options;
- Assess the regional economic impacts of a 600 megawatt (MW) offshore wind power plant installed at a representative site in the GOM.

Based on the findings from the first phase, during which all renewable energy sources in the GOM were evaluated[3], the National Renewable Energy Laboratory (NREL) determined that offshore wind has the highest potential to deliver utility scale electricity from ocean-based renewable energy in the GOM. This conclusion is based on the quantification and relative scoring based on three factors: resource adequacy, technology readiness, and cost competitiveness. As shown in Figure S-1, the technical resource potential for offshore wind in the GOM is 508 gigawatts (GW), the largest of any of the technologies examined (red bars)[4]. In addition, its ability to serve a large percentage of the electric load primarily depends upon achieving lower cost. If current cost trends observed in Europe and the northeast United States (US) continue, the economics of offshore wind in the GOM over the next decade will approach positive net values in some regions, particularly in Texas and Louisiana.

The offshore wind resources were assessed for each of the GOM states. These wind resources are generally lower than northern Atlantic and Pacific coastal states, but the quantity of resource capacity in the GOM is large, especially in shallow water less than 60 meters (m) (197 feet [ft]) deep. As shown in Figure S-2, when considering all US states and considering only sites with average wind speeds of greater than 7 meters per second (m/s) (15.7 miles per hour [mph]) and water depths less than 1,000 m (3,280 ft), three of the top four states with the highest offshore wind resource capacity are within the GOM (Louisiana, Texas, and Florida).

[1] Levelized cost of energy (LCOE) determines how much money must be made per unit of electricity to recoup the lifetime cost of the system. This includes initial capital cost, maintenance cost, and operational cost.
[2] Levelized avoided cost of energy (LACE) represents the electrical system value to the grid. In other words, it measures what it would cost the grid to generate the electricity that is otherwise displaced by a new generation project or a measure of the market value of that electricity.
[3] Survey and Assessment of the Ocean Renewable Energy Resources in the U.S. Gulf of Mexico, OCS Study BOEM 2020-017, which evaluated offshore wind, wave energy, tidal energy, ocean current energy, offshore solar photovoltaics, and ocean thermal energy conversion.
[4] One GW of offshore wind capacity can generate the average electricity used by approximately 300,000 US homes, based on a capacity factor of 40%.

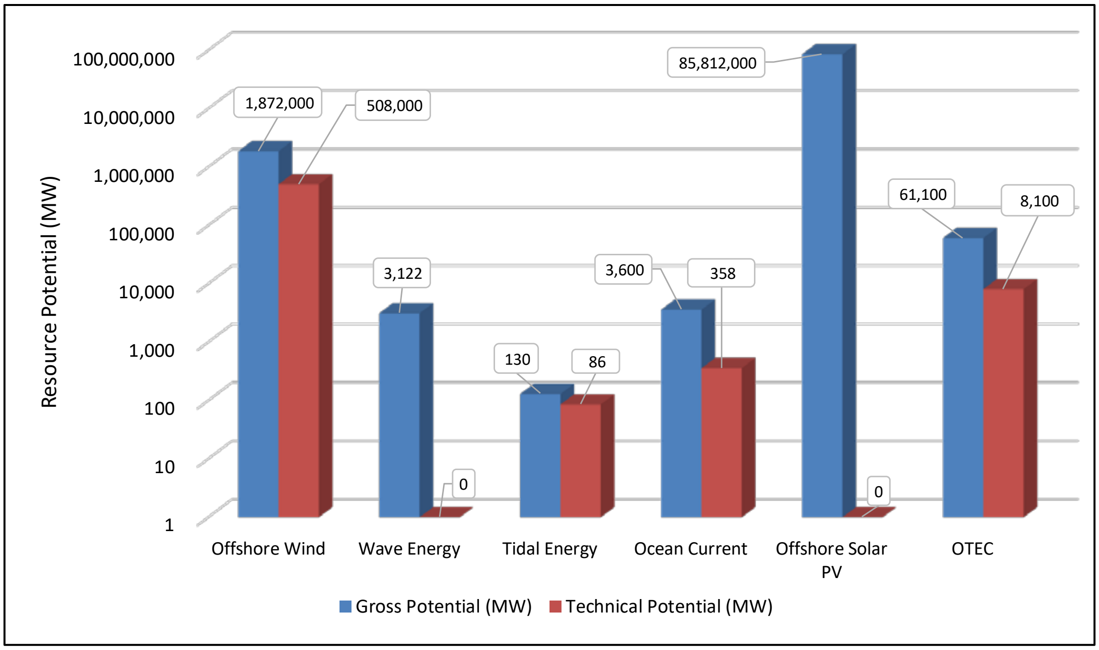

Figure S-1. Gross and technical offshore renewable energy potential in megawatts (MW) for the Gulf of Mexico by technology type[5].

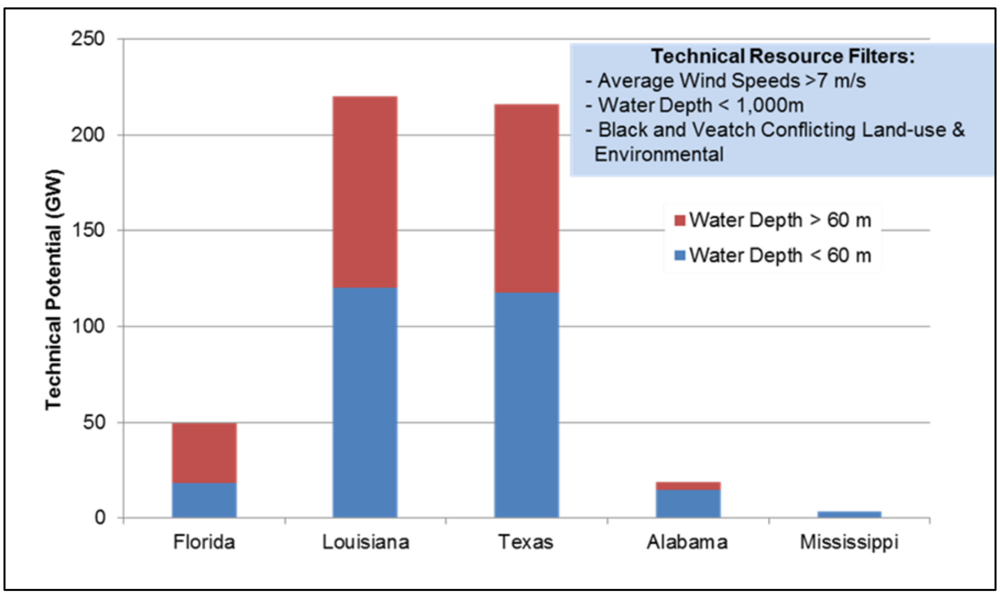

Figure S-2. Technical offshore wind resource potential by state in the Gulf of Mexico.

[5] Although NREL did not disqualify any technology type from consideration, it should be noted that BOEM's jurisdiction is limited to technologies feasible for placement in Federal waters, 3 to 9 nautical miles (nm) from shore; these include: offshore wind, ocean current, and wave energy.

The characteristics of the GOM region are very different from the North Sea (Europe), where offshore wind development has been maturing rapidly (20 years of experience), or in the northeastern United States where regional utility scale development is now taking hold. The primary technical challenges for offshore wind turbines in the GOM are gaps around hurricane design, lower wind speeds, and lower soil strength. None of these challenges are insurmountable, but all will require some additional investment in research, development, and deployment to adapt the technology and gain the experience needed for commercial acceptance. Each challenge could result in incremental capital cost increases, but these increases did not receive a full treatment in this study.

There may also be significant cost benefits to help offset possible cost increases resulting from these challenges. These benefits may include better turbine access, shallow water siting, lower labor cost, and direct access to the existing industrial supply chains of the oil and gas industry. These benefits may lower capital costs, operation and maintenance costs, and the cost of fabrication and installation.

NREL's Offshore Regional Cost Analyzer (ORCA) and geographic information system (GIS) databases were used to estimate offshore wind energy development potential for the GOM States (Florida, Alabama, Mississippi, Louisiana, and Texas [see Section 3]) (Beiter et al. 2016). Regional maps were produced to document the offshore wind resources and economics. The LCOE, LACE, and net value were calculated on a grid, approximately 10.8 by 10.8 kilometers (km) (6.7 by 6.7 miles [mi]), representing the approximate footprint of a hypothetical 600 MW offshore wind power plant used for wake loss calculations for the entire Outer Continental Shelf (OCS) (Beiter et al. 2016). Regional results are detailed for the target year of 2030.

The optimum turbine specific-power rating for each GOM subregion (based on annual average wind speed) was determined from the annual average wind speed data used in NREL's 2016 resource assessment (Musial et al. 2016) and an internal analysis performed at NREL (Dykes et al. 2016). Four conceptual turbines with different specific-power ratings were custom-designed (234 watts (W)/m^2, 257 W/m^2, 280 W/m^2, 303 W/m^2) to maximize annual energy production at lower wind speed regimes within subregions representing the ranges of average annual offshore wind speeds from 7 to 9 m/s (15.7 to 20.1 mph) found in the GOM (see Section 3.3.2).

The NREL cost model, ORCA, is undergoing continuous upgrades and validation to keep up with industry progress. The modeling runs for these analyses were performed in early 2018 and the modeling parameters were limited to the data and capabilities available at that time. For this study, ORCA was run with GOM site parameters inputs using modeled years 2015, 2022, and 2027. These data were then extrapolated to estimate costs for 2030.

In addition, the following assumptions were made to the ORCA model for the GOM-specific model runs[6]. Many of these assumptions are unique to the GOM or reflect industry trends not captured in previous models published by NREL in 2016 and 2017 (Beiter et al. 2016, Beiter et al. 2017):

1. Relatively mature supply chains (e.g., US flagged vessels and suitable ports, harbors, and assembly areas) will be available.
2. New low wind speed, hurricane resilient turbines will be adapted for 2030 commercial operations.
3. A 25% increase in the insurance costs was added to account for hurricane uncertainty.

[6] Note that the cost of offshore wind is rapidly changing, and the assumptions made for this report do not reflect all the cost dynamics of this technology. Generally, the cost trends reflected in this study are conservative relative to costs obtained after the analysis was completed.

4. A fixed charge rate of 9.1% was used to represent the financing rates (the previous rate was 10.5%).
5. 3 to 14% cost was added to the low wind speed turbine costs, respectively, to account for low wind speed turbine enhancements (larger rotors had a higher cost added).
6. Increased annual energy production (AEP) was realized because of lower sea states and the milder GOM climate. These effects were previously captured by Beiter et al. (2017) resulting in lower downtime and higher turbine availability.
7. Net capacity factor (NCF) and net annual energy production were calculated using the same loss functions used in Musial et al. (2016).
8. A cost adder was applied to the jacket substructures to account for higher costs as a result of softer soils. The adder effectively increased the water depth by 5 m (16.5 ft) to provide equivalent substructure stiffness that is similar to structures with a higher soil strength (e.g., northeastern United States).
9. Supply chain cost reductions were applied to some cost elements (e.g., jacket substructure) to account for closer proximity to substructure fabrication, lower mobilization costs, and better access to US flagged vessels.

Figure S-3 presents the results of the net value regional GOM analysis, which shows that regions with locally high electricity prices (i.e., LACE) and lower LCOE have the highest net value. Under the assumptions used for this analysis, if net value is positive (i.e., > 0) then offshore wind can potentially compete in that location without additional subsidies. Figure S-3 shows a heat map of the net value estimated for the GOM for 2030. Net value ranges from -$5/megawatt-hour (MWh) to -$125/MWh in 2030 commercial operation date (COD), indicating that the estimated cost (proxied by LCOE) of producing power from offshore wind at all GOM sites was above the required revenue opportunities (proxied by LACE) in 2030. Many sites were modeled to have net value near 0 by 2030, which were within the margin of error for determining economic potential. These sites with relatively high net value (i.e., relatively close to zero) can be found in close to shore sites off Texas and western Louisiana, particularly off 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.

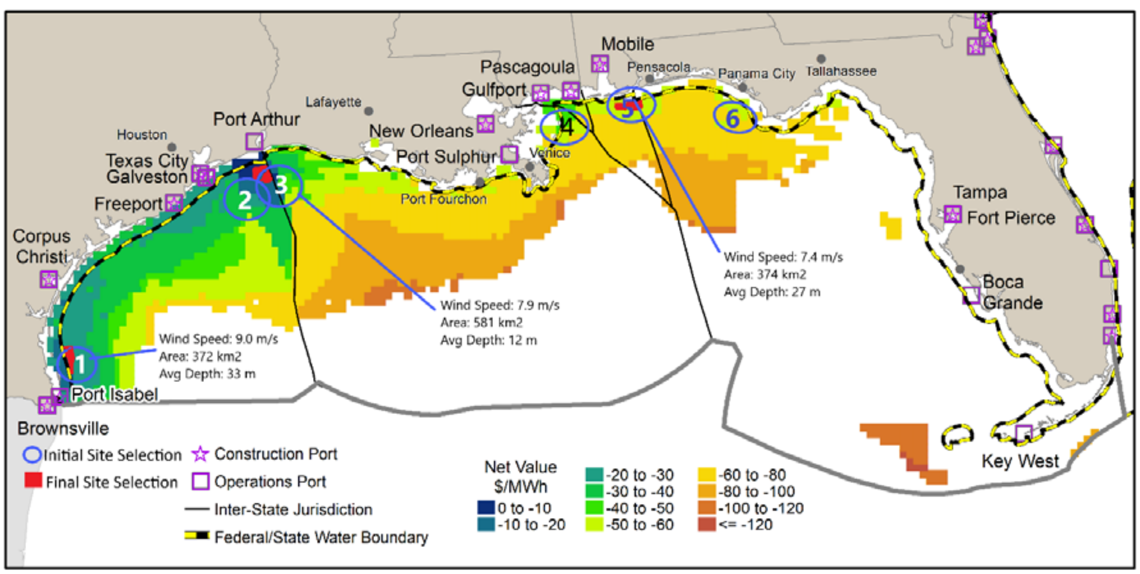

Figure S-3. Estimated net value for the Gulf of Mexico (2030 COD).
Note: 2030 data were extrapolated from modeled data for 2015, 2022, and 2027 in Beiter et al. (2017).

NREL provided BOEM with the regional GOM heat maps, which included technical offshore wind resource potential, LCOE estimations, and a summary of net value (Figure S-3). Site selection criteria for hypothetical offshore wind power plant locations in the GOM were established by NREL and initial recommendations were made to BOEM for six viable study areas: 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, three sites were down-selected for more detailed cost analysis to represent possible future offshore sites in the GOM, including Site 1 (Port Isabel), Site 3 (Port Arthur), and Site 5 (Pensacola) (Figure S-3).

The three sites that were selected for detailed analysis met most of the following criteria:

- High net value within the region identified. This criterion ensures that sites with the highest economic potential and closest proximity to viable ports were selected.
- Large enough area (i.e., at least 350 km^2/86,487 acres [ac]) to support the commercial development of a utility scale offshore wind power plant, realize economies of scale, and demonstrate the economics of plant scaling to at least 1,000 MW (assuming an array density of 3 MW/km^2),
- Low LCOE; (note that best economic potential (net value) and lowest LCOE do not always correlate),
- Located in Federal waters (BOEM jurisdiction) and far enough from shore to avoid conflicts with coastal communities over viewshed issues (see Figure 22),
- Located in shallow waters for economic reasons (less than 40 m [131 ft]), respecting viewshed setbacks needed for coastal communities,
- Minimize potential use conflicts by avoiding environmentally sensitive areas, shipping lanes, and oil and gas infrastructure[7].

Figure S-4 shows the calculated LCOE for the three selected GOM study sites for the years 2015 through 2030 (COD). The LCOE values for hypothetical projects located at each of the three down-selected sites, commissioned in 2015, range from $139/MWh (Site 1, Port Isabel), to $149/MWh (Site 3, Port Arthur), to $183/MWh (Site 5, Pensacola). The LCOE values decline for each of the three sites in a similar trajectory calculated by the NREL cost model, ORCA (Beiter et al. 2016). The extrapolated 2030 LCOE values range from $73/MWh (Site 1, Port Isabel), to $79/MWh (Site 3, Port Arthur), to $91/MWh (Site 5, Pensacola).

These LCOE values indicate trends consistent with other cost declines seen in Europe and the northeastern US, though at a slower pace (4C Offshore 2018). The slower pace can be attributed to the need for further technology to address hurricanes and lower wind speeds, less favorable economics relative to the northeastern US, and lack of current state policy commitments that are driving offshore wind development in other regions of the US.

[7] Note that a comprehensive assessment of all possible use conflicts and environmental sensitivities is beyond the scope of this report.

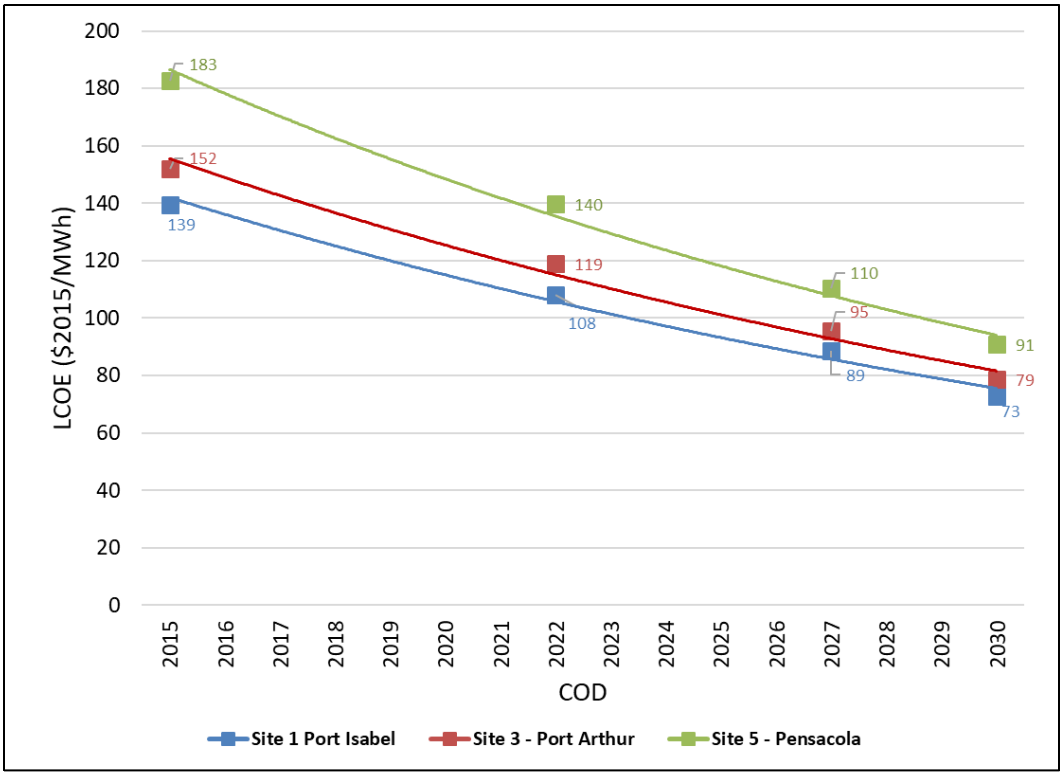

Figure S-4. Estimated levelized cost of energy (LCOE) for the three modeled Gulf of Mexico sites from 2015 to 2030 (COD).

Customized turbines and lower finance costs contributed to lower LCOE estimates when compared with previous studies conducted by NREL (Beiter et al. 2016). Overall, this report concludes:

- The highest wind resources are in the western GOM, which corresponds to the most favorable economics.
- Low LCOE is not the best predictor for economic viability; this study found the highest net value near the Texas-Louisiana border (Site 3 Port Arthur), where higher LACE makes potential offshore wind development more attractive.
- No site in the study achieved the goal of reaching positive net value; (e.g., where LCOE is less than the LACE).
- Some north Texas sites near Port Arthur were estimated to have a net value greater than -$10/MWh, which is within the margin of error to determine economic viability (e.g. positive net value).

Further analysis is warranted to assess:

- Technology design and cost requirements for the GOM in terms of hurricanes and wind speed and how they may impact siting;
- Impact of larger capacity turbines (12 MW to 15 MW) (expected over a timeframe that extends to 2032 COD), lower unit cost for turbines in general, and lower finance rates to as low as 7% fixed charge rate (FCR);
- Technology risk and how it may affect insurance cost and insurability;
- Siting conflicts with other ocean uses and the ocean environment.

Finally, an analysis of jobs, earnings, regional gross domestic product (GDP), and regional economic output to support the construction and operation of a 600 MW offshore wind project in the GOM was analyzed using Site 3 (Port Arthur) as the reference site. The regional analysis assessed the construction and operation to support jobs and economic growth in the GOM region. The results indicate that a single offshore wind project could support approximately 4,470 jobs and $445 million in GDP during construction and an ongoing 150 jobs and $14 million annually from operations and maintenance (O&M) labor, materials, and services. Results are based on a project with a commercial operations date of 2030 (Figure ES-5).

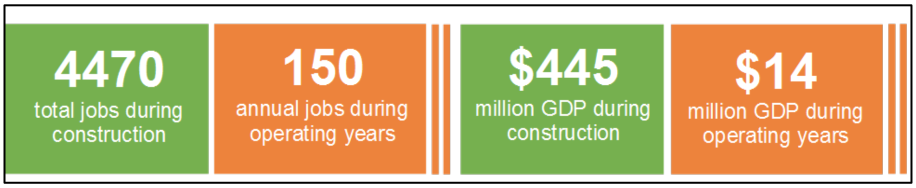

Figure S-5. Economic activity supported from the construction and operation of a 600 MW Gulf of Mexico offshore wind project.

The results represent the potential economic impacts for the entire region and are proportional to the level of deployment. The precise location where the wind installation is installed offshore does not affect the jobs and economic activity that results from the scenario developed for the Jobs and Economic Development Impact (JEDI) model, but it may affect which local and state facilities are engaged. A 600 MW offshore wind power plant with similar technical parameters and costs installed along the GOM coastline at any location will yield similar jobs and economic activity similar to the site analyzed.

1 Overview and Project Background

The Bureau of Ocean Energy Management (BOEM) and the National Renewable Energy Laboratory (NREL) are working together to assess the technical and economic potential for offshore wind technology development in the Gulf of Mexico (GOM) and to help inform and guide development activities within BOEM's purview under the Energy Policy Act of 2005 (EPAct). The EPAct authorizes BOEM to regulate renewable energy projects on the Outer Continental Shelf (OCS). In 2009 BOEM developed regulations under 30 CFR [Code of Federal Regulations] 585, which provide the framework for issuing leases, easements, and rights-of-way for OCS activities that support the production and transmission of renewable energy sources.

Offshore wind turbines are almost twice the size of land-based wind turbines and turbine manufacturers are being pushed by developers to build even larger sizes. Currently, the average capacity of installed offshore wind turbines is over 5 megawatts (MW), but turbine sizes of up to 10 MW are available. Turbines that are 12 MW in capacity with rotor diameters greater than 200 meter (m) (656 feet [ft]) have been announced (General Electric 2018) with the expectation that 15 MW turbines will be available by 2030 (Musial et al. 2019b). Turbines are typically arranged in arrays of 400 MW to 800 MW per project for commercial scale power generation and optimal cost. They are usually connected to an offshore substation located near the offshore wind power plant, and the aggregated power is transmitted to shore via a high voltage subsea cable.

By the end of 2018, the global offshore market for offshore wind had reached 22,592 MW of commissioned capacity, with over 5 gigawatts (GW) of new additions in 2018, a new industry record. Projections for 2019 indicate expected global new capacity additions to exceed the 2018 deployment numbers, with over 10 GW currently under construction. The pipeline of offshore wind development capacity, as of December 31, 2018, was about 272 GW, indicative of a growing and robust industry worldwide. Major countries contributing to the industry growth include the United Kingdom, China, Germany, Denmark, the Netherlands, and several others (Musial et. al. 2019b).

In the US, the current pipeline for offshore wind development totals over 25 MW of potential installed capacity, including all projects, lease areas with exclusive site control, unauctioned lease areas (North Carolina), and unsolicited proposals. Developers have obtained exclusive site control of over 21 sites, totaling over 19 MW of potential capacity (including state water projects). Figure 1 shows a map of the Federal leases auctioned by BOEM between 2011 and 2018.

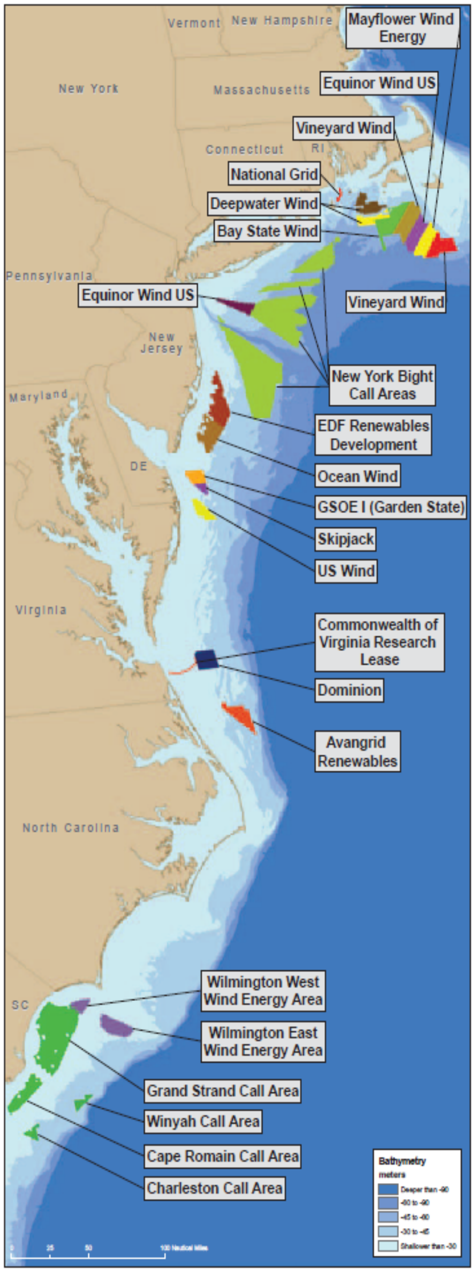

Figure 1. 2011 to 2018 BOEM offshore wind lease areas in the Atlantic.

Most of the near-term activity is concentrated in the North Atlantic region, but projects have been proposed in all five US regions[8] (DOE 2015). Most notable, in December 2016, Deepwater Wind completed the commissioning of the Block Island Wind Farm, the first commercial offshore wind project operating in the US. The 30 MW project is in Rhode Island state waters off the southern coast of Block Island. It comprises five 6 MW Haliade wind turbines manufactured by General Electric (formerly Alstom Wind Power). In addition, the project included laying a power cable to connect the grid on Block Island which connects to the mainland grid. The project's plan was to produce enough electricity to power 17,000 Rhode Island homes (Chesto 2017).

[8] The five regions as defined by the Wind Vision Study are: North Atlantic, South Atlantic, Gulf of Mexico, Pacific, and Great Lakes.

Renewable energy resources under BOEM's jurisdiction include, but are not limited to, offshore wind, ocean solar, ocean waves, and ocean current. BOEM and NREL are publishing a companion report to this one, which focuses on the technical and gross potential for all ocean renewable resources in the GOM (Musial et al. 2020). In that report, each resource was evaluated based on technology readiness, resource adequacy, and cost. Offshore wind ranked the highest among the other resources and was selected to be evaluated in this current study (Section 1.1).

This study provides a feasibility assessment for offshore wind energy and is intended to inform BOEM's regional planning related to potential future OCS renewable and alternative use development and leasing activities in the GOM. This study also includes information on offshore wind energy potential in state waters and will provide data for possible near-term and long-term offshore renewable energy planning at the state level. It examines the offshore wind potential comprehensively including technical and economic potential for commercial development, along with the GOM-related supply chain.[9]

Offshore wind energy technologies have significantly evolved in the last 10 years and they continue to evolve. Recent assumptions about cost, technology maturity, and resource are incorporated in this report. In the US, several commercial offshore wind projects with locations proposed on the OCS in the mid- and north Atlantic are currently in the permitting and planning phases. Though offshore wind energy development looks very promising for near-term development in the northeastern US, we focus on the GOM in this study.

BOEM's Environmental Studies Program has a history of over 40 years in the support of scientific research to inform policy decisions regarding the development of OCS energy and mineral resources. BOEM has worked together with NREL since EPAct was passed to collaborate on offshore renewable energy projects and studies related to energy potential assessment, stakeholder engagement, and feasibility analyses to develop offshore opportunities across all BOEM regions.

This study is divided into six sections:

- Section 1.1 reviews the findings of the companion report assessing all renewable energy sources and Section 1.2 provides the parameters of the study on a geospatial basis.
- Section 2.0 provides information on the unique attributes of the GOM including offshore wind resources, and the advantages and disadvantages of offshore wind development.
- In Section 3.0, reports the regional geospatial economic assessments are reported for all potential ocean sites including regional distributions of levelized cost of energy (LCOE), levelized avoided cost of energy (LACE), and net value (economic potential) for present and future cost trajectories (2030). These analyses considered factors, such as: capital expenditures, operational expenditures, annual energy production (AEP), and the fixed charge rate (FCR). Geospatial cost variables include water depth, wind resource, substructure type, turbine size, distance to port, distance to cable interconnect, installation method, and sea state. Heat maps of these variables show where the best potential sites are from an economic perspective.
- Section 4.0 provides a more detailed assessment of three study sites selected to illustrate the economics of offshore wind in the GOM.
- Section 5.0 gives an overview of the findings from a high-level GOM infrastructure survey.

[9] In July 2011, another BOEM-funded study was published, "Assessment of opportunities for alternative uses of hydrocarbon infrastructure in the Gulf of Mexico" (Kaiser et al. 2011). It is targeted primarily at examining the potential for offshore wind to benefit the existing oil and gas infrastructure and the feasibility of offshore wind in terms of the regulatory process. It concluded that offshore wind could provide little value to the oil and gas industries.

- Section 6.0 provides the results of the jobs and economic impact study for a 600 MW offshore wind power plant.

1.1 Summary of Gulf of Mexico Renewable Energy Survey

During Phase 1[10], NREL evaluated which renewable energy technology was the most feasible for the GOM using resource adequacy, technology readiness, and cost competitiveness as the defining criteria. The renewable energy sources that were evaluated included offshore wind, solar photovoltaics (PV), tidal current, ocean thermal energy, wave energy, and ocean current. Offshore wind received the highest score based on these criteria, with a total score of 13 out of a possible 15 points (Figure 2).

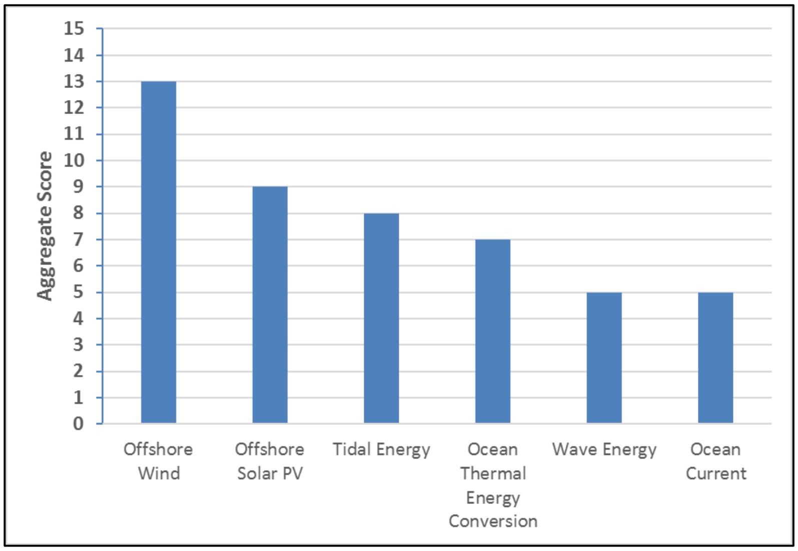

Figure 2. Gulf of Mexico ocean renewable energy technology scoring in rank order.
Musial et al. 2020.

Hence offshore wind is the primary technology focus of this report, and the second phase of this study. The technical resource potential for offshore wind in the GOM is 508 GW, the largest of any of the renewable technologies examined in Phase I (Figure 3) (Musial et al. 2016).

[10] Survey and assessment of the ocean renewable energy resources in the US Gulf of Mexico, OCS Study BOEM 2020-017.

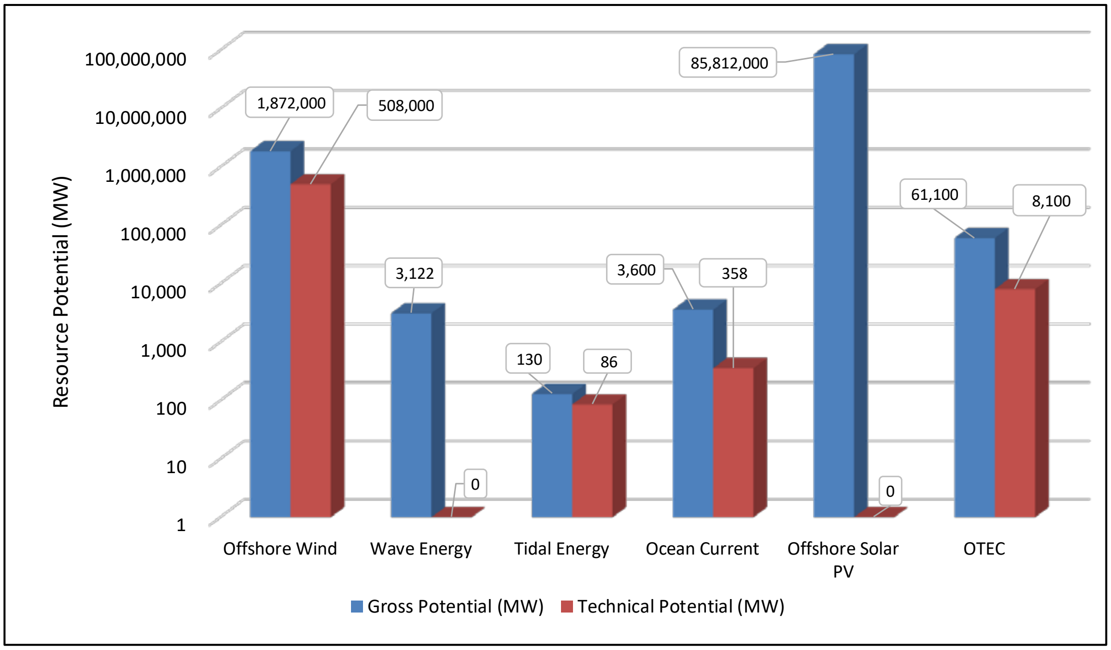

Figure 3. Gross and technical offshore renewable energy potential in MW for the Gulf of Mexico by technology type.

The ability of offshore wind to serve a large percentage of the electric load primarily depends on lowering the cost, rather than speculation about technical feasibility or resource adequacy. If current trends toward cost competitiveness observed in Europe and the US Atlantic region continue, the economics of offshore wind in the GOM will likely follow suit, approaching positive net values over the next decade in some regions, particularly in Texas and Louisiana. These global trends suggest that cost competitive offshore wind in the GOM could be possible by 2030 (Beiter et al. 2017). During this timeframe, there will be a need to adapt current wind turbine designs to optimize energy capture for low wind speed operation, increased understanding of hurricane risk, and robust designs and supporting equipment for hurricane-prone areas.

1.2 Study Parameters

The goal of this study is to assess potential offshore wind energy resources in the GOM and to quantify the technical and economic potential. This will help inform Federal and GOM states' strategic planning over the next decade.

The study objectives are to:

- Describe site-specific and regional benefits and challenges of deploying offshore wind in the GOM and discuss the current research to mitigate challenges;
- Review and quantify the wind resource capacity and energy potential in the GOM region for each GOM state including state and federal waters, distance from shore, and water depth;

- Perform geospatial regional economic assessments of LCOE[11], LACE[12], and net value (Section 3.4.2) for the GOM;
- Evaluate three representative hypothetical locations for site-specific economic analysis
- Perform a high-level assessment of local supporting infrastructure availability, including existing services (e.g., fabrication facilities, vessels, ports) and possible grid connection options;
- Assess the regional economic impacts of a 600 MW offshore wind power plant installed at a representative site in the GOM.

1.2.1 Definition of Study Area: State and Federal Water Distance Zones

Within the total offshore wind resource area, data were classified into the following four distance zones (Figure 4):

- **0-to-3-nautical miles (nm) zone**. This zone generally comprises state waters and is outside BOEM's jurisdiction. For Texas and the western coast of Florida, state waters extend to 9 nm (Musial and Ram 2010).
- **3-to-12-nm zone**. This zone extends to the territorial water's boundary at 12 nm. In this zone, conflicting-use impacts may be higher than in areas farther out. Some studies have found that opposition to offshore wind projects based on view shed, or aesthetics begins to decline rapidly beyond 12 nm (Lilley et al. 2010).
- **12-to-50-nm zone**. The 50-nm boundary was selected in early resource studies to focus evaluations of the near-shore area where access to grid and shore-based support services is more feasible (Schwartz et al. 2010). Subsequent assessments show that project feasibility is not necessarily limited to 50 nm. For this study, the 50-nm delineation was retained as a reference to help describe the differences between far-shore and near-shore impacts out to the 200-nm Exclusive Economic Zone (EEZ) limit.
- **50-to-200-nm zone**. This zone is included in the gross resource area to provide the possibility of development beyond 50 nm, as conflicts may be lower with large areas of developable water. It is unlikely that projects in the GOM would need to access this far from shore resource, as abundant resource area exists closer to shore.

[11] Levelized cost of energy (LCOE) determines how much money must be made per unit of electricity to recoup the lifetime cost of the system. This includes initial capital cost, maintenance cost, and operational cost.

[12] Levelized avoided cost of energy (LACE) represents the electrical system value to the grid. In other words, it measures what it would cost the grid to generate the electricity that is otherwise displaced by a new generation project or a measure of the market value of that electricity.

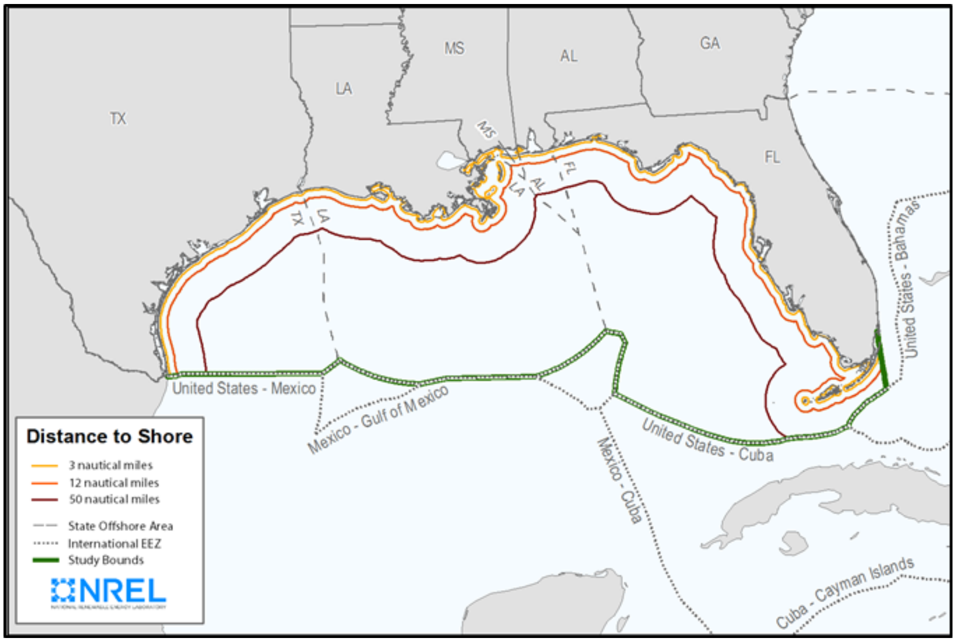

Figure 4. Map showing distance-to-shore zones for the Gulf of Mexico.

1.2.2 Water Depth Zones

Water depth has a critical role in determining whether a resource is suitable and economically feasible for offshore wind development. Nearly all offshore wind installations to date have been built in water depths less than 50 m (164 ft), but new floating turbine technologies may allow installations at much greater depths. Though there is no industry-defined limit, most experts agree that 1,000 m (3,281 ft) may be a practical cut-off when calculating technical resource limitations (Musial et al. 2016). Figure 5 shows the bathymetry (water depth) of the OCS in the GOM.

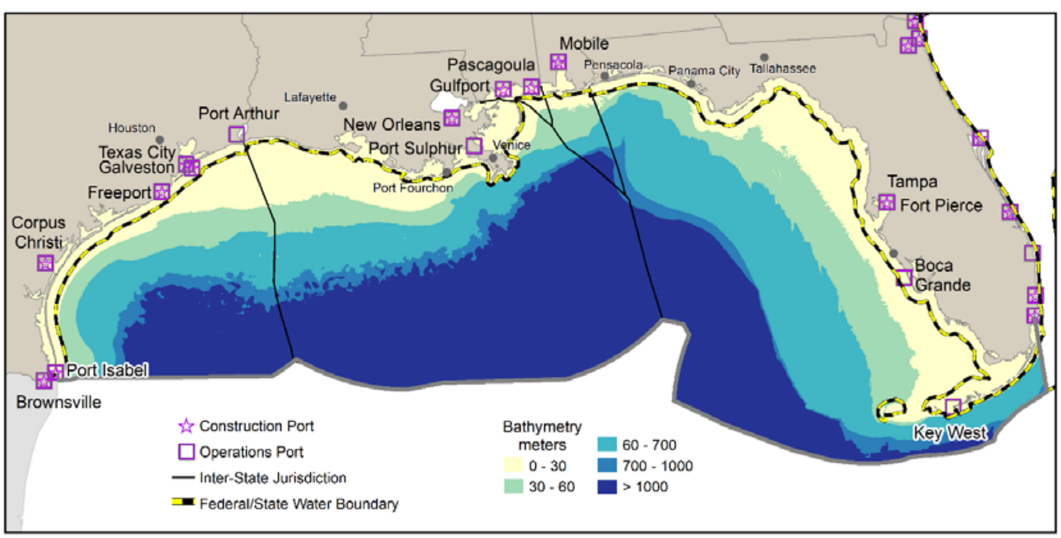

Figure 5. Bathymetry map of the Gulf of Mexico out to the International Exclusive Economic Zone.

1.2.3 Competing Uses and Siting Considerations

Historically, the ocean areas of the US have served multiple users and are home to many species. The GOM has a long history of energy extraction from the oil and gas industry; significant use conflicts with pipelines and oil platforms can exist. The Department of Energy's (DOE) 2015 *Wind Vision* was used to identify areas of competing use and environmental exclusions as shown in Figure 6 in red (DOE 2015).

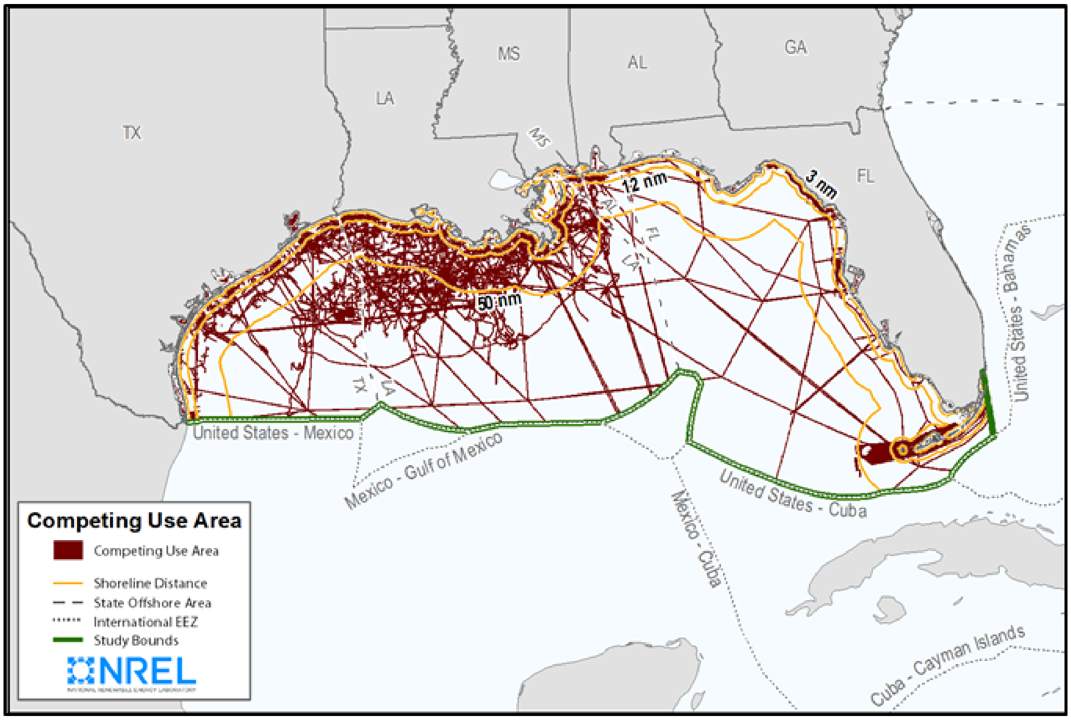

Figure 6. Areas with possible environmental and human use conflicts.
Source: DOE 2015.

This unpublished study, originally performed for NREL by Black and Vetch in 2010, does not include all conflicting use layers that might be identified during a more rigorous marine spatial planning process and the quantity of affected area would likely increase with full stakeholder participation. However, "excluded area" in this case includes areas of conflicting use or areas where coexisting use could be negotiated. These areas include national oil and gas operations, pipelines, sand resources, marine sanctuaries, marine protected areas, wildlife refuges, shipping and towing lanes, and offshore platforms and pipelines. In Figure 6, not all of the area in dark red would necessarily be excluded for offshore renewable energy development.

In a later study, Musial et al. calculated the percentage of use conflicts as a function of distance to shore (Musial et al 2016). These space-use data were used to limit the wind resource on a percentage basis as a coarse method to reduce the total resource to a more realistic level, but this result should not be considered as part of a more rigorous marine spatial planning process that would need to accompany OCS leasing for offshore wind. Because a complete analysis of use conflicts was not performed, the sites chosen for analysis, although they are representative of the cost of offshore wind, may not be optimal locations for future offshore wind power plants.

There may also be synergies between offshore wind and oil and gas infrastructure apart from supply chain advantages. Opportunities may exist to use oil and gas platforms to facilitate renewable energy development or for renewable energy to aid in oil and gas production. For example, Equinor (formally Statoil) announced their Hywind 3 project in which an 88 MW floating wind farm that is, scheduled for deployment in 2022, will power a cluster of existing oil rigs in the North Sea (Equinor 2018). Although it is possible that these offshore wind applications may show promise in some regions of the world, they are generally beyond the scope of this study.

2 Offshore Wind Challenges and Benefits in the Gulf of Mexico

Planning for offshore wind energy in the Gulf of Mexico (GOM) has unique challenges (Section 2.3), such as potentially damaging tropical cyclones and low average wind speeds. These challenges may be unfavorable to some stakeholders; however, most challenges could be resolvable with available engineering tools and incremental design upgrades. There may also be significant cost benefits in the GOM to help offset these challenges, such as a milder climate, shallower water, lower labor cost, and access to the existing supply chains of the oil and gas industry (Figure 7).

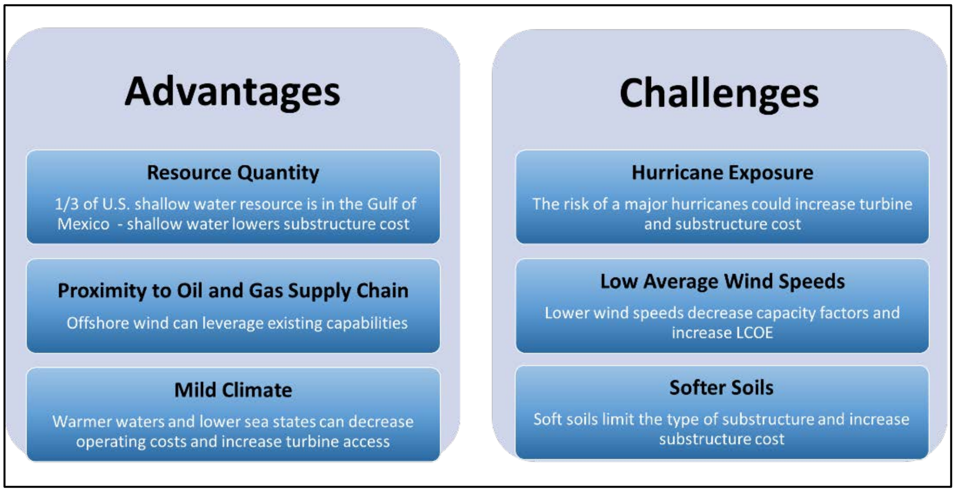

Figure 7. Unique attributes of offshore wind in the Gulf of Mexico, including advantages and technical challenges.
Source: NREL.

2.1 Overview of Offshore Wind in the Gulf of Mexico

The resource capacity and energy potential are calculated for each GOM state on a geographic information system (GIS) grid showing details of distance from shore, wind speed, and water depth. This analysis considers gross and technical resource potential as defined by Musial et al. 2016. The GOM is one of the five offshore regions of the US, as defined by the Department of Energy (DOE) and Department of the Interior (DOI) offshore wind strategy (Gillman 2016). The offshore wind resource for the GOM was evaluated in terms of net capacity in gigawatts (GW) and in terms of energy generating potential in Terawatt-hours per year (TWh/yr) (Musial et al. 2016). Based on the technical wind resource, the GOM was found to have a resource capacity of 508 GW and an energy generating potential of 1,556 TWh/yr.

The GOM offshore wind resource is similar in magnitude to other regions of the US as shown in Figure 8, but its geo-spatial characteristics present some unique technical challenges, such as turbines that need to resist extreme wind speeds due to hurricanes, lower average wind speeds, and softer soils[13]. However, there may be some interesting benefits in terms of project costs and regional economics, including job creation due to increased local content (see Section 6) relative to other US regions.

13 Note that the GOM technical offshore wind resource in Figure 8 is slightly higher than the 508 GW and 1,556 TWh/year calculated in this report because a more precise method was used to split Florida's GOM offshore wind resource from the rest of the state. Only 18% of Florida's technical offshore wind resource is in the GOM.

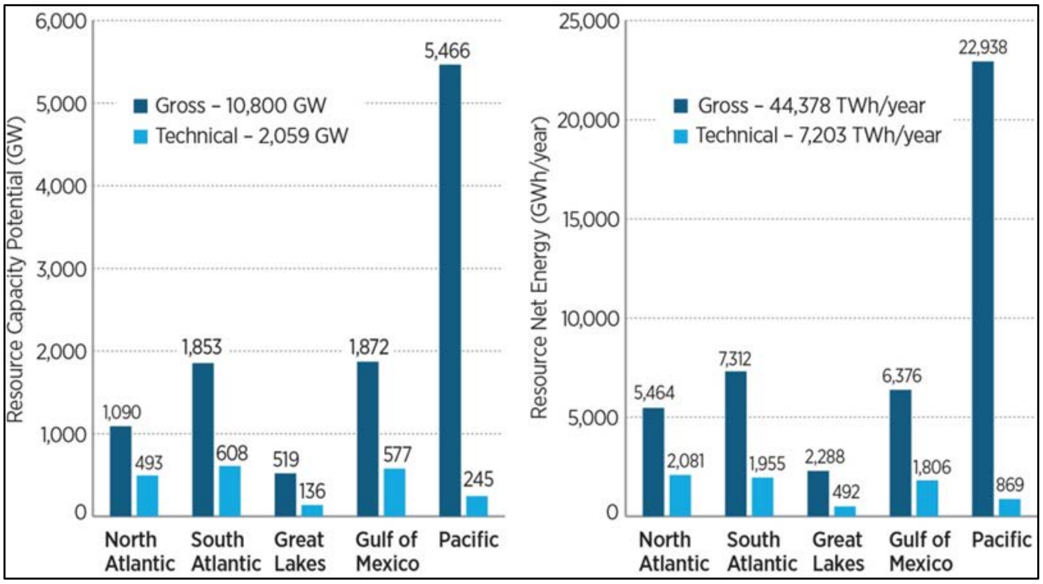

Figure 8. Capacity (left) and net energy (right) offshore gross resource (dark blue) and final net technical (light blue) potential estimates for five US offshore wind resource regions.
Source: Gilman et al. 2016.

2.2 Advantages for Offshore Wind in the Gulf of Mexico

This section discusses the regional advantages of offshore wind in the GOM. These benefits may lower capital costs, operation and maintenance (O&M) costs, and the cost of fabrication and installation. These benefits will need to be considered together with the challenges to make informed judgements about the future of GOM offshore wind development.

2.2.1 Abundant Shallow Water Resources

The GOM has lower wind speeds relative to other US regions, but the quantity of resource capacity in the GOM is large, especially in shallow water less than 60 m (197 ft) depth. Figure 9 shows the technical offshore resource energy capture potential in TWh/year on a state by state basis for all US offshore states. The chart ranks each state from left to right by the quantity of technical energy potential it possesses. From a GOM resource perspective, it is compelling that three of the top four highest ranked states are in the GOM. In fact, GOM states combined have 32% of the shallow offshore wind resource potential in the entire US.

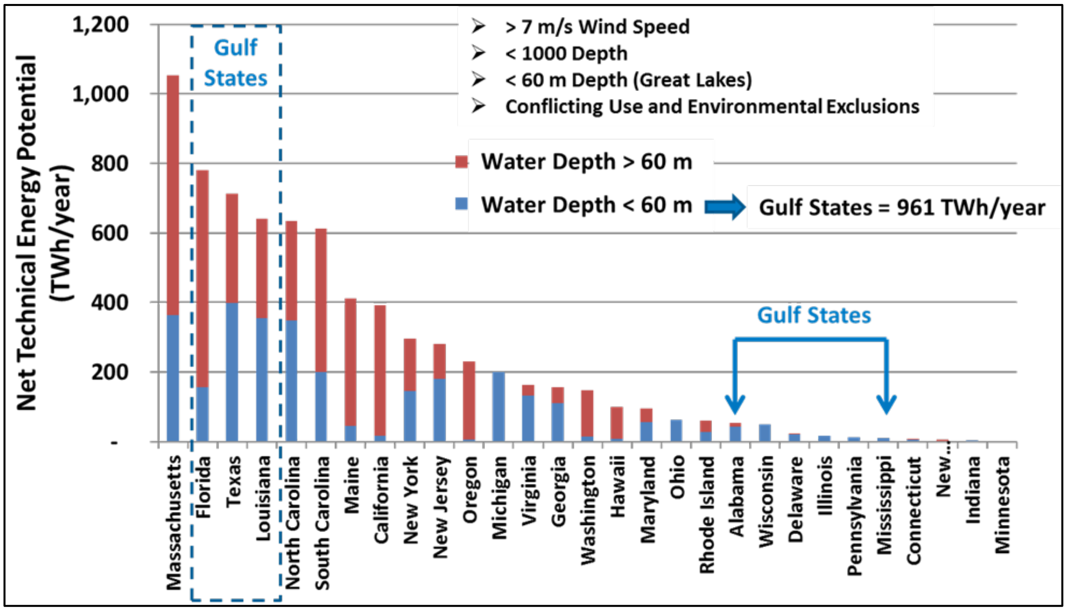

Figure 9. Technical energy potential (by depth class) of offshore wind resource showing abundant resource energy potential in three GOM states.
Musial et al. 2016.

Figure 10 shows the technical resource potential capacity in GW by state for each GOM state studied.

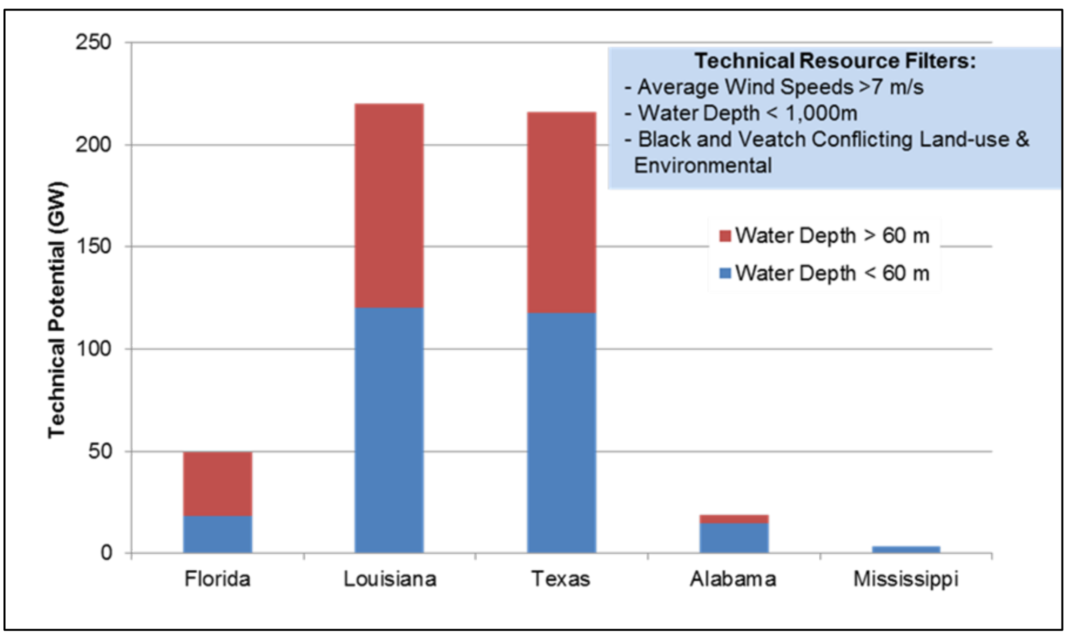

Figure 10. Technical offshore wind resource potential by state in the Gulf of Mexico.
Data source: NREL.

For each state, the chart in Figure 10 shows the quantity of resource in waters shallower than 60 m (197 ft) (blue color), and the quantity of technical resource greater than 60 m (197 ft) (red color). The resource shown for Florida includes only the western side of the state, which is in the GOM[14].

[14] Note that in Figure 9 the total offshore wind resource for Florida is plotted.

As noted earlier, the quality of much of this resource is lower than other regions (e.g., the northeast Atlantic) due to lower wind speeds, but the quantity of shallow water is very large relative to the total resource area of the US. Low wind regimes typically warrant machines with larger rotors (e.g., low specific power[15]) to compensate. For this study, four conceptual low wind speed machines were developed to illustrate what GOM wind turbines might look like (Section 3.3.1).

This abundance of shallow water resource provides substantial opportunity for siting projects without deploying more expensive deeper water substructures. Figure 11 shows a simple cost model developed by the National Renewable Energy Laboratory (NREL) for the balance of station of a 600 MW offshore wind farm using fixed-bottom foundations. The data show the relative change in cost as the project is sited in deeper waters. As shown, the balance of station (BOS) costs for a project in 30 m (98 ft) of water can be 10% to 20% lower than a project sited in water 50 m (164 ft) deep. Remaining in shallower waters will lower the project cost.

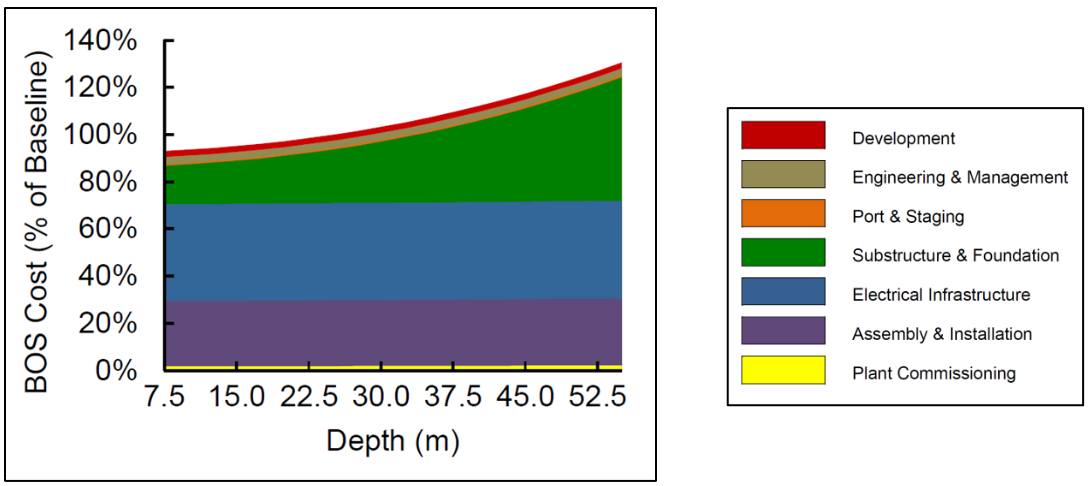

Figure 11. Shallower waters have lower substructure cost.
Maness et al. 2016.

2.2.2 Warmer Climate and Lower Sea States

The GOM has a lower wave climate than other US bodies of water, including the Atlantic and Pacific oceans. The smaller sea states result from shorter fetches and lower wind speeds. In addition, the waters of the GOM and the climate remain mild for most of the year. The combination of low sea states and mild weather will significantly increase turbine accessibility throughout the year. This will have a significant impact on lowering O&M costs over the turbines' lifetimes. Reduced O&M costs will increase turbine availability and will significantly increase the annual energy production (AEP) when compared to a turbine operating in more severe conditions, such as the Pacific Ocean.

[15] Turbine specific power (SP) is defined as the turbine power nameplate rating (PR) divided by the area swept by the rotor (A) in square meters.

2.2.3 Lower Labor Rates and Proximity to Supply Chains

According to the Energy Information Administration (EIA), the GOM generally has lower labor rates than the national average; this may encourage offshore wind power plant developers to proactively seek a local labor force, although there is no guarantee that all labor would come from the GOM. Figure 12 shows that in the GOM, labor cost multipliers may reduce labor costs up to 10% or more relative to national averages for certain activities, which will lower overall LCOE for a given project (NREL 2018; EIA 2016). However, these studies did not investigate why labor costs are lower. Additional labor and material cost benefits might be realized by proximity to oil and gas supply chains, which would provide local access to construction and service vessels, experienced labor, and large component steel fabrication facilities.

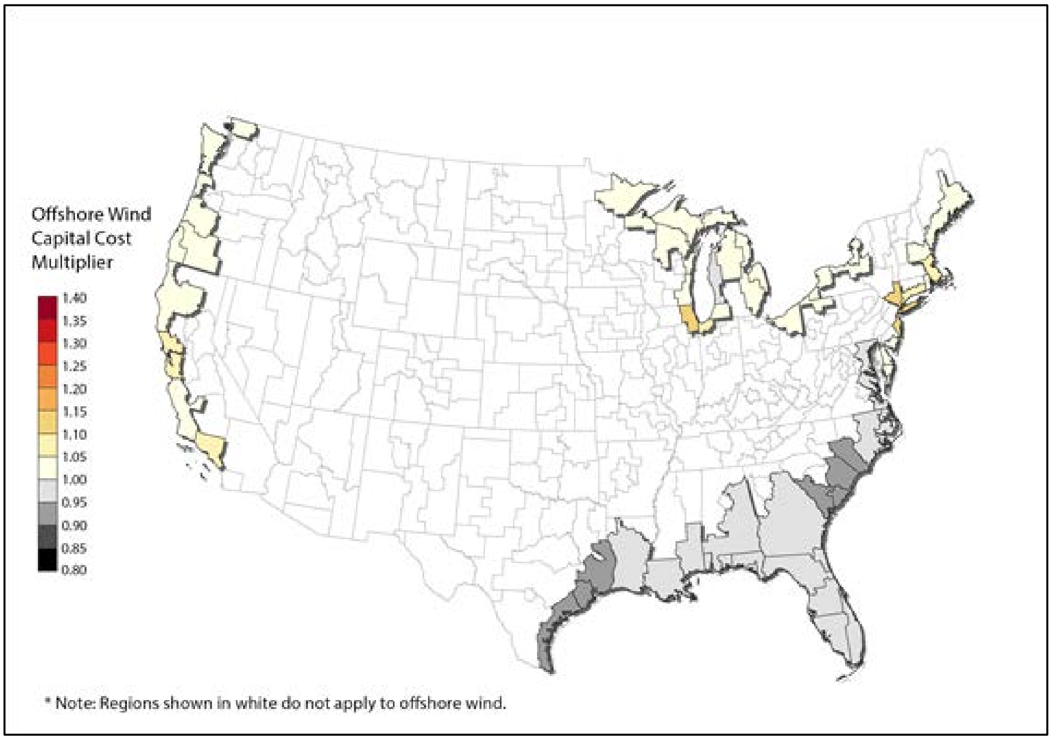

Figure 12. Regional labor cost multipliers implemented in the National Renewable Energy Laboratory cost model for the Gulf of Mexico.
Data source: EIA 2016.

2.3 Challenges for Offshore Wind in the Gulf of Mexico

The GOM region is characteristically very different than the North Sea (Europe), where offshore wind has been maturing for over 20 years, or the northeast US, where regional utility scale development is now taking hold. Physically, GOM sites may have more in common with Asian markets, which are now beginning to evolve. The primary technical challenges for offshore wind turbines in the GOM are engineering gaps around hurricane design, lower wind speeds, and softer soils which will require additional investment in research, development, and deployment to gain the experience needed for commercial acceptance. Each solution could also result in incremental capital cost increases that must also be evaluated.

2.3.1 Hurricane Survival

The US Atlantic, the GOM, and Hawaii all experience hurricanes that have the potential to bring extreme wave heights and wind speeds exceeding design specifications. Offshore wind turbines are currently designed using International Electrotechnical Commission [IEC] standards. IEC 61400-01 and IEC 61400-03 standards are the governing documents that define the limit state load cases, including a load case for the 3 S maximum gust condition of 70 m/s (156 mph). In hurricane regions, this is typically the governing extreme wind design load case (IEC 2019a; IEC 2019b).

Similarly, fixed-bottom wind substructures are designed using the American Petroleum Institute (API) Recommended Practice (API RP) 2A design standard, which includes robustness criteria using regionally developed “hazard curves” (API 2018). The most recent version of IEC 61400-03 includes a robustness check in the appendix, but US installations in the Atlantic and the GOM will likely use robustness criteria as default guidance because the method has been proven to work successfully in the GOM by the oil and gas industry. It should also be noted that despite the empirical incidence of extreme hurricanes in the GOM (e.g., Katrina, Michael, Harvey), hazard curves in the GOM are less steep relative to many Atlantic sites. Therefore, it is not yet clearly understood if and to what extent additional provisions for hurricane design will be necessary. If environmental conditions at the site can be determined (e.g. return periods for 50 years, 100 years, and 500 years), the proven practices of the oil and gas industry (e.g., API Standards) appear to be sufficient for the design of fixed-bottom support structures with an acceptable degree of confidence. However, one of the most difficult problems is understanding the site conditions well enough to estimate the probability and severity of major hurricanes at specific locations.

The application of current IEC/API standards will not sufficiently address hurricane design for the wind turbine itself in all locations because, unlike the support structure, wind turbines are not custom designed for site conditions. Therefore, site-specific risk assessments are needed to determine where turbine designs need to be enhanced to accommodate hurricanes, or where alternative load mitigation strategies (e.g., auxiliary on-board power supplies to maintain yaw authority during hurricanes) should be implemented. The recently released 2019 edition of IEC 61400-01, the primary design standard for wind turbines, has just added provisions for a wind turbine Typhoon Class which upgrades the 3 S gust criterion to 80 m/s (179 mph), ostensibly requiring strengthened components such as blades and towers.

In the future, more sophisticated hurricane-resilient wind turbine designs may evolve using cost optimization schemes that balance higher energy production and increased load resistance (see Section 2.3.1). Optimized hurricane resilient turbines may have lower rotor solidity (smaller blade profiles), fewer blades, highly ruggedized sensors, active advanced load control systems, uninterruptible yaw positioning, or other features that are not found or needed in offshore wind turbines operating in the North Sea.

2.3.2 Low Wind Speeds

Relative to Europe or US offshore wind lease areas in the New England and Mid-Atlantic regions, which have annual average wind speeds between 8.5 and 10 m/s (19 and 22.4 mph) or greater, the GOM has lower annual average wind speeds between 7 m/s and 9 m/s (15.7 and 20.1 mph). To compensate for lower wind speeds, new low wind speed offshore wind designs will be needed. This trend already exists for land-based turbines where low specific power rotors have been introduced at low average wind sites. It is expected that lower turbine specific power ratings seen for land-based wind turbines will eventually be designed and developed for offshore turbines. New turbine designs optimized to operate in low average wind conditions may feature increased rotor diameters, with specific power ratings between 230 watts[W]/m^2 and 300 W/m^2. Larger rotor diameters will provide increased swept rotor area and greater energy production. Larger rotors cannot completely offset lower energy production due to less wind, but they may eventually allow turbines in the GOM to compete in utility markets by optimizing energy extraction for site conditions. The greater challenge may be in overcoming the competing objectives of making turbines stronger and more resistant to hurricanes while simultaneously increasing blade length to extract more energy at low wind speeds.

2.3.3 Soft Soils

A wide range of possible substructures is available in the offshore wind industry, but soft soil conditions, shallow waters, and the existing supply chain infrastructure in the GOM all favor jacket-type substructures (Figure 13). The GOM has softer soils compared to other regions where offshore wind development has occurred. Monopile design is the most common substructure type used in offshore wind development globally, but this substructure type would be difficult to use in the GOM due to soft soils and the likelihood of shallow water breaking waves under extreme conditions, which would intensify wave loading and increase substructure cost. Jacket substructures, which are commonly used by the oil and gas industry throughout the GOM, can more easily mitigate soil strength and breaking wave loads. Although jackets may be the preferred substructure type, lower soil strength requires additional steel to react lateral forces, which will increase their weight and cost. Proposed mitigation strategies include adding more steel and/or using longer piles to offset lower natural frequencies. This issue does not require specialized engineering capabilities but is expected to add some cost and must be considered early in the design. A first order analysis for these substructures was performed for this study (see Section 3.3.5.2).

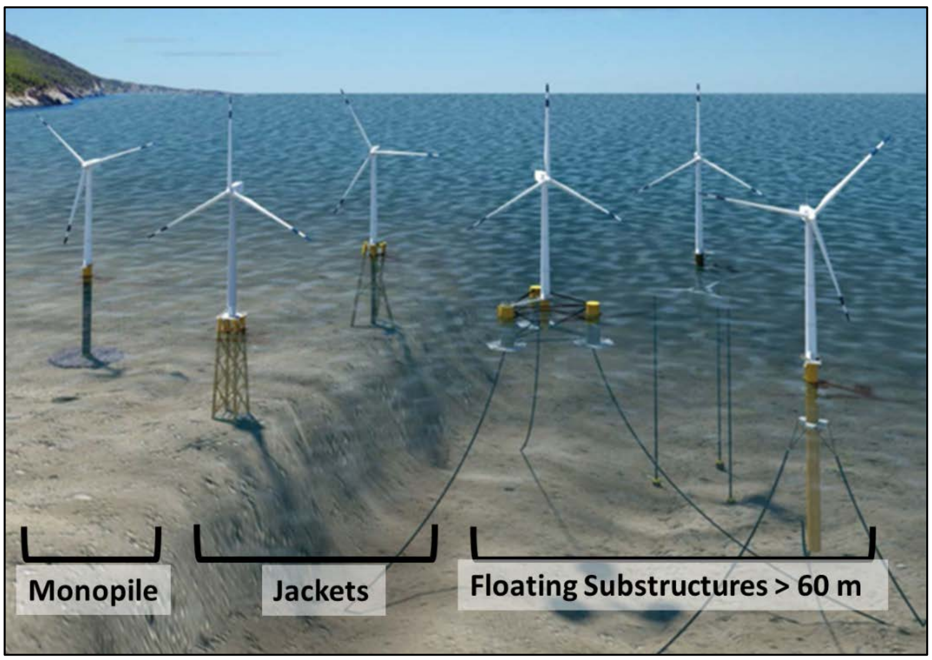

Figure 13. Taxonomy of common offshore wind turbine substructures.

3 Regional Offshore Wind Economics in the Gulf of Mexico

Regional geospatial data were generated and analyzed to determine the potential for offshore wind to be deployed over the Gulf of Mexico (GOM) region. The data generated were plotted into heat maps that can be used by GOM policy makers and state agencies for their consideration of offshore wind in future state energy planning.

3.1 Methodology

Using existing wind resource data from Musial et al. (2016), heat maps were developed that show wind speeds, water depth, and, distance from shore for both the gross and technical resource areas, including: Western Florida, Alabama, Mississippi, Louisiana, and Texas. The National Renewable Energy Laboratory (NREL) Offshore Wind Cost Analyzer (ORCA) and GIS databases were used to estimate offshore wind energy development potential for these GOM States (Beiter et al. 2016) with modifications made to account for updated assumptions for finance rates, low wind speed turbine costs, increased insurance for hurricanes, and customized jacket substructures. Regional maps were produced to document the offshore wind resources and economics.

The levelized cost of energy (LCOE), levelized avoided cost of energy (LACE), and Net Value were calculated on a high-resolution grid, approximately 10.8 by 10.8 km to (6.7 by 6.7 mi), representing the footprint of the hypothetical 600 MW offshore wind power plant (Beiter et al. 2016). Regional results are detailed for the target year of 2030.

From the annual average wind speed data used in the 2016 NREL resource assessment (Musial et al. 2016) and internal analysis performed at NREL (Dykes et al. 2016), the optimum turbine specific power rating for each GOM sub-region was determined. Four turbines with different specific power ratings were conceptually designed for the purpose of maximizing annual energy production at four low wind speed sub-region. Each sub-region represents a range of average annual offshore wind speeds in bands of 0.5 m/s (1.1 mph) from 7 to 9 m/s (15.7 to 20.1 mph).

The NREL offshore wind cost model, ORCA, was run for site-specific GOM parameters for the modeled years 2015, 2022, and 2027. These data were then extrapolated to estimate costs for 2030.

The following is a summary of the major assumptions made in ORCA for the GOM cost modeling:

1. Relatively mature supply chains (e.g., US flagged vessels and suitable ports, harbors, and assembly areas will be available).
2. New low wind speed, hurricane resilient turbines will be available for 2030 commercial operations.
3. 3% to 14% cost was added to the turbine cost to account for low wind speed turbine enhancements.
4. A 25% increase in the insurance costs was included to account for hurricane uncertainty.
5. A fixed charge rate of 9.1% was used to represent the financing rates.
6. Increased annual energy production (AEP) was realized due to lower sea states and the milder GOM climate. These effects were previously captured in ORCA resulting in lower downtime and higher turbine availability.
7. Net capacity factor (NCF) and net annual energy production were calculated using same loss functions used in Musial et al. (2016).

8. A cost adder was applied to the jacket substructures to account for higher costs due to softer soils. The adder effectively increased the water depth by 5 m (16.5 ft) to provide equivalent substructure stiffness as similar structures with higher soil strength (e.g., northeastern US).
9. Supply chain cost reductions were applied to some cost elements (e.g., jacket substructure) to account for closer proximity to substructure fabrication, lower mobilization costs, and better access to US flagged vessels.

3.2 Regional Cost of Energy Modeling

3.2.1 Cost of Energy Introduction

ORCA is applied in this analysis to assess the levelized cost of energy across the GOM region. This section provides details about the model, its underlying spatial cost relationships, and assumptions. ORCA follows the general definition of LCOE described in Beiter et al. (2016) using Equation 1:

$$LCOE = \frac{(FCR \times CapEx) + OpEx}{AEP_{net}} \tag{1}$$

where:

FCR	=	fixed charge rate (%)
CapEx	=	capital expenditures (\$/kW)
OpEx	=	average annual operational expenditures (\$/kW/year)
AEP_{net}	=	net average annual energy production (kWh/year).

3.2.2 ORCA Model Description

In the ORCA model, cost elements are divided into three categories: fixed costs, variable costs, and cost multipliers. Fixed costs are not impacted significantly by the geo-spatial parameters based on available information and market information available and therefore do not have an empirically discernable relationship that could be included in the model. Offshore wind turbine procurement costs, for example, are assumed to be site-agnostic given that commercially available models are typically designed for International Electrotechnical Commission (IEC) Class 1 sites. In practice, however, wind turbine original equipment manufacturers hold liabilities associated with warranty provisions and may adjust the pricing structure for a given site to account for the perceived level of risk associated with exposure to environmental conditions (e.g., hurricanes). Nevertheless, we assume that these costs are constant from one project to another.

Variable costs are expenditures that have distinct relationships with the geo-spatial parameters. For example, installation costs are expected to vary with logistical distances (e.g., distance from port to site), water depth, and prevailing metocean conditions.

Cost multipliers are indirectly related to environmental conditions. They are not explicitly linked to individual spatial factors but tend to vary with total project cost to reflect the complexity of other items. For instance, engineering and management costs incurred from financial close through commercial operations are applied as a percentage of capital expenditures (CapEx).

Further details about the bottom-up method for calculating CapEx, operational expenditures (OpEx), and AEP from spatial parameters and financial parameters such as the FCR[16] are documented in Beiter et al. (2016).

ORCA estimates the LCOE[17] of offshore wind technologies in the US for hypothetical projects with commercial operation dates (COD) between 2015 and 2027. It considers a variety of spatial parameters (e.g., wind speed, water depth, distance to shore, and metocean conditions) and a temporal cost reduction trajectory. LCOE varies by location because of geographic factors that affect energy production (e.g., average wind speed variations) and CapEx (e.g., varying sea states, distance from shore, water depth, sediment and substructure suitability, and availability of critical infrastructure). Estimated cost reductions were based on an assessment conducted by BVG Associates documented in Beiter et al. 2016). Beiter et al 2016 analyzed the LCOE of fixed-bottom (monopiles and jackets) and floating (semi-submersible and spars) offshore wind technologies across more than 7,000 US coastal locations, including the GOM.

Most spatial-cost relationships are based on a detailed assessment of a 6 MW turbine rating, scaled to turbine ratings between 3.4–10 MW that were assumed to represent model years 2015 (3.4 MW), 2022 (6 MW), and 2027 (10 MW). To understand the coincidence of costs and revenue opportunities along the US coastline, Beiter et al. (2017) also compared the estimated LCOE to the levelized revenue from projected wholesale electricity prices and the sale of capacity during the lifetime of a project, also known as "levelized avoided cost of energy" (LACE). LACE provides a metric for assessing the economic potential of offshore wind relative to other sources (e.g., fossil fuels). The difference between LCOE and LACE at a given site location was defined as "net value" in Beiter et al. (2017). The offshore wind capacity associated with sites where LACE exceeds the LCOE indicates that a site has economic potential (see also Section 4).

3.3 Annual Energy Production

3.3.1 Gulf of Mexico Specific Wind Turbines

Commercial land-based wind turbines are typically available with different rotor sizes corresponding to different site-specific wind characteristics. 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. Large rotors have lower specific power ratings[18].

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 2:

$$SP = P_R/A \qquad (2)$$

Historically, offshore wind turbines have been deployed at European sites (e.g., North Sea) where typical wind resources are very strong (i.e., annual average wind speeds greater than 10 m/s [22.4 mph] are typical) and proven industry wind turbines have high specific power ratings. However, most sites in the GOM have annual average wind speeds between 7 to 9 m/s (15.7 to 20.1 mph). Therefore, for optimum performance, larger rotors than are currently available on the offshore wind market will likely be needed.

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[16] The fixed charge rate (FCR) is used to approximate the average annual payment required to cover the carrying charges on an investment and tax obligations.
[17] LCOE determines how much money must be made per unit of electricity to recoup the lifetime cost of the system. This includes initial capital cost, maintenance cost, and operational cost.
[18] An analogy for specific power is in sailboats, where larger sails (e.g., spinnakers) are used during lower wind speeds to maintain similar travel speeds.

These larger rotors, and hence longer blades, must also consider the additional loads imposed by hurricanes, which may require additional strength to achieve reliable designs.

Figure 14 illustrates a rotor system optimization study performed at NREL (unpublished), which shows how turbine specific power and capacity factor vary with average wind speed (Dykes et al. 2016).

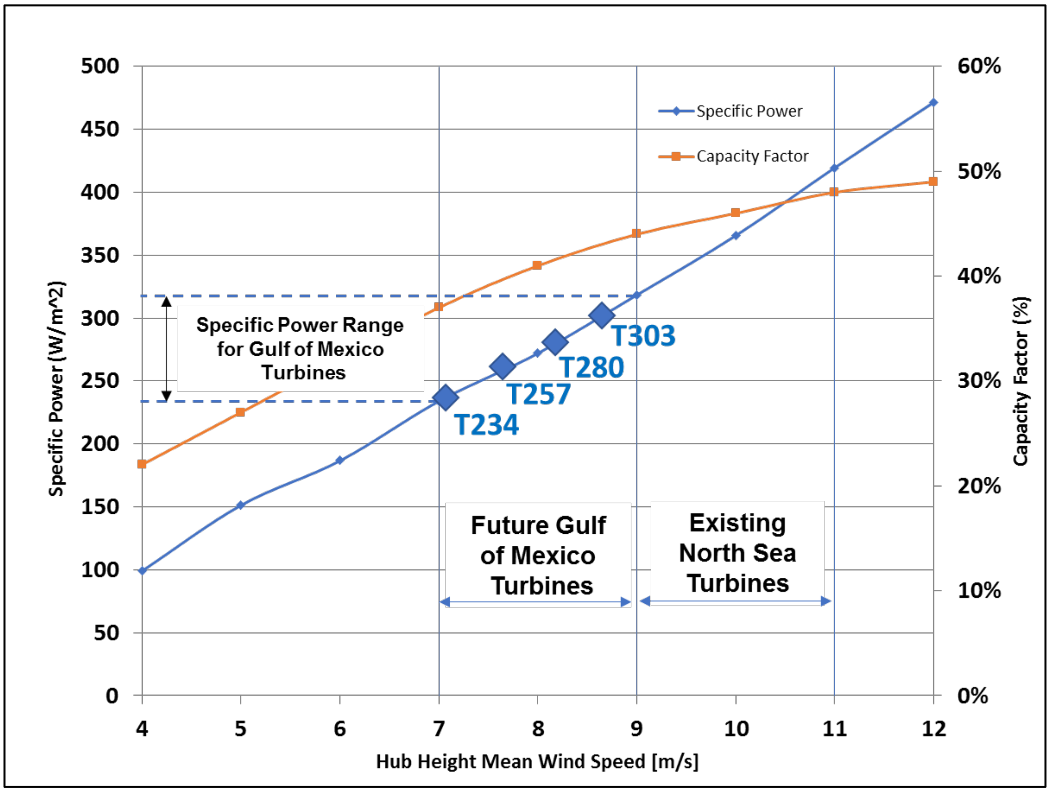

Figure 14. Ideal specific power and wind speed, showing lower specific power turbines between 230 W/m^2 and 320 W/m^2 needed for the Gulf of Mexico.
Source: Dykes et al. 2016.

Using this type of analysis, wind turbine rotor systems can be optimized for maximum energy production based on turbine specific power for a given annual average wind speed. The figure shows the theoretical optimum SP varying with the hub height annual average wind speed. Although this optimization study was conducted in the context of land-based wind turbines, it illustrates a methodology for approximating the best rotor size for offshore wind turbines in the GOM. The figure indicates that the best size for the offshore wind turbines designed specifically for North Sea wind conditions (9 to 11 m/s [20.1 to 24.6 mph] average annual wind speed), would have SP ratings between 300 W/m^2 and 400 W/m^2, which is close to the size of today's commercial fleet.

The new set of hypothetical GOM-specific wind turbines developed for this study (Figure 15) correspond to annual average wind speeds of 7 to 9 m/s (15.7 to 20.1 mph). Using Figure 14 as guidance, a set of four turbines was identified corresponding to SP levels ranging from 234 W/m^2 to 303 W/m^2 (T234, T257, T280, and T303, respectively). Table 1 lists these turbines and their assigned rotor diameters, hub heights, turbine power nameplate ratings, and corresponding wind speed ranges. Figure 15 shows the relative scale of each of these turbine's rotor and hub height to help visualize and illustrate the size differences among this set of wind turbines, which are variants of the 10 MW reference turbine developed by the Danish Technical University (DTU) recently updated to a 205 m (673 ft) diameter (Bak 2013).

Table 1. Turbine Technology Assumptions for Gulf of Mexico Offshore Wind Cost Analysis

Turbine Designation	Baseline DTU 10 MW	T234	T257	T280	T303
Applicable Wind Speeds (m/s [mph])	9.0 (20.1)	<7.25 (16.2)	7.25 to 7.75 (16.2 to 17.3)	7.75 to 8.25 (17.3 to 18.5)	> 8.25 (18.5)
Rotor Diameter (m / ft)	205/673	233 / 764	223/732	213/699	205/673
Specific Power	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

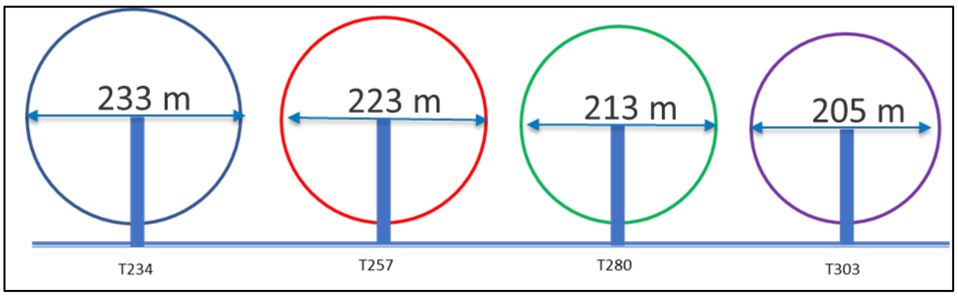

Figure 15. Comparative scale of four 10 MW conceptual Gulf of Mexico turbines, showing increasing rotor diameter with decreasing specific power.

The conceptual turbines all have nameplate ratings of 10 MW but range in rotor diameters from 205 m (673 ft) (DTU reference turbine) to 233 m (764 ft), designed for the lowest wind rotor for sites below 7.25 m/s (16.2 mph). Figure 15 is drawn to scale to illustrate the subtle changes in rotor size that can be difficult to discern without the juxtaposition of the other turbines. The size differences are indeed significant, however. The 233 m (764 ft) rotor has 29% more swept area than the DTU reference turbine, which allows for a much greater yield, but more challenging blade design.

Figure 16 shows the power curves corresponding to the four 10 MW turbines described earlier. The primary observable difference in the power curves of these four conceptual turbines is that the lower SP turbines reach their rated power of 10 MW (10,000 kW) at a lower wind speed.

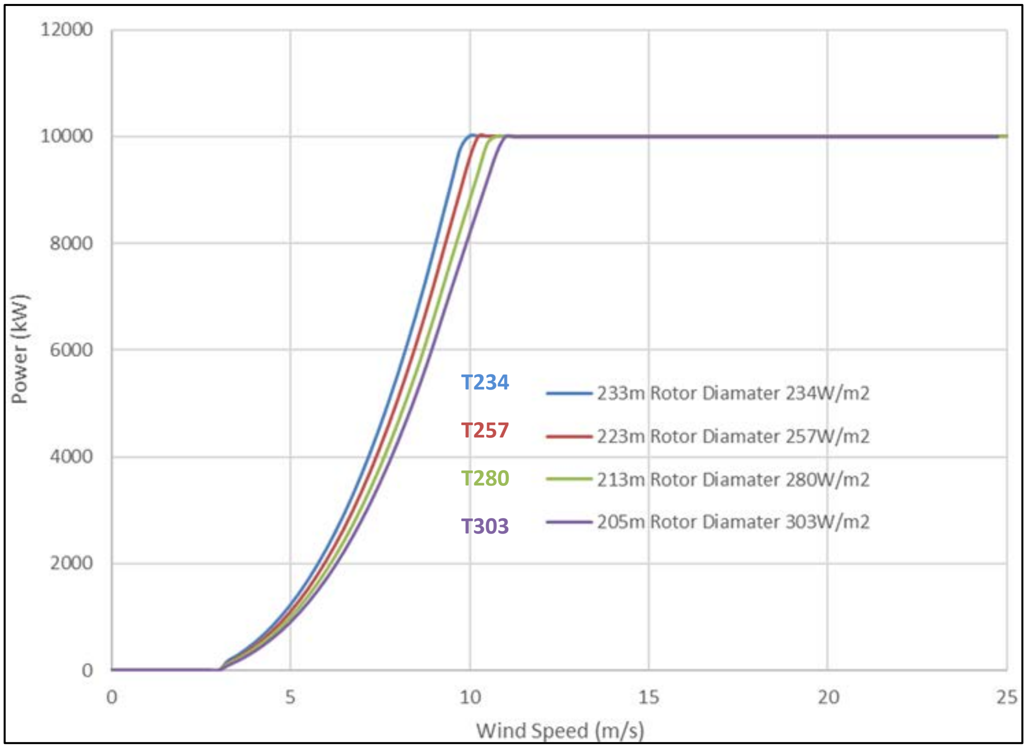

Figure 16. Power curves for four 10 MW conceptual Gulf of Mexico turbines with custom specific power ratings.

Turbine nameplate rating is also a major cost factor. In general, offshore wind developers tend to select the largest nameplate rating available because fewer turbines are then required to achieve a given project size. With fewer turbines, less foundations are installed, there are fewer turbines to maintain, and more energy per square kilometer can be generated. All told, larger turbines result in lower overall project cost. Although the average offshore turbine installed in 2018 was just over 6 MW, turbine ratings are increasing fast. The largest turbine on the market at the end of 2018 was the MHI-Vestas 9.5 MW turbine (Musial et al 2019). A 10 MW wind turbine was selected at the beginning of this study because there was high certainty that turbine ratings of this size would be available for deployment in 2030, the final year of deployment examined in this study. However, current market dynamics indicate that turbine growth might be accelerating faster than anticipated and turbine sizes of 12 MW and 15 MW may be available for deployment in this time frame. Consequently, the 10 MW turbine size limit for this study is likely a conservative assumption, smaller than what the industry might deliver by 2030. Future cost analysis might examine these turbines to understand the cost potential of larger turbine size.

3.3.2 Wind Resource Data

The wind resource is the most significant variable in determining the AEP. Two sets of resource data were used to cover the resource area of the GOM as documented by Musial et al. (2016). NREL licensed the primary annual average wind speed data from AWS Truepower, which covers the contiguous US, including the GOM, between 0 and 50 nm (0 and 58 mi) from shore where most of the relevant GOM wind sites are located. In addition, Wind Integration National Dataset (WIND) Toolkit data, based on the Weather Research and Forecasting (WRF) model, were used to quantify wind resources beyond 50 nm (58 mi) from shore. The WIND Toolkit contains the largest publicly available grid integration wind dataset, with both meteorological and power values (Draxl 2015). The data were output from a mesoscale model with a nominal 2 km (1.25 mi) spatial resolution, downs caled to a 200 m (656 ft) resolution (AWS Truepower. 2012). These were the same data sets used to compute the national offshore wind resource for the DOE-DOI National Offshore Wind Strategy (Gillman. 2016).

The quantification of GOM technical wind resource by NREL combined both data sets with technology filters that eliminated the deepwater regions greater than 1,000 m (3,281 ft), and the lowest wind regions where annual average wind speeds are below 7 m/s (15.7 mph) (Figure 17).

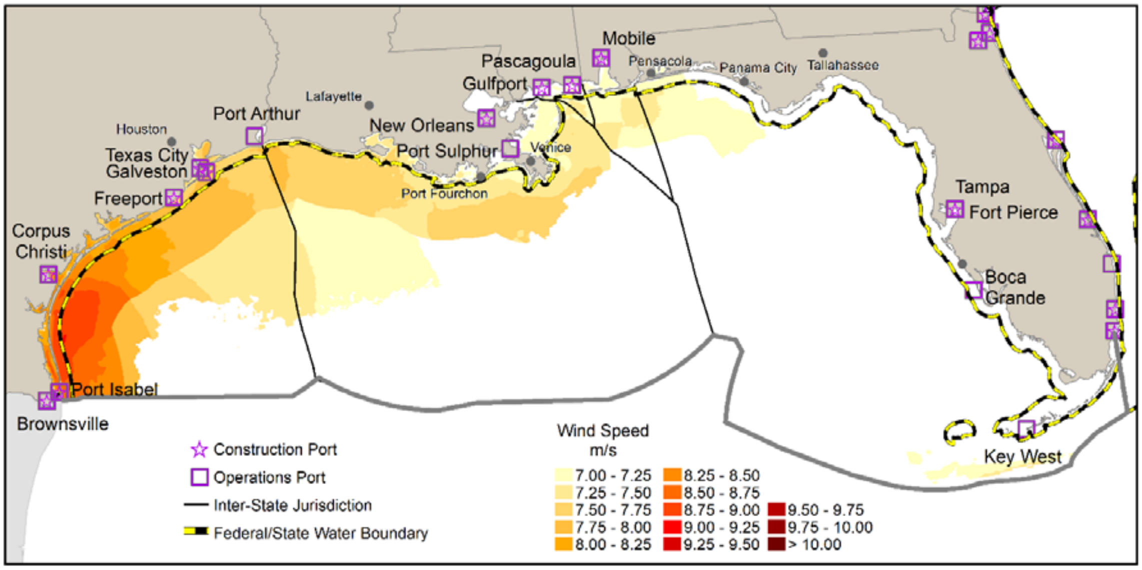

Figure 17. Gulf of Mexico technical offshore wind resource area, showing average wind speeds at 100 m (328 ft).

These wind speed data sets provide long-term annual average wind speeds (m/s) at a 100 m (328 ft) height and 150 m (492 ft) above the surface, although only the 100 m (328 ft) elevation data area plotted on the map. The best offshore wind resource is in the western GOM. Low wind speed areas above 7 m/s (15.7 mph) are in smaller patches that extend to the Florida panhandle (Figure 17). Almost no wind resource above 7 m/s (15.7 mph) was found on the west coast of Florida south of Tallahassee. Generally, this map shows that wind speeds are lower in the GOM, compared to European and northeast Atlantic sites.

To calculate the energy production for the GOM, the turbines in Figure 15 were matched to a region based on the suitability of their SP rating relative to the local wind resource (Figure 18). The lowest SP turbine, T234, is best suited for the eastern GOM where wind speeds are the lowest; T303, the highest SP turbine, is assigned to the regions of the western GOM (i.e., south Texas), where the average wind speeds are the highest.

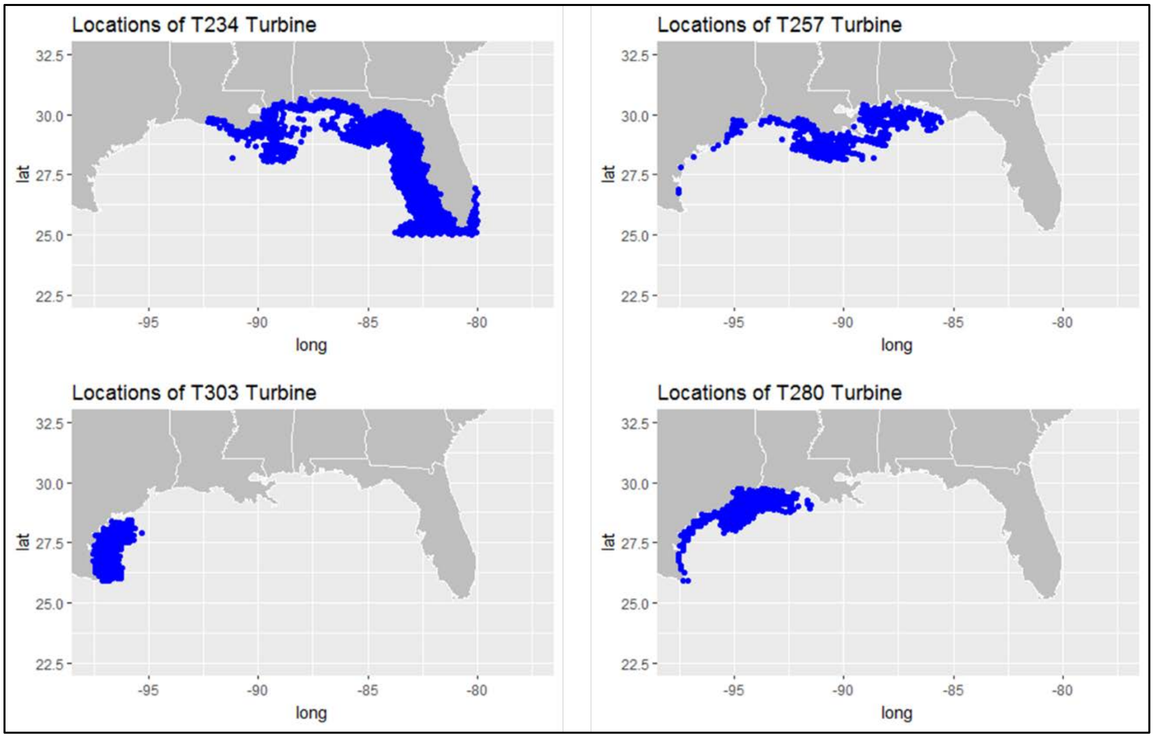

Figure 18. Regional maps showing locations of the four 10 MW conceptual Gulf of Mexico turbines with custom specific power ratings (T234, T257, T280, and T303) used in the analysis.

3.3.3 Regional Gross Annual Energy Production

Annual energy production (AEP) is the most important variable in the calculation of the cost of energy. AEP is the theoretical amount of energy that a wind power plant can produce in an average single year. The gross AEP is determined first. It is the theoretical energy that would be produced from a wind power plant if there were no losses. A calculation of gross AEP was carried out for each potential site on a 10.85 by 10.85 km (6.74 by 6.74 mi) geospatial grid. This grid was selected because each grid cell is the approximate area of a 600 MW offshore wind power plant. This grid was also used to perform the wake loss analysis. From the analysis of the AWS Truepower (AWST) resource data between 0 and 50 nm (0 and 58 mi), over 1,000 grid cells were evaluated representing a total area of 249,439.6 km^2 (61,637,868 ac), which is estimated to be approximately 16% of the total ocean area of the GOM. For each grid cell, the hourly power production was calculated using a synthetic wind speed time series with the same statistical characteristics of the resource data closest to the centroid of each grid cell.

The most suitable wind turbine for a given site was selected by calculating the annual average wind speed at each site at each turbine's hub height. These hub height wind speeds were computed by linear interpolation using available data sets at 110 and 150 m (361 and 492 ft) heights from the AWST data. The turbines were selected based on wind speed ranges provided in Table 1. Once a turbine was selected (Figure 18), the statistically matched 8,760 hourly wind speed time series was applied to the turbine's power curve (Figure 16) to compute gross AEP for each grid point. Over 222,500 unique wind speed, pressure, and temperature data points were applied to the appropriate turbine power curve to compute gross capacity factor (GCF) and gross AEP data layers in the GIS analysis. These layers were used to compute net capacity factor (NCF) and Net Annual energy production (AEP_{net}).

3.3.4 Loss Assumptions

Net capacity factor (NCF) and Net Annual energy production (AEP_{net}) are determined by subtracting the calculated energy losses from the gross AEP. The loss percentages were applied to the gross AEP to compute the net AEP. Total loss estimates for years 2015, 2022, and 2027 are provided in energy summaries contained in Table 2.

Losses can result from blockages between turbines in an array, electrical transmission to shore, downtime due operation and maintenance issues, and turbine performance issues that range from blade roughness to curtailments. Losses account for differences between the energy output of an ideal turbine operating at a site without obstruction from other turbines and the actual electricity delivered to the grid by the entire wind power plant. Losses are divided into two categories: generic losses and site-specific losses. Losses were assessed using standard industry assumptions (AWS Truepower 2014). Generic losses values were assigned for this analysis and held constant for all sites and over time. Site-specific losses varied among the individual grid cells.

1.1.1.1 Generic Losses

Generic losses include environmental losses resulting from blade surface roughness (e.g., leading-edge erosion), lightning damage, or shutdowns caused by extreme temperatures. Generic losses also include technical losses caused by operational inefficiencies, such as drivetrain wear or pitch system imbalance. The generic losses include 1% for energy lost as a result of blade soiling or leading-edge erosion. In addition, generic losses include 0.6% for lightning losses and low temperature shutdowns, 1% losses as a result of hysteresis, 0.1% for on-board equipment (parasitic load), and 0.1% for rotor misalignment loss across all turbines. The researchers recommend that these typical generic loss numbers be further assessed if financial consequences are higher; however, for this analysis they are assumed to be sufficient as a baseline loss assumption.

1.1.1.2 Site-Specific Losses

Site-specific losses include energy lost as a result of turbines operating in the wake of other turbines, electrical losses due to the transmission of the electricity to shore, and turbine availability issues that are driven by accessibility limitations caused by the wave environment and general turbine reliability. The wake losses, electrical losses, and availability losses were calculated for the spatial conditions at each grid point (e.g., electrical losses vary with distance to the grid interconnect and water depth).

Wake losses are typically one of the largest loss contributors for large wind turbine arrays and can vary from 5% to 15% depending on the number of turbines, turbine spacing, wind speed, wind direction, atmospheric turbulence, and many other factors. Wake losses for a 600 MW wind turbine array (one hundred 6 MW turbines) were computed using the method documented in Beiter et al. (2016). The wake loss dataset was calculated for the contiguous US offshore wind resource area from 0 to 50 nm (0 and 58 mi) using Openwind, a software program developed by AWS Truepower (AWS Truepower 2010). As described by Beiter, turbines were arranged in 10-by-10 arrays with 7 rotor diameter (D) spacing[19]. For years 2022 and 2027, the 2015 loss assumptions were modified (see Table 2) to account for reduced losses resulting from improved technology such as larger and fewer turbines, more optimized site layouts, and active offshore wind power plant wake control strategies, all which are currently under development.

[19] Rotor diameter is used to measure turbine separation in an array. 7D spacing means that there are 7 rotor diameters of distance between towers. A 6 MW turbine with a diameter of 155 m (509 ft) would have (7 x 155 m) or 1,085 m (3,560 ft/0.67 mi) of distance between towers.

Table 2. Summary of Annual Energy Production Calculations and Loss Assumptions for the Gulf of Mexico for Years 2015, 2022, and 2027

Baseline Energy Summary 2015

Level	Category Name	Fixed Value or Factor (if applicable)	Site 1 - Port Isabel	Site 3 - Port Arthur	Site 5 - Pensacola
			Percentage	Percentage	Percentage
1	Environmental Losses		1.59%	1.59%	1.59%
2	Icing/Blade Soiling Loss	1.00%	1.00%	1.00%	1.00%
2	Low/High Temp Shutdown	0.50%	0.50%	0.50%	0.50%
2	Lightning Loss	0.10%	0.10%	0.10%	0.10%
1	Technical Losses		1.20%	1.20%	1.20%
2	Hysteresis	1.00%	1.00%	1.00%	1.00%
2	Onboard Equipment (parasitic load)	0.10%	0.10%	0.10%	0.10%
2	Rotor Misalignment	0.10%	0.10%	0.10%	0.10%
1	Site Specific Losses		18.24%	17.34%	18.27%
2	Wake Loss	Site Specific	9.90%	11.41%	12.09%
2	Total Electrical Loss	Site Specific	3.67%	3.58%	3.56%
2	Availability Loss	Site Specific	5.80%	3.22%	3.59%
	TOTAL LOSSES	12	20.51%	19.63%	20.53%
			(MWh)	(MWh)	(MWh)
	Gross AEP		1,751,138	1,370,498	1,231,911
	Gross Capacity Factor	11	55.5%	43.5%	39.1%
	Net AEP		1,392,035	1,101,486	978,954
	Net Capacity Factor		44.1%	34.9%	31.0%

Energy Summary for 2022 Commercial Operations

Level	Category Name	Fixed Value or Factor (if applicable)	Site 1 - Port Isabel	Site 3 - Port Arthur	Site 5 - Pensacola
			Percentage	Percentage	Percentage
1	Environmental Losses		1.59%	1.59%	1.59%
2	Icing/Blade Soiling Loss	1.00%	1.00%	1.00%	1.00%
2	Low/High Temp Shutdown	0.50%	0.50%	0.50%	0.50%
2	Lightning Loss	0.10%	0.10%	0.10%	0.10%
1	Technical Losses		1.20%	1.20%	1.20%
2	Hysteresis	1.00%	1.00%	1.00%	1.00%
2	Onboard Equipment (parasitic load)	0.10%	0.10%	0.10%	0.10%
2	Rotor Misalignment	0.10%	0.10%	0.10%	0.10%
1	Site Specific Losses		18.24%	17.34%	18.27%
2	Wake Loss	Site Specific	9.90%	11.41%	12.09%
2	Total Electrical Loss	Site Specific	3.67%	3.58%	3.56%
2	Availability Loss	Site Specific	5.80%	3.22%	3.59%
	TOTAL LOSSES	12	19.06%	18.25%	19.09%
			(MWh)	(MWh)	(MWh)
	Gross AEP		2,378,919	1,869,587	1,685,037
	Gross Capacity Factor	11	58.7%	46.2%	41.6%
	Net AEP		1,925,439	1,528,458	1,363,409
	Net Capacity Factor		47.5%	37.7%	33.7%

Energy Summary for 2027 Commercial Operations

Level	Category Name	Fixed Value or Factor (if applicable)	Site 1 - Port Isabel	Site 3 - Port Arthur	Site 5 - Pensacola
			Percentage	Percentage	Percentage
1	Environmental Losses		1.59%	1.59%	1.59%
2	Icing/Blade Soiling Loss	1.00%	1.00%	1.00%	1.00%
2	Low/High Temp Shutdown	0.50%	0.50%	0.50%	0.50%
2	Lightning Loss	0.10%	0.10%	0.10%	0.10%
1	Technical Losses		1.20%	1.20%	1.20%
2	Hysteresis	1.00%	1.00%	1.00%	1.00%
2	Onboard Equipment (parasitic load)	0.10%	0.10%	0.10%	0.10%
2	Rotor Misalignment	0.10%	0.10%	0.10%	0.10%
1	Site Specific Losses		18.24%	17.34%	18.27%
2	Wake Loss	Site Specific	9.90%	11.41%	12.09%
2	Total Electrical Loss	Site Specific	3.67%	3.58%	3.56%
2	Availability Loss	Site Specific	5.80%	3.22%	3.59%
	TOTAL LOSSES	12	17.86%	17.09%	17.88%
			(MWh)	(MWh)	(MWh)
	Gross AEP		3,028,573	2,482,832	2,362,824
	Gross Capacity Factor	11	63.8%	52.3%	49.8%
	Net AEP		2,487,742	2,058,441	1,940,329
	Net Capacity Factor		52.4%	43.4%	40.9%

Electrical losses were based on physical mathematical relationships in an electric cable parameter study that is now part of ORCA (Beiter et al. 2016; Musial et al. 2016). Electrical losses vary as a function of distance to shore, turbine spacing, array cable voltage, and water depth because of their impact on cable length requirements. As larger turbines are deployed, less cable and fewer turbines are needed, and the electrical losses decline.

Availability losses are site-dependent but are lower in the GOM due to lower average sea states and milder climates relative to other parts of the US. These conditions will benefit operations and maintenance (O&M) activities and can help offset lower LCOE due to other effects. Therefore, turbine availability is likely to be higher in the GOM (Beiter et al. 2016). Over time, additional O&M strategies for turbine access are likely to continue to improve turbine access and availability.

AEP_{net} was calculated by applying the loss assumptions described above to the gross AEP. These values are given in Table 2 for each of the modeled years. The data layers for NCF and AEP_{net} were used in the ORCA model to calculate LCOE and LACE.

3.3.5 ORCA Cost Model Assumptions

This section summarizes the ORCA modeling assumptions and findings in estimated LCOE and Net Value for hypothetical 600 MW projects across the GOM with a COD in 2027. All modeling assumptions correspond to the assumptions made in Beiter et al. (2016), except those specifically described in this section. Additional modifications were made to ORCA to account for technology and spatial conditions specific to the GOM. These are also discussed in the section below.

1.1.1.3 Optimized 10 MW Turbine Design

To be conservative, NREL used 10 MW turbines, which will arrive on the market in 2019 and assumed to be widely available by 2030. The original baseline 10 MW DTU turbine (Bak 2013) was upgraded by DTU in 2018 to include a 205 m (673 ft) rotor, which is more compatible with GOM sites. New industry data suggest that within the study time frame, which extends to 2030, 12 MW or even 15 MW turbines might be possible, which could lower the project LCOE estimates below what is modeled in this study.

As discussed, three additional 10 MW rotors were developed from the DTU baseline for the specific power corresponding to the low wind speed regimes in the GOM (Figures 14 and 15). Each of the four 10 MW turbines was customized for regional GOM-specific wind speed ranges in which the turbines maximize their annual energy production. The AEP of these turbines is generally higher for the wind regimes in the GOM than the generic 10 MW turbine that was applied in Beiter et al. (2016 & 2017).

Higher energy production is achieved by extending the length of blades and the height of the towers. This approach has the negative consequence of higher blade and tower mass, which incrementally increase turbine costs. These cost scaling relationships used in the model were derived from the DTU reference turbine study (Bak 2013).

1.1.1.4 Jacket Substructures

The original offshore geospatial cost model was configured to consider jacket, semisubmersible, and spar substructure technologies. Monopiles were excluded from this analysis due to the soft soils in the GOM, and semisubmersibles were not considered because of the abundance of shallow water resources. As a result of the softer soils in the GOM, deeper pile driving, and stiffer structures are necessary for the jacket substructures, thereby resulting in higher mass.

A cost multiplier was applied to the baseline cost of the jacket substructure cost multiplier accounting for soft soils in the GOM and turbine rotor size growth with lower specific power (Figure 19). Generally, the multiplier value increases with water depth but as the rotor diameter increases with lower specific power the substructure also gets taller (i.e., more costly) to maintain tip clearance of approximately 30 m (98 ft) with the sea surface.

Consequently, the larger rotors also have taller towers and hub heights, which add some cost due to larger overturning base forces (i.e., longer lever). Although the jacket substructure multipliers appear to have a similar relationship with water depth for the 205, 213, and 223 m (673, 699, and 732 ft) rotor diameter turbines (T303, T280, T257, respectively), the relationship has a different characteristic for the 223 m (732 ft) rotor diameter turbine (Figure 19). This is because the T234 substructure design was modified to avoid coalescence between the support structure's natural frequency (tower and jacket combined) and the turbine operating speed. In a more rigorous cost-focused design, such conditions may be avoided in the design phase. However, in this analysis the T234 was disadvantaged, especially in the shallower water depths.

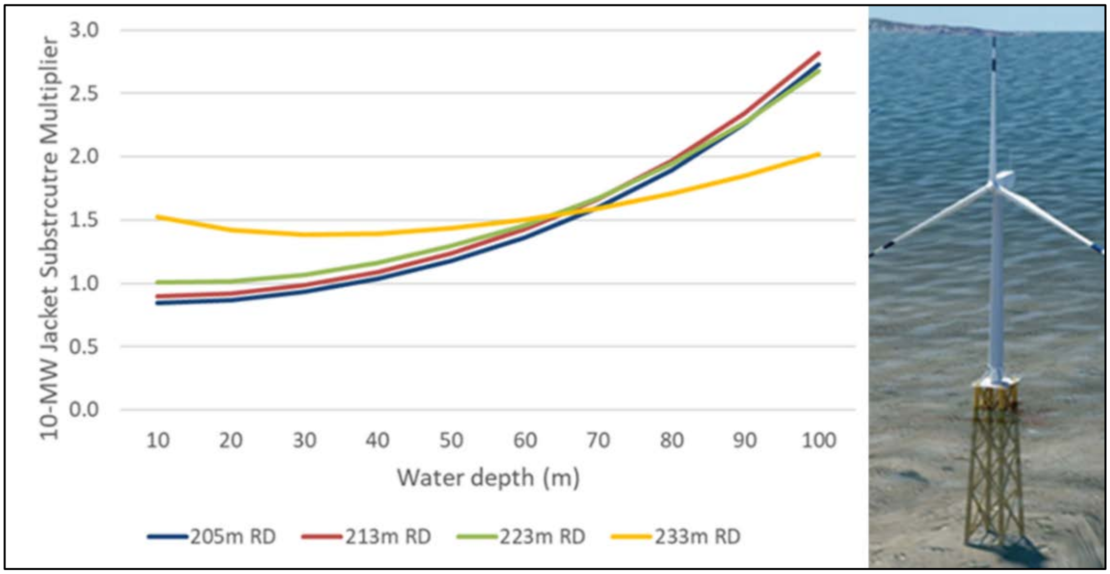

Figure 19. Jacket substructure multipliers and water depth.

These increases in blade, tower, and jacket substructure mass were captured as cost multipliers that were applied to the 10 MW turbine, substructure, and installation CapEx estimates from Beiter et al. (2016 & 2017) (Table 3).

The substructure multiplier relationships from Table 3 were implemented only for the jacket but not for semisubmersible and spar substructure types, which would require different anchor mooring specifications resulting from the soft sediment structure in the GOM. Cost estimates for the spar and semisubmersible may therefore be underestimated, and this caveat should be considered when interpreting the results. It is likely that enough shallow sites would be available in the GOM, so that deep water floating systems would not be needed to meet future electricity demands in the GOM.

Table 3. Cost Multipliers to Account for Optimized 10 MW Turbine and Jacket Designs (COD 2027)

		Cost Component		
		Turbine Capex Multiplier	Turbine Cost (RNA and Tower)	Jacket Substructure
Rotor diameter (m)	Hub height (m)	Accounts for taller tower and increased blade length	Accounts for low wind speed designs ($/kW)	Accounts for soft sediment structure in the GOM
233 (764 ft)	141.5 (464 ft)	17.94%	1,828	See Figure 19
223 (732 ft)	136.5 (448 ft)	14.22%	1,773	See Figure 19
213 (699 ft)	131.5 (431 ft)	3.15%	1,604	See Figure 19
205 (673 ft)	126.5 (415 ft)	0.17%	1,552	See Figure 19
205 (673 ft)	125.0 (410 ft)	Baseline	1,550	Baseline

1.1.1.5 Port and Grid Infrastructure in the Gulf of Mexico

The geospatial input data set from Beiter et al. (2016, 2017) used for this analysis was updated to reflect the latest information on available port and grid infrastructure available to offshore wind development in the GOM.

1.1.1.6 Financing

Financing cost assumptions were updated in ORCA for the GOM to correspond to the latest market trends in 2018 (when the study began) which indicate lower levels of finance risk and corporate taxes. The original value of the weighted average cost of capital (WACC) assumed in Beiter et al. (2016) was 7.3% (Table 4), which assumed a generally higher level of risk for offshore wind in the US relative to European markets. The new WACC rate assumed for this study was 5.9%. This new rate corresponds to a FCR of 9.1%, which is used to calculate an annuity of the installed capital costs for estimating LCOE.

The FCR was lowered because interest rates were reduced from 8.0% to 4.4% (NREL 2018) and a higher debt share from 50% to 70% was assumed from recent industry sources (Green Giraffe 2016). In addition, corporate federal tax rates in the US were reduced in 2017, allowing the assumed tax rate to be reduced (federal and state combined) from 40% to 26%. These less conservative financial assumptions are supported in the literature by a recent cost study by Valpy which documented a WACC rate of 5.7% (2027 COD) and 5.4% (2032 COD), respectively for cost modeling of European fixed-bottom offshore wind projects (Valpy et al. 2017).

The impact from reducing the financing rates in this GOM assessment compared to the baseline is considerable (Beiter et al. 2017). Among sites analyzed for the GOM, reducing the FCR from 10.5% to 9.1% results in an average LCOE decline of approximately 12% from the 2016 baseline study (Beiter et al. 2017). Current NREL finance rate estimates for European offshore wind projects and new assessments made by NREL for the Vineyard Wind LLC project in Massachusetts indicate that lower FCRs between 7% and 8% may be attainable if risk commensurate with other offshore wind projects in the North Atlantic can be demonstrated (Beiter et al. 2019; Guillet 2018).

Table 4. Gulf of Mexico Financing Parameters (2027 COD)

	Updated Values	Baseline Beiter et al. (2017)
Debt interest rate (%)	4.4	8.0
Economic life (year)	20	20
Debt share (%)	70	50
Equity return (%)	12	10
Tax rate (federal and state) (%)	26	40
Modified Accelerated Cost-Recovery System (years)	5	5
Weighted Average Cost of Capital (%)	5.9	7.3
FCR (%)	**9.1**	10.5

Note: Election of Investment Tax Credit [ITC] or Production Tax Credit [PTC]) not considered; all values in nominal terms.

1.1.1.7 Insurance Costs

To account for the risk of tropical storms in the GOM, a 25% premium was assumed for construction insurance expenses, as well as procurement and installation contingency levels on top of the values assumed in Beiter et al. (2017). Overall, these markup adjustments to insurance and contingency levels have only a 1.5% increase on LCOE. However, these premium levels were implemented arbitrarily to acknowledge that there is an additional risk factor for offshore wind installation and operation in the GOM. Follow-on studies should consider more detailed analysis in this area. These studies should account for additional capital expenditures that may be necessary to accommodate a potentially more stringent set of design standards that may be required for some hurricane-prone regions. In addition, studies should consider a more detailed monetization of insurance expenses and contingency levels with market validation in the future. Risk management experience from oil and gas platform installation and operation in the GOM may offer some initial guidance but is beyond the scope of this study.

3.4 Regional Economic Results

3.4.1 Offshore Wind Levelized Cost of Energy in the Gulf of Mexico

The regional LCOE estimates are presented for hypothetical projects with a COD of 2030[20]. As the modeled LCOE values only extend to 2027, the modeled data between 2015 and 2027 were extrapolated to 2030. The 2030 development scenario is highlighted in this analysis because it was assumed that development in the GOM would lag the current industry expansion in the northeastern US because of greater technical and economic challenges and that commercial development in the GOM would not evolve until late in the 2020s. It is possible that market conditions may change, as we have seen in other

[20] All model dates are commercial operation dates.

regions, and that GOM development could accelerate due to lower costs than those modeled here, or that synergies created with other regions could help mature the markets faster than expected.

Estimated GOM LCOE values in 2030 range from below $70/MWh to $170/MWh (Figure 20). This range of LCOE is close to offshore wind costs currently estimated for European projects planned in the near-term. The lowest LCOE sites corresponded to sites with higher prevailing wind speeds that were closer to shore (and construction and operation ports), and in shallower water. These lowest LCOE conditions ($70MWh to $80/MWh) are most prevalent near coastal sites in Texas and Western Louisiana, particularly south of the municipal areas of Corpus Christi and off Galveston, Port Arthur, Texas, and Lake Charles, Louisiana, as seen in Figure 20. Outside of the western GOM, regional clusters of relatively low LCOE potential, below $100/MWh, were also identified off the municipal areas of Biloxi, Mississippi, and Pensacola, and Panama City, Florida. These LCOE values estimated for this analysis are lower than previous GOM estimates published in earlier NREL studies (Beiter et al. 2016, 2017). This is primarily the result of the updated FCR (Table 4) and, to a smaller degree, the optimized 10 MW GOM turbines.

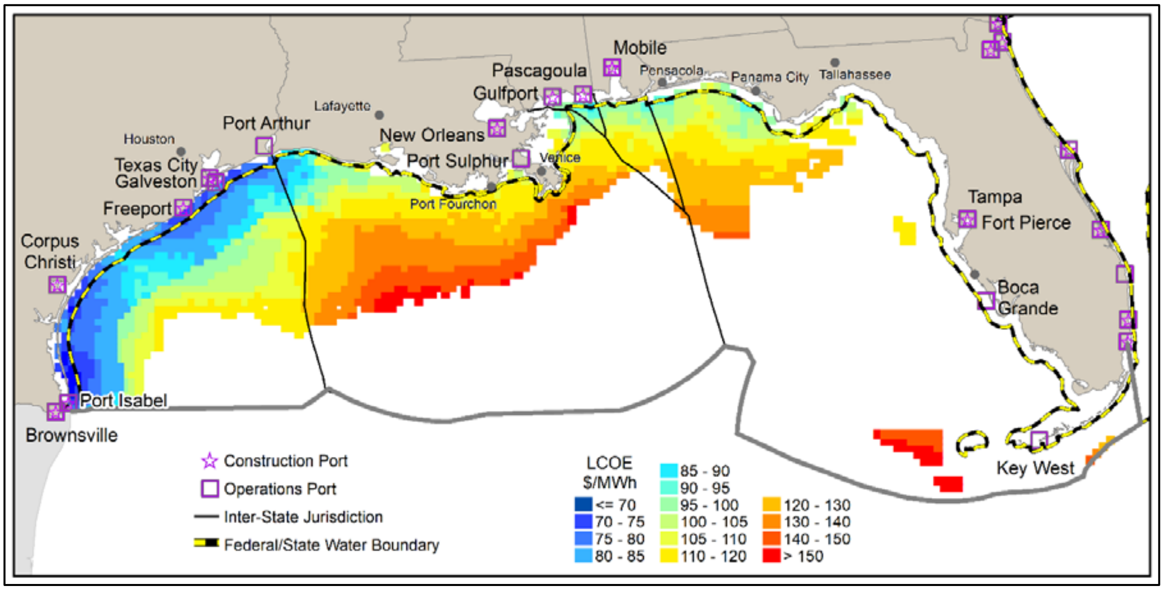

Figure 20. Gulf of Mexico levelized cost of energy (LCOE) (2030 COD).
Note: 2030 data were extrapolated from modeled data for 2015, 2022, and 2027 in Beiter et al. (2017).

3.4.2 Levelized Avoided Cost of Energy

LCOE provides an indicator to assess economic viability of an energy project but it is generally not sufficient to predict deployment because it does not capture its economic valuation of the produced electricity at different points of the electric grid. To calculate economic potential, Beiter et al. (2017) compared the estimated LCOE with the levelized revenue from projected wholesale electricity prices and the sale of capacity during the lifetime of a project, also termed as “levelized avoided cost of energy” (LACE). LACE provides a metric for assessing the economic potential of offshore wind relative to other sources (e.g., fossil fuels). The difference between LCOE and LACE at a given site location was defined as “net value” in Beiter et al. (2017) (Equation 3).

$$\text{Net value } (\$/\text{MWh})_i = \text{LACE}_i - \text{LCOE}_i \qquad (3)$$

A more detailed description of how LACE was determined and for various sites around the US is provided in Beiter et al. (2017). LACE values in the GOM were not altered from Beiter et al. (2017). LACE varies regionally across the GOM, with the highest LACE values occurring near the Texas-Louisiana border where interfaces between Electric Reliability Council of Texas (ERCOT) and the Louisiana grid create a local pocket of higher electricity prices around $70 MWh (Figure 21).

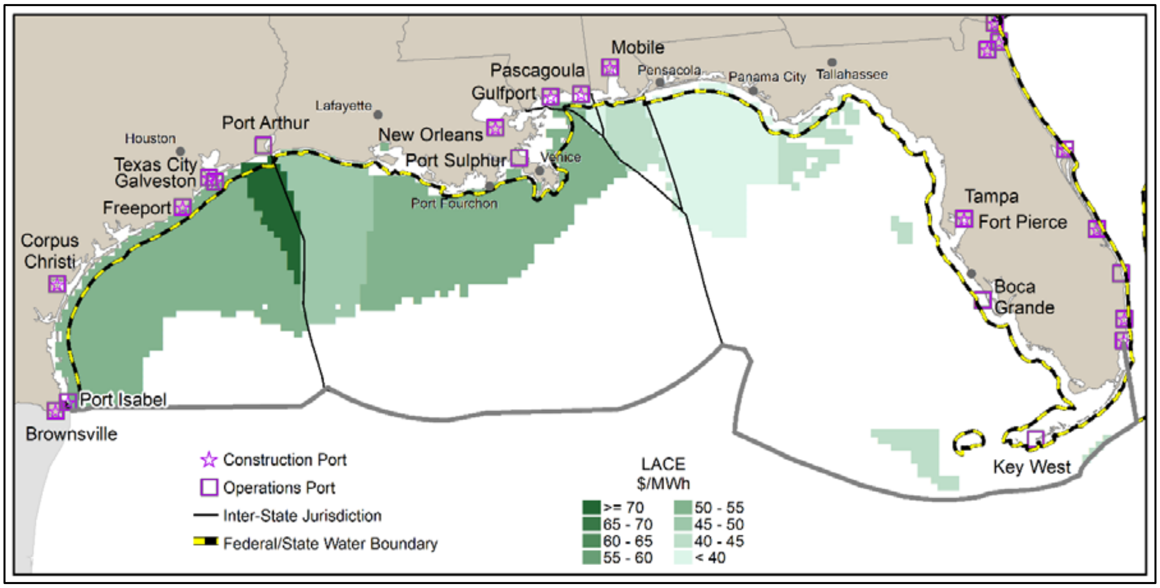

Figure 21. Gulf of Mexico levelized avoided cost of energy distribution (2030 COD).
Note: LACE value for 2030 (COD) was derived by extrapolating the modeled LACE values from 2015, 2022, and 2027 (COD) from Beiter et al. (2017).

3.4.3 Net Value

Regions where locally high electricity prices (i.e., LACE) coincide with lower LCOE have the highest net value (Equation 3), which is our primary indicator for economic viability. If net value is positive (i.e., > 0), then it can also be assumed that offshore wind can compete in that location without additional subsidies. Net value for the GOM ranges from -$5/MWh to -$125/MWh in 2030 (COD), indicating that the estimated cost (proxied by LCOE) of producing power from offshore wind at all GOM sites was above the required revenue opportunities (proxied by LACE) in 2030 (Figure 22). However, there were many sites with a net value near 0 which would be considered within the margin of error for this analysis. There is considerable uncertainty because of changing global market conditions, technical immaturity of some of the modeled cost parameters, and speculation of the future projected wholesale prices in 2030 (Beiter et al. 2017). Sites with relatively high net value (i.e., relatively close to zero) can be found among nearshore sites off Texas and western Louisiana, particularly off the municipal areas of Port Arthur and Corpus Christi, Texas. Regional clusters of relatively high net value were also identified off Gulfport, Mississippi and Pensacola, Florida.

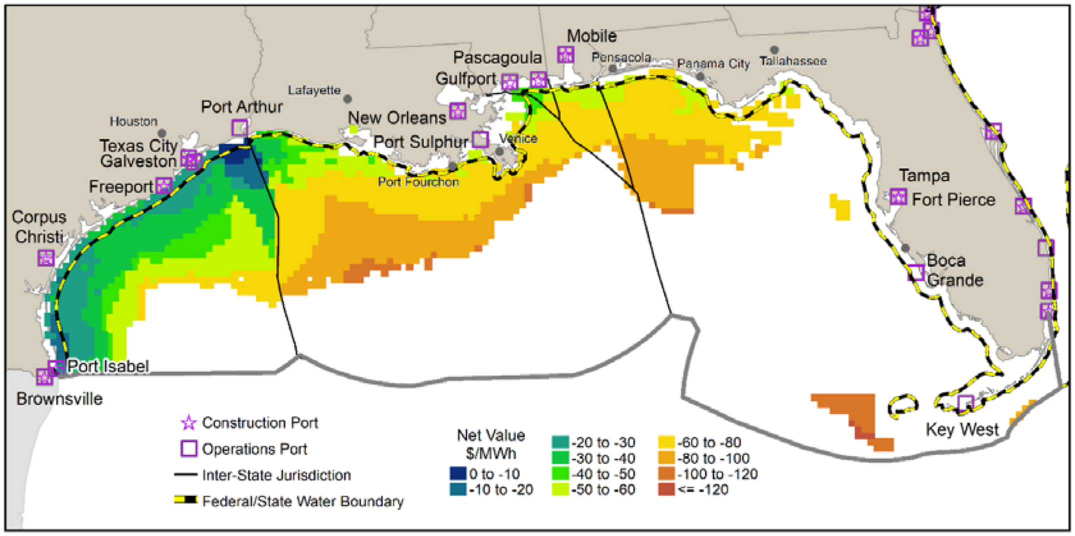

Figure 22. Estimated net value for Gulf of Mexico (2030 COD).
Note: 2030 data were extrapolated from modeled data for 2015, 2022, and 2027 in Beiter et al. (2017).

Unfortunately, the economic model had the capability only to assess projects to the year 2030. However, cost trajectories from the modeled data indicate that costs will continue to decrease beyond 2030 and that the cross-over for economic viability may be just beyond this time horizon. Key factors that may increase the net values for sites in the GOM include rapid supply chain maturity due to industry expansion in other regions, increases in turbine size up to 15 MW by 2030, lower finance costs, lower turbine costs, and gradually increasing LACE.

3.5 Regional Economic Summary

This study focused on the regional aspects of installing offshore wind in the GOM from both a technical and economic perspective. The GOM has not yet received much consideration as a viable region for offshore wind deployment because of several considerations. GOM states have not conducted as much renewable energy planning as states where offshore wind is now beginning to proliferate[21]. Existing utility rates tend to be lower than the national average, thereby making renewable energy less attractive. In addition, as discussed there are technical challenges related to lower average wind speeds and the threat of major hurricanes which could increase technical risk. However, there are many advantages to siting offshore wind in the GOM, including milder climates (temperature and waves), proximity to existing oil and gas supply chains, low labor costs, and large areas of shallow offshore wind resource.

Resource assessments conducted by NREL estimate that 32% of the total shallow water resource (< 60 meters depth) is in the GOM states. The GOM was found to have a notable total resource capacity relative to its electric load, with 508 GW and an energy generating potential of 1,806 TWh/year. The challenges in recovering this resource for utility scale offshore wind are significant but can be addressed and solved with available engineering technology. Offshore wind development in southern states may indeed delay the Pacific and Atlantic States by several years due to the resulting economic disadvantages, but cost trends in Europe and in the early projects of the US favor reducing cost and increasing economic viability which must be evaluated on a local or regional basis. By 2030, the economic models used in this study indicate that the lowest LCOE sites will be located close to shore near Houston, south of Corpus Christi,

[21] Not addressed in this report.

and near the Texas-Louisiana Border. Clusters of relatively low LCOE sites may develop in western Louisiana, and off Pensacola, Florida and Biloxi, Mississippi. The sites with the highest net value, which is the best indicator for economic potential, are located off Houston, south of Corpus Christi, and on the Texas-Louisiana border where LACE was found to be the highest. No economic potential (i.e., positive net value) was found without subsidies in GOM before 2030, but trends show offshore wind may be economical in GOM States without subsidies by the early 2030s.

4 Site-Specific Analysis for Offshore Wind in the Gulf of Mexico

This section describes the detailed site-specific economic analyses of possible future offshore wind projects conducted at three locations in the Gulf of Mexico (GOM). The objective here is to provide a more detailed analysis and a description of the characteristics of a typical project to allow stakeholders and policymakers to have better insights about the prospects for future offshore wind development.

4.1 Offshore Wind Site Selection in the Gulf of Mexico

4.1.1 Method of Site Selection

Before the site-specific analysis was conducted, the National Renewable Energy Laboratory (NREL) provided the Bureau of Ocean Energy Management (BOEM) with the regional GOM heat maps described in Section 3, which included technical offshore wind resource potential, LCOE estimations, and a summary of net value. Site selection criteria for hypothetical offshore wind power plant locations in the GOM were established by NREL and initial recommendations were made to BOEM for six candidate study areas.

The six sites that were selected for detailed analysis meet most of the following criteria:

- High net value within the region identified. This criterion ensures that sites with the highest economic potential and closest proximity to viable ports were selected,
- Large enough area (i.e., at least 350 km^2/86,487 acres [ac]) to support the commercial development of a utility scale offshore wind power plant, realize economies of scale, and demonstrate the economics of plant scaling to at least 1,000 megawatt (MW) (assuming an array density of 3 MW/km^2),
- Lowest levelized cost of energy (LCOE); (note that best economic potential (net value) and lowest LCOE do not always correlate),
- Locate in Federal waters (BOEM jurisdiction) and far enough from shore to avoid conflicts with coastal communities over viewshed issues (see Figure 23),
- Minimize use conflicts by avoiding environmentally sensitive areas, shipping lanes, and oil and gas infrastructure[22].
- Locate in shallow waters for economic reasons (less than 40 meters (m) [131 ft]), respecting viewshed setbacks needed for coastal communities.

In general, viewshed issues decrease with distance from shore and the sites beyond the territorial sea boundary[23] become more difficult to see from shore (Figure 23) although they will still be visible to some degree (Sullivan et al. 2013). The exact distance from shore that will be required to satisfy viewshed concerns is very site specific and will be addressed on a case-by-case basis. The figure shows that for the three study sites the minimum distance from shore is about 9 nautical miles (nm) for Port Isabel for the three study sites, but most of the area of the sites studied are beyond the territorial sea boundary that is included for reference.

[22] A comprehensive assessment of all possible use conflicts and environmental sensitivities was beyond the scope of this report.
[23] The National Oceanic and Atmospheric Administration (NOAA) defines the territorial sea at 12 nm measured from the maritime boundary of the low-water line along the coast.

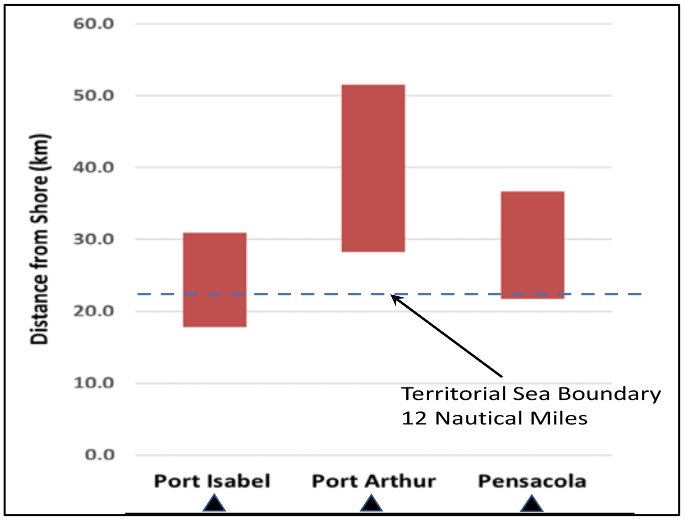

Figure 23. Distance-from-shore range for three down-selected Gulf of Mexico offshore wind sites.

The six candidate study areas were Site 1 (Port Isabel), Site 2 (Galveston), Site 3 (Port Arthur), Site 4 (New Orleans), Site 5 (Pensacola), and Site 6 (Panama City) (Figure 24)[24]. Figure 24 shows the same net value data from Figure 22 but with the six initial study areas identified. The six sites are identified with ovals that correspond to the candidate study areas. NREL and BOEM conducted a webinar meeting to discuss the merits of each site, and through this discussion the group narrowed down the selection to three final sites for this analysis. Three sites (Site 1 Port Isabel, Site 3 Port Arthur, and Site 5 Pensacola) were down selected from this group for further study. BOEM GIS specialists identified candidate sites boundaries along the existing BOEM lease block grid approximately within each oval area, which resulted in the red polygons indicated roughly inside each of the ovals in Figure 24.

As noted earlier, the most economical offshore wind sites are in the western GOM along the Texas border and in western Louisiana. Port Isabel was chosen because it was among the sites having the lowest LCOE in the GOM region. Port Author was chosen because it corresponds with the part of the GOM having the highest levelized avoided cost of energy (LACE), and as a result, the highest net value. Also, this site provides the possibility of investigating load serving across the border into Louisiana in future studies.

It was desirable to choose at least one site in another part of the GOM to provide geographic diversity and to understand the economic range across the GOM states. There were several areas of locally high LCOE and net value from which the Pensacola site was selected. Pensacola was chosen as a representative site in the eastern GOM that could potentially serve loads in Mississippi, Alabama, and Florida. Although this site did not show as high a net value as the other two sites, the results are useful for comparison.

The site selection process was designed to identify feasible wind development areas for the purpose of modeling potential cost. The study is designed to provide cost estimates for a typical site. Economic assessments of each site were made based on LCOE, LACE, and net value. The use of these results should be limited to informing economic and technical decisions about offshore wind trends for renewable energy planning. The selected study areas have not been vetted by the ocean user communities and are not intended to be a precursor for any potential future BOEM offshore wind energy Call Areas.

[24] Site names were selected based on geographic proximity to local cities but do not indicate any actual plans for further development.

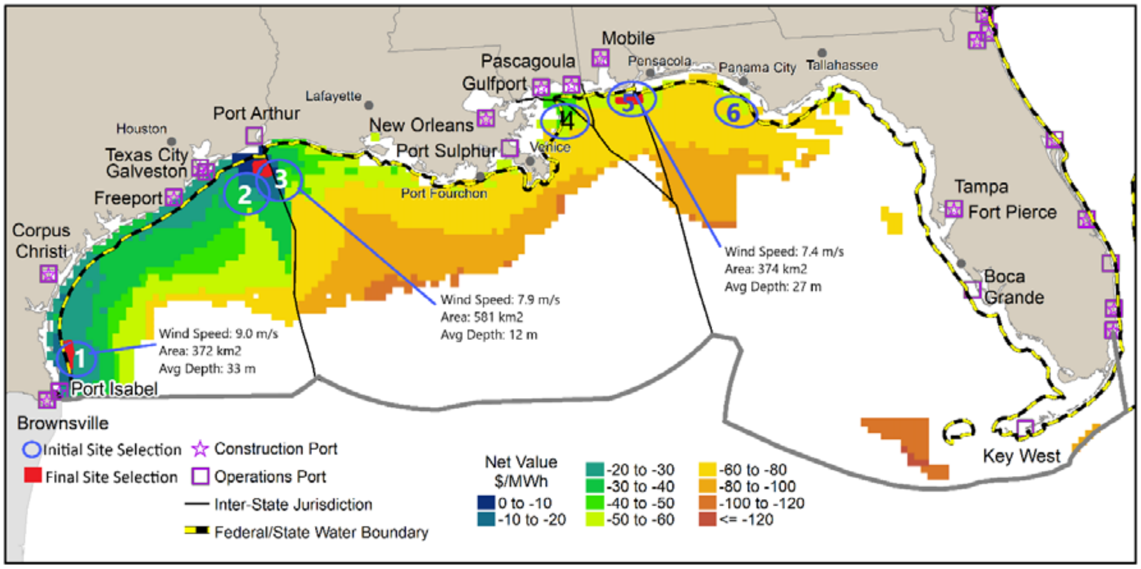

Figure 24. Estimated net value for Gulf of Mexico (2030 COD) with candidate sites.
Note: 2030 data were extrapolated from modeled data for 2015, 2022, and 2027 in Beiter et al. (2017).

4.2 Description of Offshore Wind Power Plant in Gulf of Mexico

This section characterizes a typical offshore wind power plant in the GOM. Many different variables may alter this description, but a generic description helps provide a mental image of what the technology would look like. The unique variables that have been mentioned will govern the offshore wind power plant architecture including low wind speeds between 7 and 9 meters per second (m/s) (15.7 and 20.1 mph), shallow water depths less than 40 m (131 ft), soft seabed conditions, and local supply chain synergies. Generally, a wind power plant must be at a scale large enough to enable amortization of the fixed cost items such as production tooling, operations and maintenance (O&M), export cables, substations, land-based interconnect, and development costs. Therefore, a 600 MW project was modeled for all cost comparisons, economic impacts, and energy production values. In all scenarios, a 10 MW turbine is assumed, with variable rotor diameters matched to the low wind regions described in Section 3.3.1.

The low wind speed turbine concepts for these projects have rotors that range in size from 205 to 223 m (673 to 732 ft) in diameter (Table 5).

Table 5. Turbine Technology Selected for GOM Sites

	Site 1 Port Isabel	Site 3 Port Arthur	Site 5 Pensacola
Turbine Rated Power (MW)	10		
Substructure Technology	Fixed-Bottom Jacket (Lattice)		
Average Wind Speed (m/s [mph])	9.04 (20.2)	7.87 (17.6)	7.37 (16.5)
Turbine Rotor Diameter (m)	205 (673 ft)	213 (699 ft)	223 (732 ft)
Turbine Hub Height (m)	127 (415 ft)	132 (431 ft)	137 (448 ft)
Turbine Specific Power (W/m^2)	303	280	257

These rotor diameters are larger than the European fleet of offshore wind turbines. Lower wind speed sites used larger rotor diameter turbines for optimal performance, and the tower heights increased with blade length. These turbines are NREL's best estimation of future technology extrapolated from current technology trends. A qualitative assessment of best practices for mitigation of hurricane loads and augmentation to meet regional low wind requirements was considered for each site (see Section 3.2.1).

Plant capacity and turbine size dictate an array of 60 turbines in 8 rows of 7 turbines (with one short row of 4 turbines). Turbine spacing is measured by the number of rotor diameters between towers but can vary depending on specific requirements. Increasing the turbine spacing is the best way to reduce wake losses. The degree of wakes losses is a design trade-off between the cost of the additional intra-array cable and the lost energy, but these trade-off analyses are beyond the scope of this study. We assume that 7 rotor-diameter (7D) spacing is used along the row and between rows, but it is likely that alternative layout options would be used by developers in more rigorous design studies to optimize performance, and to meet stakeholder requirements while staying within the site boundaries. To illustrate turbine spacing, the Pensacola site uses the 223-m rotor based on its average wind speed of 7.37 m/s (16.5 mph). With spacing of 7D, these turbines would be separated by 1.56 km (0.94 mi).

By comparison, Figure 25 shows a photo of the Block Island Wind Farm, the first US offshore wind facility.

Figure 25. Block Island Wind Farm with jacket substructures, showing 0.5 mi (0.8 km) turbine spacing.
Photo credit: Dennis Schroeder, NREL.

The Block Island Wind Farm comprises 6 MW turbines with 150 m (492 ft) diameter rotors. Turbine spacing was approximately 0.5 mi (0.8 km) according to the project's construction and operations plan (TetraTech 2012). For reference, this distance represents a 5.5 diameter spacing between turbines. Therefore, the turbine spacing for Block Island Wind Farm turbines is almost half as much as the estimated spacing of a offshore wind power plant built in the GOM near Pensacola (Musial et al. 2013).

Each of the three selected GOM sites is large enough for a 1,000 MW offshore wind power plant. Site conditions and geographic location are specified in ORCA based on the values computed at the centroid for each site. The turbines are assumed to be mounted on fixed-bottom jacket support structures, which we expect will be the least cost solution for the GOM because they provide the best structural capacity for soft soils, resistance to breaking waves, and can enable the existing regional manufacturing supply chains.

The Block Island turbines are also supported by jacket-type substructures (Figure 26). These substructures were manufactured in Louisiana at Gulf Island Fabricators and exemplify the GOM local supply chain capabilities for producing the jacket substructures.

Figure 26. Block Island Wind Farm with jacket-type substructures (yellow).
Photo credit: Dennis Schroeder, NREL.

Table 6 lists specific site characteristics used as inputs for the cost model.

Table 6. Characteristics of three offshore wind study areas in GOM chosen for detailed analysis

Site Name	Site 1: Port Isabel	Site 3: Port Arthur	Site 5: Pensacola
ID Number	1	3	5
Centroid Latitude	26.66	29.34	30.03
Centroid Longitude	-97.06	-93.84	-87.60
Average Annual Wind Speed (m/s [mph])	9.04 (20.2)	7.87 (17.6)	7.37 (16.5)
Min, Mean, Max Significant Wave Height	1.19, 1.19, 1.2	0.53, 0.63, 0.94	0.7, 0.73, 0.73
Min, Mean, Max depth	26, 33.0, 39	7, 11.8, 15	19, 26.8, 35
Construction Port	Kiewit Offshore Services	Dynamic Industries Inc	World Marine of Alabama LLC
Construction Port (lat/long coordinates)	27.851487, -97.226998	30.103639, -93.29429	30.678387, -88.041107
Centroid Distance to Construction Port (straight line – km [mi])	132.21 (82.2)	99.77 (62)	83.66 (52)
Centroid Distance to Construction Port (avoids land – km [mi])	151.78 (94.3)	108.42 (67.3)	99.11 (61.6)
O&M Port	Port Isabel	Port Arthur	Mobile
O&M Port (lat/long Coordinates)	26.0833, -97.2	29.8333, -93.9667	30.6833, -88.1167
Centroid Distance to Centroid Distance to O&M Port (avoids land – km [mi])	71.71 (44.6)	60.10 (37.3)	104.43 (64.9)
Interconnection Point	Harlingen	Port Arthur	Pensacola
Interconnection Point (lat/long coordinates)	26.2593, -97.6228	29.8967, -93.9284	30.4281, -87.2388

Site Name	Site 1: Port Isabel	Site 3: Port Arthur	Site 5: Pensacola
Centroid Distance to Interconnection (offshore until landfall) (avoids land – km [mi])	76.80 (47.7)	66.51 (41.3)	60.21 (37.4)
Distance Point of Cable Landfall to Interconnect (Overhead; km [mi])	38.41 (23.9)	25.60 (15.9)	14.23 (8.8)
Site Area (km^2)	371.86 (91,889)	374.22 (92,472)	581.32 (143,647)
Total Potential Capacity (MW)	1115.58	1122.66	1743.96
Total Potential Capacity of All Sites (MW)	**3,982**		

Average wind speed is a key variable that significantly affects the amount of energy a project makes. Site specific location relative to service ports, construction ports, manufacturing facilities, and point of land-based interconnection to the grid all affect the cost of the project. Increased distances generally add time to vessel day rates and decrease turbine accessibility. Longer distances also mean longer export cable runs which add capital expense.

A schematic of a 100-turbine rectangular array (Figure 27) using 6 MW turbines, similar to the 60-turbine array with 10 MW turbines that is modeled, is shown. Array cables, with an assumed rating of 66 kilovold (kV) come together at an offshore substation where the voltage is increased to a nominal level of 120 kV or more and the power is brought to shore through an export cable that interconnects with a shore-based substation. In most cases, the land-based interconnect substation is not located exactly at the shore. Therefore, the cost of an additional cable run over land is assumed to tie the offshore wind power plant to the grid.

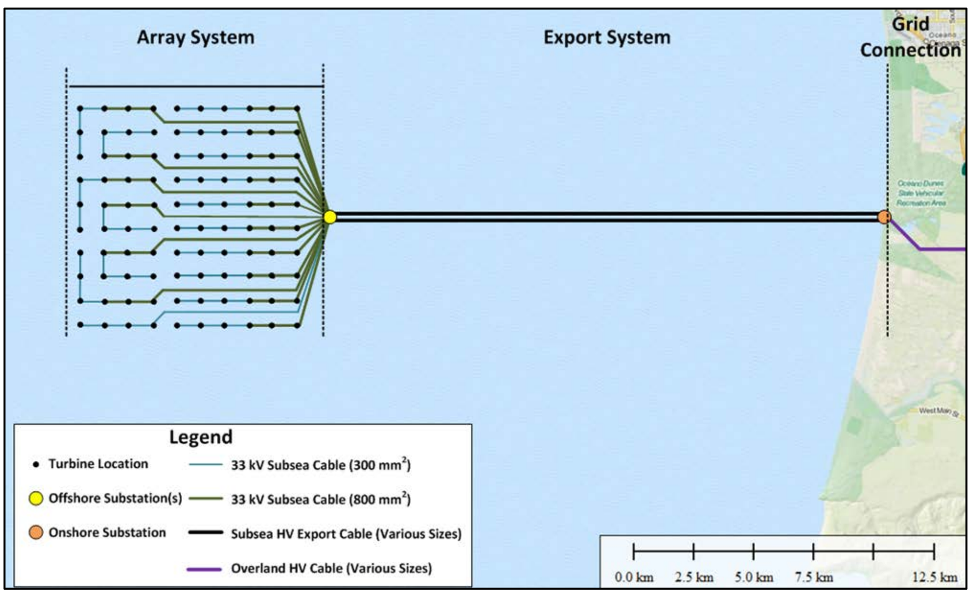

Figure 27. Schematic of typical modeled array cable layout and electrical export cable system for 6 MW wind turbines.
Source: Reprinted from Beiter et al. (2016).

4.3 Gulf of Mexico: Site Descriptions

4.3.1 Site 1: Port Isabel

The Port Isabel, Texas site (Site 1) is made up of 16 lease blocks[25] with a centroid located at 26.66 degrees latitude and -97.06 degrees longitude. The total area of this site was determined to be 372 km^2 (91,923 acres) which can support about 1,116 MW of offshore wind capacity[26]. The depth range for this site was determined to be between 26 and 39 m (85 and 128 ft) which is relatively shallow and not significantly challenging using locally sourced fixed-bottom support structures. This site has an average wind speed of 9.04 m/s (20.2 mph), which is among the windiest offshore wind sites in the GOM. The turbine used for this site was T303, with a specific power of 303 W/m^2. This turbine was the same specific power and size as the baseline turbine, so there was no additional cost premium for Site 1 Port Isabel. The turbine cost was modeled to be $1,552/kW in 2027.

The Port Isabel site had among the lowest LCOE of any site in the GOM; it is estimated to be near $78/MWh in 2030 (Figures 28 and 29). This site has a well-defined prevailing wind direction from the south-southeast (see wind rose in Figure 28).

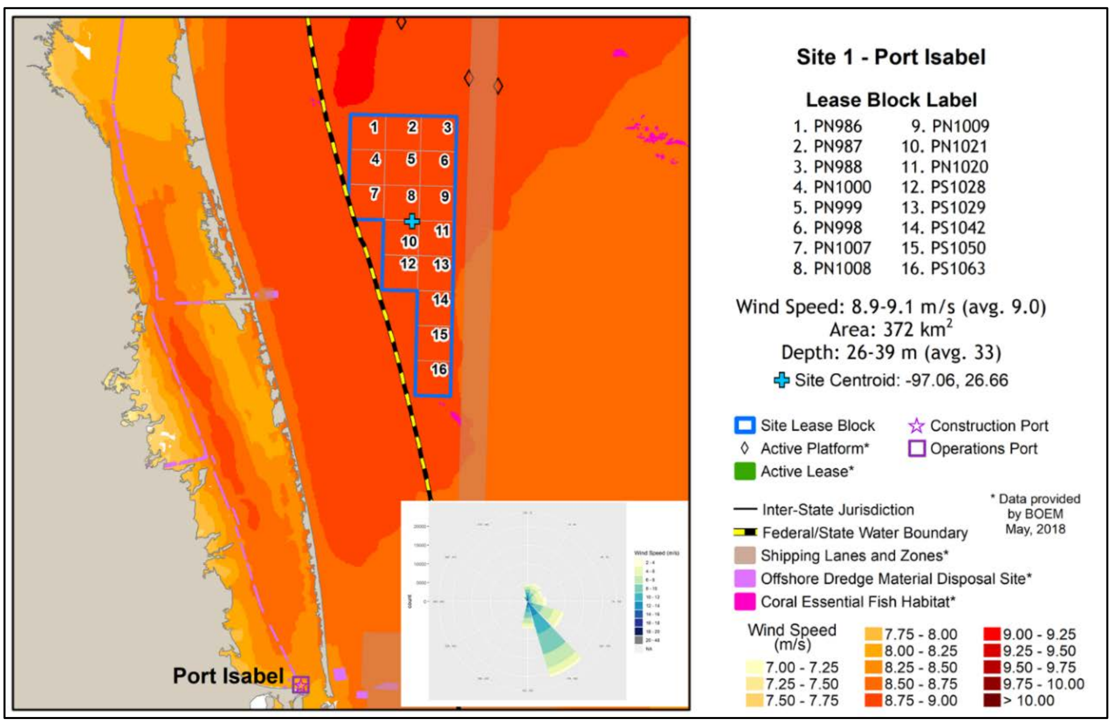

Figure 28. Location for the Port Isabel Site 1, showing average annual wind speed.

[25] One lease block is a square area with dimensions of 4.8 by 4.8 km (3 by 3 mi).

[26] Lease area installed capacity potential is calculated based on an array power density 3 MW/km^2.

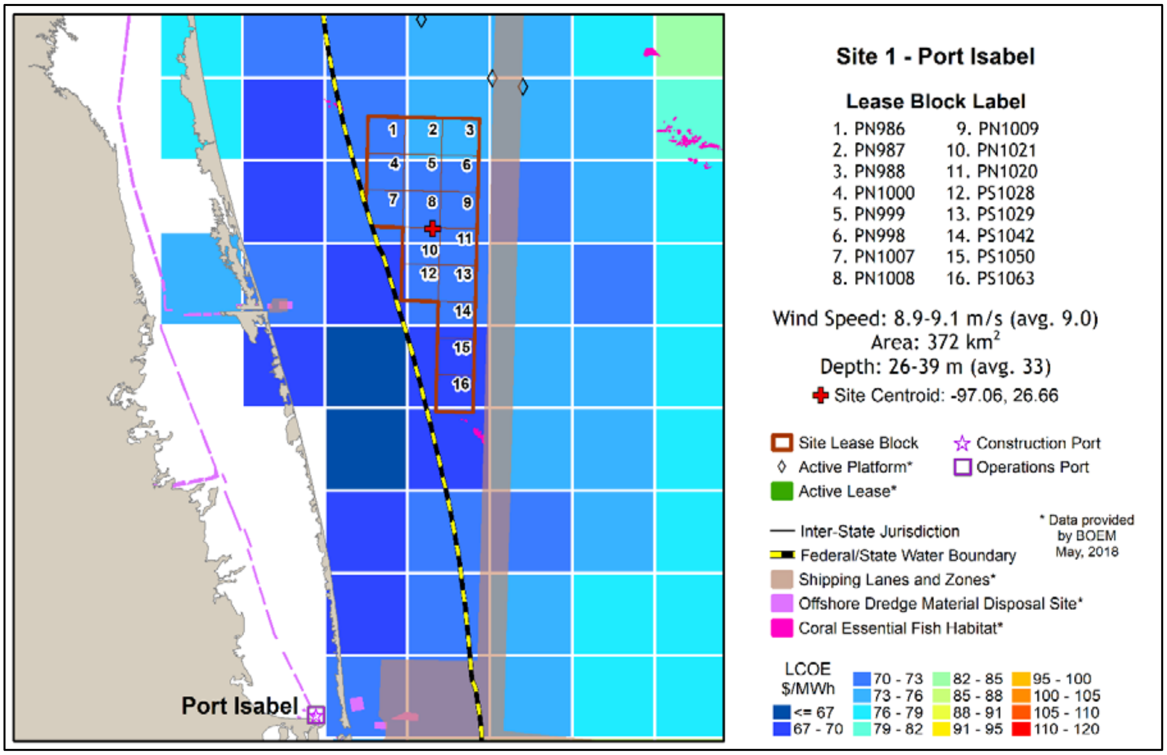

Figure 29. Location for the Port Isabel Site 1, showing estimated LCOE in 2030.

The sites closest to shore have the lowest LCOE; however, because of the large number of cost-driven variables, the lowest LCOE sites do not follow a predictable gradient (Figure 29). The LCOE grid is a matrix of squares, each representing the approximate footprint of a 600 MW array using 10 MW turbines. The annual energy production (AEP) and losses from each of these locations determine the cost of a project at that location in 2030 using turbine spacing of 7D. LCOE values incorporate site-specific challenges such as water depth, soft sediments, transmission losses, distances to ports, interconnection points, manufacturing areas, and the accessibility and downtime which is reflected in the estimated AEP.

4.3.2 Port Arthur: Site 3

The Port Arthur site is made up of an area the size of approximately 26 lease blocks, using pieces of 31 different lease blocks (Figure 30 and 31). This site has a centroid located at 29.34 degrees latitude and -93.84 degrees longitude and has a total area of 581 km^2 (143,568 acres) which can support an installed capacity of about 1,743 MW of offshore wind generation.

The depth range for this site was determined to be between 7 and 15 m (23 and 49 ft) which is very shallow compared to most offshore wind sites. This water depth should provide a cost advantage by minimizing steel in fixed bottom jackets from local manufacturing sources. However, shallow water could be challenging for some construction vessels with deeper drafts. This site has an average wind speed ranging from 7.8 to 8.2 m/s (average 7.9 m/s) (17.4 to 18.3 mph, average 15.7 mph), which uses the custom turbine (T280) with a specific power of 280 W/m^2 (Table 4). A cost premium of 3.15% was assigned to this site's turbine cost due to the slightly higher hub height and larger rotor; which was modeled to be $1,604/kW in 2027. The additional cost may be offset by the additional energy that the turbine will produce. The prevailing wind direction is from the south southeast but with more directional variability than the Port Isabel site (Figure 30).

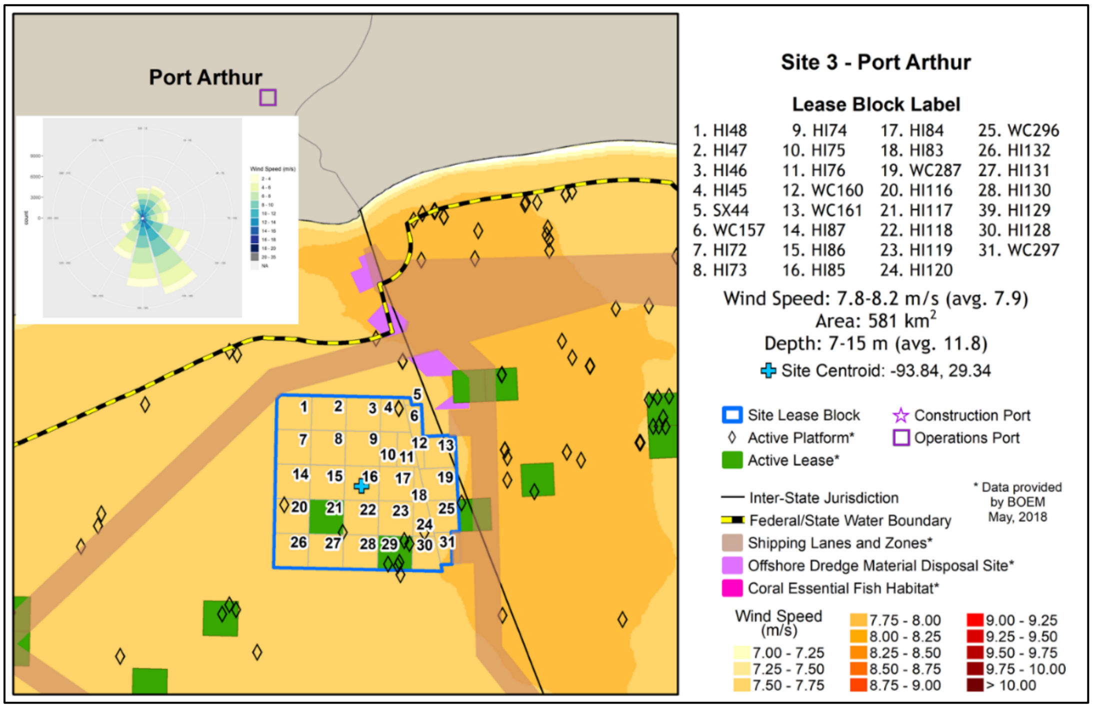

Figure 30. Location for the Port Arthur Site showing average wind speed.

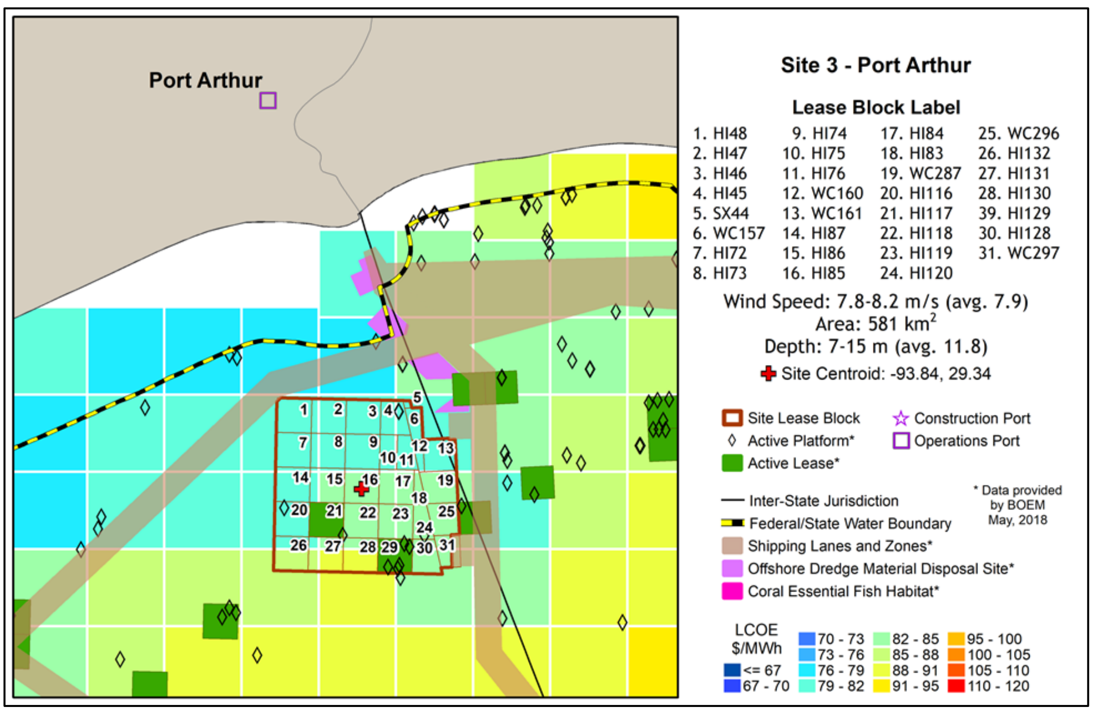

Figure 31. Location for the Port Arthur Site showing estimated LCOE in 2030.

As a result of the lower wind speeds, the LCOE values were estimated to be higher than at the Port Isabel site, ranging from $79/MWh to $90 MWh across the site in 2030, with the lowest LCOEs located closest to shore (Figure 31). These estimated LCOE values incorporate site-specific challenges that relate primarily to low wind speeds which are reflected in the estimated AEP.

Despite the higher LCOEs, the most compelling aspect of this site is that the LACE is the highest in the entire GOM region, with values above $70/MWh in northeast Texas near the Louisiana border in 2030 (Figure 21). Because the net value of a project is the difference between LACE and LCOE, a project at the Port Arthur site is estimated to have the highest net value in the GOM region, between $0/MWh and -$10/MWh in 2030. Theoretically, this site would be expected to be the most economically feasible of the three sites investigated.

4.3.3 Pensacola: Site 5

The Pensacola site is made up of an area the size of approximately 16 lease blocks (Figure 32). This site has a centroid located at 30.03 degrees latitude and -87.60 degrees longitude. The total area of this site was determined to be 374 km^2 (92,417 acres), which can support an installed capacity of about 1,122 MW of offshore wind generation. The depth range for this site was determined to be between 19 and 35 m (62 to 115 ft), which is considered shallow compared to most BOEM sites in the northeast Atlantic. This water depth should be an advantage because of cost savings gained by minimizing steel in fixed bottom jackets, which can be sourced from local manufacturing. The Pensacola site would not impose the same challenges as the Port Arthur site, where water depths were very shallow and could limit the type of vessels that could access the site.

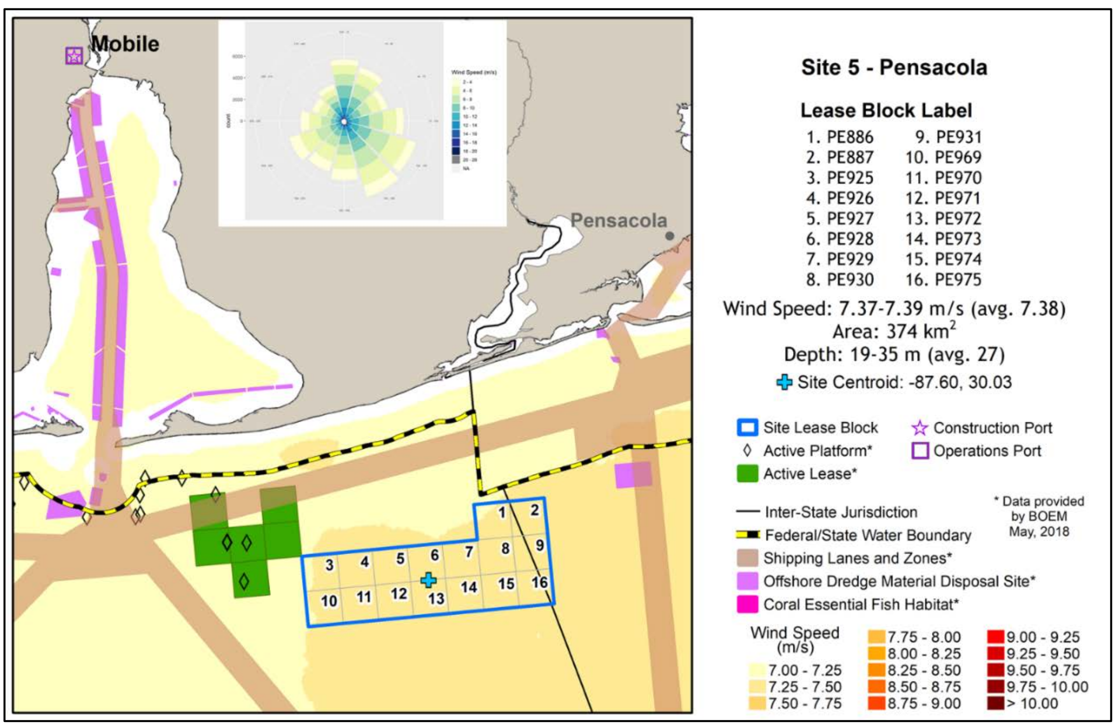

Figure 32. Location for the Pensacola Site, showing average wind speed.

The Site 5 Pensacola has an average wind speed range from 7.37 to 7.39 m/s (average 7.28 m/s) (16.4 to 16.5 mph, average 16.3 mph), which used the custom turbine with a specific power of 257 W/m^2, T257, and a rotor diameter of 223 m (732 ft) (Table 4). A cost premium of 14.22% was assigned to this site's turbine cost due to the higher hub height and larger rotor costs, which was modeled to be $1,773/kW in 2027. The additional cost may be offset by the additional energy that the turbine will produce. The prevailing wind direction is from the southeast but with still more directional variability than Site 1 Port Isabel and Site 3 Port Arthur.

As a result of even lower wind speeds at Site 5 Pensacola, the LCOE values were also higher than the Site 1 Port Isabel and Site 3 Port Arthur, ranging from $91/MWh to $105 MWh across the site in 2030, with the lowest LCOEs located closest to shore on the eastern end (Figure 33). These estimated LCOE values incorporate site-specific challenges that primarily relate to low wind speeds that are reflected in the estimated annual energy production. Because the net value of a project is the difference between LACE and LCOE, a project at this site is estimated to have a net value between -$50/MWh and -$60/MWh in 2030, making this site less economically attractive than Sites 1 Port Isabel and 3 Port Arthur under the current economic conditions.

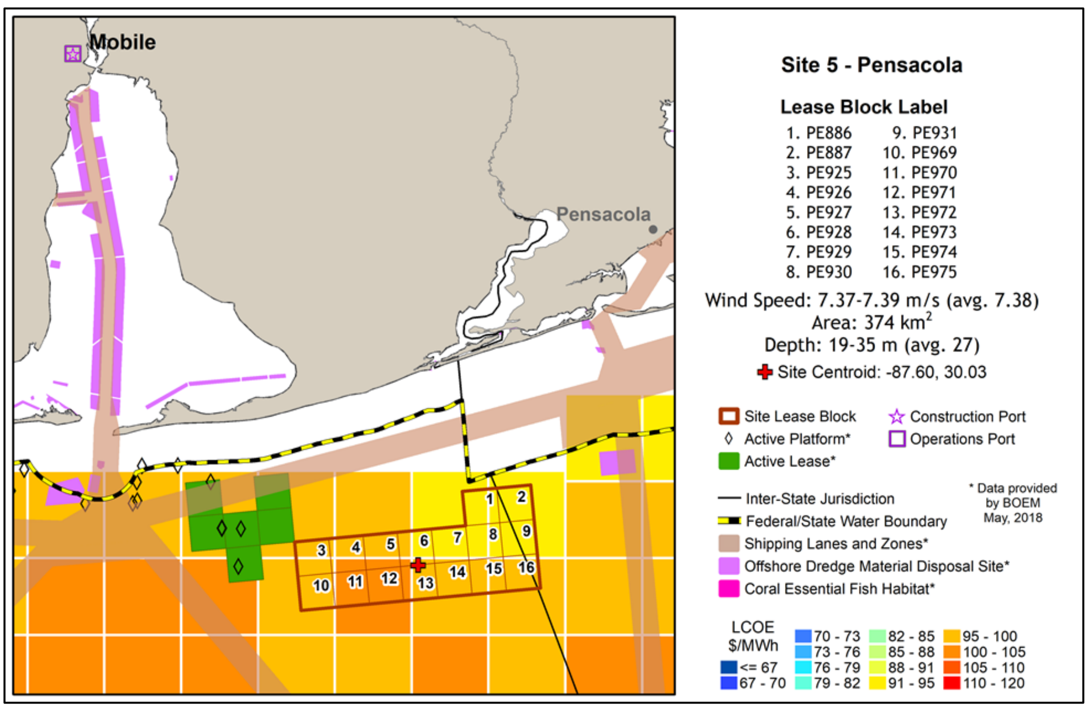

Figure 33. Location for the Pensacola Site, showing estimated LCOE in 2030.

4.3.4 Diurnal Site Characteristics

The time of day when offshore wind energy is delivered can be very important in integrating the power to the GOM (e.g., ERCOT) grid. The diurnal characteristics help utilities, states, regulators, and offshore wind developers understand the relationship of the offshore wind resource to the rest of the energy mix. The three diurnal average wind speed curves (Figure 34) exhibit similar day-night characteristics, where all three sites have peak winds in the late evening. Port Isabel shows an earlier peak at about 21:00 whereas the other sites peak around midnight. The low point of the cycle corresponds with mid-day for all sites. Depending of the ratio of other renewable sources, such as solar, this could be advantageous in avoiding overproduction during peak solar hours.

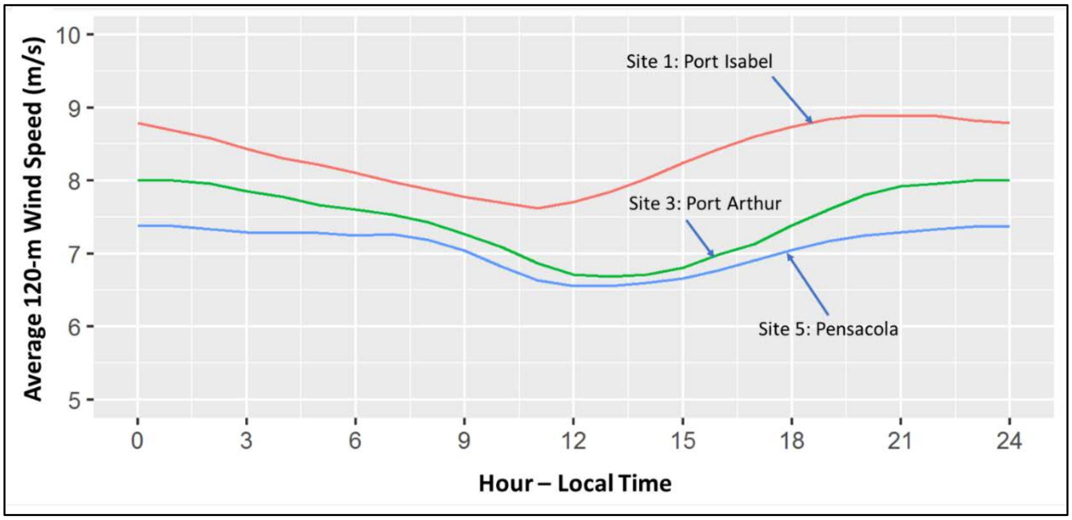

Figure 34. Average diurnal wind characteristics at Gulf of Mexico sites modeled at 120 m (394 ft) height.

4.4 Cost Comparisons for the Three Sites

The LCOE for each site for hypothetical projects commissioned in 2015 ranges from $139/MWh (Site 1 Port Isabel), $149/MWh (Site 3 Port Arthur) to $183/MWh (Site 5 Pensacola) (Figure 35). The LCOE values decrease for each of the three sites along a similar trajectory defined by the NREL cost model, ORCA (Beiter et al. 2016). The extrapolated 2030 LCOE values show a range from $73/MWh (Site 1 Port Isabel), $79/MWh (Site 3 Port Arthur) to $91/MWh (Site 5 Pensacola).

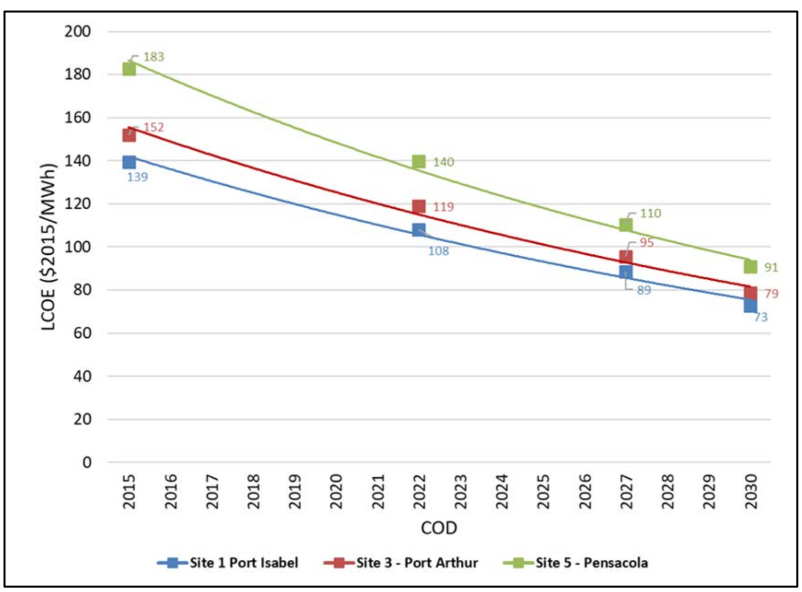

Figure 35. Estimated LCOE for the three modeled sites, from 2015 to 2030 (COD).

The trajectory over time for cost components of LCOE (capital expenditure [CapEx], operational expenditure [OpEx], and net capacity factor [CF_{net}]) is shown in Figures 36–38. The CapEx and OpEx costs are the lowest for Site 3 Port Arthur, which is not the site with the lowest LCOE. Low costs at Site 3 Port Arthur (red curve) are driven by its proximity to the site's interconnection point, construction, and O&M ports. In addition, the unusually shallow water and mild climate at this site contributed to further reductions in the estimated CapEx and OpEx costs.

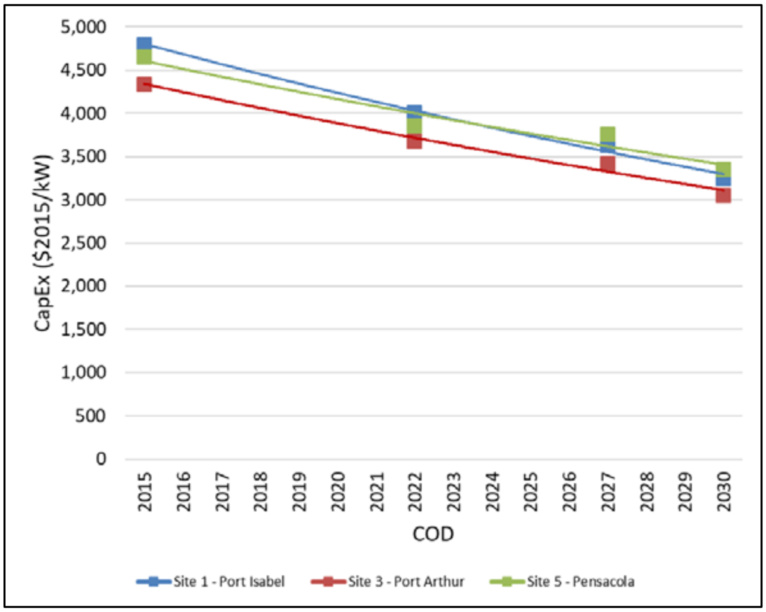

Figure 36. Estimated CapEx for the three modeled Gulf of Mexico sites from 2015 to 2030 COD.

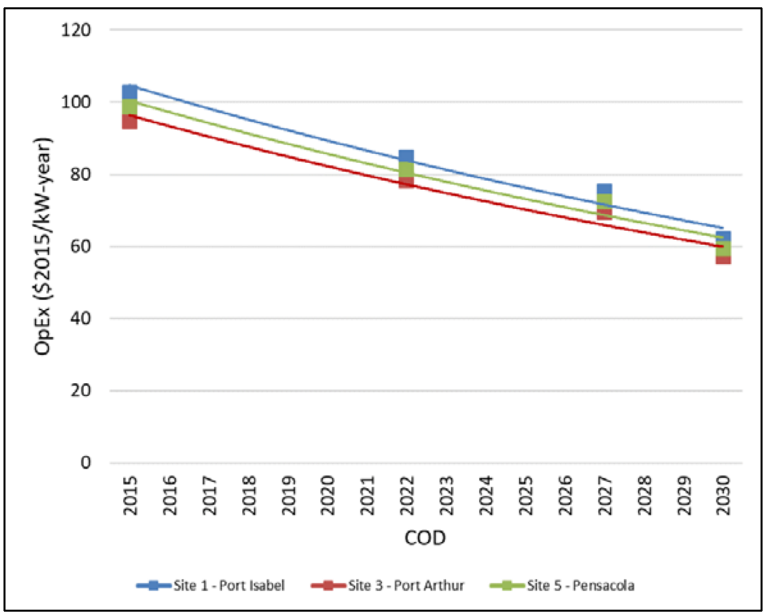

Figure 37. Estimated OpEx for the three modeled sites from 2015–2030 COD.

As turbine costs increase slightly because of larger rotors with lower specific power at Site 3 Port Arthur and Site 5 Pensacola, most of the net CapEx cost reductions are realized due to lower balance of plant costs. Specifically, substructure costs decline as water depth is decreased, and export cable costs decrease as distance to interconnects decrease. Similarly, O&M costs are lower for these two sites due to lower wave climates and proximity to service ports.

Site 1 Port Isabel had the lowest overall LCOE, primarily because of the higher net capacity factor of more than 54% that was estimated in 2030. Net capacity factors for Site 3 Port Arthur and Site 5 Pensacola are estimated to be significantly lower at 44% and 42%, respectively, as a result of lower wind speeds. The net capacity factors are modeled to increase over time due to improvements in turbine efficiency and reliability, taller towers, improved turbine access, and reduced plant wake and electrical losses.

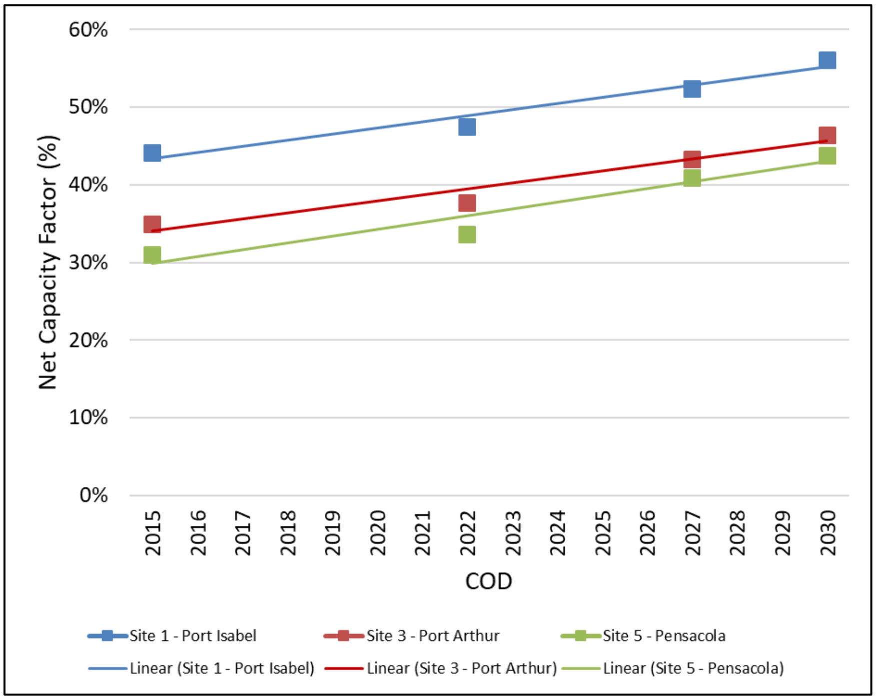

Figure 38. Estimated net capacity factor for the three modeled sites, from 2015 to 2030 COD.

4.5 Economic Modeling: Caveats and Limitations

A comprehensive discussion of caveats and limitations related to the modeling of LCOE and economic potential is documented in Beiter et al. (2016, 2017). The cost-reduction pathway used in Beiter et al. (2016, 2017) and applied here assumes that enough domestic deployment and maturing of the supply chain will occur in the US by 2030 to support these cost reductions. Although it is not well understood if the recent price and cost reductions observed across European and early US offshore wind projects (Beiter et al. 2019) will be realized in the GOM by 2030, it appears that existing oil and gas GOM supply chains will provide a cost advantage and may give the GOM states a head start.

Additional assumptions that are specific to this analysis of LCOE and economic potential in the GOM include:

- Installation vessels and a robust supply chain for the installation and operation of fixed bottom offshore wind power plants with 10 MW turbine ratings will be available in the GOM when offshore wind deployment begins.
- Any additional cost related to increasing the hurricane survivability of the conceptual 10 MW turbines was not considered (e.g., it is likely that the blades and towers would have to be strengthened in some parts of the GOM).
- Current industry information suggests that the turbine costs assumed for this study $1,552/kW for Site 1 Port Isabel to $1,773/kW for Site 5 Pensacola are conservative. Some sources indicate these costs may be overstated by as much as 30%. These inflated turbine cost should be addressed in follow-on studies.
- Only jacket substructures were considered. Other floating or fixed bottom types might be feasible; however, because of an abundance of shallow water, floating foundations were not considered.
- Turbine ratings exceeding 10 MW may be available by 2030 but were not considered in this study. Based on current industry progress, it is expected that 12 MW and possibly 15 MW wind turbines will be available by 2030. The growth of wind turbine capacity has been shown to be one of the leading factors for decreasing LCOE.
- The study uses a potential risk premium of 25% to the insurance costs that is associated with tropical cyclones in the GOM. Perceptions of higher risk due to hurricanes have not been fully evaluated in the context of financing or insurance rates and the assumption of 25% could be low.
- Despite the risk uncertainty caused by hurricanes, the financing parameters documented in Table 4 may be higher than rates indicated from commercial projects using mature technology in other US regions. Some sources indicate FCR could be as low as 7% if the cost of money the GOM is the same as other US regions. These effects should be investigated further in future studies.
- The global uncertainty over steel tariffs and possible trade barriers may impact domestic content and costs for some components, especially the substructures.
- The wind resource data used for this study are subject to significant uncertainty in both its spatial and temporal characteristics, and very few validation measurements exist to improve the empirical accuracy. Higher resolution modeled data and more observations at hub height are needed.
- The economic model used only had the capability to assess projects to the year 2030. However, it is expected that most commercial GOM deployments will take place after 2030, which is based on current cost trajectories and a status quo assumption on new state and federal policy incentives (i.e., we assumed that additional state and federal incentives in the GOM will not be enacted over the next decade).

4.6 Summary and Conclusions

A site selection process was implemented from the regional cost analysis to examine three offshore wind sites in the GOM that exhibited potential for future economic viability. Initially, six locations were identified that met the criteria for site selection, including low LCOE, high net value, relatively low use conflicts, federal waters, and reasonable geographic diversity. From those six sites, three sites were selected for more detailed study: Port Isabel, Port Arthur, and Pensacola.

Port Isabel, in south Texas, had the lowest LCOE; Port Arthur, in north Texas, had the highest net value; and Pensacola, near Florida and Alabama border, had the lowest wind speed site. Using varying specific power wind turbines, customized for the site-specific wind conditions, the economics were evaluated for each site with ORCA and extrapolated to the year 2030. Customized turbines and lower finance costs contributed to lower LCOE estimates from previous studies conducted by NREL (Beiter et al. 2016).

The Port Arthur site, despite having higher LCOE, had the highest LACE in the entire GOM region, with values above $70/MWh. Because the net value of a project is the difference between LACE and LCOE, a project at the Port Arthur site is estimated to have the highest net value in the GOM region, between $0/MWh and -$10/MWh in 2030. Theoretically, this site would be expected to be the most economically feasible of the three sites investigated.

Other conclusions from this investigation include:

- Highest wind resources are in the western GOM, which also corresponded to the most favorable economics.
- Low LCOE was not the best predictor for economic viability; the study found the highest net value was at Port Arthur, where higher levelized avoided costs made potential offshore wind development more attractive.
- No site in the study achieved the goal of reaching positive net value by 2030, which is found only where LCOE is less than the LACE.
- Some sites were estimated to have net value greater than -$10/MWh by 2030, which was with the margin of error for the study and close to economic viability.
- Further analysis is warranted to assess the impact of hurricanes and larger capacity turbines (12 MW to 15 MW) over a longer timeframe that extends to at least 2032 COD.

4.7 Recommendations for Future Work

The costs of fixed bottom offshore wind projects continued to decline globally, during this study, and new power purchase agreements (PPA) in the US revealed that some cost variables in this study may be conservative relative to 2019 industry data. Some technology trends that are known to lower cost could be modeled, which would result in lower LCOE than estimated herein. The primary recommendation for future study is to continue to assess the GOM technology options that would lower cost by using updated cost inputs from most recent market trends and implementing more robust updated cost models.

Some critical variables that did not receive full treatment in this study are described below.

Turbine scaling: By 2030, turbine size is expected to increase beyond the 10 MW rated capacity assumed for this study. Larger turbine size is a primary factor lowering LCOE. For example, GE has announced that a 12 MW turbine will be deployed in the early 2020s and other manufacturers are likely to follow with turbines up to 15 MW by 2030 (General Electric 2018). Larger turbines above 10 MW will likely contribute to lower LCOE in the GOM. The Vineyard Wind project, off Massachusetts (800 MW), with commercial operations expected in 2022 and/or 2023, has recently announced the use of a V164 9.5 MW turbine, which now leads the trend toward larger turbines, with 12 to 15 MW commercial turbines possible for US deployment by the late 2020s. For the GOM, where we can probably expect 12 MW turbines by 2030, larger turbines could push LCOE lower than what is reported in this study.

Turbine prices: Turbine prices are not typically made public and are difficult to obtain. However, current turbine costs in 2019 appear to be trending lower than reflected in the baseline assumptions for this study. Various studies suggest that turbine CapEx may reach levels of $1,200/kW by 2020 (e.g., Valpy et al. 2017)[27] and are expected to further decline to approximately $1,000/kW by the mid-late 2020s. Reducing the turbine CapEx by 30% would reduce LCOE by nearly 6% across all GOM sites considered. The net effect on turbine price/cost among the relevant factors, which include low wind speed turbines, hurricane resilient turbines, and lower industry costs, is expected to be downward relative to the model baseline assumptions, but these effects are not fully captured herein.

Detailed site analysis: More detailed analysis is needed that explores areas of conflicted use within the sites which were selected for their optimal characteristics for offshore wind development within the GOM. Because of the limited scope of this effort, NREL was unable to identify and assess all types and areas of conflicted use for Site 1 Port Isabel, Site 3 Port Arthur, and Site 5 Pensacola.

It may also be beneficial to investigate potential mitigations for bottom-disturbing activity and the associated costs and layout considerations associated with those mitigations. Surveys may be required before construction to make sure all sensitive benthic habitat is identified, and that placement of substructures and cables are considered with respect to these sensitive habitats.

Insurance Costs and Hurricane Risk Mitigation: Hurricanes were addressed in this study by increasing the insurance costs by 25%; however, a more rigorous study of the hurricane risk and its impact on all costs should be conducted. These studies should address the hurricane resiliency of turbines that may be sited in the GOM, as well as in the south Atlantic or other areas that my encounter typhoons or severe tropical cyclones. There is currently a high degree of uncertainty about the risk of wind turbines in these regions but future work outside this study promises to reduce that uncertainty so that wind turbines can be deployed with the same confidence as at other sites. As such, it is expected that insurance rates and risk perception can be managed in the same way as other structures exposed to such extreme weather (e.g., skyscrapers in Miami or oil platforms). As the engineering science regarding hurricane design improves, this information should be integrated into the cost analysis.

Although this study accounts for rising turbine costs resulting from higher hub heights and larger rotors associated with low specific power (low wind speed) turbines, it does not provide any engineering to account for additional costs to outfit turbines to defend against hurricanes. These upgrades may include design features, such as uninterruptable yaw ride-through power, ruggedized sensors, and stronger blades and towers.

[27] Valpy et al. (2017) estimates a 10 MW Turbine CapEx of EUR1,051/kW by 2020 (scenario “10-D-20”), which corresponds to approximately $1,200/kW.

5 Gulf of Mexico Offshore Wind Infrastructure

5.1 Background

The offshore oil and gas industry emerged from the Gulf of Mexico (GOM) region in the 1960s and 1970s when a robust offshore industrial base and supply chain took root. In the past decades, this region has become the world's center of marine activity for manufacturing, offshore engineering design, training, shipping, offshore construction, and energy production. As the world's energy supply diversifies toward renewable energy, particularly offshore wind, these vast GOM resources are poised to capitalize on the nascent, but enormous emerging offshore wind industry.

Scenarios from the DOE "Wind Vision: A New Era for Wind Power in the United States" suggest that as much as 86 gigawatts (GW) of offshore wind may be deployed in the US over the next 30 years (DOE 2015). At this scale, the US alone would make investments of up to $300 billion in USD; short-term projections indicate 150 GW may be installed globally by 2030. In the northeastern US, the offshore wind market is being spurred by state policy, from Massachusetts to Maryland, where almost 20 GW of offshore wind has been committed, and well capitalized developers representing a range of European oil companies and major utilities have staked claims and are beginning to develop projects. Much of this development depends on mature supply chains and vessels developed in Europe, but the experience and expertise of the GOM states is likely to be tapped to deliver these development services more efficiently and at a lower cost, not just to the early offshore wind markets in the northeast US, but to serve the GOM electric grid and the rest of the world.

The purpose of this section is to:

- assess the current state of the facilities in the GOM to support the rapid growth of the offshore wind industry in the US,
- make recommendations where infrastructure investments can be made to support domestic growth and capitalize on export markets,
- assess the current infrastructure and estimate its benefit to lower the domestic cost,
- assess barriers to ramping up the existing oil and gas infrastructure to support the offshore wind industry,
- inform jobs and economic impacts analysis (Section 6) to identify specific GOM issues related to local content, infrastructure, labor rates, and economic advantages and challenges that may impact the regional GOM economy.

A general assessment was performed of the availability of and advantages of local supporting infrastructure to offshore renewable energy development in the GOM. Design services, fabrication facilities, vessels, ports, and associated labor forces that are traditionally used by the oil and gas industry have the capacity to fabricate, install, and maintain offshore wind projects, and may be able to support other types of offshore renewable energy projects, as well. This analysis will inform understanding of the costs and benefits associated with different offshore transmission infrastructure configurations and strategies. Consideration will also be given to opportunities to leverage existing supply chains, as well the remaining gaps remain in the development of sustained domestic supply chains.

5.2 Supply Chain Investigations

Offshore wind projects in the US are expected to heavily leverage the GOM supply chain and manufacturing facilities that already exist for oil and gas. This is especially true for projects built in the GOM, but projects built anywhere in the US may use GOM supply chain facilities. An assessment of the infrastructure and supply chain was conducted by reviewing literature and interviewing regional stakeholders. As part of the economic case studies, a general assessment of the availability and advantages of local supply chain and supporting infrastructure to offshore renewable energy development in the GOM was examined. The focus of the examination was to determine what design services, fabrication facilities, vessels, ports, and associated labor forces, traditionally used in oil and gas, have the capacity to fabricate, install, and maintain offshore wind energy projects in the GOM, and what barriers there are in adapting to this new industrial paradigm.

Industry interviews were conducted with two regional industry stakeholders (Keystone Engineering, Inc. and Gulf Island Fabrication, Inc.). Five primary categories were discussed during the interviews, with focus placed on theoretically constructing an offshore renewable energy project in the GOM region. The five categories were:

1) regional organizations for engineering or design services,
2) available skilled labor force,
3) existing manufacturing or fabrication facilities,
4) existing port infrastructure, and
5) available vessels to install and maintain an offshore renewable energy project in the GOM.

The available labor force in the GOM is rich with the skills required for successful installation of offshore oil and gas projects (Table 7).

Table 7. Summary of Gulf of Mexico Industry Interviews

Organization	General Discussion Topic	General Findings
Keystone Engineering, Inc.	Labor	• Experienced regional labor force with useful skills from the oil and gas industry that may be applied to the offshore wind industry.
	Manufacturing	• Highly capable manufacturing facilities for fabrication of offshore wind jackets, monopiles, and towers.
	Ports	• Easy access to ports (i.e., limited overhead clearance issues from bridges) and capable port-side cranes to lift heavy turbine foundation components.
	Vessels	• Current vessels are generally capable of installing offshore substructures in shallower waters (e.g., less than 40 meters [m]); beyond 40 m water depth there is a lack of available vessels. • The challenge for the wind industry is having a vessel with large lifting capabilities at high hook heights.
Gulf Island Fabrication, Inc.	Manufacturing	• The GOM region has steel rolling mills capable of fabricating jackets, monopiles, towers, and floating spar structures. However, the rate at which the components are fabricated is constrained at about 2–3 units per month (estimate provided for jacket substructures). • Large scale spars on the order of 427 m in length and weighing 45,400 metric tons have been fabricated in the GOM region. • The steel rollers are capable of rolling 11.43-centimeter-thick steel plates into 26-m diameter cans but are not capable of rolling tapered cans.

Organization	General Discussion Topic	General Findings
	Ports	• There are multiple quayside yards in the GOM region within protected waters that include graving docks, large-scale fabrication capabilities, and access to heavy lift cranes.
	Vessels	• The GOM region has expertise in shipbuilding capabilities and have built US-flagged vessels equipped with 454 metric ton cranes with boom length of 102 m. • Unique catamaran vessels have been built with lift capacities up to 9,072 metric tons.

From the perspective of the industry stakeholders, there will not be a shortage of skilled labor to install and maintain offshore wind energy projects if built in the GOM. This also applies to the labor supporting the manufacturing facilities, capable of fabricating complex steel structures including monopiles and jackets for fixed-bottom substructures, and semisubmersibles and spars for floating substructures. The interviews indicated that large offshore spar structures for oil and gas have been fabricated with scales on the order of 427 m (1401 ft) in length and weighing around 45,000 metric tons, many times larger than an offshore wind substructure. The steel rollers used to fabricate these structures are capable of rolling steel 11 centimeters thick into 26 m (85 ft) diameter cans, which could be adapted for rolling steel turbine towers. However, the steel rollers are not currently capable of producing a tapered cylinder but would still be useful for offshore wind applications. At the current scale of the substructure and tower components, manufacturing facilities in the GOM are easily capable of meeting the size requirements for the offshore wind support structures, but the current volume of production at most facilities may be too slow for large offshore wind energy projects. It is estimated that fabricating these types of substructures may be limited to 2–3 units per month (estimate assuming a jacket substructure) which would be insufficient for offshore wind project installation timing, assuming 600 MW scale developments. Because there is no simple solution to increase production volumes, investments in faster plant through-put should be investigated to meet future demand as industry demand increases.

The ports infrastructure in the GOM are generally well equipped to support the renewable offshore wind industry because the desired port characteristics for oil and gas are similar to those for offshore wind. The ports on the coast of Texas and Louisiana serve as the primary manufacturing and operational ports for offshore energy projects. These ports are not only equipped with quayside high-capacity cranes to lift large components from the fabrication facilities but are placed in protected waters shielded from undesired metocean conditions. Many ports also offer easy vessel access with limited overhead clearance issues and shallow draft restrictions. A few of the ports are equipped with dry docks that may be adapted for floating offshore wind substructure fabrication and load-out to on-site construction sites and for operations and maintenance of projects.

The oil and gas industry inventory includes several heavy lift offshore jack-up vessels with large crane capacities (>1,000/ton). However, offshore wind projects require the ability to lift heavy components to higher elevations (hub heights increasing up to 140 m (459 ft) or greater). This height requirement is unique for the installation of wind turbine nacelles weighing over 500 tons and requires purpose-built turbine installation vessels that do not currently exist in the US fleet.

An important constraint to conducting offshore work in the US is the Jones Act, which allows only US-flagged vessels to transport components from one US port to another. Currently, there are no US-flagged vessels capable of installing modern offshore wind turbines. The jack-up vessels serving the oil and gas industry in the GOM can install the turbine's substructure (for fixed-bottom) and its transition pieces (connecting the top of the substructure to the bottom of the turbine tower). From the industry interviews, the general limitations of the jack-up vessels in the GOM were identified. The vessels are generally able to operate in water depths up to 40 m (131 ft) and have crane capacities about 450 metric tons. Though some of these vessels have boom lengths up to 100 m (328 ft), the lifting capacity is greatly reduced when lifting to heights required for installing turbine components. For floating offshore wind, the GOM may be able to use the already existing port infrastructure and heavy-lift crane capabilities to erect the turbines at quayside and float the turbines out to site using a US-flagged tug. Significant investment is needed in repurposing or building a new fleet of offshore wind turbine installation vessels.

Existing jack-up vessels can still be used as feeder barges to transport turbine components from port to the project site to serve a purpose-build turbine installation vessel. Such a feeder barge strategy was used to construct the Block Island Wind Farm and is a viable strategy that complies with the Jones Act.
The industry stakeholder interviews also identified over a half-dozen large-scale organizations located within the GOM region that may have capabilities to support the offshore renewable energy industry. These organizations primarily consist of engineering, procurement, construction, and installation (EPCI) contractors and shipbuilders. These EPCI organizations have a history of successfully installing complex offshore energy projects and are willing to take on the challenges and opportunities of the offshore wind industry. The shipbuilding yards may also be able to contribute their skilled labor and specialty tooling that could be adapted for fabrication of floating offshore structures. These interviews were limited in scope. The list (Table 8) is believed to be a small fraction of the capabilities that exist in the GOM region and that may be brought to bear on the US offshore wind industry.

Table 8. Identified Gulf of Mexico Fabricators and Shipbuilders

Organization	General Location	Primary Capabilities
Gulf Island Fabrication, Inc.	Corpus Christi, TX Houma, LA	Fabrication of complex structures, shipyards, onsite services, engineering, procurement, and construction
Dynamic Industries, Inc.	Corpus Christi, TX Lake Charles, LA New Iberia, LA Harvey, LA	Fabrication, engineering, procurement, construction, installation, and maintenance
Twin Brother Marine, LLC	Franklin, LA	Heavy industrial steel fabricator of offshore oil and gas platforms and steel modules
State Service	Corpus Christi, TX	EPC and/or EPCI solutions in every energy sector
Kiewit Offshore Services	Corpus Christi, TX	Construction of offshore oil and gas structures and large structural steel components
Ingalls Shipbuilding	Pascagoula, MS	Largest supplier of US Navy surface combatants
World Marine, LLC	Mobile, AL	Ship repair and engineering

5.3 GOM Infrastructure: Key Findings and Recommendations

A general assessment of the availability of the local GOM supply chain and supporting infrastructure for offshore wind energy development was performed. The survey found that substantial capabilities currently exist to support engineering design services, fabrication, vessels for load-out and service, ports, and associated labor forces that are traditionally used by the oil and gas industry. The GOM is generally better outfitted than other parts of the country but there are several areas where investment is needed to close gaps and adapt the supply chain to meet the needs of the offshore industry. In doing so, these investments can potentially reestablish the GOM as an industrial center for a new offshore wind economy. Potential benefits could come from not just offshore wind power plants installed locally, but from economic activity associated with near-term production in the northeastern US and other offshore regions of the world.

The GOM is well established in the fabrication of steel support structures that comprise all offshore wind installations. This fabrication capability of large steel structures, common to the oil and gas industry, is perhaps the most obvious near-term industrial component to adapt for offshore wind and has already been demonstrated during the first US offshore pilot project, the Block Island Wind Farm, where five large scale jackets were fabricated at Gulf Island Fabricators in Louisiana. The survey found, however, that the capabilities were limited to only 2–3 units per month. A 600 MW offshore wind power plant would require 60 such substructures. As such, investments to increase factory output are likely needed to meet industry demand, as over 1,000 MW per year of US deployment is expected for the foreseeable future.

Another key area where the GOM can participate in the emerging domestic economy for offshore wind is in the supply of vessels. Dozens of specialty vessels are required to build a project, and most must be compliant with the Jones Act in order to be useful to a developer. The major constraint identified is that there are currently no Jones Act compliant turbine installation vessels in the GOM. Major investments are needed to either develop new US-flagged ships that can install the next generation of 15 MW turbines, or adapt and modify ships from the existing fleet, repurposing heavy lift vessels for these activities.

Further study is needed to assess the impacts of tariffs placed on the import of steel, which is the major material comprising a wind turbine. Steel tariffs have been cited as a barrier to establishing new factories to manufacture extra-large monopiles, which are now made exclusively in European factories.

6 Jobs and Economic Development

6.1 Introduction

Offshore wind deployment in the Gulf of Mexico (GOM) has the potential to spur economic development in the region. Existing GOM manufacturing capabilities, skilled labor, and a maritime infrastructure can all be used in the development of new offshore wind equipment, facilities, and supply chain, creating new jobs and additional economic activity for the region. Moreover, the GOM offshore wind industry could mature more rapidly if the current plan to deploy 20 gigawatts (GW) of offshore wind by 2035 in the northeastern United States (US) is carried out. This near-term deployment is likely to activate the regional GOM supply chains, vessels, and workforce before offshore wind power plants are installed in the GOM.

This section analyzes jobs, earnings, regional gross domestic product (GDP), and regional economic output supported from constructing and operating a 600 MW offshore wind power project in the GOM. Site 3 Port Arthur, described in Section 4, was used to model the jobs and economic development impacts of GOM offshore wind development. Results are based on a project with a commercial operation date (COD) of 2030. Under this scenario, the offshore GOM wind industry is expected to be mature, having taken advantage of demand for offshore wind equipment and services from other US regions.

This regional analysis uses the Offshore Wind Jobs and Economic Development Impact (JEDI) model (NREL 2017). The Offshore Wind JEDI spreadsheet-based tool is an input-output (I-O) model that incorporates the unique aspects of offshore wind development into an economic impact tool that is freely available to the public. This model requires inputs of project capital costs, operation and maintenance (O&M) costs, and local content data (i.e., percentage of expenditures spent within the region of analysis) to estimate the gross[28] economic impacts to a study area made up of Texas, Louisiana, Mississippi, Alabama, and Florida (all states that border the GOM).

The results are representative of the potential economic impacts for the entire region and are proportional to the level of deployment. The precise location where the offshore wind power plant is installed does not affect the jobs and economic activity that result from the scenario developed for the JEDI model, but it may affect which local and state facilities are engaged. A 600 MW offshore wind power plant with similar technical parameters and costs installed along the GOM coastline at any location will yield similar jobs and economic activity as the Port Arthur site that was analyzed.

Several unique characteristics of the GOM region could increase the economic impacts from offshore wind development, as compared to other regions where offshore wind is being considered. Existing GOM manufacturing facilities and labor, which have supported the oil and gas industry, have existing capabilities that can be leveraged to build the fixed-bottom jacket substructures for GOM offshore wind turbines. These manufacturing plants may also produce tower components as the market matures. In addition, the presence of a skilled maritime workforce, port infrastructure, and existing vessels in the GOM add to the local content that could be used during construction and maintenance.

Methodology

This section analyzes the potential economic impacts to the entire GOM region from installing a single, 600 MW offshore wind power plant 28 km (17 mi) off the coast of the Texas-Louisiana border in 2030. Jobs and economic impacts are regional estimates for the GOM; therefore, the results should not be applied to individual states in the region or extrapolated to other parts of the US.

[28] JEDI estimates gross impacts. It does not consider far-reaching potential impacts, such as changes in prices, taxes, or utility rates. For more information about how to interpret JEDI results, see Section 6.2.

Construction and O&M costs and local content assumptions for the GOM region are inputs for the Offshore Wind JEDI model. Construction and O&M costs were modeled using ORCA. Local content percentages are input to the model based on interviews with local stakeholders and previous economic impact studies completed for the GOM. This study considers the unique regional supply chain and labor force that will play a role in the establishment and growth of the GOM offshore wind industry.

6.1.1 Description of Project Site

The Port Arthur site was selected for the JEDI model using the technical and cost parameters for a single wind installation (Figure 39).

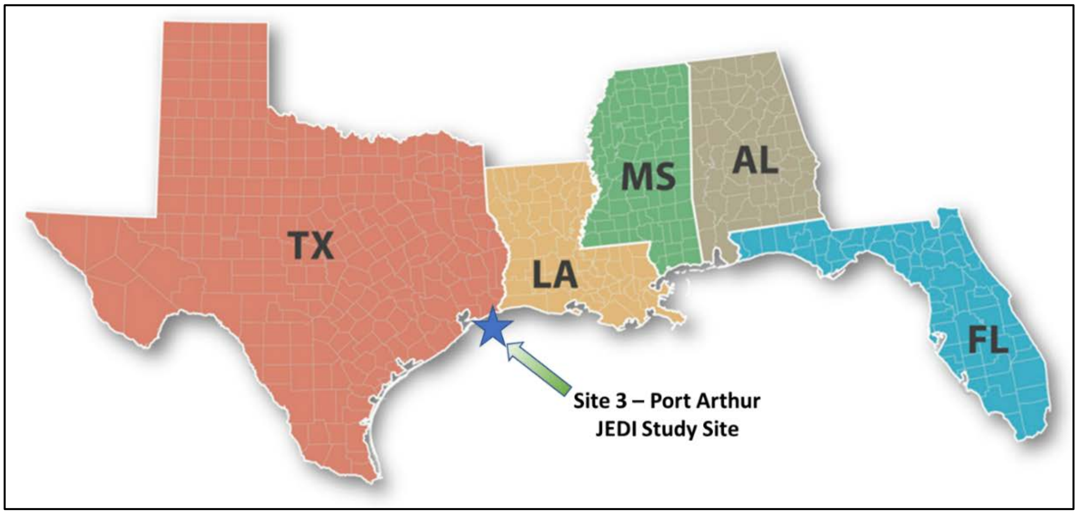

Figure 39. Map of the Gulf of Mexico region of analysis and the JEDI study site (Site 3).

The closest O&M port to this site is in Port Arthur, Texas. The JEDI study site in Port Arthur is a 600 MW wind installation located 28 km (17.4 mi) offshore near the Texas and Louisiana border (Figures 30 and 31). The water depth is 7 to 15 m (11.8 m average) (23 to 49 ft, 38.7 ft average). Fixed-bottom jacket substructures are assumed to support sixty 10 MW wind turbines.

1.1.1.8 Gulf of Mexico Region

The GOM region is defined as all US states bordering the GOM: Texas, Louisiana, Mississippi, Alabama, and Florida. Results should be viewed as the potential economic impacts that can result in the entire region. The precise location where the wind installation is placed offshore does not affect the jobs and economic activity that results from this JEDI model scenario, but it may affect which local and state facilities are engaged. If a wind installation with similar technical parameters and costs is installed along any GOM coastline, similar jobs and economic activity would be supported. As such, this analysis does not breakdown the individual states' economic impact. However, the JEDI model results from this study can be scaled to estimate the economic impacts for larger GOM deployment capacities, or to estimate impacts on an individual GOM states.

To analyze the GOM region, state-specific type I and type II multipliers and personal consumption expenditure patterns were aggregated to calculate the results. These multipliers for employment, wage and salary income and output (economic activity), and personal expenditure patterns were derived from the Impact Analysis for Planning (IMPLAN) Professional Model using individual state data from 2016, the most recent available at the time of this publication. IMPLAN data are based on the US Bureau of Economic Analysis, the US Bureau of Labor Statistics, and the US Census Bureau information.[29]
The GOM region also has several unique characteristics that potentially increase the use of regional content in offshore wind development and operation, including (EERE 2014):

- Adequate wind resource in the shallow waters of the Gulf could reduce offshore wind costs;
- The manufacturing infrastructure and workforce that supports the oil and gas industry could be used to build foundations and substructures and offshore wind turbine towers;
- An existing maritime infrastructure (ports, inland waterways, laydown areas) could allow a mature offshore market to develop faster;
- Existing vessels and crews could expand their activities into the offshore wind industry to accelerate industry maturation.

6.1.2 JEDI Model

1.1.1.9 JEDI Model Overview

This study uses the Offshore Wind JEDI model.[30] JEDI models provide estimated economic impacts for several energy technologies. Funded by DOE, MRG & Associates created the Offshore Wind JEDI model to incorporate the unique aspects of offshore wind development into an economic impact tool.

I-O models are widely recognized tools that are used to estimate economic impacts associated with investments or expenditures. These models map how economy sectors such as businesses, households, workers, capital, and governments interact with one another via purchases and sales at a single point in time. Because sectors are related to one another, an increase in demand for one can lead to an increase in demand for another. An increase in demand for steel towers, for example, results in increased demand for iron ore.

JEDI and other I-O models estimate economic impacts that are supported by changes in demand for goods and services produced by industries and households. Goods or services produced by households include labor and property (such as land) that is sold or leased to industries. JEDI estimates changes in demand for these goods and services with data from the project scenario.

JEDI requires a set of data that describes a project. Each project contains two sets of line item expense categories, such as equipment (blades, towers, turbines, etc.), materials and services, and labor. One set covers the project construction and the other covers the O&M.

[29] IMPLAN, the "IMpacts analysis for PLANing" is a proprietary software and data tool for conducting input-output economic analysis. Further information about IMPLAN can be found at http://www.IMPLAN.com.
[30] For more information about the Offshore Wind JEDI model, data, and methodology, see the user reference guide at: https://www.nrel.gov/docs/fy13osti/58389.pdf.

The JEDI model also allows a model user to specify which portions of expenditures are made within the region of analysis. For example, the model allows users to specify whether jacket substructures were manufactured in the region where the project is being built, or outside the region. The JEDI model uses expenditures made within the region of analysis, or "local content," to estimate economic impacts. The JEDI model does not estimate economic impacts outside the region of analysis (e.g., generator parts from China).

JEDI reports four metrics for each type of impact: jobs, GDP, earnings, and gross output. Each metric has a specific definition that informs how it should be interpreted:

- **Jobs:** expressed as full-time equivalent (FTE). One job is the equivalent of one person working 40 hours per week, year-round. Two people working full-time for 6 months equal one FTE. Two people working 20 hours per week for 12 months also equal one FTE. An FTE could alternately be referred to as a person-year or job-year. Jobs, as reported by JEDI, are not limited to those who work for an employer; they could include other types of workers, such as self-employed ("sole proprietors").
- **GDP:** the value of an industry's production to the region of analysis. It consists of labor payments, property-type income (including profits), and taxes.
- **Earnings:** any type of income from work, generally an employee's wage or salary and supplemental costs paid by employers, such as health insurance and retirement.[31]
- **Gross output:** the total amount of economic activity that occurs within an economy (within the region of analysis). It is the sum of all expenditures. A scenario in which a developer purchases a locally manufactured $500,000 wind turbine rotor blade that used $100,000 of locally procured fiberglass represents $600,000 in gross output.

1.1.1.10 Caveats, Limitations, and Sensitivities

As with all economic models, there are caveats and limitations to the use of the JEDI model. I-O models in general use fixed, proportional relationships between economy sectors. Factors that could change economic sectors, such as price changes that lead households to change consumption patterns, are not considered.

JEDI provides estimates of economic impacts given the user-specified expenditures and economic conditions when input-output data were compiled. Impacts that extend into the future (such as O&M impacts) are assumed to do so if all else is constant. There can be any number of changes in a dynamic economy that JEDI does not consider, so these results should not be considered a forecast for future activity. They simply reflect how a project might look if it were completed in the current economy under the user-specified cost and local content assumptions.

JEDI results are based on project inputs, and these inputs can change from project to project. This is especially true of nascent technologies or technologies that have not yet been widely deployed in the US. JEDI does not evaluate whether inputs are reasonable, nor does it determine whether a project is feasible or profitable.

[31] It could also be other non-wage compensation for work performed, such as proprietor earnings.

Results from JEDI models are gross, not net. JEDI calculates what economic activity would be supported by demand created by project expenditures. Other macroscopic economic changes may take place which JEDI does not consider, including supply-side impacts such as price changes, changes in taxes or subsidies, tariffs on foreign steel, or utility rate changes. JEDI also does not incorporate far-reaching effects such as those due to greenhouse gas emissions, displaced investment, or potential side effects of a project such as recreation or tourism.

The order of magnitude of JEDI results is largely a function of a project's scale and how much is spent within the region being analyzed. Larger, more expensive projects tend to generate more jobs. These jobs may not be onsite; they may be further down the supply chain, or they may be a result of expenditures made by investors. Changes in assumed expenditures or local shares can have a large impact on estimates, depending on the expenditures and size of the change. The changes can vary from line item to line item.

6.1.3 Research and Data Assumptions

The primary model inputs for the Offshore Wind JEDI analysis are cost data, percentage of local content, and the economic multipliers. The inputs for the construction and O&M phases as well as other economic parameters are outlined below. The data and assumptions in this analysis were derived from cost models, prior GOM wind economic research, and interviews with stakeholders.

1.1.1.11 Construction Costs

Cost data were derived primarily from ORCA, which creates cost scenarios that differentiate geospatial, technology, and market variables to quantify levelized cost of energy (Beiter et al. 2016). The turbine type, number of turbines, substructure type, water depth, and distances from port or cable landfall to site are important variables considered in ORCA (Table 9).

Table 9. Construction Cost JEDI Model Inputs for a 600 MW Offshore Wind development in 2030

	Cost ($2015)	Cost Per kW ($)	% of Total Project Cost
Turbine Equipment			
Nacelle/Drivetrain	780,254,392	1,300	37.0
Blades	29,674,635	49	1.4
Towers	152,586,177	254	7.2
Turbine Equipment Total	***962,515,203***	***1,604***	***45.6***
Materials and Other Equipment			
Foundation (including alternatives for fixed bottom types)	18,236,485	30	0.9
Substructure	136,134,734	227	6.5
Project Collection System	46,982,689	78	2.2
HV Cable (project site to point of grid interconnection)	97,380,603	162	4.6
Onshore substation (formerly converter station)	47,592,070	79	2.3
Offshore substation (formerly substation)	84,608,124	141	4.0
Materials and Other Equipment Total	***430,934,704***	***718***	***20.4***
Labor Installation			
Substructure	77,376,971	129	3.7
Erection/Installation	48,164,389	80	2.3
Project Collection	79,997,551	133	3.8

	Cost ($2015)	Cost Per kW ($)	% of Total Project Cost
Grid Interconnection (including substation)	52,435,709	87	2.5
Management/Supervision	31,524,416	53	1.5
Labor Installation Total	***289,499,036***	***482***	***13.7***
Insurance During Construction			
CAR/Third Party liability/business interruption, etc.	21,223,570	35	1.0
Development Services/Other			
Engineering	25,429,508	42	1.2
Legal Services	6,357,377	11	0.3
Public Relations	3,178,688	5	0.2%
Ports and Staging	32,051,438	53	1.5%
Site Certificate/Permitting	48,879,160	81	2.3%
Decommissioning Bonding	17,599,256	29	0.8%
Development Services/Other Total	***133,495,427***	***222***	***6.3%***
Construction Financing (AFUDC)			
Interest During Construction	149,041,468	248	7.1%
Reserve Accounts (MRA/DSRA)	122,836,471	205	5.8%
Construction Financing Total	***271,877,939***	***453***	***12.9%***
Total Construction Cost	**2,109,545,879**	**3,516**	**100.0%**

Note: Totals may not add up precisely due to independent rounding.

The total construction cost for a 600 MW wind installation at the JEDI study site in 2030, using 10 MW wind turbines is $3,516/kW, of which $1,604/kW is turbine costs. The JEDI model categorizes CAPEX costs differently than the spatial-economic model so cost categories may be assigned differently than other sections in this report. Turbine costs were adjusted for an optimized 10 MW GOM offshore wind turbine (e.g., taking into consideration added costs such as insurance and specific parameters like the relatively soft sediments found in the GOM waters).

1.1.1.12 Construction Local Content

Local content is the percentage of total expenditures in the region where the plant is constructed (Table 10). To estimate local content for the GOM region, analysts interviewed stakeholders in the manufacturing industry. A literature review was also completed of prior offshore wind economic impact studies. Several studies estimated local content in the US offshore wind industry, and specifically the GOM, by 2030.[32] Local content percentages assume a relatively mature offshore wind supply chain will exist by 2030 in the GOM region, supporting projects in the GOM and US waters.

Table 10. Local Content JEDI Model Inputs during the Construction Phase

	Local Content (%)
Turbine Equipment	
Nacelle and/or Drivetrain	0
Blades	0
Towers	25

[32] Literature review included Offshore Wind Market and Economic Analysis (Navigant 2013) and Offshore Wind Jobs and Economic Development Impacts in the United States: Four Regional Scenarios (Tegen et al. 2015).

	Local Content (%)
Materials and Other Equipment	
Foundation (including piles or alternatives for fixed bottom types only)	62
Substructure	62
Project Collection System	0
HV Cable (project site to point of grid interconnection)	0
Onshore substation (formerly converter station)	10
Offshore substation (formerly substation)	25
Materials and Other Equipment Total	
Labor Installation	
Substructure	100
Erection/Installation	50
Project Collection	0
Grid Interconnection (including substation)	30
Management/Supervision	90
Insurance During Construction	
CAR/Third Party liability/business interruption, etc.	0
Development Services/Other	
Engineering	100
Legal Services	100
Public Relations	100
Ports and Staging	100
Site Certificate/Permitting	100
Decommissioning Bonding	0
Construction Financing (AFUDC)	
Interest During Construction	0
Reserve Accounts (MRA/DSRA)	---

Blade manufacturing and nacelle assembly plants are more likely to be built in areas where offshore wind deployment occurs first or at the greatest levels. The Block Island Wind Farm, constructed off the coast of Rhode Island, is the first offshore wind power plant in the US. Current trends indicate that the initial development of an offshore wind industry will occur on the north Atlantic coast. If comparable manufacturing facilities are built on the Atlantic coast, it may not be cost effective to build additional facilities in the GOM (Tegen et al. 2015). Therefore, the development of an offshore wind supply chain in the GOM may not include nacelles or blades by 2030.

During telephone interviews with GOM jacket manufacturers, researchers learned that existing plants that support the oil and gas industry would be able to manufacture towers for offshore wind turbines. Based on the cost of materials (which are assumed to be imported to the GOM) and cost of labor, towers are estimated at 25% local content.

Similarly, existing manufacturing plants in the GOM that have supported the oil and gas industry, have the capabilities to produce fixed-bottom jacket substructures. Typical four-leg jacket substructures with lattice bracing could be deployed in the GOM region (Figure 40).

Figure 40. Fixed-bottom jacket substructures that were manufactured in the Gulf of Mexico region for the Block Island Wind Farm.
Photo: Gary Norton, NREL 41193.

Based on interviews, 60% of the costs to manufacture foundation and substructures are labor costs. The remaining costs are for materials, the majority of which would be imported from outside the region. Foundation and substructure local content is estimated at 62%.

For offshore cable systems, many of the high-voltage cables for collection systems and export cables are sourced from Europe as are the installation vessels and labor. It is not expected that the US incentives will be large enough to support a full subsea cable supply chain, including manufacturing, US-flagged cable laying vessels, and crew that can install undersea cables (Navigant 2013).

However, for other labor installation and development services, such as substructures and erection, an existing maritime infrastructure and workforce could support the offshore wind industry. It is expected that existing vessels and employees could support the GOM offshore wind industry. Other local content percentages are based on a peer review of offshore wind economic studies.[33]

1.1.1.13 Operation and Maintenance Costs

The ORCA model provides annual O&M costs for a wind installation at the GOM JEDI study site (Table 11). Unlike the construction costs where the spatial-economic model provides a cost for each category, for O&M costs, analysts used the JEDI model to proportion costs between labor, materials and services. The total O&M cost modeled is $70/kW.

[33] The literature review included Offshore Wind Market and Economic Analysis (Navigant 2013) and Offshore Wind Jobs and Economic Development Impacts in the United States: Four Regional Scenarios (Tegen et al. 2015).

Table 11. O&M Cost JEDI Model Inputs for a 600 MW Offshore Wind Development

	Cost ($2015)	Cost per kW ($)	% of Total Project Cost
Labor			
Technician Salaries	3,240,144	5.40	7.7
Administrative	600,027	1.00	1.4
Management/Supervision	2,880,128	4.80	6.9
Labor Total	*6,720,298*	*11.20*	*16.0*
Materials and Services			
Water Transport	8,096,981	13.49	19.3
Site Facilities	4,048,490	6.75	9.6
Machinery and Equipment	1,735,067	2.89	4.1
Subcontractors	2,602,601	4.34	6.2
Corrective Maintenance Parts	18,796,562	31.33	44.8
Materials and Services Subtotal	*35,279,702*	*58.80*	*84.0*
Total Operational Cost	42,000,000	70.00	100.0

Note: Totals may not add up precisely due to independent rounding.

1.1.1.14 Operation and Maintenance Local Content

Local content assumptions for the O&M phase are based on previous GOM economic impact studies.[34] The GOM has a maritime infrastructure and workforce that could be used to operate and maintain GOM wind development, including ports, vessels, crews, and laydown yards. Table 12 provides local content inputs for the O&M phase.

Table 12. Local Content JEDI Model Inputs During O&M Phase

	Local Content (%)
Labor	
Technician Salaries	100
Administrative	100
Management and/or Supervision	95
Materials and Services	
Water Transport	100
Site Facilities	100
Machinery and Equipment	100
Subcontractors	100
Corrective Maintenance Parts	0

[34] Studies include Offshore Wind Market and Economic Analysis (Navigant 2013) and Offshore Wind Jobs and Economic Development Impacts in the United States: Four Regional Scenarios (Tegen et al. 2015).

1.1.1.5 Other Parameters

Payroll parameters are based on Bureau of Labor Statistics (BLS) data for workers in the construction and O&M labor categories (Table 13).

Table 13. Payroll Parameters for JEDI Model Associated with Offshore Wind Development (2017)

	Wage per hour ($2015)	Employer Payroll Overhead (%)
Construction Labor		
Foundation	49.00	37.6
Erection	49.00	37.6
Electrical	51.00	37.6
Management/ Supervision	46.59	37.6
O&M Labor		
Technician Salaries	43.00	37.6
Monitoring & Daily Operations Staff and Craft Labor	34.00	37.6
Administrative	24.00	37.6
Management/Supervision	58.00	37.6

6.2 Results: Estimated Economic Impacts

The JEDI model estimated that 4,472 FTEs would be generated for the construction period and a GDP contribution of $445M (Table 14). Annual O&M phase would create 151 FTEs and $14M in GDP. Construction-phase results from the JEDI model are one-time totals that span the entire construction process.[35] A realistic time frame for offshore wind project development in a mature industry may take from 4 to 6 years, from the moment site control is obtained to commercial operations. O&M results are presented on an annual basis and ongoing for the life of the project.

Table 14. Summary of Estimated Economic Impacts During Construction and O&M of a 600 MW Offshore Wind Development in the Gulf of Mexico

	Jobs (FTEs)	GDP Contribution (in millions $)	Earnings (in millions $)	Output (in millions $)
Total impacts during construction period	4,472	445	330	754
Total impacts during operating years (annually)	151	14	11	19

Note: Earnings and Output are reported in millions of dollars in year 2015 dollars. Construction and operating jobs are full-time equivalent or a period of one-year (1 FTE = 2,080 hours). Wind development onsite labor includes field technicians, administration and management. Economic impacts “During operating years” represent impacts that may occur from wind development operations/expenditures on an annual basis. The analysis does not include impacts associated with spending of wind development “profits” and assumes no tax abatement.

[35] For example, if JEDI reports a construction-phase impact of 50 workers to build a project that takes 2 years to complete, this is the equivalent of an average of 25 workers per year (50 / 2 = 25). If the same project required 3 years to complete, the average would be 17 (rounded) workers per year.

All impacts are based on the costs and local content inputs for a single offshore wind development in the GOM. The construction and O&M spending have a "ripple effect," which is captured by economic multipliers, aggregated for the GOM region. These results are broken out into the three JEDI categories, including 1) project development and onsite labor, 2) turbine, substructure, and supply chain, and 3) induced impacts (i.e., impacts to restaurants, hotels, etc.).

6.2.1 Employment Impacts

1.1.1.6 Construction Jobs

Estimated total jobs in the GOM during the construction period is 4,472 FTEs (Figure 41). Construction-related jobs include:

- **Project development and onsite labor -**
  - **Onsite labor:** Referred to as construction and interconnection labor in the JEDI model. Includes construction and interconnection workers, vessel operators, and other employees that install the jacket substructures, erect the offshore wind turbines, and lay undersea cables.
  - **Project development:** Referred to as construction related services in the JEDI model. Includes engineers, surveyors, administrative employees and managers who support development before construction.
- **Turbine, substructure, and supply chain:** Encompasses workers who design, engineer, and build the fixed-bottom jackets in the GOM region, as well as manufacture towers for offshore wind turbines and other construction-related materials.
- **Induced impacts:** Jobs from workers spending their earnings in the regional economy.

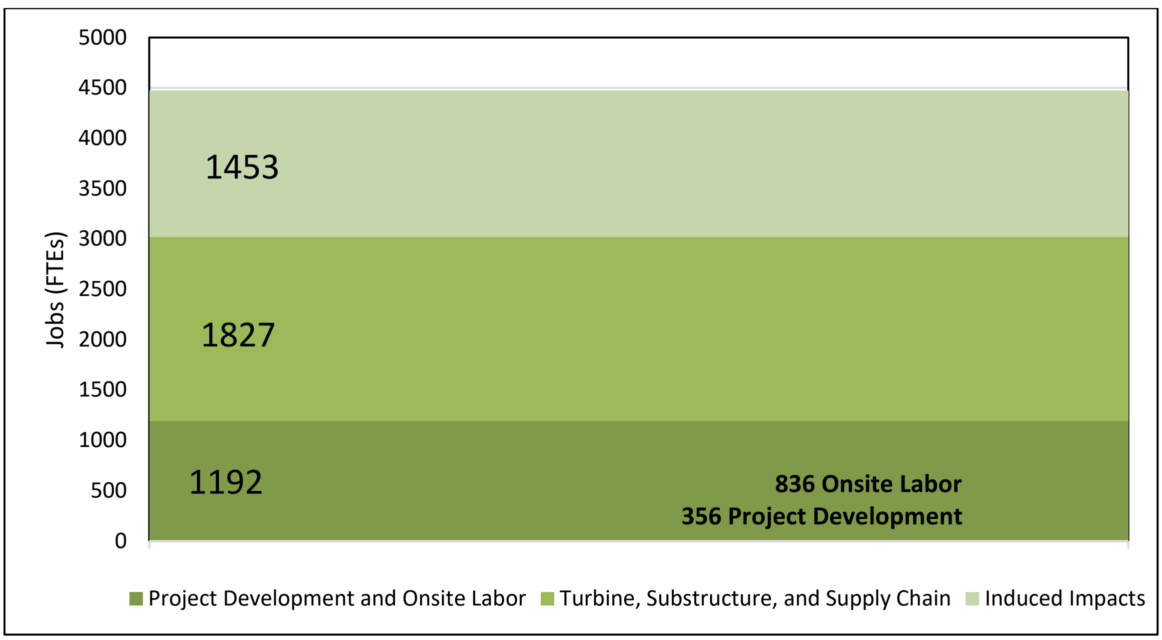

Figure 41. Estimated number of jobs (FTE) supported during the construction of a 600 MW offshore wind development in the Gulf of Mexico.

Manufacturing associated with the wind turbine, jacket substructure, and its supply chain has the potential to provide the largest number of jobs in the GOM region from the development of offshore wind. Manufacturing the fixed-bottom substructures is a unique opportunity for the GOM region.

During the construction phase, these workers live in the project area and support regional economic activity. Workers may already live in the GOM region or may settle within the region, depending on industry needs and skills of the existing workforce. Another category of workers includes out-of-region workers who live within the region only during construction, moving on when construction is complete. Workers who reside in-region spend their earnings on groceries, childcare, education, utilities, tax payments, family entertainment, and recreation, clothing, and so on. Out-of-region workers generate a different set of economic impacts. These temporary workers support a smaller ripple effect in the region's economy because more of their earnings are spent outside of the region, with a smaller portion circulating through the coastal economy, mostly on temporary lodging and restaurants. As the offshore wind industry matures in the GOM, it is expected that more workers will live and work in the region.

Induced jobs are related to the additional spending in the region from in-state and out-of-state workers and other money circulating in the economy from direct and indirect impacts. An example of an induced job is a server in a local restaurant where offshore wind construction workers eat lunch. Only a small sliver of this job counts toward JEDI results, because only a portion of this person's work is due to the demand from the offshore wind workers.

1.1.1.7 Operations and Maintenance Jobs

Estimated total jobs supported in the GOM during O&M is 151 FTEs annually (Figure 42). O&M jobs include:

- **Onsite labor:** Workers who operate and maintain the onshore wind development, including O&M vessel crews to perform repairs, technicians to inspect the turbines and substructures and replace components, workers to monitor offshore wind power plant performance, and administrative and management directly related to the offshore wind development.
- **Local revenue and supply chain:** Off-site labor to manufacture materials and provide equipment or services to maintain the offshore wind project.
- **Induced Impacts:** Household spending of earnings in the region's economy from the onsite and local revenue and supply jobs supported. Induced impact jobs may include supporting workers to within local economies.

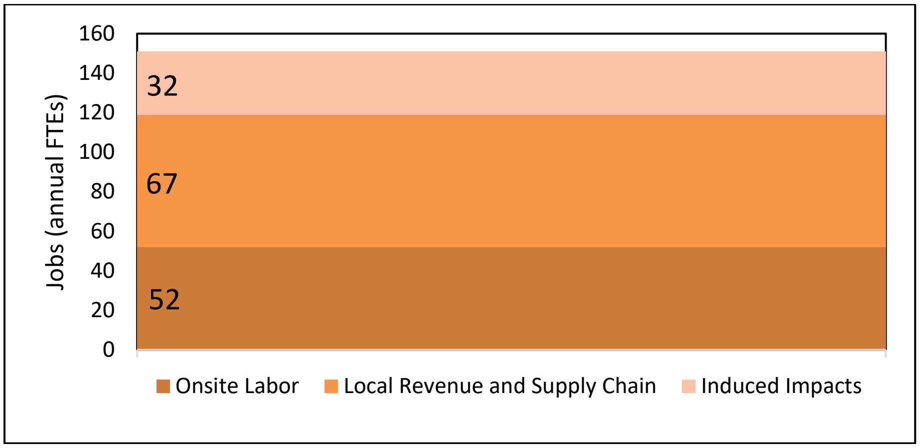

Figure 42. Estimated number of annual jobs (FTE) supported during the operating years of a 600 MW offshore wind development in the Gulf of Mexico.

O&M phase results are annual and ongoing for the operating life of the offshore wind development. O&M jobs are considered permanent, highly skilled jobs for the GOM region. Because an offshore wind power plant is expected to have a 25-year life, 151 O&M-related jobs will exist for 25 years in the GOM. The analysis assumes that most of these positions are filled by people currently living in the GOM or by people who relocate to the region. Additional offshore wind installations in the GOM are expected to produce a similar number of jobs and economic impacts.

6.2.2 Gross Domestic Product

1.1.1.8 Construction Gross Domestic Product

Construction of a 600 MW offshore wind power plant would support an estimated $445 million in total GDP in the GOM region (Figure 43). GDP includes labor payments, gross operating surplus, and taxes. The GDP would be supported from project development and onsite labor, turbine, substructure, supply chain, and induced impacts.

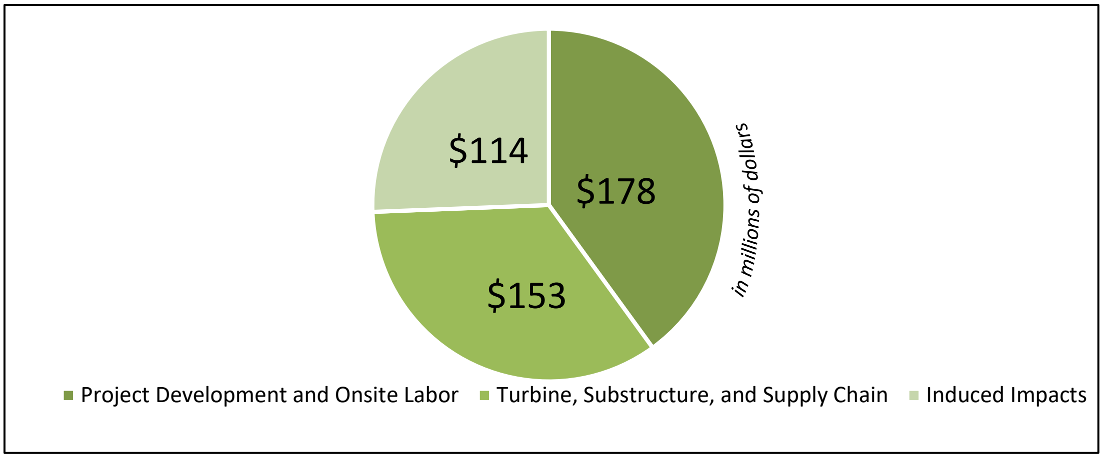

Figure 43. Estimated GDP from the construction of a 600 MW offshore wind power plant in the Gulf of Mexico.

Turbine, substructure, and supply chain is the second largest category that contributes to GDP, supporting approximately $153 million the economy in the GOM. The potential for the region to manufacture jacket substructures and towers significantly contributes to this category. GDP associated with project development and onsite labor is supported by expenditures for existing GOM workforce and infrastructure to construct the offshore wind development, as well as regional firms to engineer, design, and permit the project.

1.1.1.9 Operations and Maintenance Gross Domestic Product

Operation and maintenance of an offshore wind development supports approximately $14 million in GDP annually in the GOM region (Figure 44). GDP includes labor payments, gross operating surplus, and taxes each year.

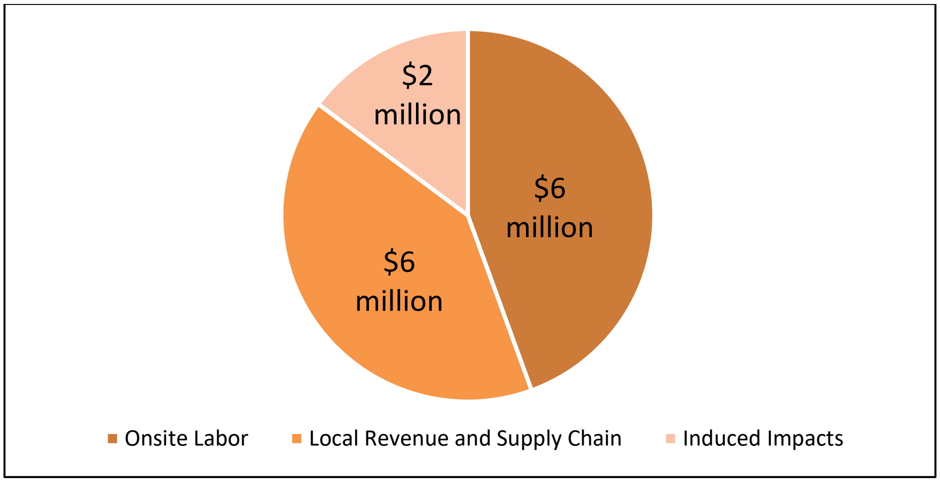

Figure 44. Estimated annual GDP during operating years from the operation and maintenance of a 600 MW offshore wind power plant in the Gulf of Mexico.

Local revenue and supply chain are one of the largest contributors to GDP, supporting approximately $6 million to the economy in the GOM. Local revenue and supply chain include sales and property tax payments and impacts from O&M spending on components and equipment. The $6 million contribution to GDP from onsite labor includes wages and salaries (including benefits) for O&M employees. Induced impacts support approximately $2.5 million to the GOM economy.

6.2.3 Earnings and Output

1.1.1.10 Construction Phase

The estimated earnings of $330M and output of $754M would be supported during construction of the wind development at the GOM JEDI study site (Table 15). Estimated earnings refer to wage and salary compensation paid to workers, including benefits. Economic output is the gross expenditures, or the value of all production in the region during construction, including wages and salaries.

Table 15. Estimated Earnings and Output Supported during the Construction of a 600 MW Offshore Wind Development in the Gulf of Mexico

	Earnings (in millions $)	Output (in millions $)
During construction period		
Project Development and Onsite Labor Impacts		
Construction and Interconnection Labor	117	
Construction Related Services	50	
Subtotal Project Development and Onsite Labor Impacts	167	214
Turbine and Supply Chain Impacts	96	339
Induced Impacts	67	201
Total Impacts	**330**	**754**

Note: Totals may not add up precisely due to independent rounding.

Earnings during construction are estimated at $330 million, which are paid to employees in the GOM. These earnings represent well-compensated jobs. Average annual earnings (including benefits) are $140,000 for project development and onsite labor. Turbine, substructure, and supply chain earn about $53,000 annually; jobs related to induced impacts jobs earn approximately $46,000 per year.

The construction of an offshore wind development in the GOM is estimated to support $754 million in gross economic output. The largest portion of this output is related to turbine, structure, and supply chain impacts, such as manufacturing jacket substructures and towers.

1.1.1.11 Operations and Maintenance Phase

The estimated earnings $11M and output of $19M would be supported during O&M of this wind development project (Table 16). Estimated earnings refer to wage and salary compensation paid to workers, including benefits each year. Economic output is the gross expenditures in the region during construction, including wages and salaries. For O&M, the earning and output are reported on an annual basis.

Table 16. Estimated Earnings and Output Supported Annually During the Operating Years of a 600 MW Offshore Wind Development in the Gulf of Mexico

	Earnings (in millions $)	Output (in millions $)
During operating years (annual)		
Onsite Labor Impacts	6	3
Local Revenue and Supply Chain Impacts	3	11
Induced Impacts	2	5
Total Impacts	**11**	**19**

Note: Totals may not add up due to independent rounding.

Earnings for O&M are estimated at $11 million annually, which are paid to employees in the GOM. These earnings represent well-compensated jobs. The average salary (including benefits) for all jobs supported by O&M is about $73,000 per year. Onsite laborers, including wind technicians and plant management, have the highest salaries, with average annual earning (including benefits) about $120,000. Supply chain and induced impact related jobs respectively earn about $50,000 and $45,000 annually.

Operating and maintaining an offshore wind facility in the GOM is estimated to support approximately $19 million in gross economic output each year. The largest portion of this output is related to turbine, structure and supply chain impacts, such as spending on materials and equipment for O&M activities.

6.3 Conclusions

6.3.1 Summary

Based on the analysis performed and summarized in Sections 6.1 and 6.2, Figure 45 shows a summary of the jobs and GDP supported by the development of a single 600 MW wind project in the GOM during the construction period and operating years.[36] Note that this does not include the likely jobs or impacts in the GOM that may be used to support offshore wind projects being built in other regions of the US or the world.

[36] Jobs numbers are rounded to the nearest 10.

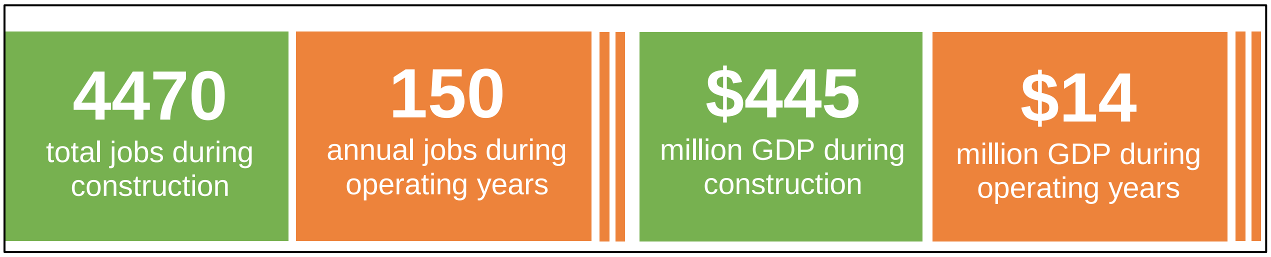

Figure 45. Economic activity supported from the construction and operation of a 600 MW Gulf of Mexico offshore wind project at Site 3, Port Arthur Site.

This regional analysis assesses the development of a 600 MW offshore wind power plant to support jobs and economic activity in the GOM region. The results indicate that a single offshore wind project could support approximately 4,470 jobs and $445 million in contributions to GDP during construction and an ongoing 150 jobs and $14 million in contributions to GDP annually from O&M labor, materials and services.

With a technical resource potential for offshore wind in the GOM of 646 GW, the region has the potential to support a robust labor workforce during the construction of each new wind project (Musial et al. 2016). Each offshore wind project installed would also need additional operations and maintenance workers, which represent long-term and well-paid employment opportunities for the GOM region.

Offshore wind development in the GOM is a unique opportunity for the existing manufacturing industry, which has historically supported the oil and gas industry. Results indicate that manufacturing is the largest economic driver for offshore wind development. Based on discussions with the existing manufacturing industry, GOM region has the potential to manufacture fixed-bottom jacket substructures and turbine towers. As such, the offshore wind industry could allow the GOM manufacturing industry to diversify its production, sustaining and growing the existing manufacturing workforce.

Results are based on a maturing offshore wind industry in the GOM through 2030, assuming a moderate level of labor, materials, and services can be sourced from the region. Actual jobs and economic activity results may vary based several factors, including number of projects and turbines installed, type of substructures used, maturity and availability of a wind supply chain, and a whether a trained workforce is used. Investment in manufacturing, equipment, vessels, and other important industries, as well as workforce training, will be needed to support the jobs and economic activity reported during construction and operation of an offshore wind power plant in the region.

6.3.2 Areas for Further Research

Although this report found that offshore wind has the highest potential of all the other offshore renewable energy sources there are many areas that still need investigation to reduce the uncertainty of offshore wind development in the GOM. Additional analysis would help fill data gaps and identify workforce opportunities in the region. Areas for further research include:

- **Economic impacts from manufacturing jackets in GOM:** As the offshore wind industry develops in other areas of the US, the GOM may serve these other regions by producing jacket substructures. This will support the regional economy in the GOM, supporting jobs and economic impacts from additional manufacturing. Additional analysis could better understand the magnitude of these potential impacts.
- **State-by-state analysis:** To understand economic impact potential for each state, JEDI should be used to model the jobs and economic activity from installing an offshore wind development at the state-

level. Results from this study are based on the aggregated economic multipliers for the GOM region. Each state has different economic multipliers and local content potential, which affects the number of jobs, GDP, earnings, and regional economic output reported for each state.

- **Assess GOM regional buildout of offshore wind industry under high penetration scenarios:** Conducting a sensitivity analysis, by varying the deployment size, cost and local content JEDI model inputs, would provide a better understanding of economic impact scenarios in the GOM region. This analysis is based on a single wind development of a set nameplate capacity, with conservative assumptions for labor, materials, and services that could be sourced for the GOM region by 2030. Jobs and economic activity results may be higher or lower based on how the offshore industry develops in the GOM and in other regions across the US.
- **Identifying existing industry stakeholders:** Further research into the capabilities of existing manufacturing facilities and installation vessels would provide insights on the industry changes required to support the GOM offshore wind market. Examples could include workforce training, manufacturing plant modifications, or vessel retrofitting. Identifying and engaging with stakeholders in the GOM region could help reduce potential barriers to establishing a robust offshore wind workforce.

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Department of the Interior (DOI)

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Bureau of Ocean Energy Management (BOEM)

The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program

The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM’s Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).