Wind Energy Costs in Puerto Rico Through 2035

Patrick Duffy, Gabriel R. Zuckerman, Travis Williams, Alicia Key, Luis A. Martínez-Tossas, Owen Roberts, Nina Choquette, Jaemo Yang, Haiku Sky, and Nate Blair

National Renewable Energy Laboratory

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NREL/TP-5000-83434
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Executive Summary

Through an interagency agreement with the Federal Emergency Management Agency (FEMA), the U.S. Department of Energy (DOE) and its national laboratories support resiliency and natural disaster recovery efforts in Puerto Rico by augmenting planning, operational activities, and capacity building for both local public entities and federal agencies, ensuring investment decisions are driven by world-class data, modeling, and analysis. As part of these efforts, the National Renewable Energy Laboratory (NREL) evaluated wind energy costs and technical potential in Puerto Rico to provide a better understanding of this resource and inform future planning processes. The study's objectives are to:

- quantify the long-term wind resource in and around Puerto Rico (offshore and over land);
- conduct exploratory interviews with key stakeholders to better understand the unique challenges of deploying wind energy technologies in Puerto Rico;
- account for unique conditions in Puerto Rico to calculate costs, produce generation profiles, and provide technology information about land-based, fixed-bottom offshore, and floating offshore wind energy;
- provide cost, performance, and technical data to the government-owned utility and system operator to meet regulatory requirements to include wind resources in planning processes; and
- coordinate data sharing with other DOE studies, including the Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100 Study) (U.S. Department of Energy 2022).

The study was split into two tasks. Task 1 focuses on assessing and validating the wind resource in Puerto Rico. Task 2 focuses on utilizing that wind resource data and a suite of land-based and offshore wind energy techno-economic analysis tools to assess costs, performance, and technology options. This report presents the results of Task 2. Wind resource data and another report documenting the results from Task 1 will be made public at a later date.

We used NREL's Renewable Energy Potential model (reV) to calculate how capital expenditures, operational expenditures, net annual energy generation, and levelized cost of energy (LCOE) vary in time and space for wind energy projects around Puerto Rico, excluding policy incentives (subsidies). To do this, the model uses site-specific conditions (e.g., topography, distances to critical infrastructure, wind resource data generated in Task 1) to calculate costs based on relationships derived from current market data and industry feedback.

We consulted with technical stakeholders to better understand unique conditions impacting wind energy in Puerto Rico and adapted NREL's cost models to account for these conditions. These adaptations included how to mitigate hurricane risks with Typhoon-Class wind turbine design standards and insurance, as well as how these strategies impact costs for projects in regions with high natural catastrophe risks. We also worked with the electric system operator and the Puerto Rico Ports Authority to study how existing and planned grid and ports infrastructure could support land-based and offshore wind. NREL began to identify spatial data sets for protected areas and critical habitats, and established pathways to share data and findings with the U.S. Department of Energy's (DOE) PR100 Study.

After adapting the cost models to the unique characteristics and costs of Puerto Rico, we defined land-based wind energy technology pathways to project costs from 2022 through 2035, and offshore wind technology pathways from 2030 through 2035 due to a potentially longer deployment timeline for offshore wind. Table ES - 1 summarizes these scenarios.

Table ES - 1. Summary of wind energy technology scenarios for Puerto Rico

Parameter	Land-Based Wind Scenarios	Offshore Wind Scenarios
Turbine Rated Power	4.2 MW	15 and 18 MW
Commercial Operation Dates	2022, 2030, 2035	2030, 2035
Plant Ratings, megawatts (MW)	4.2–200	600
Foundation	Land-based foundation	Fixed-bottom and floating offshore wind
Wind Turbine Array Layout	Varies	7D x 7D spacing on square grid

As a result of this modeling effort, we expect LCOE for land-based wind in Puerto Rico to range from approximately \$58/megawatt-hour (MWh)–\$228/MWh (5.8 cents/kilowatt-hour [kWh]–22.8 cents/kWh) with a mean of \$107/MWh in 2022 and decline to \$43/MWh–\$139/MWh with a mean of \$69/MWh by 2035. This cost reduction (mean percentage change of 33.7% from 2022 to 2035) is driven primarily by improved installation techniques such as climbing cranes and wind turbine design advancements enabling larger rotor blades to capture more available energy at lower wind speeds. For fixed-bottom and floating offshore wind technologies, we expect LCOE to range from about \$71/MWh–\$156/MWh in 2030 with a mean of \$116/MWh and decline to \$64/MWh–\$130/MWh by 2035 with a mean of \$100/MWh. This mean percentage reduction of 14% from 2030 to 2035 is a result of maturing offshore wind supply chains, increased wind turbine ratings, and technology improvements that enable higher energy capture and more cost-effective maintenance strategies. The LCOE values for land-based and offshore wind energy in 2035 are presented in Figures ES - 1 and ES - 2, respectively.

Note that transmission system upgrades are not included in the LCOE values we present. Interconnection costs for land-based wind are included in LCOE, whereas for offshore wind, we only included offshore export cable line costs to the landfall at the nearest point of interconnection with 115 kilovolt (kV) (or greater) substation. The plant capacities for land-based wind vary, as we took potential use conflict areas, or areas where wind energy development may not be feasible, into account when estimating costs. For offshore wind, we assumed a standard 600 MW plant capacity as we did not take potential use conflict areas into account when estimating costs, although we did include them on maps of cost results. To represent offshore wind plant layouts, we assumed a simplified square grid layout with turbine spacing expressed in terms of number of turbine rotor diameters (D). A spacing of 7D is used, matching recent NREL cost analyses (Shields et al. 2021b; Musial et al. 2021a; Beiter et al. 2020).

For reference, the U.S. national average LCOE of unsubsidized land-based wind projects installed in 2021 was \$32/MWh (Wiser et al. 2022). The lowest cost land-based wind sites in Puerto Rico are likely higher than this average due to lower wind speeds throughout the year. LCOE estimates for present-day fixed-bottom projects in North America range from \$60–\$110/MWh and decrease to between \$40–\$80/MWh by 2035 (Musial et al. 2022). For floating projects, projections range from \$95–\$180/MWh today and fall to \$50–\$110/MWh by 2035 (Musial et al. 2022). While the mean 2035 offshore wind LCOE calculated in the present study (\$100/MWh) falls towards the upper end of these projections, the lowest cost sites in Puerto Rico are all in the lower halves of the projected ranges for North America.

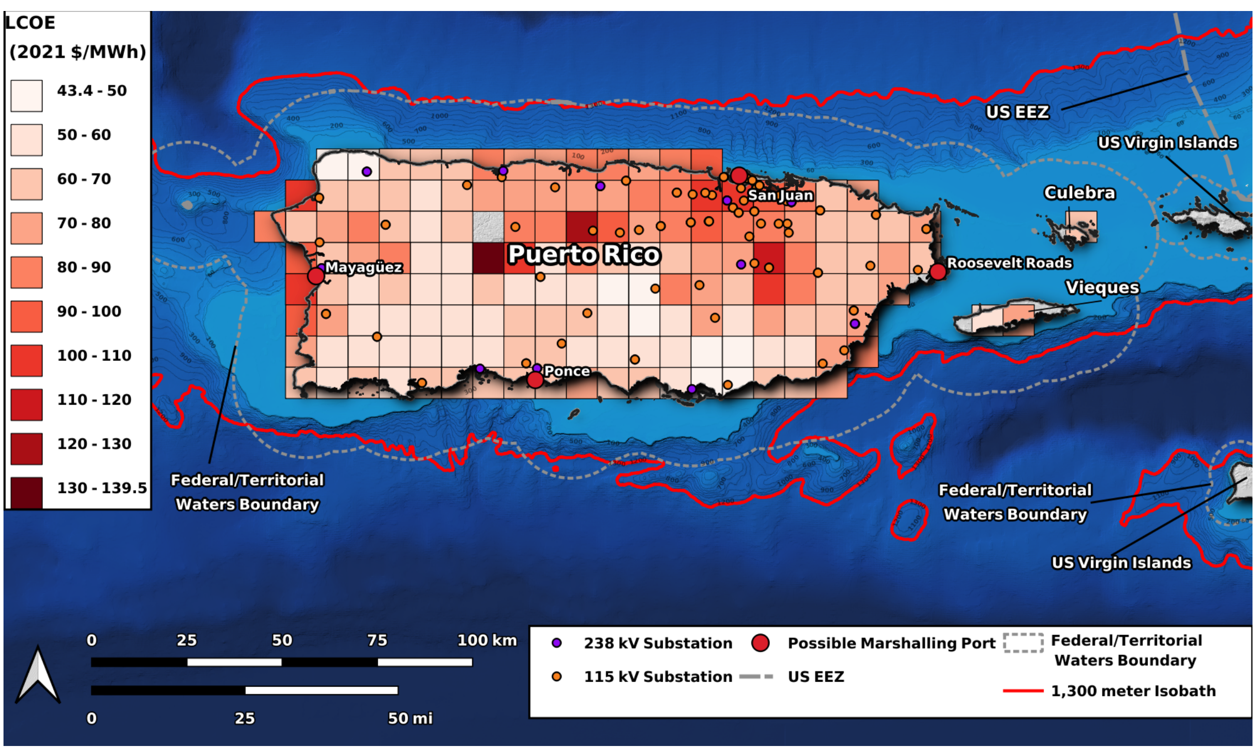

Figure ES - 1. Land-based wind LCOE in 2035

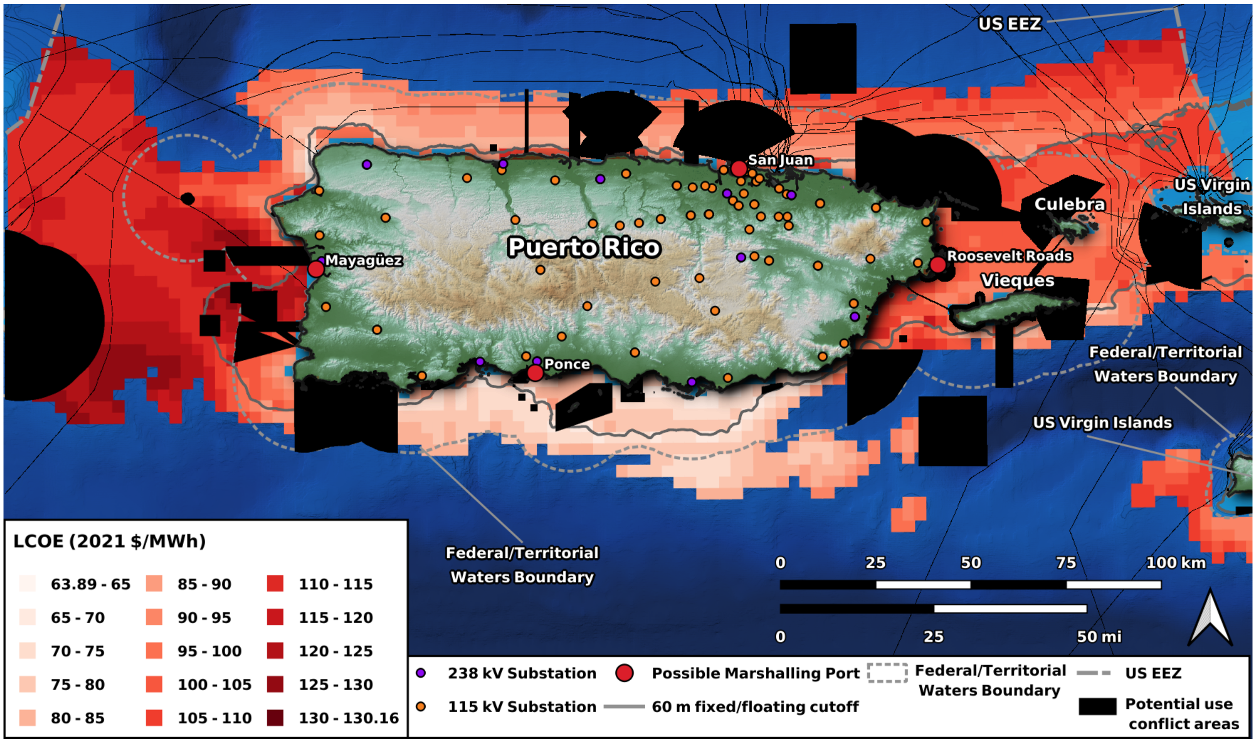

Figure ES - 2. Offshore wind LCOE in 2035 with potential use conflict areas in black

Figures ES - 3 and ES - 4 present maps of expected 2035 wind plant annual energy production (AEP) expressed in terms of net capacity factor (NCF) for both land-based and offshore wind, respectively. Throughout the report, AEP is frequently expressed in terms of NCF, or the fraction of the year the plant would need to operate at its rated capacity to generate the total AEP. We find that by 2035, NCF values for land-based projects range from 0.19 to 0.53, with an average of 0.36. Offshore, NCF values in 2035 range from 0.26 to 0.5, with a mean of 0.37. While the offshore resource is stronger, the lower specific-power ratings (ratio of rotor swept area to generator rating) of the land-based machines assumed for 2035 help capture more energy at more frequent low wind speeds. The spatial variation in land-based NCF values is driven by site-specific wind resource data. Offshore, site-specific resource and wake losses explain the spatial variation in wind plant performance.

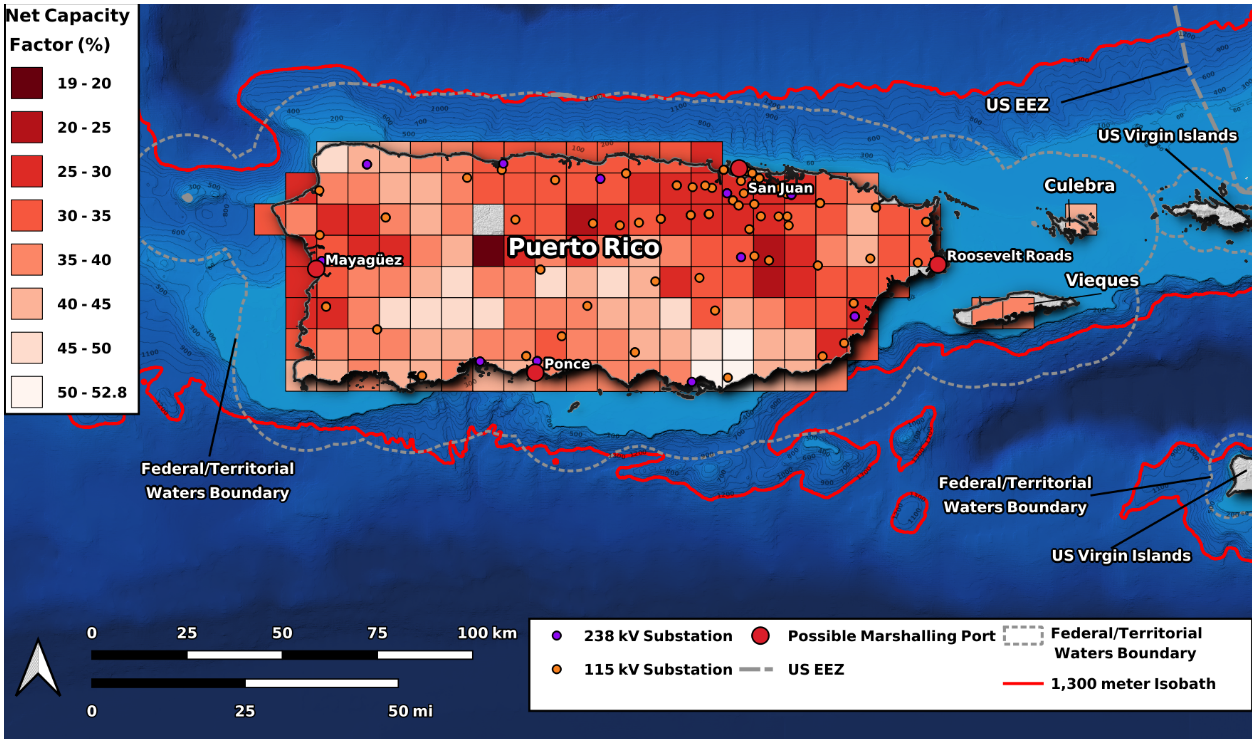

Figure ES - 3. Land-based wind net capacity factors in 2035

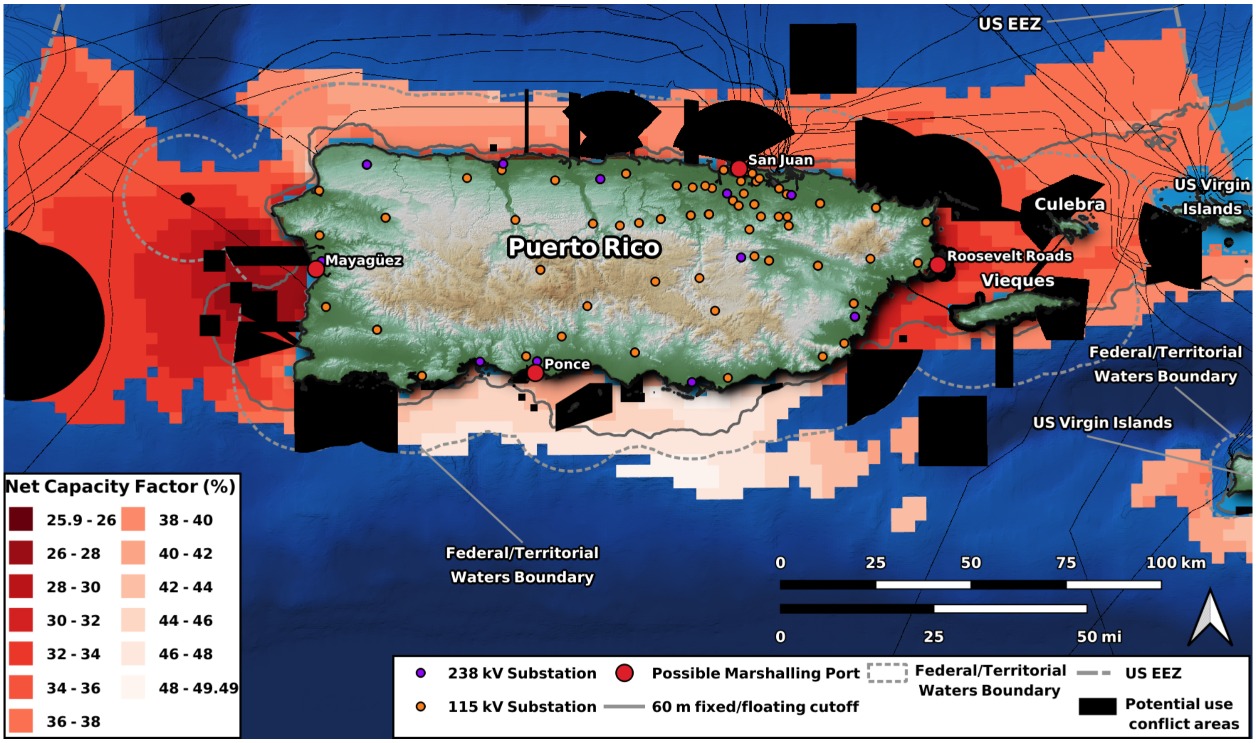

Figure ES - 4. Offshore wind net capacity factors in 2035 with potential use conflict areas in black

Based on our modeling efforts, wind energy represents a viable, low-cost option for helping Puerto Rico achieve its clean energy and grid reliability goals. Existing Typhoon-Class turbine designs can help enable wind energy development in hurricane-prone regions. Wind turbines can add value by providing grid services through grid-forming inverters and complement solar energy generation with evening and nighttime electricity production, especially offshore. We estimate the technical potential capacity could be as high as 6.81 gigawatts (GW) for land-based wind and 40.76 GW for offshore wind, representing many times more than the projected peak demand for the 2023 fiscal year of just under 3 GW (LUMA 2022). By 2035, we expect unsubsidized costs for land-based and offshore wind energy in Puerto Rico to be as low as $43/MWh (4.3 cents/kWh) and $74/MWh (7.4 cents/kWh), respectively. While these future cost projections do not include transmission system upgrade costs, they are significantly lower than current (June 2022) electricity prices reported by the Energy Information Administration of almost 30 cents/kWh (U.S. Energy Information Administration 2022). The PR100 Study will build on this analysis by continuing to explore the role wind energy can play in helping Puerto Rico reach its renewable electricity goals.

Acknowledgements

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In addition, we would like to acknowledge valuable conversations with technical stakeholders who shared knowledge and expertise to help better understand how unique conditions around Puerto Rico are likely to impact the feasibility and costs of wind energy projects there. These included teams at wind turbine manufacturers, wind energy insurance underwriters, floating offshore wind project developers, representatives from the Puerto Rico Ports Authority and individual ports, and spatial data experts at The Nature Conservancy. We leave them anonymous to respect their privacy.

All figures, unless otherwise noted, were created by Gabriel R. Zuckerman, Patrick Duffy, and Travis Williams.

List of Acronyms

AEP annual energy production

BOS balance of system

BOEM Bureau of Ocean Energy Management

CapEx capital expenditures

CSM Cost and Scaling Model

COD commercial operation date

DEA drag embedment anchors

DOE U.S. Department of Energy

EEZ exclusive economic zone

FCR fixed change rate

GCF gross capacity factor

IBTrACS International Best Track Archive for Climate Stewardship data set

IEA International Energy Agency

IEC International Electrotechnical Commission

km kilometer

kW kilowatt

LCOE levelized cost of energy

MACRS Modified Accelerated Cost Recovery System

MW megawatt

MWh megawatt-hour

NCF net capacity factor

NRWAL National Renewable Energy Laboratory Wind Analysis Library

NREL National Renewable Energy Laboratory

O&M operations and maintenance

OpEx operational expenditures

ORCA Offshore Regional Cost Analyzer

ORBIT Offshore Renewables Balance-of-system and Installation Tool

POI point(s) of interconnection

PREPA Puerto Rico Electric Power Authority

PREB Puerto Rico Energy Bureau

reV Renewable Energy Potential Model

RPS Renewable Portfolio Standard

SAM System Advisor Model

WACC weighted-average cost of capital

WRF Weather Research and Forecasting

WIND Wind Integration National Dataset

WISDEM Wind plant Integrated System Design and Engineering Model

WTIV wind turbine installation vessel

WTK-LED WIND Toolkit Long-term Ensemble Dataset

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1 Introduction

The Puerto Rico Energy Public Policy Act of 2019 (Law 17-2019) establishes a renewable portfolio standard (RPS) mandating that 40% of Puerto Rico's electricity come from renewable sources by 2025, 60% by 2040, and 100% by 2050 (Puerto Rico 2019). The Act further requires the utility to perform electrical system planning through an Integrated Resource Plan (IRP)—consistent with the Puerto Rico Energy Transformation and RELIEF Act of 2014 (Act 57-2014)—that describes the combination of energy supply resources and conservation that satisfies, in the short-, medium-, and long-term, the current and future needs of Puerto Rico's energy system and of its customers at the lowest reasonable cost (PREB, n.d.).

On August 24, 2020, the Puerto Rico Energy Bureau of the Puerto Rico Public Service Regulatory Board (PREB) issued a Final Resolution and Order approving the 2019 IRP and ordering the Puerto Rico Electric Power Authority (PREPA) to incorporate certain information regarding wind resources in the next IRP review cycle. Specifically, PREB ordered PREPA to:

- conduct an offshore wind energy study tailored to Puerto Rico's wind resource and electric grid that evaluates the cost generation profile and other characteristics of fixed-bottom and floating wind turbine options;
- properly and fully account for market-based costs and evening peak performance of land-based wind resources, and especially considering the performance of land-based wind resources designed for "low-wind" regimes; and
- properly and fully account for market-based costs and evening peak performance of offshore wind resources.

On June 1, 2021, LUMA Energy, LLC (LUMA) began executing a contract to provide management, operation, maintenance, repair, restoration, replacement and other related services for the transmission and distribution system. Among these functions is the responsibility to lead the IRP preparation and review cycle. Through a September 15, 2021 resolution, LUMA is responsible for complying with implementing all required activities related to the required wind study.

Through an interagency agreement with the Federal Emergency Management Agency (FEMA), the U.S. Department of Energy (DOE) and its national laboratories support resiliency and recovery efforts in Puerto Rico by augmenting planning, operational activities, and capacity building for both local public entities and federal agencies, ensuring investment decisions are driven by world-class data, modeling, and analysis (U.S. Department of Energy, n.d.). As part of these efforts, the National Renewable Energy Laboratory (NREL) worked with LUMA to evaluate wind energy costs and technical potential in Puerto Rico to provide a better understanding of this resource and inform future planning processes.

2 Study Scope and Goals

NREL evaluated wind energy costs and technical potential in Puerto Rico to provide a better understanding of this resource and inform future planning processes. The study's main objectives are to:

- quantify the long-term wind resource in and around Puerto Rico (offshore and over land);
- conduct exploratory interviews with key stakeholders to better understand the unique challenges of deploying wind energy technologies in Puerto Rico;
- account for unique conditions in Puerto Rico to calculate costs, produce generation profiles, and provide technology information about land-based, fixed-bottom offshore, and floating offshore wind energy;
- provide cost, performance, and technical data to the government-owned utility and system operator to meet regulatory requirements to include wind resources in planning processes; and
- coordinate data sharing with other DOE studies, including the Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100 Study) (U.S. Department of Energy 2022).

The study is divided into two tasks, each with a corresponding report. Task 1 focuses on quantifying the wind resource in Puerto Rico by using the Weather Research and Forecasting (WRF) numerical weather prediction model to simulate and validate 20 years of wind resource data, which will be made publicly available. Task 2 focuses on using this wind resource data to assess costs, performance, and technology options for wind energy deployment in Puerto Rico. **This report presents the methods and results from Task 2**.

Separately, in February 2022, DOE's Office of Electricity kicked off a 2-year (yr) study investigating pathways to 100% renewable electricity (PR100 Study) in partnership with the Federal Emergency Management Agency and DOE national labs including NREL (U.S. Department of Energy 2022; National Renewable Energy Laboratory 2022b). The PR100 Study represents a comprehensive effort to evaluate pathways to a 100% clean energy future in Puerto Rico and is modeled off the Los Angeles 100% Renewable Energy Study, or LA100 (National Renewable Energy Laboratory 2022d). The PR100 Study will build on the work outlined in this report with comprehensive analysis including stakeholder engagement to inform modeling pathways to 100% renewable energy, assessments of climate risks and energy justice impacts, as well as electricity demand projections. The PR100 Study will also conduct capacity expansion, production cost, and power flow modeling to quantify value for different generation technologies (including wind energy) and understand risks, resilience, reliability, and stability. The authors of this report have shared cost data, modeling information, stakeholder contacts, and results which will be incorporated into the PR100 Study.

2.1 Puerto Rico Analysis Domain

Puerto Rico has a population of over 3 million people and an area of nearly 3,500 square miles (U.S. Census Bureau 2020). The majority of the population is concentrated around San Juan and near the island's coastline. The majority of the electricity demand is also concentrated in the northeast portion of the island near San Juan. Figure 1 depicts topography and bathymetry (water depth) around Puerto Rico. Mountains run through the center of the island and water depths increase quickly with distance from the coast, especially to the north and south. A dashed gray line indicates the boundary between Puerto Rico's territorial waters and U.S. federal waters (9 nautical miles from the coast). The U.S. Exclusive Economic Zone is plotted as a faint gray dashed line in the north corners of the map, where the United States shares borders with the Dominican Republic to the west and British Virgin Islands to the east. We also present existing electrical substations and possible offshore wind marshalling ports based on data from LUMA and the Puerto Rico Ports Authority. More details on critical infrastructure are presented in Section 5.

The analysis domain in which we assessed wind energy costs is defined by the extent of the wind resource data modeled in Task 1 and technology specific considerations for deploying wind energy in Puerto Rico. The analysis domain for land-based wind energy encompasses the main island of Puerto Rico, Vieques and Culebra. The offshore wind domain covers Puerto Rican territorial and U.S. federal waters up to the 1,300-meter (m) water depth contour (bright red line in Figure 1) or the extent of the wind resource data modeled in Task 1. For the purposes of this study, we utilized similar technology cost assumptions for Vieques and Culebra as the rest of Puerto Rico, although more in-depth, site-specific investigation is necessary to fully understand the two islands' unique conditions. The U.S.

Virgin Islands are not formally considered in this study, but as previous work has shown, there are opportunities for shared infrastructure or collaboration with Puerto Rico on a more resilient clean energy future for the region (Gevorgian, Baggu, and Ton 2019).

The assumed 1,300-m maximum water depth limit is consistent with recent NREL floating offshore wind cost and resource studies (Beiter et al. 2020; Musial et al. 2021a; Shields et al. 2021b) but does not represent a hard technology limit. Industry practitioners agree that floating wind systems in deeper waters beyond 1300-m are technically feasible provided the seabed slopes are not steep, and that the primary issue to moving into deeper water would be cost. The industry is actively exploring mooring system designs to enable floating offshore wind development in waters more than twice as deep, so this assumption is conservative for offshore wind technologies likely to be deployed by 2035.

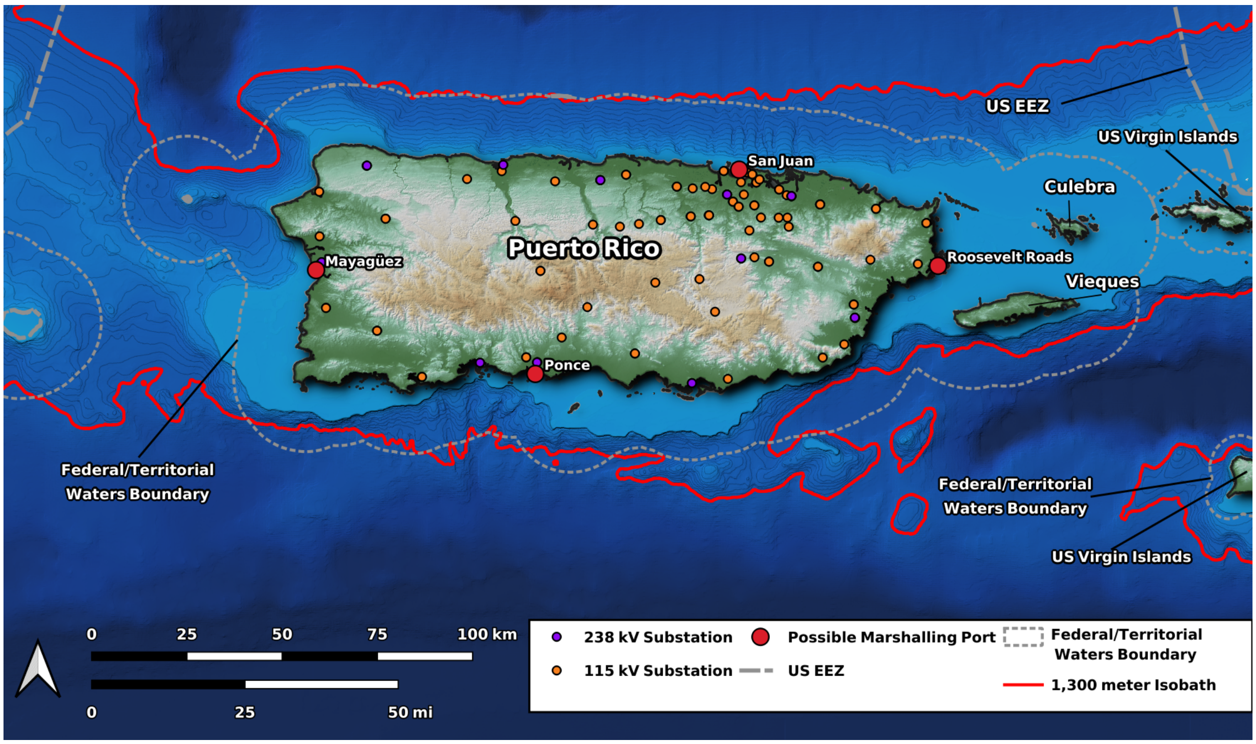

Figure 1. Map of Puerto Rico with key boundaries. The land-based analysis domain is made up of the main island, as well as Vieques and Culebra. The offshore analysis domain comprises Puerto Rican territorial and U.S. federal waters (within the U.S. Exclusive Economic Zone [US EEZ]) adjacent to the islands of Puerto Rico, Culebra and Vieques within the 1,300-meter depth cutoff (red line). Waters outside of the federal/territorial boundary around the U.S. Virgin Islands (3 nautical miles) are also considered in this analysis.

Notably for offshore wind energy development, the signing of the Inflation Reduction Act in August 2022 includes U.S. territories in the Outer Continental Shelf Lands Act and allows the Secretary of the Interior to conduct offshore wind energy lease sales in federal waters after consulting with the territorial governors (Service 2022; Congress.gov 2022). This law grants the federal agency responsible for managing offshore wind energy leasing and permitting—the Bureau of Ocean Energy Management (BOEM)—jurisdiction to lease federal areas offshore Puerto Rico, contingent on consent from the governor. This applies beyond the 9- nautical-mile territorial waters boundary.

Siting of export cables in waters less than 9 nautical miles from shore would be governed by Puerto Rico and interconnections by the PREB. Presently, if a developer wants to permit and build an offshore wind energy project within the Puerto Rican territorial waters (up to 9 nautical miles), they would need approvals from the Commonwealth of Puerto Rico's Department of Natural and Environmental Resources and the U.S. Army Corps of Engineers.

2.2 Scope Boundaries

The focus of this study is to provide wind energy cost and performance data to decision makers in Puerto Rico so they can make informed decisions as they evaluate the potential roles for different energy technologies in meeting renewable electricity goals established by the Puerto Rico Energy Public Policy Act. This study focuses primarily on comparing the levelized cost of energy (LCOE) for land-based and offshore wind energy technologies throughout the analysis domain. It should be noted the study is not part of a formal project planning process or official stakeholder engagement effort. Further, it does not:

- identify or make formal recommendations about specific areas where projects should be built;
- replace a formal stakeholder engagement effort or planning process for wind development;
- conduct detailed environmental, social, cultural, or workforce development studies;
- recommend specific companies for supplying technology, equipment, project development services, or labor for potential projects; or
- calculate the direct impacts to ratepayers of wind energy deployment in Puerto Rico.

2.3 Summary of Stakeholder Engagement

In order to better understand how conditions unique to Puerto Rico are likely to impact the feasibility and costs of local wind energy projects, NREL engaged with key technical stakeholders identified in collaboration with LUMA and DOE. It should be noted that this effort **was not** intended to be an all-encompassing wind energy stakeholder outreach campaign, but rather to begin:

- characterizing risks, technology choices, and cost impacts of developing wind energy projects in a hurricane-prone region;
- assessing how ports in Puerto Rico may support offshore wind energy deployment; and
- identifying spatial data sets for key sensitive habitats and environmentally protected areas.

More work is needed in all of these areas to support a resilient, reliable, cost-effective, and equitable energy transition in Puerto Rico, but we incorporate initial findings through Puerto-Rico-specific assumptions in our models.

Wind turbines in a hurricane experience increased forces compared to normal operating conditions as a result of extreme wind speeds, gusts, and rapid changes in wind direction. To mitigate damage, turbines operating in hurricane-prone regions must be designed to a more rigorous set of standards. We spoke with engineers at several leading wind turbine manufacturers to learn more about how they design and certify wind turbines to meet the standards set by the International Electrotechnical Commission (IEC) for the more robust Tropical (Typhoon) Class wind turbines. Compared to the most common fixed-bottom offshore IEC Class I turbines, the blades and components of IEC Tropical (Typhoon) Class offshore wind turbines must be strengthened and go through additional structural testing corresponding to the increased loads they may experience in tropical environments. For fixed-bottom offshore wind turbines, the majority of the cost difference for this additional robustness stems from reinforcing the tower and foundation, and represents an approximately 5%–10% increase in both the tower and foundation costs, depending on the site. More investigation is needed to understand the cost impacts for floating substructure technology. Most turbine manufacturers offer backup power systems to help maintain control of the blade pitch and turbine yaw systems in the event of a grid outage. The power backup system helps prevent damage by enabling the wind turbine to attempt to turn into a more favorable position during a storm. Additional information is provided in Section 4.

In addition to designing wind turbines for extreme conditions, insuring wind energy projects can help manage natural catastrophe risks in regions like Puerto Rico. To help understand how insurance premiums impact offshore wind project costs, NREL spoke with an offshore wind insurance underwriter that provided confidential, high-level guidance for the same generic fixed-bottom offshore wind project in multiple locations and for levels of risk appetite ranging from conservative to aggressive (P80-P40). Based on the data shared, we assume wind energy projects in Puerto Rico will see higher insurance premiums than projects on the U.S. East Coast, which in turn has higher premiums than the more developed offshore wind markets in the North Sea. This dynamic is driven primarily by higher wind storm exposure (including hurricanes) and perceived risks for an emerging offshore wind region that may have a less mature supply chain (e.g., customized vessels, installation expertise, and manufacturing facilities). We aggregated assumptions around higher premiums and incorporated them into the capital expenditure (CapEx) and operational expenditure (OpEx) cost calculations separately for the (approximately) 3-yr construction and 25-yr–30-yr operation phases, because different instruments are used to manage risk profiles during each project phase. More details are outlined in Section 6.

Any large wind energy project in Puerto Rico will rely on port infrastructure to assist with transporting components, cranes, and other tools needed to build the project. This approach is especially true of offshore wind energy due to the sheer size of the machines (a turbine blade can be longer than 130-meters). While one of the land-based wind projects used the Port of Ponce to import blades, we conducted a high-level assessment of ports and met with the Puerto Rico Ports Authority to better understand which additional ports might be best suited to support offshore wind energy development in Puerto Rico. We first narrowed the list by examining the existing vessel traffic and physical requirements (such as water draft, bearing capacity, and lay-down area), and then met with representatives from the Port of Ponce, the Port of Mayagaüez, and the Puerto Rico Industrial Development Company to learn about existing port development plans. The initial analysis of ports is included in Section 5.

Note that the PR100 Study has a broad stakeholder engagement task. Contacts, data sets, and other information gathered as part of the present study were passed along to the PR100 team and PR100 stakeholder advisory group.

2.4 Report Structure

This report is structured as follows: Section 3 provides an overview of the wind resource around Puerto Rico, Section 4 outlines the key wind energy technology assumptions, and Section 5 assesses how existing and planned infrastructure could support wind energy development. Next, Section 6 describes the modeling approach and Section 7 explains key cost and performance results. Section 8 synthesizes the critical takeaways from the study and Section 9 explores caveats and future work.

3 Wind Resource in Puerto Rico

Parallel to this cost analysis (Task 2), Task 1 aims to develop public, long-term wind resource data sets quantifying the wind resource in Puerto Rico. NREL will publish a companion report covering the methodology and data in detail after this cost study. In this section, we summarize the key findings from this parallel effort and provide an overview of the resource for the Puerto Rico region. These wind resource data serve as the primary input for estimating the energy production and costs presented here.

NREL has made significant efforts to produce, update, and expand its public wind resource data available through the Wind Integration National Data set (WIND) Toolkit (Draxl et al. 2015). Wind resource data for the full continental United States with the updated WIND Toolkit Long-term Ensemble Dataset (WTK-LED) are expected in late 2022[1] (National Renewable Energy Laboratory 2021b). The data for Puerto Rico will also be made public through the WIND Toolkit.

3.1 Development of a New Wind Resource Data Set for Puerto Rico

For Puerto Rico, we used the WRF model Version 4.3 (Skamarock et al. 2019) to produce 3-kilometer (km) wind resource data sets that cover the 20-year period from 2001 to 2020. WRF is the worldwide numerical weather prediction model of choice that has been developed and updated by the National Center for Atmospheric Research and its partners. The WRF model can simulate high-resolution wind data sets specialized for various wind energy applications.The model was configured with two nested domains that have 9 km (outer) and 3 km (inner) horizontal grid spacing (3 km refers to the spatial resolution of the modeling domain of interest and this domain covers the entirety of Puerto Rico and the U.S. Virgin Islands). We also produced WRF outputs on a 5-minute time step for the inner domain. We use "PR20" as the name for the new offshore wind resource data set for Puerto Rico. Note that a report detailing the methodology of the wind resource assessment (Task 1) will be published after the present cost and feasibility study (Task 2), as stakeholders prioritized the wind performance cost data for the IRP.

To simulate the 20-yr wind resource, we first tested a number of different model configurations and compared them with confidential meteorological data at hub heights to pick the setup that best captures the physics around Puerto Rico. We also compared the modeled wind speeds against measurements from the National Oceanic and Atmospheric Administration's National Data Buoy Center, and we found the validation results to be reasonable in terms of statistical metrics. More validation details will be published in the companion report for Task 1. The tested configurations were informed by Optis et al. (2020) and included different physical parameterizations and representations of planetary boundary layer physics. The planetary boundary layer includes the lowest part of the atmosphere where wind turbines are likely to be built, so this information helps accurately model the wind speeds relevant for current wind energy technology. After identifying the best-performing WRF model configuration, we modeled the full 20 years of data.

We used the ERA5 reanalysis data (0.25°-by-0.25°resolution; hourly time interval) developed by the European Centre for Medium-Range Weather Forecasts (Hersbach et al. 2020) for the initial and boundary conditions. The postprocessed WRF outputs include offshore/land-based wind profiles and basic meteorological variables with a downstream-model-friendly format. The new PR20 resource data set assumes that the meteorological conditions are stationary over time, which may not account for possible changes in the climate. Considering potential impacts of climate change on energy resources may be important, and should be considered in future studies where possible.

3.2 Overview of Puerto Rico's Wind Resource

This study uses the new wind resource data set to provide the best possible assessment of the energy production for wind power plants in and around Puerto Rico. Note that computational time requirements and the timing of this report allowed for only 15 of the 20 years of the PR20 data set to be completed in time for the analysis, so only the years from 2006 to 2020 are considered. The resulting 15-yr mean wind speeds are shown for the region around Puerto Rico in Figure 2. Offshore wind speeds are presented at 160 m and land-based wind speeds are presented at 100 m.

Figure 2 indicates the 15-yr mean wind speeds surrounding Puerto Rico range from under 4 meters per second (m/s) to nearly 9 m/s at 100 m land-based and 160 m offshore. The red line in the figure shows the 1,300 m depth contour

[1] Access the data: https://www.nrel.gov/news/program/2021/offshore-wind-data-release-propels-wind-prospecting.html

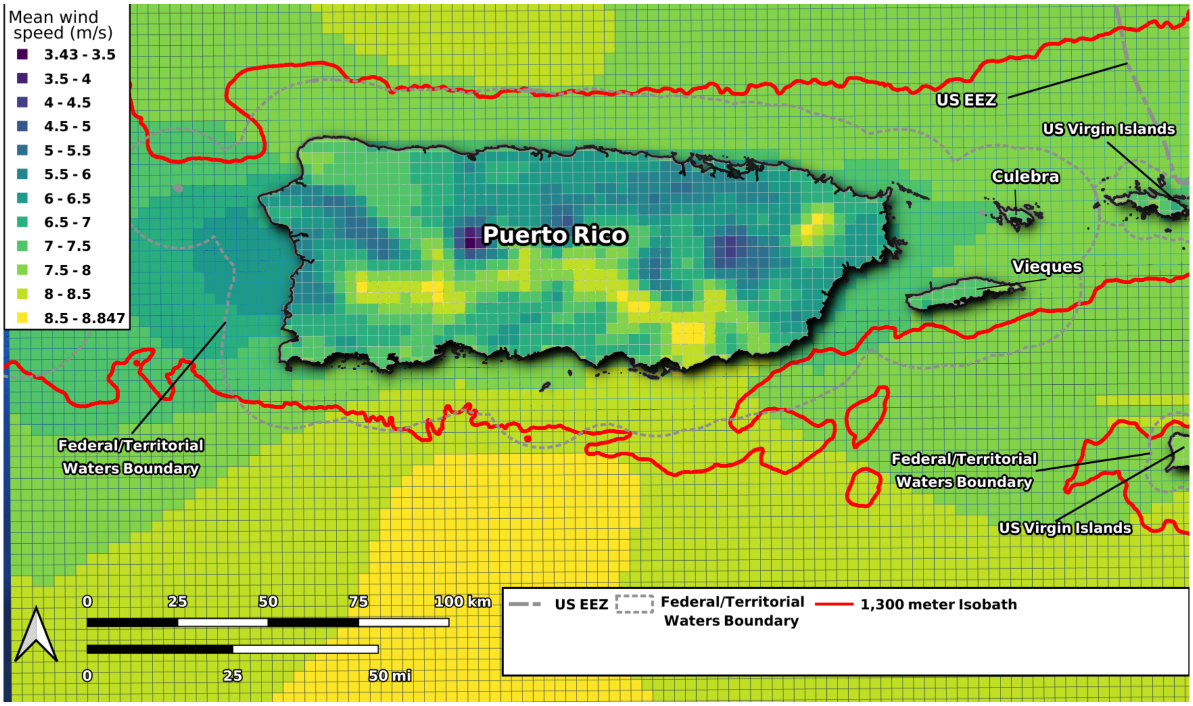

Figure 2. Map of modeled 15-yr mean wind speeds (from PR20 data set) at 100 m for land-based wind and 160 m for offshore wind. The red line indicates the cost analysis domain defined primarily by water depths up to 1,300 m.

used to define the analysis domain for the cost assessment, which should be distinguished from the WRF model domain described previously. The figure shows the highest long-term mean wind speeds offshore are found south of the island. The area off the West Coast has the lowest mean offshore wind speeds, due to the dominant easterly and east-northeasterly wind directions (see Figures 10 and 7) and the resulting "island wake" or "wind shadow" on the leeward (west) side of the island. Over land, the mean wind speeds depend heavily on topography (see Figure 1).

Previously in 2007, NREL worked with AWS Truewind to generate an initial wind resource assessment for Puerto Rico and the U.S. Virgin Islands. Figure 3 presents the results from this study at a height of 50 m, which shows general agreement in the spatial distribution of the resource—notably higher wind speeds to the north and south of the island and a pocket of lower wind speeds west (leeward) of the island.

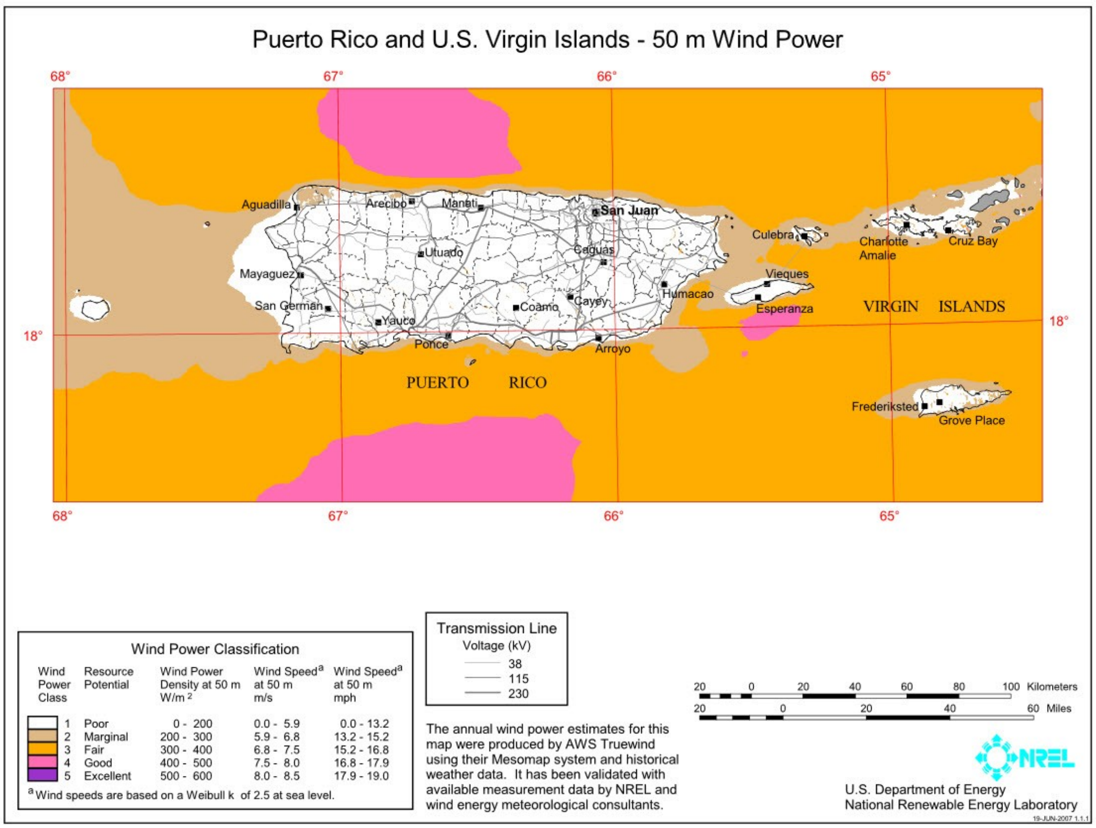

Figure 3. Map of AWS Truepower data set mean wind speeds at 50 m offshore Puerto Rico and the U.S. Virgin Islands. ***Map previously produced by NREL (National Renewable Energy Laboratory 2007).***

3.3 Location-Specific Wind Resource Characteristics

It is helpful to examine location-specific wind resource characteristics around the island to understand how the resource varies spatially. We selected four land-based wind (LBW) points and four points offshore (OSW) at which to explore the wind resource in greater detail (see Figure 4). It is important to note that these points do not represent specific wind energy projects. The color of each marker in the figure indicates the site-specific wind resource characteristics.

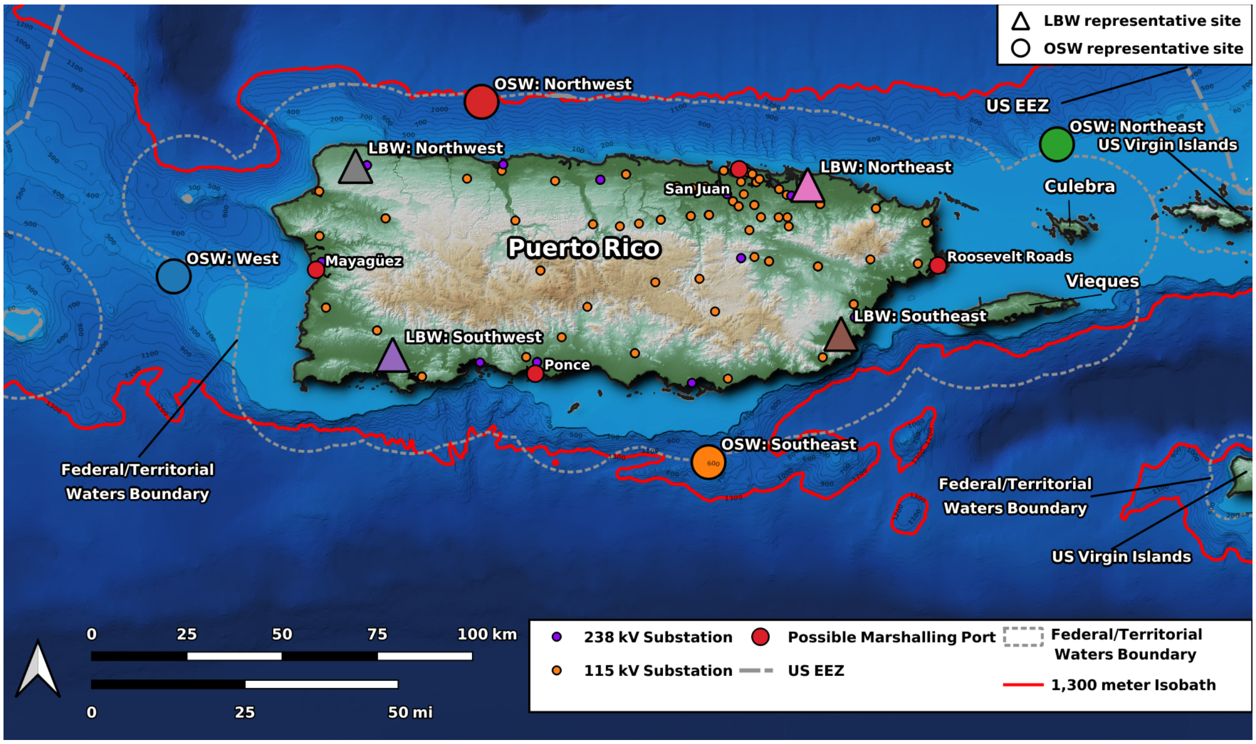

Figure 4. Eight points at which to investigate location-specific wind resource characteristics. Land-based wind denoted "LBW" and offshore wind denoted "OSW."

The 15-yr mean vertical wind shear profiles at the eight points identified earlier are presented in Figure 5. The color of the line corresponds with the color of the points identified in Figure 4.

From the vertical wind profiles in Figure 5, it is clear that the highest average wind speeds are found offshore, especially to the southeast. On land, there appears to be greater vertical wind shear (change in wind speed with height). This means that land-based wind turbines in Puerto Rico may benefit from taller towers to access more available energy at higher wind speeds. The offshore points identified have flatter vertical profiles.

3.3.1 Wind Resource Over Land

Figure 6 presents a 15-yr wind speed distribution at 100 m in histograms to understand the frequency of different land-based wind speeds.

From Figure 6, it is clear that the land-based winds spend a majority of the time between the cut-in wind speed and rated wind speed at the four locations identified. This range of wind speeds is often referred to as "Region 2" of the power curve, where the power produced increases proportional to the wind speed cubed. Figure 7 shows that at all four locations over land, the winds predominantly come from the east or east-northeast.

To better understand daily variation in the wind resource by season, we present diurnal profiles in Figure 8.

Figure 8 shows that the winter and summer tend to be the windiest seasons at the four points over land, and the fall tends to be the least windy season. Additionally, while the average wind speeds in the east are slightly lower than the west, they are also more consistent throughout the day. At the southwest point, winds tend to peak in the middle of the day, which may align with peak solar energy production.

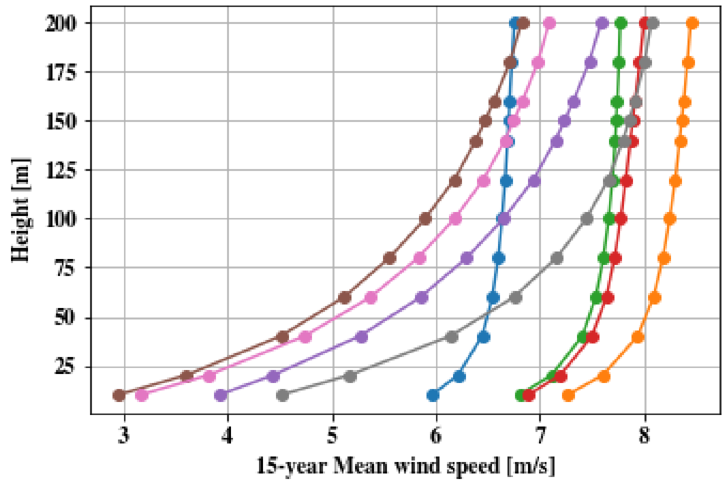

Figure 5. The 15-yr mean vertical wind shear profiles at eight locations around Puerto Rico

3.3.2 Wind Resource Offshore

Figure 9 presents the 15-yr wind speed distribution at 160 m in histograms to understand the frequency of different wind speeds offshore. The dashed black lines in the figure indicate the cut-in, rated, and cut-out wind speeds of the International Energy Agency (IEA) 15-MW reference wind turbine.

Figure 9 reveals that the offshore points exhibit similar trends as points over land in terms of wind speed distributions—the majority of the time wind speeds fall between cut-in and rated wind speeds. Note that wake losses tend to be highest when wind turbines operate near their rated wind speed since this represents the point when they exert the peak thrust force on the wind. Notably, the wind roses plotted in Figure 10 demonstrate a predominant range of wind directions coming from the east and east-northeast. This may help developers optimize the wind farm layout to reduce wake losses through intentional wind plant layout design.

Figure 11 underscores that offshore wind can play a valuable role in the transition to 100% clean electricity by contributing power to the grid in the evening and at night, potentially complementing solar electricity production. In the figure, we observe that the two sites in the east have the least wind speed variation throughout the day and that the highest wind speeds are in the southeast. This highlights how offshore wind in some areas can contribute power to the grid during peak demand in the evening (see Section 5), and potentially reduce the need for battery or other energy storage infrastructure. The strongest daily variations come in the summer at the northwest, with an uptick in the afternoon. As was the case over land, the highest seasonal wind speeds occur in the summer and winter, and the lowest seasonal wind speeds occur in the fall. More work will be done to investigate the production profiles of wind energy and how they may be complementary to other generation sources in the PR100 Study.

While the mean wind speeds surrounding Puerto Rico are lower relative to sites on the U.S. West Coast or Northeast, the offshore wind resource is favorable for electricity generation. This is especially true offshore to the north and south of the island and is shown in Figure 2, which maps the strength of the wind. The possibility for generating power in the evening and at night is likely complementary with solar generation resources, but more work needs to be done to investigate the generation profiles of wind energy in relation to other generation sources and electricity demand profiles.

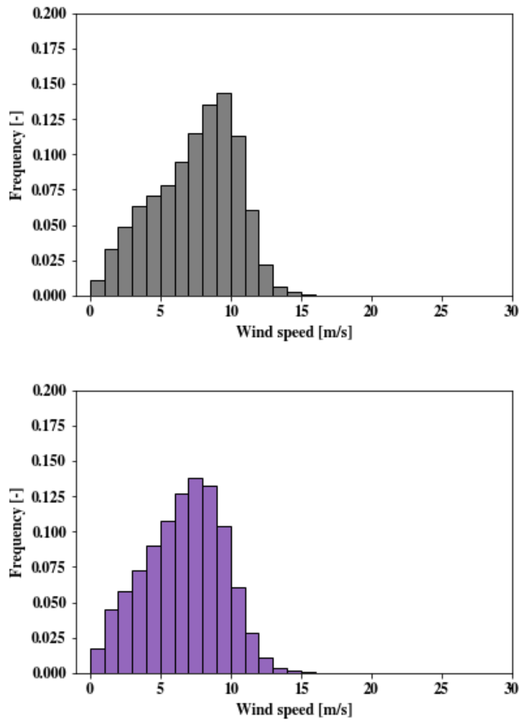

Figure 6. The 15-yr wind speed distributions at 100 m over land for the (clockwise from top left) northwest, northeast, southeast, and southwest

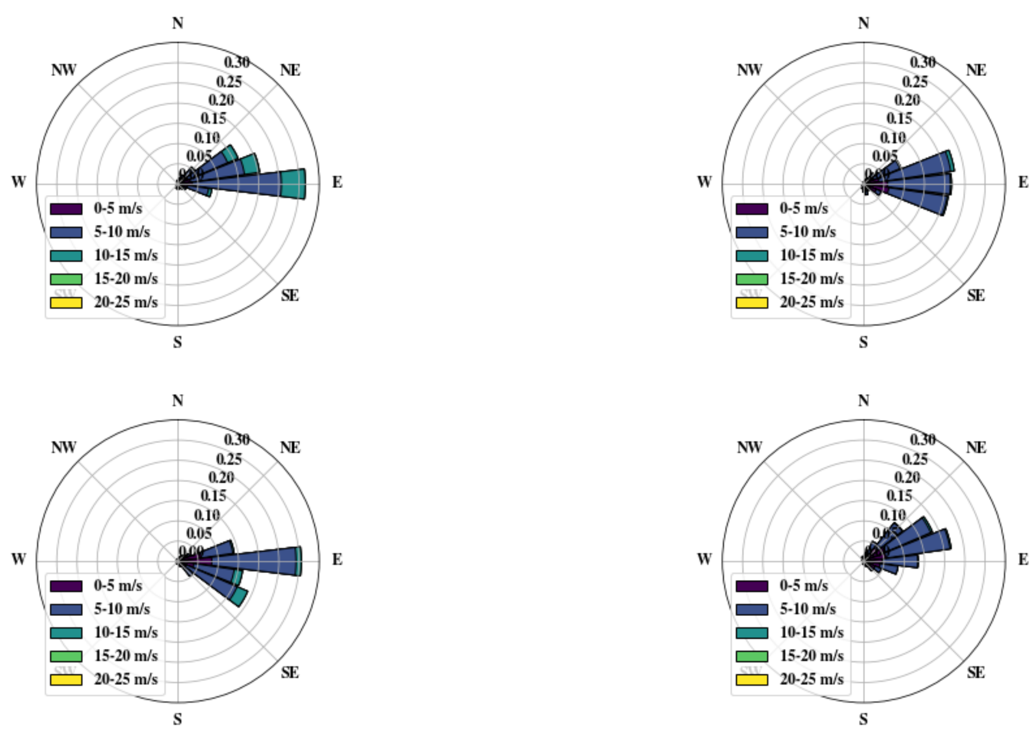

Figure 7. Wind roses at 100 m over land for the (clockwise from top left) northwest, northeast, southeast, and southwest

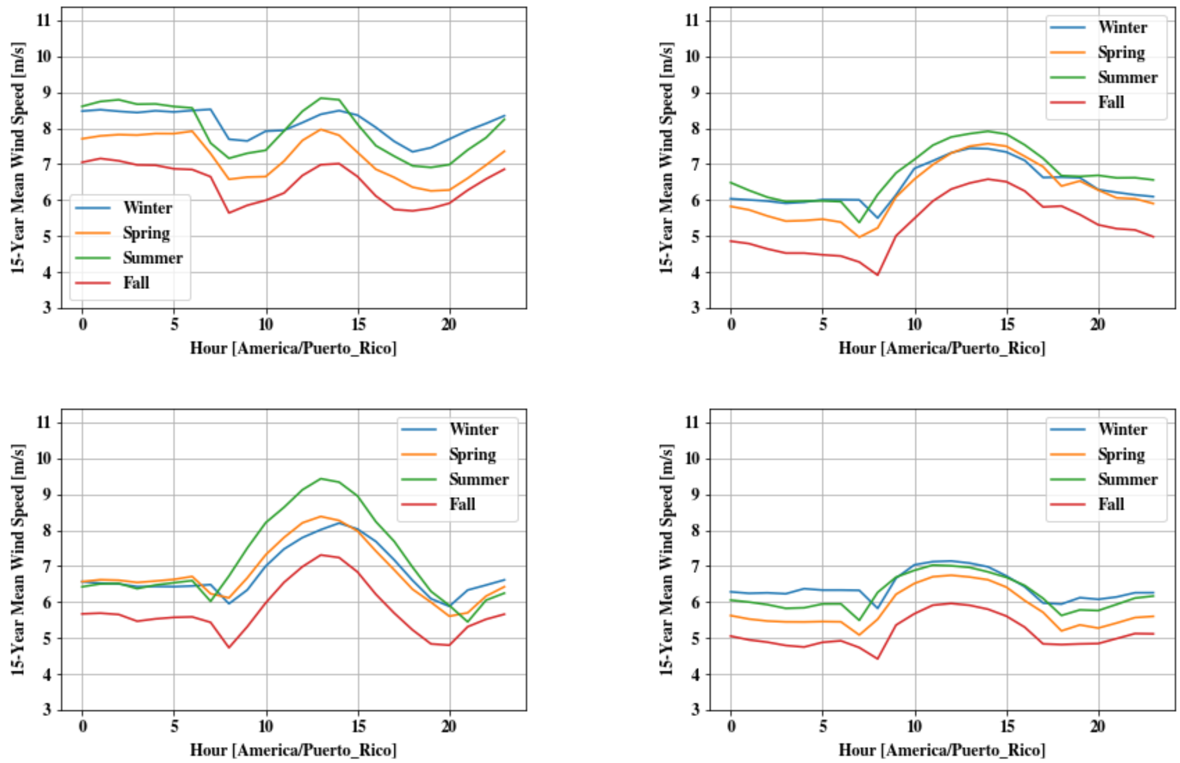

Figure 8. Seasonal diurnal profiles at 100 m on land for the (clockwise from top left) northwest, northeast, southeast, and southwest

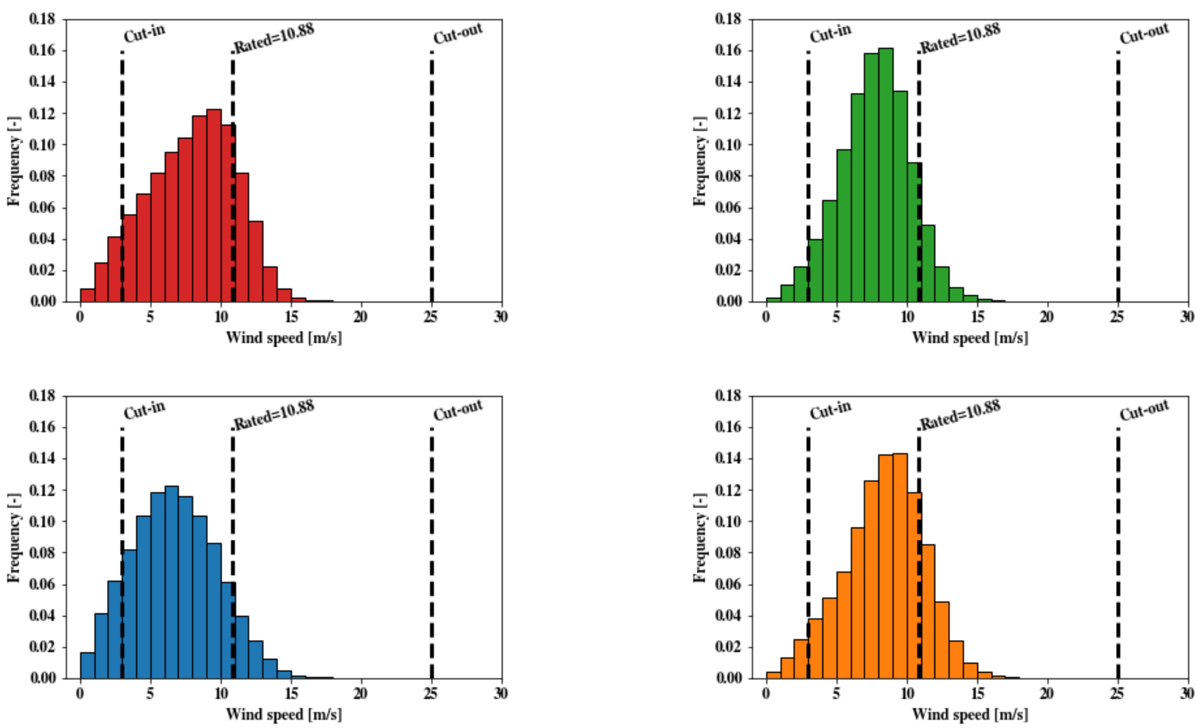

Figure 9. The 15-yr offshore wind speed distributions at a 160-m height for the (clockwise from top left) northwest, northeast, southeast, and west. Cut-in, rated, and cut-out wind speeds indicated from offshore wind turbines used in the modeling below (see Section 4).

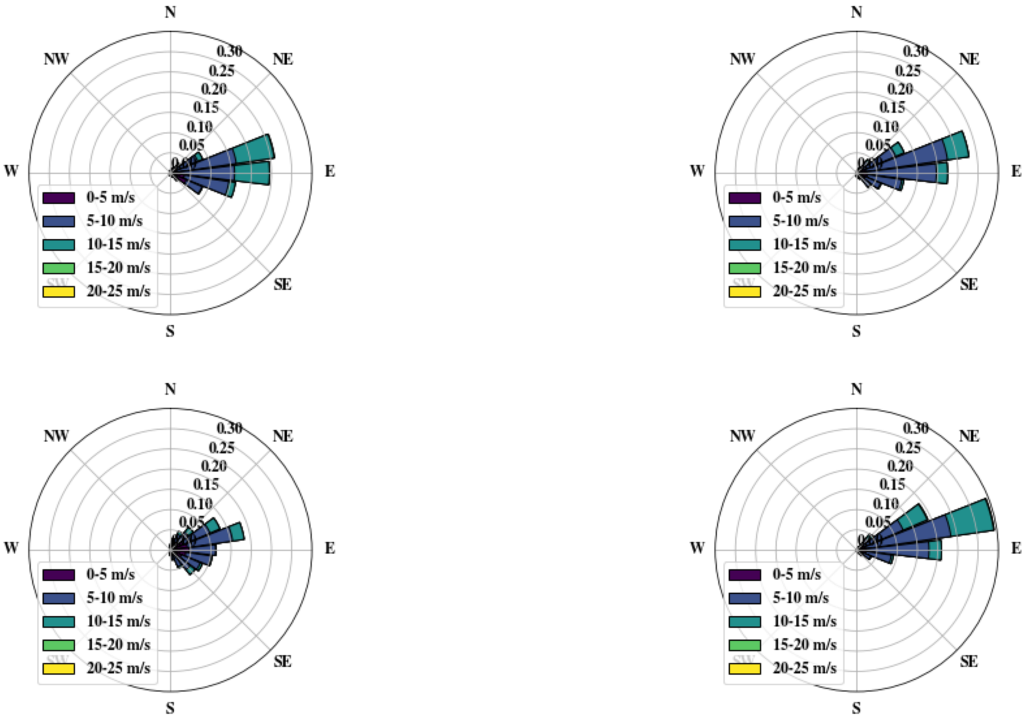

Figure 10. Wind roses offshore at a 160-m height for the (clockwise from top left) northwest, northeast, southeast, and west

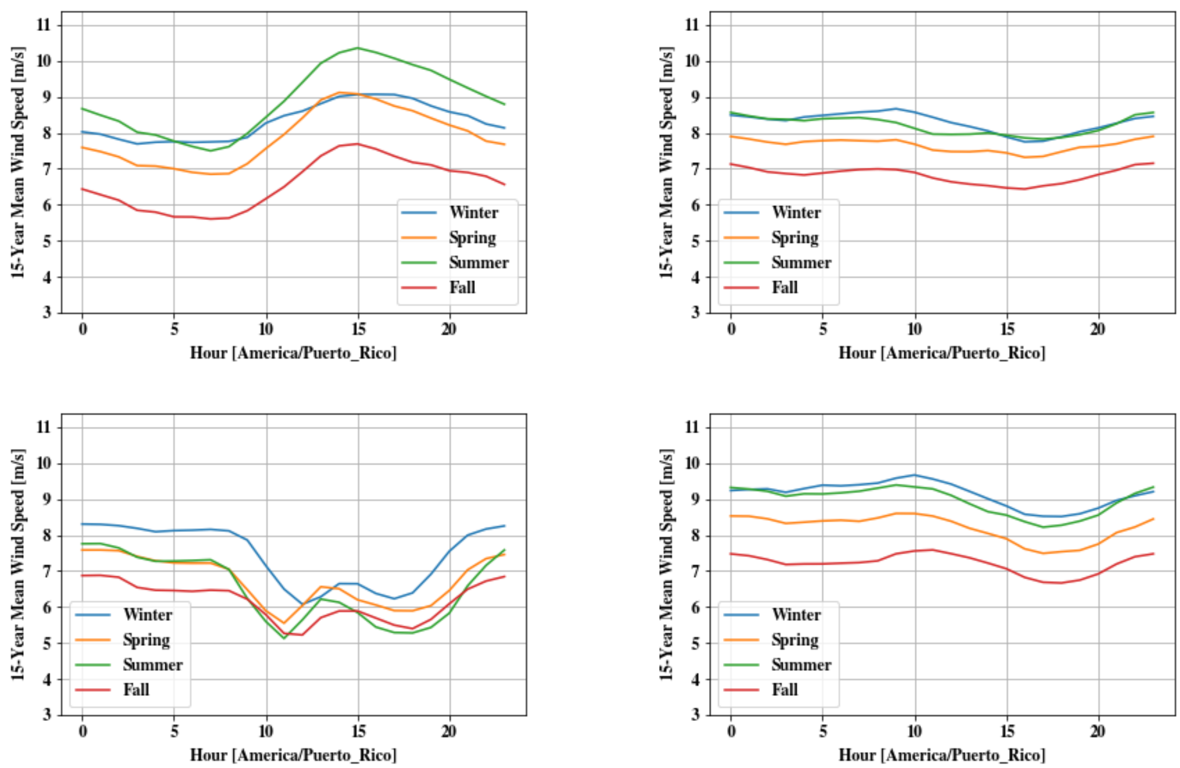

Figure 11. Diurnal profiles at 160 m offshore for the (clockwise from top left) northwest, northeast, southeast, and west

4 Wind Energy Technology Overview

In this study, we calculate costs and performance of land-based and offshore wind energy based on representative technology options assumed for different commercial operation dates (CODs). Because developing wind energy projects in hurricane-prone regions poses multiple challenges, we focus on characterizing and accounting for those risks with Puerto-Rico-specific technology and cost assumptions. We selected 2022, 2030, and 2035 as the reference COD years for land-based wind and 2030 and 2035 as the reference COD years for offshore wind based on discussions with BOEM, LUMA, and others about possible deployment timelines. For each COD, we define a specific technology that serves as input to the cost modeling effort. These assumptions include wind turbine ratings, hub heights, rotor diameters, power curves, and support structure, as well as the cost and performance impact of technological innovations. These choices are intended to reflect recent global wind energy technology and cost trends, incorporating market data where possible. We used NREL's bottom-up cost modeling tools to confirm assumptions or fill data gaps.

4.1 Wind Turbine Design and Hurricane Risks

Wind turbines convert the kinetic energy in the wind to electrical energy and have varying ranges of wind speeds over which they operate (typically 3 m/s to about 25 m/s or 30 m/s). Generating power at the rare wind speeds above that range increases physical loads and strain, and the small amount of additional power is not worth the additional investment. Therefore, turbines typically idle in high wind conditions to ensure operation throughout their lifetime (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, n.d.). Hurricanes are rotating tropical cyclone storms with high wind speeds (over 33 m/s or 74 miles-per-hour at 10 m above the surface). Figure 12 depicts approximate paths of the centers of historical storms and hurricanes around Puerto Rico based on the International Best Track Archive for Climate Stewardship (IBTrACS) data set (BOEM, n.d.). From the figure, it is clear that any wind energy projects in the region must evaluate hurricane risks and attempt to mitigate them, especially because continued climate change could lead to more intense hurricanes (Knutson et al. 2021; Kossin et al. 2020).

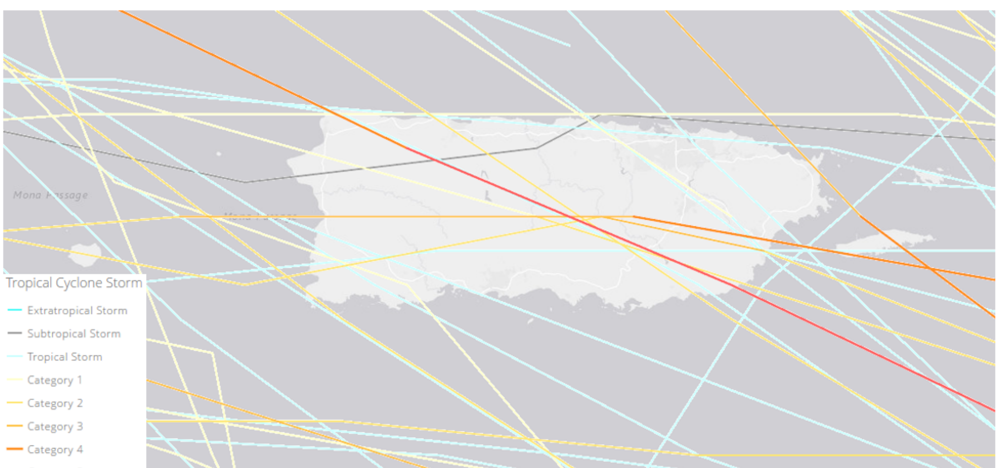

Figure 12. Tropical storm segments and categories passing through the Puerto Rico region from 1900 - 2016 according to the International Best Track Archive for Climate Stewardship data set. ***Accessed through the BOEM Marine Cadastre Layer: Tropical Cyclone Storm Segments (BOEM, n.d.).***

The IEC develops and maintains standards, such as IEC 61400 for the design and certification of wind energy systems (IEC, n.d.). The IEC "focuses on the engineering integrity of the structural components of an offshore wind turbine but is also concerned with subsystems such as control and protection mechanisms, internal electrical systems and mechanical systems." By certifying that a wind turbine design meets certain engineering standards, wind turbine manufacturers can give their customers confidence that the turbines will survive the stated product lifetime in a variety of wind conditions. The IEC has different certification levels, or wind classes, representing different wind climates and extreme conditions. Generally, lower-numbered wind classes (ranging from Class I to Class III) indicate the wind turbine is designed for higher wind speeds.

In 2003, Typhoon Maemi damaged several wind turbines in Japan when a peak gust of 74 m/s exceeded the Class I design standard of 70 m/s, underscoring a need to better how understand the interaction between tropical storms (including hurricanes) and wind turbines (Ishihara et al. 2005). A new classification for turbines designed to withstand higher wind speeds (limits of 57 m/s average over a 10-minute period and 80 m/s over a 3-s gust) was created specifically for typhoon-prone areas (IEC Typhoon-Class wind turbines, or IEC Class T). The current version of the relevant standard (IEC 61400-1) focuses on typhoon-prone areas outlines design load cases and conditions specific to the assessment of storm probability and risk. Note that IEC 61400-1 and 61400-3-1 are for fixed-bottom systems. The newer IEC 61400-3-2, which describes floating offshore wind design standards, are less proven since the majority of offshore wind systems installed to date relied on fixed-bottom technologies.

Installing more robust Class T wind turbines for a project in hurricane-prone regions is an important step to reduce risk, but is not a guarantee that the machines will survive every hurricane unscathed. It is clear that risks increase with storm severity and proximity to the hurricane's eyewall, where both mean wind speeds and gusts tend to be highest. Worsnop et al. (2017) indicates that the radius of maximum winds is typically about 20 km from the eyewall.

During Hurricane Maria, there were two land-based wind farms in Puerto Rico (78 km apart): Punta Lima and Santa Isabel. The storm severely damaged the wind turbines in the Punta Lima wind farm, but not at the Santa Isabel wind farm. Figure 13 shows a radar image from Masters (2019) based on National Weather Service data from just before Hurricane Maria made landfall in Puerto Rico. While further analysis of turbine designs and specific wind conditions at each wind farm would be needed to draw conclusions about failures in Punta Lima, the image supports the idea that risks increase closer to the eyewall. The image shows how the eyewall of Hurricane Maria passed through the Punta Lima wind farm. Masters (2019) suggests that Punta Lima could have experienced high Category 4 extreme conditions of close to 70 m/s, whereas Santa Isabel likely only saw Category 1 or 2 conditions (up to 50 m/s).

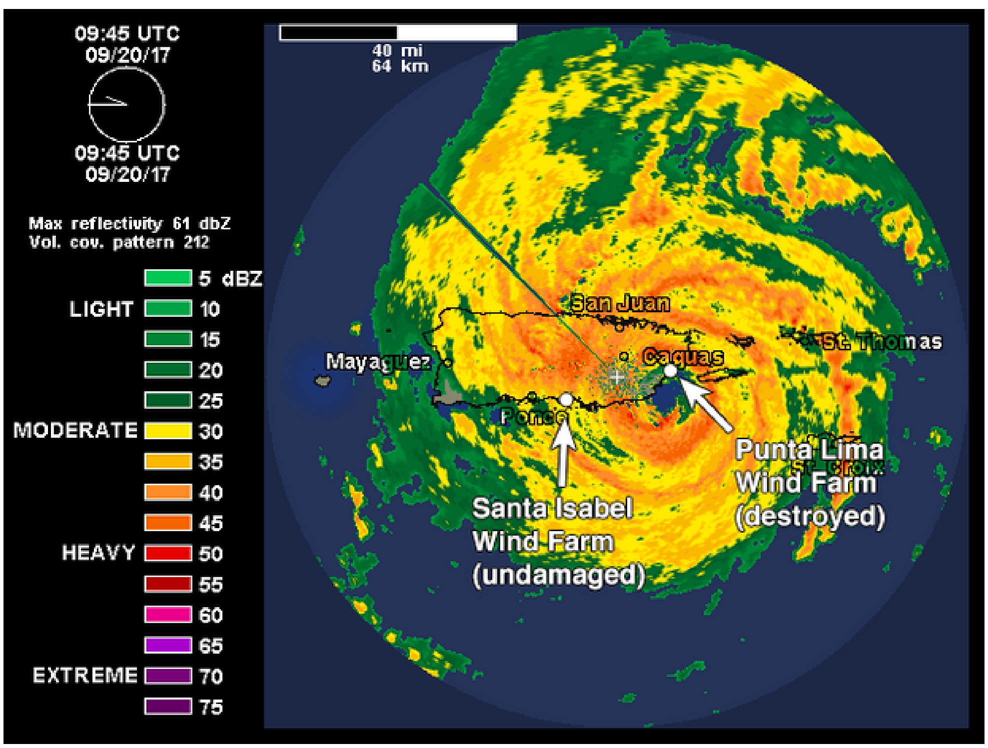

Figure 13. The National Weather Service radar image of Hurricane Maria just before making landfall in Puerto Rico, reproduced from Masters (2019). ***Image from The Weather Company, an IBM Business (used with permission)***

Worsnop et al. (2017) demonstrated the value of modeling hurricanes for wind energy applications by simulating an idealized Category 5 hurricane to spatially quantify mean wind speed, 3-s gusts, gust factors, and wind direction shifts in storms. Additional research is needed to connect expected hurricane conditions to IEC design standards for different return periods, understand the behavior of wind turbines in hurricane-like extreme conditions, and quantify hurricane risks spatially.

4.1.1 Typhoon-Class Offshore Wind Turbines

Most leading offshore wind turbine manufacturers (Siemens Gamesa Renewable Energy, General Electric [GE] Renewable Energy, Vestas, and MingYang) offer Typhoon-Class offshore turbines ranging in size from 4.2 to 15 MW. The Asia Pacific and U.S. offshore markets need typhoon-rated turbines, and several have already been installed at the Akita Noshiro Offshore Wind Farm (Vestas 2020; Lewis 2022).

GE announced that the Haliade-X platform in 12-MW and 13-MW configurations has been certified to IEC Typhoon-Class conditions (GE Renewable Energy 2022). Vestas offers the V117 4.2-MW, V164 10-MW, V174 9.5-MW, and V236 15-MW turbines with a Typhoon-Class rating (Vestas 2022b). Siemens Gamesa offers all offshore wind turbines greater than 8-MW with a Typhoon-Class rating (Siemens Gamesa Renewable Energy 2021). In June 2022, the Chinese wind turbine manufacturer MingYang Smart Energy began producing its first Typhoon-Class offshore wind turbine with a rated power of 12 MW (Memija 2022). According to MingYang, a dual-drive pitch control system helps the turbine reduce loads in extreme operating conditions. Some of these wind turbines are currently available with Typhoon-Class ratings but many are in the prototype stage and should be available commercially in 1–2 years. Each of these turbine platforms require additional component strengthening for blades, pitch systems, and drivetrain bearings, as well as stronger towers and substructures due to increased extreme wind speeds.

Per IEC 61400-1 and IEC 61400-3-1, the Typhoon-Class fixed-bottom offshore wind turbines must withstand sustained (10-min) wind speeds of up to 57 m/s and gusts (3-s) of 80 m/s (IEC 2019; IEC and Danish Standards 2019). Compared to an IEC Class 1 wind turbine, this represents an up to 30% increase in mechanical loads on some components (though not all components see this level of increased loads). We spoke with several leading turbine manufacturers to better understand the key design changes, certification process, and cost impacts of a fixed-bottom offshore IEC Typhoon-Class machine compared to an IEC Class I specified by the standards. Key design changes include:

- reinforcing turbine blades, primarily toward the blade root;
- including more robust sensors to ensure continued operation in high winds; and
- strengthening the tower, yaw system, and blade pitch system to handle idling loads.

Wind turbine blades and components must go through additional structural testing corresponding to these increased loads during the wind turbine design certification process. The design load cases come during idling conditions. Turbine manufacturers sell backup power systems for when the power grid shuts down, which helps the turbine to maintain yaw authority during a storm and reduces the wind loads (especially fatigue loads).

Overall, increasing the strength of a turbine from Class I to Typhoon Class represents a small cost increase relative to the total cost of the turbine (<1% cost difference in most components). Making the tower and foundation more robust is the primary driver of cost changes, representing approximately a 5%–10% increase in tower and foundation costs for fixed-bottom offshore wind, depending on the site. The same level of detail was not yet available for floating offshore wind, so we assumed this cost difference was the same as fixed bottom for an initial estimate. More work is needed to quantify design changes (IEC 61400-3-2) the cost increase for Typhoon-Class floating offshore wind turbines.

4.1.2 Typhoon-Class Land-Based Wind Turbines

Vestas currently offers a land-based V117 4.2-MW wind turbine with a Typhoon-Class rating as well as an “Extreme Climate” V136 4.2-MW wind turbine, which falls between Class I and Typhoon-Class design conditions (Vestas 2022c, 2019). The differences between land-based Class III and Typhoon-Class turbines are found in rotor diameter (D, in meters), specific power (ratio of rotor swept area to the generator rating), energy production. Current Typhoon-Class offerings have shorter blades relative to Class III machines of the same rated power, which means less energy capture in lower wind speeds but also reduced loads in extreme conditions. Offshore Class I turbines are comparable to land-based Typhoon-Class turbines, with differences in turbine performance and cost.

While extreme wind survivability is an important factor to consider when selecting turbines, under normal conditions the onshore wind regime in Puerto Rico will fall in the range of Class II or Class III based on the mean wind speeds presented in Section 3. With multiple configurations of land-based and offshore turbines available, the critical next step in choosing turbines is to assess storm risk in land-based and offshore locations around Puerto Rico. Site-specific turbine design decisions are possible with such assessments.

4.1.3 Wind As Part of a Reliable, Resilient Grid

As Puerto Rico considers the makeup of its future electricity grid, reliability and resilience must be part of the design process. In this context, reliability means mitigating the impacts of outages (reducing the number, frequency, magnitude, and recovery time of these outages), and resilience is the ability to prevent or reduce the magnitude of and quickly recover from a disturbance such as a hurricane. Integrating high percentages of variable renewable generation poses several challenges to these goals including adequacy and stability (Hirschhorn and Brijs 2021). Adequacy refers to having enough power supply to meet demand as well as sufficient transmission capacity to deliver that power. Stability requires the voltage and frequency of the grid to remain in a relatively narrow range. The PR100 Study will investigate these dynamics for different energy generation technologies, including how the generation profiles influence risks. In this report, we provide an initial qualitative description of risks, as well as the role, wind energy can play.

To estimate the natural catastrophe risk to U.S. offshore wind energy, Rose et al. (2013) simulated thousands of years of hurricane activity along the U.S. coastline populated with offshore turbines from likely buildouts. When calculating the capacity value of offshore wind, they recommended incorporating risk of losses (damaged turbines) due to hurricanes scaled by the capacity credit of offshore wind. A direct strike by the eyewall of a high-category hurricane could potentially damage even Typhoon-Class turbines as well as associated electrical infrastructure. Because major repairs or reconstruction take time, this accounting can help ensure sufficient generation capacity remains to meet demand.

If major repairs are required, wind turbines could take longer to fix than transmission if specialized components or vessels are needed. Further, the distributed nature of wind and solar systems mean that risks are inherently spread out geographically. This diversification might increase the probability of low-consequence outages (when a small percentage of generation is at risk of being taken offline), but also reduces the risk of a major outage resulting from a single, large generation facility being taken offline. Building in redundancy such as a second export cable, while more costly upfront, can help keep more capacity online in the event that a core piece of transmission fails under extreme conditions. In normal operation, both geographic and generation resource diversification increases the chance that at least some resources are contributing to supply adequacy at a given time (see Figure 11). Wind energy resources in northern Puerto Rico could potentially help with system adequacy because most of the existing demand is near San Juan.

The rotating mass of fossil-fuel generators historically provided inertia, which helped stabilize grid voltage and frequency during small disturbances. Most operational inverter-based systems, such as wind and solar, have not provided these benefits. However, NREL demonstrated that wind turbines can provide stability to the grid using grid-forming controls to set grid voltage and frequency or operate without power from the electric grid (National Renewable Energy Laboratory 2022e). Other experiments that have assessed the potential for wind turbines to provide grid services support the idea that they can contribute to stability and load balancing (Wind Energy Technologies Office 2018). Further development of similar strategies could help facilitate high-penetration renewable grids by increasing the value of wind energy plants to the grid. The cost of grid-forming inverters should be marginal compared to the total cost of wind energy projects.

Cicilio et al. (2021) indicates that increased adoption of connected digital technologies (digitalization) is facilitating high-penetration renewable grids through improved monitoring and forecasting capabilities, but that it involves cybersecurity risks, which must be considered while planning. Smart-grid infrastructure is characterized by networked devices that help monitor and control the grid in response to changes. These sensors also help with "self-healing," wherein automated processes help diagnose and isolate portions of the grid with faults, enabling rapid restoration of power to undamaged areas. Statistical tools such as machine learning help process vast amounts of data collected to improve forecasts of supply or demand. The prevalence of connected devices leaves the grid vulnerable to cybersecurity threats, and Sanghvi et al. (2020) outlines some of these challenges as well as best practices for wind energy.

4.2 Wind Turbine Technology Trends

4.2.1 Land-Based Wind Technology Trends

One of the key trends emerging for land-based wind turbines has been continued growth in height, rating, and rotor diameter over time (Wiser et al. 2021c; Bolinger et al. 2021).

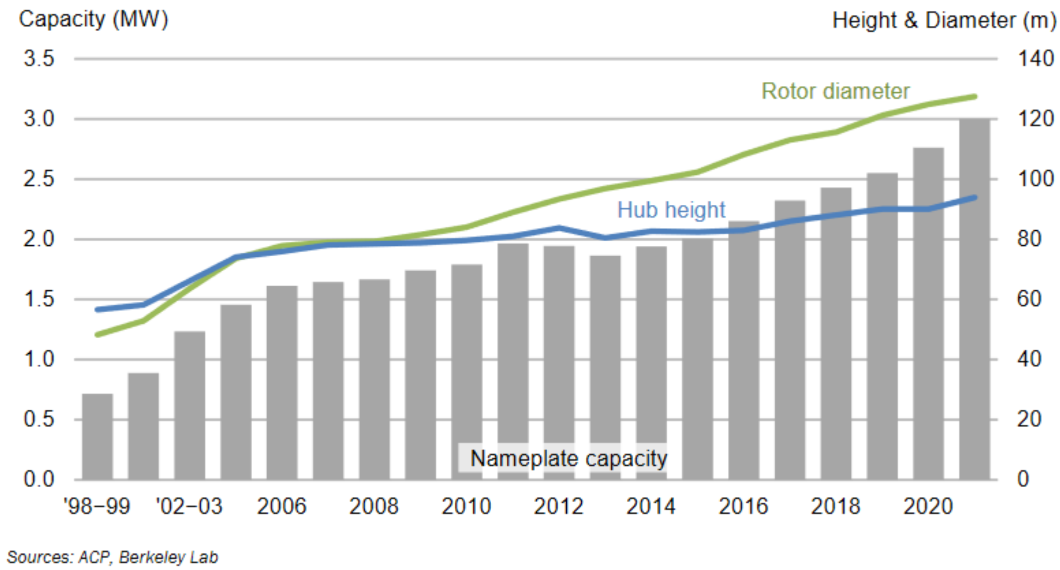

Figure 14. Average wind turbine capacity, hub height, and rotor diameter for U.S. land-based wind projects over time. ***Image reproduced from Wiser et al. (2022) with permission***

Wind turbines are typically designed for the strength of the wind resource, turbulence, and extreme conditions as well as for the type of market they can be most cost-effective in. Typically, the markets are called "capacity-constrained" or "land-constrained." In capacity-constrained markets, there is an abundance of land upon which to place wind turbines, but there is limited power transmission capacity available at the grid connection. In land-constrained markets, there is typically limited land upon which to place turbines, but an abundance of power transmission capacity at the grid connection. Typically, a capacity-constrained market is best served by using low-specific-power turbines which have lower rated capacities for a given rotor diameter (or larger rotors for a given rated power and associated higher rotor costs). A land-constrained market tends to be best served by higher specific-power turbines to increase the ability to deploy capacity. Presently, Puerto Rico may be considered both capacity- and land-constrained, though the capacity constraints can be alleviated with more transmission infrastructure.

Land-Based Wind Turbine Technology Considerations for Puerto Rico

Puerto Rico may have several factors that drive turbine selection and feasibility. First, the Puerto Rico market appears to be land-constrained. Second, the lower-than-average wind speed resource will drive the minimum LCOE solution to a lower specific-power rating, which typically would call for 3- to 4.5-MW wind turbines. Note that over the next 10 years, we expect low specific-power turbines to be deployed in the range of 3-4.5 MW, though they are not necessarily limited to this capacity range. Third, logistics and transportation constraints arising from topography and roads may limit turbine ratings because higher rated turbines require larger components to be transported. For example, 6-MW turbines with blades that are 80 m or more in length may not be transportable on many roads in Puerto Rico. Fourth, depending on location, a wind power plant may be constrained by the availability of the power transmission infrastructure. Fifth, extreme wind speeds may constrain maximum turbine rating and rotor diameter. Based on these technology considerations, land-based wind turbines installed in Puerto Rico through 2035 are likely to have rated powers of between 3 MW and 6 MW.

Land-Based Wind Installation Systems

The cranes required to install wind turbines are typically between 500 and 750 metric tonnes in capacity. Cranes this size may not be available in Puerto Rico. Therefore, we assume that they will need to be shipped from and back to the continental United States. We account for the additional shipping costs with two assumptions. First, we assume there will be an additional 2 months of crane rental time to cover the round-trip shipping time. Second, we assume the mobilization cost to be double that of a continental U.S. mobilization to cover the additional labor required to ship a crane across the Gulf of Mexico. The assumed doubling of crane mobilization cost accounts for labor and shipping costs from the U.S. mainland on a barge, unloading in Puerto Rico, transporting the crane components to the wind farm, and assembling the crane. While these estimates may differ from actual costs of crane mobilization during construction of an actual wind plant, they do serve as an estimate of mobilization costs and time required to model wind plant construction.

In the cost estimates presented below, we assume the use of two crane technologies: crawler cranes (near-term installations) and climbing cranes (future installations). A crawler crane is attached to a set of tracks (crawlers) that allow it to move along the ground under its own power. A climbing crane attaches to the turbine tower and 'climbs' as it assembles the tower sections, nacelle, and rotor. Climbing cranes use the tower of a turbine to support itself and all of the components being lifted during turbine assembly. Climbing cranes are expected to lower the total installed cost of land-based wind in Puerto Rico due to turbine size, cost of cranes for the assumed turbines, and small plant capacities.

4.2.2 Offshore Wind Technology Trends

Global offshore wind energy deployment is accelerating rapidly, with approximately 34% (17,399 MW) of the total installed offshore wind capacity (50,623 MW) coming online during 2021 (Musial et al. 2022). The offshore wind energy industry has predominantly matured in Europe and Asia, with only 42 MW of operational offshore wind installed in the United States to date. This is expected to change rapidly with 932 MW of U.S. offshore wind under construction, 20,603 MW in permitting, and the recently announced national offshore wind target of installing 30 gigawatts (GW) by 2030 (Musial et al. 2022; U.S. Department of Energy 2021). Globally, estimates range from 261,000 MW to 286,000 MW of installed offshore wind capacity by 2031, a more than fivefold increase (BloombergNEF 2022; 4C Offshore 2022a).

Like land-based wind energy, the size and rate power of offshore wind turbines has grown as the technology has matured (Veers et al. 2019). The first offshore wind farm installed in 1991 had turbines with a hub height of 35 m, rotor diameter of 35 m, and rated power of 0.45 MW (4C Offshore 2022b). Currently, the largest operating wind turbines in the world by rated power are the GE Haliade-X prototype (14 MW nameplate capacity, 220 m rotor diameter and a hub height of up to 260 m) and the Siemens Gamesa SG 14-222 DD (14 MW nameplate capacity, 222 m rotor diameter and site-specific hub heights)(GE Renewable Energy 2020; Lewis 2021). The largest turbine is expected to change when the V236 15-MW prototype comes online in Denmark (Vestas 2022a). Further, MingYang Smart Energy has announced the largest wind turbine with a rated power of 16 MW (MingYang Smart Energy 2021). All of these machines have rotor diameters upward of 220 m—more than 2.75 times the wingspan of an Airbus A380 (Airbus 2021).

Figure 15 shows a floating offshore wind turbine based on the International Energy Agency (IEA) 15-MW reference turbine (Gaertner et al. 2020), highlighting the main components and the overall dimensions. Figure 16, reproduced from Musial et al. (2022), highlights how offshore wind turbine sizes have grown significantly over the past few decades.

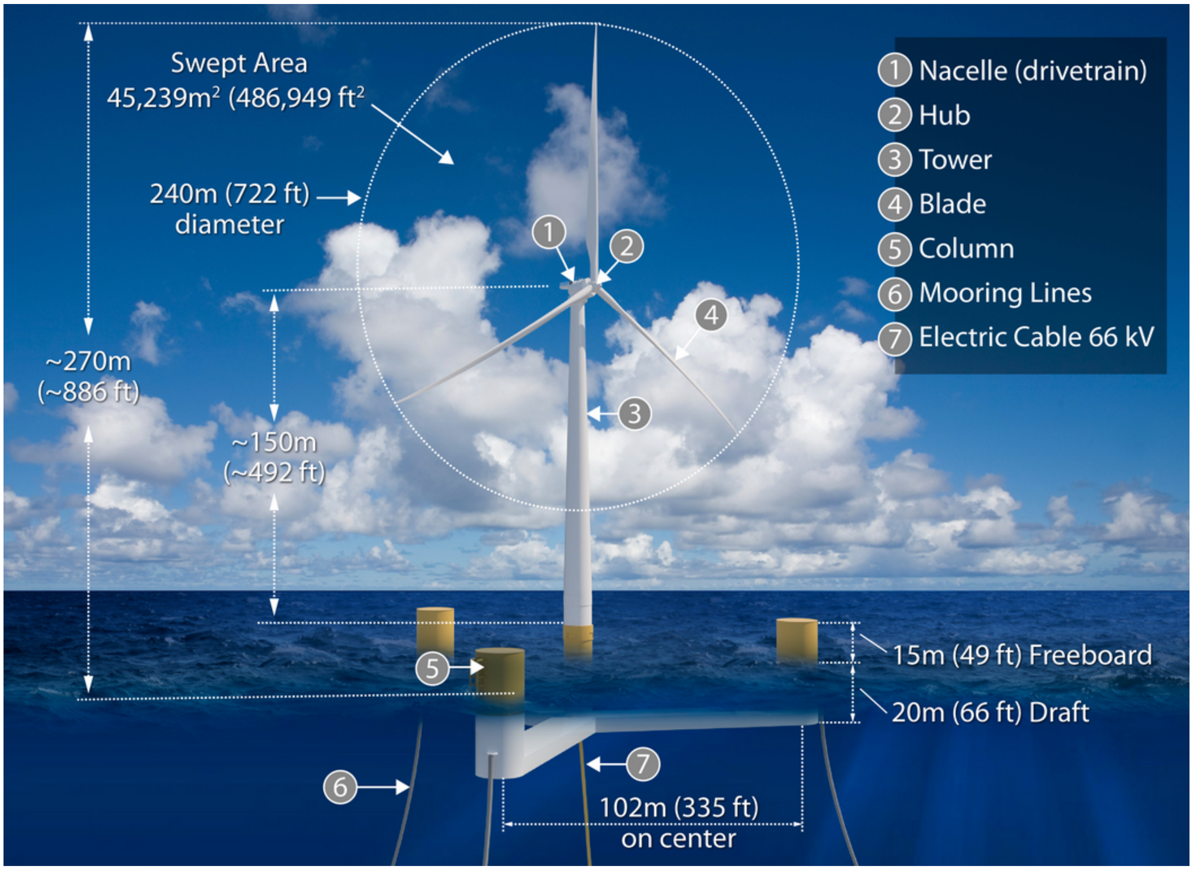

Figure 15. Representative offshore wind turbine technology assumptions for 2030. ***Illustration by Joshua Bauer, NREL***

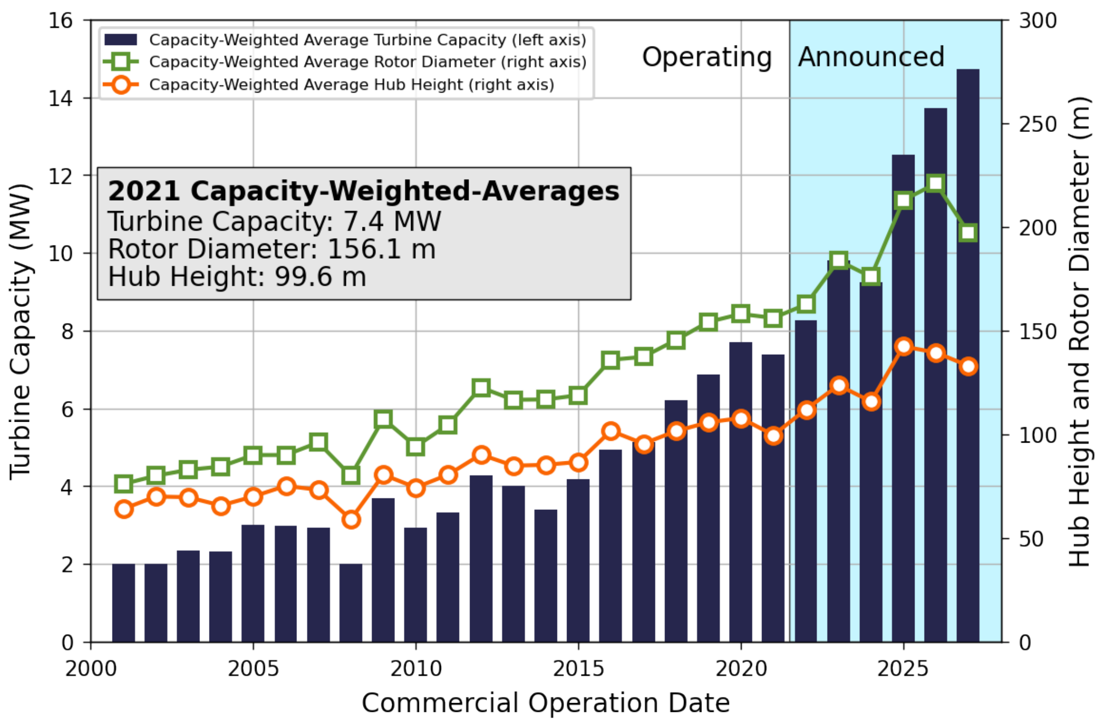

Figure 16. Comparison of offshore wind turbine prototypes with commercial offshore turbine growth. ***Image reproduced from Musial et al. (2022)***

Offshore Wind Substructures

The substructures used to attach offshore wind turbines to the seabed are critical to a wind farm's design, and can be a significant contributor to the overall project cost. They fall into two broad categories: fixed-bottom and floating substructures, with the main distinction being that fixed-bottom substructures are rigidly attached to the seabed and floating substructures are connected to the seabed with mooring lines and anchors. The current maximum cost-effective water depth for fixed-bottom substructures is estimated at around 60 m, beyond which the amount of material required becomes cost-prohibitive. NREL estimates the current cost-effective water depth limit for floating substructure technologies is around 1,300 m, but does not represent a hard technology limit (Beiter et al. 2020; Musial et al. 2021a; Shields et al. 2021b). Industry practitioners agree that floating wind systems in deeper waters beyond 1300-m are technically feasible provided the seabed slopes are not steep, and that the primary issue to moving into deeper water would be cost. Note that floating offshore wind technologies —including mooring system designs—are developing rapidly. The announced Central Atlantic Call Areas include areas with depths of up to 2,600 m. Figure 17 shows the assumed substructure technology (fixed-bottom vs. floating) based on water depth around Puerto Rico.

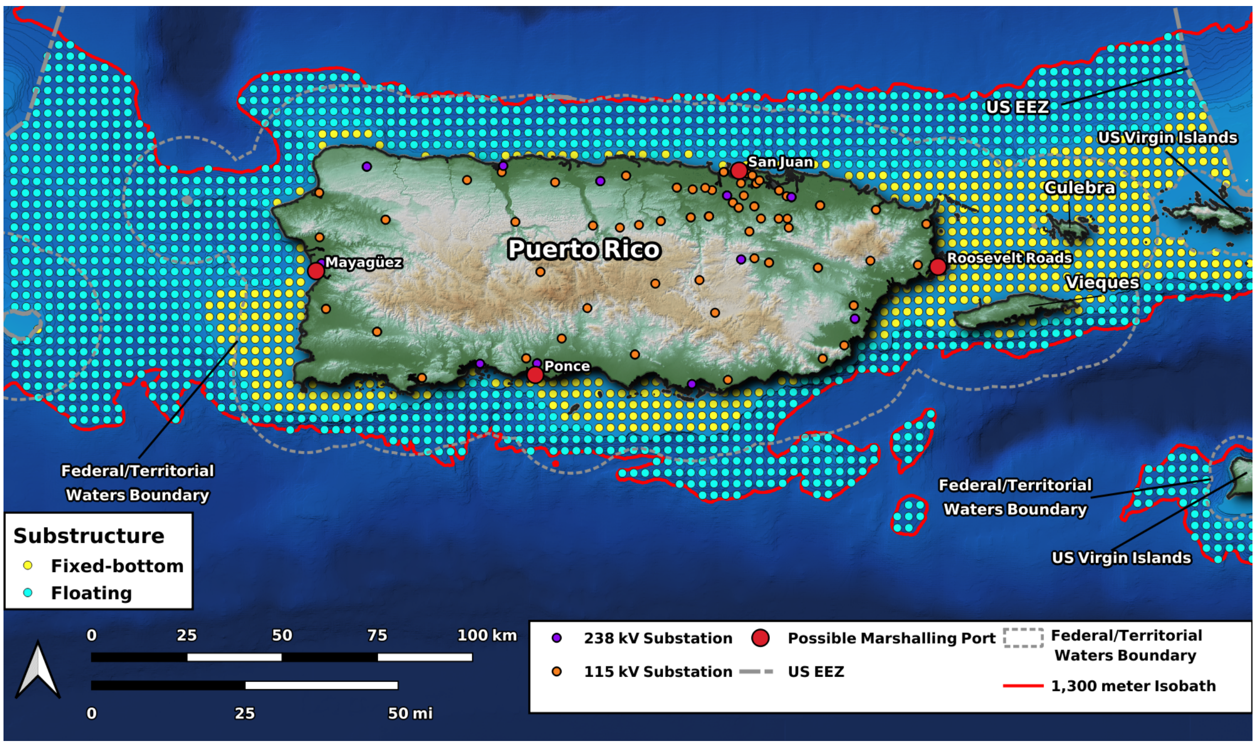

Figure 17. Fixed-bottom and floating wind resource points shown based on water depth. Fixed-bottom substructure are used in waters with depths between 5-m and 60-m, while floating substructures are used between 60-m and 1,300-m.

The most common foundation type to date is the monopile, representing more than 65% of installed capacity and 57% of announced foundation choices for offshore wind energy projects (Musial et al. 2022). A monopile is a long, cylindrical, fixed-bottom structure that supports the wind turbine. In the United States, more than 58% of the total technical offshore wind resource is above waters with depths greater than 60 m, representing a significant opportunity for floating wind energy (Musial et al. 2016). There are three main branches of floating offshore wind substructures under development: the spar, semisubmersible, and tension-leg platform. Figure 18 illustrates some of the most common fixed-bottom and floating substructure technologies.

Cooperman et al. (2022) highlights the potential impact of mooring footprints, which increase with depth (and provide estimated mooring radii for 1,000-m depths and greater). Figure 19 illustrates the footprint for different floating substructures. The mooring lines are attached to anchors to prevent the floating substructure from drifting. Mooring lines and electric cables are located underwater. Different mooring technologies have different design and cost implications. Floating offshore wind technologies are developing rapidly.

Figure 18. Example fixed-bottom and floating offshore wind substructures from left: monopile, jacket, twisted jacket, semisubmersible, tension-leg platform, and spar buoy. ***Illustration by Joshua Bauer, NREL***

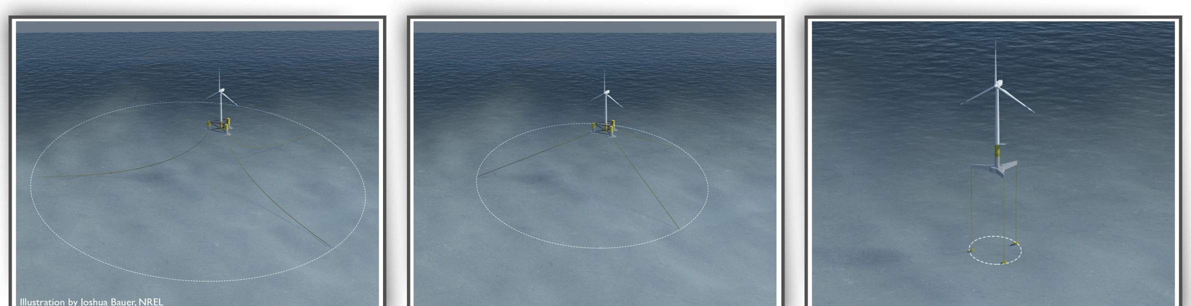

Figure 19. Floating offshore wind turbine mooring system footprint with mooring configurations from left: catenary, semitaut, and tension-leg platform. ***Illustration by Joshua Bauer, NREL***

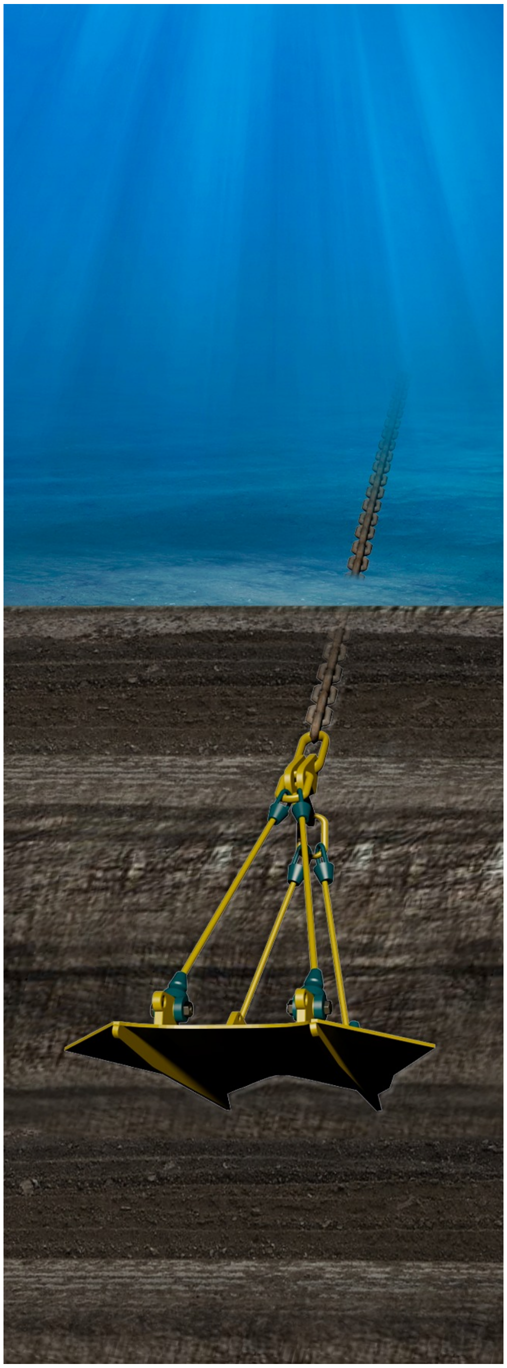

Figure 20. A drag embedment anchor. ***Illustration by Joshua Bauer, NREL***

4.3 Technology Assumptions

4.3.1 Land-Based Wind

We model land-based wind costs at three different COD years (2022, 2030, 2035) to capture the impacts of technology trends in the near, mid, and long terms. Cost reductions over time are primarily assumed to be driven by improved installation technologies that lower balance-of system (BOS) costs and increasing rotor sizes that capture more energy in lower wind speeds. Balance-of-system costs are capital costs incurred to install turbines at a wind power plant. As a baseline we assume Typhoon-Class turbines are required in Puerto Rico.

As 4.2-MW Typhoon-Class land-based wind turbines with a 117-m rotor diameter are already available, we assume this to be representative of the years 2022 and 2030. This rating falls withing the 3- to 6-MW range described earlier. In both 2030 and 2035, climbing cranes are assumed to be available for installation. Through innovations in blade technology, materials, and controls, we assume that rotor blade diameter on Typhoon-Class machines will increase in length (to 150 m) to allow for higher energy capture reflective of Class III machines currently available. Table 1 summarizes the land-based wind technology trajectory used to model performance and costs. Note that to demonstrate the impact of longer blades on energy capture, we include a sensitivity comparing a present-day Class III turbine to the baseline Typhoon-Class assumption for 2022.

Table 1. Land-Based Wind Technology Assumptions

Year	Turbine Rating	Rotor Diameter	Hub Height	IEC Wind Class	Erection Method
2022	4.2 MW	117 m	91.5 m	Typhoon Class	Crawler cranes
2022 (sensitivity)	4.2 MW	150 m	105 m	Typhoon Class	Crawler cranes
2030	4.2 MW	117 m	91.5 m	Typhoon Class	Climbing cranes
2035	4.2 MW	150 m	105 m	Typhoon Class	Climbing cranes

4.3.2 Offshore Wind

The selection of the wind turbine has a large impact on costs and performance of an offshore wind farm. We base the offshore wind turbine technology assumptions for 2030 on the IEA 15-MW reference wind turbine described in Gaertner et al. (2020). For 2035, we assume a turbine rating of 18-MW and scale up the rotor diameter, hub height, and power curve off the 15-MW reference turbine assuming a constant specific-power and rotor tip clearance with the mean sea level. This trajectory is conservative given announcements of prototypes in the 16-MW range, but Musial et al. (2022) indicate that it takes several years between the announcement of a new prototype, its installation and testing period, and the serial production phase. Again, we assume that Typhoon-Class wind turbines are required for Puerto Rico.

Table 2. Offshore Wind Turbine Technology Assumptions

Year	Turbine Rating	Rotor Diameter	Hub Height	IEC Wind Class	Source
2030	15 MW	240 m	150 m	Typhoon Class	Gaertner et al. (2020)
2035	18 MW	263 m	161 m	Typhoon Class	Scaled from Gaertner et al. (2020)

For fixed-bottom substructures, we model costs for monopiles because they are the dominant choice in existing offshore wind projects. Floating offshore wind projects are modeled assuming semisubmersible substructures with catenary mooring systems attached to drag embedment anchors. Ultimately, these choices will depend on a number of factors, including the site-specific water depth, soil conditions, slopes, and proximity to supply chains.

5 Infrastructure and Logistics

In this section, we describe the existing grid infrastructure as of summer 2022 and provide a high-level assessment of ports in Puerto Rico that may be able to support offshore wind installation activities.

5.1 Grid Infrastructure and Points of Interconnection

According to a resource adequacy study LUMA submitted to the PREB in August 2022 (LUMA 2022), the installed nameplate, front-of-the-meter generating capacity from thermal power plants in Puerto Rico is approximately 5,000 MW, without considering extended outages or unit deratings. Ninety-five percent of the operational capacity is from thermal generation stations (natural gas, oil, coal, diesel). The renewable generation fleet has a nameplate capacity of over 200 MW, and the behind-the-meter generation capacity is estimated to be 455 MW (mainly rooftop solar).

Figure 21 shows a map of existing power plants in Puerto Rico based on data from the Energy Information Administration (U.S. Energy Information Administration 2021). Figure 1 shows a current map of substations based on data provided by LUMA. Much of the existing generation capacity is located in the south, while most of the electricity demand is concentrated in the north, near San Juan.

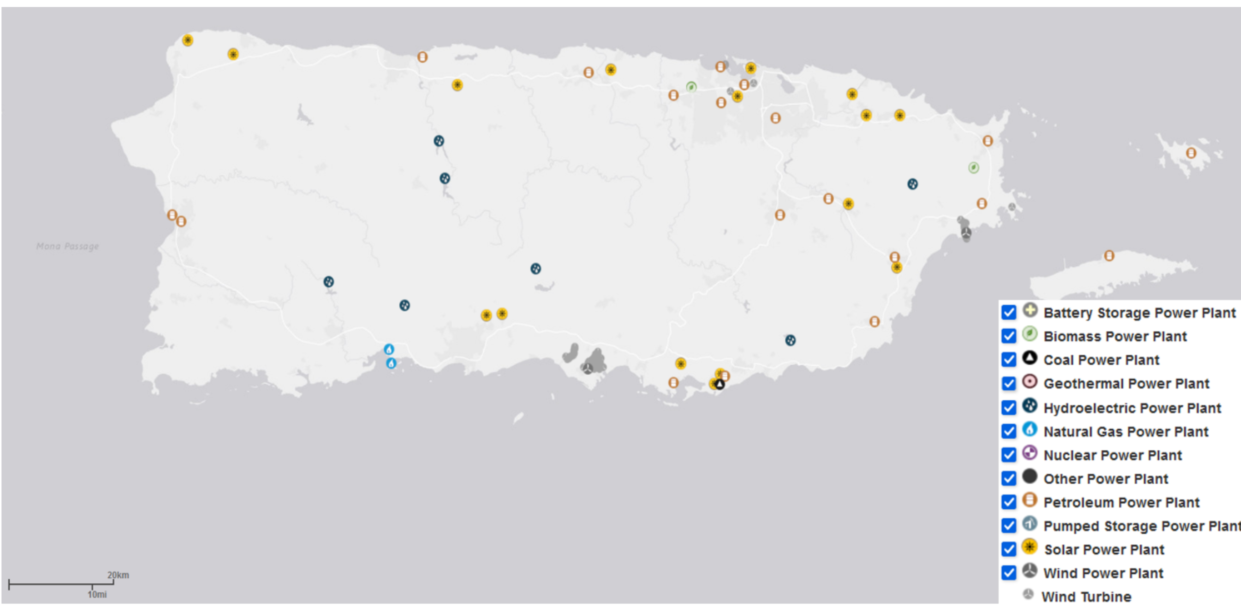

Figure 21. Map of existing power plants in Puerto Rico (U.S. Energy Information Administration 2021)

Based on forecasts for the 2023 fiscal year, electricity demand in Puerto Rico rises steadily over the course of the day and peaks in the evenings—driven primarily by residential air conditioning use (LUMA 2022). As a result, solar generation plants must be paired with energy storage to provide power during the evening peak. Higher temperatures in the summer and early fall lead to greater electricity use in those months. The peak demand in the highest load month (August) is estimated to be 2,960 MW (LUMA 2022). An earlier study by Gevorgian, Baggu, and Ton (2019) also found that the power system load in Puerto Rico ramps up in the evening before reaching a nighttime peak higher than any daytime peak.

Analyzing pathways to 100% clean electricity under different possible future demand scenarios will be a crucial part of the PR100 Study. Changes in weather due to climate change might alter electricity demand, as could widespread adoption of electric vehicles.

Although the grid infrastructure will certainly evolve between now and 2035, we use the current state of the grid to estimate transmission costs for land-based wind plants modeled in this study. The Renewable Energy Potential (reV) model (described in Section 6) identifies the nearest 115 kilovolts (kV) or greater substation for each modeled wind plant and calculates the cost to connect. For offshore wind, we include the costs of the export cable to shore, but do not include transmission interconnection costs. We do not capture upgrades to the bulk power system that may

Table 3. Minimum requirements for offshore wind fabrication and marshalling activities. Reproduced from Shields et al. (2022)

Parameter	Minimum Fixed-Bottom Value	Minimum Floating Value
Draft	6 m (feeder barge), 12 m (WTIV)	12 m (installation)
Air Draft	150 m	150 m
Laydown Area (Total)	25 acres	70 acres
Quayside Length	500 m	660 m
Bearing Capacity	15 tonnes (t)/square meter (m^2)	15 tonnes (t)/square meter (m^2)

be required, though further analysis of these dynamics will be conducted in the PR100 Study (including capacity expansion and production cost modeling).

5.1.1 LUMA Minimum Technical Requirements

As part of the IRP, PREPA established minimum technical requirements for interconnecting different generation resources to the power system in Puerto Rico. Integrating high percentages of variable renewable electricity generation poses several technical challenges, especially to an island grid. Puerto Rico is not subject to the same interconnection requirements the Federal Energy Regulatory Commission establishes for the continental United States, so PREPA established the minimum technical requirements to help with grid safety, reliability, and performance. NREL previously assisted with evaluating the PREPA minimium technical requirements and helped to update them based on technology advancements and changes to the grid (Gevorgian and Booth 2013; Gevorgian, Baggu, and Ton 2019).

LUMA developed the most recent minimum technical requirements for interconnecting wind energy generation projects are detailed in Appendix B. Requirements for wind (and solar) include specific ramp rates for powering plants up and down. This requirement means that both wind and photovoltaic systems need to be paired with a battery electrical storage system to connect to the grid. LUMA indicated that it is possible that future requirements may include a need to have grid-forming inverters. Both of these requirements will add costs that are not modeled here, but must be considered in the PR100 Study (U.S. Department of Energy 2022).

5.2 Offshore Wind Construction and Operations Ports

5.2.1 Physical Requirements for Offshore Wind Ports

Ports are crucial infrastructure for developing wind energy projects. With rotor blades as long as 115.5 m for a 15-MW turbine, offshore wind component sizes and weights place demanding requirements on ports supporting construction. Many offshore wind turbine components are too large for road or rail transport, so they are assembled in factories next to the water before being staged and loaded by cranes onto specialized wind turbine installation vessels (WTIVs) for fixed-bottom projects or assembled and towed out from the quayside for floating projects. Marshalling ports used for staging the components typically have the most demanding physical requirements of any stage in an offshore wind project. Stefek et al. (2022) shows that much of the job creation associated with offshore wind energy is concentrated in and around ports.

A recent NREL analysis (Shields et al. 2022) of the domestic offshore wind supply chain in the United States presents ranges of the physical characteristics required of ports during the marshalling/installation phase in an offshore wind project. These characteristics are reproduced in Table 3.

Draft (water depth) should be large enough for vessels to safely enter and exit the port and load components at the quayside. For floating offshore wind turbines, the water depth requirements are driven by the draft of the floating substructure after the turbine has been attached. An air draft (overhead limit) is the minimum required clearance from the surface of the water, which could be impacted by bridges or aviation. This limit is driven by the height of components transported on vessels for fixed-bottom projects and the height of the turbine mounted on the substructure for floating projects. Laydown area is the area of the port available for storing, maneuvering, or assembling wind turbine subcomponents.

According to Shields et al. (2022), a commercial-scale offshore wind energy project would ideally have access to a laydown area of 50–70 acres. Conversations with industry partners revealed that using smaller areas may not prevent a project, but could result in installation delays. The trend of growing turbine size highlighted in Section 4 could further increase the demand for space if it continues. Quayside length impacts how many vessels can access the port at a given time. Ideally, there should be at least two berths along the quayside: a delivery berth to receive components, and a second "export berth," where the turbine will leave port for installation on-site. Lastly, due to the weight of some components, the quayside and or laydown area should have sufficient load-bearing capacity to support lifting components with cranes. Other physical constraints may include crane-lifting capacity or dry-dock availability, depending on the substructure type and installation strategy. Note that the 70 acres of laydown area and 660 m of quayside length recommended in Table 3 for floating projects includes separate floating substructure assembly, turbine installation, and mooring system marshalling zones for increased installation efficiencies.

5.2.2 High-Level Assessment of Puerto Rican Ports

Puerto Rico's existing port infrastructure predominantly serves cruise ships, cargo ships, ferries, and recreational vessels. In order to determine which Puerto Rican ports may be able to support future offshore wind installations, we compiled a list and filtered it using publicly available data on water draft, air draft, laydown area berth length, and bearing capacity. We presented the public data in discussions with the Puerto Rico Ports Authority, Puerto Rico Industrial Development Company, and Roosevelt Roads Local Redevelopment Authority, who helped identify the three most likely candidate ports: the Port of Ponce, Roosevelt Roads Naval Station, and the Port of Mayagüez. Table 4 summarizes the results of this high-level ports assessment. A more rigorous technical analysis of port specifications and capabilities, as well as upgrade costs, should be conducted to inform the development of future renewable energy projects. Note that bearing capacity was hard to obtain from public data or initial conversations with port representatives.

Table 4. Summary of port characteristics

Port Name	Draft (m)	Air Draft (m)	Laydown Area (acres)	Total Berth Length (m)	Number of Berths	Bearing Capacity (t/m^2)
Port of Ponce[1]	7.1-15	No limit	NA	613	2	NA
Roosevelt Roads[2]	9.4-13.7	No limit	10	354	3	NA
Port of Mayagüez[3]	7.1	No limit	NA	410	1	NA

[1] Data from (hyperlinks): i, ii, iii, iv, v.
[2] Data from (hyperlinks): i, ii.
[3] Data from (hyperlinks): i, ii, iii.

Port of Ponce

The Port of Ponce (Rafael Cordero Santiago Port of the Americas) is close to the best offshore wind resources around Puerto Rico (Figure 2). It has relatively low maritime and air traffic as well as space to develop a project. There is interest in further developing port infrastructure for cruise ships and cargo vessels (Department of Economic Development and Commerce, n.d.[b]). Further, the land-based Punta Lima Wind Farm used the port of Ponce to import wind turbine blades (Foss Maritime Company, n.d.).

Roosevelt Roads

Local Redevelopment Authority for Roosevelt Roads is in charge of redeveloping 3,400 acres of the former naval base (Department of Economic Development and Commerce, n.d.[a]). Existing development plans focus on the design of a Marine Business, Research and Innovation Center and attracting the nautical tourism industry (The San Juan Daily Star 2022). Plans for the waterfront include a solar energy microgrid, water treatment and drinking water facilities, a sanitary plant, building and road improvements, and a mega yacht marina. Some infrastructure upgrades will be funded by Federal Emergency Management Agency grants as well as a combination of other public and private funding sources in the wake of damage during Hurricane Maria (Kantrow-Vázquez 2021). Roosevelt Roads has space to develop a project and access to some of the best offshore wind resources around the island, though there could be competition for areas with some of the existing development plans.

Port of Mayagüez

The Puerto Rico Industrial Development Company developed the industrial area at the Port of Mayagüez in the 1960s. It was damaged by Hurricane Maria and the Federal Emergency Management Agency is funding major repair work, although the work has progressed slowly (Pacheco 2022). The Port of Mayagüez has access to deep waters in the Mona Channel, but may be constrained by Puerto Rico Highway 64.

Notable Exclusions

It is worth noting that the largest port, the Port of San Juan, is congested with shipping vessel traffic, so we included a sensitivity in the cost analysis. Specifically, the port is dominated by container and leisure vessel traffic, as well as air traffic. There are natural reefs and flood control systems that further constrain the congested space. Puerto Nuevo also has high commercial maritime and air traffic.

Overall, locating laydown area with sufficient bearing capacity appears to be the main challenge as other industries and planned infrastructure projects compete for space. Depending on the type of substructure and the method of installation used, the ports listed in Table 4 above will likely require upgrades to support offshore wind energy projects. Although we do not assess the specific upgrades required at each, it is likely based on the data presented in Table 4 that dredging would be needed to install fixed-bottom substructures with specialized wind turbine installation vessels or floating substructures. As the demands on ports supporting the operations and maintenance activities are often less stringent than the marshalling and installation, we assume that operations and maintainence (O&M) ports are co-located with the installation ports. Each offshore wind plant modeled is installed and maintained from the nearest port considered, as costs for each site depend on the distance to port.

In the cost calculations we do not include costs to upgrade existing ports or construct new ports, because these costs are typically recovered through port rental fees to whichever industries use it. We do include a capital cost line item to account for the rental of the port facilities during the construction phase, and this cost varies with the project site distance from the port to account for additional installation time. We also assume additional component transport costs for importing the major components of the wind farm (see Section 6 for details). Note that this initial assessment is only to indicate which ports in Puerto Rico might be capable of supporting wind energy projects. We did not investigate the possibility of shared infrastructure with neighboring islands or other parts of the Caribbean. Delays or bottlenecks could result from staging projects out of suboptimal ports.

6 Modeling Approach

To calculate the techno-economic potential for both land-based and offshore wind energy around Puerto Rico, we used a cost modeling pipeline centered on the Renewable Energy Potential (reV) model (Maclaurin et al. 2021). We used the most up-to-date wind resource data for Puerto Rico and customized assumptions for the unique conditions in the region including hurricane risks and transportation costs. reV coordinates outputs from several other models to generate a field of possible wind power plants at all locations considered to be technically feasible for wind deployment. Accounting for the cost impacts of spatial parameters at each site, such as bathymetry, topography, and wind resource data generated by Task 1 (see Section 3), we used this modeling pipeline to estimate the total potential generation capacity, CapEx, OpEx, time series of hourly generation, and LCOE. Time-series outputs were then aggregated into average annual energy production (AEP) at each point in the analysis domain. Note that policy incentives and bulk power system upgrade costs are not included in this analysis. This section first provides an overview of the modeling pipeline and each model used before outlining technology-specific (land-based and offshore wind) modeling and financing assumptions.

6.1 Modeling Pipeline Process

The reV model combines wind resource data, technology assumptions, land or water use, and transmission infrastructure data sets with cost relationships to calculate LCOE at each location within the analysis domain using Eq. 6.1 from Short, Packey, and Holt (1995):

$$
\begin{aligned}
LCOE &= 1000 \times \frac{FCR \times C_{CapEx} + C_{\text{OpEx}}}{AEP_{net}}, \\
&= 1000 \times \frac{FCR\,(C_{\text{Turbine}} + C_{\text{BOS}}) + C_{\text{OpEx}}}{AEP_{net}},
\end{aligned}
\tag{6.1}
$$

where $LCOE$ is the levelized cost of energy (in dollars per megawatt-hour [$/MWh]), FCR is the fixed charge rate (%/year), C_{CapEx} represents the total capital expenditures (dollars per kilowatt [$/kW]), C_{Turbine} are the total turbine capital expenditures ($/kW), C_{BOS} are the balance of system capital expenditures ($/kW), C_{OpEx} are the operational and maintenance costs ($/kW-year), and AEP_{net} is the net average annual energy production (MWh/year).

LCOE represents the cost of each unit of energy produced over the lifetime of a project, and can be helpful for comparing costs between different energy generation technologies (see: National Renewable Energy Laboratory 2022a; Lazard 2021). Care must be taken when doing so because LCOE does not capture the value of different generation profiles (how these align with demand and other available forms of generation). It is similar to net present value in the sense that future costs are discounted to a base year, but LCOE does not consider forms of revenue for a project and costs are normalized by the project's average annual AEP over its financial life. As such, the LCOE data presented in this report help understand the cost of wind energy. Quantifying the full value of wind energy in Puerto Rico requires further modeling and optimization of the whole electric system under a range of scenarios, which the PR100 Study will develop based on these cost data. Note that we report the unsubsidized LCOE and not account for tax credits which may be available. This means that LCOE cannot be compared directly with electricity prices (Beiter et al. 2019).

The reV modeling pipeline accounts for site-specific conditions and potential use conflict areas when calculating CapEx, OpEx, and AEP. A potential use conflict layer of areas where wind energy development is not likely due to either regulatory restrictions, competing uses, or physical barriers is developed to prevent the model from placing turbines in those locations. This overall modeling process is summarized in Figure 22, which depicts the models in the pipeline and the flow of data required to calculate LCOE. Descriptions of each model in the pipeline are provided in the subsequent sections.

For land-based wind, we derived input CapEx costs from NREL's Land-based Balance of System Systems Engineering (LandBOSSE) (Eberle et al. 2019) and OpEx costs from the 2021 Annual Technology Baseline (National Renewable Energy Laboratory 2021a). Offshore wind energy requires additional inputs to account for the added complexity in capturing costs. Site-specific offshore wind costs are calculated with reV using the spatial cost relationships in the National Renewable Energy Laboratory Wind Analysis Library (NRWAL) (Nunemaker et al. 2021).

The reV model has an input of wind turbine technology and associated costs, wind resource data, and losses assumptions to calculate AEP, which we express in terms of net capacity factor (NCF), or the fraction of the year the plant needs to operate at its rated capacity to generate an equivalent amount of energy. It uses the System Advisor Model (SAM) to simulate generation time series at every point in the study area. Land-based wind energy relies on SAM to compute NCF values, which accounts for a fixed set of electrical losses. Offshore, the gross generation time series are passed to NRWAL, which computes total losses and NCF based on the methodology outlined in Beiter et al. (2016), where site-specific wake losses are calculated with NREL's FLOW Redirection and Induction in Steady State (FLORIS) wake modeling toolbox.

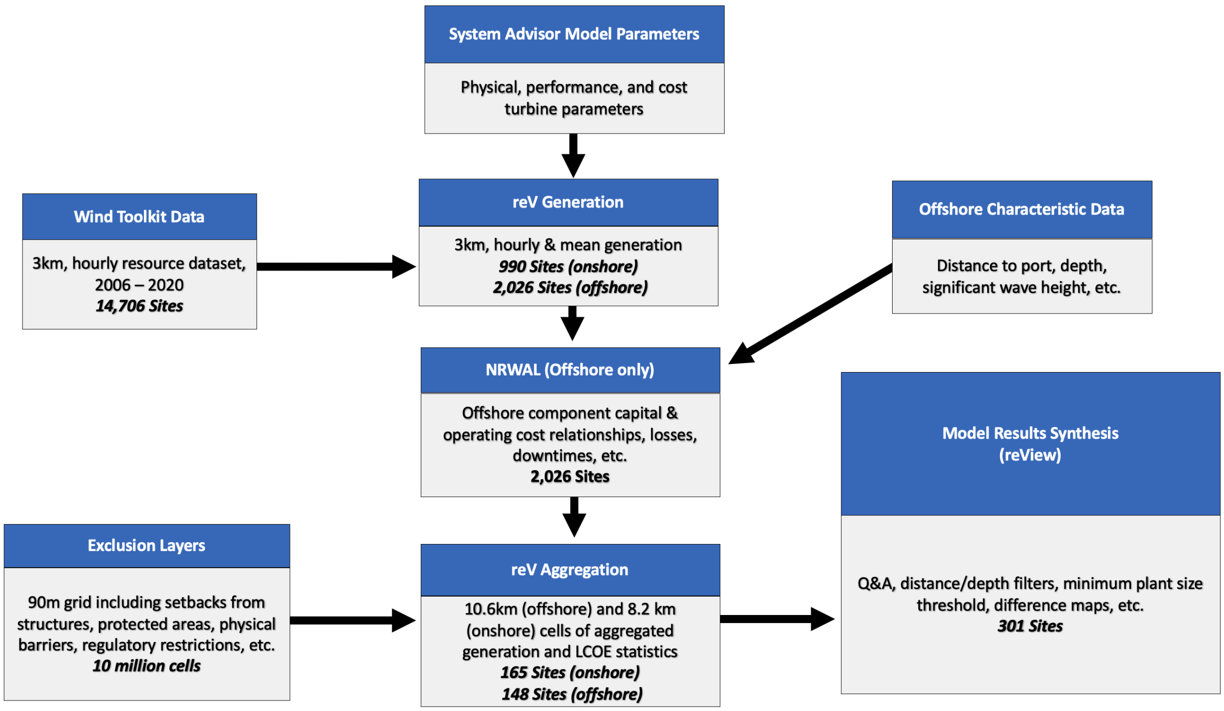

Figure 22. Summary of the reV modeling pipeline

6.1.1 Renewable Energy Potential Model

The reV[2] model is split into two submodules: reV-Generation and reV-Aggregation (Maclaurin et al. 2021). reV-Generation coordinates with SAM to translate wind resource data into generation values that are used to estimate initial LCOE values at every available resource point. reV-Aggregation aggregates the 4-km^2 generation time series and LCOE values into larger areas that represent individual wind farms (in this case, 66.7 km^2 for land-based and 200 km^2 for offshore). reV calculates costs everywhere in the domain, but uses a 90-m grid for potential land- or water-use conflict areas to exclude areas where wind energy development may not be physically or legally possible (e.g., terrain slopes, existing infrastructure, protected areas, and military areas). Final capacities are derived using an assumed capacity density of 3 MW/km^2 after potential use conflict areas are accounted for, which is in line with previous modeling for the United States (Lopez et al. 2021; Musial et al. 2016). Capacity density expresses how much wind power capacity is located in a given area, and it results from the wind turbine generator rating and spacing between turbines. Higher capacity densities increase the total generation potential, but may also lead to greater wake losses.

6.1.2 System Advisor Model (SAM)

SAM[3] is a techno-economic energy production model used to develop time series of generation estimates and LCOE values for a given time series of resource data and technology (Blair et al. 2018). SAM is used as a submodule in reV to calculate site-specific generation profiles and NCF values for land-based wind sites.

[2] Access reV: https://www.nrel.gov/gis/renewable-energy-potential.html.
[3] Access SAM: https://sam.nrel.gov/.

6.1.3 LandBOSSE

To model the BOS costs for land-based wind power plants, we use NREL's LandBOSSE[4] model (Eberle et al. 2019; Key, Roberts, and Eberle 2022). LandBOSSE calculates BOS costs in eight modules that follow different scopes of work for constructing a land-based wind plant (e.g., construction costs associated with erection, foundations, grid connection, site preparation, management, development, collection system, and substation). Input parameters to the model include plant size, turbine rating, hub height, and labor and equipment costs. LandBOSSE outputs itemized costs for each scope of work as well as the total BOS cost for a particular plant.

6.1.4 NRWAL

To estimate how offshore wind capital and operations and maintenance costs vary as a function of turbine rating, plant capacity, and geospatial parameters (e.g., water depth, distance to port, and distance to cable landfall), we use the NRWAL[5] model (Nunemaker et al. 2021). NRWAL is an open-source version of NREL's Offshore Regional Cost Analyzer (ORCA) model (Beiter et al. 2016) designed to be easy to update based on current offshore wind cost trends and local conditions. The NRWAL/ORCA framework of offshore wind spatial cost relationships has been used for regional offshore wind cost assessments in Hawaii, Oregon, California, Maine, and the Gulf of Mexico (Shields et al. 2021b; Musial et al. 2021a; Beiter et al. 2020; Musial, Beiter, and Nunemaker 2020; Musial et al. 2020).

6.1.5 FLORIS

NREL's FLORIS[6] includes Python-based engineering analysis tools for wind turbine wakes in a wind farm National Renewable Energy Laboratory 2022c. We use FLORIS v3.1 to analyze site- and technology-specific wake losses at all offshore points in the study domain. The wake loss estimates are combined with other energy losses in NRWAL to calculate the net NCF. We assumed a square grid layout with 7 rotor diameters of spacing between each wind turbine.

6.2 Land-Based Wind Costs

The land-based wind modeling follows the workflow depicted in Figure 22, excluding NRWAL and offshore data inputs. We use reV-Generation with the turbine costs from LandBOSSE along with OpEx costs from the Annual Technology Baseline and turbine power curves to create generation profiles and site-based LCOE estimates. We then use reV-Aggregation to scale up the costs to wind power plant levels and account for potential use conflict areas.

6.2.1 Cost Modeling: LandBOSSE

As highlighted by Eq. 6.1, the sum of wind turbine capital costs ($C_{Turbine}$, or turbine CapEx) and BOS make up the total capital expenditures of purchasing turbines and installing them at a land-based wind power plant.

To model turbine CapEx and component masses—which include the costs and masses of the tower, rotor, and nacelle—we used the NREL Cost and Scaling Model (CSM) (*Wind turbine design cost and scaling model*). The CSM is open source and part of the NREL Wind-Plant Integrated System Design & Engineering Model (WISDEM®) software collection.[7] The CSM takes specifications of a wind turbine (e.g., rotor diameter, hub height, turbine rating in kW, IEC wind class) and estimates component masses and costs based on scaling relationships.

Table 5 describes what is covered in the costs calculated for each work scope. LandBOSSE uses the wind turbine component masses obtained with the CSM to choose cranes and, from those choices, to calculate turbine erection cost. Input parameters to the model (e.g., plant size, turbine rating, hub height, labor and equipment costs) are used to estimate the BOS costs. Foundation cost is reflected in the BOS costs. For Typhoon-Class turbines, we adjusted the cost of the foundation in LandBOSSE input data to match the needs of those turbines.

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[4] Access LandBOSSE: https://github.com/WISDEM/LandBOSSE.
[5] Access NRWAL: https://github.com/NREL/NRWAL.
[6] Access FLORIS: https://github.com/NREL/floris.
[7] Access WISDEM: https://github.com/WISDEM/WISDEM.

Table 5. Summary of costs included in the LandBOSSE model. (Reproduced From Key, Roberts, and Eberle (2022))

Module	Summary of Costs Included
Foundation	Operations specific to foundation construction, including excavating the base; installing rebar and a bolt cage; pouring concrete; constructing the pedestal; and backfilling the foundation
Erection	Operations specific to erecting the tower and turbine, including removing components from delivery trucks by offloading cranes and erecting the lower tower sections onto the foundation using a base crane and the upper pieces of the tower and the components of the nacelle using a topping crane
Development	Evaluating the wind resource; acquiring the land; completing environmental permitting; assessing distribution costs; and marketing the power to be generated
Management	Obtaining insurance and construction permits; arranging site-specific engineering; constructing facilities for site access and construction staging; managing the site; and providing bonding, markup, and contingencies
Collection	Operations specific to constructing a collection system, which consists of cabling from the wind turbines to the substation (does not include power electronics or cabling already included in the turbine CapEx)
Grid connection	Operations specific to grid connection (i.e., transmission and interconnection), including conducting a land survey; clearing and grubbing the area; installing stormwater and pollution mitigation measures; installing conductors; and restoring the rights of way
Site preparation	Operations to prepare the wind power plant site for other construction operations, including surveying and clearing areas for roads; compacting the soil; and placing rock to allow roads to support the weight of trucks, components, and cranes
Substation	Operations specific to constructing the substation, including conducting a land survey; installing stormwater and pollution mitigation measures; constructing dead-end structures, foundations, conductors, transformers, relays, controls, and breakers; and restoring the rights of way

Economies of Scale

Larger wind power plants benefit from economies of scale because fixed equipment mobilization costs are spread across a greater number of wind turbines. For each year in the land-based wind technology pathway outlined in Table 1, we combine the turbine CapEx estimates from the CSM and BOS costs from LandBOSSE to generate an economies-of-scale curve for plant capacities between 10 and 400 MW. Because the baseline land-based wind costs are calculated for a 200-MW plant, each curve is normalized by the respective costs at this size to yield a scaling factor of 1. Figure 23 highlights the resulting impact of plant scale on total CapEx. Once potential use conflict areas are taken into account, the economies-of-scale CapEx multipliers are applied in the reV-Aggregation step to yield CapEx for the available plant capacity after potential use conflict areas.

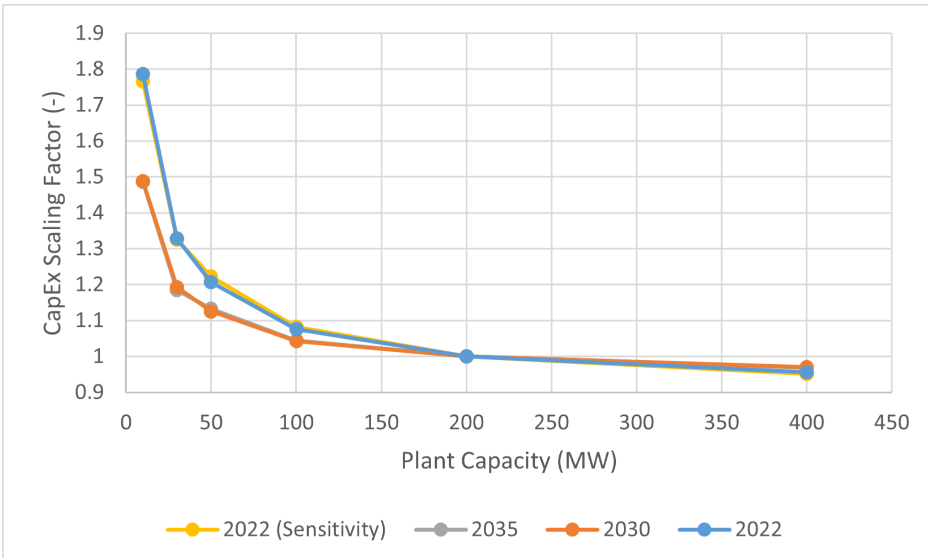

Figure 23. Land-based CapEx scaling factors for economies of plant size

6.2.2 Annual Energy Production

We used SAM to compute generation profiles based on the wind resource, assumed turbine technology (see Table 1), and energy losses. We used a constant loss assumption of 16% for modeled land-based wind plants. The generation profiles and costs from SAM are scaled to the appropriate wind plant capacity to account for the available area after excluded potential use conflict areas. Figure 24 presents the representative power curves for the 4.2-MW wind turbines, which are normalized by their rating. The power curves are assumed to be the same for different IEC wind classes with a given rotor diameter.

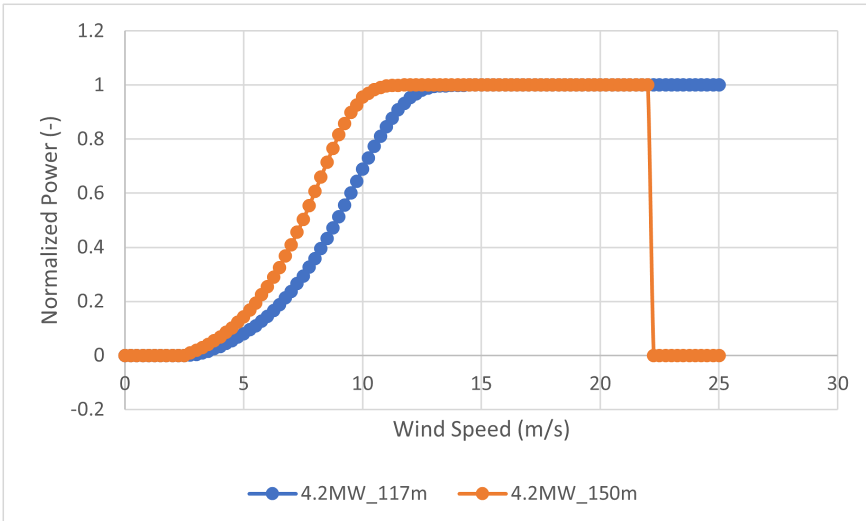

Figure 24. Land-based power curves used for energy yield calculations

6.2.3 Cost Projection Methodology

Changes in land-based wind energy costs over time are driven primarily by the assumed technology trajectory defined in Section 4. Table 6 summarizes the primary technology changes and their impacts on costs.

Table 6. Assumed evolution of land-based wind technology over time

Parameter	Rationale	Impact
Crane specifications	Crawling cranes used in 2022 replaced by climbing cranes in future years to reduce crew, mobilization times, and weather delays (Key, Roberts, and Eberle 2022)	Lower BOS from reduced installation costs
Rotor diameter	Increasing rotor diameter mirrors historical land-based trends (Wiser et al. 2021a)	Higher NCF from larger rotors that capture more energy at low wind speeds
Turbine class	Typhoon-Class wind turbines with larger rotors assumed available by 2035 based on improved blade designs and controls, expansion to new markets	Increased NCF from enabling larger rotors
Hub height	Increasing hub height mirrors historical land-based wind energy trends (Wiser et al. 2021a)	Higher NCF from accessing better winds higher up

6.2.4 Literature Cost Estimates

Figure 25 shows how LCOE of land-based wind energy has declined rapidly over the past two decades for a number of reasons. Land-based turbine costs have decreased as a result of standardization and modularization in turbine design and serial manufacturing (Barla 2019, 2021). Modularization allows multiple turbine variants to be assembled from a core collection of modules. These modular variants can be customized as needed without incurring higher supply chain costs associated with custom components. Operating expenses for wind plants have dropped as increases in turbine ratings means that fewer turbines need to be maintained for a given power plant size (Wiser et al. 2021a).

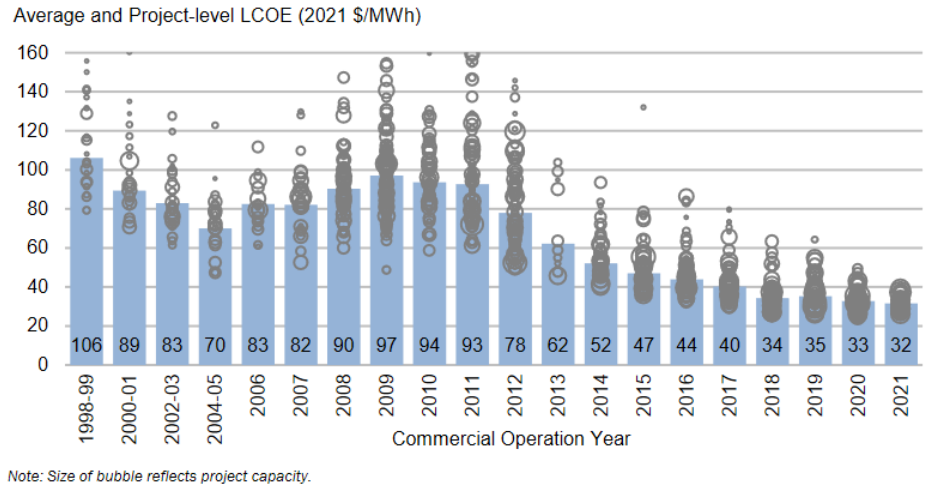

Figure 25. Historical LCOE data for land-based wind in $2021/MWh. ***Figure reproduced from Wiser et al. (2022) with permission.***

Wind turbine design lifetimes have increased as the industry has matured and techniques to manufacture and maintain turbines with a 30-year life span have emerged, as shown in Figure 26 from Wiser and Bolinger (2019). Note that we assume a 25-yr project lifetime in the calculation of the financing terms for LCOE, which may be conservative. Finally, wind power plants that use increasingly common low-specific-power turbines operate at a higher capacity factor in regions with lower average wind speeds (Bolinger et al. 2021).

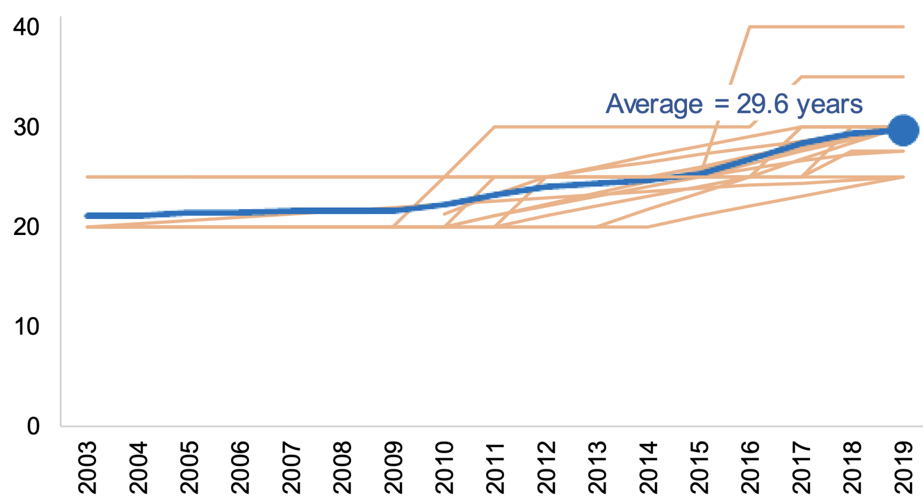

Figure 26. Historical useful life of land-based wind turbines. ***Figure reproduced from Wiser and Bolinger (2019) with permission.***

6.2.5 Potential Use Conflict Areas

In modeling land-based wind costs, we account for some potential use conflict areas, or areas that are not legally, technically, or physically suitable for wind development, as outlined in Table 7 and shown in Figure 27. **This is not a comprehensive list, and decisions around suitable wind energy areas should be made in Puerto Rico with broad stakeholder and community engagement.** For this initial cost study, the intent is to highlight the challenges of spatial planning considering only the most basic nondevelopable areas, such as existing land structures and water bodies, as well as protected areas and areas infeasible to development due to topography. Given the size of Puerto Rico, this relatively "open access" scenario helps better understand the maximum wind energy potential if all available area is utilized. With this in mind, the potential use conflict areas did not include any setbacks (for example, minimum distance from buildings). In the continental United States, setback requirements are often set by local and regional governments. This "open access" scenario, Figure 27 highlights the how spatially constrained wind energy development in Puerto Rico could be, even before accounting for additional spatial constraints. It is possible that offshore wind development could help mitigate some of these challenges, while also presenting a different set of planning challenges.

Spatial data sets are sourced primarily from the U.S. Geological Survey (USGS) and Humanitarian OpenStreetMap Team (HOTOSM). It is possible that potential use conflict areas layers from these sources are incomplete, but this data set has been shared with the PR100 stakeholder advisory group for review. There are ongoing discussions with stakeholders as to whether additional types of land use, such as habitats of particular species of concern [8], should be excluded from consideration in the PR100 Study. However, these areas are often determined by multiple stakeholder groups that may have differing views on what is considered suitable for development. Therefore, the potential use conflict areas used for this study should be considered provisional, and are only a start to understanding spatial constraints and challenges to meeting Puerto Rico's 100% renewable energy goals.

Table 7. Land-Based Wind Potential Use Conflict Areas

Potential Use Conflict	Explanation	Source
Slope >13%	Construction difficult (limited access)	USGS National Elevation Dataset
Water bodies	Cannot build land-based wind in water	USGS National Hydrology Dataset
Protected areas	No development in protected areas	Protected Areas Conservation Action Team
Buildings	Cannot build on existing buildings	HOTOSM
Transmission infrastructure	Cannot build on existing transmission	LUMA
Roads	Cannot build on roads	HOTOSM
Airports and runways	Cannot build on airports	HOTOSM

[8] Online interactive map of possible potential use conflict area layers: https://nrel.carto.com/u/gds-member/builder/c2fde0d4-b73e-4e23-bd1a-2bece6534d2a/embed

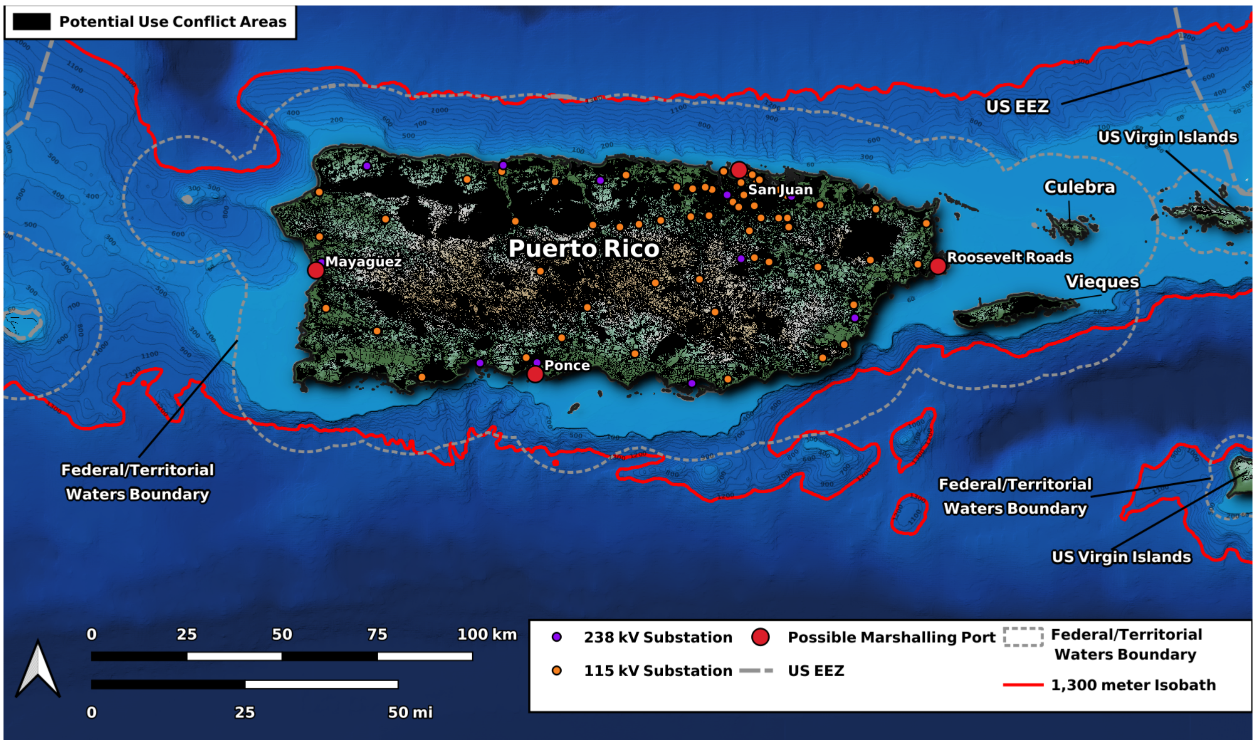

Figure 27. Map depicting the potential use conflict areas (blacked-out areas) used in the land-based wind modeling pipeline

6.3 Offshore Wind Energy Costs

The offshore wind energy modeling follows the workflow depicted in Figure 22. The primary difference from the land-based workflow is that the NRWAL module is used to calculate site-specific offshore wind energy costs as a function of spatial variables (including wind resource) and the technology choices. We assumed that fixed-bottom substructures are used in areas with water depths less than 60 m, and that the remaining sites up to a 1,300-m depth rely on floating substructures (see Figure 17). The NRWAL module is coupled with NREL's FLORIS model to calculate energy production and losses (such as wake, electrical, and environmental losses). Future costs are driven by a CapEx learning rate derived from market data as well as the assumed technology evolution described in Section 4. Each of the modeling tools used for the major components of LCOE (see Eq. 6.1) are presented in Table 8.

Table 8. Modeling tools informing offshore wind energy cost analysis

Cost Component	Model	Source
Wind Resource Data	Modeled with WRF	Task 1 based on Optis et al. (2020)
CapEx, OpEx, LCOE	NRWAL/reV	National Renewable Energy Laboratory (2022f), Beiter et al. (2016), and Maclaurin et al. (2021)
Wake Losses	FLORIS	National Renewable Energy Laboratory (2022c)
Additional Losses	NRWAL	National Renewable Energy Laboratory (2022f) and Beiter et al. (2016)
Future Costs	NRWAL/FORCE	Shields, Beiter, and Nunemaker (forthcoming)

Note: FORCE is NREL's Forecasting Offshore wind Reductions in Cost of Energy tool.

6.3.1 Cost Modeling: NRWAL

Each term in Eq. 6.1 is broken down into the major subsystems or line items needed to install and operate an offshore wind energy farm. NRWAL models the costs for each of these items using a combination of spatially dependent, spatially independent, and cost multiplier approaches. Spatially dependent costs change from site to site (e.g., installation costs are a function of the distance from a project to the closest port). Spatially independent variables are held constant throughout the analysis domain (e.g., turbine cost, financial assumptions, site auction fee). Lastly, variables modeled using cost multipliers are assessed as a function of other project costs (e.g., construction insurance, contingencies, and decommissioning costs). The NRWAL model contains the equations representing these relationships, which are regularly updated based on public market data, bottom-up modeling studies, and industry feedback and review. A summary of the major line items and how they are derived is provided in Table 9. An input-output flow diagram for NRWAL is provided in Figure 28 based on Shields et al. (2021b). NRWAL assumes a standard rate of $1,300/kW for the wind turbine procurement cost (e.g., blades, tower, and nacelle assembly). While the procurement costs for offshore wind turbines have been relatively constant over time on a per-kilowatt basis, recent high levels of inflation and price pressures impacting turbine manufacturers may influence this (Musial et al. 2022).

NRWAL requires a data set of physical offshore characteristic layers for each model site. This data set includes water depth (NOAA National Geophysical Data Center 2006), distance to the export cable landfall near the point of interconnection, and significant wave height (available here), as well as the distance to the nearest construction and operations port.

Table 9. Summary of NRWAL modeling approaches for different cost and performance terms, reproduced based on Shields et al. (2021b).

Item	Cost Category	Modeling Approach	Description
Turbine	C_{CapEx}	Spatially independent	Wind turbine
Support structure	C_{BOS}	Spatially dependent	Floating platform, mooring lines, anchors
Electrical infrastructure	C_{BOS}	Spatially dependent	Array and export cables, offshore substation, onshore grid connection
Installation	C_{BOS}	Spatially dependent	Installation of all components
Soft costs	C_{BOS}	Spatially independent Cost multipliers	Engineering, management, development, insurance, decommissioning bond, contingencies
Operations	C_{OpEx}	Spatially independent	Fixed annual costs (administration, insurance, facility rental)
Maintenance	C_{OpEx}	Spatially dependent	Variable annual costs (spare parts, vessel charter fees)
Gross capacity factor	GCF	Spatially dependent	Ratio of the wind power plant energy production without losses to the maximum possible energy production
Net capacity factor	NCF	Spatially dependent	Ratio of the actual wind power plant energy production (including wake, electrical, availability, and other losses) to maximum possible energy production
Weighted-average cost of capital	FCR	Spatially independent	The average after-tax return required by equity and debt investors
Fixed-charge rate	FCR	Spatially independent	A factor that approximates the average annual payment required to cover the carrying charges on investment and tax obligations
Levelized cost of energy	$LCOE$	Spatially dependent	The total project cost per megawatt-hour of lifetime electricity generation

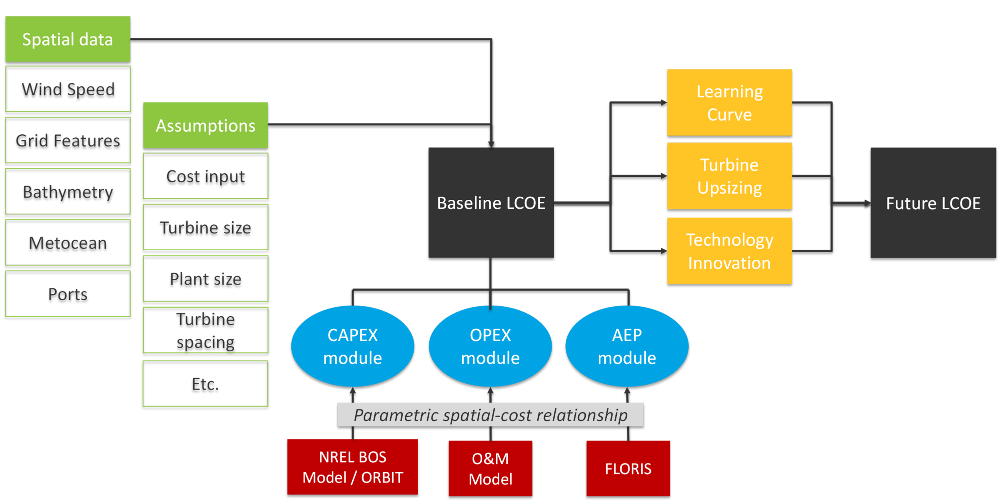

Figure 28. The LCOE calculation process with NRWAL and reV

Electrical System

As noted earlier, electrical system costs calculated with NRWAL do not include transmission system upgrades that may be required to deliver power to the grid. They do include the cost to procure and install the array cable collection system, offshore substation, and transformer and ancillary equipment, as well as the export cable to the point of cable landfall at the point of interconnection. We prioritized interconnecting to 238-kV substations, representing the distance to landfall at the point of interconnection as that to the nearest 238-kV substation if it was within 5 km of the distance to the nearest 115-kV substation, and otherwise the distance to the landfall at the nearest 115-kV substation. These cost relationships are modeled as parametric curve fits from bottom-up models (Maness, Maples, and Smith 2017), and are represented in NRWAL as functions of the substructure technology (fixed or floating), the distance to shore, and water depth. Floating offshore wind plants are assumed to have dynamic cables between the offshore substation and the seabed.

Lease Price

The assumed lease auction price in NRWAL is $100 million, which matches Nunemaker et al. (2020). This auction price represents the amount the developer pays through the leasing process to obtain site control. There is uncertainty around whether floating offshore wind leases could command prices near the record-setting values in the New York Bight, where the amount for one (fixed-bottom) offshore lease area exceeded $1 billion. The value appears to depend on a number of factors including the size of the area, depth, distance to shore, regional subsidy schemes, and existing offtake agreements (Musial et al. 2022).

Historical revenues from BOEM offshore wind lease auctions have primarily gone to the U.S. Treasury as miscellaneous receipts, though proposed legislation exists to direct greater investment into coastal communities near offshore wind energy projects (Congressional Research Services 2021, 2022). The Proposed Sale Notice for the Morro Bay and Humboldt lease areas in California includes details about a newer multifactor auction format that is intended to incentivize greater local investment and cooperation with communities affected by development activities (BOEM 2022). As the first floating lease auctions in the United States, the California leases could shed light on how developers are valuing leases for floating offshore wind.

As mentioned previously, the signing of the Inflation Reduction Act includes U.S. territories in the Outer Continental Shelf Lands Act and allows the Secretary of the Interior to conduct offshore wind energy lease sales in federal waters after consulting with the territorial governors (Service 2022; Congress.gov 2022). This law grants BOEM jurisdiction to lease federal areas offshore Puerto Rico, contingent on consent from the governor. This applies beyond the 9-nautical-mile territorial waters boundary.

Siting of export cables in waters less than 9 nautical miles from shore would be governed by Puerto Rico and interconnections by the PREB. Presently, if a developer wants to permit and build an offshore wind energy project within the Puerto Rican territorial waters (up to 9 nautical miles), they would need approvals from the Commonwealth of Puerto Rico's Department of Natural and Environmental Resources and the U.S. Army Corps of Engineers.

Additional Component Transport Costs

Offshore wind energy projects in Puerto Rico would likely rely on developed wind supply chains in the United States or Europe to manufacture components such as wind turbine blades or nacelles. These would likely be shipped to the construction port where major components would be assembled and installed. Installation costs are captured in NRWAL using parametric cost relationships that are a function of water depth and distance from the port to site, and likely weather downtime during installation. There is also a port, staging, logistics, and transport line item that captures the likely staging costs and port rental fees, but not the additional cost to ship components to Puerto Rico from supply chains on the continental United States.

Following the methodology outlined in Shields et al. (2021b), we use the Offshore Renewables Balance-of-system and Installation Tool (ORBIT) to approximate this additional transport cost for each of the major components (e.g., array and export cables, substation, turbines, and foundation or substructure components). To do so, we specify a nominal barge type that could be used to transport components from ports in the Gulf of Mexico to Puerto Rico. ORBIT was used along with the key vessel parameters (e.g., deck space, cargo tonnage, transit speed) to estimate how many components of each type could be carried on the barge and how long each journey would take. After accounting for the number of trips based on the type and number of each component, we estimated the total vessel rental cost based on the vessel day rate (assumed $30,000/day) and mobilization/demobilization costs.

6.3.2 Annual Energy Production

Unlike the calculation of AEP for land-based wind, which uses SAM, the offshore AEP is calculated by combining FLORIS and NRWAL. The NRWAL loss module incorporates estimates of potential wake losses from FLORIS as well as site-specific technical, environmental, electrical, and availability losses (Beiter et al. 2016) into the total loss variable used to calculate the net AEP. A detailed breakdown and description of the loss framework is outlined in Beiter et al. (2020), but a summary of the losses considered is provided in Table 10. Note that energy production results are presented in Section 7 in terms of NCF, which is equivalent to the net AEP normalized by the plant capacity times the number of hours in a nonleap year.

Table 10. Offshore wind energy losses used to calculate net capacity factors

Loss Category	Value (% of Gross Energy Production)	Additional Information
Wake losses	7.8%-16.5%; mean 11.9%	Evaluated using FLORIS for 600-MW wind plants made up of 15-MW and 18-MW turbines at 7D-by-7D square grid spacing
Environmental losses	1.6%	Includes lightning- and temperature-related shutdowns
Technical losses	Fixed: 1%; Floating: 1.2%	Includes power curve hysteresis, on-board equipment power usage, and rotor misalignment
Electrical losses	2.2%-4.7%; mean 3.4%	Losses in export cable system, varies with distance to point of interconnection
Availability losses	1.1%-8.1%; mean 5.1%	Losses during periods when system is unavailable (e.g., maintenance and repair)

Wake losses are internal, therefore we did not consider wake losses from wind turbines in other wind farms. Technical losses include high-wind hysteresis and power curve adjustments. Hysteresis losses arise from shut-down and restart behavior near the wind turbine's cut-out wind speed. Environmental losses intend to capture losses caused by blade degradation and temperature-related shutdowns. Electrical losses include array and export cable losses but do not include land-based transmission and substation losses. Availability losses account for lost generation due to scheduled and unscheduled O&M for the turbine and balance of plant. Electrical losses increase with water depth and distance to the point of interconnection, whereas availability losses increase as significant wave height and distance from the operations port increase.

Figure 29 presents the assumed wind turbine layouts for which wake losses are calculated using site-specific wind resource data generated in Task 1. Developers will optimize turbine layouts, so we use a generic and conservative square grid layout with turbine spacings along rows and columns of 7 times the rotor diameter of the turbine (7D). This approach is in line with previous NREL offshore wind energy cost studies (Beiter et al. 2020; Shields et al. 2021b; Musial et al. 2021a).

As mentioned in Section 4, we use power and thrust curves from the IEA 15-MW reference wind turbine (Gaertner et al. 2020) and a scaled version to model the energy production and wake losses with FLORIS. Figure 30 presents the power curves for different assumed air densities.

We use the gauss-curl-hybrid wake model in FLORIS to estimate the wake losses for the nominal 600-MW offshore wind power plants. Offshore turbulence intensity is set at 6% per recommendations of the FLORIS development team at NREL, and we adjusted other model tuning parameters based on their input.

6.3.3 Cost Projection Methodology

We use a learning-curve-based cost projection methodology developed by Beiter et al. (2020) to estimate future offshore wind energy costs in Puerto Rico. We estimate cost reductions over time from supply chain learning, technological innovations, and economies of turbine and plant size and apply these reductions to the baseline, site-specific,

Figure 29. Assumed wind turbine layouts for (top) COD 2030 with 15-MW turbines and (bottom) COD 2035 with 18-MW turbines

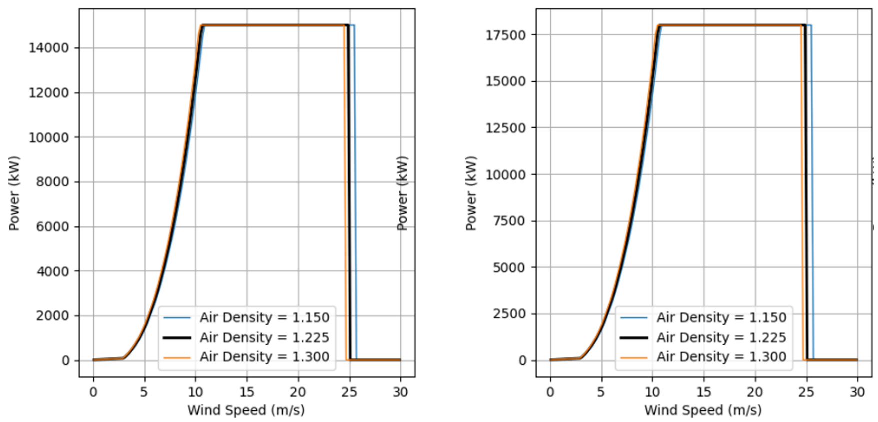

Figure 30. The 15-MW (left) and 18-MW (right) offshore wind power curves used for energy yield calculations based on the IEA 15-MW reference wind turbine (Gaertner et al. 2020)

bottom-up costs obtained with reV and NRWAL. Cost reductions associated with the assumed turbine and plant scaling trajectory from Section 4 (see Shields et al. (2021a)) are captured with the geospatial cost curves in NRWAL.

Learning and experience curves represent the decrease in input costs as an increasing number of units of a good or service are produced (Louwen and Lacerda 2020). In the context of the offshore wind industry, a learning rate represents the percentage cost reduction for each doubling of cumulative installed offshore wind capacity. Louwen, Junginger, and Krishnan (2018) indicate these cost reductions stem from:

- learning by doing,
- learning by researching,
- improved supply chain and manufacturing efficiencies, and
- investment.

We use NREL's Forecasting Offshore wind Reductions in Cost of Energy (FORCE)[9] model (Shields, Beiter, and Nunemaker, forthcoming) to derive learning rates with a multivariate linear regression of publicly available historical global offshore wind CapEx data going back to 2014. Offshore wind learning rates are expressed in terms of the percentage CapEx reduction per doubling of installed capacity worldwide. Limited cost data are available for the few existing floating offshore wind projects in 2022, therefore commercial-scale, fixed-bottom cost data are analyzed to obtain the experience factor for floating offshore wind. The linear regression process controls for costs related to turbine rating, plant capacity, water depth, distance to shore, and installation country to remove their effects from the learning curve, as they are already accounted for in the bottom-up modeling in NRWAL.

[9] Access an early version of the FORCE model: https://github.com/JakeNunemaker/FORCE.

Table 11. Global offshore wind deployment projections and CapEx learning rates derived from market data

Year	Data Sources	Fixed Capacity	Floating Capacity
2020	Musial et al. (2021b)	32.9 GW	0.08 GW
2030	Global Wind Energy Council, 4C Offshore, Equinor, Wood Mackenzie, Strathclyde	229 GW	9.7 GW
2035	ORE Catapult	277 GW	14.4 GW
CapEx Learning Rate	FORCE model (Shields et al. forthcoming)	7.3%	7.3%

We translate the learning rate into a learning curve (and cost reductions over time) based on current and projected global fixed-bottom and floating offshore wind deployment. We combine deployment projections from literature to estimate global offshore wind deployment levels in 2030 and 2035 for fixed-bottom and floating turbines, respectively. The projections are shown in Table 11.

Figure 31 presents offshore wind CapEx reductions from learning for fixed-bottom and floating as a percentage of the base year costs obtained with NRWAL. Note that more aggressive reductions are expected for floating offshore wind because it is in an earlier stage of total global deployment, technology is rapidly maturing, and the onset of commercial deployment expected in the next few years will result in several “doublings” of the global floating offshore wind energy market.

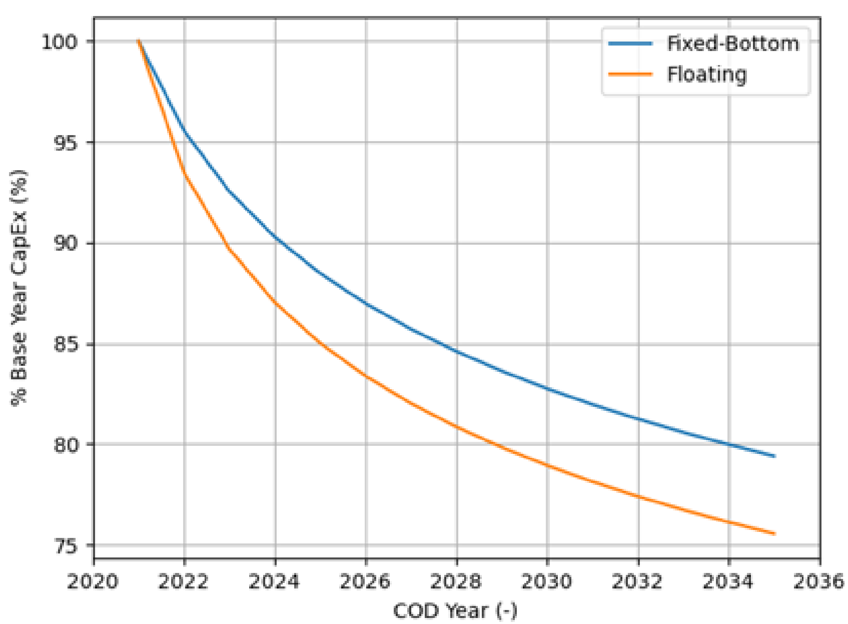

Figure 31. Learning CapEx reductions over time for fixed-bottom and floating offshore wind presented as a percent of the base year CapEx

Because public empirical data are largely unavailable to derive learning curves for OpEx and AEP, we instead rely on expert elicitation to estimate the impacts from technology improvements. Total OpEx reductions of 12% between 2019 and 2035 for fixed-bottom wind and 22% for floating, and AEP improvements of 7% and 11%, respectively, over the same period are based on Wiser et al. (2021a). Total reductions for each CapEx, OpEx, and AEP input are computed for each future year and applied to the baseline costs before calculating future LCOE.

6.3.4 Literature Cost Estimates

As was the case for land-based wind, fixed-bottom offshore wind costs have declined substantially in the past two decades—faster than experts predicted (Wiser et al. 2016, 2021a). Although the floating offshore wind energy industry is in the nascent stage, it is expected to benefit from the experience and supply chains of the fixed-bottom wind energy industry. Figure 32 shows select offshore wind cost projections for fixed-bottom and floating technologies. LCOE estimates for fixed-bottom projects in North America range from $60–$110/MWh today to $40–$80/MWh by 2035. For floating projects, these estimates range from $95–$180/MWh today to $50–$110/MWh by 2035.

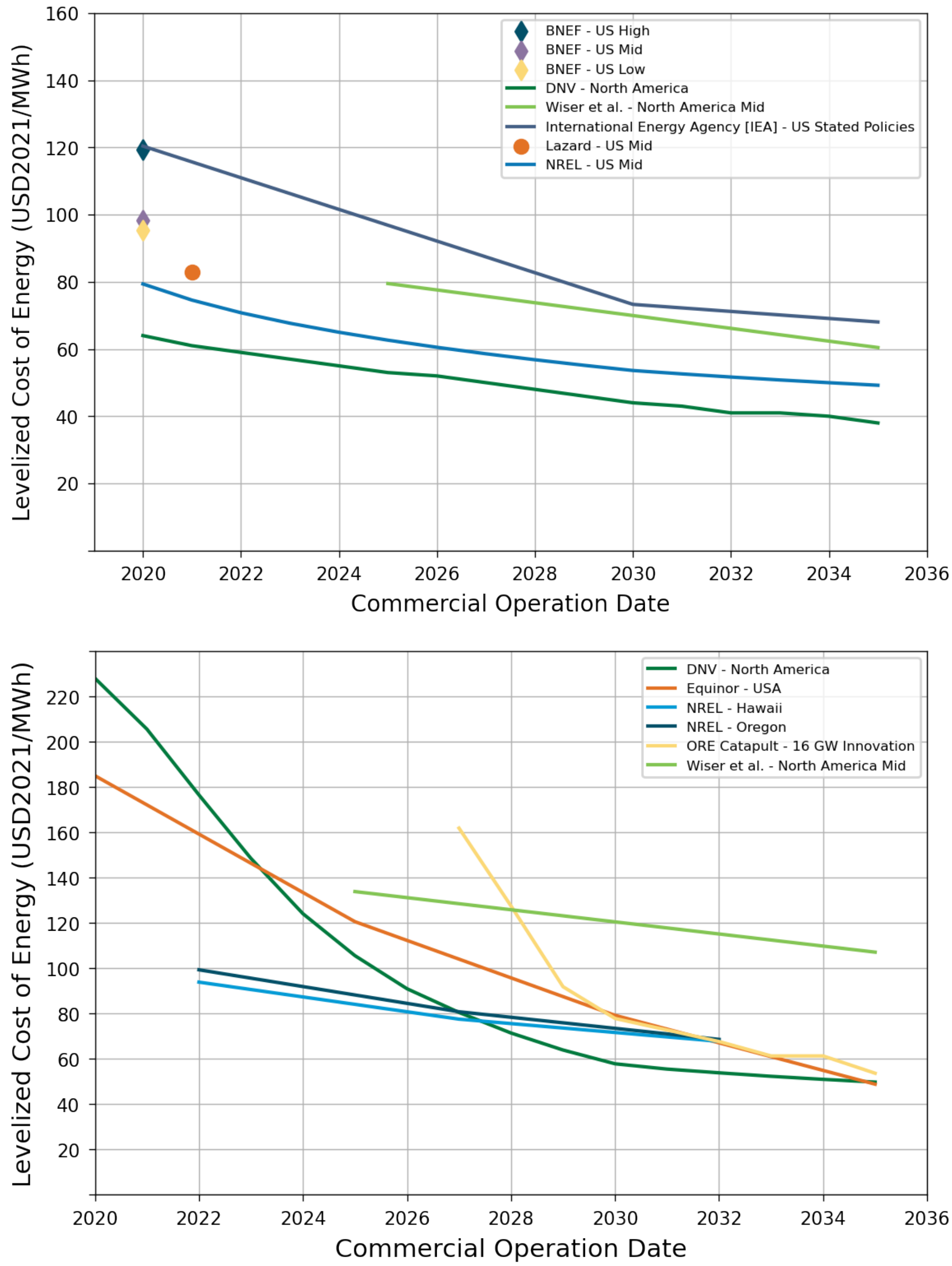

Figure 32. LCOE estimates from literature for fixed-bottom (top) and floating offshore wind (bottom). ***Images reproduced from Musial et al. (2022).***

6.3.5 Potential Use Conflict Areas

We also incorporate some potential use conflict areas (areas not legally, technically, or physically suitable for offshore wind development) into modeling of offshore wind energy potential in Puerto Rico[10]. For this initial cost study, the intent is to highlight the challenges of marine spatial planning considering only the most basic nondevelopable areas, such as existing protected areas, existing submarine infrastructure, and military zones. In practice, offshore wind development areas are determined by multiple stakeholder groups that may have differing views on what is considered suitable for development. BOEM conducts marine spatial planning for U.S. federal waters through a formal process engaging many stakeholders, and the Inflation Reduction Act requires BOEM to consult with territorial governors before conducting offshore wind leasing in federal waters (Service 2022; Congress.gov 2022). Potential use conflict areas and geospatial data sources considered in this initial modeling effort are summarized in Table 12 and shown in Figure 33. **As with land-based wind, this is not a comprehensive list.** There are ongoing discussions within the PR100 Study stakeholder advisory group regarding potential use conflict areas and impacts to development of different generation sources, including offshore wind.

Because of the bathymetry, or sea floor topography (Puerto Rico trench north of the island, and rapid drop off in the south of the island), we sought to present the most open-access scenario to illustrate a potential upper bound to the developable area, and subsequently the offshore wind energy potential.

Table 12. Offshore wind energy potential use conflict areas

Potential use conflict area	Explanation	Source
Protected areas	No development in protected areas	PA-CAT & MPA Inventory
Danger zones and restricted areas	Areas used for target practice and other hazardous operations by armed forces	CFR
Submarine cables	Cannot build on top of existing cable infrastructure; includes a buffer of 100 feet	NASCA Submarine Cable & CFR
Ocean disposal sites	Areas containing past or active disposal of sediment and waste	MPRSA
Unexploded ordinance areas	Areas containing explosive weapons that still pose risk of detonation	USACE & FUDS

In the offshore wind modeling effort, we model plants with a fixed capacity of 600 MW. Offshore potential use conflict areas overlaid with results presented in Section 7 and used to calculate total area and offshore technical potential.

6.4 Wind Energy Project Financing and Insurance

In this work, we established wind energy project financing assumptions in line with commercial-scale projects. For land-based wind, we use a nominal weighted-average cost of capital (WACC) of 5.23% and resulting nominal fixed charge rate (FCR) of 7.59%, and for offshore wind we use values of 5.29% and 7.64%, respectively. These values are calculated in line with Stehly and Duffy (2022), and have been informed by literature (Feldman, Bolinger, and Schwabe 2020; National Renewable Energy Laboratory 2022a; Guillet 2018) and updated based on conversations with industry partners. Table 13 details the financing assumptions used in the derivation of FCR, and a more detailed description of each term can be found in Beiter et al. (2016). For the depreciation schedule, we use the 5-year Modified Accelerated Cost Recovery System (MACRS), which is standard for U.S. wind energy projects. We do not consider any benefits from the Production Tax Credit or Investment Tax Credit in the costs presented below.

Note that real FCR (and real LCOE) accounts for the assumed long-term inflation rate from the commercial operation date of the project through the end of the capital recovery period. Nominal FCR and nominal LCOE ignore effects of inflation. We used nominal FCR and make no assumption about inflation between the present date and future CODs. While inflation rates in 2021 and 2022 have been the highest in decades (U.S. Bureau of Labor Statistics

[10] Online interactive map of possible potential use conflict area layers: https://nrel.carto.com/u/gds-member/builder/a7d3fc28-3418-472f-bcb3-ef5505fbe5e8/embed

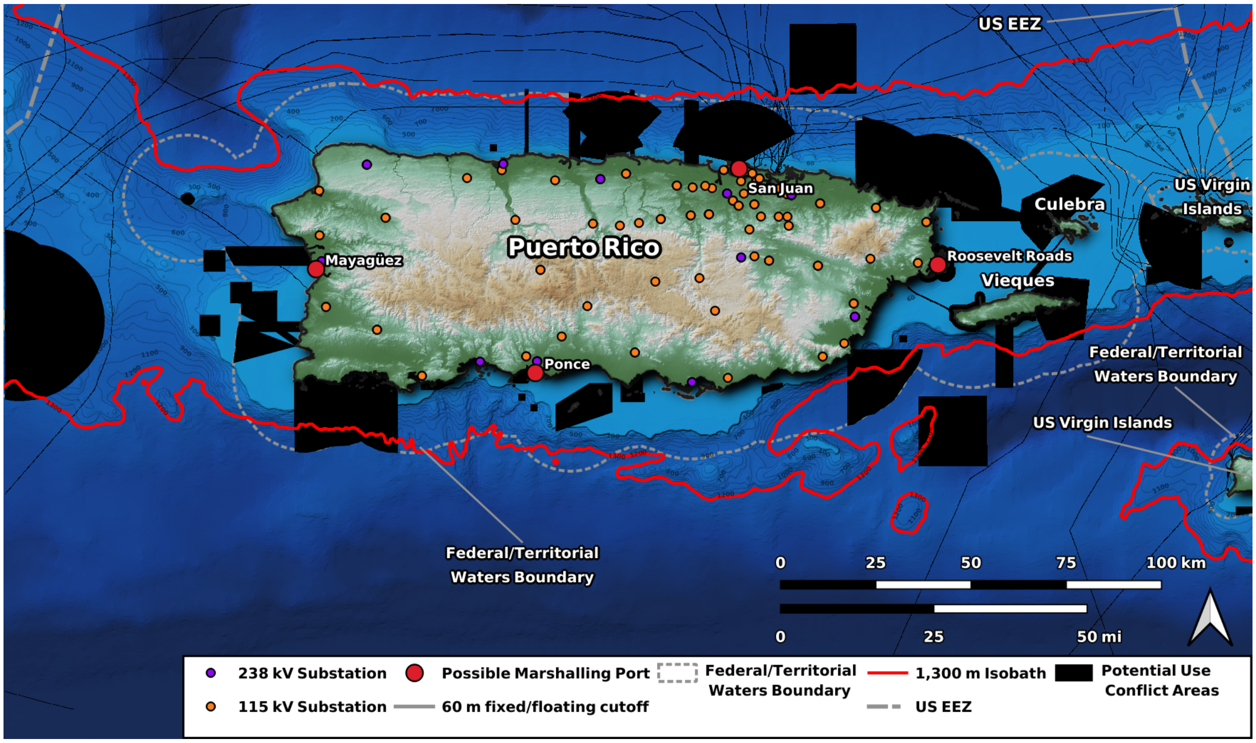

Figure 33. Offshore wind energy potential use conflict areas (blacked out areas) in Puerto Rico

Table 13. Commercial-scale wind energy project financing assumptions

Parameter	Land-Based Value	Offshore Value
Capital recovery period, years	25	25
Tax rate, %	26	26
Inflation, %	2.5	2.5
Share of debt, %	47.9	67
Nominal debt rate, %	2.61	4.0
Nominal return on equity, %	8.25	10.0
Nominal after-tax WACC, %	5.23	5.29
Real after-tax WACC, %	2.66	2.72
Nominal after-tax capital recovery factor, %	7.26	7.3
Real after-tax capital recovery factor, %	5.53	5.6
Depreciation basis, %	100	100
Depreciation schedule	5-year MACRS	5-year MACRS
Present value of depreciation, %	87	87
Project finance factor,%	105	105
Nominal after-tax FCR, %	7.59	7.64
Real after-tax FCR, %	5.78	5.82

2022), we retain a 2.5% long-term (periods over 25 years) inflation rate assumption in line with National Renewable Energy Laboratory (2022a).

We assume the same financing terms for commercial-scale, fixed-bottom and floating offshore wind projects. Although this may not be a conservative estimate for the first projects in the nascent floating industry before 2030, we feel it is justified as there are many similarities between fixed-bottom and floating project execution. These similarities include project developer experience, mature supply chains, low political risk, wind urbine technology maturity, limited-to-no revenue risk, insurance coverage, contract management practices, and contingency budgets, which means that full-scale commercial floating wind project financing could resemble fixed-bottom project financing (Weber 2020). Using common risk management strategies (e.g., technical, contractual, financial, insurance) from the fixed-bottom wind energy industry has helped the floating offshore wind industry secure financing for early projects, demonstrating financing availability for well-structured projects (Weber 2021).

In addition to designing wind turbines for extreme conditions, insuring wind energy projects can help manage financial risks due to natural catastrophes in regions like Puerto Rico. We spoke to an offshore wind insurance underwriter to better understand how offshore wind energy developers insure projects and what the cost impact of insurance premiums would likely be in these regions. Before a project is built, detailed risk engineering analysis helps developers understand the credible worst-case scenario a project could experience during its operational life and how turbines and other assets might behave under a number of different risk scenarios. The insurer provided NREL with confidential, high-level guidance for a generic fixed-bottom offshore wind project in different locations and for levels of risk ranging from conservative to aggressive (P80-P40). The estimates assumed limited/no claims occurring on these projects, and no adverse insurance market conditions. Separate estimates of coverage and premiums were provided for the (approximately) 3-year construction phase and 30-year operations phases, because different instruments are used to manage risk profiles during each project phase. In general, pricing in new territories increases to accommodate uncertainties (especially weather). The cost of offshore wind insurance would likely be higher in Puerto Rico than for the northeast United States, where insurance premiums are already higher than the United Kingdom due to perceived risks around an emerging market with a less mature supply chain (e.g., customized vessels, installation expertise, and manufacturing facilities) and higher wind storm exposures. To respect confidentiality, estimated insurance premiums for the Puerto Rico region were aggregated and incorporated into the cost models, but not explicitly identified as a separate line item in the cost results presented in Section 7.

Interestingly, there are currently a limited number of insurers covering the entire offshore wind energy industry, and they collectively have a finite amount of natural catastrophe insurance available. This limitation matters because offshore wind projects tend to be concentrated in specific regions around strong resources and electricity demand, which increases the maximum potential damage if a strong storm were to hit multiple wind farms in a given region. Geographic diversification of a region's electricity generation portfolio helps strengthen energy security in the face of a large disaster. Insurers must work to understand the spatial and temporal correlation of hurricane risks to wind energy assets in a given region.

While we accounted for the costs of hurricane risks in the wind turbine and foundation technology and insurance costs, we did not alter the financing terms, as we have outlined several strategies for mitigating these risks. Additionally, we did not assume that the low credit ratings of public entities in Puerto Rico (AAFAF, n.d.) impact the financing terms for the baseline modeled costs we present. We therefore include a sensitivity of LCOE to FCR in Section 7 to demonstrate the possible range of outcomes if these financing terms were to differ from what we present in Table 13.

7 Results

This section presents the wind energy cost and performance results generated with the reV model based on the methodology described in Section 6. We discuss land-based and offshore wind energy cost results in the form of heat maps showing spatial variation around Puerto Rico and the surrounding waters. In addition, we investigate the sensitivity of these results to a several parameters. All costs are presented in 2021 U.S. Dollars, unless otherwise specified.

7.1 Land-Based Wind Energy in Puerto Rico

7.1.1 Technical Potential

We present estimates for the total technical potential for land-based wind energy in Puerto Rico including all modeled grid cells with sufficient area for at least one 4.2-MW turbine using an "open-access" potential use conflict area scenario without setbacks from existing infrastructure defined in Section 6. We found a total of 2,270 km^2 of developable area (see Figure 34), which is about 24% of Puerto Rico's land mass (including Culebra and Vieques). This highlights how land-based wind development in Puerto Rico can be considered "land-constrained." Using a capacity density assumption of 3 MW/km^2 from Lopez et al. (2021), we estimate there is a total technical potential of 6.81 GW of land-based wind. Capacity density is the ratio of wind energy generation capacity to the area over which it is built. A higher capacity density leads to increased energy production in the same area, though there are trade offs such as higher wake losses.

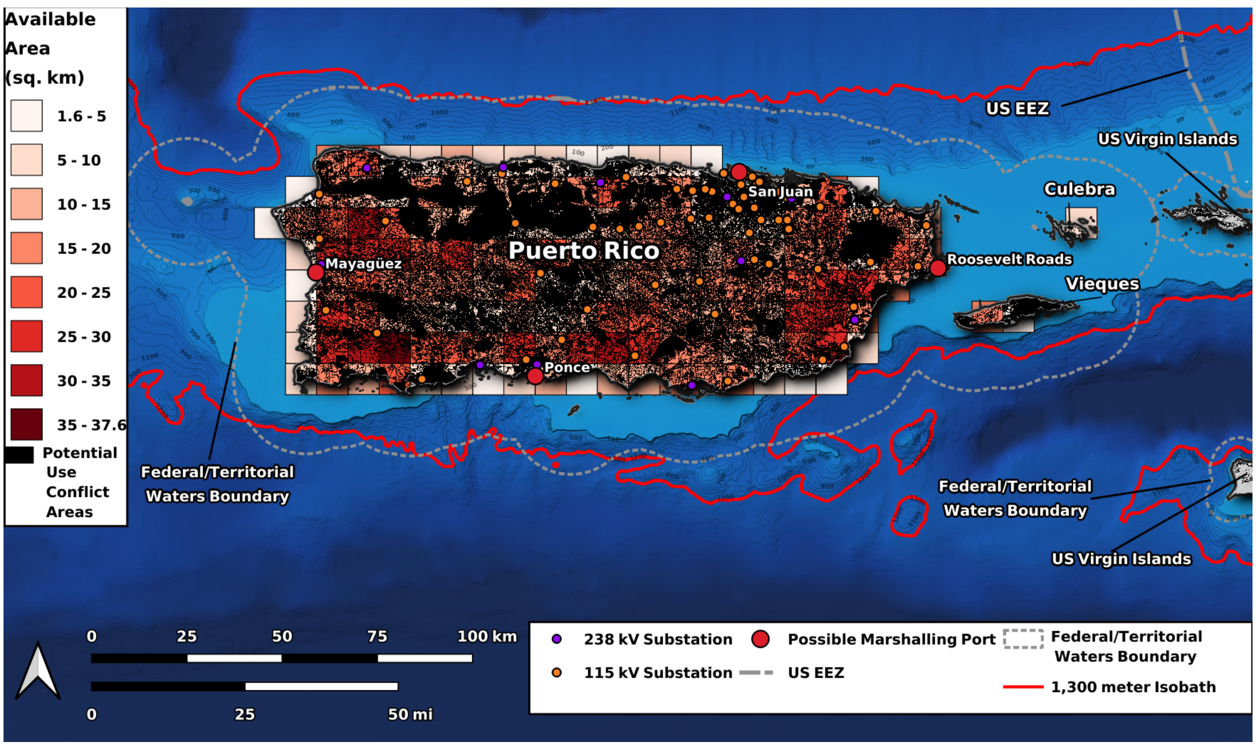

Figure 34. Available area after applying potential use conflict areas; each grid cell represents 66.7 km^2 with a capacity density of 3 MW/km^2; a grid cell with 66.7 km^2 of available area could fit a 200-MW plant

7.1.2 Capital Expenditures

Based on our modeling efforts, we expect capital expenditures for land-based wind energy in 2022 to range from \$1,450/kW to \$2,404/kW, with an average of \$1,845/kW. Capital expenditures in 2035 range from \$1,864/kW to \$2,666/kW, with an average of \$2,202/kW (see Figure 35). While this may seem contrary to the historical trend of decreasing capital expenditures, we assume turbines in later years incur higher costs due to their typhoon rating and larger size (higher hub heights and larger rotor blades). However, the turbines deployed in 2035 also capture more available electricity, which offsets the increased CapEx when looking at total LCOE (see below). Grid cells that have reduced capacities due to potential use conflict areas have the highest CapEx, because of the upward scaling of CapEx in smaller capacity grid cells.

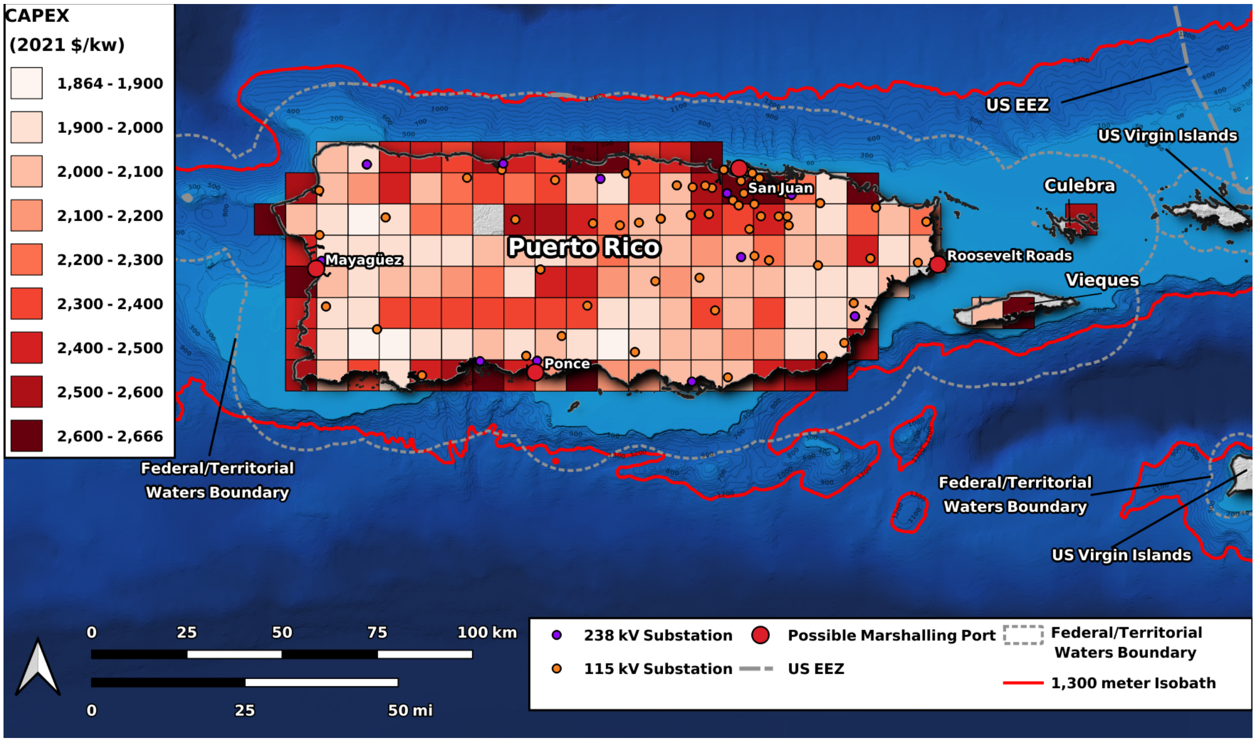

Figure 35. CapEx in 2035, considering potential use conflict areas and economies of scale

7.1.3 Operational Expenditures

Operational expenditures for land-based wind energy, derived from the Annual Technology Baseline (National Renewable Energy Laboratory 2021a), are assumed to be constant at $36.36/kW in 2035. The 2035 OpEx represents a decrease of 22% from the 2022 OpEx of $46.47/kW.

7.1.4 Annual Energy Production and Production Profiles

Energy production results are presented in terms of NCF, or the fraction of the year that the plant would need to operate at rated capacity to produce an equivalent amount of energy. The computed NCF values in 2035 ranges from 0.19 to 0.53, with an average of 0.36 across all grid cells (see Figure 36). This represented a steep increase from 2022, in which NCF values range from 0.11 to 0.36, with an average of 0.22. Given the assumption of deploying a single type of wind turbine in a given year with a constant loss assumption, the spatial variation in plant performance depends only on the wind resource. NCF values are generally higher on the southern and northwestern parts of the main island. The winter and summer months tend to have higher wind speeds and greater energy production, across all regions, followed by spring and then fall. Diurnal wind patterns (see Section 3) varied across the island, although there seemed to be a fairly consistent afternoon peak. Although this afternoon peak may coincide with that of solar generation, there is still consistent production of energy around the clock, which could be valuable for meeting renewable energy targets in Puerto Rico. Taking into account the available capacity within each grid cell as well as its losses, 2035 estimated total annual generation for individual plants ranges from 12,043 MWh to 381,536 MWh, with a mean of 139,626 MWh. The grid cells with the highest annual generation are ones with both high capacity factors and available area.

7.1.5 Levelized Cost of Energy

We found that LCOE ranges from $58/MWh to $228/MWh (mean of $107/MWh) in 2022 and declines to $43/MWh to $139/MWh (mean of $69/MWh) by 2035 (see Figure 37). The 2035 LCOE is projected to be, on average, two-thirds of the present day LCOE (see Figure 38. This decrease is largely due to the higher capacity factor associated

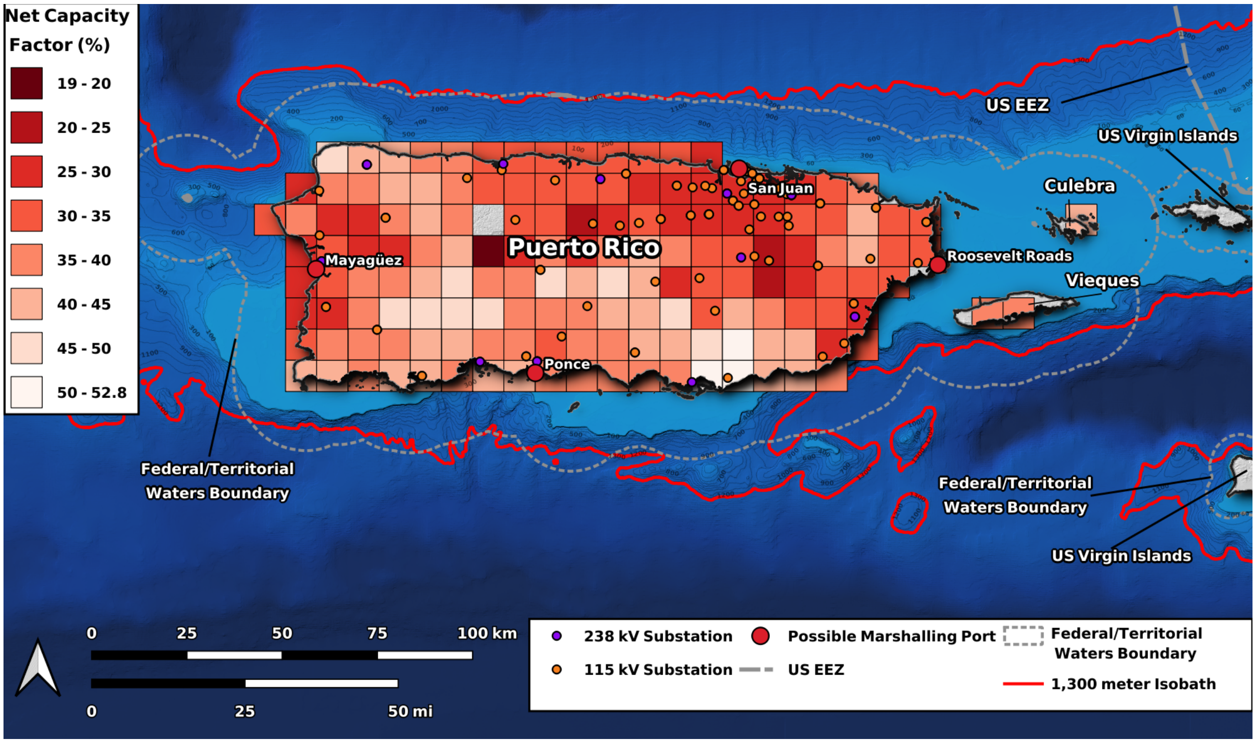

Figure 36. Net capacity factors in Puerto Rico in 2035

with the 150-m rotor diameter assumed in 2035 (vs. the 117-m rotor diameter in 2022), and despite the associated increase in CapEx.

Low LCOE values are driven by a combination of higher capacity factors and greater available area, and secondarily by proximity to existing transmission infrastructure. The lowest LCOE sites are found in the southeast portion of the main island, near the city of Guayama, which is approximately 25 km east of the Santa Isabel Wind Farm. Higher LCOE is found in areas with either minimal developable area or poor wind resource.

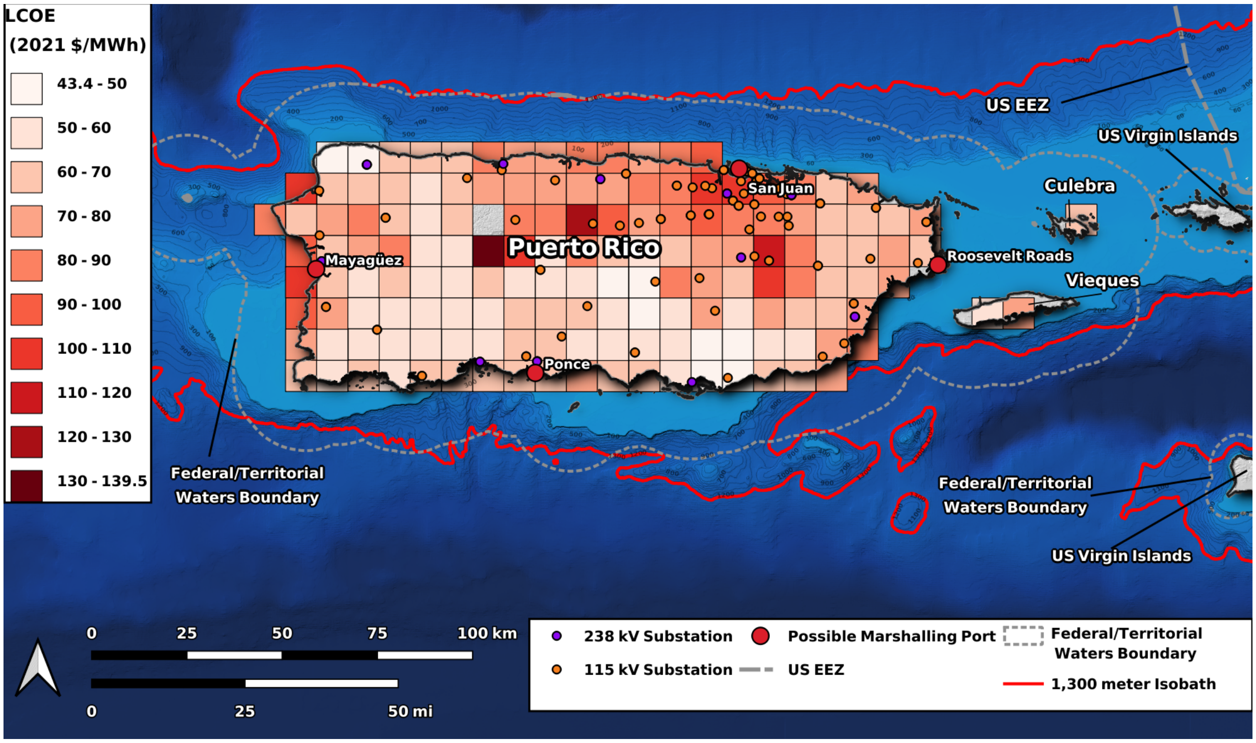

Figure 37. Total LCOE (including the cost of interconnection) in 2035

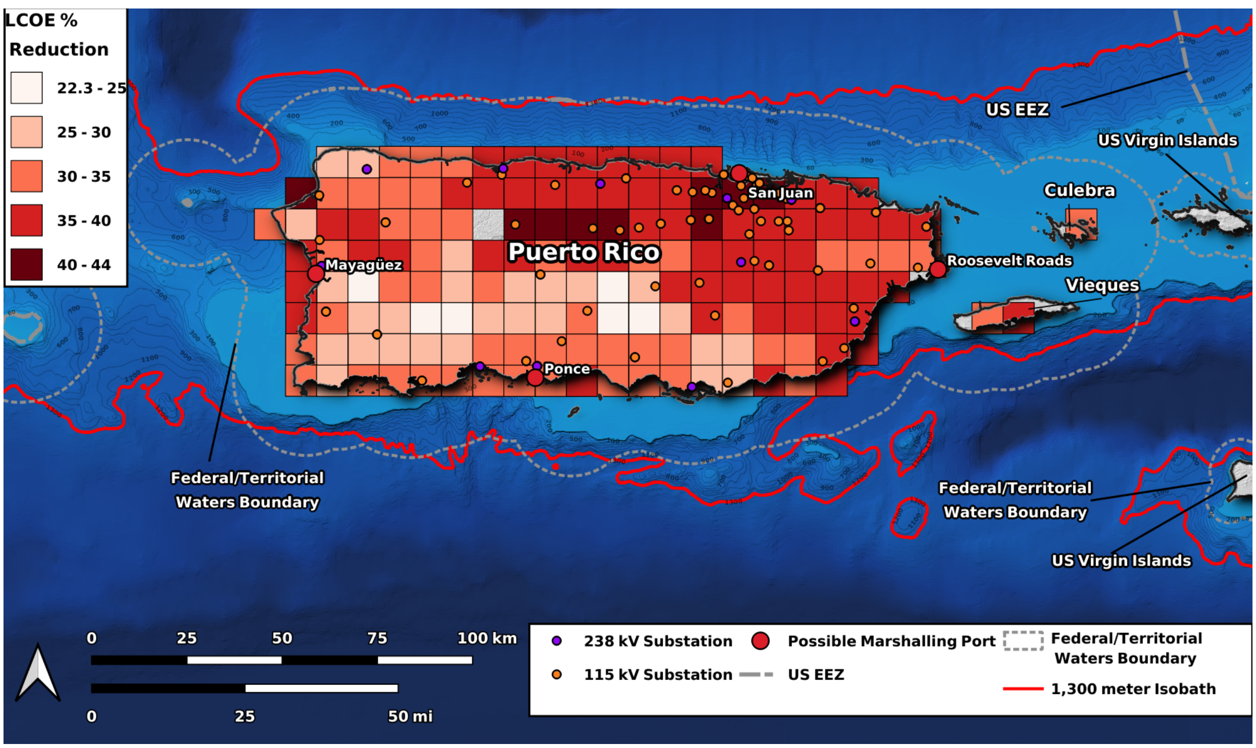

Figure 38. Total projected LCOE reductions between 2035 and 2022; mean reduction of 33.8%

7.1.6 Sensitivities

To better understand the range of possible results, we include sensitivities of the land-based technical potential to assumed capacity density and LCOE to its primary inputs.

Land-Based Technical Potential

Using a capacity density assumption of 3 MW/km^2, we estimated a total technical potential of 6.81 GW of land-based wind. While 3 MW/km^2 is a standard conservative capacity density for land-based wind in the continental United States (Lopez et al. 2021), the Santa Isabel wind farm in southern Puerto Rico has a capacity density of around 10 MW/km^2. Extending this local assumption to the whole of Puerto Rico, the maximum capacity per grid cell would be 667 MW and the technical potential would increase to 22.7 GW. This increased capacity density may not be feasible across all developable area in Puerto Rico, but it illustrates the possible range of technical potential depending on how projects are built.

Uncertainty in Input Costs

We investigate the impacts of the main primary inputs of LCOE (e.g., CapEx, OpEx, NCF, finance parameters). We do this by taking the mean values of each of these components in 2035 and calculate a reference LCOE of $65/MWh. Then we recalculate LCOE after varying each of the primary inputs one at a time by plus and minus 10%. The resulting ranges of LCOE are presented in Figure 39. It can be seen that NCF has the largest impact on LCOE, followed by the FCR and CapEx.

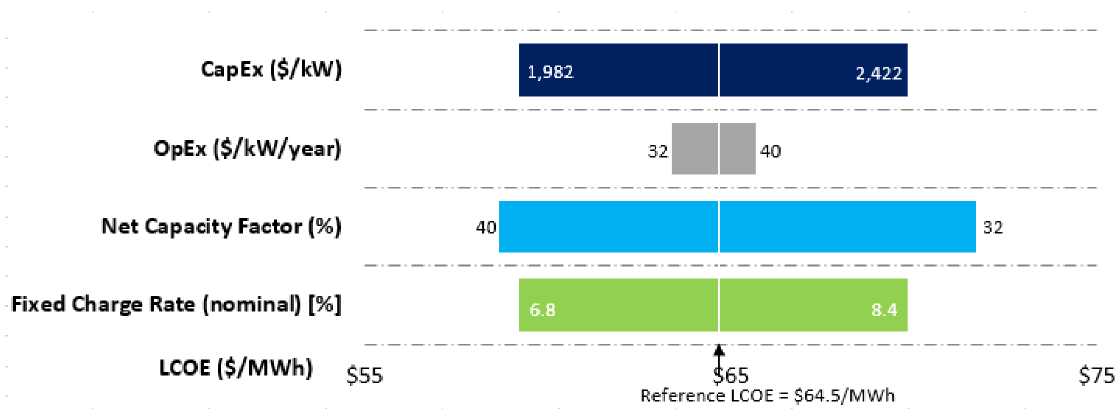

Figure 39. Land-based wind LCOE sensitivity to primary inputs (2035 average values of CapEx, OpEx, NCF, finance parameters)

7.2 Offshore Wind in Puerto Rico

7.2.1 Technical Potential

We found a total of 13,587 km^2 of developable area for offshore wind in Puerto Rico (see Figure 40) after accounting for basic potential use conflict areas. Using a capacity density assumption of 3 MW/km^2, there is nearly 40.76 GW total technical potential of offshore wind. A capacity density assumption of 3 MW/km^2 could be considered conservative, but is consistent with previous NREL modeling (Musial et al. 2013; Musial et al. 2016; Musial et al. 2022). Some offshore wind farms in Europe have capacity density assumptions in excess of 5 MW/km^2 (Borrmann et al. 2018).

Of the 40.76 GW of technical potential, 21.24 GW are within territorial waters and 19.52 GW are in federal waters (see Table 14). We also identify technical potential within three additional distance from shore thresholds, finding that nearly three quarters is within 15 nautical miles from shore.

Table 14. Quantity of wind resource potential at various distances to shore thresholds. Note that these are estimated using a capacity density of 3 MW/km^2. Nine nautical miles reflects the boundary between territorial and federal waters.

Distance from shore	Potential
0 - 9 nautical miles	21.24 GW
9 + nautical miles	19.52 GW
15 + nautical miles	11.24 GW
25 + nautical miles	4.69 GW
35 + nautical miles	0.65 GW

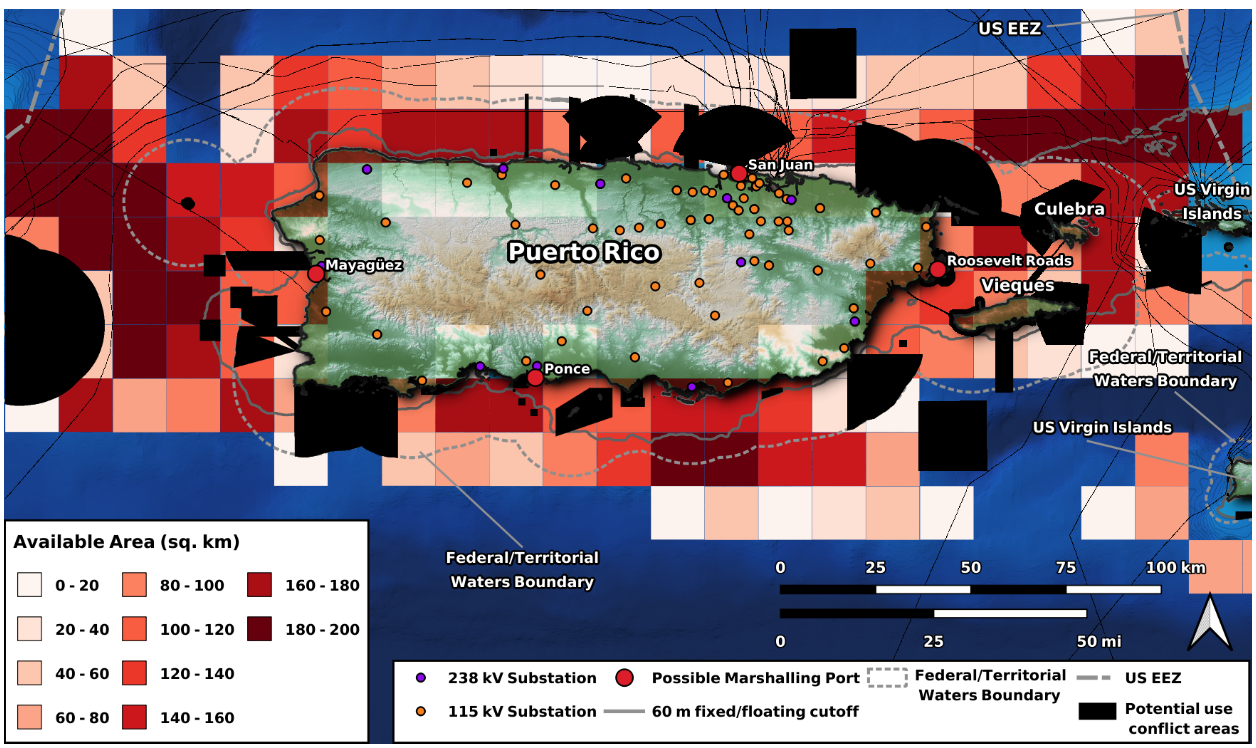

Figure 40. Available area after accounting for the 1,300-m technology depth cutoff and potential use conflict areas. Each grid cell represents 200 km^2. With a capacity density of 3 MW/km^2, a grid cell with 200 km^2 of available area could fit a 600-MW plant. Note: some of the available area in the federal waters off the coast of the U.S. Virgin Islands is not pictured here.

7.2.2 Capital Expenditures

Modeled capital expenditures in 2035 range from $2,769/kW to $4,440/kW, with a mean of $3,439 (see Figure 41), a decrease from the $3,093/kW to $4,944/kW range in 2030, despite using a larger wind turbine. Decreases during the 5-year period are associated with increased global supply chain and technology maturation. In both 2030 and 2035, the primary drivers of CapEx are the turbine costs, the substructure, and the array and export cabling. Rotor and nacelle assembly is a fixed cost, depending only on the capacity and number of turbines, whereas the substructure and cabling are site-dependent. The substructure and array cable vary primarily with the water depth, whereas export cable costs vary with distance to the point of interconnection. A detailed breakdown of relative CapEx is provided in Table 15 for the four representative offshore wind sites. The total capital costs pictured in Figure 41 are inclusive of the CapEx reductions shown in Figure 32.

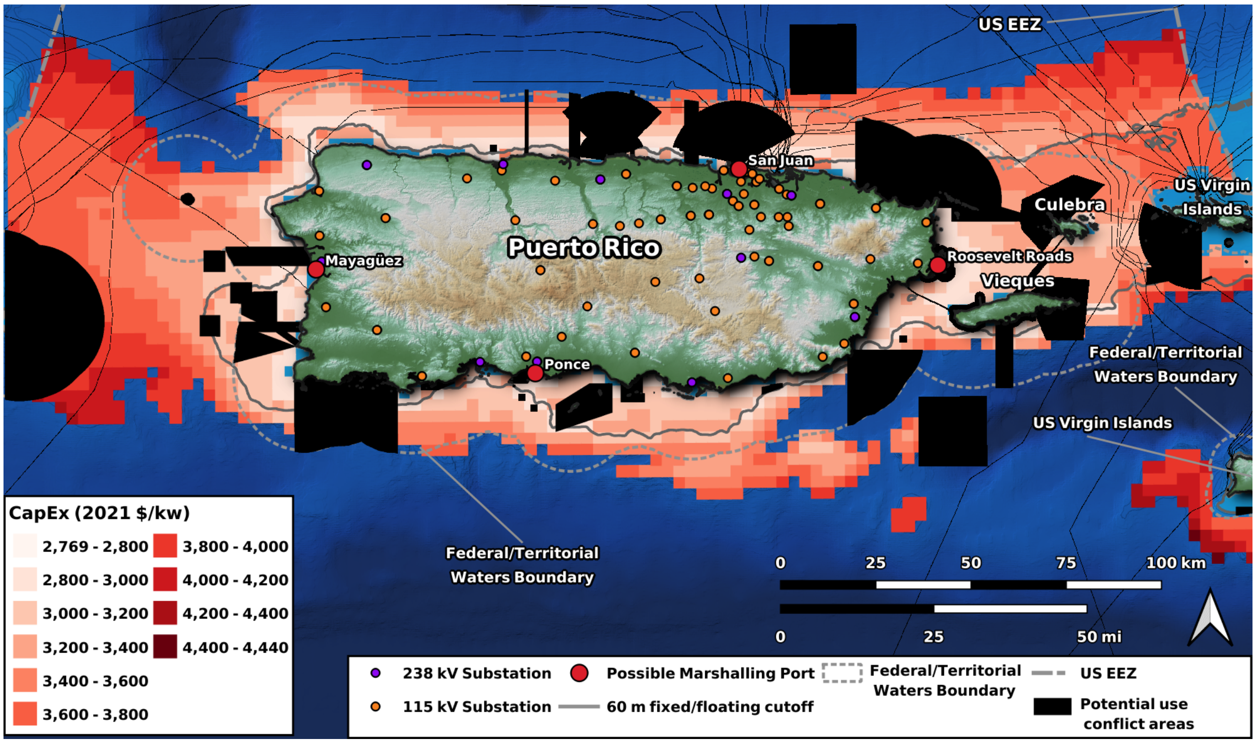

Figure 41. Capital expenditure estimates in 2035

Table 15. Relative breakdown of capital expenditures in 2035 as a percentage of total CapEx. Bold lines represent the three CapEx categories, and sum to 100% of the costs. The line items in each category are components and sum to the bolded percentage.

Line Item [values expressed as % Total CapEx]	West (Floating)	Northwest (Floating)	Southeast (Floating)	Northeast (Fixed)
Lease price	4.35	3.93	4.29	4.30
Development	3.12	3.13	3.12	3.01
Project management	1.56	1.57	1.56	1.50
Substructure	19.69	25.59	22.19	16.89
Turbine installation	1.02	1.11	1.05	2.38
Substructure installation	0.45	0.65	0.54	6.43
Port staging, logistics, and transportation	1.34	1.27	1.35	1.19
Array cables	10.45	14.25	12.98	8.02
Export cables	16.40	9.53	11.65	11.93
Balance-of-system costs	**58.39**	**61.03**	**58.73**	**55.64**
Contingencies	6.43	6.51	6.46	8.33
Construction financing and insurance	6.21	6.21	6.21	6.14
Decommissioning	0.25	0.30	0.27	1.52
Soft costs	**12.90**	**13.02**	**12.95**	**15.99**
Rotor and nacelle assembly	24.45	22.10	24.13	24.17
Tower	4.25	3.85	4.20	4.20
Turbine costs	**28.71**	**25.95**	**28.33**	**28.37**

7.2.3 Operational Expenditures

We found operational expenditures in 2035 to range from \$45/kW-yr to \$66/kW-yr, with a mean value of \$53/kW-yr (see Figure 42), a decrease from the range in 2030 of \$52.38/kW-yr to \$76.06/kW-yr . These decreases are associated with improvements in technology efficiency as well as learning associated the growth of the offshore wind energy industry. OpEx primarily vary with technology: fixed-bottom OpEx ranged from \$46.9/kW-yr to \$65.52/kW-yr, with a mean value of \$57.72/kW-yr, whereas floating OpEx range from \$45.01/kW-yr to \$63.10/kW-yr, with a mean value of \$50.76/kW-yr. Floating offshore wind OpEx costs rely on a tow-to-port maintenance strategy for large maintenance tasks based on Beiter et al. (2016). In addition to the variation associated with substructure technology, OpEx increases with distance from the construction and operations port, water depth, and significant wave height. The OpEx shown include the reductions associated with future technological and efficiency improvements.

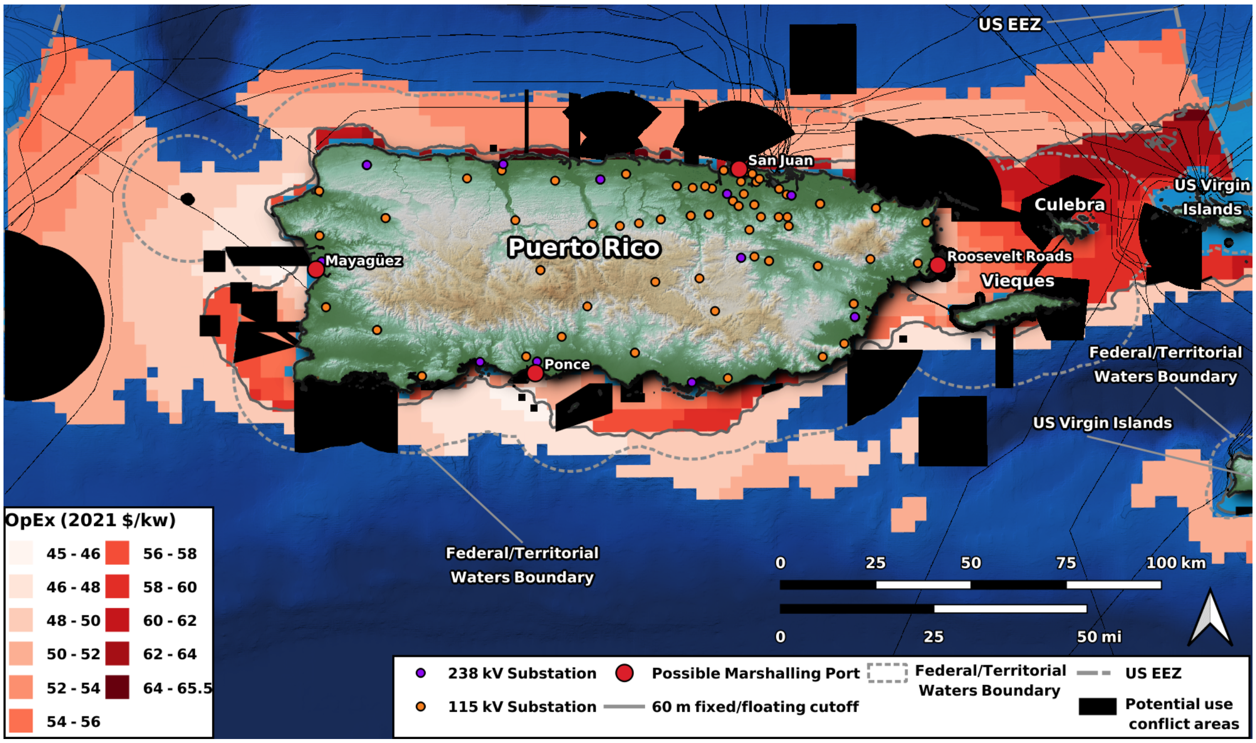

Figure 42. Projected operations and maintenance expenditures in 2035

7.2.4 Annual Energy Production and Production Profiles

We found AEP, expressed in terms of NCF, in 2035 range from 0.26 to 0.50, with a mean of 0.37 (see Figure 43), a slight increase from the 2030 range of 0.25 to 0.48 (mean = 0.35). Wake losses internal to the wind plant are computed with FLORIS, and electrical and availability losses vary primarily with distance from shore and significant wave heights. Technical and environmental losses, are constant for all sites (see Section 6). NCF values are highest to the south of Puerto Rico, and lowest directly west of the main island. Net capacity factors shown include the increase associated with future technological improvements. Wind plant performance tends to be highest in the winter months and during the night, although diurnal patterns vary significantly across space. Despite some variations in diurnal patterns in production (see 11, winds tend to be more consistent at night.

7.2.5 Levelized Cost of Energy

We found LCOE in 2035 to range from \$64 MWh to \$130 MWh, with a mean of \$100 MWh (see Figure 44), which is lower than the 2030 LCOE range of \$71/MWh to \$156/MWh. This finding represents an average decrease in LCOE of 14% across all sites in 2035 compared to 2030 (see Figure 45). Much of the reduction comes from the the maturation of the floating substructure technology, as well as the transition from 15-MW to 18-MW wind turbines. Although fixed-bottom costs are still projected to decrease over the 5-year period, the largest reductions in LCOE come from floating sites that are relatively shallow and closer to shore.

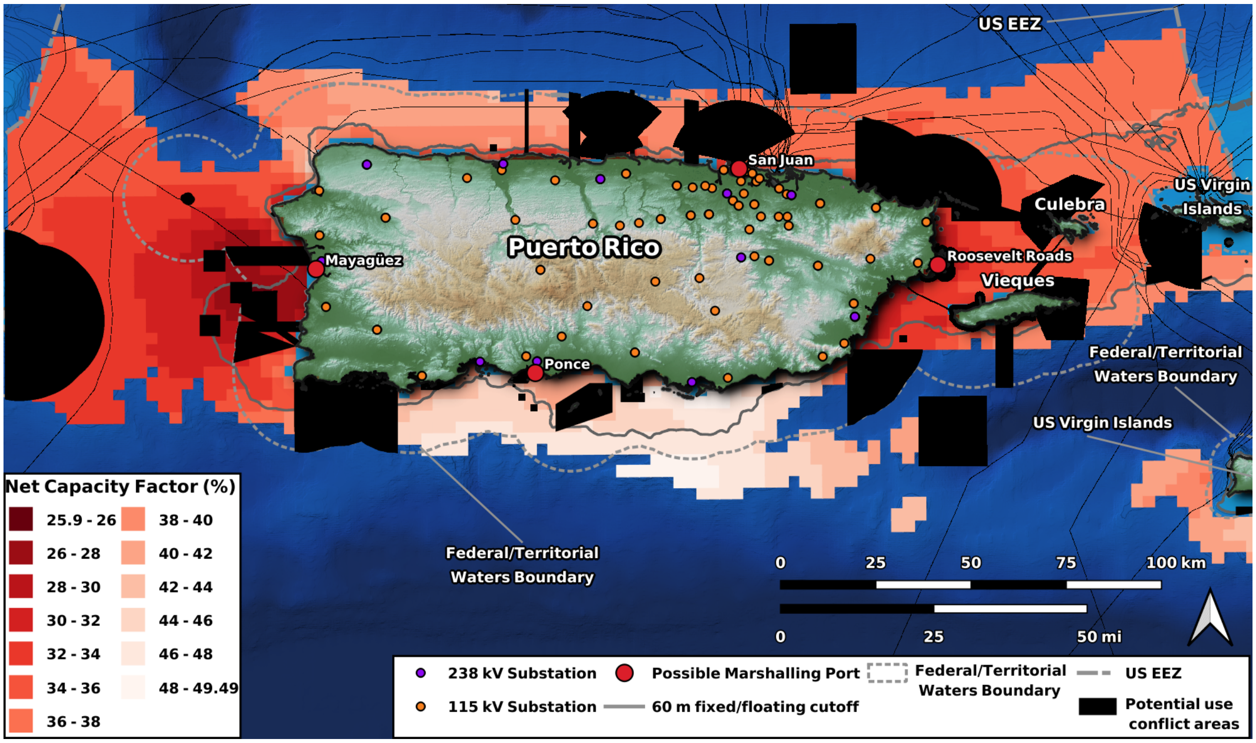

Figure 43. Net capacity factors in 2035

LCOE is highly dependent on the average annual NCF, as well as the CapEx. The lowest LCOE are found south of the main island, where the NCF values are highest, or in areas with moderate NCF values and low CapEx, such as the nearer-to-shore floating sites northwest of the main island.

Compared with the offshore wind cost projections presented in Figure 32 for North America, the mean 2035 offshore wind LCOE calculated in the present study ($100/MWh) falls towards the upper end of the projected range for floating offshore wind ($50–$110/MWh). The lowest cost sites in Puerto Rico are all in the lower halves of the projected ranges for North America. In addition, a recent NREL analysis of floating offshore wind in Hawaii projected 2032 LCOE values between $51/MWh–$115/MWh for 400 MW plants (Shields et al. 2021b). Linearly interpolating both fixed-bottom and floating offshore wind calculated in Puerto Rico to 2032 yields a range of $68/MWh–$146/MWh and mean of $110/MWh (11 cents/kWh). The higher costs in Puerto Rico are driven by lower wind speeds throughout the year and resulting lower values of NCF. Development of offshore wind turbine designs optimized for regions with lower average wind speeds like Puerto Rico and the Gulf of Mexico (lower specific-power turbines), could potentially result in lower costs than those presented here, if they also account for typhoon design conditions. See Appendix A for discussion of the impact of lower specific-power land-based turbines on energy production and LCOE.

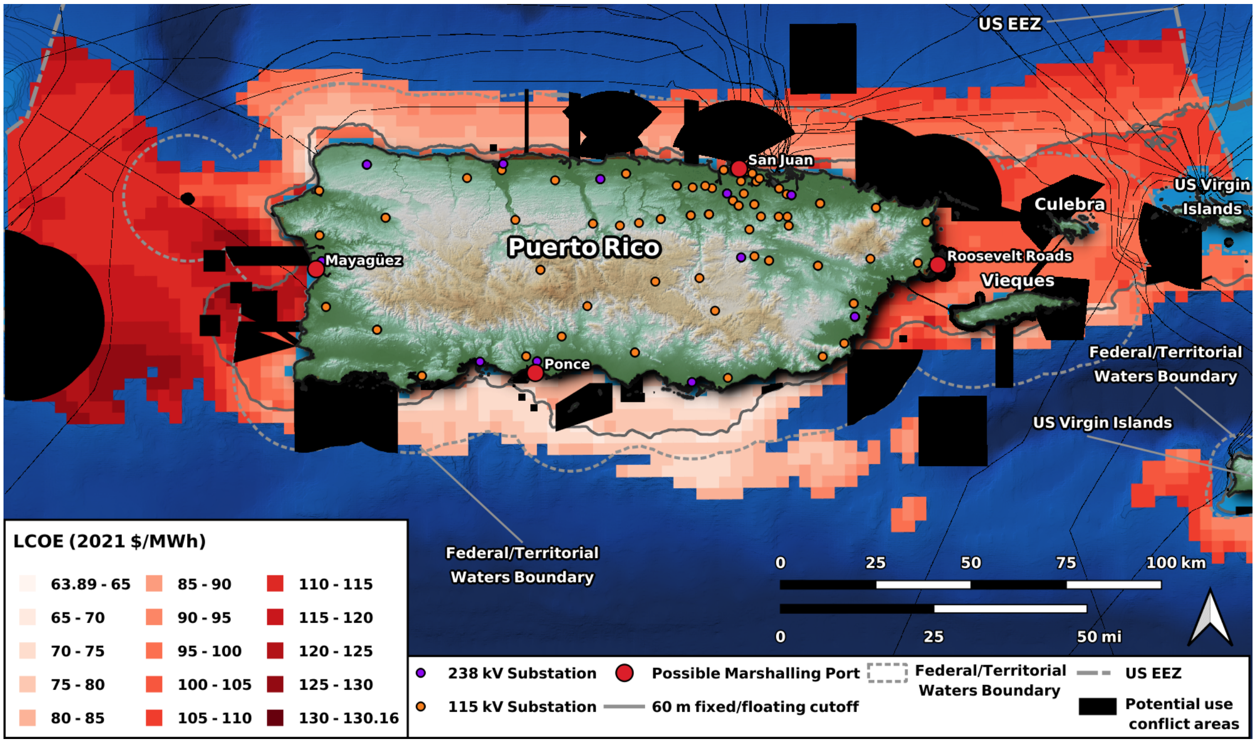

Figure 44. Projected LCOE in 2035

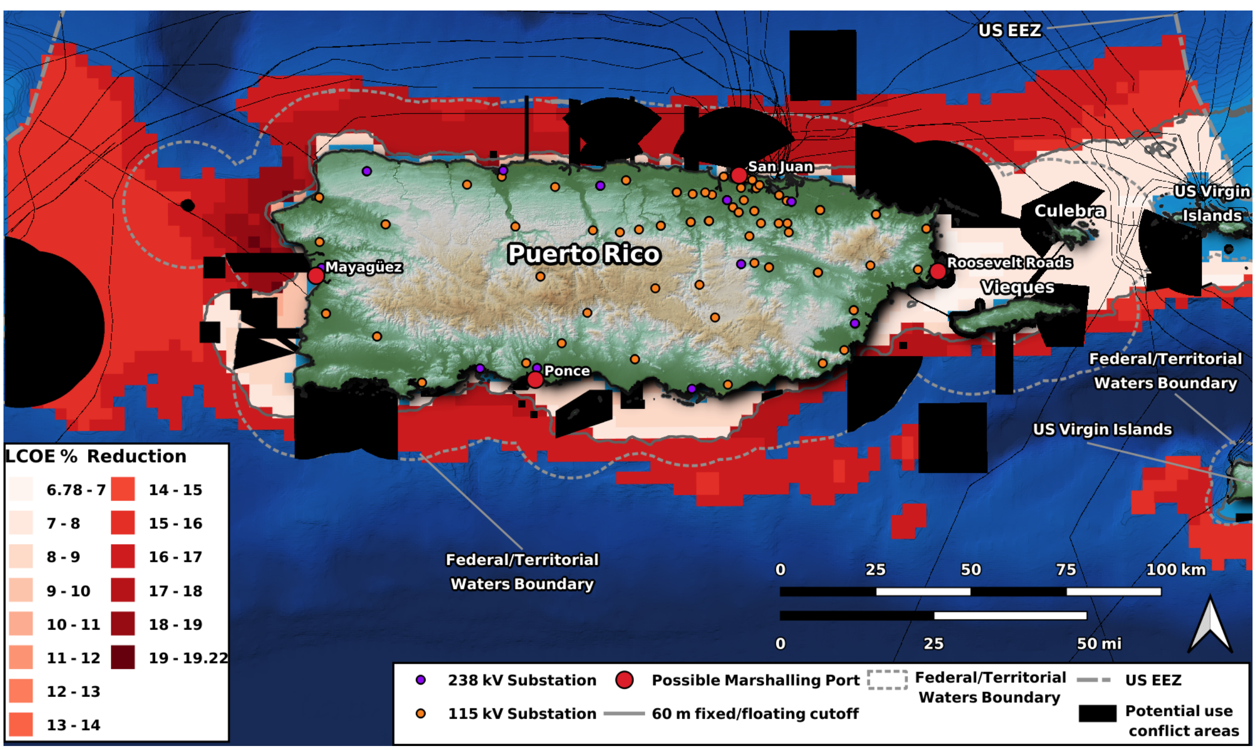

Figure 45. Reductions in LCOE between 2030 and 2035. LCOE is, on average, 14% lower in 2035 than in 2030.

7.2.6 Sensitivities

To better understand the cost results for offshore wind we investigate sensitivities relating to technical potential, uncertainty in primary LCOE inputs, and the possibility of using the (congested) Port of San Juan to support offshore wind construction.

Offshore Technical Potential

In Section 2, we defined the boundaries of the offshore study area based on 1,300 m technology depth limit. This reflects the cost effective limit of current mooring technologies, though these are rapidly developing with the floating offshore wind industry as a whole. If future mooring systems enable projects in deeper waters, the 1,300 m depth constraint underestimates the technical potential. Increasing the depth limit from 1,300 to 2,600 m- in line with announced BOEM Call Areas in the Central Atlantic- increases the available area from 13,587 km^2 to 19,004 km^2. Technical potential increases from just under 41 GW to 57 GW (based on an assumed capacity density of 3 MW/km^2). This represents a 39% change. Note that we do not account for potential use conflict areas which may exist between 1,300 m and 2,600 m, nor does this consider any constraints related to seafloor topography..

The other factor impacting technical potential is the assumed capacity density of 3 MW/km^2. While consistent with previous NREL work (Musial et al. 2013; Musial et al. 2016; Musial et al. 2022), this value is likely conservative and should just be used for initial planning purposes. An analysis of existing European wind farms in the Baltic Sea found capacity densities exceeding 5 MW/km^2 (Borrmann et al. 2018). If applied to Puerto Rico, increasing the assumed capacity density from 3 MW/km^2 to 5 MW/km^2 yields a maximum capacity per modeled grid cell of 1 GW and a total technical potential of nearly 68 GW.

Uncertainty in Input Costs

As with land-based wind, we investigate the impacts of the main primary inputs of LCOE (e.g., CapEx, OpEx, NCF, finance parameters). We do this by taking the mean values of each of these components in 2035 and calculate a reference LCOE of $97/MWh. Then we recalculate LCOE after varying each of the primary inputs one at a time by plus and minus 10%. The resulting ranges of LCOE are presented in Figure 46. It can be seen that NCF has the largest impact on LCOE, followed by the FCR and CapEx.

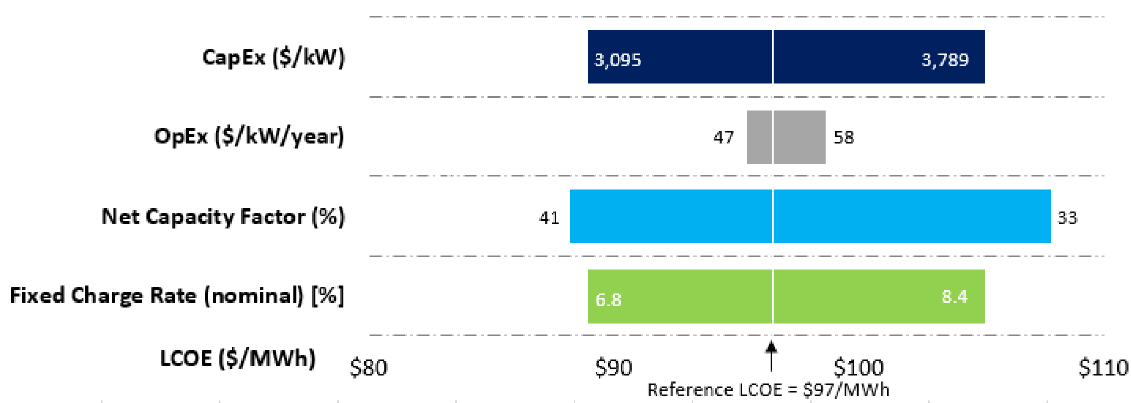

Figure 46. Offshore wind LCOE sensitivity to primary inputs (2035 average values of CapEx, OpEx, NCF, finance parameters)

Additional Construction Port in San Juan

Given that installation and O&M costs are primarily functions of the distance to port, we conducted a sensitivity analysis to identify if including San Juan as a possible marshalling and O&M port would result in lower costs. As mentioned in Section 5, the Port of San Juan was not utilized in the main cost modeling analysis because it is congested with vessel traffic from other industries. We found that including the port resulted in a maximum reduction in LCOE of less than 3%, and an average reduction in LCOE of 0.11% across all sites (see Figure 47). This estimate does not include port upgrade costs or any other factors that could impact the availability and costs of offshore wind installation ports in Puerto Rico.

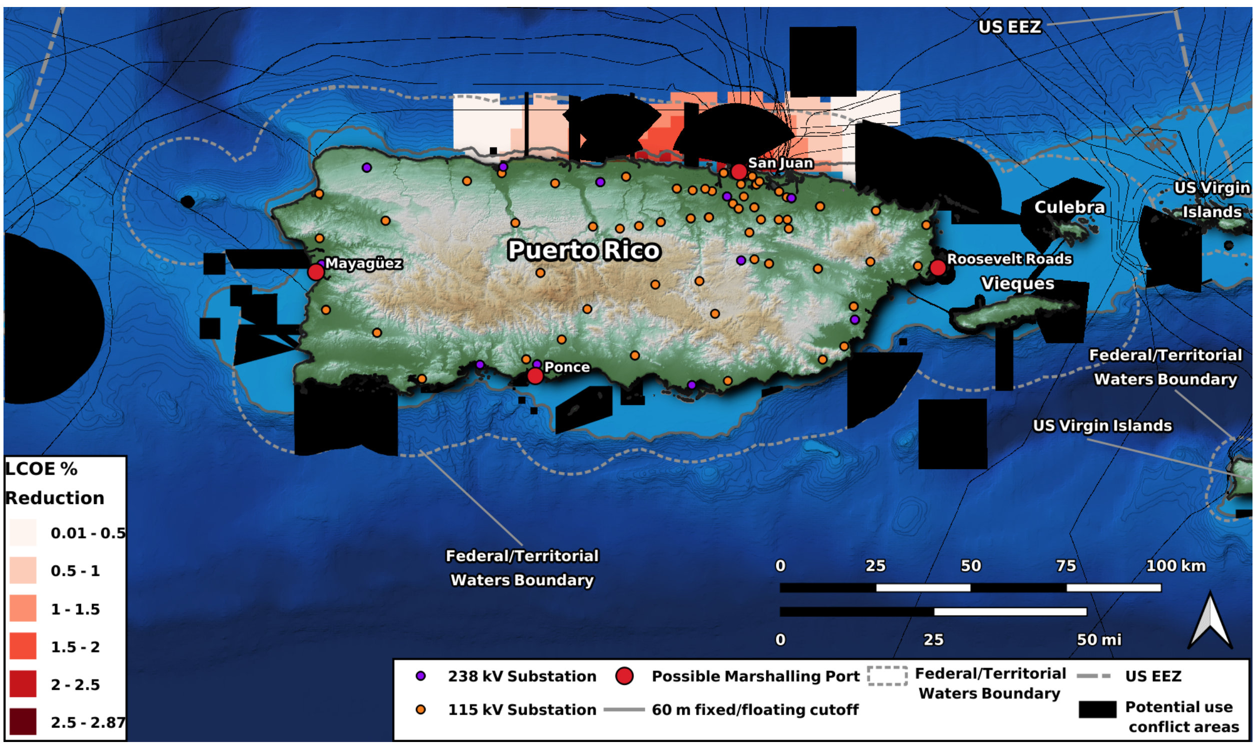

Figure 47. LCOE reductions when including San Juan as a construction and operation Port; mean reduction of 0.11 % across all sites

8 Conclusion

NREL evaluated wind energy costs and technical potential in Puerto Rico to inform decision makers about this resource before the next integrated resource plan as they consider pathways to 100% renewable electricity. We used NREL's reV model to estimate how capital expenditures, operational expenditures, net annual energy generation, and levelized cost of energy vary in time and space for both land-based and offshore wind energy plants around Puerto Rico. This project was funded through an interagency agreement between the Federal Emergency Management Agency and the U.S. Department of Energy.

The key results from the study include:

- Puerto Rico's small size means that land use presents a series of challenges as the grid moves towards 100% renewable electricity, as required by the Puerto Rico Energy Public Policy Act of 2019 (Law 17-2019). Deployment of offshore wind energy may help mitigate some of these concerns, but presents other challenges.
- An estimated technical potential capacity of 6.81 GW for land-based wind and 40.76 GW for offshore wind, represents many times more than LUMA's projected 2023 peak power demand of 2.96 GW in the highest load month.
- Turbine technology development is critical for low-cost wind energy deployment in Puerto Rico. Existing Typhoon-Class turbine designs can help enable wind energy development in hurricane-prone regions, at a marginal cost premium relative to the total turbine cost. Future development of offshore wind turbines optimized for lower wind speed regions like Puerto Rico and the Gulf of Mexico may lead to even lower costs than estimated in this report.
- Evening and nighttime electricity production from wind, especially offshore, can complement the solar resource, which is only produced during daylight hours.
- Resulting LCOE ranges for land-based and offshore wind energy are summarized in Tables 16 and 17, respectively. The lowest land-based wind LCOE is in the southeastern region of the island, where capacity factors are highest despite limited developable area. The lowest offshore wind costs are south of the island, encompassing both floating and fixed-bottom substructures.

Table 16. Summary of land-based wind costs and energy production

Year	Mean LCOE ($/MWh)	Minimum LCOE ($/MWh)	Maximum LCOE ($/MWh)	Mean NCF (%)
2022	$107	$58	$228	22%
2030	$95	$52	$204	22%
2035	$69	$43	$139	36%

Table 17. Summary of offshore wind costs and energy production

Year	Mean LCOE ($/MWh)	Minimum LCOE ($/MWh)	Maximum LCOE ($/MWh)	Mean NCF (%)
2030	$116	$71	$156	35%
2035	$100	$64	$130	37%

While these projections do not include transmission system upgrade costs, these future costs are significantly lower than current (June 2022) electricity prices in Puerto Rico as reported by the Energy Information Administration of almost 30 cents/kWh ($300/MWh). Based on this analysis, wind energy can play a key role in helping Puerto Rico achieve its clean energy goals.

9 Caveats and Future Work

Over the course of this study we attempted to customize wind energy cost models and develop representative wind energy technology deployment scenarios to help understand the likely range of costs in Puerto Rico. Where possible, we indicated points of conservatism and optimism. Below are the main caveats and limitations which, with additional research, would help increase the robustness of the results presented in this report.

- The baseline offshore wind cost models used in this study assume mature supply chains in the Gulf of Mexico produce and ship major components to Puerto Rico where they are assembled quayside at the construction port. The fixed-bottom offshore wind supply chain must develop rapidly to support the existing pipeline of projects on the U.S. East Coast.
- The LCOE estimates provided in this report did not include bulk power system upgrade costs or additional infrastructure costs associated with batteries and grid-forming inverters required by the PREPA minimum technical requirements. Depending on the location and size of wind farms, these could be substantial.
- Floating offshore wind technologies assumed the same cost increase for IEC Typhoon-Class machines and foundations as fixed-bottom technologies, but more understanding is needed of how extreme designs and costs differ between fixed and floating technologies.
- O&M costs presented in this report are based on the legacy ORCA model and offshore assume cost advantages for floating offshore wind based on a tow-to-port strategy. O&M cost data is difficult to obtain and NREL is actively validating its new offshore wind O&M model (WOMBAT[11]).
- Offshore depth limits potential capacity based on the current understanding of cost-effective mooring designs for floating systems. As mooring technology improves, the buildable area offshore will likely increase as will the potential for floating offshore wind energy.

Future Work

More information is necessary to fully understand the comprehensive impacts and value of wind energy development in Puerto Rico. We recommend the following future work, some of which has already begun:

- Quantifying the full value of wind energy in Puerto Rico via detailed modeling (capacity expansion and production cost modeling) of the whole electric system under a range of scenarios, which the PR100 Study will develop based on the cost data presented in this report.
- Investigating opportunities for shared infrastructure investments with Caribbean neighbors and the role Puerto Rico could play in the supply chain or jobs creation. These investments could be in transmission, ports, or manufacturing-related infrastructure to support renewable energy development. Further discussions with project developers and component manufactures are needed to better understand their perspectives. There is also a need for a comprehensive investigation of workforce requirements and potential benefits.
- Assessing the detailed physical requirements and necessary upgrade costs for ports in Puerto Rico to support offshore wind energy. The Energy Public Policy Program of the Department of Economic Development and Commerce in Puerto Rico is working to develop an offshore wind ports assessment with Ana G. Mendez University and Simply Blue Group.
- Developing deeper understanding and cooperative partnerships regarding wind and solar energy siting to meet clean energy goals and balance the land use and water use needs of stakeholders.
- Conducting wind energy viewshed analysis in conjunction with a broad spatial planning discussion between stakeholders.
- Quantifying hurricane risks for Typhoon-class wind turbines in more detail. NREL is actively working with BOEM and other entities to better understand hurricane risks to offshore wind energy.

[11] Follow the progress on GitHub: https://github.com/WISDEM/WOMBAT.

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Appendix A. Lower-Specific-Power Wind Turbines

This sensitivity aims to quantify the difference in operating costs, such as insurance cost, that could be incurred between a Class III and Typhoon-Class wind turbine for an equivalent LCOE. This exercise may help in decision-making once hurricane extreme wind speed risk is determined for various locations in Puerto Rico. We opted to include this in an appendix because while this quantification is important, our discussions with insurers indicated that securing insurance for a project opting for non-Typhoon-Class machines in a hurricane-prone region may be difficult-to-impossible.

For land-based wind turbines in 2022, modeled costs with a representative Typhoon Class turbine with a 117-m rotor. In this example, we compare costs of the 117-m 4.2-MW Typhoon Class and the 150D 4.2-MW Class III wind turbines. Both turbines are 4.2 MW with the Typhoon-Class-rated turbine having a rotor diameter of 117 m and the Class III turbine having a 150-m rotor diameter.

Under the assumptions listed in Table A.1, a wind farm using the 150D turbines could incur a $46.8/kW yr, or $197,000/yr per turbine, higher OpEx than the 117D turbine for the equivalent LCOE value. This is due to the higher energy production enabled by the larger rotor. The OpEx assumed for the 117D turbine is taken from the 2021 Land-based Wind Technologies Market report of $26/kW-yr for U.S. wind farms from 2015 to 2019 with a 25% additional cost for wind farms in Puerto Rico (Wiser et al. 2021b). If a location can use the 150D turbine in this example an had insurance costs less than $197,000/yr compared, then overall LCOE would be lower for the 150D turbine compared to the 117D Typhoon-Class turbine.

When examining the effects that an increased rotor diameter has on net capacity factor in Puerto Rico, we found the 150D turbine has an average net capacity factor that is 64.3% higher than the 117D turbine, across all sites, due to the larger rotor swept area and higher hub height (see Figure A.1). This is critical when considering the value of a less Typhoon-Class turbine at a location compared to a Class III turbine with greater NCF, especially in an area where available land is minimal.

Table A.1. 2022 Land-Based Wind Typhoon Class Vs. Class III - Breakeven OpEx

Note: these numbers to not represent a specific site in this study.

Turbine	Turbine Configuration	BOS Cost ($/kW)	Turbine Cost ($/kW)	Capacity Factor (%)	LCOE ($/MWh)	OpEx ($/kW-yr)
117 D (Typhoon-Class)	4.2 MW T 91.5-m hub height	$527	$1,015	29.3%	$52.0	$32.5
150 D (Class III)	4.2 MW T 105-m hub height	$510	$1,011	41.6%	$52.0	$79.3

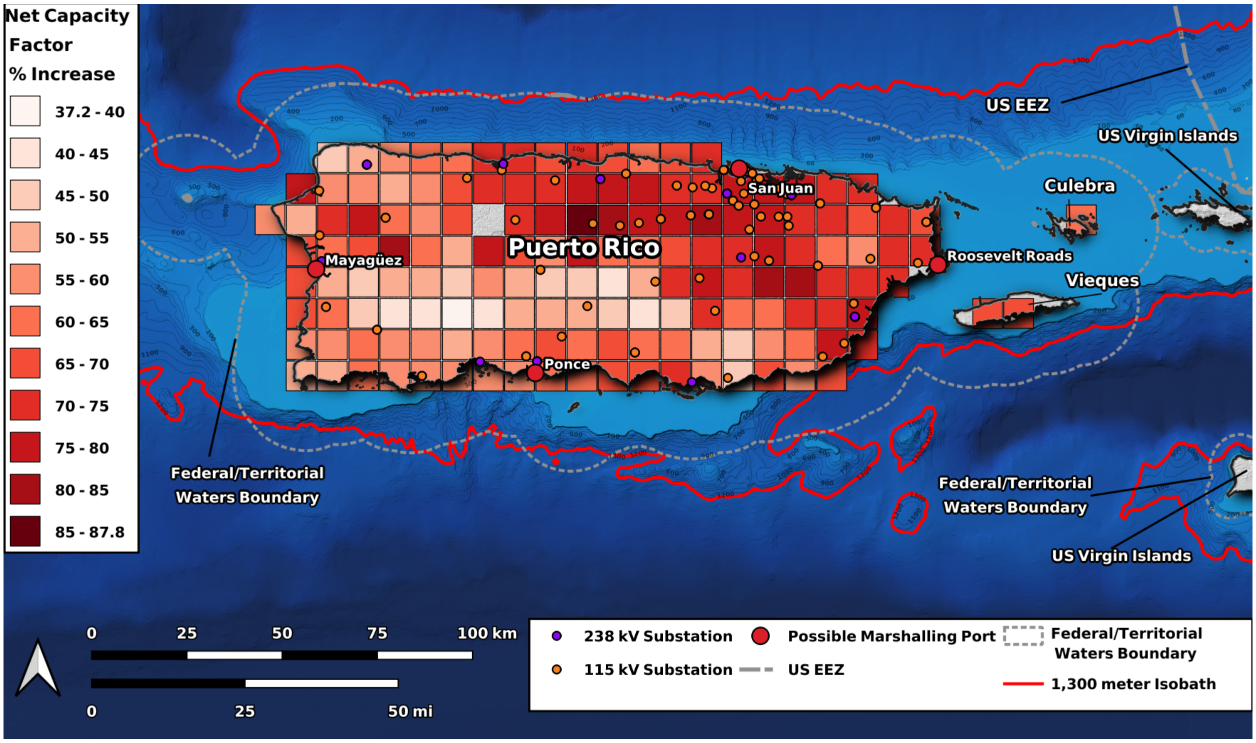

Figure A.1. NCF increases when using the 150-m rotor diameter turbine in 2022 compared to the 117D rotor diameter turbine also in 2022; mean increase of 64.3%

Depending on site-specific insurance costs and extreme wind speed risk resulting from hurricanes wind turbines not rated for typhoon conditions may present an opportunity to increase the generation of land-based wind in Puerto Rico. The increased energy captured by the larger 150D rotor turbine can offset increased operational or insurance costs compared to the 117D Typhoon-Class-rated turbine. Due to the increased energy production, we found the LCOE for the 150D turbine in 2022 would be, on average across all sites, 40.9% lower than the LCOE for the 117 D Typhoon-Class turbine in 2022 (see Figure A.2). Given the significant reduction in LCOE associated with larger rotors, the trade-off between the increased costs of insuring a 150D wind turbine that is not Typhoon Class and the lowered LCOE needs to be investigated further.

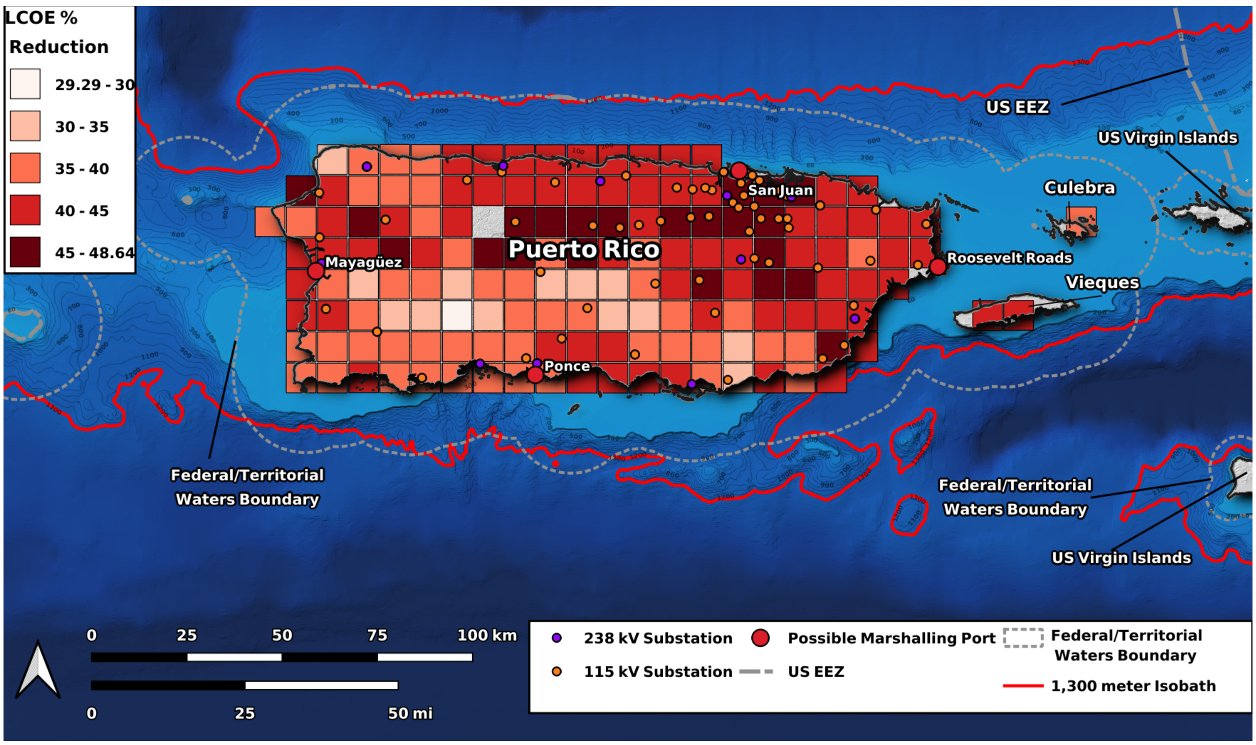

Figure A.2. LCOE reductions when using 150D wind turbine in 2022 compared to 117 m RD also in 2022; mean reduction of 40.9%

Appendix B. PREPA Minimum Technical Requirements

The most recent minimum technical requirements from the PREPA IRP are included below:

MINIMUM TECHNICAL REQUIREMENTS FOR INTERCONNECTION OF WIND TURBINE GENERATION (WTG) PROJECTS

The Seller shall comply with the following minimum technical requirements:

1. VOLTAGE RIDE-THROUGH:

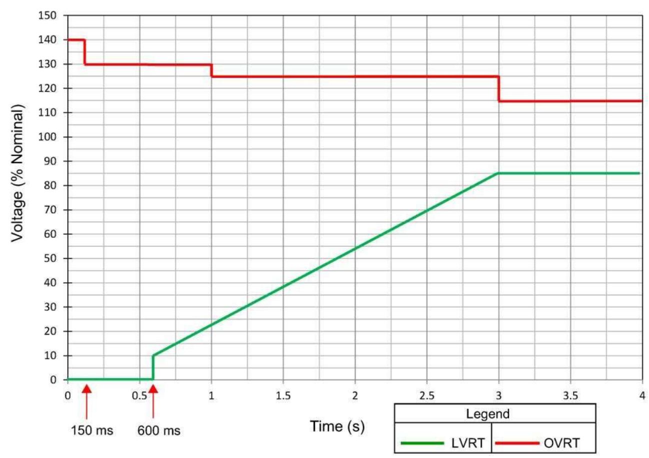

Figure 1 Voltage Ride-Through Requirements

a. T&D OPERATOR's Low Voltage Ride-Through (LVRT) Requirements:

i. From Figure 1, T&D OPERATOR requires all generation to remain online and be able to ride-through three phase and single phase faults down to 0.0 per-unit (measured at the point of interconnection), for up to 600 ms.

ii. All generation remains online and operating during and after normally cleared faults on the point of interconnection.

iii. All generation remains online and operating during backup-cleared faults on the point of interconnection.

iv. During the low voltage fault conditions, the wind generation facility shall operate on reactive current injection mode. This mode of operation shall be implemented with a reactive current droop characteristic which shall have an adjustable slope from 1 to 5%. A dead band of 15 % is required.

b. T&D OPERATOR's Overvoltage Ride-Through (OVRT) Requirements:

   i. T&D OPERATOR requires all generation to remain online and able to ride- through symmetrical and asymmetrical overvoltage conditions specified by the following values illustrated in Figure 1:

Overvoltage (pu)	Minimum time to remain online
1.4 – 1.3	150 ms
1.3 – 1.25	1 s
1.25 – 1.15	3 s
1.15 or lower	indefinitely

2. VOLTAGE REGULATION SYSTEM (VRS)

Constant voltage control shall be required. Wind Turbine Generation (WTG) technologies in combination with Static Var Controls, such as Static Var Compensators (SVCs) and STATCOMs are acceptable options to complywith this requirement. A complete and detailed description of the VRS control strategy shall be submitted for evaluation.

a) Wind Generation Facilities (WGF) must have a continuously-variable, continuously-acting, closed loop control VRS; i.e. an equivalent to the Automatic Voltage Regulator in conventional machines.

b) The VRS set-point shall be adjustable between 95% to 105% of rated voltage at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer). The VRS set-point must also be adjustable by T&D OPERATOR's Energy Control Center via SCADA.

c) The voltage regulation at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer) shall be based in direct measurement of the Interconnection Facility Interconnection Facility (connection toT&D OPERATOR TC or sectionalizer) voltage. Line drop compensation or similarstrategies shall not be permitted.

d) The VRS shall operate only in a voltage set point control mode. Controllers such as Power Factor or constant VAR are not permitted.

e) The VRS controller regulation strategy shall be based on proportional plus integral (PI) control actions with parallel reactive droop compensation. The VRS Droop shall be adjustable from 0 to 10%.

f) At zero percent (0%) droop, the VRS shall achieve a steady-state voltage regulation accuracy of +/- 0.5% of the controlled voltage at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer).

g) The VRS shall be calibrated such that a change in reactive power will achieve 95% of its final value no later than 1 second following a step change in voltage. The change in reactive power should not cause excessive voltage excursions or overshoot. If a voltage overshoot is generated during a change in reactive power its value shall be less than 1%.

h) The generator facility VRS must be in service at any time the WGF is electrically connected to the grid regardless of MW output from the WGF.

i) The VRS dead band shall not exceed 0.1%.

3. Reactive Power Capability and Minimum Power Factor Requirements

The total power factor range shall be from 0.85 lagging to 0.85 leading at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer). Thereactive power requirements are necessary to provide support to the system operation based on the voltage profile and reactive power needs. The intent is that a WGF can ramp the reactive power from 0.85 lagging to 0.85 leading in a smooth continuous fashion at the Interconnection Facility(connection to T&D OPERATOR TC or sectionalizer).

The +/- 0.85 power factor range should be dynamic and continuous at the point of interconnection Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer). This means that the WGF has to be able to respond to power system voltage fluctuations by continuously varying the reactive output of the plant within the specified limits. The previously established power factor dynamic range could be expanded if studies indicate that additional continuous, dynamic compensation is required. It is required that the WGF reactive capability meets +/- 0.85 Power Factor (PF) range based on the WGF Aggregated MW Output, which is the maximum MVAr capability corresponding to maximum MW Output. It is understood that positive (+) PF is where the WGF is producing MVAr and negative (-) PF is where the WGF is absorbing MVAr.

This requirement of MVAr capability at maximum output shall be sustained throughout the complete range of operation of the WGF as established by Figure 2. The MVAr capability shall also be sustained throughout the complete Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer) voltage regulation range (95% to 105% of rated voltage at the Interconnection Facility).

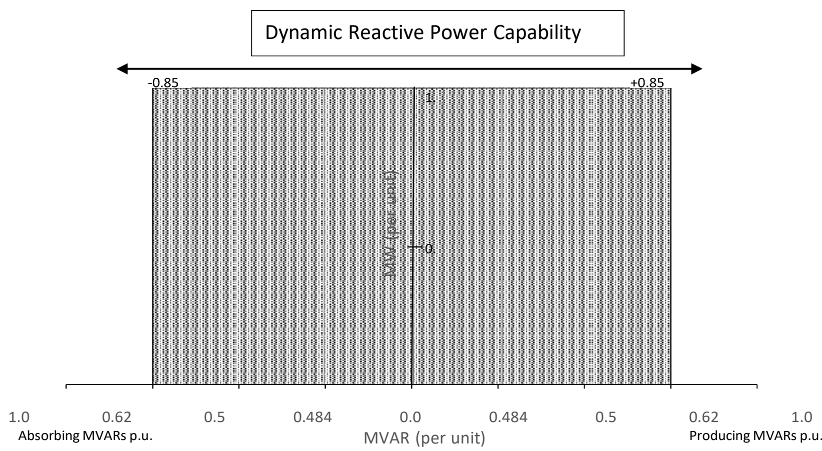

Figure 2 Reactive Power Capability Curve

4. SHORT CIRCUIT RATIO (SCR) REQUIREMENTS:

Short Circuit Ratio values (System Short Circuit MVA at POI/WGF MVA Capacity) under 5 shall not be permitted. The Seller shall be responsible for the installation of additional equipment, such as synchronous condensers, and controls necessary to comply with T&D OPERATOR's minimum short circuit requirements.

T&D Operator will study the short-circuit strength requirements using the equivalent short-circuit ratio (ESCR) as part of system impact studies and will advise the developer of any required upgrades.

5. SUBSYNCHRNOUS RESONANCE and SUBSYNCHRONOUS TORSIONAL INTERACTION SCREENING:

An interconnection study for a wind farm shall include screening for the potential of causing subsynchronous stresses on nearby generation. This screening shall examine N-1, N-1-1 and other potential contingent or operating conditions specified by the T&D OPERATOR.

6. FREQUENCY RIDE THROUGH (FRT):

- 57.5 - 61.5 Hz No tripping (continuous)
- 61.5 - 62.5 Hz 30 sec
- 56.5 - 57.5 Hz 10 sec
- < 56.5 or > 62.5 Hz Instantaneous trip

7. FREQUENCY RESPONSE/REGULATION:

WTG facility shall provide an immediate real power primary frequency response, proportional to frequency deviations from scheduled frequency, similar to governor response. The rate of real power response to frequency deviations shall be similar to or more responsive than the droop characteristic of 3-5% range used by conventional generators. WTG facility shall have controls that provide both for down-regulation and up-regulation. Wind turbine technologies, in combination with energy storage systems such as, but not limited to battery energy storage systems (BESS), and flywheels are acceptable options to comply with T&D OPERATOR's frequency response and regulation requirements.

The WTG facility response shall be proportional to the frequency deviation, based on the specified 3-5% range droop characteristic. The droop shall be configurable from 3% to 5% in steps of 0.5% (3.0%, 3.5%, 4.0%, 4.5%, 5.0%). The frequency response dead band shall not exceed 0.02%. For large frequency deviations (for example in excess of 0.3 Hz), the WGF shall provide an immediate real power primary frequency response of at least 10% of the maximum AC active power capacity (established in the contract). The time response (full 10% frequency response) shall be less than 1 second. Frequency response shall not be limited by, and shall be decoupled from, the ramp rate control. The frequency response of the facility shall be continuously in operation, even during ramp rate events. After the two decoupled functions are added together, the facility shall be able to simultaneously comply with both requirements.

If energy storage systems are utilized to comply with the frequency regulation requirements, and during a disturbance the system frequency stays below 59.7 Hz, the facility frequency response shall be maintained for at least 9 minutes. After the ninth minute the real power primary frequency response shall not decrease at a ramp rate higher than 10% of the maximum AC active power capacity per minute. The energy storage systems utilized to comply with the frequency regulation requirement shall be designed based on a storage capacity equivalent to at least 9.5 minutes of the 10 % AC contracted capacity measured at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer) for downward frequency events, and a similar amount for upward frequency events. This represents an equivalent of 9 minutes full participation, plus one minute ramp down complying with the ramp rate requirement. This energy will be used on a continuous basis for regulation against frequency deviations. During

periods of time were the energy storage system utilized to comply with the frequency regulation requirement is completely charged (cannot absorb more power), the WTGs inverters will assume the responsibility of the upward frequency events. If the energy available for frequency regulation is drained, the function shall be restored in a time period less than 10 minutes and with at least 95% of the energy capacity restored. The energy charging process shall not affect the ramp rate control requirement or the frequency regulation of the grid.

The operational range of the frequency response and regulation system shall be from 10% to 110% of the maximum AC active power capacity (established in the contract). The WGF power output at the POI shall not exceed the maximum AC active power (established in the contract) except to comply with the frequency response requirement.

8. Ramp Rate Control:

Ramp Rate Control is required to smoothly transition from one output level to another. The WTG facility shall be able to control the rate of change of power output during some circumstances, including but not limited to: (1) rate of increase of power, (2) rate of decrease of power, (3) rate of increase of power when a curtailment of power output is released; and (4) rate of decrease in power when curtailment limit is engaged. A 10 % per minute (0.1667 % per second) rate (based on AC contracted capacity) limitation shall be enforced. This ramp rate limit applies both to the increase and decrease of power output and is independent of meteorological conditions. The ramp rate control tolerance shall be +10%.

The energy storage system utilized to comply with the ramp rate control requirement shall be designed based on a minimum storage capacity equivalent to 25 minutes of the 30 % AC contracted capacity measured at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer). Theminimum nominal power output capacity of the energy storage system utilized to comply with the ramp rate control requirement shall be 30% of AC contracted capacity measured at Interconnection Facility (connectionto T&D OPERATOR TC or sectionalizer); and for at least one (1) minute, a minimum effective power output capacity of 45% of AC contracted capacity measured at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer). The transition from effective power output capacity tonominal power output capacity shall not exceed the ramp rate requirement of 10% per minute.

The Frequency Response/Regulation and Ramp Rate Control functions shall be decoupled, continuously in operation and the facility shall be able to comply simultaneously with both requirements, while the windgeneration facility is generating and injecting power to the grid. This meansthat the energy storage system shall include, as a minimum: 10% of the contracted capacity for Frequency Response/Regulation for at least 9.5 minutes (see section 6 for details) and 30% of contracted capacity for Ramp Rate Control for at least 25 minutes. The energy storage system shallalso be able to provide a minimum effective capacity of 45% of the contracted capacity for at least one (1) minute at the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer). Therefore, the minimum acceptable capacity for the energy storage system is a total combined size of 40% of contracted capacity, and for at least one (1) minute, the system has to have an effective capacity of 45% of the contracted capacity.

Rates of change in active power at the wind generation facility's Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer) in excessof the 10 % per minute rate requirement caused by the loss of generating resource (wind availability) that require more than the minimum storage capacity defined in this MTRs document, will not be considered in non- compliance with the ramp rate control requirement. Therefore, if the ramp is controlled within the limits specified in the requirement, or if the storage system cannot control the ramp rate because it is outside of its minimum required capabilities, but performs as specified, the wind generation facility will not be considered in non-compliance. However, if the energy storage system cannot control the ramp rate as required because does not perform according to at least with the minimum required capabilities specified in this MTRs document, the wind generationfacility will be considered in non-compliance.

9. Auto-curtailment

The Seller shall implement an auto-curtailment strategy for the WTG Facility to address and compensate deficiencies that can affect the Plant compliance with the MTRs. Some of the conditions to apply auto-curtailment are:

a. A reduction on the reactive power capacity of the facility (by example due to WTGs out of service, any other condition that can reduce the required reactive power capacity of the facility).

b. A reduction in the active power capacity of the storage system (by example loss of some of the battery strings, a BESS inverter out of service, any other condition that can reduce the required active power capacity of the energy storage system).

c. Loss of the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer) readings used for the different controls (voltage, frequency, ramp, etc.) of the facility. This can happen due to a malfunction of the equipment used for the Interconnection Facility (connection to T&D OPERATOR TC or sectionalizer) readings. In this case the curtailment should be to zero.

d. A fault in the Voltage Control, Frequency Response Control, Ramp Rate Control. In this case the facility should be curtailed to zero output.

e. Any other condition not mentioned here but that based in the facility design can cause a non-compliance with the MTRs.

A complete and detailed description of the auto-curtailment strategy shall be submitted for evaluation.

10. Power Quality Requirements:

The Seller shall address, in the design of their facilities potential sources and mitigation of power quality degradation prior to interconnection. Design considerations should include applicable standards including, but not limited to IEEE Standards 142, 519, 1100, 1159, and ANSI C84.1, IEC 61400-21, IEC 61000-3-7 and IEC 61000-3-6. Typical forms of powerquality degradation include, but are not limited to voltage regulation, voltage unbalance, harmonic distortion, flicker, voltage sags/interruptions and transients.

11. Wind Power Management

WTG facility shall provide adequate technology (communicating technology and the corresponding control equipment) and implement wind power management requirements (ramp rate limits, output limits, curtailment) as established by T&D OPERATOR.

12. Special Protection Schemes:

WTG facility shall provide adequate technology and implement special protection schemes as established by T&D OPERATOR in coordination with wind power management requirements.

13. Wind Generation Forecasting Systems

WTG facility shall provide adequate technology to support wind generation forecasting systems (short term and day-ahead) as established by T&D OPERATOR. Individual turbine's availability shall be included.

14. General Interconnection Substation Configuration

An interconnecting generation producer must interconnect at an existing T&D OPERATOR switchyard, unless otherwise approved by T&D OPERATOR in the contract. The configuration requirements of the interconnection depend on wherethe physical interconnection is to occur and the performance of the system with the proposed interconnection. The interconnection must conform, at a minimum, to the original designed configuration of the switchyard. T&D OPERATOR, at its sole discretion, may consider different configurations due to physical limitations at the site.

15. Modeling and Validation

Once final adjustments and parameter settings related with commissioning and MTR compliance tests are completed, the Seller shall submit a mathematical model compatible with versions 33.12 and 34.7 of PSS/E, and validation report.

When referred to the mathematical model, this shall include but is not limited to wind generator, transformers, collector systems, plant controllers, control systems and any other equipment necessary to properly model the WTG facility for both steady-state and dynamic simulation modules.

The Seller shall be required to submit user manuals for both the Wind Turbine Generator and WTG Facility models including a complete and detailed description of the voltage regulation system (VRS) and frequency regulation system model implementation. The mathematical models shall be fully compatible with versions 33.12 and 34.7 of PSS/E. It is preferred that the models are PSS/E standard models. In the case that the Seller submits user written models, the Seller shall be required to keep these models current with the future versions of the PSS/E program until such time that PSS/E has implemented a standard model. The Seller shall submit to T&D OPERATOR an official report that validates and certifies the required mathematical models, including subsequent revisions. The Seller shall be responsible of submitting the official reports and certifications, otherwise the mathematical model shall not be considered valid.

The Seller shall be responsible to submit validated PSS/E mathematical models of any kind of compensation devices (ie. SVC, STATCOMs, BESS, etc.) used on the WTG facility. It is preferred that the models are standard models provided with PSS/E. In the case that the Seller submits user written models, the WTG facility Seller shall be required to keep these models current with the future versions of the PSS/E program until such time that PSS/E has implemented a standard model. In its final form, the mathematical model shall be able to simulate each of the required control and operational modes available for the compensation device and shall be compatible with the latest and future versions of PSS/E. The model shall reflect final adjustments and parameters settings related with the control system commissioning process and shall be incorporated to the PSSE mathematical model and tested accordingly by the WTG facility Seller and T&D OPERATOR system study groups. The Seller shall be responsible of submitting the official reports and certifications, otherwise the mathematical models shall not be considered valid.

WTG facility Owners that provide user written model(s) shall provide compiled code of the model and are responsible to maintain the user written model compatible with current and new releases of PSS/E until such time a standard model is provided. T&D OPERATOR must be permitted by the

Owner to make available WGF models if required to external consultants with an NDA in place.

The Seller shall submit a PSS/E model validation report. This report shall demonstrate PSS/E simulation results that show the model MTR compliance and performance, based on final adjustment and parameter settings of MTR and commissioning field tests. The Seller shall be responsible of submitting the official reports and certifications, otherwise the mathematical models shall not be considered valid.

Additional details for the adequate PSS/E modeling and the contents of the PSS/E validation report can be found in T&D OPERATOR's "Guidelines on PSS/E Mathematical Models" document.

16. Transient Mathematical Model

The Seller shall be responsible of providing a detailed transient model of the WTG facility and to show that it is capable of complying with T&D OPERATOR's transient Minimum Technical Requirements.

PSCAD simulation shall be performed under as similar conditions as possible to the PSS/E simulations discussed above, for the best possible comparison.

PSCAD models are required to support current and future study efforts which are required to maintain a reliable power system. A study based on PSCAD would require a model which has the following characteristics, and unless specified otherwise, this type of model is what is required:

a. Model Accuracy Features

For the model to be sufficiently accurate, it shall:

i. Represent the full detailed inner control loops of the power electronics. The model cannot use the same approximations classically used in transient stability modeling, and shall fully represent all fast inner controls, as implemented in the real equipment. It is possible to create models which embed the actual hardware code into a PSCAD component, and this is the best type of model.

ii. Represent all pertinent control features (e.g., external voltage controllers, plant level controllers, phase locked loops, etc). Operating modes that require system specific during the system impact study adjustment shall be user-accessible. In particular, plant level voltage control shall be represented along with adjustable droop characteristics.

iii. Represent all pertinent electrical and mechanical configurations, such as filters and specialized transformers. There may be other mechanical features (such as gearboxes, pitch controllers, etc.) which shall be modeled if they impact electrical performance.

iv. Have all pertinent protections that are relevant to network performance shall be modeled in detail for both balanced and unbalanced fault conditions. Typically this includes various OV and UV protections (individual phase and RMS), frequency protections, DC bus voltage protections, and overcurrent protection. There may be other pertinent protections that shall be included.

b. Model Usability Features

In order to allow study engineers to perform system analysis using the model, the PSCAD model must:

i. Have control or hardware options which are pertinent to the study accessible to the user. (For example, adjustable protection thresholds or real power recovery ramp rates) Diagnostic flags (e.g. flags to show control mode changes or which protection has been activated) shall be accessible to aid in analysis.

ii. Be capable of running at a minimum time step of 20 microseconds, or no less than 10 microseconds if required by specific control parameters. Most of the time, requiring a smaller time step means that the control implementation has not used the interpolation features of PSCAD, or is using inappropriate interfacing between the model and the larger network. Lack of interpolation support introduces inaccuracies into the model at higher time-steps.

iii. Include user model guide and a sample implementation test case. Access to technical support engineers is desirable.

c. Model Efficiency Features

In addition, the following elements are required to improve study efficiency and enable other studies which include the model to be run as efficient as possible:

i. Model should be compiled using Intel Fortran compiler version 1 2 or higher. Model should not be dependent on a specific Fortran sub-version to run.

ii. Model must run on PSCAD version 4.6.3 or higher.

iii. Initializes as quickly as possible (e.g. < 1-3 seconds) to user supplied terminal conditions.

iv. Support multiple instances of the model in the same simulation.

v. Support the PSCAD “snapshot” feature.

vi. Support the PSCAD “multiple run” feature.

17. Dynamic System Monitoring Equipment

The Seller of the Renewable Energy Facility shall be required to provide, install and commission a dynamic system monitoring equipment that conforms to T&D OPERATOR’s specifications.